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Key Points:

- Meandering and anabranching rivers are found along the transition from the Andes to the Amazon lowland
- The Manseriche Gorge acts as a natural boundary condition for hydrogeomorphology and fish diversity
- If the Manseriche hydropower dam was built, the Santiago River will disappear, and river connectivity and sediment supply to the Amazon lowland will be impacted

Supporting Information:

Supporting Information may be found in the online version of this article.

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River Geomorphology and Fish Diversity Around the Manseriche Gorge, the Last Andean Crossing Is in Peril

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Abstract The transition from the Andes to the Amazon lowland hosts a high biodiversity and currently is facing several anthropogenic activities, including hydropower infrastructure projects. Little is known about the geomorphology of the Andean gorges, rivers and the interaction with the fish diversity upstream and downstream of gorges. The Marañón River is a major river that connects the Andes to the Amazon lowland and it carries 40% of the sediment load arriving to Brazil. The Santiago River is the last tributary into the Marañón River before the last gorge (Manseriche). Current plans for hydropower reservoirs include the construction of several dams along the Marañón River, being the largest with a 4,500 MW capacity at the Manseriche Gorge (MG). This study seeks to characterize the baseline processes of the hydrogeomorphology and fish diversity. Results show that the Santiago River is under transitional morphodynamic regime while the Marañón River is a fully developed anabranching river. This study reveals a clear difference in fish species richness and abundance between the upstream and downstream regions of the MG, with some species only found in specific regions. The MG acts as a natural boundary condition for the hydrogeomorphology and fish diversity. If the hydropower dam at MG was built, the reservoir in the upstream reach will produce the Santiago River to disappear and sedimentation to occur, consequently modifying sediment transport boundary conditions for the lower Marañón River. Downstream of the potential dam incision will occur, reducing lateral connectivity, particularly at sites where unique species were found.

Plain Language Summary The Manseriche Gorge located at the transition from the Andes to the Amazon lowland imposes natural boundary conditions for hydrogeomorphology and fish diversity. If a hydropower dam is built at the Manseriche Gorge, several impacts will be observed such as the disappearance of tributary Santiago River, geomorphic and fish diversity alterations between upstream and downstream regions.

1. Introduction

The dynamics of the Andean mountain range plays a significant role in understanding the lowland's Amazon landscape (e.g., rivers, lakes, wetlands) and their linkage to freshwater diversity, especially along the western Amazon basin (Figure 1a), hotspot of biodiversity (Boschman et al., 2023; Hoorn et al., 2010). Due to significant differences in timing of crustal shortening, exhumation, and surface uplift between the different Andean regions (northern, central and southern), a complex three-dimensional landscape is observed (Boschman, 2021), thus promoting a wide spectrum of river patterns and shifts during a wide geological time scale (Albert et al., 2018). Calvès et al. (2019) showed the Cenozoic sequences of the Marañón basin, where straight, meandering and anastomosing channels were observed (of similar dimensions as the modern ones). Regarding sediment load, Guyot et al. (2007) and Armijos et al. (2013) estimated that the total suspended sediment yield transferred from Peru to Brazil (having the Andes as the source of the sediments) is around 570Mt/y where 40% is carried out by the Marañón River.

Biodiversity connectivity between the different geological landscapes depends on fluvial connectivity (hydrological and geomorphological, Fassoni-Andrade et al. (2021)). Caldas et al. (2023) described that freshwater species such as dolphins, turtles, and fish require some degree of longitudinal and lateral connectivity, including other terrestrial and semi-aquatic species that also rely on river-floodplain connectivity. Diversification of freshwater fish is occurring since earlier geological epochs, with a faster rate from the Miocene to the present

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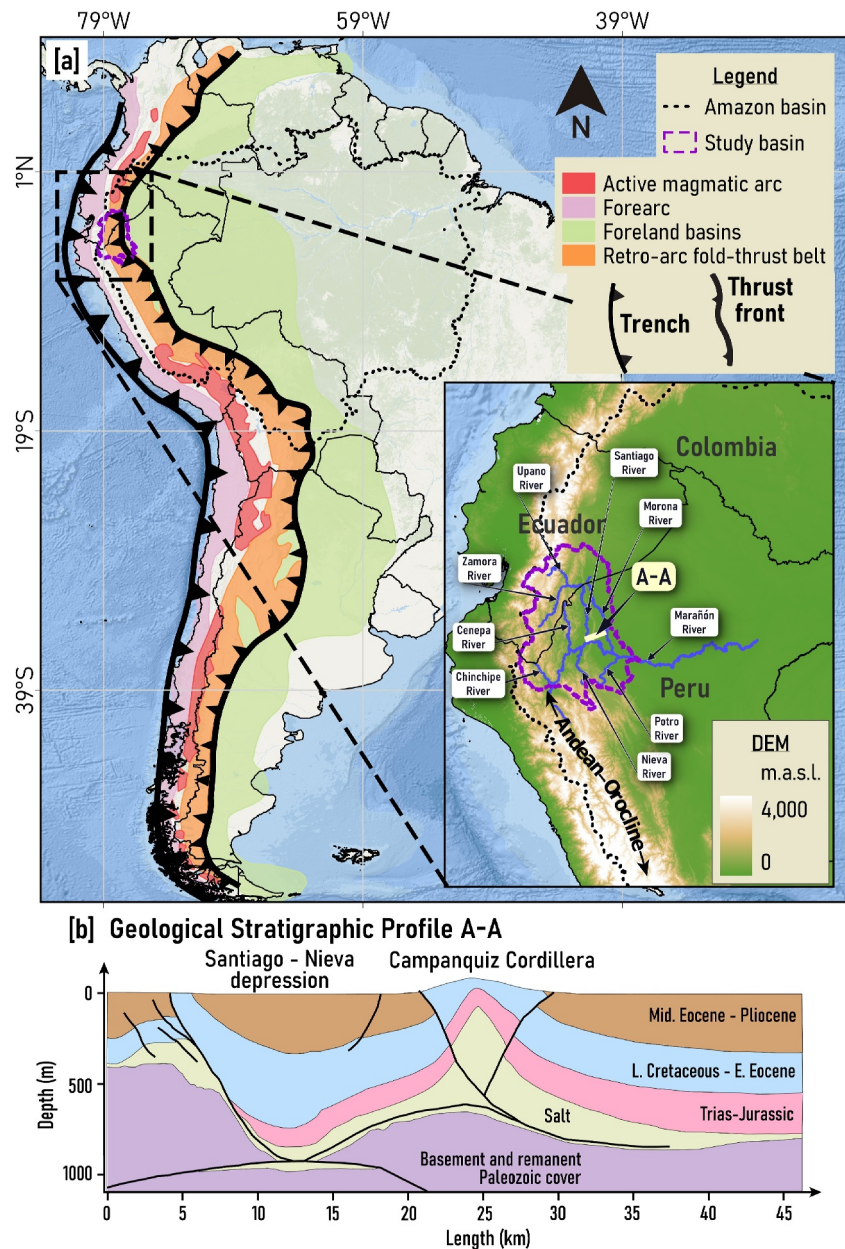


Figure 1. (a) Geological zones, adapted from Baby et al. (2019), DEM (200 m resolution using ALOS World 3D, 30 m using the Google Earth Engine platform), (b) Stratigraphic profile A-A (adapted from Baby et al. (2019)) showing the Santiago-Nieva depression to the left of the Campanquiz cordillera.

(influenced by the geology). The complex landscape dynamics that have shaped the drainage basin, with events such as mountain uplift and river re-arrangement events, especially in the western Amazon basin has nurtured the highest rates on in situ diversification (Cassemiro et al., 2023). For the case of the Pacaya-Samiria National Reserve, Rojas et al. (2023) contrasted the fish extraction in the Ucayali and Marañón rivers; the extraction is larger in the Ucayali River, which has more meandering activity and has significant lateral connectivity shown by abundant paleochannels and oxbow lakes, in contrast to the Marañón River, which has less geomorphic structures along the floodplain. Lateral connectivity is more active during high- than low-flow conditions, where flooding is a driving factor (Caldas et al., 2023). The seasonal pulses produced by the annual hydrological cycles (Reis et al., 2019) are a dominant component of the migration of freshwater species (Caldas et al., 2023), especially during spawning and nursing. Goulding et al. (2010) described migratory patterns of characiformes species of

different sizes along the Amazon River and its tributaries, which represents 67% of the annual fisheries based in the catchment (Duponchelle et al., 2021). Barthem et al. (2017) and Goulding et al. (2018) mapped out the migratory fish patterns of the Amazonian goliath catfishes, and showed that the main spawning region of these catfishes are in the western Amazon. The Manseriche Gorge (MG), located 4,847 km upstream from the Amazon River mouth (Barthem et al., 2017), is a frequent spot for four main species (*Brachyplatystoma rousseauxii* (Castelnau 1855), *B. platynema* Boulenger 1898, *B. juruense* (Boulenger 1898), and *B. vaillantii* (Valenciennes 1840)), which are under threat by fish over-exploitation, deforestation, climate change and especially hydropower dams (Duponchelle et al., 2021).

Currently, the development of several infrastructure projects is in progress along the Amazon basin, especially around the Andes-lowland transition; some of them are missing detailed and integral studies of their impacts. Valverde et al. (2024) showed that the Terms of Reference of the Environmental Impact Assessment Study for the Peruvian Waterway Project (Hidrovia Amazónica in Spanish) demanded insufficient analysis on river processes. For the case of the western Amazon, hydropower dam development might have a major impact on fluvial processes, biodiversity and might produce river fragmentation (Anderson et al., 2018; Flecker et al., 2022; Forsberg et al., 2017; Latrubesse et al., 2017; Opperman et al., 2023). Flecker et al. (2022) described that there are more than 350 sites for potential development of hydropower dams along the Amazon basin, and recommended strategic evaluation of trade-offs between the different ecosystem services. Existing and potential hydropower dams induce pressure on healthy rivers and their linked ecosystem services, such as fisheries, agriculture, transportation, and carbon sequestration (Caldas et al., 2023). Maeck et al. (2013) described that trapped sediments in reservoirs are a major source of methane emissions. Generally, dams produce upstream and downstream hydrological alterations (Timpe & Kaplan, 2017) such as flooding, water discharge control (frequency, duration), morphological adaptations and fish diversity changes (Chen et al., 2023). Swanson et al. (2021) presented an analysis of the six mega-dams along the Tocantins River in Brazil and showed that flooding extent and hydroperiod were reduced downstream, as well as the flood timing has been changed (based on hydropower operations). Chaudhari and Pokhrel (2022) used a hydrologic model to describe the effect of existing dams along the Xingu, Madeira and Tocantins River, and showed that the river flow amplitude ($Q_{max}-Q_{min}$) downstream of dams has increased in magnitude. Hydrogeomorphic changes induce changes on fish diversity, Sá-Oliveira et al. (2015) performed fish sampling upstream and downstream of the Coaracy Nunes Dam along the Araguari River in Amapá, Brazil, and found negative impacts (changes on abundance, biomass, species richness, alpha diversity and species dominance, besides, a higher presence of small-bodied fish population and a complete absence of long-distance migratory species) especially upstream of the dam, where a transition from a lentic to a lotic habitat occurred.

Based on the freshwater connectivity corridor index, Caldas et al. (2023) suggested that the Marañón is among the eight most vulnerable rivers; similar findings were presented by Latrubesse et al. (2017) and Anderson et al. (2018). Several dams are proposed along the Marañón River, including the largest hydropower proposed dam at the Manseriche Gorge (MG) (Anderson et al., 2018; Forsberg et al., 2017) (Figure 2a), which is planned to produce 4500 MW (QVIngenierosSAC, 2007; Rubio et al., 2017). Forsberg et al. (2017) estimated a reduction in sediment discharge of around 166Mt/y, and nitrogen and phosphorus fluxes of 0.119Mt/y and 0.144Mt/y, respectively if the Manseriche dam is built. The Santiago River is the last Andean tributary to the Marañón River before the MG, indeed, it arrives just upstream of the MG. The Santiago River transports around 35% of the Marañón River's flow discharge (Armijos et al., 2013; Guyot et al., 2007). Little is known about the river geomorphology and fish diversity around the MG, and what could be the impacts of building the Manseriche hydropower dam. This study seeks: (a) to develop a baseline characterization of the hydrogeomorphology of the main rivers around the MG, describing the main drivers for their morphological activity, (b) to develop a baseline characterization of fish diversity around the MG, especially if there are differences in species and abundance upstream and downstream of the MG, (c) to describe potential environmental impacts regarding hydrogeomorphology and fish diversity if the Manseriche dam is built.

