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RESEARCH ARTICLE

Damming induces convergence of riverscapes in the Nile, Yangtze, and Amazon Basin: The importance of localized watershed management

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Abstract Understanding changes in riverscapes and their influencing factors is crucial for effective biological conservation. Although the impact of dams on riverscape changes has been investigated, comparative research is limited. This study first conducted a comparative analysis of riverscape configuration patterns from different perspectives using the Landscape Fragmentation Index of Configuration among three major global dammed rivers: the Aswan High Dam on the Nile River, the Three Gorges Dam on the Yangtze River, and the Jirau and Santo Antônio dams in the Amazon Basin. Subsequently, through the Analysis of Similarity of various indices, we identified a significant trend toward resemblance in the configurations across the three dammed rivers. Further, we found that this resemblance progressed in a trend similar to that of riverscape composition, with built-up and water land-use type being the primary factor explaining the similarity across these regions. These findings provide valuable insights for localized management measures in dam-affected areas.

Keywords Amazon River · ANOSIM · Configuration · Damming riverscape · Nile River · Yangtze River

INTRODUCTION

Natural rivers are globally recognized as unique and diverse ecosystems (Whipple and Viers 2019), providing essential ecosystem functions and services to human societies. However, the rapid expansion of the global economy and population growth has led to an increase in human activities impacting rivers, such as dam construction, aquaculture, and sediment extraction (Hsu-Kim et al. 2018; Wu et al. 2023). Among these activities, dams play a pivotal role as engineering structures that significantly alter river flow regimes and discharge patterns, thus becoming key drivers in shaping the world's riverscapes (Graf 2006; Liro 2019). The construction of dams results in widespread transformations, both upstream and downstream. Upstream, reservoirs are created that inundate vast areas of land, submerging existing habitats, vegetation, and whole riverbank biological communities. Downstream, the impact of dam construction can dampen hydrodynamic processes, dramatically reducing or even eliminating flood pulses, which serve as critical disturbance regimes for rivers. The elimination of these natural flood pulses has profound effects on river floodplains, influencing their ecological dynamics and biodiversity. Consequently, dams contribute to a continental-scale effect of homogenizing regionally distinct environmental conditions (Poff et al. 2007). Riverscapes, which include river channels, floodplains, and the biotic communities that form the valley floor, are shaped by longitudinal, lateral, and vertical dimensions (Murphy et al. 2022; Torgersen et al. 2022). Dams disrupt these dimensions by altering natural flow regimes longitudinally (Grill et al. 2019), affecting the diversity of floodplain vegetation and fauna along with their landscape matrix laterally (Barbarossa et al. 2020; Medeiros et al. 2023; Parasiewicz et al. 2023), and impacting biogeochemical cycles vertically (Maavara et al. 2020). Through these disruptions, dams fundamentally alter the natural ecological and physical processes that sustain diverse river ecosystems.

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Furthermore, the construction of dams, which leads to the destruction and degradation of natural watershed ecosystems, is a critical factor contributing to global biodiversity loss (Pereira et al. 2010; Wu et al. 2019). A well-composed and configured landscape, characterized by features such as the management of semi-natural habitats and increased edge density, can enhance functional biodiversity and ecosystem services (Martin et al. 2019). Therefore, understanding the role of dams in shaping riverscapes is crucial for developing effective conservation and management strategies. Protecting and restoring the uniqueness and distinctiveness of various watershed ecosystems is essential to counteract the trend of environmental convergence and maintain ecological integrity. In measuring riverscape change, the landscape configuration is key. Riverscape configuration refers to the physical distribution and spatial characteristics of landscape patches and their relationships to one another. Correspondingly, landscape composition refers to the proportion of each land-use patch type within the landscape (McGarigal and Marks 1995). Therefore, landscape configuration can be understood as ecological changes induced by human activities, where once continuous and undisturbed natural landscapes are fragmented into numerous patches, affecting the structure and function of ecosystems (Forman 1995). However, inspired by the Environmental Convergence Hypothesis (Ahouangbe and Turcu 2024), as landscape configuration becomes increasingly fragmented, a parallel process of homogenization emerges (the consistency of landscape characteristics and ecological functions between different regions) (Foley et al. 2005; McKinney 2006), driven by uniform environmental management practices.

Globally, the rapid increase in dam constructions across the three major rivers—the Amazon, Nile, and Yangtze—has accelerated the fragmentation of riverscapes within these river systems, raising serious concerns about the health of their ecosystems (Nilsson et al. 2005; Aguiar et al. 2016). Although the Environmental Convergence Hypothesis is originally based on socioeconomic environments, it can be inferred that, in terms of riverscape composition and configuration, riverscapes in different regions may independently develop similar characteristics under uniform environmental management practices. The convergence of landscape composition and configuration is likely to manifest through the processes of economic globalization and urbanization. This convergence reflects the homogenization of landscapes driven by standardized land management practices and increased connectivity facilitated by global trade and urban expansion. Research has found that during the period from 1960 to 2019, approximately one-third of the global land area underwent significant changes, leading to a noticeable reshaping of landscapes. The acceleration of land-use changes before 2005, followed by a deceleration, can be explained by the impact of global trade on agricultural production (Winkler et al. 2021).

Understanding how dam construction influences riverscape configurations across diverse geographical contexts is vital. The expansion of inundated areas following dam construction frequently results in considerable population displacement (Fan et al. 2022) and changes in land use (Rufin et al. 2019). Conducting such comparative analyses can inform adaptive management strategies, thereby enabling the design of more robust environmental management and conservation policies to minimize the potential adverse impacts of dam construction on biodiversity and ecosystem services. Furthermore, given the complexity of environmental and socioeconomic contexts across different regions, cross-regional comparative studies will offer a more comprehensive perspective, identifying commonalities and differences, and providing globally relevant guidance for water resource management. Ultimately, this will contribute to achieving sustainable development goals while safeguarding critical ecosystems and the natural resources upon which human livelihoods depend.

Based on relevant studies of major global rivers and the Environmental Convergence Hypothesis, we hypothesize that dam construction may result in similar riverscape configuration and composition within the dam-affected areas of three renowned dammed rivers: the Three Gorges Dam on the Yangtze River, the Aswan High Dam on the Nile River, and the Jirau and Santo Antônio Dams in the Amazon Basin. To test this hypothesis, our overarching objectives are:

(1) What differences exist in the riverscape configurations in areas impacted by dams on the Amazon, Nile, and Yangtze Rivers?
(2) What similarities can be observed in the river landscape composition and configuration among these river systems?
(3) Which landscape indices primarily contribute to the similarity in riverscape configuration or composition?
(4) How do potential influencing factors such as population density, precipitation, temperature, and land-use types correlate with the similarity in riverscape configuration and composition?

MATERIALS AND METHODS

Study area

In this study, the Jirau Dam and Santo Antônio Dam in the Amazon Basin, Aswan High Dam in the Nile Basin, and Three Gorges Dam in the Yangtze River Basin were selected as the world's largest run-of-river hydropower plants (Fig. 1a). The Jirau and Santo Antônio dams are located about 1000-km upstream in the Madeira River of the Amazon Basin (Fig. 1c), primarily within a humid tropical monsoon climate, receiving 2250–2750 mm of annual rainfall and average temperatures of 24–26 °C. Their construction aims to meet Brazil's growing electricity demand while reducing greenhouse gas emissions. Together, they account for about 30% of the installed capacity of China's Three Gorges Dam (Almeida et al. 2019). The Aswan High Dam (Fig. 1d), situated on the Nile in a hyper-arid desert climate, creates the world's third-largest artificial reservoir. It ensures reliable irrigation,

