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An Integrated Environmental Assessment of a Peri-Urban Amazonian River Informed by Sociohydrological Concepts

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Abstract

Peri-urban Amazonian rivers are increasingly affected by interacting pressures associated with recreational use, land-cover change, water-quality degradation, and flood exposure, requiring integrated approaches to support environmental management. This study developed a multi-indicator environmental assessment of the Tena River (Ecuador), informed by sociohydrological concepts. Flood exposure was evaluated using outputs from a TETIS–Iber hydrological–hydraulic modeling framework previously calibrated and validated for the Tena River basin. Simulated inundation scenarios for 2-, 10-, and 100-year return periods were analyzed at the Puente Ikiam and Tazayaku recreational sites. Riparian vegetation dynamics were evaluated using PlanetScope-derived NDVI (2016–2024), recreational water quality was assessed according to Ecuadorian Ministerial Agreement AM 097-A, and community perception was characterized through surveys and participatory mapping. Hydraulic simulations identified increasing water depths and inundation extents with increasing return periods, while NDVI analysis revealed a decline in dense riparian vegetation between 2016 and 2024. Water-quality monitoring showed episodic fecal coliform exceedances at urban recreational sites, and community responses highlighted strong concern about river degradation but limited collective environmental action. Rather than developing a fully coupled sociohydrological model, this study integrates hydrological, ecological, and social evidence within a sociohydrological framework to identify priority areas for flood-risk management, riparian restoration, water-quality protection, and participatory governance in an urban Amazonian river.

Keywords: Amazonian rivers; flood-prone areas; integrated assessment; participatory management; sociohydrology

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1. Introduction

A crucial theoretical foundation for environmental management is acknowledging that environmental systems are complex, where social and natural components interact dynamically [1]. Sociohydrology is one specific field of this approach that studies the dynamic interactions and co-evolution of human and water systems, emphasizing the feedback mechanisms between these coupled systems [2,3].

Sociohydrology is based on the premise that water and human systems co-evolve, with each system influencing the other bidirectionally [2,4]. Urbanization, land-use changes, and

population growth alter natural water cycles, leading to increased flooding, water scarcity, and ecological degradation [5]. Poor planning amplifies the impact, making urban areas particularly vulnerable [6]. This study aims to promote participatory water management processes among stakeholders, grounded in the sociohydrology framework.

From a sociohydrological perspective, environmental indicators can help explain interactions between human activities and hydrological processes. These indicators provide valuable information on local environmental conditions, supporting impact assessment, adaptive management, and evidence-based decision-making [7]. By quantifying changes in environmental conditions together with human responses, they contribute to evaluating ecosystem resilience and sustainability [8,9]. Within this conceptual framework, integrated assessments combine environmental and social information to identify emerging sociohydrological pressures, characterize human–water interactions, and provide a scientific basis for future coupled sociohydrological modeling.

In Ecuador, a central management instrument for water resources is the delimitation of the Public Water Domain (PWD), a legally defined spatial framework that establishes the areas under direct state jurisdiction for regulation, management, and protection of water bodies [10]. These components include flood-prone zones and natural floodplains, which serve as critical habitats for a diverse range of flora and fauna. They provide breeding and feeding grounds for both aquatic and terrestrial species, especially during low-flow periods [11]. Consequently, identifying and delimiting these floodable areas is an essential tool for water governance, risk management, and land-use planning.

The city of Tena is a clear example of rapid, poorly planned urban expansion in the Ecuadorian Amazon. At the same time, tourism infrastructure has proliferated along riverbanks, often within the PWD, reducing natural riparian buffers and increasing ecosystem vulnerability. Tourism activities can lead to pollution, soil erosion, habitat loss, pressure on endangered species, and increased vulnerability to forest fires [12]. Vegetation cover decreases, and plant populations become simpler, leading to biodiversity loss [13]. Tourism infrastructure negatively affects wildlife, causing stress, disease transmission, and habitat fragmentation [14,15]. These processes illustrate a coupled human–water dynamic in which urbanization and tourism development generate economic opportunities while simultaneously intensifying environmental pressures.

The integrated assessment was complemented with hydrological and hydraulic outputs from the coupled TETIS–Iber modeling framework developed by Hurtado-Pidal et al. [16], together with satellite monitoring based on NDVI. Hydrological and hydraulic modeling and satellite monitoring provide complementary tools for floodplain delineation and vegetation-change assessment [16–18]. TETIS is a spatially distributed hydrological model used to simulate rainfall–runoff processes and generate discharge hydrographs [17], whereas Iber is a two-dimensional hydrodynamic model used to simulate unsteady flood propagation and spatially distributed hydraulic variables in complex river–floodplain systems [18]. Two-dimensional hydrodynamic models allow detailed representation of flood propagation and floodplain inundation patterns [16,17,19]. NDVI, derived from satellite imagery, is widely used to monitor vegetation conditions and detect land-cover changes. It effectively tracks agricultural phenology, assesses ecological responses, and monitors vegetation dynamics over time [20,21].

Protecting and planning the PWD are essential for maintaining hydrological connectivity, biodiversity, and ecosystem services [19]. Climate change and water resource developments pose threats to hydrological connectivity, necessitating adaptive management strategies [20,21]. Community involvement in environmental management can lead to more sustainable social-ecological systems by leveraging local knowledge and fostering a sense of ownership [22–24].

Sociohydrology emphasizes the co-evolution of human and hydrological systems, where changes in one system influence the other through feedback mechanisms [2,4,25]. This approach integrates natural and social sciences to understand how these systems co-evolve over time [26,27]. By integrating hydrological modeling with community perceptions and local knowledge, sociohydrology improves the understanding of current conditions and supports the development of future environmental and management scenarios.

It was hypothesized that recreational and urbanized sectors of the Tena River would exhibit converging indicators of environmental pressure and human exposure, including riparian vegetation modification, exposure to flood-prone areas, water-quality concerns, and community-recognized environmental pressures. This study therefore aimed to develop an integrated environmental assessment of the Tena River informed by sociohydrological concepts. Specifically, the study (i) identified potentially flood-prone areas relevant to river management within the Ecuadorian PWD regulatory framework, (ii) assessed recreational water quality, (iii) quantified temporal changes in riparian vegetation, and (iv) analyzed environmental perceptions and community responses to river degradation. The resulting indicators were integrated to identify management priorities and discuss plausible future management trajectories.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Tena River basin, Napo Province, Ecuador, which drains approximately 240 km^2 in the upper Amazon basin (Figure 1). The Tena River basin exhibits a humid tropical rainfall regime with annual precipitation exceeding 4000 mm and an average temperature of 24 °C [28]. Rainfall is distributed throughout the year; however, the wettest period generally occurs between April and July, while precipitation is relatively lower between December and February. These seasonal variations influence river discharge, floodplain inundation, sediment transport, and water quality dynamics [29].

