Human-induced changes in South American sediment fluxes from 1984 to 2019

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Abstract

Sediment flows dynamics (erosion, transport and deposition) have been disrupted in South America (SA), a continent with the highest erosion and sediment transport rates globally. However, the magnitude and spatial distribution of the main drivers of changes have been poorly identified and explored. Here, we performed simulations using a hydrological-hydrodynamic-sediment model to comprehensively estimate the spatial and temporal sediment changes and trends in SA from 1984 to 2019. We found that 51% of the main SA rivers experienced significant changes in simulated sediment transport (QST) over this period, with 36% due to Amazon deforestation and river damming and 15% due to precipitation changes. We also estimated a 10% reduction in the average sediment delivery to the oceans. Deforestation was responsible for QST changes above 80% in some Amazon sites, and hydropower expansion led to a greater reduction of sediment flows (as high as 80-100%) in the Tocantins, Uruguay, Upper Paraná, lower São Francisco, Desaguadero, and Negro rivers. In addition, our results suggest that reservoirs built in the Amazon region in the last decade are also affecting sediment transport. Our modeling outputs provide unprecedented information about the status of sediment dynamics in SA, and a means to develop evidence-based strategies and transboundary policies related to continental-wide sediment dynamics and the conservation and restoration of ecosystems.

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Key Points:

- Comprehensive analysis of sediment flows changes in SA over the last 36 years
- 51% of the main SA rivers have undergone significant changes
- Amazon deforestation and river damming are the main responsible for changes

Abstract

Sediment flows dynamics (erosion, transport and deposition) have been disrupted in South America (SA), a continent with the highest erosion and sediment transport rates globally. However, the magnitude and spatial distribution of the main drivers of changes have been poorly identified and explored. Here, we performed simulations using a hydrological-hydrodynamic-sediment model to comprehensively estimate the spatial and temporal sediment changes and trends in SA from 1984 to 2019. We found that 51% of the main SA rivers experienced significant changes in simulated sediment transport (QST) over this period, with 36% due to Amazon deforestation and river damming and 15% due to precipitation changes. We also estimated a 10% reduction in the average sediment delivery to the oceans. Deforestation was responsible for QST changes above 80% in some Amazon sites, and hydropower expansion led to a greater reduction of sediment flows (as high as 80-100%) in the Tocantins, Uruguay, Upper Paraná, lower São Francisco, Desaguadero, and Negro rivers. In addition, our results suggest that reservoirs built in the Amazon region in the last decade are also affecting sediment transport. Our modeling outputs provide unprecedented information about the status of sediment dynamics in SA, and a means to develop evidence-based strategies and transboundary policies related to continental-wide sediment dynamics and the conservation and restoration of ecosystems.

Keywords: Sediment transport, large-scale modeling, reservoir, land use.

1 Introduction

Sediment flows (erosion, transport and deposition) play an essential role providing social, economic, and environmental services. The surface flow, rich in organic and inorganic compounds, supports healthy agriculture and natural fertilization (Montanarella et al., 2016), provides nutrients for aquatic ecosystems (Best, 2019), and helps maintain the structural stability of rivers, shorelines, mangroves, and wetlands (Costanza et al., 1997; Ezcurra et al., 2019; Nagel et al., 2022). However, sediment flows (sand, silt and clay) have been considerably disrupted by accelerating human-induced erosion, sediment trapping in dams, and long-term changes in precipitation patterns (Ezcurra et al., 2019; Grill et al., 2019; Latrubesse et al., 2017; Quinton et al., 2010).

Over the last three decades, 60% of South America (SA) territory experienced land use and land cover changes (LULCC), with extensive areas converted into pastures, cropland, and tree plantations, mainly in the Chaco and Amazon ecosystems (Zalles et al., 2021). Over the same period, more than 100 large reservoirs were constructed, with a storage capacity of more than 400 billion cubic meters, affecting aquatic species throughout SA. The continent has more than 6,800 reservoirs (Mulligan et al., 2020), of which more than 340 are large reservoirs (Lehner et al., 2011). In addition, 1,300 hydroelectric generation reservoirs are under construction or planned in the continent (Zarfl et al., 2015), with 288 only in the Amazon region (Latrubesse et al., 2017). These numbers constantly change due to the new developments and environmental licensing procedures. In addition, several flood and drought events have been recorded in recent years (Cai et al., 2020), with increasing precipitation trends in the Amazon region and decreasing precipitation in Central Argentina and the Brazilian Northeast.

These ongoing changes can induce detrimental effects on SA ecosystems (e.g., Central Amazon floodplains and Pantanal), one of the world's richest locations in terms of above-ground, soil, and aquatic biodiversity (Albert et al., 2021; Barbarossa et al., 2020; Kemppinen et al., 2020). For example, unsustainable agricultural expansion requires more fertilizers(Borrelli et al., 2017), which can be responsible for both the water bodies eutrophication and damage to human health(Dissanayake and Chandrajith, 2009). In addition, the reservoirs storage capacity can be considerably reduced by aggradation, threatening the water supply (Wisser et al., 2010). In contrast, lower sediment delivery to the oceans can induce the erosion of coastal terrestrial ecosystems (Ezcurra et al., 2019). Also, floodplains and mangroves are very productive areas

(Costanza et al., 1997) that can be eroded by reducing sediment to the rivers, making them a source of carbon to the atmosphere instead of a sink (Ezcurra et al., 2019). Moreover, a disturbance in sediment flows can also affect the meander migration, generating social and economic damage to riverine communities (Nagel et al., 2022).

Therefore, it is essential to understand the magnitude of changes in sediment fluxes, their associated key drivers, and their role in mitigating ecosystem degradation effects. New insights are needed to narrow the knowledge gap for river sediment dynamics, especially for large geographical domains encompassing transboundary regions like SA river systems. However, the lack of observed data represents a major barrier to develop analyses for large scales (continental or global) that require long time series for many sites (Best, 2019). For these scales, no studies with in situ data have been found in the literature. The most notable work published recently used remote sensing data to show changes in global sediment fluxes (Dethier et al., 2022). However, this work did not show the climatic influence on sediment supply and focused on assessing changes at the mouths of major rivers. This approach does not provide a broad understanding of the sediment processes that occur in the basin. For example, it is known that the concentration of sediments at the mouth of the Amazon River tends to be higher than in upstream regions due to local processes such as resuspension (Fassoni-Andrade and Paiva, 2019). An isolated analysis of this process occurring at the mouth can lead to a misinterpretation of the processes occurring throughout the basin.