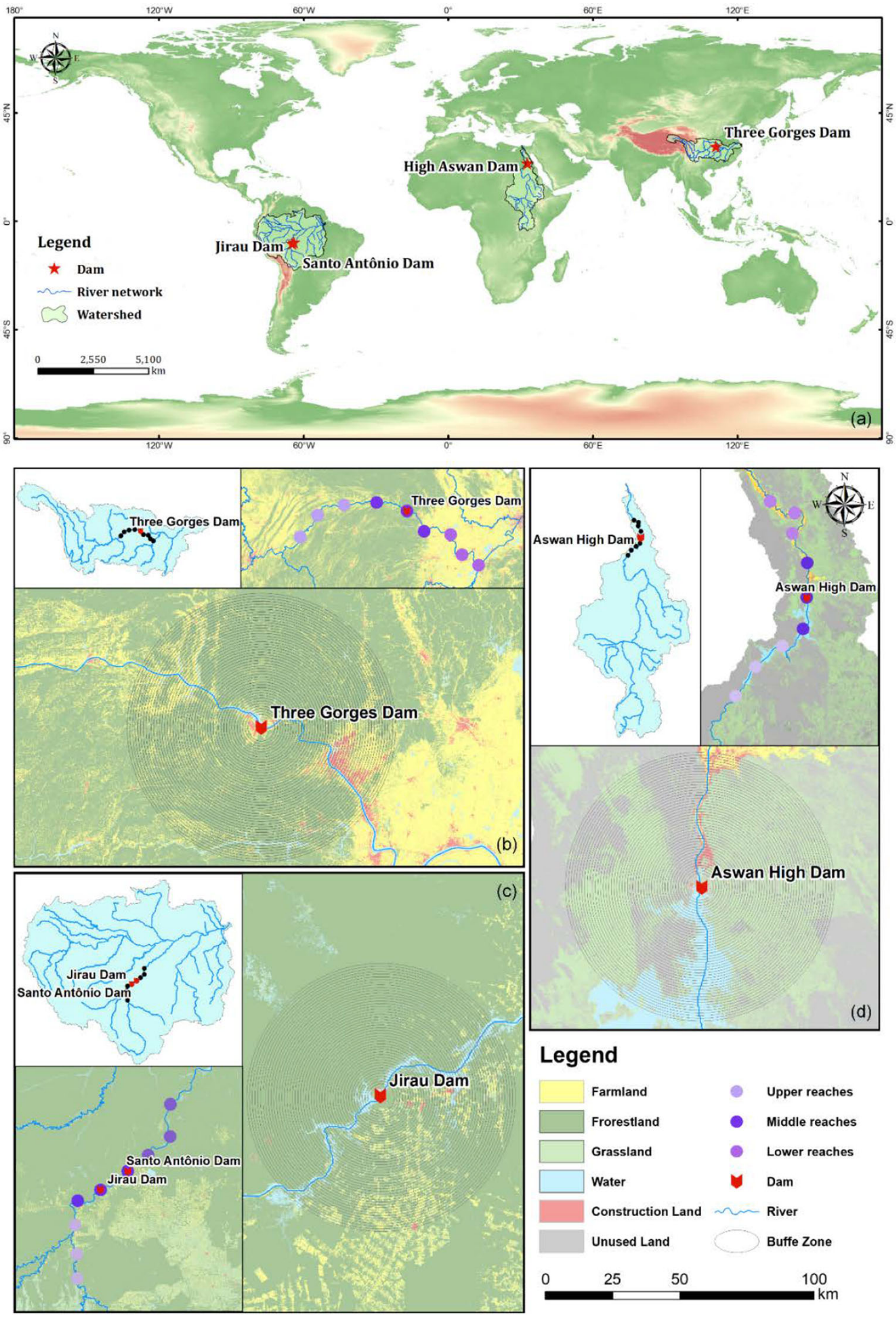

Fig. 1 **a** Geographical location of the dams on the studied three global major rivers, **b** sampling sites and their varied buffer radii in the region of the Three Gorges Dam in the Yangtze River, **c** sampling sites and their varied buffer radii in the region of the Jirau and Santo Antônio dams in the Amazon Basin, and **d** sampling sites and their varied buffer radii in the Aswan Dam in the Nile River

enhances soil quality, and promotes navigation along the Nile River, significantly aiding Egypt's socioeconomic development (Abd-El Monsef et al. 2015). Located on the Yangtze River, the Three Gorges Dam operates in a subtropical monsoon climate with rainfall of 1,000 to 1,500 mm and temperatures of 15–18 °C (Fig. 1b). It was built mainly for water conservation and flood control but also supports hydroelectric power and irrigation, contributing to socioeconomic growth. However, it has led to ecological impacts like soil erosion and increased nonpoint source pollution (Li et al. 2013).

Riverscape sampling design

Drawing from prior studies, insights from research on the Jirau Dam (Medeiros et al. 2023) and Santo Antônio Dam (Coura et al. 2021), as well as findings pertaining to the Aswan High Dam (Abd-El Monsef et al. 2015) and the Three Gorges Dam (Xu et al. 2012), we opted to conduct spatial sampling along the river sections that include these dam locations. Each dam will serve as the central point for sampling within a range of 800 kms (Fig. 1b, c, d).

Longitudinally, to analyze changes in the response to the riverscape configuration at different distances from the dam construction site, the sampled river section was divided into three parts: upstream, midstream, and downstream, and sampling points were taken at 100-km intervals upstream and downstream from the center of each dam. Further, laterally, the concentric buffer radii ranging from 5 to 50 km were made around each sampling site (Cooley et al. 2021; Fan et al. 2022), resulting in 414 buffer radii along each of the three dammed rivers.

Analysis overview

For objective 1, assessing the Differences in Riverscape Configuration and Composition in Dam-Affected Areas of the Amazon, Nile, and Yangtze Rivers in Lateral and Longitudinal Directions.

In each study area, we selected nine sample points and established 46 different radii buffer zones around each point, resulting in a total of 414 buffer zones for collecting land-use data. Based on these data, we calculated 11 landscape configuration indices at the landscape level to reflect the characteristics of riverscape configuration. Then, we selected the PLAND index at the class level to represent the characteristics of riverscape composition (Table 1).

To address the issue of overlapping explanations among the 11 indices, we employed principal component analysis (PCA) to reduce dimensionality, thereby providing a visual representation of the level of riverscape fragmentation of configuration (RFIOCF) in dam-affected areas of the three river basins. Furthermore, we utilized the Kruskal–Wallis nonparametric test instead of ANOVA to evaluate differences in riverscape configuration among the three regions across various sample points and buffer radii over the study period (McIntosh 2015).

For objective 2, determine the similarity in riverscape composition and configuration.

To assess the riverscape configuration, we employed the Analysis of Similarities (ANOSIM) to evaluate the statistical similarity among the dammed rivers. For the riverscape composition assessment, we calculated the PLAND index for six major land-use types in each region, allowing us to assess the similarities in riverscape composition among the rivers.

For objective 3, identify the key contributing indices or land-use types.

We employed Similarity Percentage Analysis (SIMPER) to pinpoint the components that most significantly contribute to similarity in riverscape configuration and composition.

For objective 4, association between potential influencing factors and riverscape configuration and composition similarity.

To explore the relationship between riverscape configuration similarity and potential influencing factors, we utilized Pearson correlation analysis. This analysis allowed us to examine how variables such as population density, temperature, precipitation, and land-use type composition might influence the similarity in riverscape configuration.

All landscape metrics were calculated using the FRAGSTATS software (Version4.2) (McGarigal et al. 2023). Principal Component Analysis (PCA) and correlation analyses were conducted using SPSS 25. The ANOSIM and SIMPER analyses were performed using the ANOSIM and SIMPER modules in PRIMER-7 software (Clarke 2015). All data sources used by the Institute are listed in Table 2.

Details of each method are given in the supplementary information.

