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A Two-Stage Framework to Prioritize Monitoring of Authorized River Aggregate Extraction in the Andean Amazon

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Abstract

River sand and gravel extraction can generate geomorphological and ecological pressure, yet environmental management is often constrained by incomplete information on actual extraction volumes. We developed a two-stage prioritization framework for the Misahuallí River basin in the Ecuadorian Andean Amazon using administrative authorizations issued during 2015–2025. Of 132 records examined, 68 authorizations were located within the basin and 62 were associated with the fluvial system, representing 1,067 ha and a cumulative authorized volume of 8.69 million m³. In the first stage, an Authorized Potential Pressure Index (APPI) integrated total authorized volume, daily authorized volume, authorized daily intensity per unit area, and administrative recurrence. The index was calculated for 52 records with complete information and ranged from 1.00 to 2.85; 22 records (42.3%) were classified as low, 13 (25.0%) as medium, and 17 (32.7%) as high potential pressure. Sensitivity analyses showed high rank concordance under alternative weighting and criterion-exclusion scenarios (Spearman's ρ = 0.939–0.992). In the second stage, ecosystem services, social uses, field observations, multitemporal imagery, and an exploratory survey of 29 adult stakeholders were used to contextualize monitoring needs without being mathematically incorporated into the index or interpreted as evidence of causal impact. The framework provides a transparent screening approach for targeting administrative verification and environmental monitoring where extraction data are incomplete. Its use for current management requires verification of authorization status and should be complemented with measurements of effective extraction, sediment dynamics, channel change, water quality, and aquatic habitat.

1 Introduction

Natural aggregates, particularly sand and gravel, are essential materials for infrastructure and urban development, but rising demand has turned their extraction into a global sustainability and resource-governance challenge (Park et al. 2026). River extraction is especially sensitive because sediment performs geomorphological, ecological, and social functions, while information on actual removal volumes and sediment replenishment is frequently incomplete (Koehnken et al. 2020).

When sediment removal exceeds natural replenishment, in-stream sand and gravel extraction can disrupt sediment budgets and channel morphology, promoting bed incision, bank instability, altered sediment transport, and changes in aquatic habitat. These effects may extend beyond extraction sites and affect riparian vegetation, infrastructure, biodiversity, water quality, and ecosystem services, although their magnitude and direction depend on extraction method, hydrogeomorphic setting, sediment supply, and interacting pressures (Kondolf 1994; Koehnken et al. 2020; Rentier and Cammeraat 2022; Tripathi et al. 2025).

In Ecuador, the mining legislation includes a special regime for the free use of construction materials for public works. Under Article 144 of the Mining Law, public entities, directly or through contractors, may obtain authorizations whose duration and authorized volumes are defined according to technical

production requirements and the execution period of the public work. Materials obtained under this regime must be used for the authorized public work (Ley de Minería 2009). Administrative resolutions therefore contain information on duration, destination, authorized volume, area, and coordinates. These records can characterize the magnitude of authorized extraction pressure, but authorized volumes do not necessarily represent material actually removed from the river system.

The Misahuallí River basin, in Napo Province and primarily within the cantons of Tena and Archidona, contains numerous areas authorized for aggregate extraction for public works. Its rivers simultaneously support water supply, fisheries, recreation, tourism, and other benefits (Celi and Villamarín 2020). Integrated assessments in Ecuadorian basins have documented degradation associated with multiple anthropogenic pressures, including agriculture, livestock production, mining, and urban discharges (Chancay et al. 2021). In the Ecuadorian Amazon, a case study in San Pedro on the Tena River documented community perceptions of socioenvironmental change associated with gravel extraction and emphasized the relevance of local participation in planning and restoration (Sarduy-Pereira et al. 2024). However, a basin-scale approach linking the distribution and magnitude of authorizations with socioenvironmental context to establish explicit monitoring priorities is still lacking. More broadly, environmental decision-support studies show that transparent multicriteria screening can help structure priorities when information is incomplete and management resources are limited (Huang et al. 2011; Jaramillo-Álvarez et al. 2026).

This study therefore aimed to characterize the magnitude and spatial-temporal distribution of potential pressure associated with authorized river aggregate extraction in the Misahuallí basin during 2015–2025, and to contextualize the resulting priorities using information on ecosystem services, social uses, observed transformations, and local perceptions. We combined administrative records, GIS analysis, multitemporal observations, and an exploratory stakeholder survey while explicitly separating authorized pressure, socioenvironmental context, and evidence of environmental impact.

2 Study Area

The Misahuallí River basin is located in Napo Province in the Ecuadorian Amazon and includes territory in the cantons of Tena and Archidona (Fig. 1). The basin was delineated using hydrological analysis tools and the Copernicus Digital Elevation Model GLO-30, with a 1 arc-second grid spacing (approximately 30 m in the study area), complemented by hydrographic network data in WGS 84 / UTM zone 18S (EPSG:32718). The basin covers approximately 167,131.6 ha (1,671.3 km²), ranges from 380 to 3,787.8 m a.s.l., and contains approximately 1,301.9 km of rivers and streams. CHIRPS v3.0 estimates for 2015–2025 indicate mean annual precipitation ranging from 3,384.7 to 5,154.5 mm yr^{-1} (Funk et al. 2026).

Land cover in 2024 was dominated by forest (1,231.37 km²; 73.45%) and agricultural mosaic (376.10 km²; 22.44%). The mapped mining category occupied 0.54 km² (53.75 ha; 0.032%), while each remaining land-cover class represented less than 3% of basin area (MapBiomas Ecuador 2024). The basin's topographic, hydrological, climatic, and ecological characteristics underpin water provision and

regulation, sediment transport, river-based livelihoods, and cultural and recreational services, while also supporting aggregate extraction.

3 Methods

3.1 Study design

We used an integrated quantitative–qualitative design organized in two stages. Stage 1 characterized and ranked authorized potential pressure using administrative records and the Authorized Potential Pressure Index (APPI; Spanish acronym IPPA). Stage 2 used spatial analysis, field observations, multitemporal comparisons, ecosystem services, social uses, and local perceptions to contextualize the priorities identified in Stage 1. These socioenvironmental components were not mathematically incorporated into the APPI and were not interpreted as evidence of causal impact.

3.2 Spatial and administrative data

Administrative records provided by Ecuador's Mining Regulation and Control Agency (ARCOM), Napo District Office, covered free-use authorizations for construction materials in Tena and Archidona during 2015–2025 (Memorandum ARCOM-DDN-2025-1499-M, 15 December 2025). The database included 132 authorizations with information, where available, on cadastral code, authorization name, holder, location, area, administrative dates, authorized volumes, and status.