In this way, large-scale assessments of sediment fluxes are usually performed using global sediment transport models to characterize their spatial or temporal dynamics. These models were developed to estimate the impact of human activities on sediment delivery to the oceans (Syvitski et al., 2005), characterize rivers in terms of transported sediment loads (Cohen et al., 2013;

Pelletier, 2012), and assess regional trends and variabilities (Cohen et al., 2014). However, they do not typically attempt to understand the relative contributions of precipitation, dams, and LULCC on sediment fluxes. From the literature, we noted that most studies focused on describing changes in sediment fluxes by considering one or two of these drivers (Almagro et al., 2017; Diodato et al., 2020; Forsberg et al., 2017; Huang et al., 2020; Latrubesse et al., 2017; Syvitski et al., 2009; Vörösmarty et al., 2003; Wei et al., 2019), and few have provided detailed analyses on these changes (Huang et al., 2020; Wei et al., 2019). Some studies have performed integrated analyses with all the aforementioned drivers, but the information was presented for specific locations or with a broad perspective (Li et al., 2020; Macklin and Lewin, 2019).

This study provides the first comprehensive analysis of the spatiotemporal changes in sediment fluxes in SA over the last 36 years (1984 to 2019), accounting for changes in precipitation, dams, and land use and land cover (LULC). To pursue this goal, we simulated multiple scenarios with the continental-scale sediment model MGB-SED AS (acronym in Portuguese for 'Modelo de Grandes Bacias', Fagundes et al., 2021) using daily precipitation, eight LULC maps, and 234 large dams. In addition, relationships between these changes and impacts on ecosystems are presented. These simulations enabled us to isolate each driver's contribution and also to assess their combined effects on sediment flows.

2 Study area

South America (SA, Figure 1-A) is one of the continents with the highest erosion and sediment transport rates globally (Borrelli et al., 2017; Doetterl et al., 2012; Latrubesse et al., 2005), has a large biodiversity (Kemppinen et al., 2020), is one of the few regions having free-flowing rivers

(Grill et al., 2019), and contributes significantly to global food production (Sartori et al., 2019). Most of SA is located in tropical regions that have little interannual variability between sunrise and sunset and receive high solar incidence. The Intertropical Convergence Zone (ITCZ) directly influences the establishment of dry and rainy seasons; El Niño events; and the South Atlantic Convergence Zone (SACZ), which causes heavy precipitations in the summer. Annual precipitation variability is strong, with desert regions in Chile (0.05 to 10 mm/year, Bozkurt et al., n.d.) and very humid regions in Colombia (~10,000 mm/year, Latrubesse et al., 2005). The Amazon, Orinoco, Paraná and Magdalena rivers are the main sediment transporters, meaning 44%, 14%, 11% and 3%, respectively, of total South America sediment discharges values to the ocean (Fagundes et al., 2021). In addition, floodplains in SA has an important role in retaining 12% of total suspended sediment carried by the rivers (Fagundes et al., 2021).

However, the rapid expansion of agriculture on the continent (Figure 1-B) in recent decades (Song et al., 2018; Zalles et al., 2021) is accompanied by increasing erosion rates, directly affecting food production and the economy (Borrelli et al., 2017; Sartori et al., 2019). In addition, many existing reservoirs (Figure 1-C) have been reducing the sediment load in rivers and oceans (Syvitski et al., 2005), causing negative impacts in these regions (Syvitski et al., 2009). Nevertheless, the concern is even greater with SA planned reservoirs (see Figure S1 - Supporting Information S1), especially in the Amazon region, as they may dramatically affect river connectivity (Grill et al., 2019), sediment exchange between rivers and floodplains (Latrubesse et al., 2017), biodiversity (Albert et al., 2021; Barbarossa et al., 2020), fish migration (Forsberg et al., 2017), and deltas (Dunn et al., 2019). SA has also been showing changes in annual precipitation (Figure 1-D), with increasing trends in intense rainfalls in some regions (e.g. Amazon, Diodato et al., 2020), while others have experienced severe droughts in recent years (e.g. Northeast Brazil, Marengo et al., 2022).