2. Field Site

The Manseriche Gorge is the last of five gorges located along the Marañón River in the study basin defined in Figure 1a. Figure 1a shows the retro-arc fold-thrust belt along the Eastern Cordillera of South America and the foreland region (Boschman, 2021). The Andean mountains modulate the existing geology (Figure S1 in Supporting Information S1), sedimentary deposits (Figure 1b) and terrain elevation (DEM; digital elevation model)

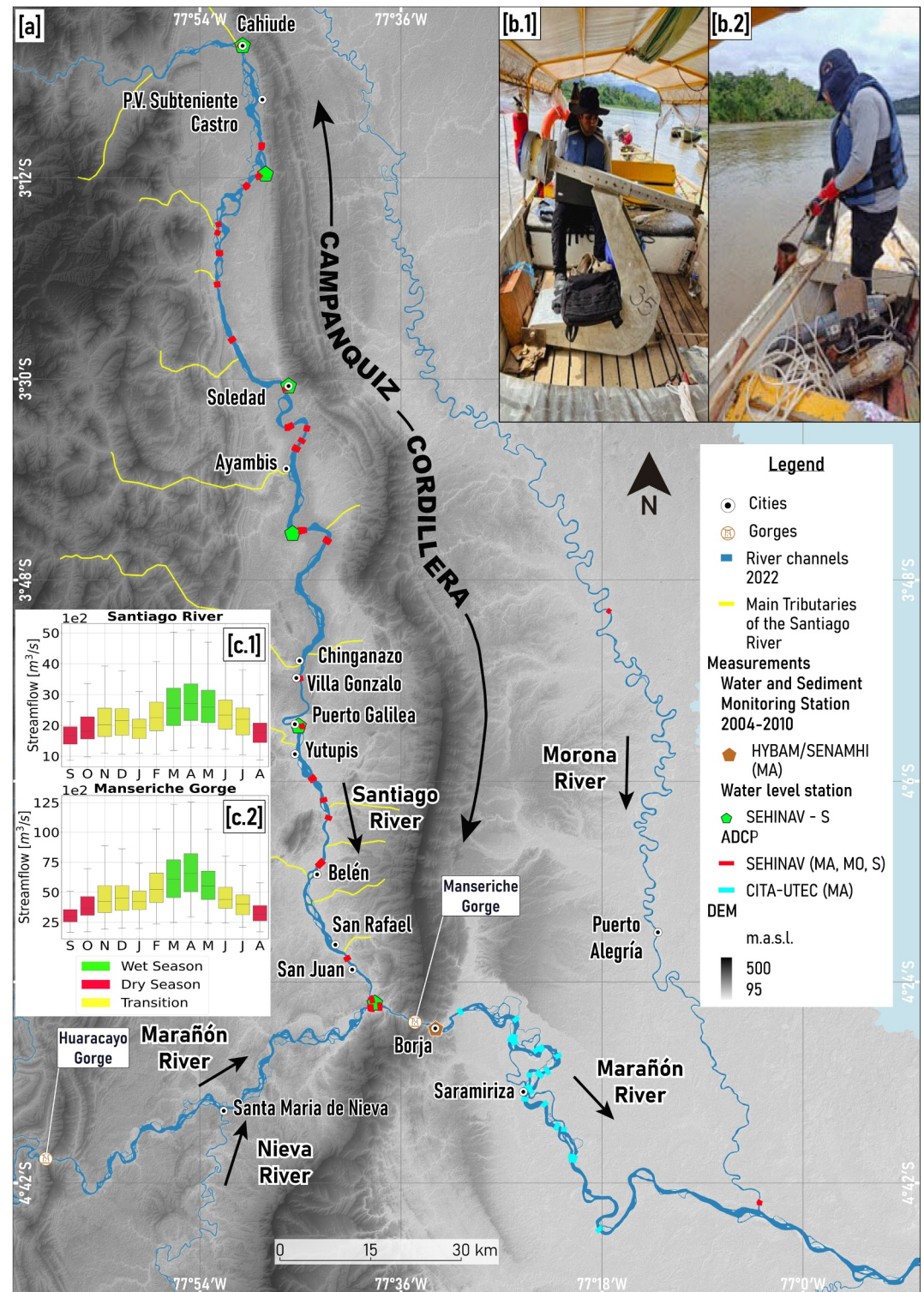


Figure 2. (a) Flow measurement stations along the Santiago, Marañón and Morona rivers, (b.1) and (b.2) pictures from field campaigns. (c.1) and (c.2) Hydrographs at the Santiago River and Manseriche Gorge, respectively. The hydrographs were generated using the gridded SONICS product from SENAMHI (Llauca et al., 2023). In 2022, gaging stations were installed in Cahuide, Candungos, Alianza Progreso, Galilea and Teniente Pinglo. In 2023, the Soledad gaging station was added. The legend notations in parentheses are: MA, Marañón River; S, Santiago River; MO, Morona River.

patterns (Figure S2 in Supporting Information S1). Several rivers (Santiago, Morona, Nieva, Cenepa, Potro, Chinchipe, Zamora, Upano, and Marañón, see Figure S1 in Supporting Information S1) run parallel and perpendicular to the mountains. Several rivers such as the Chinchipe, Cenepa, Nieva, Santiago, Morona and Potro are tributaries of the Marañón River. The Santiago and Morona Rivers are located within the maximum precipitation region, where rainfall-based erosivity is also significant (see Figure S3 in Supporting Information S1). The Santiago River is formed in Ecuador by the confluence of the Zamora and Upano Rivers, in a biodiversity hotspot known as the Kutukú-Condor corridor (Aguirre et al., 2021). Along the Peruvian region, the Santiago River runs in a valley confined by the Campanquiz and Huaracayo cordilleras that form the Santiago-Nieva depression which is covered by Tertiary-aged sediments (Parsep, 2001) (see Figure 1b, where sedimentary records from the Jurassic, Cretaceous and Tertiary (Eocene-Pliocene) periods are depicted, Baby et al. (2019) and Gil and Flinch (2022)). Parsep (2001) and Chacaltana et al. (2012) described that the Campanquiz mountains have ridges with Cretaceous-aged sediments along the core, while exhibiting Tertiary-aged sediments along the flanks. The Santiago, Chinchipe, Nieva, Potro, and Morona Rivers are tributaries of the Marañón River (see Figure S1 in Supporting Information S1). The gorges along the Marañón River are Rentema, Cumbinama, Escurrebraga, Huaracayo and Manseriche, where large hydropower dams are proposed at Rentema (1,525 MW), Escurrebraga (1,800 MW) and Manseriche (4,500 MW) Gorges. In this region, deforestation has been increasing from 2001 to 2022, as noted in Figure S4 in Supporting Information S1 (data from Hansen et al. (2013)). The largest losses are mostly around the Zamora and Upano Rivers in Ecuador and along the Chinchipe River in Peru; a possible consequence is that more sediments will arrive to downstream reaches of the rivers.

3. Methodology

3.1. Hydrogeomorphology

3.1.1. Planform Geomorphology

Geomorphological metrics based on planform and its temporal evolution were assessed from satellite images. The Landsat collections of the Earth Engine Data Catalog (USGS Landsat 4, 5, 7, 8, all Level 2, Collection 2, Tier 1) were used to characterize the planform river geomorphology (see Table S2, Figure S6 in Supporting Information S1). The selected Landsat satellite images were merged to create a single multiband image (Green, Red, NIR, SWIR1, SWIR2). The fusion of satellite images was performed using Python code and geemap graphical interface (Wu, 2020) linked to GEE (Google Earth Engine). The study period ranges from 1986 to 2022 at a 4-year interval, using preferably images from the low-flow condition (May–September). Subsequently, after obtaining the fused multiband images, the threshold or river versus non-river classification was done by adapting the Pyris Python code (Monegaglia et al., 2018) (Figure S6a in Supporting Information S1). To enhance the classification three indices were used, NDVI: Normalized Difference Vegetation Index, MNDWI: Modified Normalized Difference Water Index, and SWIR1: Short-Wave Infrared 1. Anabranching and meandering metrics were estimated according to the planform configuration described by Figures S6b and S6c in Supporting Information S1, respectively. Similar geomorphological characterization was previously presented by Boothroyd et al. (2021), Abad et al. (2022, 2023), Rojas et al. (2023), and Valverde et al. (2024). In our analysis, metrics such as sinuosity (length along the channel centerline divided by the valley length) and channel width were calculated using Rivgraph (Schwenk & Hariharan, 2021). Based on the erosion (E) and deposition (D) areas along the rivers (see Figure S6 in Supporting Information S1), the activity is defined as:

$$\text{Activity} = \left(\frac{\sum A_D + \sum A_E}{\text{Area} \times Y} \right) \times 100\%$$

where $\sum A_D$ and $\sum A_E$ refer to the sum of the areas of deposition and erosion, respectively, and Y represents the number of years between the images analyzed. The total area (Area) corresponds to the intersection area calculated locally for each segment (as described by Abad et al. (2024)). For this purpose, the river structure has been divided into 10-km and 1-km segments along the valley axis, as the valley is a stable element that does not change over time. The areas of deposition (A_D) and erosion (A_E) are summed for each 10-km segment, and for the Marañón River at the Manseriche Gorge, 1-km segments were considered. Although the sum of the areas of deposition and erosion is done by segments, the total area (Area) corresponds to the total intersection area of each

segment. This approach allows the calculation and plotting the activity for each 10-km and/or 1-km segment, using the valley as a constant reference that does not change in time.

3.1.2. Hydrogeomorphic Field Measurements

The hydrogeomorphic field campaigns along the Santiago River (Figure 2a) were carried out at the ending of the transition from high- to low-flow condition (July/August 2022) and at the beginning of the transition from high- to low-flow condition (May/June 2023), considering the hydrograph at the Santiago River's mouth, Figure 2c.1. The field campaign along the Marañón River (downstream of MG) was carried out during high-flow condition in May 2019 (see the hydrograph for the Marañón River at the MG in Figure 2c.2). The hydrographs for all rivers in the studied area (Figure S1 in Supporting Information S1) can be found in Figure S5 in Supporting Information S1. The Inreach Explorer System coupled to a Satellite Garmin tracking device was used to maintain data field connectivity and daily reporting from personnel. Due to flow conditions for navigability and operation of instruments (e.g., highly turbulent flows along the MG), no detailed hydrogeomorphic measurements were collected upstream (between the Huaracayo and Manseriche Gorges) and along the MG. Hydrodynamic field measurements were collected using ADCP (acoustic Doppler current profiler) instruments (Teledyne Workhorse 600 Khz for the Santiago River, Teledyne RiverRay 600 Khz for the Marañón River, all coupled to a GNSS Atlas Link Hemisphere). The ADCP, single beam Bathy 500 M/F (bathymetry) and sediment transport mechanisms (Niskin sampler for suspended sediments, trawl sampler for bed material sediments) were mounted and operated from a 60 HP aluminum vessel (see Figures 2b.1 and 2b.2). Software for post-processing the data included: Trimble business Center (v5.0), Hypack (2021), and WinRiver (v2.22). Additionally, the Velocity Mapping Toolbox (VMT, Parsons et al. (2013)) was used to display the primary and secondary flow velocities. Bathymetry measurements were carried out along the Santiago River at 50-m cross section intervals (excepts along bends where a 10-m interval was used).

3.1.3. Hydrogeomorphic Modeling

The two-dimensional (2D) depth-averaged hydrodynamic model TELEMAC (Lang, 2014) was used to describe the hydrogeomorphic processes of the existing and post-dam conditions at MG (if the dam is built). 2D modeling has been extensively used by the authors in similar projects (Abad et al., 2008, 2022; Frias et al., 2015; Langendoen et al., 2016; Li et al., 2023; Mendoza, Abad, Frias, et al., 2016; Mendoza, Abad, Langendoen, et al., 2016), since it helps to understand interactions between hydraulic and river morphologic processes. Fassoni-Andrade et al. (2023) presented a 2D hydrodynamic modeling of the lower Amazon River (between the confluence of the Negro and Xingu Rivers) and showed the importance of mapping out the river-floodplain interaction particularly during high-flows, where connectivity is more significant. Similarly, Pinel et al. (2020) used TELEMAC to characterize the water circulation and inundation patterns along the Amazon River's floodplain in the Janauacá watershed near Manaus City, Brazil. The model was carried out using the following characteristics: (a) Pre-dam conditions: the domain considered the Marañón River upstream and downstream MG, and the Santiago River (Figure S19 in Supporting Information S1). The mesh was composed by 447,607 triangular elements (30-m long in the main channel, with elements of 15-m long in the narrower secondary channels of the anabranching structures), (b) Post-dam conditions, upstream of MG: The mesh was created using 2,688,846 triangular elements (300-m long in the floodplain and 30-m long along the tributaries and main channels), the initial condition was set with the reservoir full up to 351 m.a.s.l. (meters above sea level) (Fong, 2014; QVIngenierosSAC, 2007; Rubio et al., 2017), the inlet boundary conditions were similar to existing conditions except for the Santiago River's tributaries that were set upstream in the valley (above 351 m.a.s.l.), the outlet boundary condition (Manseriche dam) was set to 351 m.a.s.l., (c) Post-dam conditions, downstream of MG: the mesh was created based on the existing condition (pre-dam) with 216,509 triangular elements (30-m long in the main channel and with elements 15-m long in the narrower secondary channels of the anabranching structures) along the Marañón River. The inflow boundary condition at the Manseriche dam was extracted from Oyague et al. (2016), the downstream boundary condition was set as stage-discharge using interpolated values from Borja and San Lorenzo gaging stations. The hydraulic modeling was performed considering the k-epsilon turbulence model, the bed evolution model was simulated using the Meyer-Peter and Muller bedload equation (Garcia, 2008), considering two classes of sediment (class 1 with 0.2 mm, and class 2 with 10 mm). Along this region (downstream of MG), sediments are adjusting to the planform configuration of the Marañón River, as the MG exerts a morphodynamic boundary condition.