RESULTS

Differences in riverscape configuration in the dam-affected areas of the Amazon, Nile, and Yangtze Rivers

In the three dam-affected areas under evaluation, although there are differences within the year, the trend of RFIOCF changes is consistent ($P < 0.05$), showing an upward trend, indicating that the riverscape configuration is becoming more fragmented (Fig. 2a). In 1985, 1990, and 1995, there were no significant differences in riverscape fragmentation among the three areas. However, from 2000 to 2020, there is no significant difference between the Jirau & Santo

Table 1 Landscape metrics for calculating riverscape configuration and composition (McGarigal and Cushman 2002; Zou et al. 2022; McGarigal et al. 2023)

Class	Level	Landscape metrics	Equation	Ecological meaning
Riverscape configuration	Patch size (landscape-level)	Mean Patch Size (MPS/AREA_MN)	$MPS = \frac{A}{N}\left(\frac{1}{10000}\right)$	It refers to the riverscape fragmentation degree. The riverscape system with the smaller MPS value is more fragmented than that with the larger MPS value
		Largest Patch Index (LPI)	$LPI = \frac{\max(a_{ij})}{A}(100)$	It confirms the riverscape dominance type and determines the dominant species and internal species abundance in the riverscape. The change of this value shows the interference strength and frequency and reveals the direction and strength of human activities
	Patch shape (landscape-level)	Area-Weighted Mean Shape Index (AWMSI/SHAPE_AM)	$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{0.25P_{ij}}{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{A}\right)\right]$	It is one of the important indices to measure the riverscape space pattern complexity and shows the marginal effect on the shape analysis of the natural patch or natural riverscape
		Area-Weighted Mean Patch Fractal Dimension (AWMPFD/FRAC_AM)	$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{2\ln(0.25P_{ij})}{\ln(\sqrt{a_{ij}})}\right)\left(\frac{a_{ij}}{A}\right)\right]$	It is an important index to reveal the overall features of the riverscape pattern and to display the impacts of human activities on the riverscape pattern. Roughly, the natural riverscape has the higher-grade fractal dimension, while the artificial riverscape has the lower-grade fractal dimension
	Patch density (landscape-level)	Edge Density (ED)	$ED = \frac{E}{A}(10000)$	It represents the riverscape fragmentation degree. The higher value is, the higher the riverscape fragmentation degree will be
		Patch Density (PD)	$PD = \frac{N}{A}(10000)(100)$	It reveals the fragmentation trend of the riverscape pattern. If the value is larger, the riverscape fragmentation degree will be higher
	Patch type (landscape-level)	Shannon's Diversity Index (SHDI)	$SHDI = -\sum_{i=1}^{m} P_i \ln(P_i)$	The more abundant the land-use type is, the more information content will be and the larger the fragmentation degree will be. Also, there will be more uncertain information
	Patch cluster (landscape-level)	Contagion Index (CONTAG)	$CONTAG = \left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left[(P_i)\times\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]\left[\ln(P_i)\times\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right]}{2\ln(m)}\right]\times 100$	It describes the cluster degree or extension trend of different patch types. The higher value indicates that a certain dominant patch type in the riverscape forms good connectivity. On the contrary, it shows the dense pattern of multiple elements in the riverscape, and the riverscape fragmentation degree is higher
		Patch Cohesion Index (COHESION)	$COHESION = \left[1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} P_{ij}^{*}}{\sum_{i=1}^{m}\sum_{j=1}^{n} P_{ij}^{*}\sqrt{a_{ij}^{*}}}\right]\times\left[1 - \frac{1}{\sqrt{Z}}\right]^{-1}\times 100$	It displays the impacts of the distance between patches and arrangement patterns on the riverscape structure, showing the apparent continuity of riverscape in space
	Patch distance (landscape-level)	Mean Nearest-Neighbor Distance (MNN/ENN_MN)	$MNN = \sum_{j=1}^{n}\left(\frac{h_{ij}}{n_i}\right)$	It measures the spatial pattern of the riverscape. If the value is larger, the distance between patches of the same type is farther and distribution is more dispersed. Conversely, the distance between patches of the same type is present in the cluster distribution
		Mean Proximity Index (MPI/PROX_MN)	$MPI = \sum_{s=1}^{n}\left(\frac{a_{ijs}}{h_{ijs}^{2}}\right)$	It measures the approaching degree and riverscape fragmentation between patches of the same type. If the value is smaller, patches of the same type will have a higher dispersion degree or riverscape fragmentation. If the value is larger, proximity between patches of the same type is higher and riverscape connectivity is also better

Table 1 continued

Class	Level	Landscape metrics	Equation	Ecological meaning
Riverscape composition	Patch area (class level)	Percent of landscape (PLAND)	$\frac{\sum_{j=1}^{n} a_{ij}}{A} \times 100$	It calculates the proportion of different land cover types within the total landscape area to identify the dominant landscape type. A patch area percentage approaching zero signifies a decline in that particular patch type within the landscape. Conversely, a ratio of 100 indicates that the entire landscape consists exclusively of a single patch type

A: total landscape area (m^2)

a_{ij}: area (m^2) of patch *ij*

a_{ij}^*: area of patch *ij* in terms of number of cells

a_{ijs}: area (m^2) of patch *ijs* within specified neighborhood (m) of patch *ij*

E: total length (m) of edge in landscape

g_{ik}: number of adjacencies (joins) between pixels of patch types (classes) *i* and *k* based on the *double-count* method

h_{ij}: distance (m) from patch *ij* to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center

h_{ijs}: distance (m) between patch *ijs* and patch *ijs*, based on patch edge-to-edge distance, computed from cell center to cell center

m: number of patch types (classes) present in the landscape, including the landscape border if present

n_i: number of patches in the landscape of patch type (class) *i*

N: total number of patches in the landscape

P_i: proportion of the landscape occupied by patch type (class) *i*

P_{ij}: perimeter (m) of patch *ij*

P_{ij}^*: perimeter of patch *ij* in terms of number of cell surfaces

Z: total number of cells in the landscape

Table 2 Data source

Data name	Data source
Regional land-use data	The earth science and engineering data sharing service system platform[1]
River basin boundaries and river networks	The HydroSHEDS database[2]
Geographical distribution data of the three river basins integrated with information	The global dam (GOODD) and the global reservoir and dam database (GRanD)[3]
Demographic data for areas along the three rivers	The WorldPop[4]
Meteorological data	The climate research unit (CRU) (Harris et al. 2020)

[1] https://data.casearth.cn/.

[2] https://www.hydrosheds.org/.

[3] https://www.globaldamwatch.org/.

[4] https://hub.worldpop.org/.

Antônio Dam-affected region and the Aswan Dam-affected region, whereas both significantly differ from the Three Gorges Dam-affected region.

At the dam site (sample site 5), the differences in riverscape configuration fragmentation among the three dam-affected areas are minimal ($P < 0.05$) (Fig. 2b). Along the 800 km stretch of river selected in the flow direction, the differences among the upstream and midstream sections are relatively small; however, in the downstream sections, particularly at sample sites 7 and 8, the differences in riverscape configuration are more pronounced. Notably, the upstream region of the Three Gorges Dam exhibits a higher mean RFIOCF (1.116) than the midstream and downstream areas, indicating the most significant degree of landscape configuration fragmentation. The highest RFIOCF value is not found in the buffer area of sample site 5, where the dam is constructed, but rather in the buffer area of sample site 6.

The RFIOCF of the three rivers affected by dam construction decreases with the increase in the buffer radius of the sample sites (Fig. 2c). Moreover, at buffer radii of 28 and 29 km, there were no significant differences in riverscape configuration among the three regions ($P < 0.05$). Within a buffer radius of 5 to 15 km, the RFIOCF values of the three dam-affected areas exhibit considerable variability, followed by a stable downward trend beyond 15 km. Overall, the RFIOCF values of the Aswan High Dam-affected region fluctuate the most with changes in radii.

Similarity in riverscape configurations and composition across the three dammed rivers

The differences in riverscape configuration among the three dam-impacted rivers from 1985 to 2020 were evaluated using the R-value from ANOSIM analysis. The results indicate that over the 35-year period, the R-value decreased by 0.116, suggesting that the riverscape configurations of the three dam-affected areas are becoming increasingly similar (Fig. 3a). The R-value approaching zero indicates less difference between groups. The most significant decrease in the R-value occurred between 2000 and 2005, dropping from 0.153 to 0.106, a decline of 30.72%. Additionally, from 1990 to 1995, the R-value decreased by 13.61%. Considering 2000 as a pivotal point, the rate of R-value changes before 2000 was 26.79%, whereas after 2000, particularly from 2005 to 2020, the rate of change slowed to 12.26%. We also analyzed the similarity of riverscape composition between different groups in river sections affected by dams and found that over the 35-year study period, the differences in riverscape composition decreased by 9.24%, mirroring the trend in increasing similarity of riverscape configurations across the three regions. The greatest reduction occurred between 1995 and 2000, with a decrease of 3.68% ($P < 0.05$).