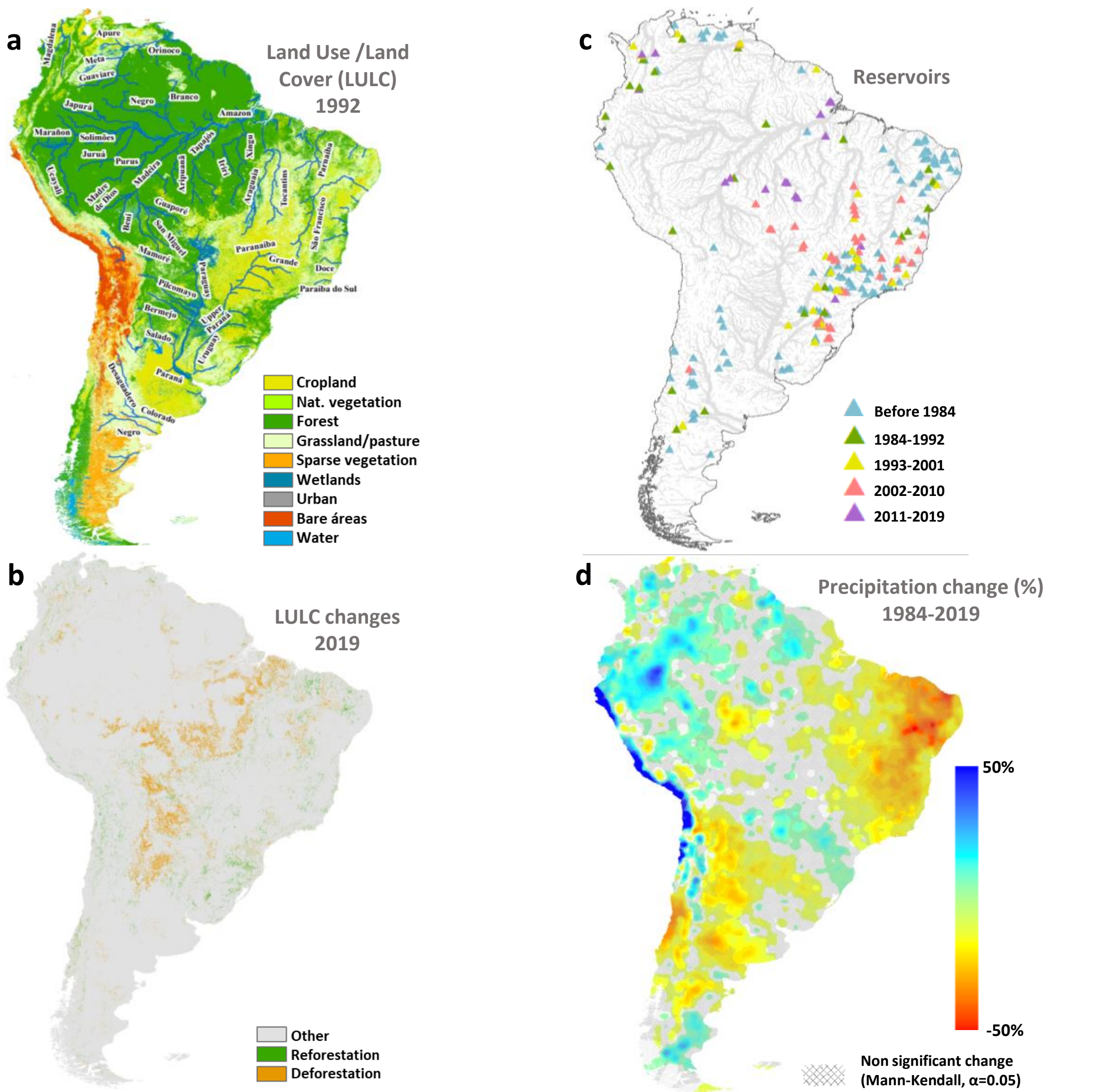

Figure 1. Overview of South America changes. a, main changes in land use/ land cover between 1992 and **b**, 2019, using LULC data from European Space Agency (http://www.esa-landcover-cci.org/). **c**, 234 large dams (storage capacity > 10^6m³) from Yigzaw dataset (see methods section), *Brazilian Water National Agency* and Brazilian *National Electric System Operator*. **d,** trends of precipitation changes from 1984 to 2019 using daily precipitation from the Multi-Source Weighted Ensemble Precipitation – MSWEP v1.1 dataset until 2014, and from 2015 onward using the NASA Global Precipitation Measurement Mission – GPM dataset.

3 Methods

3.1 Modeling South American hydrology and sediments: the MGB-SED AS model

The MGB-SED model results from the coupling of a sediment module (Buarque, 2015) with the MGB hydrological model (Collischonn et al., 2007; R. C. D. Paiva et al., 2011; Pontes et al., 2017).

This model has shown ability to simulate sediment erosion, transport and deposition at large scales (Fagundes et al., 2019, 2021, 2020; Föeger et al., 2022), and the hydrological module has been applied in many tropical watersheds to address different questions (Fleischmann et al., 2019a, 2018; R. C. D. Paiva et al., 2011; Pontes et al., 2017; Siqueira et al., 2018).

The MGB-SED AS model (Fagundes et al., 2021) was developed to investigate the spatial and temporal dynamics of suspended sediment flows in South America. This model resulted from the coupling between the sediment module and the hydrologic-hydrodynamic model MGB-SA, presented by Siqueira et al. (2018). According to Fagundes et al. (2021), this configuration was mainly chosen due: (i) MGB-SA is the first fully coupled hydrologic-hydrodynamic model, developed for regional scales, applied for SA's continental domain; and (ii) the model has a high temporal resolution (daily outputs) and was validated in most of SA using in situ and other sources of hydrological data, showing that hydrological variables were well represented (graphical and statistical analysis). Both MGB-SA (Siqueira et al., 2018) and MGB-SED AS (Fagundes et al., 2021) showed better performance to global models in simulate hydrological and sediment variables. The MGB-SED AS model (Fagundes et al., 2021) simulates suspended sediment flows for the medium to large South American (SA) rivers (river reaches with drainage areas larger than 1,000 km²). The model has a sediment module(Buarque, 2015) coupled to the MGB–SA hydrologic-hydrodynamic model (Siqueira et al., 2018). The main model's forcing variable is the daily precipitation and it was calibrated and validated in most continental areas using in situ data for both hydrological and sediment variables. The model is described in the following sections.

3.1.1 Hydrological-hydrodynamic module

The MGB-SA is a continental-scale hydrologic-hydrodynamic model developed for the South American domain (Siqueira et al., 2018). It uses simplified mathematical relations to describe runoff generation processes and physically based equations to compute evapotranspiration and channel routing processes. The main hydrological processes simulated by the model are (i) canopy interception; (ii) soil infiltration; (iii) evapotranspiration; (iv) routing of surface, subsurface, and groundwater runoff (hillslope routing); and (v) hydrodynamic propagation in river networks.

The model is discretized using a semi-distributed approach, where basins are divided into unit-catchments according to the underlying topography and a pre-defined river length, and further into Hydrological Response Units (HRUs) based on combinations of soil type and land cover. Vertical water balance and evapotranspiration (calculated with Penman-Monteith equation) are computed at the HRU level, and river routing is computed at the unit-catchment scale.