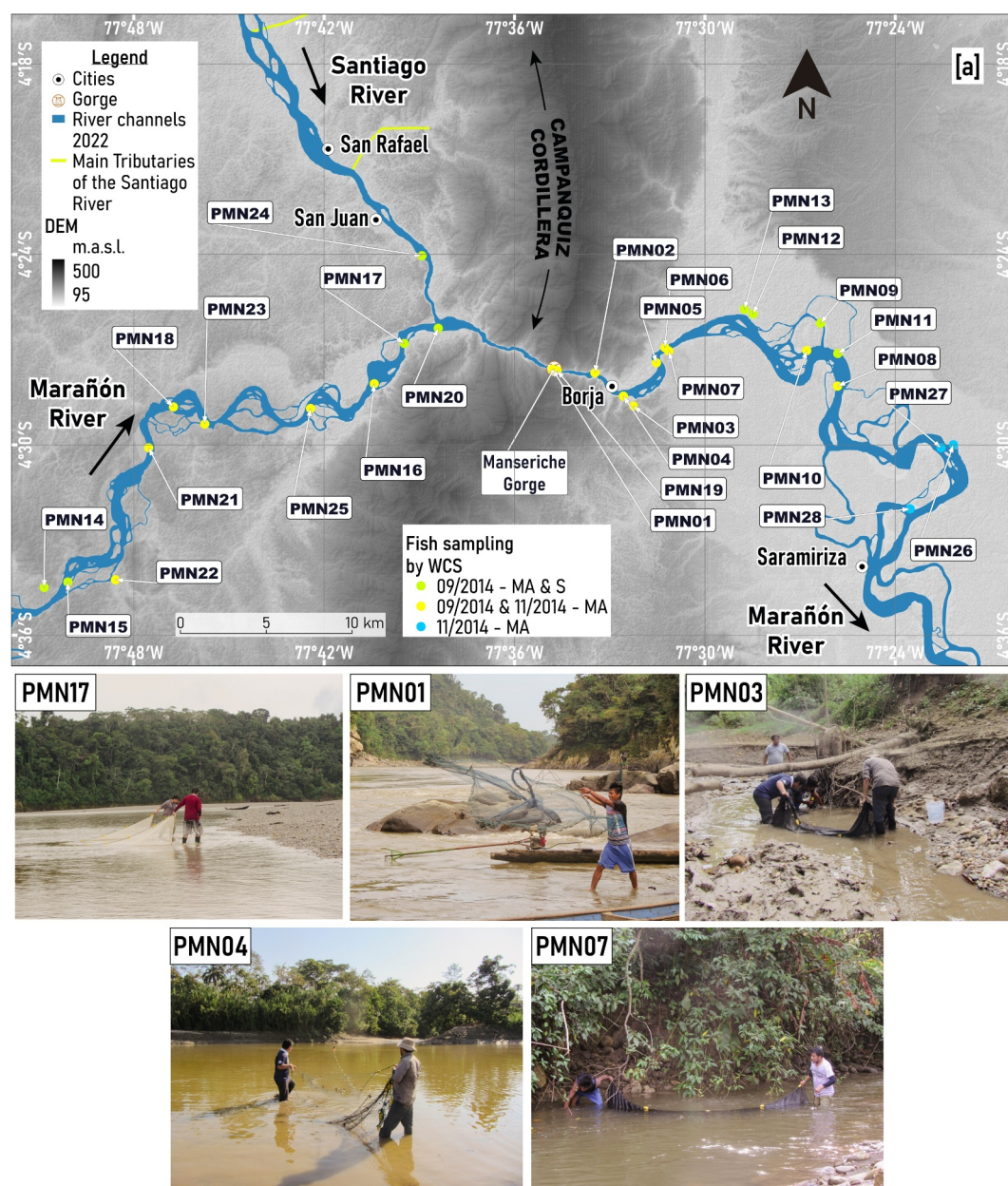


Figure 3. (a) Fish sampling stations along the Marañón and Santiago rivers near the Manseriche Gorge. Pictures are showing the fish sampling methodology used in the field.

3.2. Fish Sampling

Fish samples were collected in 28 stations (PMN01 to PMN28 shown in Figure 3a and Figure S15 in Supporting Information S1) during low-flow condition (September 2014) and during the transition from low- to high-flow condition (November 2014), considering the hydrograph for the Marañón River at the MG (Figure 2c.2), each campaign lasted around 10 days. The domain included sampling stations 50-km upstream and downstream of MG. Most of the stations were located along the Marañón River, except PMN03 (Magüña tributary), PMN06 (Agua Azul tributary), PMN12 (oxbow lake), PMN13 (Cangaza tributary), PMN14 (Domingusa tributary), PMN22 (Pajakusa tributary), and PMN24 (Santiago River). Three types of fishing devices were used to collect fish: 5-m trawl net and 10-m long with an opening of 5-mm, cast net and experimental holding net with various sizes of mesh opening, and the effort for each of the fishing tackle was recorded. Collecting methods included dragging to shore, removal of rocks, stones and plant remains, manual trapping in log holes and under the stones

(see Figure 3). For a more complete record of the ichthyofauna, interviews with local merchants and fishermen were carried out. The collected specimens were fixed in 10% formalin, the individuals that exceeded the 15-cm were injected with formaldehyde to complement its fixation, and after 48 hr, the specimens were packed in gauze, preserved in 70% alcohol and packed in plastic bags for transportation. All the fish were analyzed and deposited in the ichthyological collection of the Natural History Museum of the National University of San Marcos (MHN-UNMSM), Peru.

3.2.1. Quantitative Analysis

Sample-size based rarefaction/extrapolation curves were used to compare species richness among the three regions: upstream of MG, at MG, and downstream of MG. Rarefaction was conducted separately for each survey period (September 2024 and November 2024) following methods developed by Colwell et al. (2012) implemented within the PAST (PAleontological STatistics) (Hammer et al., 2001). Non-metric Multidimensional Scaling (NMDS) was used to visualize differences in assemblage structure between regions. Principal Component Analysis was then used to display the two dominant NMDS axes, this algorithm is implemented in PAST based on a new approach developed by Taguchi and Oono (2005). Similarity index Horn between geographic coordinates of sites was used as a starting configuration for the iterative procedure. A cluster analysis following the algorithm Paired group (UPGMA), with Similarity index of Horn was used to explore patterns of species composition across sites within each survey period (for both campaigns). Finally, the Indicator species analysis (IndVal) was applied to identify species indicative of given groups of sites (Dufrene & Legendre, 1997).

4. Results

4.1. Baseline Planform Morphodynamics

The first (Rentema) and last (Manseriche) gorges are located at 350 and 150 m.a.s.l., respectively (Figure 4a). Rentema, Cumbinama, Escurrebraga and Huaracaya Gorges, shown in Figures 4b.1–4b.4, have similar channel width. The planform evolution analysis of the Marañón River upstream and downstream of the Manseriche Gorge (9–12-km long) based on the multitemporal satellite image analysis is shown in Figure 4b.5. Bed and bank rock surfaces are observed along the MG, (pictures 1 to 10 in Figure 4), where the channel width along the MG is less than 100-m, which is smaller compared to upstream and downstream reaches (see Figure 4c). Indeed, along the upstream and downstream reaches of the MG, wider unconfined alluvial valleys with active anabranching structures are observed (Figure 4b.5). Anabranching structures are observed when water and sediment discharges are significant (Latrubesse, 2008); they develop main and secondary channels that are constantly interacting and shifting their hydraulic and sediment load capacity (Abad et al., 2024; Frias et al., 2015; Guerrero et al., 2024; Mendoza, Abad, Frias, et al., 2016). Upstream of the Rentema Gorge, anabranching structures are also observed along the Marañón River. Andean mountains suppress the development of anabranching structures of the Marañón River by the geological confinement, but when the valley confinement decreases (as in the reach from Huaracayo to Manseriche Gorges), anabranching structures are again developed. The planform dynamics between 1986 and 2022 for the Santiago and Morona Rivers are shown in Figures 5a.1–5a.3 and 5c.1–5c.3, respectively. The Santiago River is located along the Santiago-Nieva depression, where both anabranching (from km 50 to km 100, and from km 190 to km 220) and meandering planform configurations emerge. In general, the planform activity along the Santiago River (Figure 5b) is not significant, except along anabranching reaches. The main channel sinuosity is low, and the main channel width increases downstream (Figure 5b). The Morona River has a meandering planform configuration (see Figure S9 in Supporting Information S1 for typical secondary flow patterns) where some oxbow lakes (Figures 5c.1–5c.3) have formed since 1986. The sinuosity ranges between 1.2 and 2.2 and the channel width increases downstream due to small tributaries. The planform morphodynamic characterization for the Chinchipe, Nieva, Potro and Cenepa Rivers show confined and non-confined conditions (Figure S8 in Supporting Information S1), resulting in rivers of low (straight) to medium and high (meandering) sinuosities without anabranching structures.

4.2. Hydrodynamics, Sediment Transport, and Bed Morphology

The Santiago River along the Peruvian side runs from km 50 to km 232 (Figures 5a.1–5a.3), the upstream region develops an anabranching configuration (approximately until km 100), where shallow flow conditions were observed in both field campaigns, thus limiting the effectiveness of ADCP measurements (Figure S10 in

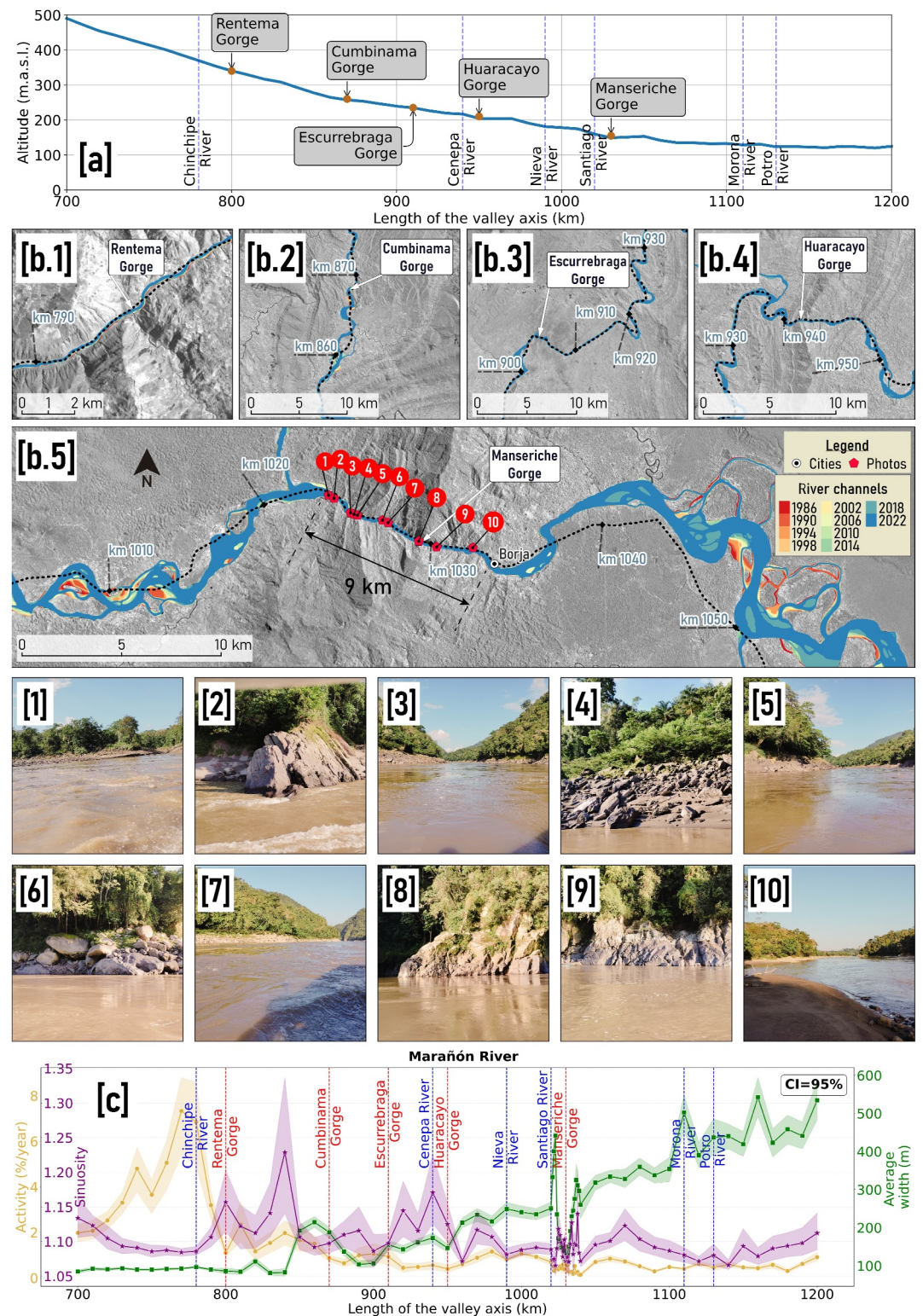


Figure 4. (a) Longitudinal profile and slope (using the 2022 river centerline) of the Marañón River valley (plotted every 10 km), (b.1–b.4) Planform locations and multitemporal analysis of the Rentema, Cumbinama, Escurrebraga and Huaracayo gorges, (b.5) Planform location of the Manseriche Gorge including pictures (1–10). The background images are obtained using the 2022 NIR band (5 m) from the Planet satellite mosaic (Norway's International Climate and Forest Initiative, NICFI and the NICFI Data Program Team: KSAT, Planet, Airbus). (c) Activity, averaged channel width and sinuosity (4-year interval) along the Marañón River, 95% confidence interval.