A comprehensive ANOSIM analysis was performed utilizing 11 riverscape configuration metrics across 9 distinct sampling sites, strategically located along separate reaches of the river. The analysis incorporated a temporal comparison of R difference (ΔR) from 1985 to 2020 across the upper, middle, and lower river reaches ($P < 0.05$) (Fig. 3b). Results indicated that the middle reaches, particularly those proximal to dam construction locations, demonstrated the highest similarity in configuration among the three river segments. The upper reaches of the affected regions displayed the next highest similarity in configuration.

In the middle reaches, a ΔR of 0.377 was observed between the regions impacted by the Jirau & Santo Antônio dams and those affected by the Three Gorges Dam. This contrasts with a ΔR of 0.360 between the regions impacted by the Jirau & Santo Antônio dams and the Aswan High Dam. Notably, the ΔR between the Three Gorges Dam and Aswan High Dam regions was significantly lower, at 0.022,

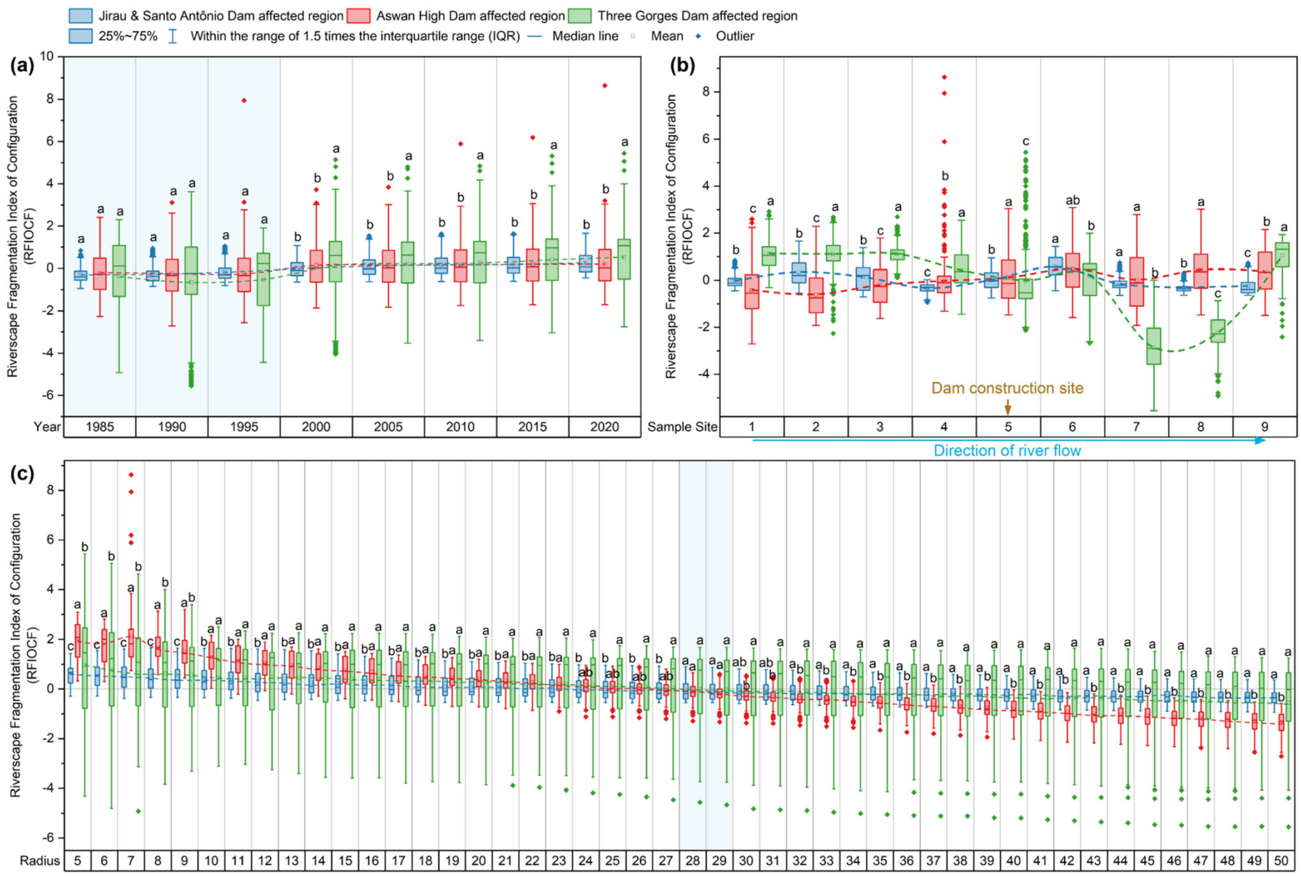

Fig. 2 The box plots illustrate the River Fragmentation Index of Coastal Fragmentation (RFIOCF) across three different regions, analyzed by year (**a**), by sample point (**b**), and by buffer radius (**c**). All these analyses employ the Kruskal–Wallis test to determine significance, with $P < 0.05$ considered statistically significant. Furthermore, to explore the differences in RFIOCF among the three regions, a Dunn–Bonferroni post hoc test was used for pairwise comparisons, where different lowercase letters indicate significant differences in these comparisons. If the background of the box plot is blue, it indicates that there is no significant difference in RFIOCF among the three regions for that year, sample point, or buffer radius. Note the different scaling of the y-axes

reflecting a reduction of 94.16% compared to the ΔR between the Jirau & Santo Antônio and Three Gorges Dam regions. In the upper reaches, the ΔR between the Jirau & Santo Antônio dams and the Three Gorges Dam regions was recorded at 0.258, compared to 0.292 between the Jirau & Santo Antônio and Aswan High Dam regions. Conversely, the ΔR between the Three Gorges Dam and Aswan High Dam regions exhibited a negative value of − 0.084, indicative of a divergent trend in riverscape configuration. In the lower reaches, the ΔR between the Jirau & Santo Antônio dams and the Aswan High Dam-impacted regions was the lowest, marked at − 0.128. In contrast, the ΔR increased to 0.176 between the Jirau & Santo Antônio and Three Gorges Dam regions, representing an increase of 0.134 over the ΔR between the Jirau & Santo Antônio and Aswan High Dam regions, with statistical significance ($P < 0.05$).

Similarity analyses of the riverscape composition at the corresponding sites of any two rivers showed that ΔR was greatest at between the Jirau & Santo Antônio Dam region and Three Gorges Dam region (i.e., the sampling site 5) (Table 3). And similarity of riverscape composition increased the most at the two sampling sites located at the dams, with statistical significance ($P < 0.05$).

Screening the contributors to the similarities in landscape configuration and composition

The influence of different landscape metrics on the similarity of river landscape configuration in the three-dam region varies (Fig. 4a). The cumulative contribution of eight metrics—PROX_MN, EN_MN, COHESION, CONTAG, LPI, AREA_MN, ED, AND SHAPE_AM—accounts for 90%. Notably, during the study period, PROX_MN exhibited the most significant impact on river landscape similarity, with an average contribution rate of 32.36%. EN_MN follows closely, with an average contribution rate of 19.38%. Additionally, at sampling sites 5 and 6, the contribution rates of the PROX_MN and AREA_MN indices to the similarity of river landscape configuration