Coordinates for all 132 records were incorporated into a GIS and intersected with the Misahuallí basin boundary. Sixty-eight authorizations fell within the basin. Two records for mountain silica sand and four associated with natural asphaltic sandstone were excluded because they represented materials and extraction environments distinct from river aggregates. The remaining 62 records formed the principal fluvial dataset.

Spatial processing was conducted in QGIS Desktop 3.40.7 using WGS 84 / UTM zone 18S (EPSG:32718). Authorization areas were represented as polygons and analyzed relative to the basin and hydrographic network. Temporal patterns were based primarily on the year each administrative record was created. Accordingly, annual patterns describe the issuance of authorizations and their associated authorized volumes, not annual trends in effective extraction.

3.3 Ecosystem services, field observations, and stakeholder perceptions

Ecosystem services and river-related social uses were identified from document review and field observations. Classification followed the Millennium Ecosystem Assessment (2005), distinguishing provisioning, regulating, supporting, and cultural services from direct land and water uses and from management or conservation designations. Their spatial relation to authorization areas was recorded for contextual interpretation; proximity was not treated as evidence of impact.

A structured survey was administered in person to 30 local respondents from Tena and Archidona between May and August 2026 using purposive non-probability sampling. For publication, analyses were restricted to 29 adult respondents (≥ 18 years); one record reporting age 17 was excluded from the analytical and public supplementary datasets. Eligibility for the field survey required residence or activities within the study area. The printed questionnaire contained 29 closed or multiple-choice questions on river relationships, aggregate extraction, perceived environmental change, participation, institutional communication, and management proposals. The instrument was designed for descriptive, exploratory use rather than as a psychometric scale, and items were summarized individually. Participation was voluntary and respondents signed a consent statement authorizing scientific and environmental-management use of the information. Question 19 asked whether extraction had "increased or decreased" but used a magnitude response scale (Mucho/Algo/Poco/Nada/No sabe); consistent with field administration and coding, it is reported as the perceived magnitude of increase and not as an objective temporal trend. The blank Spanish instrument and an English translation are provided as Online Resource 2, and only anonymized adult-participant data are included in Online Resource 3.

3.4 Authorized Potential Pressure Index (APPI)

The APPI was developed as a screening tool to establish relative monitoring and management priorities among free-use authorizations. It does not represent effective extraction volumes or a direct measure of environmental impact. Four criteria were integrated: total authorized volume (Vt), daily authorized volume (Vd), authorized daily intensity per unit area (I = Vd/authorized area; $m^3\ day^{-1}\ ha^{-1}$), and administrative recurrence (R).

The index was calculated only for records containing information for all four criteria. Of the 62 fluvial records, 52 had complete data; the remaining 10 were retained in the general characterization but were not scored. Total authorized volume (Vt) was available for 56 records, whereas daily authorized volume (Vd) and authorized daily intensity (I) were available for 58 records; the intersection of complete Vt, Vd, I, and recurrence information yielded the 52 APPI records. No missing values were imputed. Continuous variables Vt, Vd, and I were classified into three ordinal levels (1 = low, 2 = medium, 3 = high) using the 33.3rd and 66.7th percentiles of their distributions. Administrative recurrence was based on exact repetition of the X–Y coordinate pair in the ARCOM database: one record = 1, two records = 2, and three or more records = 3. This criterion represents repeated administrative reference locations and does not by itself demonstrate spatial overlap, temporal continuity, or repeated extraction at a site.

Table 1
Criteria, thresholds, and weights used in the Authorized Potential Pressure Index (APPI).

Criterion	Indicator	Low = 1	Medium = 2	High = 3	Weight
Total authorized volume (Vt)	m^3 authorized	≤ 84,031.14	> 84,031.14–131,847.64	> 131,847.64	30%
Daily authorized volume (Vd)	m^3 day^{-1}	≤ 99.74	> 99.74–384.65	> 384.65	25%
Authorized daily intensity (I)	m^3 day^{-1} ha^{-1}	≤ 8.32	> 8.32–24.06	> 24.06	30%
Administrative recurrence (R)	Records sharing exact X–Y coordinates	1 record	2 records	≥ 3 records	15%

Weights were defined a priori according to each criterion's role in the index. Vt and I each received 30%, Vd received 25%, and R received 15%. The resulting index was calculated as APPI = (0.30Vt) + (0.25Vd) + (0.30I) + (0.15R), where Vt, Vd, I, and R are ordinal scores. The theoretical range is 1.00–3.00. Final APPI values were grouped using the 33.3rd and 66.7th percentiles of the observed distribution: low (≤ 1.60), medium (> 1.60 to ≤ 2.25), and high (> 2.25). These are relative thresholds for this dataset rather than absolute impact thresholds.

3.5 Robustness and sensitivity analysis

Because I is derived from Vd and authorization area, associations among Vt, Vd, and I were evaluated using Spearman rank correlations on original, pre-classification values. Pairwise sample sizes therefore varied with data availability: Vt–Vd and Vt–I used 52 records, whereas Vd–I used 58 records. Sensitivity analyses compared the original APPI with three alternatives: equal weights (25% each); exclusion of Vd with renormalized weights Vt = 40%, I = 40%, R = 20%; and exclusion of I with renormalized weights Vt = 42.86%, Vd = 35.71%, R = 21.43%. Rank concordance with the original APPI was assessed using Spearman's ρ. Category stability was evaluated as the number and proportion of records retaining their original low, medium, or high class, using the original APPI thresholds.

3.6 Multitemporal illustrative cases

Two sites were selected as illustrative cases to document visible physical transformations. They were not selected to statistically represent all authorizations or to validate the APPI. Historical Google Earth Pro imagery, 2026 drone imagery, and georeferenced field photographs were compared descriptively to identify changes in land cover, access, channel configuration, and visible evidence of material removal or accumulation. Because transformations were not systematically quantified and hydrological conditions were not demonstrably equivalent among dates, these comparisons were treated only as complementary descriptive evidence.

4 Results

4.1 Spatial and temporal distribution of authorizations

During 2015–2025, 62 authorizations were associated with the fluvial system: 25 in Tena (40.3%) and 37 in Archidona (59.7%) (Fig. 2). The highest numbers of new records occurred in 2015 (n = 17), 2019 (n = 11), and 2016 (n = 8); no new authorizations were recorded in 2025. Together, the authorizations covered 1,067 ha, of which 607 ha (56.9%) were in Archidona and 460 ha (43.1%) in Tena. Recent annual values were generally lower than the 2015–2019 maxima, but this pattern reflects new administrative records rather than a demonstrated decline in effective extraction.