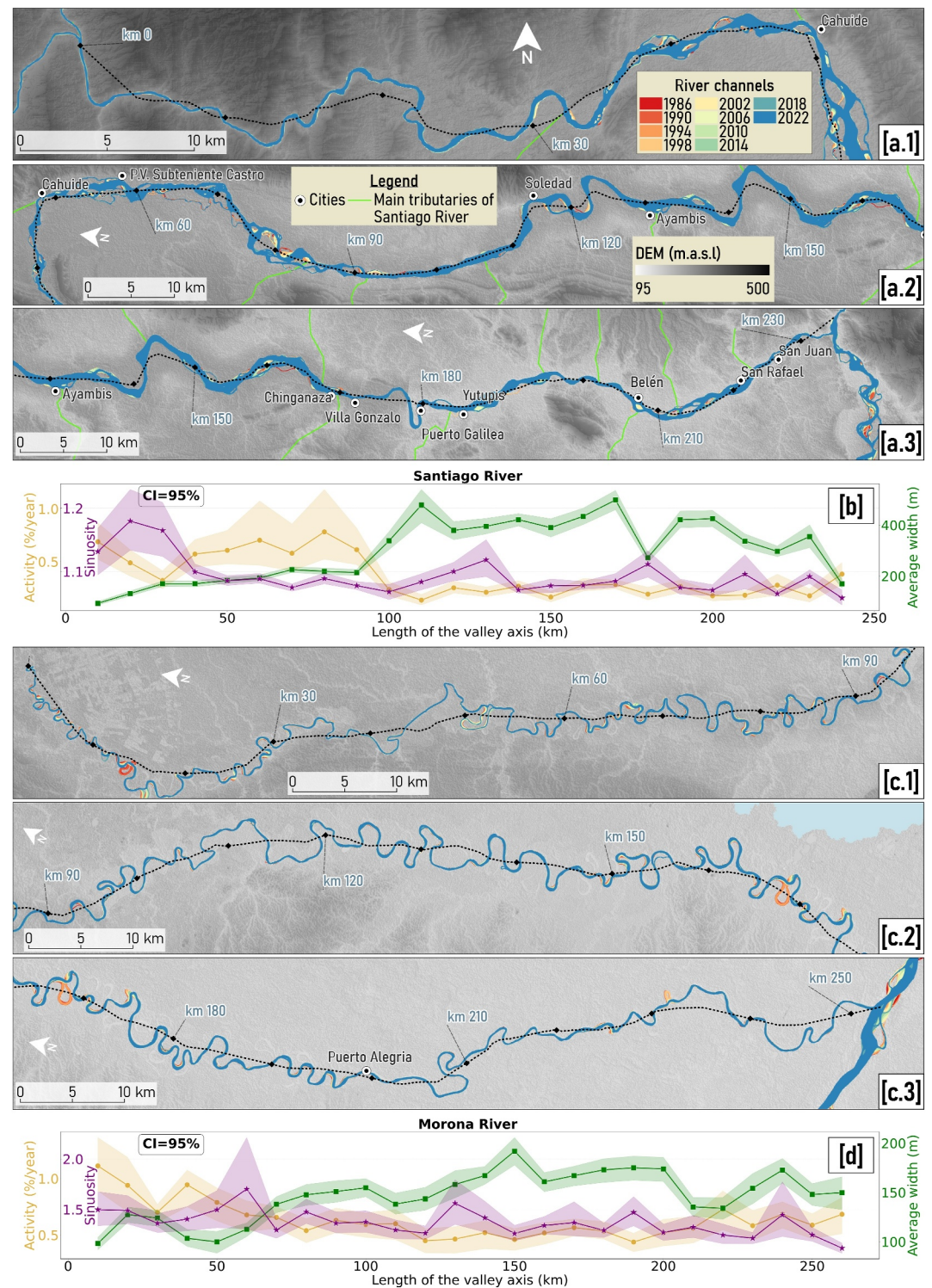


Figure 5. Multitemporal analysis from 1986 to 2022 of the (a.1–a.3) Santiago and (c.1–c.3) Morona rivers. Activity, channel width and sinuosity (using 4-year interval) of the (b) Santiago and (d) Morona rivers, 95% confidence interval.

Supporting Information S1). Figures 6 and 7 show the primary and secondary flow velocities measured in 2022 (stations A8 to A21) and 2023 (stations L9 to L23) field campaigns downstream of km 100. Stations A8/L9, A13/L14, A17, L18, A18, A19/L20 are located in reaches with low sinuosity, along the inflexion points between bends, thus shallow flow conditions are observed. Stations A9/L10, A10/L11, A12/L13, A15/L16, L19, A20/L21

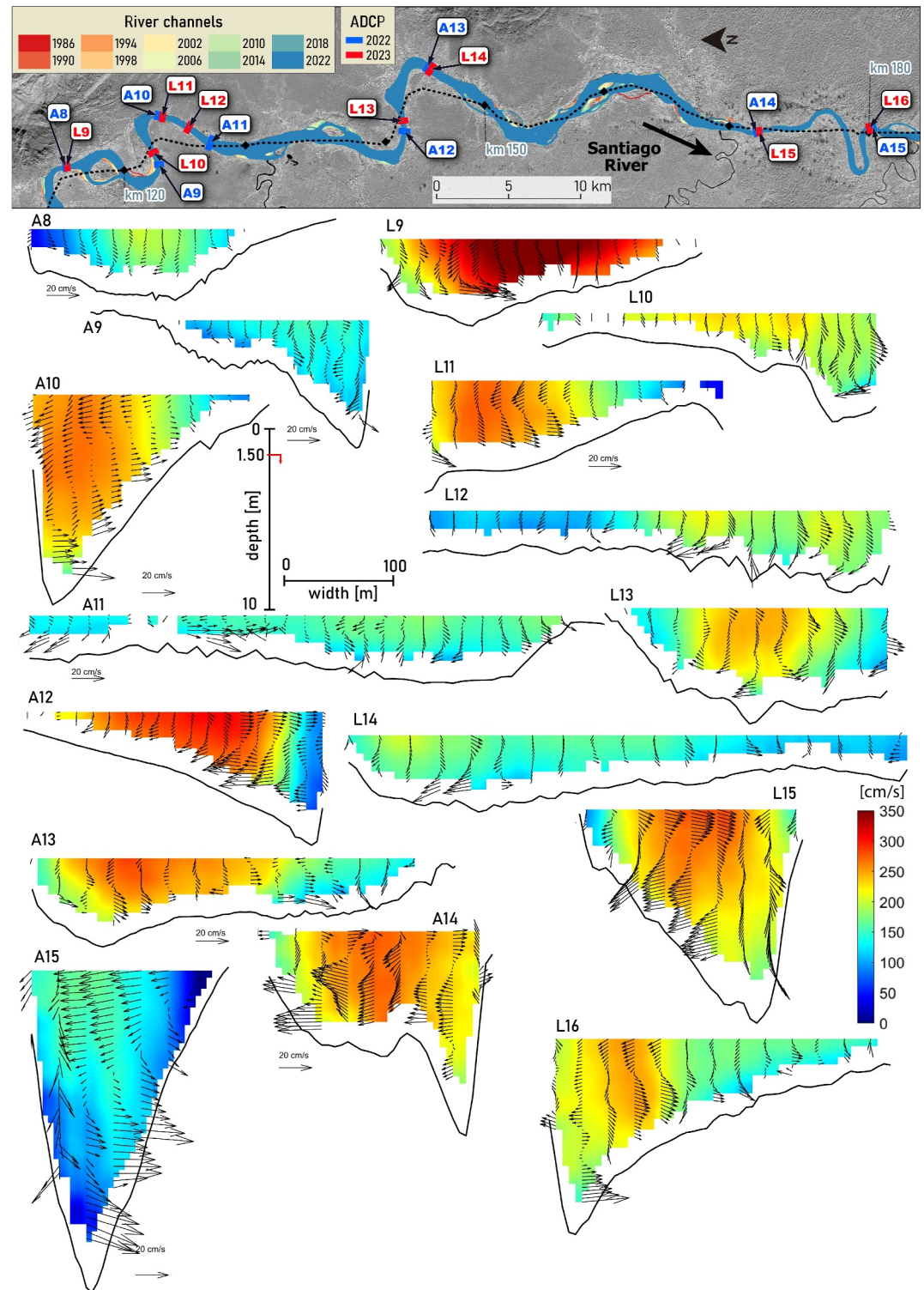


Figure 6. Field campaigns for 2022 and 2023, ADCP measurements along the Santiago River (Stations A8/L9 to A15/L16). Planform view: black dash centerline shows the mean valley centerline (Gutierrez & Abad, 2014), multitemporal analysis of river channels from 1986 to 2022.

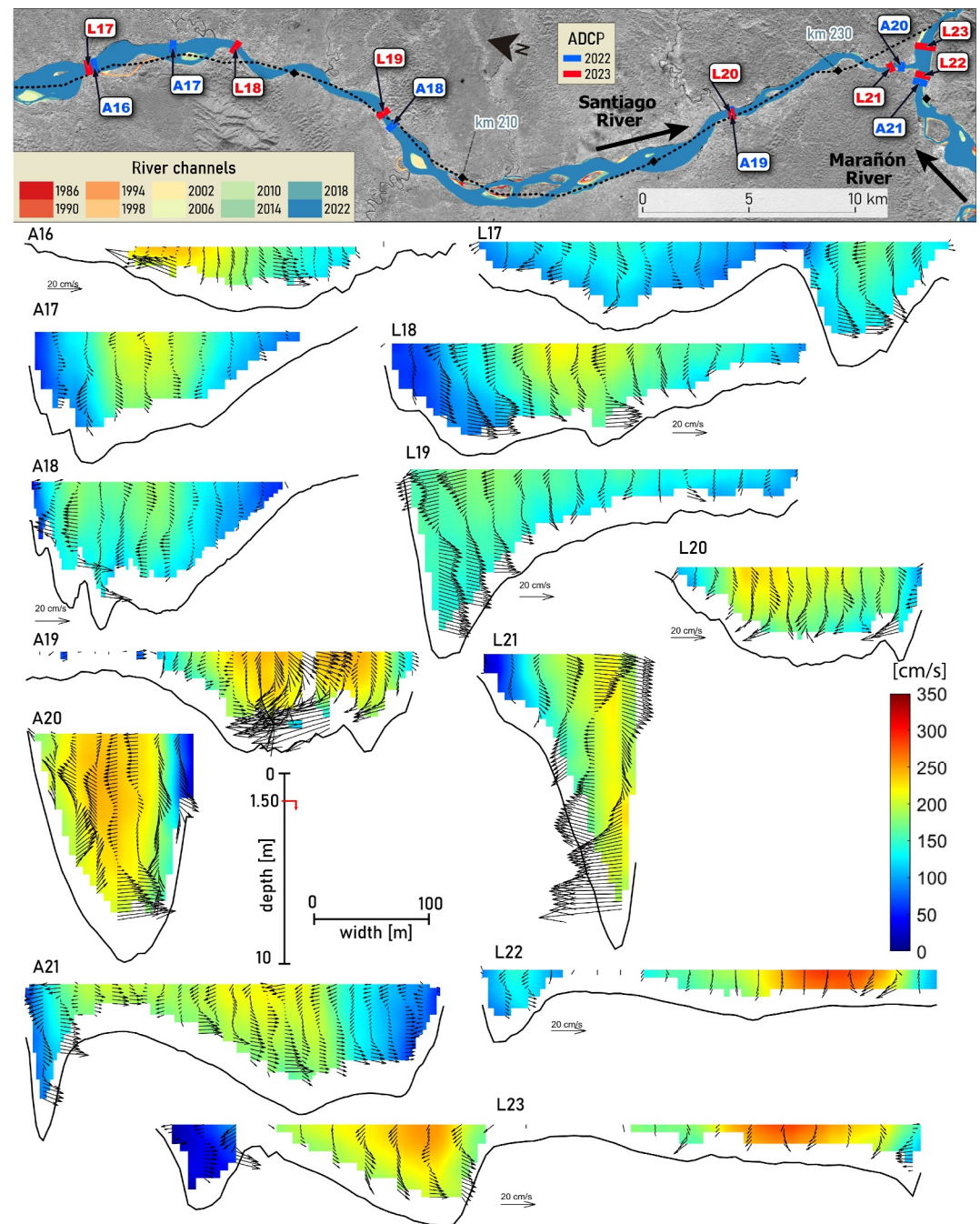


Figure 7. Field campaigns for 2022 and 2023, ADCP measurements along the Santiago River (Stations A16/L17 to A21/L23). Planform view: black dash centerline shows the mean valley centerline (Gutierrez & Abad, 2014), multitemporal analysis of river channels from 1986 to 2022.