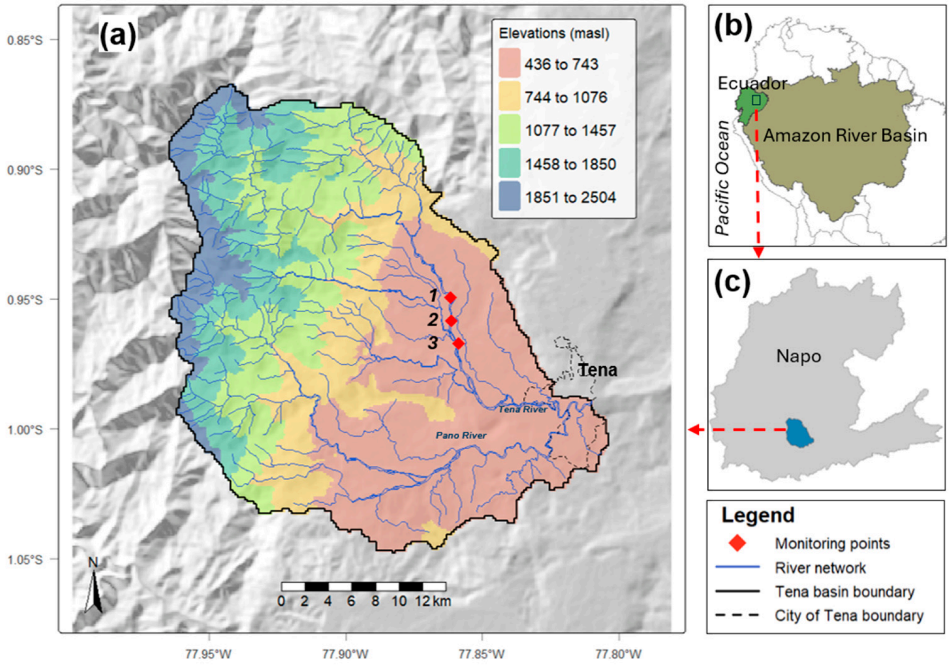


Figure 1. Study area. (**a**) Elevation, river network, monitoring points (1: Tío Mario, 2: Puente Ikiam and 3: Tazayaku), and city boundary within the Tena–Pano river basin; (**b**) location of Ecuador and the Amazon River basin within South America; and (**c**) location of the Tena–Pano river basin within Napo Province, Ecuador. Geographic coordinates are presented in decimal degrees (WGS 84).

Tena Canton has a population of 80,816. The San Juan de Muyuna parish—considered an urban neighborhood—is one of the population centers where 9% of the population resides and where the study sites are located [30]. Economic activities primarily include tourism, commerce, public services, and small-scale agriculture.

The Tena River plays a central role in local livelihoods, providing recreational spaces, supporting tourism activities, and contributing to the cultural identity of local communities. However, increasing urban expansion, riverbank occupation, wastewater discharges, and tourism infrastructure development have intensified pressures on riparian ecosystems and flood-prone areas. These dynamics make the Tena River a suitable case study for examining sociohydrological interactions among human development, environmental change, and water resource management in rapidly urbanizing Amazonian cities.

2.2. Hydrological and Hydraulic Modeling

This study used hydrological and hydraulic simulation outputs from the coupled TETIS–Iber modeling framework developed by Hurtado-Pidal et al. [16] to identify areas potentially exposed to flooding along the Tena River. The hydrological component employed TETIS, a spatially distributed model that represents rainfall–runoff processes and flow routing to generate discharge hydrographs [17]. These hydrographs provided the inflow boundary conditions for Iber, a two-dimensional hydrodynamic model that solves the depth-averaged shallow-water equations to simulate flood propagation and calculate water depths and flow velocities [18]. Iber represented terrain and channel geometry using a 3 m resolution DEM from the SIGTIERRAS project [31]. TETIS hydrographs provided the inflow boundary conditions for Iber. The source study provides full details of the model configuration, input datasets, and computational procedures.

TETIS was previously calibrated and validated for the Tena River basin [32]. Iber was calibrated against one observed flood event and validated against three additional events recorded during 2018–2019 at the downstream gauge near the Tena–Pano confluence. Hydraulic calibration involved adjusting the main-channel Manning coefficient, while floodplain roughness coefficients were assigned based on the 2016 land-cover classes from the SIGTIERRAS project [31] and held fixed. For water depth, the variable used in the present assessment, the Nash–Sutcliffe efficiency during calibration was 0.93, and the mean absolute percentage difference in peak depth across the calibration and validation events was 8.59%. Hurtado-Pidal et al. [16] report detailed validation results and model limitations.

This assessment used base-scenario land-cover conditions and design floods with return periods of 2, 10, and 100 years. Design storms were derived from [33] intensity–duration–frequency relationships using the non-symmetric alternating blocks method and transformed into discharge hydrographs with TETIS, following Hurtado-Pidal et al. [34]. The hydrographs in Figure 2 correspond to Puente Ikiam, near the upstream inflow boundary of the Tena River hydraulic domain, and show the hydrological inputs used to generate the inundation maps.

The hydraulic domain encompasses two of the three study sites: Puente Ikiam (0°57′29″ S, 77°51′36″ W) and Tazayaku (0°58′02″ S, 77°51′27″ W). Tío Mario (0°56′56″ S, 77°51′37″ W) lies upstream of the modeled reach and was therefore excluded from the hydraulic assessment (Figure 3), while remaining part of the other study components. Maximum water-depth rasters at 10 m spatial resolution were obtained from the base-scenario simulations for each return period and clipped to the Puente Ikiam and Tazayaku sites to prepare the inundation maps shown in Figure 3b,c. At each recreational site and for each return period, maximum water depth was evaluated along the corresponding cross-section.

The resulting maps provided spatial information for evaluating the potential exposure of recreational areas and associated infrastructure at Puente Ikiam and Tazayaku.

This information supported water-resource and territorial planning and helped identify management priorities within the PWD, in accordance with the Ecuadorian regulatory framework [10]. The assessment draws on model performance evaluated at the downstream gauge; inundation extent was not independently validated at the recreational sites.

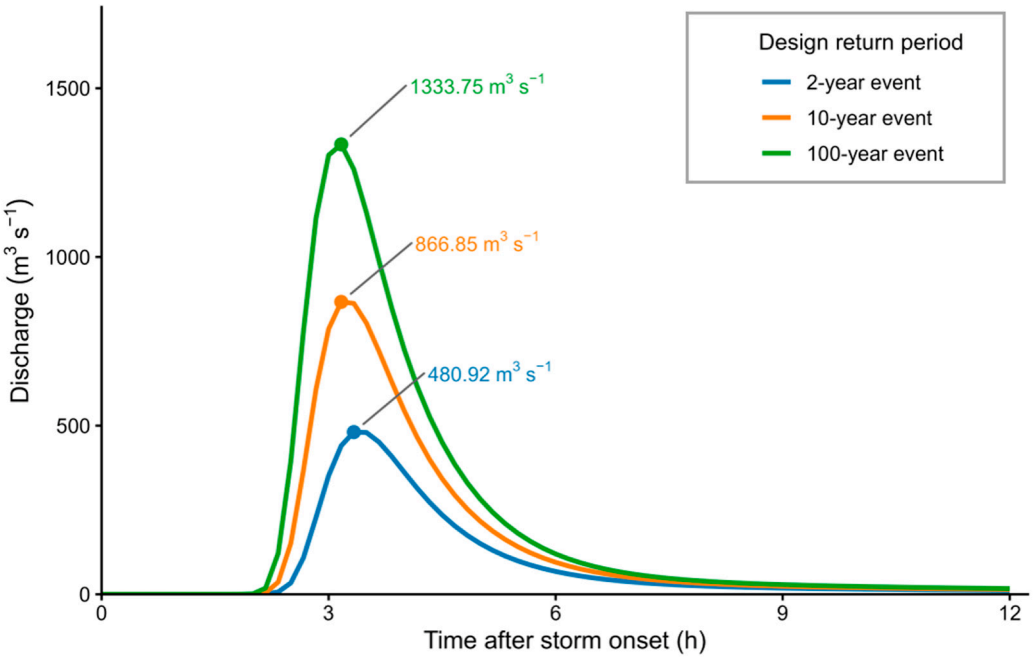


Figure 2. TETIS-simulated discharge hydrographs for 2-, 10-, and 100-year design storms at Puente Ikiam, near the upstream inflow boundary of the Tena River hydraulic domain. Peak discharges are 480.92, 866.85, and 1333.75 m^3 s^{-1}, respectively. Hydrographs were obtained from Hurtado-Pidal et al. [16] and represent inflow conditions for the Iber inundation simulations.