(Pontes et al., 2017)(Collischonn et al., 2007)(Kouwen et al., 1993)MGB–SA uses the local inertial equation (Bates et al., 2010) to route streamflow along the drainage network and to compute stored volume, flooded area, discharge, and river water levels. The water surface elevation is assumed homogeneous along a given unit-catchment. Recent works have assessed the impact of spatial discretization on MGB simulated variables and have shown that the effect on river discharges tends to be small compared with those on water level and flood extent (Fan et al., 2021a; Fleischmann et al., 2019b). Floodplains are represented as storage areas in which water can be lost through evaporation. Infiltration of floodplain water into the unsaturated soils is also computed. When compared with the full 1D Saint-Venant equations, the local inertial method is relatively simple as it has an explicit solution, and has been successfully applied to represent low-slope rivers and floodplain effects in flood inundation/river routing models with scales ranging from regional (Fleischmann et al., 2018; Getirana et al., 2017) to global (Yamazaki et al., 2013). On the other hand, it requires a smaller time step (typically 3-4 minutes) to avoid numerical instability, and has limitations to simulate river regimes with relatively high flow velocity as the advective inertia term – which is neglected in the local inertial model – may become important (Bates et al., 2010; Pontes et al., 2017, Fleischmann et al., 2018)

3.1.2 Sediment module

The sediment module is divided into basin, river, and floodplain modules. The basin module computes rill and interrill erosion of hillsides using the Modified Universal Soil Loss Equation (MUSLE – Equation 1)(Williams, 1975).

$$Sed = \alpha.\,(Q_{sur} * q_{peak} * A)^{\beta}.\,K.\,C.\,P.\,LS_{2D} \tag{1}$$

where Sed [t/day] is the sediment yield, Q_{sur} [mm/day] is the specific runoff volume, q_{peak} [m³/s] is the peak runoff rate, A [ha] is the unit-catchment area, K [0.013 · t · m² · h/m³ · t · cm] is the soil erodibility factor, C [dimensionless] is the cover and management practices factor, P[dimensionless] is the conservation practices factor, LS_{2D} [dimensionless] is a bidimensional topographic factor, and α and β are the equation fit coefficients, with values originally estimated at 11.8 and 0.56 (Williams, 1975), respectively. We used the same parameter values set for the first application of the MGB-SED AS model (Fagundes et al., 2021).

The sediment volume estimated by MUSLE is divided into three particle classes (sand, silt, and clay) and is discharged into the river through three linear reservoirs, that store these sedimentsIn the river drainage network, each of three sediment loads is routed from upstream to downstream. Fine loads (silt and clay) are routed using the 1D advection transport equation without the diffusion term, and the sediments are transported in suspension without deposition in the channel. Sands, considered bedload, are routed using the Exner sediment continuity equation and the Meyer-Peter and Müller transport capacity equation to quantify the channel's transport, erosion, or deposition (Buarque, 2015).

The characteristic diameters adopted for silt and clay particles were 0.016 mm and 0.001 mm, respectively. These assumed values have led to satisfactory results in a previous study (Fagundes et al., 2021). We began our simulations using a characteristic sand diameter value of 0.1 mm. However, because bedload has strongly heterogeneous characteristic diameters, especially when rivers with high and low slopes are compared, we developed an empirical equation to estimate the characteristic sand diameter. After an exhaustive search for South American bedload data in several journals and repositories (in Portuguese, Spanish, and English), we selected the D50 diameter from 14 river reaches (Carvalho, 2009; Fantin-Cruz et al., 2020; Filho, 2016; Latosinski et al., 2017; J. B. D. de Paiva et al., 2011; Paiva, 1988, 2007; Rizzardi, 2013; Strasser, 2008; Wiegand, 2009). We performed a unique regression (R^2=0.21) using D50 diameter against the slope ($Sl, m/km$) (estimated from a Digital Elevation Model - DEM), yielding Equation 2:

$$Dsand = 0.4476 Sl^{0.0776} \tag{2}$$

where $Dsand$ (m) is the characteristic diameter of sand for a specific river reach.

In the floodplain module, suspended sediment exchanges between rivers and floodplains are computed assuming that floodplains have a zero longitudinal velocity and complete mixing. These assumptions imply that concentrations of silt and clay are uniform in the vertical profile. Sediment deposition is computed using the fall velocity equation (Equation 3)(Wu and Wang, 2006). Sediments that are not deposited flow back to the main channel.

$$\omega_j = \frac{Mv}{Nd}\left[\sqrt{\frac{1}{4} + \left(\frac{4N}{3M^2} {D_{*,j}}^3\right)^{\frac{1}{np}}} - \frac{1}{2}\right]^{np} \tag{3}$$

where

$$M = 53.5e^{-0.65Sp} \tag{4}$$

$$N = 5.65e^{-2.5Sp} \tag{5}$$

$$np = 0.7 + 0.9Sp \tag{6}$$

$$D_{*,j} = d\left[\frac{\left(\frac{\rho_s}{\rho} - 1\right)g}{v^2}\right]^{\frac{1}{3}} \tag{7}$$

and where v is water kinematic viscosity (10^{-6} m²/s); Sp is the Corey shape factor, taken as 0.7 (WU, 2008); d[m] is the representative nominal diameter of the particle class; $D_{*,j}$ is the non-dimensional diameter for the j particle size; ρ_s/ρ is the sediment-specific gravity; and g is the gravity acceleration (9.8 m/s²).

3.1.3 Reservoir module

Within the MGB-SED AS model framework, the representation of reservoirs involves the regulation of water inflows at a given dam location and sediment trapping along the reservoir lake. These two aspects are detailed in the following two sections.

3.1.3.1 Water regulation by dams

The regulation effect of a given dam is simulated using an offline routine, i.e., the hydrodynamics of a given unit-catchment associated with a dam are replaced by a level-pool routine (lumped reservoir). Thus, the dam inflow is estimated as the inflow to that unit-catchment, using a uniform flow as the boundary condition for upstream unit-catchments with an average water slope estimated from the DEM. The dam level-storage relationship is obtained from national and global reservoir databases. Direct lake evaporation was also included and computed using the Penman equation (Shuttleworth, 1993).

The dam outflow is simulated with a simple operation scheme (Hanasaki et al., 2006; Shin et al., 2019).The suitability of this scheme for estimating large-scale reservoir regulation was recently shown (Fleischmann et al., 2021) for a test case of more than 30 reservoirs in the Paraná River Basin in Brazil. They concluded that although the proposed approach (Shin et al., 2019) is generic and simple, it provides reasonable estimates and is useful in evaluating regional hydrologic regime scale alterations.