Table 2
Annual distribution of fluvial aggregate authorizations in the Misahuallí basin, 2015–2025.

Year	Canton	n	Area (ha)	Authorized daily volume (m³ day⁻¹)	Total authorized volume (m³)
2015	Tena	6	59	1,580	878,000
2015	Archidona	11	177	2,410	1,256,640
2016	Tena	2	30	350	132,200
2016	Archidona	6	197	2,210	1,404,260
2017	Tena	2	62	800	455,180
2017	Archidona	3	42	1,491.18	766,218
2018	Tena	2	42	937.95	57,540
2018	Archidona	1	8	300.00	257,222.40
2019	Tena	6	103	1,575	495,318
2019	Archidona	5	69	2,874.33	1,405,241
2020	Tena	0	0	0	0
2020	Archidona	3	32	540.00	436,620
2021	Tena	4	43	68.18	72,000
2021	Archidona	2	9	188.00	189,068
2022	Tena	2	112	768	256,324
2022	Archidona	0	0	0	0
2023	Tena	1	9	99.74	105,325.44
2023	Archidona	4	39	359.38	379,505.28
2024	Tena	0	0	0	0
2024	Archidona	2	34	349.64	145,734.63
2025	Tena	0	0	0	0
2025	Archidona	0	0	0	0
Total		62	1067	16,901.40	8,692,396.75

4.2 Authorized volumes and administrative status

The 62 fluvial records represented a cumulative authorized daily volume of 16,901.40 m³ day⁻¹ and a total authorized volume of 8,692,396.75 m³. The Provincial Government of Napo accounted for

4,774,196.40 m³ (54.9%; 24 records) and the Municipal Government of Archidona for 3,047,392.35 m³ (35.1%; 22 records), together representing approximately 90.0% of total authorized volume. This concentration reflects administrative authorizations and does not imply differences in compliance, environmental performance, or effective extraction.

Authorized volume associated with newly created records peaked in 2015 (2,134,640 m³; 24.6% of the cumulative total; n = 17) and 2019 (1,900,559 m³; 21.9%; n = 11) (Fig. 3). Administrative status further constrained interpretation: 36 records were archived, 18 registered, and eight in process. Archived records accounted for 4,863,574 m³ (56.0%), registered records for 3,178,257.40 m³ (36.6%), and records in process for 650,565.35 m³ (7.5%). Thus, cumulative authorized volume is neither equivalent to currently valid volume nor to material actually extracted.

4.3 APPI ranking and sensitivity

For the 52 records with complete data, APPI values ranged from 1.00 to 2.85 (mean = 1.87; median = 1.85). Twenty-two records (42.3%) were classified as low, 13 (25.0%) as medium, and 17 (32.7%) as high authorized potential pressure. Mangalpa GADP Napo had the highest APPI (2.85), followed by Atacapi GADP Napo, Santo Domingo GADP Napo, Santo Domingo, Manku, and Mina San Juan (all 2.70). The remaining high-pressure records ranged from 2.30 to 2.45.

Table 3
Records classified as high authorized potential pressure (APPI > 2.25).

Authorization / record	Vt	Vd	I	R	APPI
Mangalpa GADP Napo	3	3	3	2	2.85
Atacapi GADP Napo	3	3	3	1	2.70
Santo Domingo GADP Napo	3	3	3	1	2.70
Santo Domingo	3	3	3	1	2.70
Manku	3	3	3	1	2.70
Mina San Juan	3	3	3	1	2.70
San Vicente GADP de Napo	3	2	3	1	2.45
Las Palmas GADP Napo	3	2	3	1	2.45
El Retén GADP Napo	3	2	3	1	2.45
Guinea Chimbana	3	3	2	1	2.40
San Carlos GADP Napo	3	3	2	1	2.40
La Merced	2	3	3	1	2.40
Dos Ríos 1 GADMT	2	3	3	1	2.40
Dos Ríos 2 GADMT	2	3	3	1	2.40
Mina Bancos de Arena	3	3	2	1	2.40
Mina Batancocha	3	2	2	2	2.30
San Pedro GADP de Napo	3	2	2	2	2.30

Spearman correlations among original quantitative variables were positive: Vt–Vd, $\rho = 0.596$ ($p < 0.001$; $n = 52$); Vt–I, $\rho = 0.447$ ($p < 0.001$; $n = 52$); and Vd–I, $\rho = 0.666$ ($p < 0.001$; $n = 58$), the latter being expected because I is partly derived from Vd. None indicated complete monotonic correspondence among rankings.

Sensitivity analysis showed high rank agreement with the original APPI. Equal weighting yielded $\rho = 0.992$ ($p < 0.001$; $n = 52$), with 41 records (78.8%) retaining their category. Excluding Vd yielded $\rho = 0.967$, with 37 records (71.2%) retaining category; excluding I yielded $\rho = 0.939$, with 40 records (76.9%) retaining category. Thus, rank order was robust across the tested scenarios, while categorical assignment was more sensitive: 21.2–28.8% of records changed category depending on the scenario.

4.4 Multitemporal illustrative cases

At Sinchi Sacha (ARCOM 100000627; authorized area 5 ha), comparison of historical imagery, 2026 drone imagery, and field photographs documented changes in access routes, vegetation cover, river margins, and the distribution of coarse material within the channel (Fig. 4). These observations show visible changes in the fluvial setting but cannot be attributed exclusively to extraction because hydrological conditions were not controlled and changes were not quantitatively measured.

At San Pedro GADP de Napo (ARCOM 100000363; approximately 31 ha), imagery from 2017 and 2023, together with drone and field observations from 2026, showed visible changes in the configuration of the Tena and Lupi rivers and in vegetation cover within the authorized area (Fig. 5). As at Sinchi Sacha, these observations are descriptive and do not establish extraction as the sole cause of change.

4.5 Ecosystem services and socioenvironmental context

Field surveys georeferenced ecosystem services and river-related uses (Fig. 6). Recorded elements included fishing as a provisioning service; water intakes and treatment plants as uses associated with water-service demand; and cultural services associated with swimming areas, petroglyphs, rafting, and kayaking. Authorized areas were represented as a potential use and pressure, while protected natural areas were treated as management and conservation designations.

Authorization records were concentrated mainly in central and southern fluvial environments, where some uses and services occurred close to authorized areas. Spatial coincidence identifies potential interaction zones but is not a measure of exposure and does not constitute a basin-wide inventory of ecosystem services. Similar use of georeferenced administrative and remote-sensing information has been applied to screen mining pressure in the Brazilian Amazon, illustrating the value—and limits—of spatially explicit records for environmental prioritization (Rudke et al. 2020).