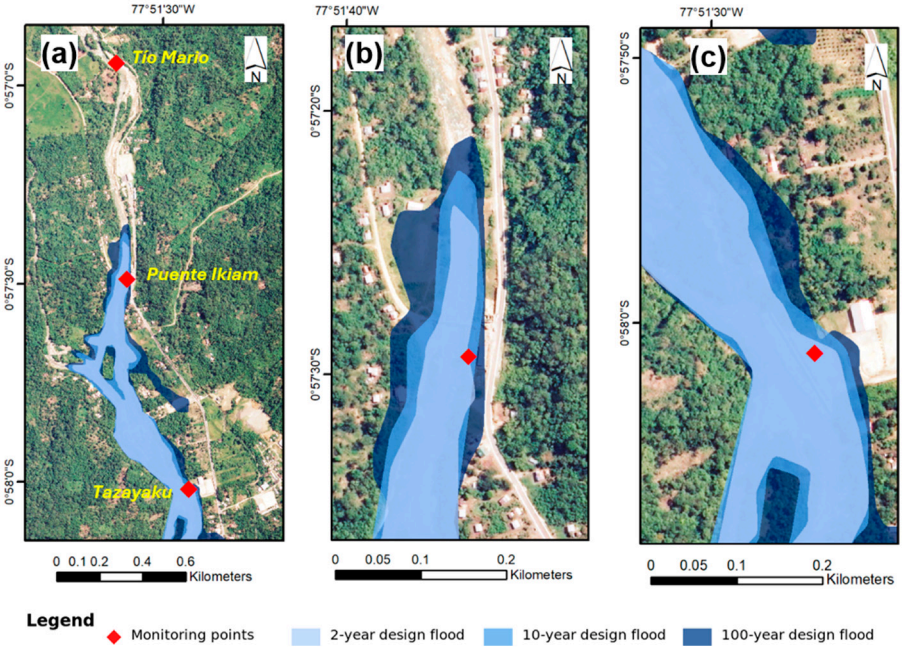


Figure 3. Iber-simulated inundation extents along the Tena River for 2-, 10-, and 100-year design floods: (**a**) overview of Tío Mario, Puente Ikiam, and Tazayaku, showing Tío Mario upstream of the modeled reach; (**b**) detailed view of Puente Ikiam; and (**c**) detailed view of Tazayaku. Hydraulic simulation outputs were obtained from Hurtado-Pidal et al. [16].

2.3. Water Quality Analysis

2.3.1. Sampling Design

Water-quality monitoring was conducted as a management-oriented assessment designed primarily to determine whether river conditions met the water-quality criteria established by Ecuadorian environmental regulations for primary-contact recreational use. The monitoring was therefore conceived as a regulatory screening and decision-support component rather than as a comprehensive limnological assessment or an inferential comparison among river sites. The resulting information was subsequently used as environmental evidence during participatory workshops to support discussion of recreational safety, environmental pressures, and river-management priorities.

The initial physicochemical and microbiological assessment consisted of two monitoring events conducted under contrasting hydrological conditions, hereafter referred to as the dry-period and rainy-period surveys. These observations reflect conditions at the time of sampling and were not treated as statistical representations of seasonal water-quality conditions.

The Colonso River was selected as a reference site because the monitored reach crosses a protected area with minimal direct human intervention and lacks the intensive urban and recreational pressures affecting the Tena River sites. It was therefore used as a comparatively low-anthropogenic-pressure reference rather than as an assumed pristine condition.

Monitoring was subsequently extended within the same research project to better characterize water-quality dynamics over time. The extended monitoring included repeated measurements of microbiological indicators and surfactants at sites representing different levels of recreational and urban pressure. The Paushiyaku River, an urban tributary crossing central Tena, was incorporated during this phase as an urban-pressure monitoring site. BOD and COD were subsequently incorporated to provide complementary information on organic matter and potential urban wastewater influence.

2.3.2. Physicochemical and Microbiological Analyses

Water temperature, pH, and dissolved oxygen (DO) were measured in situ using a YSI Professional Plus multiparameter probe (YSI Inc., Yellow Springs, OH, USA). Dissolved oxygen was recorded both as concentration (mg L^{-1}) and percentage saturation. Percentage saturation was used for regulatory assessment because Ecuadorian water-quality criteria for primary-contact recreational waters establish a minimum DO criterion of 80% saturation.

Total and fecal coliform concentrations were determined using the multiple-tube fermentation/MPN method and expressed as most probable number per 100 mL (MPN/100 mL). Results below or above the analytical quantification range were retained as censored observations (e.g., <300 or >1100 MPN/100 mL) rather than replacing them with arbitrary numerical values.

Surfactant concentrations were quantified using the methylene blue active substances (MBAS) method and expressed as mg L^{-1}. The method quantifies anionic surfactants through ion-pair formation with methylene blue and was included because the Ecuadorian water-quality criteria explicitly consider surfactants for primary-contact recreational use.

During the extended monitoring phase, biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) were incorporated as complementary indicators of organic pollution. BOD_5 was determined from dissolved-oxygen depletion over a five-day incubation period using the Winkler-based procedure, following the corresponding Standard Methods protocol. COD was determined using the closed-reflux dichromate digestion method with pre-prepared digestion vials. The analytical quantification limit for COD was 35 mg O_2 L^{-1}.

BOD_5 and COD were not used to determine compliance with primary-contact recreational-water criteria because these parameters are not included among the criteria established for this designated use under the Ecuadorian regulatory framework applied in this study. Instead, they were incorporated as complementary indicators to provide a broader characterization of organic pollution and potential urban wastewater influence.

2.4. Vegetation and NDVI Analysis

Riparian vegetation conditions were assessed using PlanetScope satellite imagery for June 2016, June 2020, and June 2024. PlanetScope imagery provides a spatial resolution of approximately 4.7 m per pixel and includes blue, green, red (RED), and near-infrared (NIR) spectral bands suitable for vegetation-index analysis [35]. Using images acquired during the same month reduced potential seasonal differences among years and improved the temporal comparability of the vegetation assessment. This consideration is particularly relevant in the humid tropical conditions of the Ecuadorian Amazon, where persistent cloud cover can constrain the availability of suitable satellite observations.

The study areas corresponding to Tío Mario, Puente Ikiam, and Tazayaku were identified in Planet Explorer, and the corresponding image tiles were downloaded for each study year. Images were selected based on image quality and the absence or minimal presence of cloud contamination over the areas of interest. NDVI uses the NIR band, which vegetation strongly reflects, and the RED band, which vegetation absorbs [36,37]. The formula for NDVI is:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

where NIR represents reflectance in the near-infrared band, and RED represents reflectance in the red spectral band. NDVI values range from −1 to +1, with higher positive values generally associated with denser green vegetation. NDVI values were classified into four categories: non-vegetated surfaces $[-1, 0)$, bare soil or very sparse vegetation $[0, 0.2)$, moderate vegetation $[0.2, 0.5)$, and dense vegetation $[0.5, 1.0]$. The same classification thresholds were applied consistently across all three sites and analyzed years.

For each study site and year, the number of pixels within each NDVI class was calculated and converted to area and percentage cover using a constant analysis extent for each site. Temporal vegetation change was assessed descriptively by comparing the area and proportional cover of each NDVI class among 2016, 2020, and 2024. Pixel counts were treated as spatially autocorrelated observations and were therefore not used as independent replicates for inferential statistical testing.

2.5. Community Survey and Participatory Assessment

The community-based component was designed to complement the environmental and hydrological assessment by incorporating local knowledge, perceptions, river-use practices, and management priorities. Participatory activities were conducted as part of the project's community-engagement component and were intended to generate locally grounded information for environmental diagnosis and participatory river-management decision-making. This participatory framework builds upon previous applied research in other ecosystems, such as mangroves [38], and environmental perception analysis [39].

Community perceptions were assessed using a structured questionnaire administered in person to 18 community stakeholders. Participants were selected through a non-probabilistic, purposive approach based on their role as community representatives participating in the project's engagement activities. The survey was therefore not designed to constitute a statistically representative sample of the entire population of Tena. Instead, it aimed to document the perceptions, experiences, and management priorities of community representatives with local knowledge of the river and its surrounding territory.