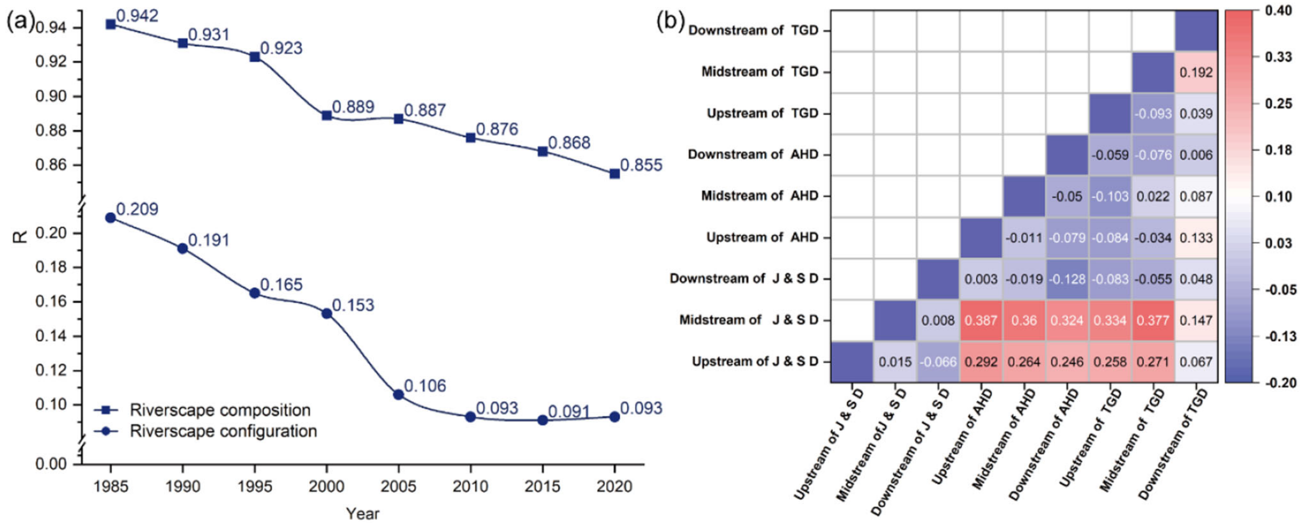

Fig. 3 **a** The dynamics of R-value of three dammed rivers was analyzed based on ANOSIM ($P < 0.05$). Note: If $R > 0$, it means that the difference between the groups is greater than the difference within the groups, and vice versa, the difference within the groups is greater than the difference between the groups, and if $R = 0$, it means that there is no difference between the groups. That is, the higher the R-value, the greater the dissimilarity of the riverscape configurations. **b** The differences in riverscape configuration similarity (ΔR) between any two rivers in the upper, middle, and lower reaches from 1985 to 2020. Note: J&SD indicates the Jirau Dam & Santo Antônio Dam-affected region, AHD indicates the Aswan High Dam-affected region, and TGD indicates the Three Gorges Dam-affected region ($P < 0.05$). If the value of $\triangle R$ is positive, it indicates that the riverine landscape configuration between the two regions has become more similar following the construction of the dam, signifying homogenization. Conversely, if the value of $\triangle R$ is negative, it suggests that the riverine landscape configuration between the two regions has become more distinct, indicating differentiation

Table 3 Mean difference in R ($\triangle R$) from 1985 to 2020 at each sampling site of any two dammed rivers

Rivers	Sites								
	1	2	3	4	5	6	7	8	9
J&SD and AHD	0	0.001	0	0	0	0	0	0	0
J&D and TGD	0	0.002	0	0	0.17	0	0	0	0
AHD and TGD	0	0	0	0	0	0	0.018	0	0

J&SD indicates the Jirau Dam & Santo Antônio Dam-affected region, AHD indicates the Aswan High Dam-affected region, and TGD indicates the Three Gorges Dam-affected region

across the three regions were substantially lower compared to their contributions at the other six sampling sites.

In terms of individual contributions, the PLAND index of forestland showed the highest impact on the similarity of riverscape compositions across the three dammed impact rivers during the study period, averaging 32.75% (Fig. 4b). This was 9.10% higher than the PLAND index of water. The contributions of the PLAND index of forestland and the PLAND index of water to the similarity of riverscape compositions have been gradually declining, with decreases of 8.34% and 2.58%, respectively, over the 35-year period. On the other hand, the PLAND index of farmland has shown a steady increase, with an average annual growth rate of 0.57% every five years.

Confirming the key drivers in influencing the similarities in riverscape configuration and composition

To identify potential factors influencing the similarity in configuration and composition of river landscapes, a preliminary analysis was conducted on the correlation between various landscape types and riverscape composition similarity using land-use data from a 50-km buffer

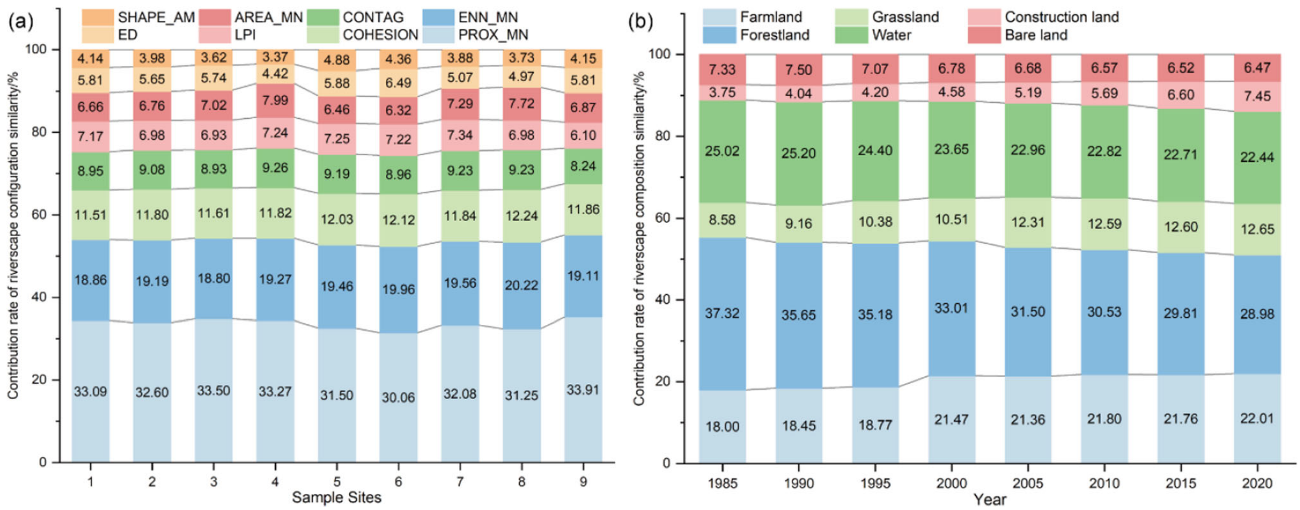

Fig. 4 **a** Utilizing SIMPER analysis, the differences in contribution rates of various riverscape configuration indices to the similarity of riverscape configuration fragmentation (RFIOCF) were examined. **b** Using SIMPER analysis, the differences in contribution rates of the PLAND index (percentage of landscape area index, indicating the proportion of various land-use types to the total area) for different land-use types to the similarity of riverscape composition were evaluated

radius zone around three rivers from 1985 to 2020. This analysis focused on a 50-km buffer radius around dams, as it is considered the optimal method for identifying statistically significant independent mesoscale effects (Fan et al. 2022).

In all cases, the similarity in riverscape configuration and composition was negatively correlated with the area of water bodies, as indicated by negative correlation coefficients (Table 3). This relationship was significant in the impact zones of the Jirau and Santo Antônio dams ($P < 0.05$), the Aswan High Dam ($P < 0.01$), and the Three Gorges Dam ($P < 0.01$). Additionally, the size of built-up land patches was also negatively correlated with the similarity in riverscape configuration and composition ($P < 0.01$).

The development of dam-associated riverscapes is influenced not only by internal compositional factors but also by external factors such as population and climatic conditions. Data on population density, annual rainfall, and annual mean temperature were focused on a 50-km buffer zone encompassing nine sample sites along the river sections. Research results indicate that changes in population density are among the primary factors influencing similarity (Table 4). However, the nature of this correlation (whether positive or negative) varies among the three rivers. In the regions of the Jirau, Santo Antônio, and Aswan High Dam-affected regions, population density showed a significant negative correlation with river landscape similarity ($P < 0.01$). In contrast, a significant positive correlation was observed in the Three Gorges Dam area ($P < 0.01$). Regarding climatic variables, a negative correlation was found between annual mean temperature and riverscape morphology in the Jirau, Santo Antônio, and Three Gorges Dam-affected regions ($P < 0.05$). However, this negative correlation did not reach significance in the Aswan High Dam impact region.