The adopted scheme is a daily inflow-and-demand-based rule suitable for hydropower dams, which do not withdraw water from the system. This approach is reasonable for South America, where most dams are used for hydropower generation. Equation 8 defines the dam outflow:

$$Q(i,t) = R_i K_{i,y} I_m + (1 - R_i) I_t \tag{8}$$

where $Q(i,t)$ is the ith dam outflow at daily time step t, R_i is a regulation capacity constant that can be calibrated with observations or estimated with Equation 9 (Shin et al., 2019), and is assumed to be equal zero for run-of-the-river dams ($R_i < 0.1$). I_m and I_t are the annual average and daily dam inflows, respectively, and $K_{i,y}$ is the storage fraction at the beginning of the hydrological year (Equation 10). The hydrological year of each dam is defined as the month where the naturalized (pristine) flow falls below the average (i.e., the beginning of drawdown season) (Hanasaki et al., 2006).

$$R_i = \min\,(1, \alpha c_i) \tag{9}$$

$$K_{i,y} = S_{first,y} / \alpha C_i \tag{10}$$

The term c_i is the ratio of the maximum dam storage C_i to the annual average dam inflow ($c_i = C_i/I_m$), $S_{first,y}$ is the storage at the beginning of the hydrological year y, $\alpha_{res}C_i$ is the target storage, and α_{res} is a constant set to 0.85 (Hanasaki et al., 2006). I_m was calculated based on a prior long-term MGB simulation (1984–2019), including dynamic land cover and climate, but not reservoirs. This approximation is reasonable because reservoir regulation has a minor impact on the long-term average discharge (mainly through evaporation).

After estimating $Q(i,t)$, the reservoir storage is updated using equation 11, which represents a lumped (concentrated) reservoir:

$$V_{act}(i,t) = V_{act}(i,t-1) + \ (I_t - Q(i,t)) * 86400) \tag{11}$$

where $V_{act}(i,t)$ is the ith dam volume at daily time step t.

On the first simulation day for a given reservoir (i.e., the first day of either the MGB simulation or the dam inauguration year), it was assumed to be full. The dams were inserted into the model in their respective inauguration years to account for the interannual changes in dam storage across the continent.

As described next,, a set of equations (12-15) were adopted to ensure the stability of the numerical scheme and to prevent unphysical behavior (e.g., to avoid negative storage).

For the run-of-the-river reservoirs:

- If the reservoir storage is under 90% after computing $Q(i,t)$ and $V_{act}(i,t)$, we compute a new discharge (Equation 12) and volume (Equation 11).

$$Q^1(i,t) = \ Q(i,t) - \frac{V_{max} - \ V_{act}(i,t-1)}{86400} \frac{V_{act}(i,t-1)}{V_{max}} \tag{12}$$

where $Q^1(i,t)$ is the updated discharge for daily time step t.

- If this scheme results in a negative volume, we return to the original values estimated using Equation 11 and compute a new outflow discharge using Equation 13.

$$Q^1(i,t) = 0.01\,\frac{V_{act}(i,t-1)}{86400} \tag{13}$$

- If Equation 12 instead results in a negative discharge, we re-compute the updated discharge as:

$$Q^1(i,t) = Q(i,t) - 0.01\,\frac{V_{act}(i,t-1)}{86400} \tag{14}$$

For the reservoirs that are not run-of-the-river reservoirs:

- If the reservoir storage is above 98% (almost overtopping) after computing $Q(i,t)$ and updating the reservoir storage (V_{act}):

$$Q^1(i,t) = Q(i,t) + \frac{V_{act} - 0.98\,V_{max}}{(1-0.98)V_{max}}\,(\max(0.0, I_t - Q(i,t)) \tag{15}$$

- If the reservoir storage is under 20% after computing $Q(i,t)$ and $V_{act}(i,t)$, we follow the process described above for run-of-the-river reservoirs when they are less than 90% full.

3.1.3.2 Sediment deposition in reservoir

To represent the deposition of fine sediments (silt and clay) in reservoirs, we used Equation 16(Julien, 2010),

$$C(i,t,j) = Co(i,t,j)e^{\frac{-X_i\omega_j}{h_i u_i}} \tag{16}$$

where $C(i,t,j)$ is the ith dam downstream sediment concentration at daily time step t for the j particle size (silt or clay); $Co(i,t,j)$ is the ith dam upstream sediment concentration at daily time step t for the j particle size; X_i is the ith dam longitudinal length; ω_j is the settling velocity (Equation 3) for the jth particle size; h_i is the ith dam average depth (Equation 17); u_i is the ith dam longitudinal velocity (Equation 18).

$$h_i = \frac{V_{act}}{Ares_i} \tag{17}$$

where $Ares_i$ is the ith dam surface area.

$$u_i = \frac{I_t}{h_i\left(\frac{Ares_i}{X_i}\right)} \tag{18}$$

For coarse sediments (sands), we assumed that the total load arriving in the reservoir is deposited.

3.2 MGB-SED AS input data and parameterization

The MGB–SA simulations used the 15 arcsec HydroSHEDS flow direction map (Lehner et al., 2008) and a 1,000km² minimum drainage area threshold. The unit-catchment discretization used a fixed river length of 15km. Floodplain topography was estimated at the sub- unit-catchment level using the Height Above Nearest Drainage (HAND) computed from the Bare-Earth SRTM v.1 DEM (O'Loughlin et al., 2016). The river hydraulic geometry (bankful width and depth) was specified using a global dataset (Andreadis et al., 2013) with additional information from regional studies (Beighley and Gummadi, 2011; Paiva et al., 2013; Paiva et al., 2011; Pontes, 2016). Manning's roughness coefficient was set to 0.03 for the entire continent, as is typical in large-scale hydrodynamic modeling (Siqueira et al., 2018).

The simulation from 1984 to 2019 was performed using daily precipitation from the Multi-Source Weighted Ensemble Precipitation – MSWEP v1.1 dataset (Beck et al., 2017) until 2014 and using the NASA Global Precipitation Measurement Mission – GPM dataset (Skofronick-Jackson et al.,

2017) from 2015 onward. For the GPM data, a correction of the precipitation bias was performed so that the values were more compatible with the MSWEP data. This correction was performed using the quantile-quantile method, parameterized by the gamma function. Long-term averages (climate normals) for surface air temperature, atmospheric pressure, incoming shortwave solar radiation, relative humidity, and wind speed were obtained from the Climate Research Unit (CRU) Global Climate v.2 data (New et al., 2002)and were used to compute evapotranspiration.