The questionnaire consisted primarily of closed-ended and multiple-response questions addressing: (i) age group and length of residence in the community; (ii) river uses and frequency of use; (iii) perceived water quality and perceived temporal changes in river condition; (iv) environmental problems directly observed by participants; (v) human activities perceived as affecting the river; (vi) previous environmental training; (vii) perceived importance of river conservation; (viii) knowledge of existing community actions for river protection; (ix) preferred management and restoration measures; and (x) household wastewater-disposal practices. No names or direct personal identifiers were collected.

Survey responses were analyzed descriptively using absolute frequencies (n) and relative frequencies (%). For multiple-response questions, each response option was quantified independently; consequently, percentages for these questions were not expected to sum to 100%. Inferential statistical tests were not applied because participant recruitment was non-probabilistic and the survey aimed at participatory environmental diagnosis and management planning rather than population-level statistical inference.

To examine the relationship between environmental concern and perceived collective action, two survey indicators were considered jointly: (i) the importance attributed by respondents to protecting the Tena River and (ii) their knowledge of existing community actions for river protection. The difference between the proportion of respondents who considered river protection important or very important and the proportion who reported the existence of community protection actions was used as a descriptive indicator of an awareness–reported-action gap. This indicator was interpreted descriptively and was not treated as a standardized behavioral or environmental-awareness index.

Participatory workshops complemented the survey, where community participants discussed environmental conditions, river uses, locally perceived pressures, socioeconomic activities, and potential management responses. The workshops provided a deliberative space to integrate local observations with project-generated environmental information and identify locally relevant management priorities.

3. Results

3.1. Flood Depths at Recreational Sites

Maximum simulated water depths were evaluated along a cross-section at each recreational site within the hydraulic domain. At Puente Ikiam, maximum depths were 0.6, 2.2, and 3.8 m for the 2-, 10-, and 100-year design floods, respectively. At Tazayaku, the corresponding values were 1.7, 2.2, and 2.7 m.

The simulated flood depths, together with the inundation patterns shown in Figure 3, indicate a potential flood hazard to infrastructure located within the inundated areas at Puente Ikiam and Tazayaku. Flooding of river-adjacent access routes and recreational spaces also affects visitor safety and site accessibility during high-flow events. Taken alongside water-quality conditions, riparian vegetation changes, and community perceptions, these findings provide complementary evidence to identify management priorities and inform participatory decisions on recreational use and riverbank occupation.

3.2. Water Quality

The initial water-quality assessment showed generally acceptable conditions but also identified isolated deviations from the Ecuadorian criteria for primary-contact recreational waters (Table 1). During the dry-period survey, the Colonso reference site showed a pH of 7.30, dissolved oxygen (DO) of 7.75 mg L^{-1} and 91.2% saturation, and total coliform concentrations below 300 MPN/100 mL. At Tena–Ikiam, pH was 6.90 and total coliforms reached 300 MPN/100 mL, both within the applicable regulatory criteria. However, DO

saturation was 71.5%, below the minimum criterion of 80%, despite a concentration of 6.08 mg L^{-1}.

Table 1. Physicochemical and microbiological conditions observed during the initial water-quality surveys, compared with Ecuadorian criteria for primary-contact recreational waters.

Parameter	Regulatory Criterion	Colonso, Dry-Period	Tena–Ikiam, Dry-Period	Colonso, Rainy-Period	Tena–Ikiam, Rainy-Period
pH	6.5–8.3	7.30	6.90	6.80	6.46
Temperature (°C)	No criterion	19.8	21.5	19.2	20.8
DO (% saturation)	≥80	91.2	**71.5**	95.4	84.6
DO (mg L^{-1})	No criterion for recreational compliance	7.75	6.08	8.10	7.19
Total coliforms (MPN/100 mL)	≤2000	<300	300	<300	400

Note: Bold values fall outside the Ecuadorian criterion used for primary-contact recreational waters. Temperature and DO concentration in mg L^{-1} are reported as supporting physicochemical information; recreational compliance for DO was evaluated using percentage saturation.

During the rainy-period survey, Colonso again met the evaluated regulatory criteria, with pH 6.80, DO of 8.10 mg L^{-1} (95.4% saturation), and total coliforms below 300 MPN/100 mL. At Tena–Ikiam, DO increased to 7.19 mg L^{-1} and 84.6% saturation, thereby meeting the recreational-water criterion. In contrast, pH reached 6.46, marginally below the regulatory range of 6.5–8.3. Total coliform concentrations remained below the regulatory limit at both sites. These two surveys represent observations under contrasting hydrological conditions and were not interpreted as statistical estimates of seasonal differences.

3.2.1. Extended Monitoring

Subsequent monitoring conducted within the same research project provided a longer temporal characterization of microbiological contamination and surfactant concentrations (Table 2). Researchers conducted seven microbiological monitoring events between October 2025 and February 2026 at Colonso, Tazayaku, Malecón, and Paushiyaku, while they measured surfactants during eight monitoring events in October 2025 at Puente Ikiam, Tazayaku, Malecón, and Paushiyaku.

Fecal-coliform concentrations remained below the Ecuadorian recreational criterion of 200 MPN/100 mL in all seven monitoring events at Colonso and Tazayaku. In contrast, episodic exceedances were observed at the more urbanized sites. At Malecón, four of seven events (57.1%) exceeded the criterion, with concentrations ranging from 6 to >1100 MPN/100 mL. At Paushiyaku, three of seven events (42.9%) exceeded the criterion, including three January observations above 1100 MPN/100 mL. These results indicate marked temporal variability and show that characterization based on isolated sampling events could fail to identify episodic microbiological deterioration.

Total coliform concentrations were generally below the applicable threshold of 2000 MPN/100 mL. Colonso, Tazayaku, and Malecón showed no exceedances during the seven monitoring events. Paushiyaku exceeded the criterion in one event (14.3%), when concentrations were reported as >2400 MPN/100 mL.

Surfactant concentrations remained below the Ecuadorian criterion of 0.5 mg L^{-1} in all eight monitoring events. Concentrations were consistently 0.1 mg L^{-1} at Puente Ikiam and Tazayaku, ranged from 0.1 to 0.2 mg L^{-1} at Malecón, and ranged from 0.2 to 0.3 mg L^{-1} at Paushiyaku. Although these concentrations did not constitute regulatory exceedances, their

spatial distribution provides complementary evidence of differing levels of urban influence among monitoring sites.

Table 2. Summary of the extended microbiological and surfactant monitoring and compliance with Ecuadorian criteria for primary-contact recreational waters.

Parameter	Site	*n*	Observed Range	Median	Regulatory Criterion	Exceedances, n (%)
Fecal coliforms (MPN/100 mL)	Colonso	7	3–23	7.4	≤200	0 (0%)
	Tazayaku	7	0–4	0	≤200	0 (0%)
	Malecón	7	6–1100	210	≤200	4 (57.1%)
	Paushiyaku	7	0–1100	75	≤200	3 (42.9%)
Total coliforms (MPN/100 mL)	Colonso	7	3–1100	15	≤2000	0 (0%)
	Tazayaku	7	0–22	3	≤2000	0 (0%)
	Malecón	7	3–1100	240	≤2000	0 (0%)
	Paushiyaku	7	0–2400	150	≤2000	1 (14.3%)
Surfactants (mg L^{-1})	Puente Ikiam	8	0.1–0.1	0.1	≤0.5	0 (0%)
	Tazayaku	8	0.1–0.1	0.1	≤0.5	0 (0%)
	Malecón	8	0.1–0.2	0.1	≤0.5	0 (0%)
	Paushiyaku	8	0.2–0.3	0.2	≤0.5	0 (0%)

Note: Values reported above the analytical range (e.g., >1100 or >2400 MPN/100 mL) were retained as censored observations and were not replaced with arbitrary numerical values for statistical analysis. Medians are reported because of the small sample size and censored microbiological observations.

3.2.2. Complementary BOD_5 and COD Monitoring

BOD_5 and COD were incorporated during the subsequent monitoring phase at Colonso and Paushiyaku to provide additional information on organic pollution. These parameters were not used for recreational-water compliance assessment because they are not included in the Ecuadorian criteria applied to primary-contact recreational waters.