DISCUSSION

This study examined the configuration of riverscapes and their potential influencing factors—including riverscape composition, population density, and climatic conditions—across three major dammed rivers: the Aswan High Dam on the Nile River, the Three Gorges Dam on the Yangtze River, and the Jirau and Santo Antônio Dams in the Amazon Basin. Utilizing ANOSIM and SIMPER to analyze various landscape indices from 1985 to 2020 across regional, longitudinal, lateral, and temporal dimensions, we identified a global trend of increasing similarity in riverscape configurations among the dammed rivers. This trend was consistent with the similarity in riverscape composition across the three rivers and aligned with the RFIOCF trend in each river, supporting our initial research hypothesis. The similarity in riverscape configuration was primarily driven by riverscape fragmentation, triggered by the increase in built-up and water patch size. While forest, farmland, population density, and temperature also contributed to this trend in specific damming rivers, their effects varied across the three rivers. These findings underscore the necessity for localized watershed

Table 4 The Pearson correlation coefficient between the configuration and composition of riverscapes and potential natural and social factors

Factor	Similarity of riverscape configuration			Similarity of riverscape composition		
	J&SD	AHD	TGD	J&SD	AHD	TGD
Farmland	− 0.916**	− 0.925**	0.942**	− 0.982**	− 0.873**	.991**
Forestland	0.930**	− 0.887**	− 0.875**	0.913**	− 0.938**	− 0.922**
Grassland	− 0.829*	− 0.505	− 0.924**	− 0.716*	− 0.518	− 0.976**
Water	− 0.786*	− 0.891**	− 0.888**	− 0.801*	− 0.927**	− 0.924**
Built-up area	− 0.848**	− 0.840**	− 0.897**	− 0.901**	− 0.904**	− 0.945**
Unused land	− 0.856**	0.899**	− 0.909**	− 0.951**	0.929**	− 0.982**
Annual precipitation	0.304	0.108	− 0.709*	0.209	0.173	− 0.844**
Annual mean temperature	− 0.851**	− 0.699	− 0.878**	− 0.783*	− 0.541	− 0.859**
Density of population	− 0.962**	− 0.870**	0.864**	− 0.964**	− 0.926**	0.910**

(J&SD indicates the Jirau Dam & Santo Antônio Dam-affected region, AHD indicates the Jirau Dam & Santo Antônio Dam-affected region, and TGD indicates the Three Gorges Dam-affected region)

**Indicates $p < 0.01$, *indicates $p < 0.05$

management to restore the unique characteristics of riverscapes in different regions.

Resemblance of riverscape configurations across the major dammed rivers

Framed within the context of the Environmental Convergence Hypothesis, the resemblance of riverscapes and their flow patterns across dammed rivers has emerged as a significant phenomenon, as highlighted by studies such as Moyle and Mount (2007). This resemblance pertains to the increasing similarities not only in riverscape configurations but also in compositions across various global dammed river systems. These similarities may be driven by factors such as altered hydrological regimes (Peñas and Barquín 2019), sediment transport (Kondolf et al. 2014), and biodiversity changes (Williams 1997) due to damming, as well as the societal influences identified in this study. These collective influences modify vegetation patterns, reduce habitat heterogeneity, and alter river morphology, suggesting a predictable ecological change pattern following river damming.

During the period spanning 2000 to 2005, large-scale infrastructure development and urban expansion occurred in regions such as the Brazilian Amazon, the Yangtze River basin in China, and the Nile River basin, largely driven by economic growth and globalization (Sun et al. 2020; Mahtta et al. 2022). These activities often culminated in analogous land-use patterns (e.g., intensified urbanization or expanded croplands), accelerating the convergence of landscape configurations among distinct river basins. Around 2000, numerous major construction projects also reached critical implementation or adjustment stages, sparking the introduction of policies concerning resettlement, agricultural development, and ecological restoration (Liu et al. 2020). Such measures typically resulted in similar pathways of landscape transformation—such as concentrated reforestation or extensive water infrastructure expansions—thereby reducing dissimilarities across previously divergent river systems. The consequence was a phase of rapid convergence in landscape configurations, followed by a relatively stable period once these transformations were well established. For instance, during the construction of the Three Gorges Dam (Fig. 5c), significant landscape fragmentation occurred, largely due to massive relocations and land-use changes in the area, coinciding with China's economic reforms that transformed arable land into forest land. Similarly, during the construction phases of the Santo Antônio and Jirau dams (Fig. 5a), there was a 46.85% increase in the riverscape fragmentation index of configuration (RFIOCF) (Fig. 2a), exacerbated by population displacements, new settlements (Simão and Athayde 2016), crop destruction (Medeiros et al. 2023), fisheries decline (Santos et al. 2018), and deforestation (Oliveira et al. 2021). These activities not only transformed the local landscapes but also contributed to a pattern of homogenization in landscape changes associated with dam construction, underlining the profound and similar impacts of human activities on natural river systems across different regions.

Secondly, we observed that the Jirau & Santo Antônio dam area exhibits a high degree of similarity with both the Three Gorges Dam region (ΔR = 0.377) and the Aswan High Dam region (ΔR = 0.36). By contrast, the ΔR between the Three Gorges Dam and the Aswan High Dam regions is noticeably lower.

This discrepancy may stem from the different biogeographical zones in which these areas are located. Landscape configuration, as defined by McGarigal and Marks (1995), reflects the physical distribution, spatial patterns, and interrelationships of landscape patches. In the Jirau &

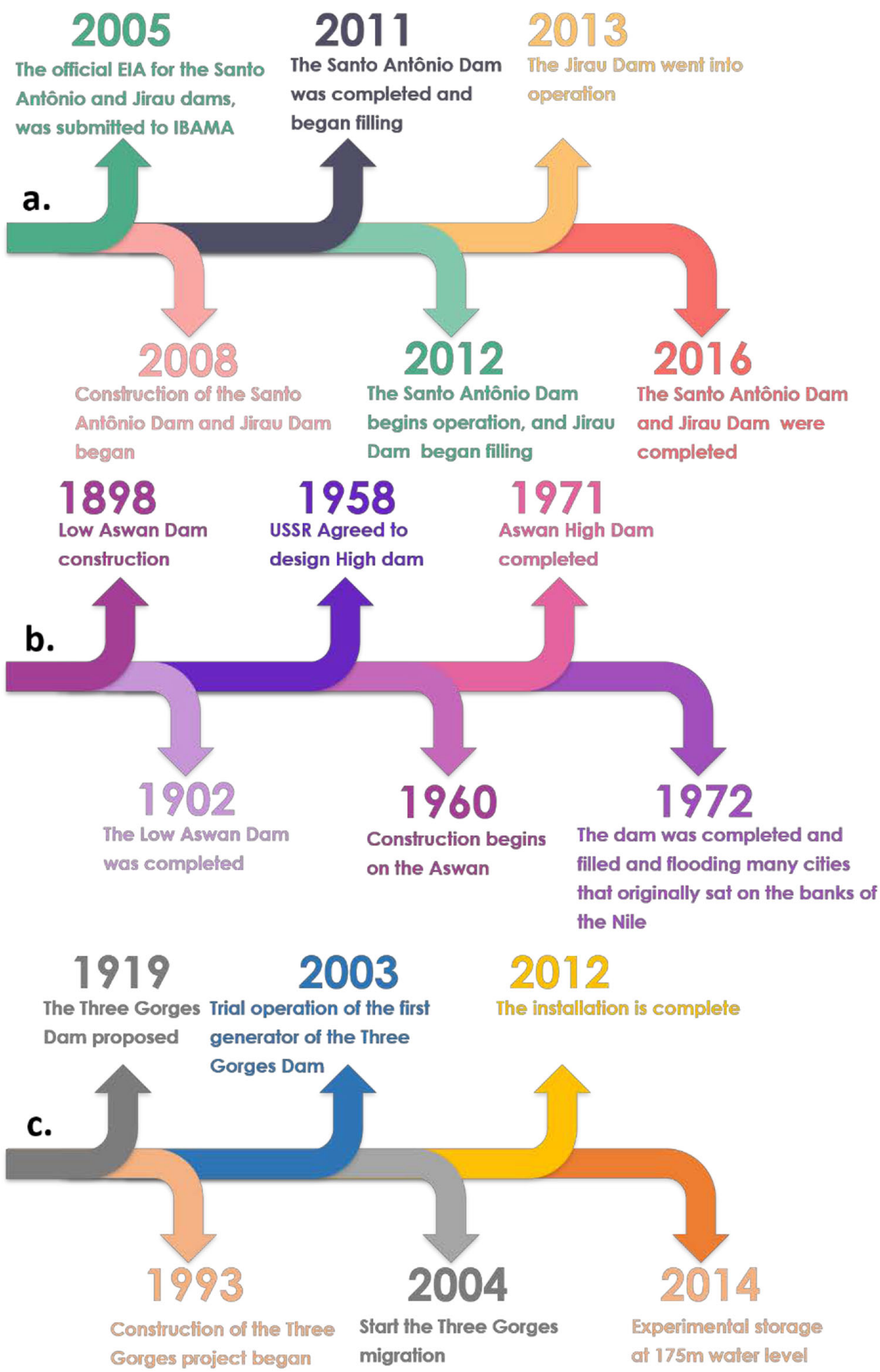

Fig. 5 Timeline of the constructions of the three river dams. **a** the Jirau Dam and Santo Antônio Dam construction timeline; **b** the Aswan High Dam construction timeline; **c** the Three Gorges Dam construction timeline

Santo Antônio dam region, the predominant vegetation is tropical rainforest, whereas the Aswan High Dam region encompasses subtropical desert, grassland, and tropical desert zones. Because these latter zones feature relatively simpler vegetation types, their patch arrangements tend to be more alike, thereby increasing overall similarity.