While a previous application using the MGB-SED AS (Fagundes et al., 2021) used the South America HRU's map (Fan et al., 2015) to simulate the influence of land use and land cover (LULC) changes, we used eight LULC maps from European Space Agency (http://www.esa-landcover-cci.org/) and built the HRU's maps for the following years (simulated period): 1992 (1984-1992), 1995 (1993-1995), 1998 (1996-1998), 2001 (1999-2001), 2005 (2002-2005), 2010 (2006-2010), 2015 (2011-2015) and 2019 (2016-2019). We used a short interval in the early years because according to literature (Zalles et al., 2021) LULC changes in this period were higher than those observed in the recent years. The maps have spatial resolution of 300m. We used the same base of the South America HRU's map (Fan et al., 2015) to represent soil type (shallow and deep).

The input data to compute the MUSLE equation in the sediment module is the same as used in the previous application of the MGB-SED AS. The K factor is computed based on the percentages of silt, clay, sand, and organic carbon comprising the soil from the Food and Agriculture Organization (FAO) of the United Nations (FAO/UNESCO, 1974); LS_{2D} is based on the Bare-Earth SRTM v.1 DEM (O'Loughlin et al., 2016); P is assumed to be 1; and C is computed as in previous studies (Benavidez et al., 2018; Buarque, 2015; Fagundes et al., 2021). For each HRU map, the C values changed according to soil cover.

The major difference between the MGB-SED AS version used here and the previous version (Fagundes et al., 2021) is the inclusion of sediment trapping by reservoirs at the continental level. Here, we used 234 large dams (storage capacity > 10^6m³) from the Yigzae dataset(Yigzaw et al., 2018), *Agência Nacional de Águas do Brasil* (ANA) and *Operador Nacional do Sistema Elétrico do Brasil* (ONS). ANA and ONS are Brazilian state agencies. The reservoirs were selected using the following three criteria: (i) they are currently operational; (ii) there are available level-area-volume relationships; (iii) they are not located in headwater unit-catchments (i.e., a drainage area of ~1.000 km²). Using area and volume information, we fitted a fourth-degree polynomial for each reservoir, which was used to compute the daily surface area from the daily stored volume. When the longitudinal dam lengths were unavailable, they were estimated using visual analysis and geographic information system tools from satellite images.

3.3 Validation of the reservoir and sediment modules

Reservoirs were validated comparing water discharge from 376 in-situ stations against simulated data with and without reservoirs. Using observed and simulated data we computed the Skill Score (SC, Equation 19, Figure S2 - Supporting Information S1) for the Nash-Sutcliffe coefficient (NSE, Nash and Sutcliffe, 1970).

$$SC = \frac{NSE_{reservoir} - NSE}{1 - NSE} \tag{19}$$

The validation of river discharge for 12 gauges located on major regulated river reaches across the continent is presented in Figure S3 - Supporting Information S1. The validation of the simulated reservoirs' volumes and dam outflows using the MGB-SED AS model is shown in Figure S4 - Supporting Information S1. The results demonstrate reasonable model performance, especially in simulating dam volumes dynamics, which is an important variable affecting sediment trapping in the MGB-SED AS model (Equations 16, 17 and 18).

After including the reservoirs and obtaining satisfactory results from the model when incorporating LULC changes, we carried out a few manual adjustments to α and β MUSLE parameters values through trial and error. The model performance for sediment flows was evaluated in three different stages: (i) we computed percent BIAS (%) of simulated suspended sediment discharge (QSS, silt+clay) relative to observed QSS, considering the period of 1992–2009 and the same 595 sediment stations used in the previous MGB-SED AS simulation (Fagundes et al., 2021). Observed data were obtained from *Agência Nacional de Águas do Brasil*, *Base de Datos Hidrológica Integrada da Argentina* (BDHI) and I*nstituto de Hidrologia, Meteorologia e Estudos Ambientais da Colômbia* (IDEAM) used in the previous MGB-SED AS simulation (Fagundes et al., 2021) (Figure S5 - Supporting Information S1); (ii) we compared the annual and daily simulated and observed sediment bedload (Figure S6 - Supporting Information S1). Bedload data were collected from local and regional studies (Alarcón et al., 2003; CNEN/CDTN - Centro de Desenvolvimento da Tecnologia Nuclear and IFNMG/Campus Januária - Instituto Federal do Norte de Minas Gerais, 2020; Gamaro et al., 2014, 2011; Latrubesse et al., 2009; Martins et al., 2009; Martins and Stevaux, 2005; SZUPIANY et al., 2005) using other approaches (e.g., acoustic techniques to monitor fluvial ripples). It should be mentioned that both daily and annual bedload data are extremely scarce for large South American rivers.

In the Figure S7 - Supporting Information S1, we present an example of the reservoir effect in simulated suspended sediment concentration downstream large dams, comparing two simulations considering the presence and absence of reservoirs against observed data from ANA.

3.4 Long-term analysis of sediment changes

We performed three main analyses to understand how sediment fluxes have changed since 1984. Our simulations assumed that precipitation changes daily, reservoirs begin operating from their first operating year (if this occurred before 1984, its operation begins at the start of the simulation), and LULCC. We started the simulations in 1979 and used five years to warm up the model. Three main scenarios were then simulated to isolate the effect of each driver (precipitation, LULC, and reservoirs), and a final simulation was run to understand the synergistic effects of these drivers on sediment flows:

- *Precipitation changes scenario* – LULC map of 1992, reservoir module disabled, and daily precipitation from 1984 to 2019.
- *Reservoir changes scenario* – LULC map of 1992, reservoir module enabled, and 2012 daily precipitation. A daily precipitation series of 36 years was created by repeating the 2012 data. We tested several years, and 2012 was chosen because it represents the median precipitation during the whole simulation period for the entire South American continent.
- *LULC changes scenario* – all LULC maps, reservoir module disabled, and 2012 daily precipitation.
- *Combined effects scenario* - all LULC maps, reservoir module enabled, and daily precipitation from 1984 to 2019.