Eleven BOD_5 measurements were available for each site between October 2025 and February 2026. At Colonso, BOD_5 ranged from 0 to 33.4 mg O_2 L^{-1}, with a median of 0 mg O_2 L^{-1}, whereas Paushiyaku ranged from 0 to 52.6 mg O_2 L^{-1}, with a median of 3.9 mg O_2 L^{-1}. The highest BOD_5 values at both sites occurred during the 5 November 2025 monitoring event.

COD monitoring comprised 16 observations per site between October 2025 and April 2026. The analytical quantification limit was 35 mg O_2 L^{-1}. At Paushiyaku, quantified concentrations included 65.8 and 66.8 mg O_2 L^{-1}, while the remaining measurements were either below the quantification limit or not detected. At Colonso, quantified concentrations included 36.3, 55.9, 155.4, and 41.9 mg O_2 L^{-1}. The occurrence of measurable BOD_5 and COD at both sites indicates that these parameters should be interpreted as complementary indicators of organic matter rather than as direct proxies for urban contamination alone.

The extended dataset therefore provides a more nuanced picture than the initial regulatory screening alone. Regulatory compliance was not uniform across all monitoring events: episodic fecal-coliform exceedances occurred at Malecón and Paushiyaku, while DO saturation and pH showed isolated deviations during the initial Tena–Ikiam surveys. At the same time, surfactant concentrations and most total-coliform observations remained within the applicable recreational criteria. These findings support repeated monitoring for management purposes and show that regulatory compliance at a single sampling event should not be interpreted as evidence of the absence of anthropogenic pressure.

3.3. Riparian Vegetation Changes

The NDVI analysis showed changes in the distribution of vegetation classes among the three recreational areas between 2016 and 2024 (Table 3). At Tío Mario, dense vegetation (NDVI 0.5–1.0) accounted for 93.70% of the analyzed area in 2016, increased to 95.49% in 2020, and then decreased to 87.45% in 2024. Conversely, moderate vegetation (NDVI 0.2–0.5) increased from 6.30% to 12.55%, representing a net increase of approximately 6.25 percentage points.

Table 3. NDVI classes and changes in riparian vegetation.

Site	Year	Non-Vegetated −1–0 (%)	Sparse 0–0.2 (%)	Moderate 0.2–0.5 (%)	Dense 0.5–1.0 (%)	Area (m^2)
Tío Mario	2016	0.00	0.00	6.30	93.70	52,195.57
	2020	0.00	0.44	4.07	95.49	52,195.57
	2024	0.00	0.00	12.55	87.45	52,195.57
Change 2016–2024 (pp)		0.00	0.00	+6.25	−6.25	
Puente Ikiam	2016	0.00	0.00	9.41	90.59	49,936.13
	2020	0.00	0.00	13.53	86.47	49,936.13
	2024	0.00	0.05	18.46	81.49	49,936.13
Change 2016–2024 (pp)		0.00	+0.05	+9.05	−9.10	
Tazayaku	2016	0.00	0.47	17.22	82.31	48,635.24
	2020	0.09	1.08	20.53	78.32	48,635.24
	2024	0.00	0.00	20.55	79.45	48,635.24
Change 2016–2024 (pp)		0.00	−0.47	+3.33	−2.86	

At Puente Ikiam, dense vegetation decreased progressively from approximately 90.59% in 2016 to 86.47% in 2020 and 81.49% in 2024. During the same period, moderate vegetation increased from 9.41% to 18.46%, an increase of about 9.05 percentage points. The sparse-vegetation class remained marginal, accounting for only 0.05% of the area in 2024.

At Tazayaku, dense vegetation represented 82.31% of the analyzed area in 2016, decreased to 78.32% in 2020, and partially recovered to 79.45% in 2024. Moderate vegetation increased from 17.22% to 20.55% over the study period. The sparse-vegetation class decreased from 0.47% in 2016 to 0% in 2024, while the non-vegetated class remained negligible.

The reduction in dense vegetation was particularly evident at Puente Ikiam, where dense vegetation decreased from 90.59% in 2016 to 81.49% in 2024. Field observations documented parking and river-access areas adjacent to the riparian corridor with visibly modified vegetation cover. The spatial coexistence of recreational infrastructure and reduced riparian vegetation supports the interpretation of anthropogenic pressure at this site; however, the NDVI analysis alone does not allow the observed vegetation change to be causally attributed to tourism infrastructure.

3.4. Community Perceptions and Participatory Environmental Assessment

The community survey included 18 representatives from the Atacapi community. Most respondents had substantial local experience, with 13/18 (72.2%) having lived in the community for more than 10 years. River use was frequent and multifunctional: 14/18 respondents (77.8%) reported domestic consumption, 13/18 (72.2%) recreational use, and 10/18 (55.6%) washing. Because respondents could select multiple river uses and perceived pressures, percentages for these questions do not sum to 100%. Appendix A, Table A1 presents detailed survey frequencies.

Perceptions of water quality were moderate rather than uniformly negative. Ten respondents (55.6%) rated river-water quality as regular, seven (38.9%) as good, and one (5.6%) as very good. Twelve respondents (66.7%) perceived that water quality had remained

unchanged in recent years, whereas six (33.3%) considered that it had deteriorated. The most frequently reported environmental problems were turbid water (15/18; 83.3%) and solid waste (14/18; 77.8%). Tourism and solid-waste accumulation were each identified as pressures by 14/18 respondents (77.8%), followed by fish farming (11/18; 61.1%).

During the participatory workshops, participants identified the Tena River as a multifunctional space associated with domestic use, recreation, washing, fishing, and other livelihood activities. Participants also identified solid-waste disposal, wastewater discharge, tourism and recreational activities, fish farming, pig farming, and agriculture as locally perceived pressures affecting the river system. These workshop findings were used as complementary qualitative information to interpret community–river interactions and management priorities, rather than as a georeferenced inventory of environmental impacts.

A marked difference was observed between expressed concern for river conservation and reported collective action. All respondents (18/18; 100%) considered protection of the Tena River important or very important, whereas only 4/18 (22.2%) reported existing community actions to protect the river. Eight respondents (44.4%) indicated that no such actions existed and six (33.3%) were unaware of existing actions. This represents a descriptive awareness–reported-action gap of 77.8 percentage points.

Regarding management priorities, municipal supervision of potentially polluting activities was the most frequently selected measure (14/18; 77.8%), followed by environmental education (10/18; 55.6%). All respondents reported using individual septic systems for household wastewater disposal rather than discharging directly to the river. Overall, the results indicate strong dependence on the river and high expressed concern for its conservation, combined with relatively limited reported collective environmental action.

3.5. Integrated Environmental Assessment

Integration of the four analytical components identified distinct but complementary management concerns within the Tena River system (Table 4). The hydrological–hydraulic assessment showed increasing maximum water depths under the 2-, 10-, and 100-year design floods at Puente Ikiam and Tazayaku, with simulated inundation patterns indicating potential exposure of recreational areas and associated infrastructure. The vegetation assessment independently showed reductions in dense riparian vegetation between 2016 and 2024 at Tío Mario (−6.25 percentage points), Puente Ikiam (−9.10 percentage points), and Tazayaku (−2.86 percentage points), with the greatest reduction occurring at Puente Ikiam.

Water-quality monitoring identified a different but complementary pressure. While several recreational-water criteria were generally met, repeated monitoring revealed fecal-coliform exceedances in 57.1% of observations at Malecón and 42.9% at Paushiyaku, demonstrating that episodic microbiological deterioration may not be captured by isolated sampling events. The community assessment further showed that all participating representatives considered river protection important or very important, whereas only 22.2% reported existing community protection actions.

Taken together, these indicators identify three management priorities rather than a single composite environmental score: (i) management of recreational infrastructure and human access in potentially flood-prone sectors; (ii) protection and restoration of riparian vegetation together with continued water-quality and pollution-source monitoring; and (iii) strengthening institutional and community capacity to translate environmental concern into collective action. Because the individual datasets differ in spatial coverage, temporal resolution, units, and sampling design, the synthesis does not imply statistical association or causality among the indicators. Instead, Table 4 provides a transparent evidence-to-management framework showing how each independently derived component contributes to river-management priorities.