4.6 Stakeholder perceptions

Among the 29 adult survey participants included in the publication analysis, 19 (65.5%) were 40–70 years old, 26 (89.7%) had lived in their community or sector for at least 20 years, and all reported secondary education or higher. Twenty participants (69.0%) used the river at least monthly, and 28 (96.6%) reported having observed or known about aggregate extraction in nearby rivers. Twenty-five (86.2%) reported a substantial perceived increase in extraction activity, while 18 (62.1%) reported seeing machinery daily or several times per week (Fig. 7). These values describe participant perceptions and experience rather than objective extraction frequency or trend.

In a multiple-response question on perceived river and riparian changes, 21 participants (72.4%) selected changes in water quality, 18 (62.1%) fewer fish, 17 (58.6%) bank erosion or land loss, and 16 (55.2%) reduced flow. Smaller proportions reported reduced river depth (10/29; 34.5%), increased dust or noise (5/29; 17.2%), and difficulty crossing the river (4/29; 13.8%). Twenty-eight participants (96.6%) rated the magnitude of river change attributed to extraction as high, and 24 (82.8%) perceived high effects on local

economic activities and ecosystem services. These responses represent perceptions and do not establish causal impacts.

Perceived benefits included provision of materials for community works (17/29; 58.6%), road or infrastructure improvement (13/29; 44.8%), and local employment (7/29; 24.1%); 12/29 participants (41.4%) stated that the activity generated no community benefits. Regarding governance, 15 participants (51.7%) reported that authorities or companies did not inform communities about extraction activities, eight (27.6%) reported that information was provided only sometimes, and 20 (69.0%) had neither participated in nor knew of meetings related to environmental control or monitoring. All 29 adult participants expressed interest in mechanisms for citizen oversight or participation.

4.7 Monitoring priorities and management implications

The two-stage framework first used APPI to rank 52 complete records by authorized potential pressure and then used available socioenvironmental information to contextualize follow-up needs without altering APPI scores or categories. High-APPI records can therefore serve as an initial priority set for administrative verification and monitoring, while proximity to water infrastructure, recreational uses, ecosystem services, or cultural elements can guide the type of follow-up required.

For example, Mina San Juan (APPI = 2.70) had an authorized daily intensity of 98.49 $m^3\ day^{-1}\ ha^{-1}$. Field work identified the Yawari drinking-water treatment plant and kayaking activities in its broader surroundings; however, the intake location and hydrological connectivity with the authorization area were not established, so these elements were treated solely as spatial context. Chimbiyacu also had high authorized daily volume and an intensity of 64.84 $m^3\ day^{-1}\ ha^{-1}$, with recreational uses nearby; recorded petroglyphs occurred outside the authorization area. Bancos de Arena and Sinchi Sacha likewise showed spatial relationships with recreational sites and visible physical transformations documented through multitemporal observations. These cases identify monitoring needs but do not attribute observed transformations to extraction.

Operational follow-up may include verification of effectively extracted volumes, field inspection, geomorphic surveys, and georeferenced photographic records. Where interaction with sensitive socioenvironmental elements is plausible, monitoring can be expanded to water quality, bank stability, sediment dynamics, riparian cover, and aquatic habitat. Restriction, mitigation, or restoration measures would require site-specific evidence on the existence, nature, and magnitude of impacts.

5 Discussion

The Misahuallí basin showed marked spatial and temporal heterogeneity in potential pressure associated with authorized aggregate extraction. The APPI provided an explicit way to integrate authorization magnitude, intensity, and administrative recurrence, while the second stage added socioenvironmental context without conflating administrative pressure with environmental impact. This distinction is consistent with evidence that the consequences of river aggregate extraction depend on

effective removal, sediment supply and replenishment, hydrogeomorphic connectivity, and local setting (Koehnken et al. 2020).

Authorized volumes are not equivalent to volumes actually removed. This is a central limitation but also the rationale for the screening framework: administrative records can reveal where authorized pressure is greatest when effective extraction data are unavailable. Sustainable extraction ultimately depends on whether sediment removal exceeds natural supply. In the lower Mekong, for example, sediment imbalance associated with sand mining has been linked to river-bank instability (Hackney et al. 2020), illustrating why future assessments in the Misahuallí should incorporate sediment budgets and measured extraction volumes.

The concentration of almost 90% of authorized volume among two public-sector authorization holders should not be interpreted as evidence of non-compliance or poor environmental performance. It does, however, identify a manageable set of institutional actors with whom reporting, verification, and monitoring could be strategically coordinated. Sustainable freshwater sand and gravel governance requires linking regulation and extraction practices with demand, social values, and collaborative governance mechanisms (Ulibarri et al. 2023).

The two-stage structure also clarifies the role of ecosystem services and local knowledge. APPI describes authorized potential pressure; co-occurrence with drinking-water infrastructure, recreation, tourism, fisheries, or cultural elements describes socioenvironmental context; and impact attribution requires quantitative biophysical evidence. Keeping these levels separate reduces the risk that spatial coincidence is interpreted as exposure or impact while still helping managers decide what should be monitored next (Shaad et al. 2022).

The two illustrative sites documented visible changes in channel configuration, banks, and vegetation cover. Such changes are consistent with hydrogeomorphic responses reported for in-stream gravel extraction, including incision, bank instability, altered sediment transport, and habitat modification (Kondolf 1994). Nevertheless, the present comparison was descriptive. Causal attribution would require hydrologically comparable observations, reference sites, time series, sediment budgets, and sufficient geomorphic and ecological measurements. This caution is especially relevant in Andean-Amazonian rivers, where floods, high sediment transport, and other interventions can rapidly modify channel geometry.

Stakeholder perceptions provided an additional line of contextual evidence. Participants frequently reported changes in water quality, fish availability, discharge, and bank erosion, consistent with concerns documented previously in the Tena River (Sarduy-Pereira et al. 2024). Local knowledge can be useful for identifying concerns and candidate monitoring sites, particularly when combined with clear recording and validation protocols (Rosero-López et al. 2026). However, the purposive sample of 29 adult participants was exploratory and cannot estimate basin-wide public perception or substitute for biophysical measurements. The questionnaire was not designed as a psychometric scale, so individual items are interpreted descriptively rather than as a latent composite construct.

The main contribution of this study is therefore a sequential framework for data-limited management. Administrative records establish a first, transparent ranking of authorized potential pressure. Spatial analysis, ecosystem services, field observations, and local knowledge then identify the kinds of additional information that are most valuable. This is particularly useful where monitoring resources are limited and decisions require explicit criteria. Structured environmental decision analysis and monitoring-design studies likewise emphasize the value of making objectives, weighting choices, and information needs explicit rather than allowing data availability alone to determine monitoring priorities (Huang et al. 2011; Marttunen et al. 2019). The sensitivity analysis strengthens this application: rank order remained highly concordant under equal weights and after removal of either Vd or I, although the movement of 21–29% of records among categories cautions against treating class boundaries as fixed ecological thresholds.