The first analysis focused on temporal changes. The entire simulated period (36 years) was divided into four nine-year periods (1984–1992, 1993–2001, 2002–2010, 2011–2019). We then computed the annual total sediment discharge (QST) for each scenario and averaged it over each period. We designated 1984–1992 as the baseline period and computed the relative change for the others (Equation 20).

$$Changes\ (\%) = 100x\frac{QST_{tf} - QST_{1984-1992}}{QST_{1984-1992}} \quad (20)$$

where tf is the future period (1993–2001, 2002–2010 or 2011–2019).

The second analysis focused on the global changes using only the combined effects scenario to identify rivers with significant changes. Here we used two statistical criteria to define significant changes: 1) the QST long-term change in a given river was above 5%; 2) the change was statistically significant to the 5% level using the Mann-Kendall test (M-K test, Kendall and Gibbons, 1975). The QST long-term change was computed using linear regression (time vs. QST) for the entire simulated period by comparing the first and last points of the fitted line. We used this approach instead of Equation 20 because we observed that the QST series exhibited great variability due to interannual precipitation variability, which could be misinterpreted if only 9-years averages were considered. For example, the last period (2011–2019) was quite dry over much of eastern South America, and this phenomena could be erroneously interpreted as a trend. In addition to the criteria presented, rivers were considered significantly affected when they presented significant QST changes in more than 40% of the main river length.

The third and final analysis was carried out to identify the main driver responsible for change for each river with a significant change. We observed that changes in the QST series were more abrupt when only reservoirs or LULC changes were considered, especially because they are timely progressive. However, precipitation changes were more variable, with alternations of dry and wet periods. Therefore, to compute long-term changes (%) appropriately for each driver, we used Equation 20 for the Reservoir changes and LULC changes scenarios and the linear adjustment for the Precipitation changes scenario.

Although we computed changes in sediment fluxes for many rivers in South America, we focused our analyses on the major rivers. The major rivers were classified as those with drainage areas greater than 100,000 km² and simulated QST without reservoirs greater than 1,000,000 t/year. The latter criterion was adopted because it considers more natural river conditions. More than one driver could be dominant for specific river reaches in some large rivers. In such cases, the dominant driver was selected based on two criteria: i) if the river was partially affected by both precipitation and LULC, the driver with more range in the river's downstream portion was selected; ii) the reservoir driver was selected when its effect was observed in a stretch with a drainage area greater than 50% of the basin's drainage area.

4 Results and discussions

4.1 Model validation and caveats

Our modeling outputs agree with previous regional studies. For instance, our analyses suggested that sediment flows are increasing in the Upper Tapajós due to deforestation and the consequent increase of erosion (Oestreicher et al., 2017), and increasing in other several regions of Amazon due to precipitation increase (Diodato et al., 2020). At the same time, we estimated a reduction in sediment flows in the Bermejo River due to the precipitation decrease in its upper basin (González and Murgida, 2012), and most recently, in the Lower Madeira and Lower Tapajós rivers due to reservoir building (Grill et al., 2019; Latrubesse et al., 2017).

Our model was satisfactorily validated in simulating reservoir dynamics. By using 376 gauge stations located downstream of dams, streamflow estimates were improved by 40% when compared to simulations without reservoirs (Figure S2 - Supporting Information S1). We also compared our daily simulated QSS against data from 595 in situ sediment stations (Figure S5 and Figure S7 - Supporting Information S1). In 60% of the stations, the relative error $BIAS$ was between -50% and 100%. We noted an improvement in QSS estimates after including the reservoirs, especially for the São Francisco (Figure S7 - Supporting Information S1), Paraná, and Tocantins rivers, compared to a previous study using the same model (Fagundes et al., 2021). We also compared simulated daily and annual bedload (sand) values against regional estimates, with $BIAS$ values of 582% and 233%, respectively (Figure S6 - Supporting Information S1). These last differences are reasonable for analyses using annual data such as those conducted in this study.

Sediment studies require considerable data, often acquired via traditional approaches using in situ measurements. However, even in this era of big data and big science, there remains a lack of hydrological and sediment data on the world's large rivers (Best, 2019). This picture is even worse when the subject is bedload data. For example, after extensive research in literature, databases, and private institutions, we achieved bedload data only for 11 sites (Figure S6 - Supporting Information S1) in the whole South America domain. This lack of data points to the great challenge in making measurements (that provide reliable results) of bed load in large rivers and the insufficient investment in this field of science.

Therefore, sediment modeling becomes an alternative to support spatial and temporal analysis but still requires good input data and validation processes (Fagundes et al., 2021). In this study, our main limitation was the lack of observed data to calibrate some model components. Furthermore, although Bolivia and Venezuela are regions with high sediment yield, we could not obtain data from these countries. Other limitations include the insufficient representation of lateral erosion, that can be important for meandering rivers (Nagel et al., 2022), as well as gully erosion and landslides that are relevant sediment processes especially for Andean rivers, like

Bermejo and Pilcomayo, and can induce underestimates in these regions (Borrelli et al., 2017). In addition, due to our continental domain of analysis, some simplifications were necessary and can be a source of uncertainties. These include equations that represent processes but are not laws of nature, the use of only three sediment sizes (sand, silt and clay), the use of only one capacity transport equation for bedload estimates in all rivers, a simplified dam operation scheme in the hydrological component, the adoption of a single value for the Manning coefficient, and the non-inclusion of sediment sources from mining activities, which can be relevant in some places.

Despite the limitations of the model and the associated uncertainties in sediment flux estimates, it is important to note that even in situ observations can have very high uncertainties (>50%, Navratil et al., 2011). More than this, for large scales (continental or global), no studies with in situ sediment data have been found in the literature, and only the recent study of Dethier (et al., 2022) has presented global results using remote sensing data. Thus, sediment transport models have proven to be the best alternative to large-scale assessments of sediment fluxes on large scales (Cohen et al., 2014, 2013; Fagundes et al., 2021; Pelletier, 2012; Syvitski et al., 2005). These models also have the advantage of providing information that makes detailed spatial and temporal analyses of what is happening in the landscape possible, and also intercomparisons between different geographic and climatic regions. More details about the model performance are discussed in the Supporting Information S1 - Text S1.