Table 4. Integrated environmental assessment and management implications for the Tena River system.

Component	Main Evidence	Environmental/Management Implication	Priority Response
Flood exposure	2- to 100-year simulated inundation encompasses recreational sectors at Puente Ikiam and Tazayaku.	Recreational users and infrastructure at Puente Ikiam and Tazayaku may occupy flood-prone portions of the river corridor	Restrict/guide infrastructure and access; field verification
Riparian vegetation	Dense vegetation declined at Tío Mario (−6.25 pp), Puente Ikiam (−9.10 pp), and Tazayaku (−2.86 pp)	Progressive modification of riparian structure, particularly at Puente Ikiam	Riparian restoration and protection
Recreational water quality	Fecal-coliform exceedances at Malecón (57.1%) and Paushiyaku (42.9%); isolated DO/pH deviations	Episodic impairment may not be detected by isolated sampling	Continued microbiological monitoring and pollution-source control
Community assessment	100% consider river protection important/very important; only 22.2% report existing community actions	Strong environmental concern but limited reported collective action	Environmental education, institutional support and participatory management

4. Discussion

4.1. An Integrated Perspective on the Tena River Socio-Environmental System

This study provides an integrated assessment of the Tena River by combining hydrological and hydraulic modeling, riparian vegetation analysis, water-quality monitoring, and community perceptions. Rather than representing a fully coupled sociohydrological model, the approach uses sociohydrological thinking as an interpretative framework to examine how hydrological processes, environmental conditions, recreational uses, infrastructure, and community responses interact within the same river corridor. This distinction matters because the individual indicators were not designed to establish direct causal relationships among all system components; instead, their integration provides complementary evidence for identifying environmental pressures, areas of exposure, and management priorities.

The results show that the three recreational sites cannot be understood exclusively in terms of flood hazard, water quality, or vegetation condition. The hydraulic simulations indicate that areas currently used for recreation may be exposed during high-flow events, while the NDVI assessment indicates changes in riparian vegetation structure between 2016 and 2024. Field observations additionally documented recreational infrastructure and modified river-access areas, including parking areas adjacent to the river at Puente Ikiam and Tazayaku and recreational facilities at the privately operated Tío Mario complex. Water-quality monitoring showed generally compliant conditions for several recreational-water criteria but also revealed specific deviations, including low dissolved-oxygen saturation during the initial survey and recurrent fecal-coliform exceedances at the more urbanized sites during extended monitoring. At the same time, the community survey showed that local perceptions and environmental awareness do not necessarily translate directly into collective environmental action. Considered together, these observations illustrate a central sociohydrological feature of the Tena River: human use of the river corridor simultaneously depends on, modifies, and is exposed to the dynamics of the fluvial system.

This interpretation is consistent with the broader sociohydrological literature, which emphasizes feedbacks between water systems and human societies rather than treating hydrological processes and human behavior as independent domains. However, the present study should be understood as an integrated multi-indicator assessment informed by sociohydrological thinking, rather than as a quantitative sociohydrological model. This approach's value lies in its capacity to organize heterogeneous environmental and social information into a common framework for river management.

4.2. Flood-Prone Areas and Implications for Recreational River Management

The TETIS simulations produced peak discharges of 480.92, 866.85, and 1333.75 m^3 s^{-1} at Puente Ikiam for the 2-, 10-, and 100-year return periods, respectively. Propagation of these hydrographs with Iber showed increasing maximum water depths with event magnitude [16]. Maximum water depth increased from 0.6 to 3.8 m at Puente Ikiam and from 1.7 to 2.7 m at Tazayaku between the 2- and 100-year floods. At both sites, simulated inundation extended into river-adjacent areas containing recreational spaces, access routes, and associated infrastructure. Flood exposure therefore concerns both physical infrastructure and people temporarily present within the river corridor. This interpretation is restricted to Puente Ikiam and Tazayaku because Tío Mario lies outside the hydraulic modeling domain.

The hydraulic assessment followed a management-oriented approach consistent with methodologies used in Ecuador to identify flood-prone areas and support delimiting and managing the PWD [10,40]. Two-dimensional hydraulic models provide spatially distributed information on inundation extent and depth that can support flood-hazard assessment and territorial planning, particularly in mountain river basins with limited observational data [29,41]. In this context, the maps provide evidence to identify potentially incompatible uses, guide recreational infrastructure and access, prioritize field verification, and support participatory management decisions. They should be interpreted as decision-support information rather than as deterministic predictions of future flood boundaries.

Although Iber was calibrated and validated against observed discharge, water depth, and flow velocity at the downstream gauge, inundation extent was not independently validated at Puente Ikiam or Tazayaku. Post-flood surveys and geomorphological evidence could provide additional information for evaluating simulated inundation patterns at these sites [42]. Furthermore, calibration focused on the main-channel Manning coefficient, while floodplain roughness coefficients were assigned by land-cover class and held fixed. Uncertainty in terrain representation and hydraulic roughness may therefore affect simulated water depths and lateral inundation extent [43,44]. These limitations constrain the interpretation of precise flood boundaries but do not preclude using the simulations to identify management priorities.

The 2-, 10-, and 100-year events were derived from stationary IDF relationships and should not be interpreted as climate-change projections. Climate change may alter extreme precipitation and flood behavior, while the resulting hydrological response also depends on catchment and land-surface conditions [45,46]. Future assessments should incorporate non-stationary precipitation scenarios, updated climate projections, site-specific flood observations, and detailed topographic information to evaluate potential changes in flood exposure.

4.3. Riparian Vegetation Change as an Indicator of Pressure on the River Corridor

The NDVI analysis provides a complementary perspective on changes occurring along the recreational river corridor. Between 2016 and 2024, the proportion of dense vegetation decreased at the three analyzed sites, although the magnitude and temporal pattern differed among locations. The most evident changes were accompanied by increases in

the moderate-vegetation class, indicating a transition in vegetation condition rather than wholesale conversion of the study areas to unvegetated surfaces.

These results are ecologically relevant because riparian vegetation performs multiple functions in tropical river systems, including bank stabilization, sediment retention, surface runoff regulation, habitat provision, and maintenance of ecological connectivity. Consequently, changes from dense to moderate vegetation may indicate progressive modification of riparian structure, even where complete vegetation removal remains spatially limited. From a management perspective, this distinction is important because degradation can precede complete land-cover conversion and may therefore provide an early indication of increasing pressure on river margins.

The observed reduction in dense riparian vegetation may have hydrological and hydraulic implications beyond the directly affected areas. Hurtado-Pidal et al. [34] showed that the contribution of forest restoration to flood regulation depends on its location within the Tena River basin, identifying an elevation threshold of approximately 590 m a.s.l. for prioritizing interventions. At the river-corridor scale, Hurtado-Pidal et al. [16] found that floodplain land-use/cover change produced stronger hydraulic responses in the main channel than in the floodplain during flash floods. Together, these findings indicate that riparian management should consider both the location of vegetation interventions within the basin and their potential effects across the channel–floodplain system. This study did not directly evaluate the hydraulic consequences of the vegetation changes observed between 2016 and 2024.

The spatial context observed during field activities supports an interpretation of anthropogenic pressure but does not demonstrate causation. Recreational facilities, parking areas, river-access paths, and other modified surfaces were observed adjacent to the riparian corridor. Nevertheless, NDVI change alone cannot establish that tourism infrastructure or urban expansion caused the observed vegetation changes. Natural channel migration, local geomorphological dynamics, vegetation succession, differences among satellite acquisitions, and classification uncertainty may also contribute to the detected patterns. Accordingly, the revised interpretation avoids attributing vegetation loss directly to tourism and instead considers the spatial coexistence of recreational use, infrastructure, and changing riparian vegetation as evidence of potential pressure requiring further investigation.