Several limitations delimit interpretation. First, all volume metrics refer to authorization, not effective extraction. Second, daily intensity depends on both authorized daily volume and administratively assigned area and is therefore comparative rather than a direct physical extraction rate. Third, recurrence is based on exact coordinate repetition and may be affected by spatial precision in the administrative database. Fourth, ecosystem-service mapping was non-exhaustive. Fifth, multitemporal analysis focused on two purposively selected illustrative cases and used images that differed in date, resolution, and hydrological conditions. Sixth, APPI depends on ordinal classification rules and a priori weights, although sensitivity analysis indicated robust ranking. Seventh, authorization status and validity were not incorporated into the index; high historical APPI therefore does not imply that extraction is currently authorized or active. Finally, the purposive stakeholder sample limits statistical generalization.

Future work should combine verified extraction volumes with sediment supply and replenishment, quantitative channel geometry, bank stability, water quality, riparian cover, aquatic habitat, and fish communities. Recent reviews of river-sand mining similarly emphasize the need to combine remote sensing and GIS with field measurements, sediment budgets, and ecological monitoring rather than relying on a single evidence stream (Rentier and Cammeraat 2022; Tripathi et al. 2025). Time series and reference sites would allow testing whether high-priority APPI locations subsequently show measurable biophysical change and would permit progressive validation and recalibration of the framework. Transfer to other tropical basins will likewise require recalibration of thresholds and weights, assessment of administrative-data quality, and adaptation of the contextual second stage to local socioenvironmental conditions.

6 Conclusions

Authorized potential pressure from river aggregate extraction was heterogeneous across the Misahuallí basin during 2015–2025; the number of authorizations alone was therefore insufficient for establishing monitoring priorities. The APPI integrated authorized magnitude, intensity, and administrative recurrence and produced a ranking that remained comparatively stable under the tested sensitivity scenarios. It

should be interpreted as a screening tool based on authorization conditions, not as a measure of effective extraction or environmental impact.

A second contextual stage using ecosystem services, social uses, field observations, multitemporal imagery, and local perceptions can refine what type of inspection or monitoring is needed without altering index scores or assuming causality. For present-day management, APPI rankings should first be cross-checked against current administrative status and validity. Validation of the broader approach will require measured extraction and geomorphological, sedimentological, hydrological, physicochemical, and ecological monitoring capable of testing whether prioritized sites exhibit quantifiable environmental change.

Declarations

Author contributions: David A. Baquero: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. Jorge E. Celi: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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Ethics approval and consent to participate: The publication analysis was restricted to 29 adult participants and involved a non-clinical, minimal-risk environmental-perception questionnaire. At the time of data collection, Universidad Regional Amazónica Ikiam did not have an institutional CEISH, and no formal CEISH review or exemption was obtained. Participation was voluntary, and participants provided written informed consent authorizing scientific and environmental-management use of their responses. No health information, biological samples, clinical procedures, or experimental interventions were involved. Direct identifiers collected for field administration were excluded from the analyses reported here and from all shared supplementary data. Survey results are reported only in anonymized or aggregate form.

Consent for publication: The manuscript contains no identifiable personal information from survey participants.

Competing interests: The authors declare no competing interests.

Data availability: The underlying administrative records were provided by the Ecuadorian Mining Regulation and Control Agency (ARCOM) and remain subject to the conditions governing access to the original administrative information. The processed 62-record APPI dataset and sensitivity results are provided as Online Resource 1. The survey instrument is provided in English and in its original Spanish version as Online Resource 2, and the anonymized adult-participant survey dataset with codebook is provided as Online Resource 3.

Supplementary information: Online Resource 1 contains the complete 62-record fluvial authorization dataset, including 52 calculated APPI values, 10 records explicitly marked as not calculated because of incomplete administrative information, and sensitivity scenarios. Online Resource 2 contains the stakeholder questionnaire in English translation and original Spanish. Online Resource 3 contains the anonymized dataset and codebook for the 29 adult survey participants included in the publication analysis.

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Data Availability

All data supporting the findings of this study are available within the article and its Supplementary Information. Administrative data on free-use authorizations for construction-material extraction were obtained from the Ecuadorian Mining Regulation and Control Agency (ARCOM) through Memorandum No. ARCOM-DDN-2025-1499-M, dated 15 December 2025. The processed administrative dataset used to identify the 62 fluvial authorization records and calculate the Authorized Potential Pressure Index (APPI), including sensitivity analyses, is provided as Online Resource 1. The blank stakeholder survey instrument is provided as Online Resource 2. The anonymized survey dataset and accompanying codebook for the 29 adult participants included in the analysis are provided as Online Resource 3. Direct participant identifiers are not publicly available in order to protect participant confidentiality.