are located along bends, where significant outer bank deepening and secondary flows are observed (some cases is larger than 10% of the primary flow). Stations A11/L12, A16/L17 are located around anabranching structures (deposition in the middle portion of the cross section) with weaker secondary flows. Stations A21/L22 are located along the Marañón River (upstream of the Santiago-Marañón confluence) where two distinct secondary flow cells are observed due to the existence of an upstream anabranching structure. Similarly, at station L23 (downstream of the Santiago-Marañón confluence), a channel widening and at least three secondary cells are observed. Generally, the Santiago River is a transitional river (combination of anabranching and meandering planform configuration),

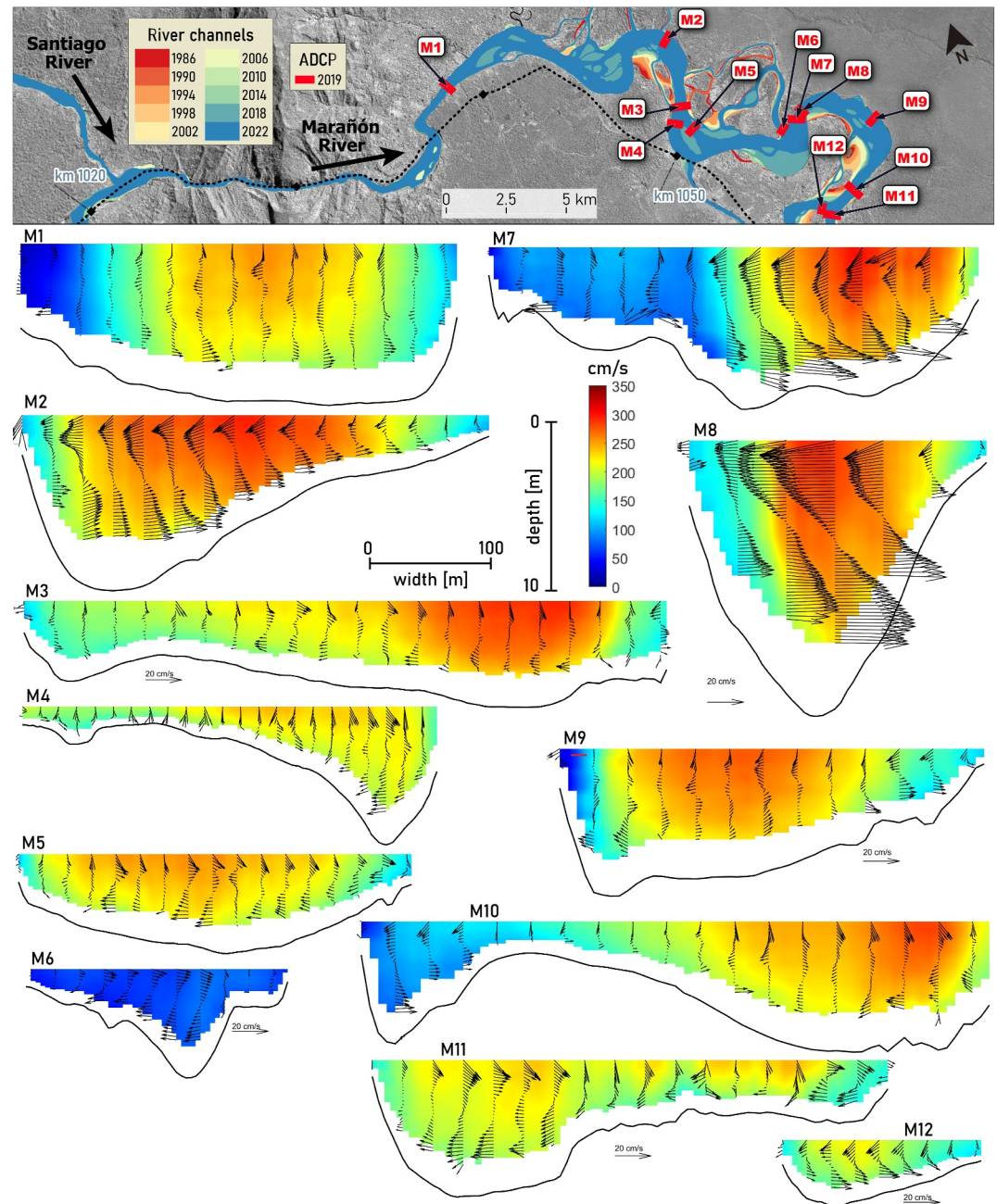


Figure 8. Field campaign for 2019, ADCP measurements along the Marañón River (downstream of the Manseriche Gorge) (Stations M1 to M12). Planform view: black dash centerline shows the mean valley centerline (Gutierrez & Abad, 2014), multitemporal analysis of river channels from 1986 to 2022.

thus, shallow flow conditions are observed around anabranching structures, particularly along the upstream reach (see Figure S10 in Supporting Information S1) and deeper scour regions (with higher secondary flow intensity) are observed around meandering reaches.

The Marañón River has fully developed anabranching structures, where main and secondary channels compete for water and sediment discharges (Frias et al., 2015; Mendoza, Abad, Frias, et al., 2016). Station M1 in Figure 8 shows a single low sinuosity channel with weak secondary flow. Station M2 is located along a bend that has been constantly migrating since 1986, thus a large secondary cell is observed along with outer bank deepening. Station M3 is located upstream of an anabranching structure, showing an additional depth channel on the left. Stations M4

and M5 show the secondary cells along the main and secondary channel, respectively. M4 shows stronger secondary cell and deeper scour hole due to higher sinuosity and water discharge. Station M6 is located along a small secondary meandering channel (low water discharge but significant secondary flow). Stations M7 and M8 are located close each other, where similar outer bank counter clockwise secondary cells are observed. However, M8 presents a higher intensity secondary flow and more important deepening. Station M9 is wider, thus shallow flow conditions and weaker secondary flow are observed. Station M10 is located upstream of an anabranching structure and shows a depositional region along the middle portion of the cross section. Stations M11 and M12 are located along the two channels of the anabranching structure. Similar measurements along main and secondary channels of anabranching structures for a downstream reach of the Marañón River are found in Figure S12 in Supporting Information S1.

Along the 9-km Manseriche Gorge, large rocks coupled with fast and complex turbulent flows (with rapids and whirlpools) imposed difficulties on navigability and field operations (see Figures 4 and 9h), particularly for hydrogeomorphic measurements where instruments are exposed to damage. At stations (see boxes on the right of Figures 9c and 9f) where ADCP measurements were carried out, water and sediment samples were collected (see Figure 9). D_{50} and D_{90} (Figures 9a and 9g) show a reduction in bed sediment size along the Santiago River from 2022 to 2023 (Figure 9a) which is attributed to resuspension processes due to the slight increase in water discharge (Q_w , from 2,084 to 2,380 m³/s, Figure 9b). The bed sediment size upstream of the confluence with the Santiago River is quite different for 2022 (A21) and 2023 (L22), this is because they are collected in stations close by, but as observed during the field campaigns, sediment distribution is fairly heterogeneous and depends on local planform characteristics of the rivers and the flow conditions coupled to geology confinement. Along the Marañón River, there is a trend of sediment size reduction downstream (L23) of the confluence with the Santiago River (Figure 9h). The channel width remains almost constant during the field campaigns. The TSS (from 542 to 1,610 mg/l) and Turbidity (from 216 to 637 NTU) along the Santiago River have increased between 2022 and 2023 field campaigns. Armijos et al. (2013) described that the annual TSS at the Santiago mouth was around 335 mg/l. Herein, the estimated Suspended Sediment load ($Q_s = TSS \times Q_w$) is higher for 2023 (336 kt/day) compared to 2022 (121 kt/day). Singewald (1927) described that downstream the MG, the Marañón River deposits great masses of debris, this was verified in the field. Under high-flow condition the floodplain is covered by water, however, under low-flow condition, the appearance of anabranching structures and bed coarsening (from sand and gravel to large boulders) just downstream of the MG are observed.

4.3. Fish Species Richness and Abundance

During the two field campaigns (September and November 2014, Figures 10a.1 and 10a.2), we collected a total of 8,115 individuals, distributed in 157 species, representing approximately 14.8% of Peru's ichthyofauna (Ortega et al., 2012). Characiformes were the most diverse, with 77 species (49%), followed by Siluriformes with 65 species (42%) and by Gymnotiformes with 4 species (2.5%). Species of marine origin, such as those from the orders Acanthuriformes, Myliobatiformes, Clupeiformes and Beloniformes, made up the remaining 9.2% of the diversity (Figure S13 in Supporting Information S1). Of the total number of species recorded, 73 species were only recorded in 09/2014, 28 species only in 11/2014 and 56 species were present in both campaigns. Notably, *Knodus septentrionalis* was highly abundant in both campaigns (Figures 10c.1 and 10c.2).

4.3.1. Fish Sampling at Different Hydrological Conditions

- Low-flow condition (09/2014):** a total of 4,298 individuals were collected, distributed in 129 species, 21 families and 6 orders. Characiformes was the most diverse order with 63 species (49%), followed by Siluriformes with 58 species (45%). Other orders included Acanthuriformes (5 species, 4%), and Gymnotiformes, Beloniformes and Myliobatiformes with one species each (Figure S13a in Supporting Information S1). *Moenkhausia aff. dichroua* was the only species present across all aquatic environments. Notable, 57 species were unique along the Marañón River, 11 to tributary streams, 6 to the oxbow lake and 3 to the Santiago River (Figure 10e). Within Characiformes, the family Characidae was the most diverse (42 species), with *Knodus septentrionalis* being the most abundant (2,193 individuals, Figure 10c.1). Migratory behaviors were observed, including the *mijano* phenomenon, where species such as the *Potamorhina altamazonica* and *Steindachnerina dobula* were migrating upstream. Siluriformes were dominated by the families Loricariidae (19 species, including *Panaque schaeferi* and *Panaque bathyphilus*, typically found at the MG, Lujan and

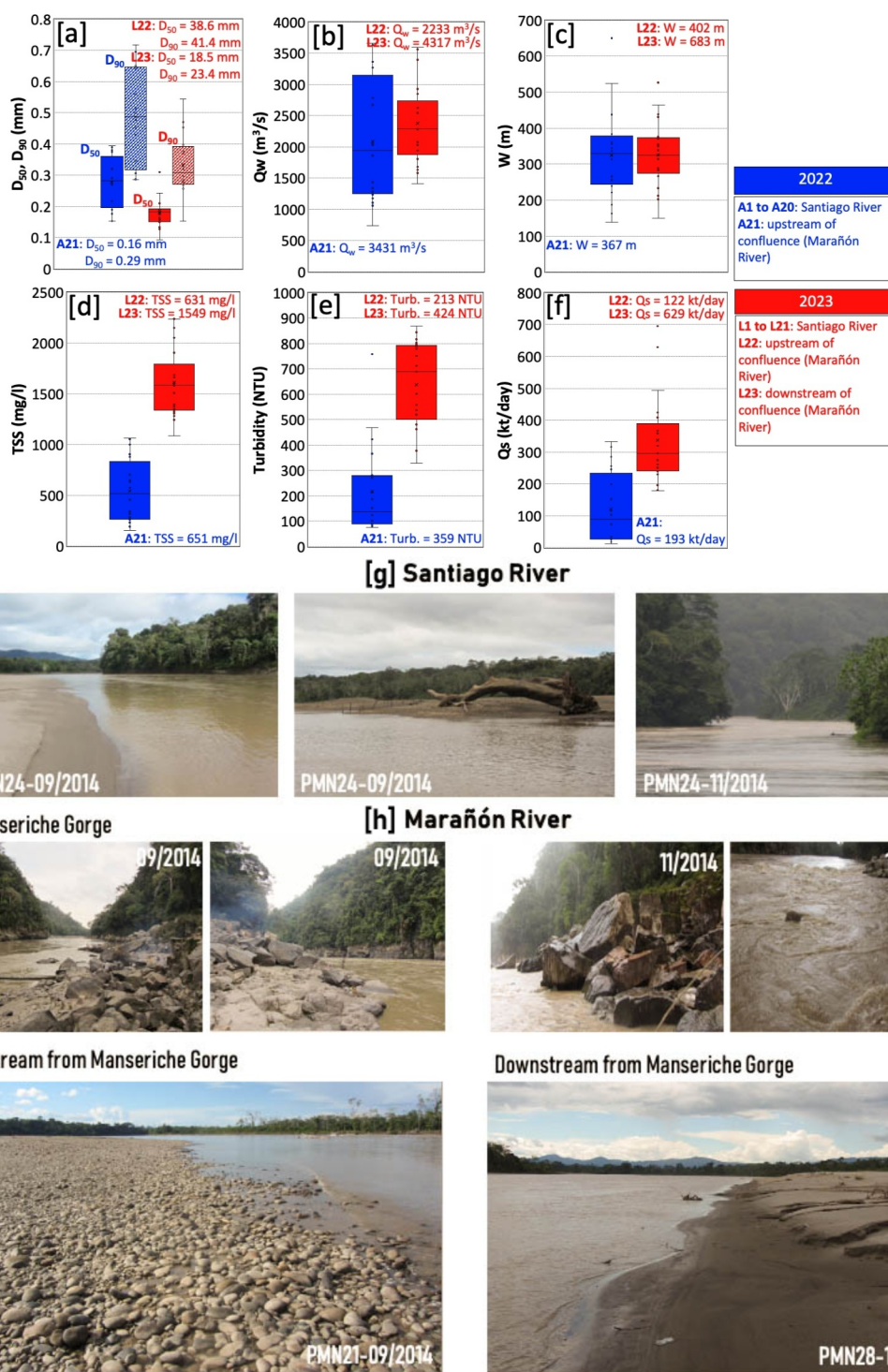


Figure 9. Field campaigns along the Santiago River (2022: A1 to A20 and 2023: L1 to L21): (a) bed material: D_{50} (mm) and D_{90} (mm), (b) Q_w (m^3/s), (c) W (m), (d) TSS (mg/l), (e) Turbidity (NTU), (f) Q_s (kt/day), (g) field conditions along the Santiago River, (h) field conditions along the Marañón River, at the Manseriche Gorge, upstream and downstream of the MG. A21 (2022), L22 (2023) at the Marañón River upstream of the confluence with the Santiago River; L23 (2023) at the Marañón River downstream of the confluence with the Santiago River.