The NDVI analysis itself also has methodological limitations. The assessment used representative PlanetScope observations from 2016, 2020, and 2024 rather than multi-date annual composites. Although all images were selected for the same month (June), thereby reducing potential seasonal and phenological differences among years, differences in atmospheric conditions, illumination, sensor characteristics, and short-term vegetation dynamics cannot be completely excluded. Furthermore, no independent ground-based assessment of classification accuracy was available.

For these reasons, pixel counts were treated as units for estimating class area and proportional cover rather than as independent statistical observations. The pixel-based chi-square analysis included in the initial version of the study was therefore removed because spatially adjacent pixels are autocorrelated and cannot be treated as statistically independent replicates. Reporting changes in area and percentage cover better describes the magnitude and direction of vegetation change given the available dataset.

Future monitoring should use harmonized surface-reflectance products, multiple observations per year, consistent cloud masking, and field-based vegetation validation. Such improvements would allow the observed trajectories to be distinguished more confidently from sensor, atmospheric, or seasonal variability.

4.4. Water Quality: Regulatory Compliance Does Not Imply Absence of Environmental Pressure

The water-quality results add another dimension to interpreting recreational river use. Rather than showing generalized severe contamination, the measurements indicate a more nuanced situation: several parameters remained within the Ecuadorian criteria for primary-contact recreational waters, while specific measurements showed departures from desirable environmental conditions.

The comparison with the Colonso River is particularly informative. Colonso flows through a comparatively protected area with substantially lower direct human pressure and was therefore used as an environmental reference rather than as a statistically equivalent control site. During the dry-season sampling, dissolved oxygen saturation reached 91.2% at Colonso but only 71.5% at Tena–Puente Ikiam, with the latter falling below the Ecuadorian criterion of >80%. During the rainy-season observation, dissolved oxygen saturation at Tena–Puente Ikiam increased to 84.6%, while Colonso reached 95.4%. The corresponding concentrations were 6.08 and 7.75 mg L^{-1} during the dry-season observation and 7.19 and 8.10 mg L^{-1} during the rainy-season observation, respectively. These differences do not establish a generalized temporal or spatial pattern because of the limited number of sampling events, but they show why compliance should not be interpreted simply as evidence of an absence of anthropogenic pressure.

This distinction is particularly relevant for environmental management. Regulatory thresholds determine whether specific conditions are compatible with a designated use; they do not necessarily indicate ecosystem integrity. A river can meet microbiological or physicochemical criteria established for recreational contact while still experiencing riparian modification, localized wastewater inputs, infrastructure expansion, or changes in dissolved oxygen. Regulatory compliance and ecosystem condition therefore address related but different questions.

The scope of the Ecuadorian recreational-water criteria also illustrates this issue. Parameters such as biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD), although widely used to characterize organic pollution and wastewater influence, are not included among the principal criteria used to evaluate primary-contact recreational use under the regulatory framework applied in this study. Consequently, their absence from the original sampling design reflects the specific management question addressed—whether water conditions met the applicable recreational-use criteria—rather than an assumption that organic pollution is environmentally irrelevant.

The limited sampling frequency remains an important constraint. The available measurements are suitable for a preliminary compliance-oriented assessment but not for robust statistical inference regarding seasonal dynamics or differences among river reaches. Therefore, the results should not be interpreted as evidence of persistent spatial differences or statistically demonstrated seasonal trends; rather, they identify conditions requiring continued monitoring.

These limitations highlight the need for longer-term and higher-frequency monitoring capable of capturing seasonal and event-driven variability. Emerging continuous-monitoring technologies, including low-cost sensor networks and Internet-of-Things platforms, could complement regulatory sampling and improve the temporal characterization of urban water-quality pressures.

This limitation has already motivated an expanded monitoring effort within the same broader research initiative. The Paushiyaku River was subsequently incorporated as an urban-pressure site, and the extended dataset reported in this study includes repeated measurements of microbiology, surfactants, BOD_5, and COD. Continued monitoring with a denser temporal design is underway to support more detailed statistical analyses of temporal variability and urban wastewater pressures. However, Paushiyaku is not included in the

spatially integrated NDVI–flood assessment because equivalent vegetation and hydraulic analyses have not yet been completed for this tributary.

4.5. Community Perceptions and the Awareness–Action Gap

The community component provides the social dimension required to interpret environmental indicators within their management context. The survey was administered to community representatives rather than through a probabilistic household sampling design; consequently, its results characterize the perspectives of participating representatives and should not be generalized statistically to the entire population of the Tena River basin.

Nevertheless, the quantified responses provide evidence that perceptions of river condition, environmental awareness, and willingness or capacity for collective action do not necessarily coincide. This matters because environmental management often assumes that increasing awareness will automatically produce behavioral or institutional change. The results instead suggest an awareness–action gap, in which recognition of environmental problems can coexist with limited participation in collective responses.

From a sociohydrological perspective, this finding matters because human responses to environmental change depend on more than environmental knowledge. Institutional capacity, access to information, perceived responsibility, economic interests, the availability of collective organizations, and confidence in public authorities may influence whether environmental concern translates into action. The community results therefore complement the physical indicators by showing that technical interventions alone cannot address environmental pressures.

The participatory findings were consistent with the quantitative survey, which revealed a marked awareness–action gap. All respondents considered river protection important or very important, whereas only 22.2% reported community environmental actions and 44.4% reported receiving no environmental training. This suggests that recognition of environmental problems does not necessarily translate into organized collective action, reinforcing the need for management strategies that combine institutional intervention with environmental education and community participation.

This separation between technical assessment and community knowledge is also methodologically useful. Participatory management does not require community observations and numerical models to produce identical spatial representations. Instead, deliberative processes can bring the two sources of knowledge together, allowing technically identified hazards and environmental conditions to be interpreted in relation to local priorities, experiences, and feasible management responses.

4.6. From Integrated Assessment to Participatory River Management

This study's main contribution lies in integrating complementary environmental and social indicators rather than in any individual analytical component. Hydraulic modeling identifies areas potentially exposed to flooding; NDVI characterizes temporal changes in riparian vegetation; water-quality monitoring evaluates conditions relevant to recreational use; field observations document recreational infrastructure and river-margin modification; and community surveys identify environmental perceptions, awareness, and constraints on collective action. Together, these components provide a broader basis for identifying sectors where environmental pressures, human use, and hydrological exposure coexist and where management interventions may be prioritized.

This integrated approach is particularly relevant within the Ecuadorian institutional context. The hydrological and hydraulic assessment follows a management-oriented framework consistent with approaches promoted by the national environmental authority to identify flood-prone areas and support delimiting and managing the PWD. In addition,

the Ecuadorian Climate Change Adaptation Plan 2023–2027 establishes a public-policy framework in which information on climate-related hazards, ecosystem condition, and territorial vulnerability is intended to support adaptation and environmental planning [40]. The expansion of urban areas increases impermeable surfaces, reducing the land's natural capacity to absorb water and increasing surface runoff and flooding [46–48]. In 2016, several neighborhoods in the city of Tena already suffered flooding. Accordingly, the value of the assessment lies not only in characterizing environmental conditions but also in generating technically grounded information that can be incorporated into existing water-management and participatory decision-making processes.

For this purpose, interpretability is an important component of the assessment. Flood-prone-area maps, changes in riparian vegetation expressed as area and percentage, water-quality measurements compared with legally established recreational-use criteria, and quantified community perceptions provide information that can be communicated to community representatives, recreational-site operators, municipal authorities, and environmental agencies. These outputs can support deliberation on riparian restoration, management of recreational infrastructure and access within flood-prone sectors of the PWD, continued water-quality monitoring, and the need for more detailed studies where environmental pressures are identified. The approach should therefore be understood primarily as a screening and decision-support framework, combining multiple sources of evidence to identify management priorities rather than provide high-precision predictions or establish direct causal relationships among all components of the river system.