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Figures

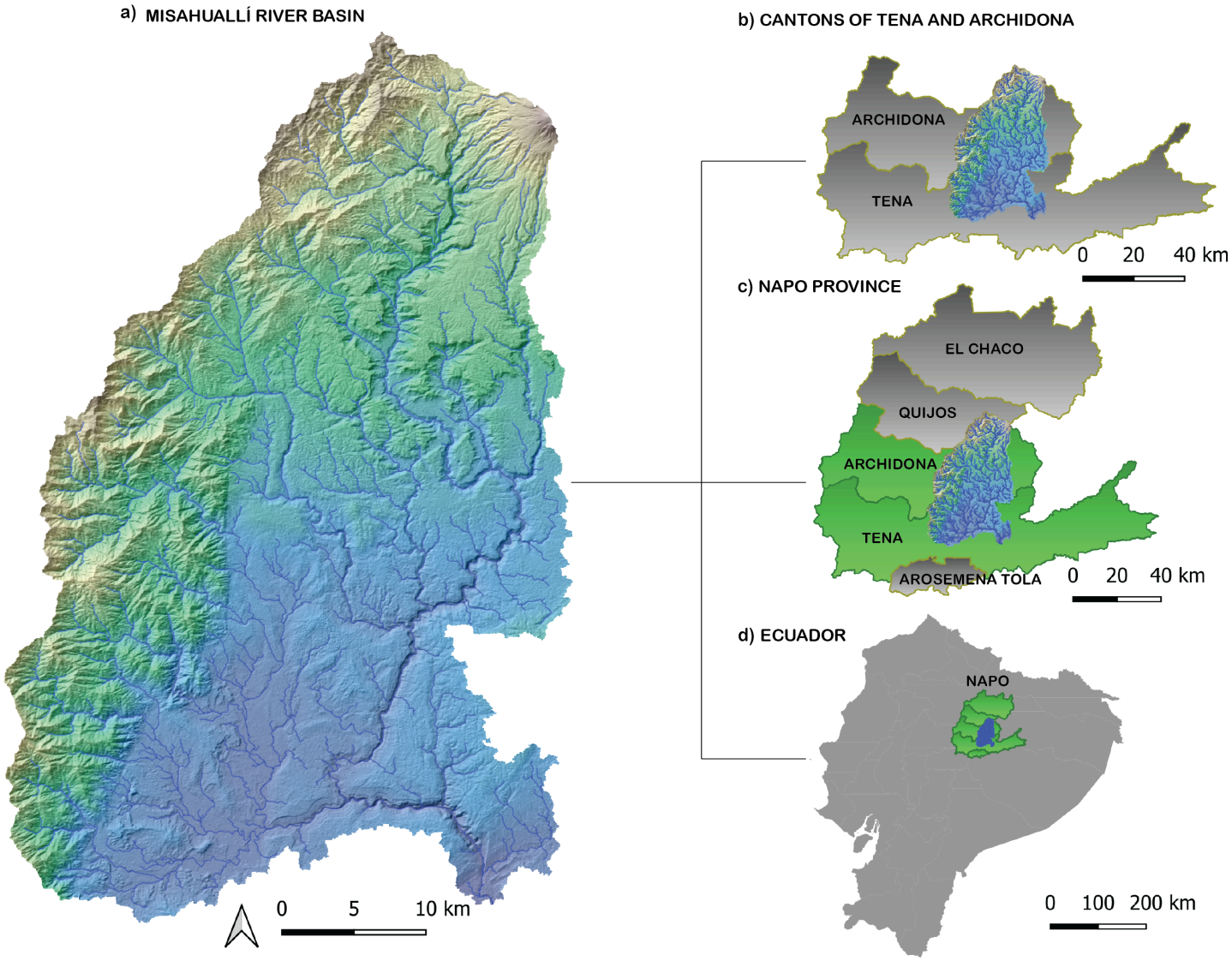


Figure 1

Location of the Misahuallí River basin, Ecuador: (a) basin delineation; (b) location relative to Tena and Archidona cantons; (c) location within Napo Province; and (d) location of Napo Province in Ecuador and the Amazon region

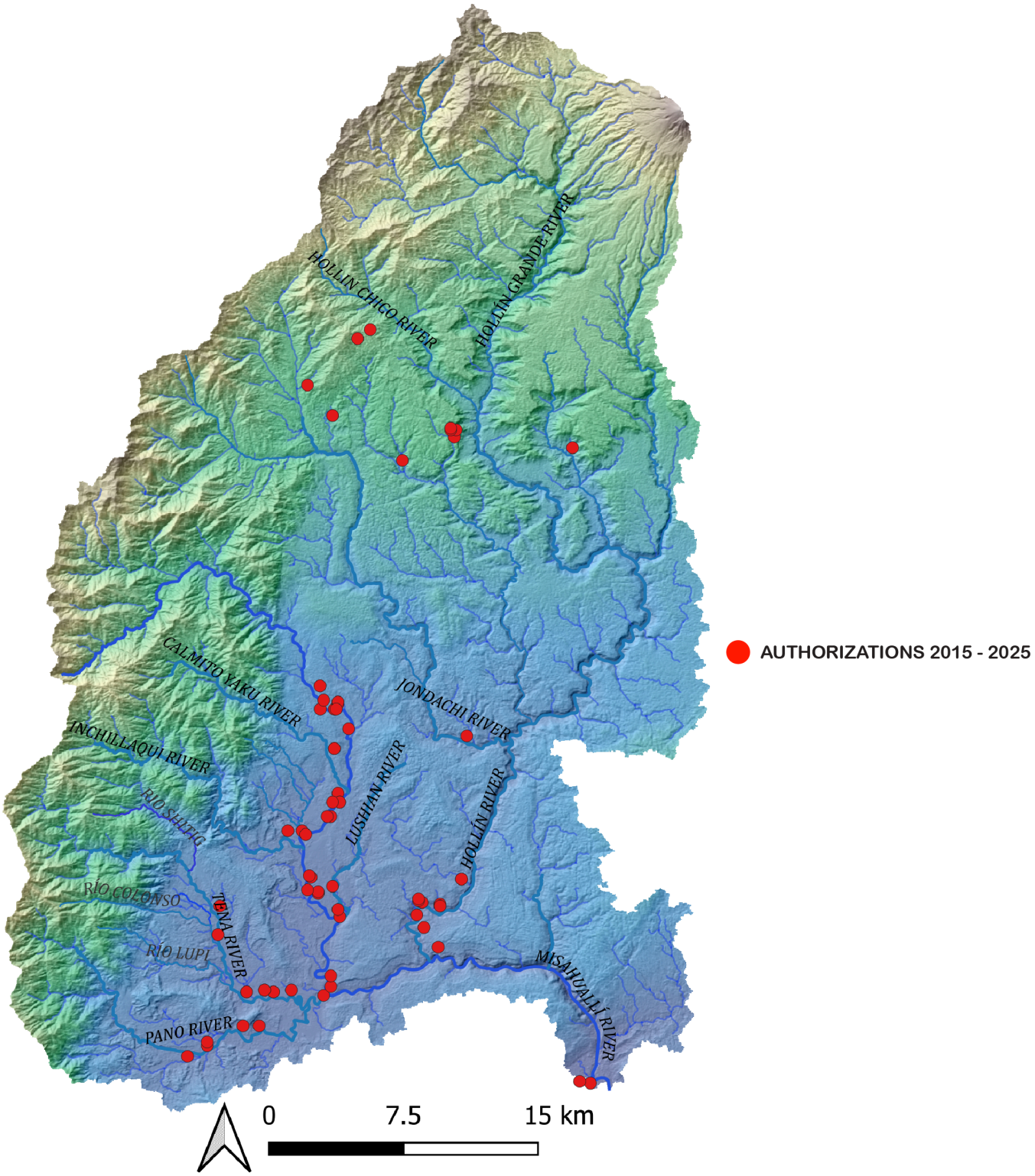


Figure 2

Spatial distribution of free-use aggregate extraction authorizations granted in the Misahuallí River basin during 2015–2025. Source: ARCOM administrative records (Memorandum ARCOM-DDN-2025-1499-M, 2025).