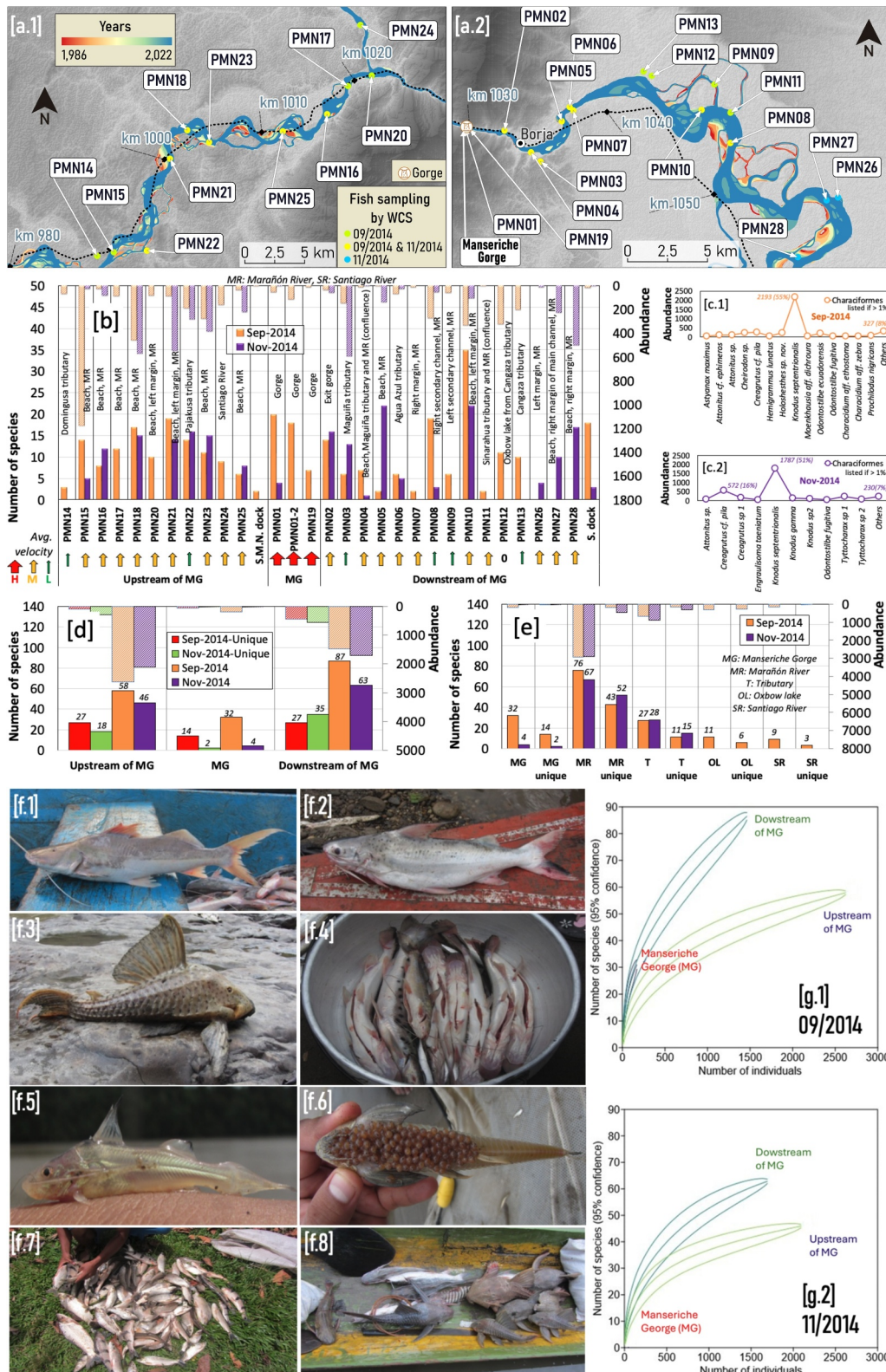


Figure 10. Multitemporal analysis from 1986 to 2022 of the Marañón River upstream (a.1) and downstream (a.1) of the MG. (b) (September/November 2014) Number of species and abundance at sampling stations upstream of MG, at MG, and downstream of MG. Abundance of the order Characiformes ((c.1): September 2014, (c.2): November 2014), (d) Total number (and unique) of species and abundance upstream of MG, at MG, and downstream of MG. (e) Total number (and only) number of species and abundance at aquatic ecosystems, (f) migratory fish along the Marañón River, (g) rarefaction analysis for both campaigns.

Chamon (2008)), the Pimelodidae (19 species). Large migratory catfish (*Brachyplatystoma vaillantii*) and other species such as *Sorubim lima* were observed during their spawning migrations (*mijano*) downstream of the Manseriche Gorge (Table S3 in Supporting Information S1). Upstream, fewer species of catfish were found, with *Pseudoplatystoma punctifer* (doncella) and *Sorubim lima* being among them (Figure 10c.1).

- **Transition from low- to high-flow condition (11/2014):** A total of 3,817 individuals were collected, representing 84 species, 17 families and 6 orders. Characiformes was again the most abundant order (3,506 individuals), see Figure S13b in Supporting Information S1, with *Knodus septentrionalis* (1787 individuals), *Creagrutus cf. pila* (572 individuals) and *Tyttocharax sp 1* (230 individuals) as the most common species (Figure 10c.2). Species diversity was lower compared to the low-flow condition, likely due to increased water volume and fewer sampling stations (20 compared to 25). In Siluriformes, the families Loricariidae (12 species) and Pimelodidae (10 species) were the most diverse, with *Pimelodus pictus* (79 individuals) and *Megalonema platycephalum* (50 individuals) being the most abundant. Juveniles and fry of migratory catfish, including *Sorubim lima*, *Pimelodus ornatus*, and *Platysilurus mucosus*, were found both upstream and downstream of MG, signaling ongoing reproductive activities in the region.

4.3.2. Fish Sampling Upstream of Manseriche Gorge (MG), at MG, and Downstream of MG

- **Upstream of MG:** A total of 4,742 individuals were recorded across 77 species, with 58 species collected in 09/2014 and 46 species in 11/2014 (Figure 10d). Notably, 28 species (36%) were exclusive to this area, comprising 18% of the expedition's recorded ichthyofauna. Key species included the marine-origin *Pseudotyllosurus microps* (pipefish), cichlids such as *Cichlasoma amazonarum* and *Crenicichla sedentaria*, and ornamental species like *Leptagoniates steindachneri*, *Paragoniates alburnus*, *Phenacogaster napaotilis*, *Aphyocharax sp.*, and *Bunocephalus sp.* Large migratory catfish, including *Aguarunichthys torosus*, were also collected in this region, alongside *Sorubim lima mijano* and *Pseudoplatystoma punctifer*, which were observed only near the Manseriche Gorge (MG) in 09/2014, indicating a limited presence of migratory catfish. Among the evaluated aquatic environments (Figures 10a.1, 10b, and 10c), certain sampling points exhibited increased species diversity. PMN16 (right bank of the river) was sampled at the beginning of the flood, while PMN22 (Pajakusa tributary) benefited from increased flow discharge, enhancing its connection to the Mara  n River. PMN23 (Santa Rosa beach), a large beach, remained unaffected by rising water levels, and PMN25 (right bank near Nieva) had not yet experienced flooding. Most evaluated environments featured wide shores dominated by boulders near the river, with sandy areas further inland. Flooding limited species collection at PMN15, PMN18, and PMN21, resulting in fewer species but a higher number of individuals. Areas near the MG, such as PMN24 (Santiago River), PMN17, PMN20, and PMN14 (Dominguza tributary), were the first to flood, with rising water levels covering their shorelines. Fry and juvenile catfish, including *Pimelodus ornatus*, *P. pictus*, *Platysilurus mucosus*, and *Megalonema platycephalum*, were collected. At PMN15, the highest abundance was recorded in 09/2014, associated with sandy substrates and schools of *Knodus* and *Creagrutus*. A total of 27 species were unique to 09/2014, while 18 species were unique to 11/2014.
- **At MG:** A total of 34 species were recorded, 32 in 09/2014 and 4 in 11/2014. Of these, 88% (30 species) were unique to 09/2014%, and 6% (2 species: *Leporellus vittatus* and *Megalonema amaxanthum*) were unique to 11/2014. The rise in water levels during 11/2014 limited fish collection, as rocks previously used for fishing and camping were submerged (Figures 4 and 9h). Sampling at PMN01 during the start of the *mijano* showed more individuals than PMN19, collected afterward, with fewer species. The gorge is a key fishing spot, especially during the *mijano* of species like *Prochilodus nigricans*, *Megaleporinus trifasciatus*, and *Mylossoma albigobum*, where fish jump near the margins, facilitating their capture with cast nets. The MG is a narrow channel (Figure 4), fish during their migration jump near the margins, facilitating its capture with the use of cast nets. The different rocks exposed under low-flow condition are used as a fishing area and camping (Figure 9h).
- **Downstream of MG:** A total of 3,185 individuals, representing 112 species, were recorded, with 87 species collected in 09/2014 and 63 species in 11/2014. Fifty percent of the species (55 species) were unique to this area, representing 35% of the total collected during the study. This suggests that a third of the ichthyofauna does not cross the Manseriche Gorge (MG) and is confined to the aquatic environments downstream of MG, including species of ornamental and migratory importance, as well as river stingrays, electric fish, croakers, and anchovies. Fishermen reported that species like *Panaque bathyphilus*, *Panaqolus nocturnus*, and *Peckoltia bachi* (loricariid catfishes) reproduce in habitats along the riverbanks, which are favorable for feeding and sheltering. Seasonal variations also affected species abundance (Figures 10a.2 and 10e). Some stations (PMN02 and PMN06) showed no significant changes in species numbers due to their location, while others

(such as PMN03) experienced an increase in the number of individuals as the water volume rose, allowing fish from the river to access ponds formed in the tributaries. In areas like PMN08 and PMN10, strong currents facilitated the dispersal of fish fauna, reducing the number of captures. In several sites (PMN07, PMN09, PMN11, PMN12, and PMN13), increased water flow made collection difficult. However, additional stations (PMN26, PMN27, PMN28) near Saramiriza were included in the study (Figure 2). The highest values in the number of individuals (Figure 10b) were recorded in 09/2014, except for PMN03 (Maguiña tributary) and PMN05 (sandy beach near the inner bank). At the Saramiriza dock in 09/2014, a high diversity of fish was noted, including large migratory catfish. In 11/2014, the presence of fish was almost non-existent, with several days passing without fishermen entering the dock. In total, 56% of the species recorded in 09/2014 were unique to that period, including migratory species such as *Megaleporinus*, *Potamorhina*, and *Steindachnerina*. Meanwhile, 40% of the species collected in 11/2014 were only present at that time, highlighting the occurrence of juveniles of various catfish species, including *Pimelodus ornatus*, *P. pictus*, *Platysilurus mucosus*, and *Megalonema platycephalum*, among others. Additionally, loricariid species carrying their eggs in their ventral areas were collected, such as *Rhadinoloricaria rhami*, *Loricariichthys sp.*, *Loricaria simillima*, and *L. clavipinna*. Only 29% of the species were common to both periods, underscoring the influence of seasonality on the composition of the fish community.