4.7. Limitations and Future Research

Several limitations should be considered when interpreting the results. First, interpret the hydrological–hydraulic results within the spatial scope of model validation. Although Iber was calibrated and validated using observed discharge, water depth, and flow velocity at the downstream gauge, inundation extent was not independently verified at Puente Ikiam or Tazayaku [16]. The simulations therefore provide a physically based representation of flood depth and extent suitable for this study's management-oriented objectives, while site-specific field validation would further strengthen local assessments. In addition, the 2-, 10-, and 100-year design floods were derived from stationary IDF relationships and do not represent future climate-change conditions.

Second, the environmental indicators have temporal and analytical limitations. The NDVI assessment relied on one representative PlanetScope observation for June of each analyzed year (2016, 2020, and 2024) and lacked an independent classification-accuracy assessment. Although using the same month and selecting images with minimal cloud contamination improved temporal comparability, atmospheric conditions, illumination, sensor characteristics, short-term vegetation variability, and natural channel dynamics may have influenced the observed patterns. The water-quality component was also designed primarily as a regulatory screening for recreational use rather than as a comprehensive characterization of river biogeochemistry. Although extended monitoring strengthened the initial assessment and identified episodic microbiological exceedances, the temporal coverage remains insufficient to characterize the full range of seasonal and event-driven variability. BOD_5 and COD provide complementary information on organic matter but should not be interpreted as direct evidence of wastewater contamination without additional chemical, microbiological, and hydrological evidence.

Third, the community component was based on a purposive, non-probabilistic sample of 18 community representatives and therefore characterizes the perceptions of the participating stakeholders rather than providing population-level estimates for Tena. The identified awareness–reported-action gap should consequently be interpreted descriptively.

Similarly, the participatory workshops were designed to identify locally perceived environmental pressures and management priorities rather than to independently delineate flood zones or validate hydraulic-model outputs. The technical and community-based datasets were therefore integrated at the interpretation and management stages rather than treated as directly comparable spatial or statistical observations.

Future research should strengthen the hydraulic model's spatial calibration and validation through site-specific observations of water levels and inundation extent at Puente Ikiam and Tazayaku, along with sensitivity analyses of floodplain roughness. Water-quality monitoring should be expanded through repeated seasonal and event-based sampling incorporating microbiological indicators, BOD_5, COD, nutrients, turbidity, conductivity, and continuous physicochemical measurements. Remote-sensing analyses would benefit from multi-temporal annual observations or composites, harmonized surface-reflectance products, standardized cloud masking, and field validation. Repeated, broader community surveys could also evaluate how perceptions, river use, environmental awareness, and collective action change over time. Together, these developments would provide the temporal, spatial, and behavioral information needed to move from the current integrated assessment toward explicitly coupled sociohydrological modeling and quantitative evaluation of alternative management trajectories.

4.8. Sociohydrological Implications and Future Management Trajectories

The integrated results suggest two contrasting but plausible management trajectories for the Tena River system. Continued modification of riparian vegetation, expansion of recreational infrastructure near the active river corridor, and increasing human use may increase exposure to flood hazards and progressively reduce ecological buffering capacity. Conversely, riparian restoration, improved wastewater management, protection of flood-prone sectors of the PWD, continuous environmental monitoring, and participatory management could contribute to a more resilient river–community relationship. These trajectories should be interpreted as management-oriented scenarios derived from the combined environmental and social evidence, rather than as quantitatively modeled future sociohydrological states.

From a sociohydrological perspective, these contrasting trajectories illustrate how hydrological conditions and human decisions can influence one another over time. Flood exposure affects where and how people use the river, while decisions related to infrastructure, vegetation removal, wastewater management, and recreational access can modify environmental conditions and future vulnerability. The present multi-indicator assessment therefore provides a baseline for identifying these interactions and for supporting adaptive management decisions within the institutional framework of river management.

5. Conclusions

This study demonstrates the value of integrating hydrological and hydraulic modeling, riparian vegetation assessment, water-quality monitoring, and community perceptions to support the management of an urban Amazonian river. Rather than a fully coupled sociohydrological model, the approach is an integrated, multi-indicator assessment informed by sociohydrological thinking, in which environmental and social indicators provide complementary evidence for identifying management priorities.

The assessment identified converging environmental pressures across the Tena River corridor. Simulated maximum water depths increased under the 2-, 10-, and 100-year design floods at Puente Ikiam and Tazayaku, with inundation patterns encompassing sectors currently used for recreation and associated infrastructure. These results highlight the importance of considering flood exposure in riverfront planning. NDVI analysis showed

reductions in dense riparian vegetation between 2016 and 2024 at the three recreational sites, identifying sectors where riparian conservation and restoration should receive management attention. Water-quality monitoring revealed recurrent fecal-coliform exceedances at the more urbanized sites, particularly Malecón and Paushiyaku, while community responses showed great concern for river conservation but limited reported collective action. Together, these findings indicate that flood exposure, riparian modification, episodic water-quality impairment, and human use coexist within the river system and should therefore be addressed through coordinated rather than isolated management actions.

The study's practical contribution lies in translating these complementary indicators into information that can support participatory management of the PWD. Flood-prone-area delineation, riparian restoration, continued water-quality monitoring, management of recreational infrastructure and access, and strengthened community participation emerge as priority actions. Although further research involving site-specific validation of inundation extent, detailed topographic information, longer environmental time series, and repeated social observations is needed to quantify human–water feedbacks, this assessment provides a management-oriented baseline for adaptive decision-making and for the future development of explicitly coupled sociohydrological analyses in data-scarce Amazonian river systems.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Before participating in the surveys and workshops, participants were informed about the research objectives, the voluntary nature of their participation, the anonymous treatment of the information collected, and their right to withdraw at any time without consequence. The authors obtained free, prior, and informed consent from all participants before data collection.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

BOD_5	Biochemical Oxygen Demand after 5 days
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DO	Dissolved Oxygen
GIS	Geographic Information System
IDF	Intensity–Duration–Frequency
INAMHI	National Institute of Meteorology and Hydrology (Instituto Nacional de Meteorología e Hidrología)
MBAS	Methylene Blue Active Substances
MPN	Most Probable Number
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
PWD	Public Water Domain
UAV	Unmanned Aerial Vehicle

Appendix A

Table A1. Community perceptions, river uses, environmental pressures, and management priorities reported by Atacapi community representatives ($n = 18$).

Dimension	Response	*n*	%
Residence time	>10 years	13	72.2
	6–10 years	5	27.8
River use *	Domestic consumption	14	77.8
	Recreation	13	72.2
	Washing	10	55.6
	Agriculture	7	38.9
	Fishing	7	38.9
Frequency of river use	Several times per week	15	83.3
	Once per week	2	11.1
	Rarely	1	5.6
Perceived water quality	Very good	1	5.6
	Good	7	38.9
	Regular	10	55.6
	Poor	0	0
Perceived temporal change	Unchanged	12	66.7
	Worsened	6	33.3
Observed problems *	Turbid water	15	83.3
	Solid waste	14	77.8
	Wastewater discharges	4	22.2
	Foam	1	5.6
Perceived pressures *	Tourism	14	77.8
	Solid waste	14	77.8
	Fish farming	11	61.1
	Pig farming	5	27.8
	Agriculture	1	5.6
	Livestock farming	1	5.6
Environmental training	Yes	4	22.2
	Some	6	33.3
	No	8	44.4
Importance of river protection	Very important	14	77.8
	Important	4	22.2
Existing community actions	Yes	4	22.2
	No	8	44.4
	Do not know	6	33.3

Table A1. *Cont.*

Dimension	Response	*n*	%
Preferred management responses *	Municipal supervision	14	77.8
	Environmental education	10	55.6
	Community clean-ups	5	27.8
	Environmental signage	4	22.2
	Wastewater treatment	4	22.2
	Discharge control	2	11.1
Household wastewater disposal	Septic system	18	100

Note: Percentages were calculated using the total number of respondents (n = 18) as the denominator. * Multiple responses were allowed; therefore, percentages within these dimensions do not sum to 100%.

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