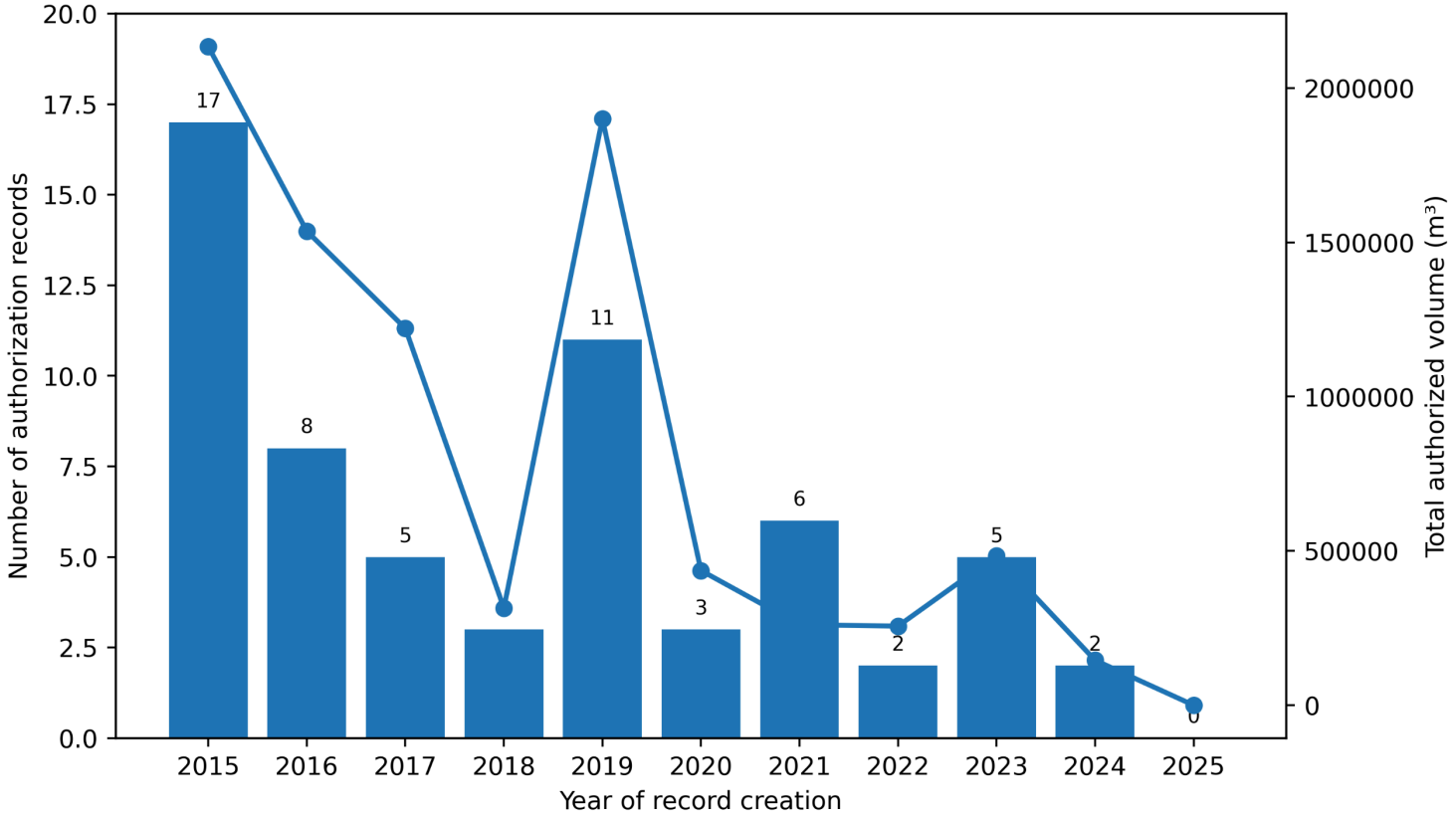


Figure 3

Temporal distribution of the 62 fluvial aggregate authorization records during 2015–2025. Bars show the number of administrative records created in each year and the line shows the corresponding total authorized volume. Years refer to record creation and do not represent annual effective extraction



Figure 4

Multitemporal changes and visible intervention at the Sinchi Sacha authorization area (ARCOM 100000627): (a) Google Earth Pro image, 16 July 2015; (b) Google Earth Pro image, 18 November 2024; (c) drone image, 2026; and (d) field photograph, 2026. Differences in discharge and seasonality among dates are an important source of uncertainty.



Figure 5

Multitemporal changes and visible intervention at San Pedro GADP de Napo (ARCOM 100000363), Tena River: (a) Google Earth Pro image, 16 June 2017; (b) Google Earth Pro image, 16 September 2023; (c) drone image, 2026; and (d) field photograph, 2026. Hydrological non-equivalence among image dates limits causal interpretation.