By contrast, the Three Gorges Dam region lies within a subtropical evergreen broadleaf forest zone, which supports a more complex vegetation mix than the other two locations (Sun et al. 2024). It also contains comparatively larger proportions of farmland and forest, which further distinguishes its patch composition from that of the Jirau & Santo Antônio area. Meanwhile, significant variations in patch types and proportions—along with different landscape patch arrangements—explain the lower ΔR value when comparing the Three Gorges Dam region and the Aswan High Dam region.

Moreover, the general configuration pattern demonstrated a dam-distance effect, implying that the observed similarities in riverscape configurations might be influenced by proximity to the dam. The analysis of the RFIOCF in relation to the buffer radius around the dams reveals a pattern that can be linked to the resemblance in riverscape configurations. As the RFIOCF decreases with increasing distance from the dam, it indicates a diminishing impact of the dam on the surrounding landscape. The observation that the RFIOCF stabilizes after 15 km and the identification of a maximal effective scale around 20 km suggest a common threshold distance within which dams influence riverscapes. This pattern of landscape fragmentation decreasing with distance from the dam, and stabilizing at a certain point, supports the concept of riverscape similarity by demonstrating a consistent and predictable response in riverscape structures across different dammed river systems. These data aid in understanding how dams similarly affect their adjacent landscapes, providing a basis for comparative studies on riverscape resemblance globally.

Urbanization appears as a key to resemble the riverscapes

The findings of this research underscore a notable trend in the similarity of riverscape configurations across three major dammed rivers. This trend could be significantly influenced by urbanization processes, including increased population migrations, expansion of built-up areas, and transformations in water land-use types, all of which are common indicators of urbanization. Furthermore, as shown in Fig. 4b, the contribution rate of built-up area changes to landscape composition similarity increased by 98%.Urban development, particularly the expansion of built-up areas near dammed rivers, plays a crucial role in shaping the landscape (Rufin et al. 2019; Tikuye et al. 2023). As cities expand, they often encroach on natural landscapes, leading to a decrease in landscape connectivity. This disconnectivity is a key driver in the similarity of riverscape configurations observed across the studied dams. The increase in built-up areas typically results in more uniform land-use patterns, which contribute to the homogenization of the landscape. Previous studies have revealed that urbanization, through mechanisms such as increased built-up areas and altered watershed land use, has a profound impact on riverscape configurations. For instance, research by Wang et al. (2021) observed similar trends in the Yangtze Basin, where urbanization linked to dam construction led to significant landscape fragmentation and homogenization.

It can also be argued that the process of urbanization fundamentally alters the structure and function of natural riverscapes (Fang et al. 2021). Urban sprawl, characterized by the outward spread of a city's population and infrastructure, typically leads to the conversion of natural watershed ecosystems into urban or suburban areas (Dadashpoor and Shahhossein 2024). This transformation disrupts natural connectivity and increases the prevalence of uniform, human-designed environments. As these built-up areas expand and watershed land-use patterns change to accommodate urban needs, the resulting riverscapes begin to resemble one another more closely. This homogenization effect is evident across various dammed riverscapes, suggesting that the urbanization process imposes a consistent and recognizable imprint on riverscape configurations globally.

Moreover, the reasons behind these results are multifaceted. Urbanization increases population density, which in turn exerts pressure on local resources, including land and water. This pressure often leads to changes in land use from natural or agricultural landscapes to urban and industrial uses, thus reducing heterogeneity. Additionally, the thermal effect of urban areas can alter local climates, further influencing ecological patterns and processes. These changes are exacerbated by the presence of dams, which themselves are agents of landscape and hydrological change. However, population migration can vary depending on different political regimes. In this study, the variation is attributed to the extensive migration prompted by the construction of the Three Gorges Dam in China, which caused a significant population shift from within the 50-km buffer zone to cities further downstream, such as Shanghai and Jiangsu (Hwang et al. 2021). Consequently, this led to a decreasing population density trend in the area (Fig. 6c), a phenomenon also linked to urbanization. Therefore, the resemblance of riverscape configurations across the studied dammed rivers could be largely a consequence of urbanization processes. The increase in built-up areas and changes in watershed land use, coupled with demographic shift, contribute to a pattern of riverscape homogenization. Understanding these dynamics is crucial for planning and managing the ecological impacts of urbanization and dam construction on riverscapes. Future research should focus on mitigating these impacts through sustainable urban planning and dam management practices that prioritize ecological and landscape connectivity.

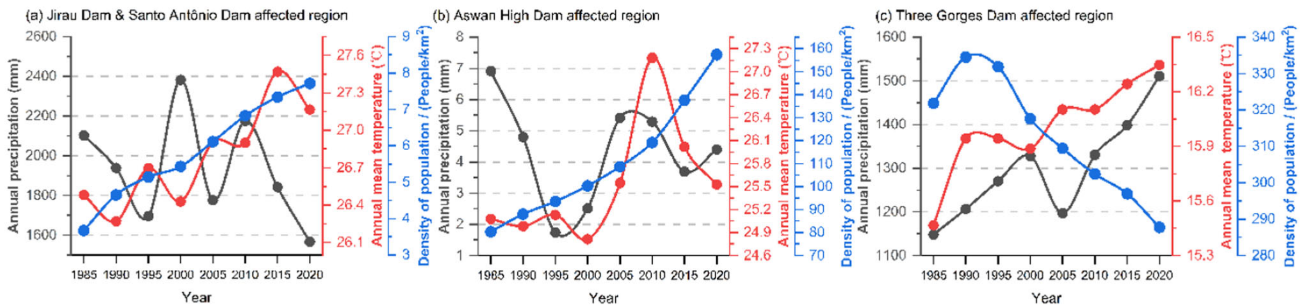

Fig. 6 Temporal variations in annual precipitation, annual mean temperature, and population density within a 50-km buffer zone of three rivers along an 800-km river stretch, including 9 sampling sites

However, it is essential to consider other influential factors such as agricultural expansion and deforestation. Results from the SIMPER analysis reveal that, besides forests and water bodies, agricultural land accounts for the greatest mean contribution over time (Fig. 4b). Because agricultural expansion and deforestation replace diverse natural habitats with uniform croplands—thereby causing habitat fragmentation—these processes present considerable challenges for preserving natural landscapes (Lee et al. 2015). Global statistics indicate that roughly 90% of deforestation results from agricultural development (Ma et al. 2022), further encroaching on natural habitats. Meanwhile, socioeconomic factors—such as market demand for agricultural products, infrastructure development policies, and evolving land-use regulations—sustain this homogenization trend (Turner and Stiller 2020; Chardon et al. 2022). Taken together, these interconnected drivers underscore the need for integrated management strategies that balance human development with the mitigation of adverse effects on riverscapes. By recognizing how settlement distribution, agricultural practices, and broader socioeconomic transformations collectively reshape these environments, policymakers can propose more effective measures to counteract the ecological consequences of dam construction and urban expansion, ultimately preserving habitat connectivity and biodiversity.