4.3.3. Quantitative Analysis

The rarefaction analysis revealed clear differences between the upstream and downstream areas of MG (Figure 10g). The rarefaction curve for the upstream region showed a more horizontal trend, approaching the asymptote, suggesting that sampling in this area captured a higher percentage of the species present in the upstream region of the MG. In contrast, the downstream curve of MG showed a steeper slope, indicating the need for additional sampling effort to fully document the ichthyofauna in that area and bring the curve closer to the asymptote. This analysis also revealed that, with the same sampling effort, species richness recorded downstream of the MG was higher than that observed upstream of MG. When comparing 09/2024 (Figure 10g.1), and 11/2024 2014 (Figure 10g.2), the difference between the curves was more pronounced in 09/2024, whereas in 11/2024 both curves showed a more horizontal trend at their apexes. The variation in MG curves between 09/2024 and 11/2024 is related to the extreme hydrological conditions in 11/2024, such as the elevated water level and river flow, which hindered species collection. The NMDS analysis revealed an overlap between the upstream and downstream regions, along with a clear separation from the MG region (Figure S16a in Supporting Information S1). This overlap was driven by a core group of species with high abundances in both regions, which were either absent or present in low abundances in the MG region. Furthermore, MG exhibited more exclusive species, distinguishing it significantly from the other regions. The dendrogram analysis (Figure S16b in Supporting Information S1), revealed slight structuring in 09/2014, where most of the upstream stations clustered together, indicating high similarity among them. In contrast, downstream stations clustered with those from MG. By 11/2014, the clustering of upstream stations persisted, indicating that, despite the rainfall, the similarity among these stations remained consistent. However, downstream stations showed lower similarity, likely related to variations in aquatic environments due to increased water volume and the arrival of new species. The indicator species analysis (IndVal) identified *Astyanax bimaculatus*, *Creagrutus sp.1*, and *Knodus septentrionales* as indicator species for the upstream of MG, whereas *Henonemus punctatus* was indicative of the downstream of MG. Additionally, *Leporellus vitattus*, *Thoracocharax stellatus*, *Lamontichthys sp.*, and *Megalonema amaxanthum* were identified as indicator species for the MG region (Figures S17 and S18 in Supporting Information S1).

4.3.4. Migratory Fish

During the field campaign, the migration of fish (*mijano*) from the orders Characiformes and Siluriformes was observed (Table S3 in Supporting Information S1). The *mijano* of a giant carachama, such as *Panaque schaeferi*, was notably recorded. The presence of large migratory catfish from the genus *Brachyplatystoma* was also noted, which undertake extensive movements from the estuary (the mouth of the Amazon River in the Atlantic Ocean) used as a growth and feeding area to the Andean foothills (where the MG is located) to spawn. This upstream movement, which involves a distance of 3,700–5,500 km, can take between 18 and 24 months (Goulding et al., 2010). It is important to highlight the differences in the records of migratory fish between Santa María de Nieva (upstream of MG) and Saramiriza (downstream of MG), where only *Pseudoplatystoma punctifer* and *Sorubim lima* were observed in the latter, while a high diversity of migratory fish was recorded at the Saramiriza

city (Figures 10f.1–10f.8). During the expedition, three phases of the migration cycle were identified: **Phase 01**: During the initial entry into the river, smaller fish *mijano* were observed, including *Steindachnerina* spp., *Tetragonopterus* sp., and *Triportheus angulatus*. In the beaches downstream of MG, the migration of schools of small characids (*Knodus* sp. and *Creagrutus* sp.) was observed. In these early days, rainfall was weak, and no significant variation in water level was noted, **Phase 02**: Four days later, rainfall altered the river conditions, limiting fish collection on that day. However, the day following the rain, the largest peak of *mijano* was observed, with over 76 larger fish collected at MG, including *Prochilodus nigricans*, *Megaleporinus trifasciatus*, and *Schizodon fasciatus*, captured through 10 hauls of cast nets. This event attracted local residents to the MG, leading to a high abundance of fish being collected as they jumped between the rocks while navigating upstream, **Phase 03**: Seven days after the peak of *mijano* at MG, records showed a drastic reduction in fish presence, particularly highlighting the collection of *Auchenipterus ambyiacus* (smaller catfish). At the same time, downstream of MG, in front of the town of Borja, the arrival of Amazon River dolphins (*Inia geoffrensis*) was observed, with eight individuals recorded, including both adults and juveniles.

5. What if the Manseriche Hydropower Dam Is Built?

If the Manseriche dam is built (OTCA, 1970), potential upstream and downstream environmental and river dynamics impacts will occur, the question is in what magnitude. To characterize the river dynamics, the existing conditions for the Santiago and Marañón rivers (upstream and downstream of MG) were simulated using TEL-EMAC. The results of flow velocities along meandering and anabranching structures of both rivers for high-flow conditions are shown in Figure S19 in Supporting Information S1. The conditions for the existing condition (Figure S19 in Supporting Information S1) were adapted to simulate the post-dam conditions to accommodate a larger domain (inclusion of the Santiago-Nieva depression), which will be inundated in a significant part by the Manseriche dam (Figure 11a). The simulation in the Marañón River downstream of the MG considered the bed morphology only, ignoring planform evolution. The modeling allowed to estimate that for the pre-dam conditions, the average shear stress (the main driver for sediment transport) along the Marañón River, upstream of MG oscillates between 7.0 and 10.2 Pa (with values exceeding 20 Pa in the upper part of the river), downstream of MG oscillates between 4.3 and 6.0 Pa, while along the Santiago River oscillates between 2.1 and 2.4 Pa, depending on the stage of the flow. For post-dam simulations in the upstream region (Figure 11a), results show that almost the entire Santiago-Nieva depression will be inundated affecting the Northern Peruvian Oil Pipeline (also submerged) and several communities (see Figure S2 in Supporting Information S1). The Santiago River will be submerged under the reservoir, also, the shear stress is reduced significantly, suppressing the bedload mechanism of sediment transport. In the reaches of rivers located above 351 m.a.s.l., the new base level will promote retrogradation in the zone of backwater flow and change of the planform geometry (Maselli et al., 2018). Sediments from the Ecuadorian Santiago River (especially if rates are increased due to deforestation, Figure S4 in Supporting Information S1) from the tributaries of the Peruvian Santiago River, from the Marañón River (at Huaracayo Gorge) and from the Nieva Rivers will be deposited along the large reservoir, thus, coarse and fine sediments might not travel downstream of the Marañón River. For the downstream region, hydro-morphological simulations indicate an incision (bed erosion) due to reduced inlet sediment supply. Figure 11b shows bed changes due to existing flow conditions, while Figure 11c shows the incision process, with magnitudes greater than 2-m in some areas after 1-year of dam operation, the incision is propagating downstream. The incision and the suppression of peak flows caused by the storage in the reservoir affect the lateral connectivity, an important process for fish diversity. For instance, the flood pulses in the Amazon River generate an interchange of flow of the river with the floodplains of about 25% of the mean annual flow (Richey et al., 1989), this example highlights the relevance of the lateral connectivity. Also, some oil pipeline river crossings will be affected by changes in the river morphology.

The construction of the Manseriche Dam would thus have profound implications for fish species and their habitats. The suppression of peak flows, a direct consequence of reservoir storage, would disrupt the natural longitudinal and lateral connectivity of the river system, which is essential for the seasonal migrations and diversity of fish species. Altered flow regimes would inhibit natural flood pulses that, in ecosystems such as the Amazon, are crucial for spawning, feeding, and overall fish survival. Upstream, the inundation of the Santiago-Nieva depression would result in the loss of critical habitats, affecting local communities and ecosystems. The significant reduction in shear stress would suppress sediment transport, leading to changes in riverbed morphology that could impact benthic habitats, which are vital for many aquatic species. Downstream, sediment starvation and bed incision caused by the dam could further degrade essential habitats, destabilizing riverbanks

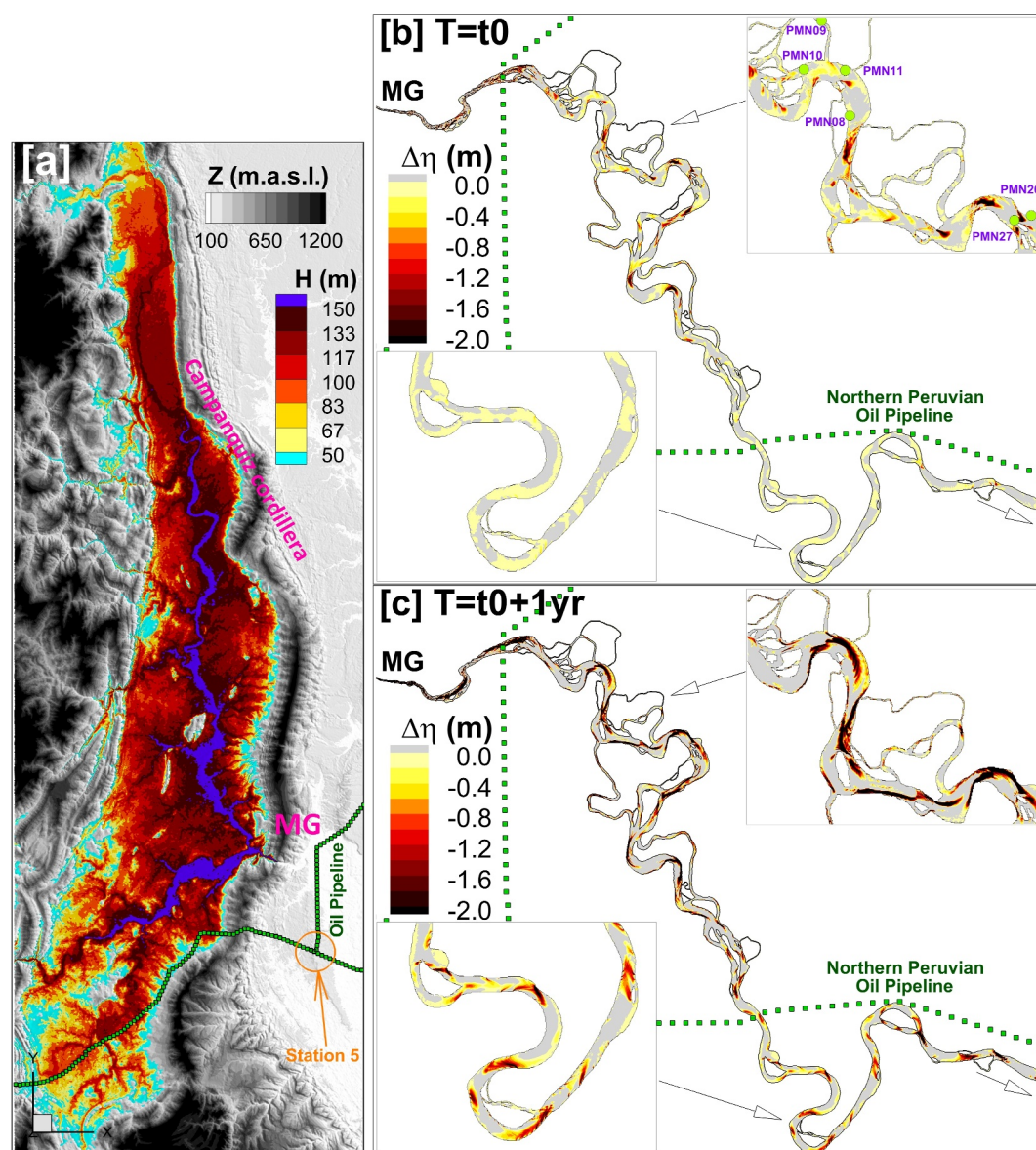


Figure 11. Potential post-dam scenario, (a) flooding upstream of MG, H: water depth (m), (b) bed evolution ($\Delta\eta$) downstream of MG ($T = t_0$), (c) bed evolution ($\Delta\eta$) downstream of MG ($T = t_0 + 1$ year).

and affecting species reliant on specific conditions for spawning and feeding. Migratory fish species would be especially vulnerable, as the dam would obstruct their natural routes between feeding and spawning grounds. Furthermore, the overall reduction in sediment transport downstream would disrupt nutrient dynamics, leading to a decline in food availability for fish populations. These changes are likely to cause significant reductions in both biodiversity and fishery productivity, with long-term impacts on the ecological integrity of the region.

6. Discussion

6.1. Baseline Characterization of Hydrogeomorphology

Peak channel activity (40% or more) is developed downstream of MG, and upstream Rentema Gorge (Figure 4c), in such reaches of larger activity, the river has anabranching patterns while moderate activity (around 20%) is observed between Huaracayo and Manseriche gorges. In such areas of larger activity, the river has anabranching patterns. The sediment load in the Marañon River, just upstream the confluence with the Santiago River was

193 kt/day in 2022, and 122 kt/day in 2023 (Figure 9f), downstream the confluence the sediment load measured in 2023 was 629 kt/day. The difference of sediment load upstream and downstream the confluence with the Santiago River indicates that the larger fraction of sediment yield arriving to MG comes from the Santiago River. A factor to consider for the sediment load is the deforestation in the region, which has an increasing trend (Figure S4 in Supporting Information S1), and implies a larger sediment yield for the fluvial system. Regarding flow regime, the Santiago River has a large variability (see A21 in Figure 9b), which is slightly damped downstream the confluence with the Marañón River (L23 in Figure 9b).