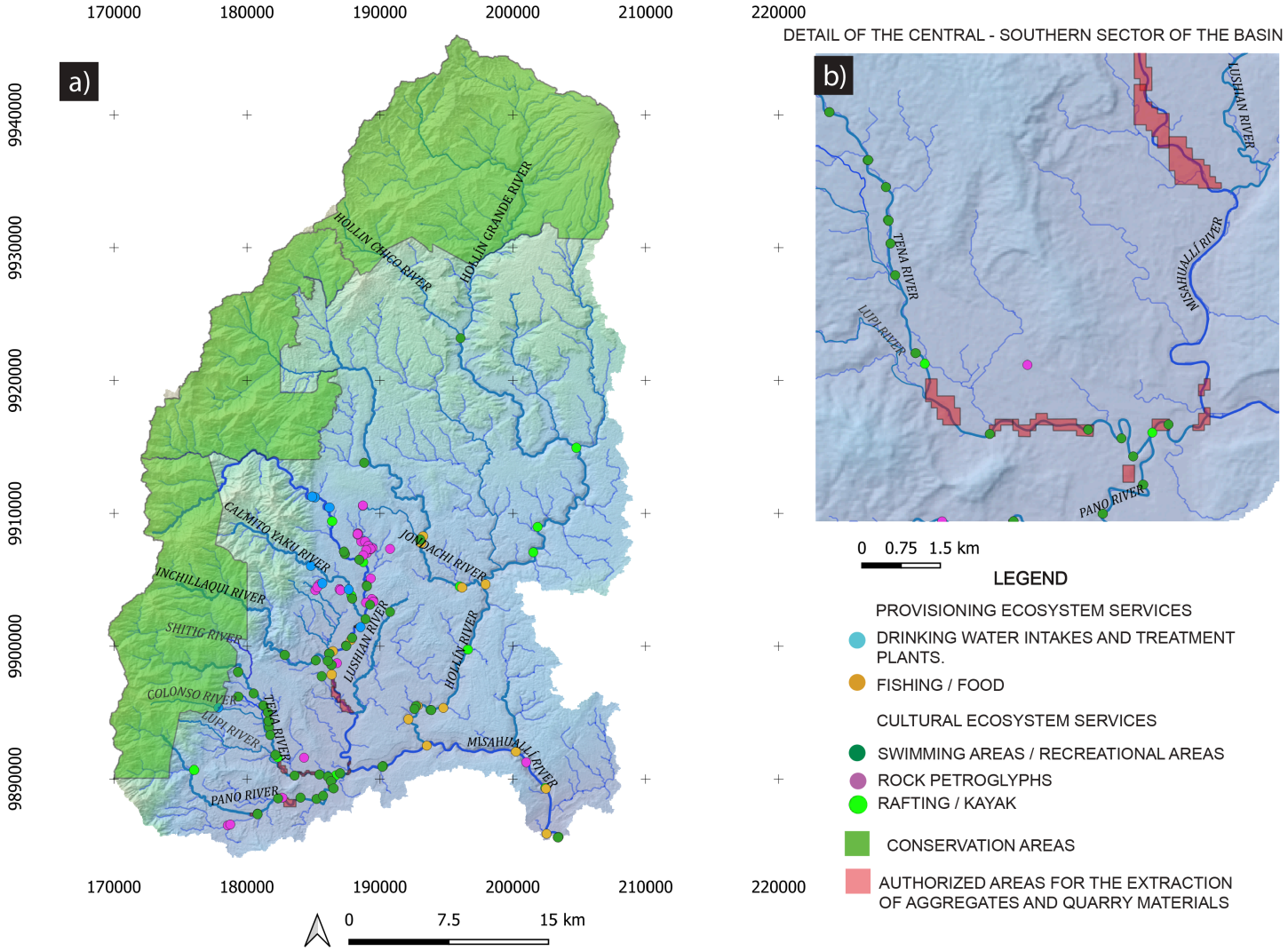


Figure 6

Spatial distribution of identified ecosystem services and authorized aggregate extraction areas in the Misahuallí basin: (a) basin-wide distribution; (b) detail of the central-southern sector showing spatial proximity among authorized areas, the river network, and sites associated with ecosystem services. Authorization areas do not necessarily indicate effective extraction

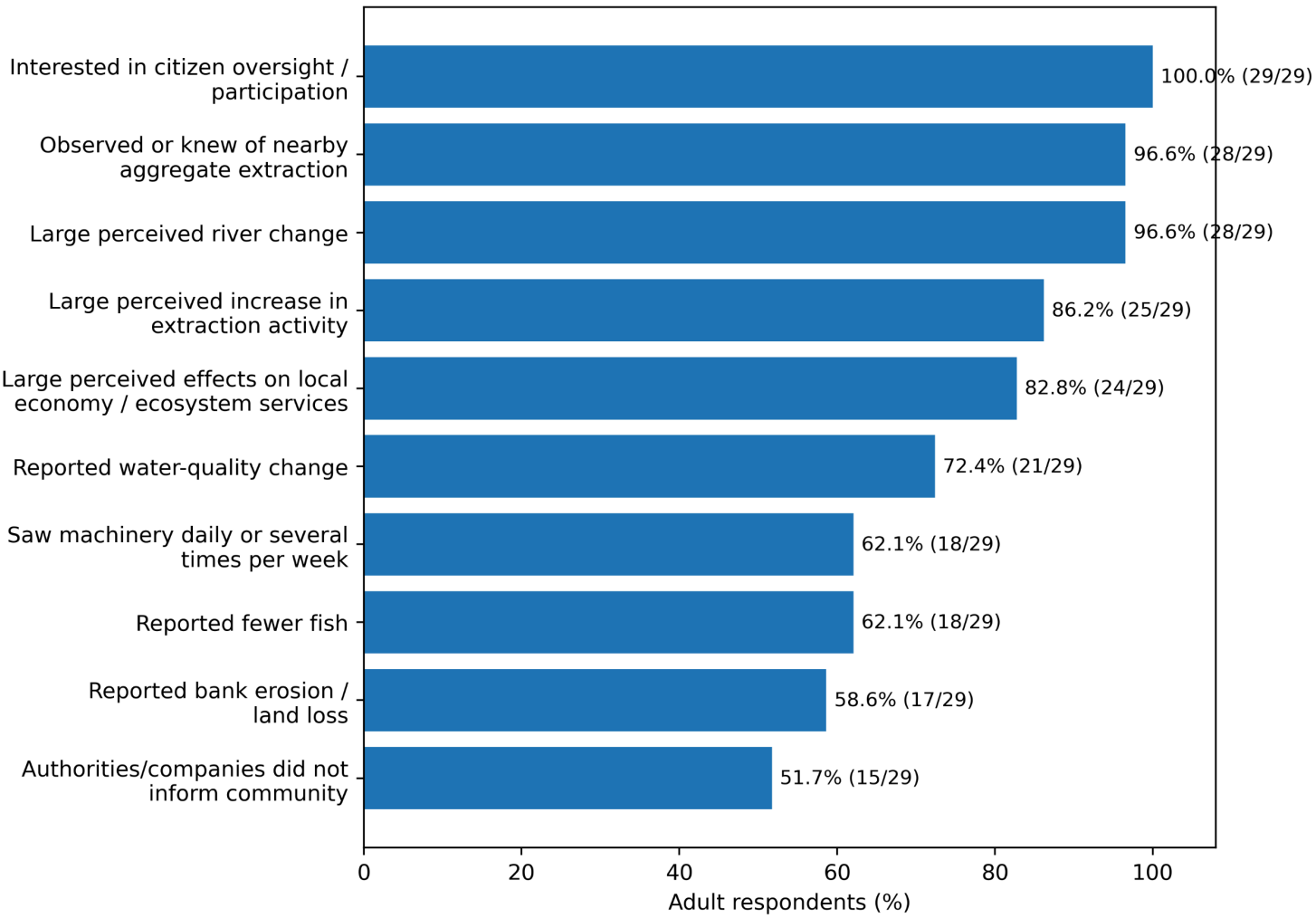


Figure 7

Selected stakeholder perceptions and reported river-related changes in the Misahuallí basin. Bars show the percentage of the 29 adult respondents selecting each displayed response; counts are shown with percentages in the figure. Items represent participant perceptions and reported observations and should not be interpreted as measured environmental impacts or as an objective extraction trend

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- OnlineResource1.xlsx
- OnlineResource2.pdf
- OnlineResource3.xlsx