Climatic change may enhance resemble riverscapes

The analysis of riverscape configurations across the three dammed rivers reveals that climatic changes—particularly rising temperatures—exert a significant influence on the observed homogenization of landscape patterns. These climatic factors do not operate in isolation; rather, their effects are amplified by anthropogenic activities, including urban expansion and modifications in waterbody land use. Such activities not only respond to climate change but also intensify it, thereby accelerating the processes of pattern standardization and homogenization in riverscapes.

Temperature increases have been identified as pivotal in reshaping river systems by affecting aquatic ecosystems and sediment transport (Milly et al. 2005). For example, heightened evaporation rates associated with warmer conditions can alter both water levels and flow patterns in dammed rivers, resulting in an overall convergence of landscape configurations across different regions. These hydrological changes mirror the broader trends documented by Whited et al. (2007), who similarly observed how climate fluctuations influence river hydrology and landscape structure.

Urbanization further compounds these climatic pressures. Built-up areas are prone to the heat island effect (Liu et al. 2024), which locally raises air temperatures, influences precipitation patterns, and interacts with dam-induced hydrological alterations. This compounding effect promotes increasingly uniform modes of water use, thereby amplifying the homogenization of riverscapes across multiple basins.

It is essential to recognize that the relationship between climate change and human interventions is not linear, but governed by dynamic feedback loops (Turner et al. 2007). As population densities in riverine urban zones expand, mounting demands on water resources and space have led to large-scale engineering projects such as dam and reservoir construction. These projects, in turn, can reinforce regional climate warming by modifying surface albedo, intensifying heat retention, and altering atmospheric conditions. Consequently, the homogenization observed is driven by the interaction of natural climatic variability with anthropogenic land-use activities, underscoring the need for integrated strategies that address both drivers to preserve the ecological integrity of riverscapes.

Implications for localized riverscape managements

This study highlights the importance of managing dam landscapes globally to mitigate the trend of ecosystem homogenization. Firstly, the impact of climate change on riverine ecosystems is becoming increasingly significant, making the implementation of adaptive management plans at the local level crucial. These management plans should be dynamic, allowing adjustments based on the latest climate predictions and ecological monitoring data to ensure their effectiveness and foresight. Additionally, these plans should align with the goals of the "Kunming-Montreal Global Biodiversity Framework" (GBF) under the Convention on Biological Diversity (Nicholson et al. 2021). Because landscape connectivity will promote the degree of species movement, gene exchange, birth spread, and metapopulation dynamics (Papazekou et al. 2022), specifically, Goal 14 emphasizes the integration of biodiversity and its multiple values into policies, regulations, planning, and development processes, which necessitates conducting biodiversity impact assessments for dam construction and implementing measures to mitigate negative impacts. Goal 15 encourages businesses to evaluate, disclose, and reduce biodiversity-related risks and negative impacts, which also applies to dam operations. Therefore, management practices should prioritize the integrity of ecosystems and the maintenance of biodiversity by restoring natural habitats, protecting endangered species, and promoting the sustainable use of ecosystem services. This approach not only aids in protecting and restoring natural ecosystems but also achieves a comprehensive consideration and balance of biodiversity conservation goals in dam construction and operation.

Secondly, localized land-use planning should prioritize enhancing green infrastructure to reduce the fragmentation of riverine landscapes. This involves integrating natural elements such as permeable pavements, green roofs, and riparian buffers into urban and suburban areas to promote habitat connectivity and create ecological corridors. Regarding the affected area of the Jirau Dam in the Amazon basin, it is crucial to ensure the restoration of tropical rainforests and the protection of endangered species, supported by the development of ecotourism and sustainable agriculture to facilitate local economic transition. For the Aswan High Dam on the Nile, comprehensive canal and wetland management is necessary to restore biodiversity, alongside cross-border cooperation to ensure fair distribution and use of water resources. The Three Gorges Dam in the Yangtze River basin requires the expansion of upstream nature reserves and the construction of fish migration channels, while also promoting sustainable development plans for downstream economic zones. Each region can be spatially integrated to achieve comprehensive management between upstream and downstream, and left and right banks, thereby promoting sustainable ecological, economic, and social development (Jia et al. 2024).

Additionally, people-centered social policies are vital as they allow communities the freedom to choose among ecosystem services and promote unrestricted migration, thus supporting the unique cultural well-being of different riverine landscapes. This principle is particularly important in the Jirau, Aswan, and Three Gorges areas, where it is essential to respect the cultures of indigenous and traditional communities and incorporate their knowledge and experience to support biodiversity conservation. Implementing economic incentive mechanisms, such as ecological compensation and payments for ecosystem services, can encourage community participation in conservation efforts.

Finally, implementing Integrated River Basin Management (IRBM) at the local level is essential (Han et al. 2023). IRBM should involve comprehensive and adaptive planning that considers entire river basins, balancing ecological, social, and economic needs in the local context. This management approach needs to incorporate specific indicators from the Global Biodiversity Framework, with active stakeholder participation to ensure the integration of opinions from local communities, environmental groups, and industry representatives, thereby achieving broad synergy of interests and knowledge. Specific actions to reduce homogenization trends include promoting diverse habitat restoration projects, localized hydrological adjustments, and tailored river landscape management practices.

By adopting IRBM strategies focused on site-specific strategies and collaborative governance, we can maintain each river landscape's unique ecological characteristics and cultural identity in the face of environmental changes, ultimately preserving their uniqueness and resilience. Furthermore, aligning these strategies with the United Nations 2030 Agenda for Sustainable Development Goals (SDGs) (Jahani Chehrehbargh et al. 2024) by localizing the SDGs to fit sub-national contexts further strengthens river landscape management. The localized 2030 Agenda empowers local and regional governments to promote inclusive and sustainable development (Bennich et al. 2023). By incorporating the principles of the 2030 Agenda, adaptive management plans, localized land-use strategies, people-centered policies, and IRBM receive additional support. This integration ensures sustainable development and environmental management reflect local priorities and resources, enhancing the ecological and cultural resilience of river landscapes in the face of global changes.

CONCLUSION

Across the rivers studied, riverscapes are continuously evolving due to the ongoing effects of dam construction, resulting in the emergence of new riverscape patterns. Our research indicates that these altered riverscape structures are becoming more resembling globally, influenced by factors such as climate conditions, proximity to the dam, and both direct and indirect human activities. In conclusion, we determined that:

(1) Resemblance of riverscapes: The resemblance in riverscape configurations across different regions suggests a trend toward riverscape homogenization. This can lead to reduced ecological complexity, which is crucial for maintaining ecosystem services such as water purification, flood regulation, and habitat provision.
(2) Fragmentation and connectivity loss: The building of dams frequently leads to the fragmentation of habitats, which is a primary factor in creating similar riverscape patterns. This disruption of ecological connectivity impedes the movement of species, potentially curtailing genetic exchange and diminishing the ability of species to adapt to environmental changes.
(3) Impact of urbanization and population migration: The expansion of urban areas and modifications to water land use due to dam building and demographic shifts signify urbanization, which results in considerable changes to watershed environments. Such transformations are the key drivers to resemble the riverscape configurations.
(4) Temperature increases: Rising temperatures may further enhance the resemblance of riverscape configurations. This trend can be exacerbated by human activities such as increased built-up areas and changes in water land use, which are themselves influenced by and contribute to climatic shifts.

Moreover, the study highlights the profound impact of human activities, particularly dam construction and associated urbanization, on shaping watershed ecosystems. These activities not only modify physical riverscapes but also influence biological and climatic conditions within the watershed. To sustain the health and functionality of these ecosystems, it is crucial to maintain their ecological complexity. This can be achieved by preserving a variety of land uses and ensuring connectivity across landscapes to support diverse species and ecological processes.

Finally, watershed management plans must include adaptive measures to address the impacts of climate variability. This involves enhancing the resilience of watershed ecosystems to withstand climate stresses and human activities. Achieving these goals requires localized strategies that consider the unique conditions and needs of each watershed. These strategies should incorporate and build upon local knowledge and resources, while aligning with global sustainable development goals. By implementing localized approaches, the challenges posed by climate change can be more effectively mitigated, thereby ensuring the continued health and functionality of watershed ecosystems.

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Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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