6.2. Challenges in Species Identification, the Need for a Comprehensive Study of Ichthyoplankton Along the Marañón River and Tributaries

The Marañón River basin, spanning the countries of Peru and Ecuador, showcases remarkable biological diversity with 747 documented species (Jézéquel et al., 2020). This diversity represents 54% of the total species recorded in Peru. Currently, the basin holds the second position in terms of fish species richness, surpassed only by the Ucayali River basin, which reports 761 species (Chuctaya et al., 2022). The MG is recognized as the type locality for three species: *Peckoltia pankimpuju* (Lujan & Chamon, 2008), *Chasmocranus peruanus*, and *Parodon pongoensis*. Herein, it is reported the presence of potentially new species for science belonging to the genera *Odontostilbe*, *Knodus*, *Moenkhausia*, among others. Additionally, the inventory has recorded numerous species identified at the genus level, designated as cf (confer) and aff (*affinis*). This observation suggests the necessity for a more comprehensive taxonomic review of many species within these genera, employing an integrative approach that encompasses both morphological and molecular aspects. The MG represents the narrowest section of the Marañón River in the lower part of the basin, serving as a conducive region for the concentration of migratory fish. During our expedition in the mid-year period, it was observed how fishermen gather along the banks to capture abundant fish. Climate change can influence the migration and spawning rates of migratory catfish in various Amazonian basins. However, these effects depend on flow conditions and migratory patterns (Feng et al., 2020). The MG possesses particular characteristics that can serve as an ideal station to assess these potential climate change impacts.

While the evidence of the presence of eggs and larvae is clearly perceptible around the MG, the precise identification of these species is hindered by exclusive morphological analysis. This limitation arises from the fact that the characterization of eggs and larvae of freshwater fish in South America has predominantly focused on a few species, particularly those from the Plata and Amazon basins (Brazil), and the majority of existing studies are incomplete (Reynalte-Tataje et al., 2020). Faced with this restriction, there is an urgent need to conduct a more comprehensive study of ichthyoplankton both upstream and downstream of MG. This study should incorporate a molecular analysis of eggs and larvae to achieve a precise taxonomic identification of these species. García-Dávila et al. (2015) conducted preliminary studies on the identification of eggs and larvae, focusing on fish from the basins of the Marañón, Ucayali, and Napo rivers. These analyses have not only allowed the identification of threatened fish spawning areas in the Beni River, including the endangered golden catfish, through a barcoding analysis but also underscore their crucial relevance for the formulation of conservation measures (Miranda-Chumacero et al., 2020). Research on larvae both upstream and downstream of the rapids will be essential to determine if the region where the rapids are located constitutes fish spawning areas, emphasizing the urgency of implementing conservation measures in this specific area.

The above studies should be carried out together with more detailed and extensive hydrogeomorphology measurements (flow, sediments, planform and altimetric geomorphology) for different stages along the MG hydrograph, thus, to answer: how does the geomorphology and bed conditions affect biodiversity and species ranges?, do different species prefer narrower/wider/less active/more active channels?, how does grain size affect fish distribution?, are there distinct assemblages in different reaches as a result?, how do changes in geomorphology and sediment fluxes affect different species and their abundance?, what are the impacts on fish diversity if the Manseriche Hydropower dam is built?, among others.

6.3. Impact on Fish Biodiversity

The Marañón River basin, an essential part of the Amazon basin and one of the main sources of water for this system, is particularly vulnerable to the impacts resulting from dam construction due to its unique biodiversity and the hydrological dynamics that support migratory and resident fish species (Finer & Jenkins, 2012). Fish

species in the Marañón depend on the river's seasonal fluctuations to navigate through the MG and access key feeding, spawning, and refuge areas. The construction of a dam in the MG could severely disrupt these ecological processes.

6.3.1. Alteration of Flow Regimes

In the Marañón basin, as in other river systems in the Amazon region, the construction of the dam in the MG would disrupt the natural flood and drought cycle, which is fundamental to aquatic ecosystems. Fluctuations in water levels allow fish to undertake longitudinal (upstream) (Barthem & Goulding, 1997; Barthem et al., 2017; Hauser et al., 2018, 2019) and lateral (into flooded areas) migrations (Fernandes, 1997; Osorio et al., 2011), as well as access spawning and feeding habitats. Building the dam in the MG would reduce or eliminate these seasonal floods, limiting species' ability to utilize these areas. This would directly affect species such as large migratory catfish, which make long upstream migrations and larval drift downstream to complete their life cycles (Barthem & Goulding, 1997; Barthem et al., 2017). Additionally, lateral connectivity between the main channel of the Marañón River and its floodplains is vital for the survival of numerous fish species, many of which rely on these temporary habitats for reproduction and feeding, such as the frugivorous species of the genus *Brycon* and *Colossoma*. The reduction of flood pulses would drastically decrease access to these environments, impacting both migratory and resident species, potentially leading to significant population declines.

6.3.2. Habitat Fragmentation

The construction of the dam in the MG would cause severe habitat fragmentation, blocking migration routes for many species. As observed in this study, the MG plays a crucial role in the passage of migratory Characiformes such as *Prochilodus nigricans*, *Megaleporinus spp.*, and *Mylossoma spp.*, among others. Moreover, large migratory species like *Brachyplatystoma spp.* (Amazonian catfish), which travel long distances to spawn, would be particularly affected, as these species utilize the MG region for spawning according to our observations. It is important to note that upstream of MG, there are other gorges that perform similar functions, although they are currently understudied. Fragmentation of the Marañón River at the MG would prevent these species from reaching their upstream spawning areas, which could lead to population declines in the basin and, eventually, local extinctions of some species. This fragmentation would also cause a loss of genetic diversity in these species, as the dams would limit genetic exchange between upstream and downstream populations, reducing their adaptability to environmental changes and impacting their long-term survival (Ferreira et al., 2017).

6.3.3. Changes in Water Quality and Temperature

The reservoir formed upstream of the MG would cause changes in water quality and temperature, affecting species adapted to the river's natural conditions, primarily those listed in this study. One significant change would be the thermal stratification that would form in the reservoir, creating layers of water with significantly different temperatures (Elci, 2008). This would negatively affect species sensitive to thermal variations, as the surface strata could reach elevated temperatures (Winton et al., 2019). Another important change would be the presence of hypoxia (low oxygen levels) in the water retained by the dam upstream of MG, which would impact the most sensitive species, especially those requiring high levels of dissolved oxygen, such as benthic species, including the loricariids mentioned in this study. Furthermore, since the Marañón basin is one of the main river basins in Peru, traversing nine regions of Peruvian territory and nine Ecuadorian provinces, a dam at MG would allow for the accumulation of nutrients and pollutants generated by all these areas, which could trigger eutrophication episodes in the reservoir, further affecting aquatic biodiversity and reducing water quality for fish.

6.3.4. Alteration of Sediment Dynamics

The Marañón basin, being one of the main high Andean rivers, is a significant source of sediment that feeds the river systems of the Amazon basin. The construction of the dam at MG would interrupt this sediment flow, leading to two main effects. The first would be the retention of sediments in the reservoir, depriving areas downstream of MG of the sediments necessary to maintain spawning and feeding habitats for many species, such as benthic fish that rely on specific substrates for reproduction, as well as those that use sediment for camouflage and predator evasion, like river stingrays. The second effect would be downstream erosion caused by the reduction of sediments, which would increase erosion of the riverbed, simplifying the habitat and reducing the

structural complexity necessary for the survival of juvenile and adult fish, affecting loricariid species that use the riverbed margins for spawning.

6.3.5. Impacts on Specialized Species

The Marañón River basin is home to numerous endemic and specialized species that depend on the river's particular conditions to survive. The MG is an ichthyological hotspot, as it is the type locality for *Parodon pongoensis*, *Chasmocranus peruanus*, and *Peckoltia pankimpuju* (Lujan & Chamon, 2008), not to mention all the endemic species described in the upper part of the Marañón basin. Changes in the geomorphology of the MG, as well as changes in flow regimes, temperature, water quality, and loss of connectivity, could lead to the extinction of these specialized species that would not be able to adapt to the new conditions created by the dam (Anderson et al., 2018; Forsberg et al., 2017). Species that depend on the geomorphology of the MG and fast water flows, such as those inhabiting rapids and rocky areas, would see their habitats transformed or destroyed.

6.3.6. Changes in Trophic Dynamics and Species Composition

The transformation of the upstream section of the MG into a stable reservoir would favor generalist species and those thriving in slower and more stable environments, displacing native species adapted to the variability of the river, such as the different species mentioned in this study. This would lead to a homogenization of fish communities and loss of local biodiversity. Additionally, the trophic networks would be affected by the reduction of key species, resulting in cascading effects on other aquatic and terrestrial organisms, including those that rely on fish for food, such as river dolphins.

6.3.7. Socioeconomic Impact on Marañón Fisheries

As observed in this study, the MG plays a primary role in the local fishery, being one of the main fishing areas for many local communities living upstream and downstream of MG. These communities would be severely affected by the decline in migratory fish populations, as well as by the disappearance of *mijano* fishing. The reduction in fish catches, both for local consumption and for sale, would directly impact food security and the livelihoods of riparian communities, exacerbating social and economic issues in the region and generating incentives to seek alternative sources of protein and income (Anderson et al., 2018).

6.4. Science-Based Studies to Reduce Socio-Environmental Concerns

This study shows complex physical processes (e.g., geology, hydrology, geomorphology) occurring at different temporal and spatial scales around the Andean region, a hotspot for biodiversity. However, anthropogenic activities such as deforestation due to illegal gold mining (Joshi, 2016) are also present. Emphasis on developing infrastructure for hydropower and waterways has raised social concerns (Asher, 2017; Joshi, 2017; Sierra, 2019). Finer and Jenkins (2012) pointed out that regional governments are prioritizing new hydroelectric dams, but the planning lacks of adequate regional and basin-scale assessment of potential ecological impacts. Finer and Jenkins (2012) suggested the need to develop: (a) a regional and basin-scale evaluation of dams, (b) a plan to maintain the Andes-Amazon connectivity and (c) to reconsider the use of hydropower as low-impact energy source. Arantes et al. (2022) stated that hydropower dams cause detrimental effects for fisheries and the livelihoods they sustain and suggested the enhancing of operational protocols at dams to minimize impacts as well as efficient fish passages structures (design using the complex physical and biological characteristics of amazonian rivers) or to explore other alternatives such as solar power, in-stream turbines, among others. Basin scale evaluation for infrastructure development requires to collect baseline data on physical, biodiversity (Sá-Oliveira et al., 2015) and account for cumulative effects of different anthropogenic activities, thus, to develop multidisciplinary studies (from hydrodynamic patterns, to sediment transport and river morphology, to biochemical processes, as well as microorganisms distribution) (Pinel et al., 2020). As shown previously, several dams are being planned for the Marañón River, thus, there is a need to develop long-term monitoring efforts and studies to properly inform EIA studies by considering all stages (avoidance, minimization, rehabilitation/restoration, and offset; compensation only if needed) of the mitigation hierarchy (Arlidge et al., 2018). In fact, Thieme et al. (2021) applied the mitigation hierarchy concept within the hydropower development, and mentioned that early usage of these concepts would avoid and reduce several socio-environmental impacts and conflicts.

7. Conclusions

Upstream of the Manseriche Gorge (MG), the Marañón River has segments with significant planform activity (20% or more), the reaches of larger activity develop anabranching patterns. The Santiago River is the last tributary to the Marañón River before it crosses the MG, it has an annual flow regime with a wide variability, condition for the flooding pulses that generate lateral connectivity. Also, the Santiago River supplies the larger fraction of sediment yield to the MG. The Santiago River's valley is located within the Santiago-Nieva depression where the geology confines the channel, thus, the Santiago River presents a transitional morphodynamic regime, showing meandering and anabranching configurations. The Marañón River is a fully developed anabranching river, where water and sediments are shifted among the channels. The MG imposes boundary conditions not only to morphodynamic processes (sediment differentiation between the upstream and downstream reaches) but also to fish diversity. Downstream (upstream) of the MG, 55 (28) species were only collected in this area representing 35% (18%) of the total collected throughout the study. During low-flow (transition from low- to high-flow) condition, 129 (84) species were collected. The increase on water stage limited the fish collection. If the Manseriche dam is built, the entire Santiago River will disappear suppressing the hydromorphological environment and promote sedimentation in the regions with backwater flow from the Marañón, Nieva and Santiago rivers. Also, the submerged condition can affect the Northern Peruvian Oil Pipeline. Due to the sediment retention in the reservoir, the region downstream of the MG, rapid incision together with the suppression of flow peaks will disrupt existing lateral connectivity, thus, affecting the oil pipeline river crossings and the more fish-based diverse and abundant regions. Also, morphological changes of the river may affect the oil pipeline crossings.

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Data Availability Statement

The post-processed data from experiments and field measurements is available in the Zenodo repository (Redyaku, 2024), which can be accessed at <https://doi.org/10.5281/zenodo.14029273>.

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