4.2 Continental analysis in time and space

The MGB-SED AS model has performed well in simulating sediment fluxes previously (Fagundes et al., 2021), and in this study further improvements have been achieved (section 4.1). Nevertheless, the presented results have uncertainties, which are not simple to quantify.

Therefore, the results presented here, especially those that present absolute values, should be regarded with caution.

Our analysis indicates that 51% of the main SA rivers have shown statistically significant changes in simulated sediment transport over the last 36 years (1984–2019). In 36% of the large rivers evaluated (Table 1), changes were directly caused by human activities such as deforestation and river damming, while precipitation alteration has driven changes in 15% of them. Absolute changes in annual sediment transport above 10% were observed in 14 of the 39 main SA rivers. Sediment flow increases were more frequent in the Amazon Basin rivers. By contrast, decreases were detected in the northeast and southeast portions of the continent (e.g., Paraná, Uruguay, Tocantins, and São Francisco rivers).

The average simulated sediment supply from SA rivers to the oceans was 834 million tons per year (Mt/year), decreasing over the analyzed period (Figure 2). From 2011 to 2019, SA delivered 771 Mt/year to the oceans, almost 10 % less than the 849 Mt/year delivered from 1984 to 1992 (Figure 3), which is a different result from a recent study (Dethier et al., 2022). Dethier et al. (2022) observed sediment changes at the mouths of major rivers and concluded that in South America fluxes are increasing. These different findings result from the different approaches used in each study. For example, it is known that the concentration of sediments at the mouth of the Amazon River tends to be higher than in upstream regions due to local processes on the estuary and coast (e.g. resuspension, Fassoni-Andrade and Paiva, 2019), and not due to the increased sediment load coming from the upstream region.

Table 1. Long-term estimates of sediment transport, mean alterations, and dominant drivers of changes for the main South American rivers. A is the drainage area, Q is the water discharge, QSS and QST are the suspended and total sediment discharge, respectively.

River	A (km²)	Q (m³/s)	QSS (Mt/year)	QST (Mt/year)	QST change (%)	Dominant Driver
Amazon	5,927,062	199,798	325.1	405.8	-6	-
Apure	137,051	2,094	16.0	18.1	-6	-
Araguaia	387,051	6,195	6.9	11.0	-6	-
Aripuanã	147,519	4,390	0.6	1.2	18*	LULCC
Beni	119,697	2,200	81.9	83.8	0	-
Bermejo	107,526	464	25.9	27.2	-31*	Precipitation
Branco	191,221	5,832	4.7	7.1	8	-
Colorado	295,416	185	0.2	0.6	-60*	Reservoir
Grande	143,928	2,277	0.5	0.6	-33*	Reservoir
Guaporé	355,220	3,315	3.9	5.4	18*	LULCC
Guaviare	139,337	6,454	10.4	14.3	4*	Precipitation
Iriri	142,686	4,563	0.6	1.1	19*	LULCC
Japurá	270,763	15,255	11.1	20.2	7	-
Juruá	182,140	5,979	29.2	34.5	-26	-
Madeira	1,372,401	28,823	155.3	172.2	-26	-
Madre de Dios	125,756	4,082	74.5	85.3	-2	-
Magdalena	261,343	7,304	28.2	38.9	-8*	LULCC
Mamoré	236,242	3,237	62.0	64.5	-7	-
Marañon	365,659	15,262	138.0	161.0	1	-
Meta	109,518	4,003	27.8	31.9	-7	-
Negro (Amazon)	716,166	34,887	9.2	14.2	10*	Precipitation
Negro (Argentina)	113,495	834	0.2	0.6	-80	-
Orinoco	940,567	33,186	116.9	151.2	-1*	Precipitation
Paraguay	535,249	2,541	6.0	8.5	-9	-
Paraná	2,602,798	21,792	59.2	65.1	-23*	Precipitation

Paranaíba	224,199	3,426	2.2	3.2	-44*	Reservoir
Parnaíba	333,763	962	1.9	3.4	-49	-
Pilcomayo	114,123	21	25.6	25.6	-2	-
Purus	379,473	11,424	24.5	33.8	9	-
Salado	226,464	175	0.3	0.9	-12*	Reservoir
San Miguel	125,840	777	2.5	2.9	7*	LULCC
São Francisco	638,874	2,779	0.9	2.6	-42*	Precipitation
Solimões	2,219,829	90,783	249.9	304.1	1	-
Tapajós	495,396	15,260	3.4	5.8	27*	LULCC
Tocantins	774,414	13,656	5.1	6.5	-46*	Reservoir
Ucayali	353,575	9,689	102.7	119.1	-4	-
Upper Paraná	954,777	15,557	5.1	6.5	-73*	Reservoir
Uruguay	267,152	7,172	4.0	4.0	-49*	Reservoir
Xingu	514,318	13,946	2.5	4.4	1*	LULCC

* Statistically significant to the level of 5% from the Mann-Kendall test.

Amazon (405 Mt/year, 48.8%), Orinoco (151 Mt/year, 18.1%), Paraná (65 Mt/year, 7.6%) and Magdalena (39 Mt/year, 4.6%) were the main SA rivers delivering sediments to the oceans (Figure 3-**a**). Comparing current and baseline periods, these rivers experienced a reduction in simulated sediment flux of 5.9%, 0.7%, 23.0%, and 7.6%, respectively. Our simulations also showed that sediment delivery to the South and North Atlantic Oceans were reduced by 26.0% and 4.7%, respectively, close to the sediment delivery reductions of the Paraná (23.0%) and Amazon (5.9%) rivers (Figure 3). The -5.0% change (Figure 3-**b**) in sediment supply to the Caribbean (69 Mt/year, 31.3%) is mainly associated with changes in the Magdalena River sediment flows.

Precipitation was the main driver responsible for reducing total simulated sediment discharge (QST) in SA rivers (Figure 2). For instance, we estimated a 6.1% decrease in the sediment delivery to the oceans for the 2011–2019 period when considering only the effect of precipitation (Fig 1-

A.4). The variable nature of precipitation over time showed that the climate driver has a widespread and important impact on sediment flux changes over large portions of SA.

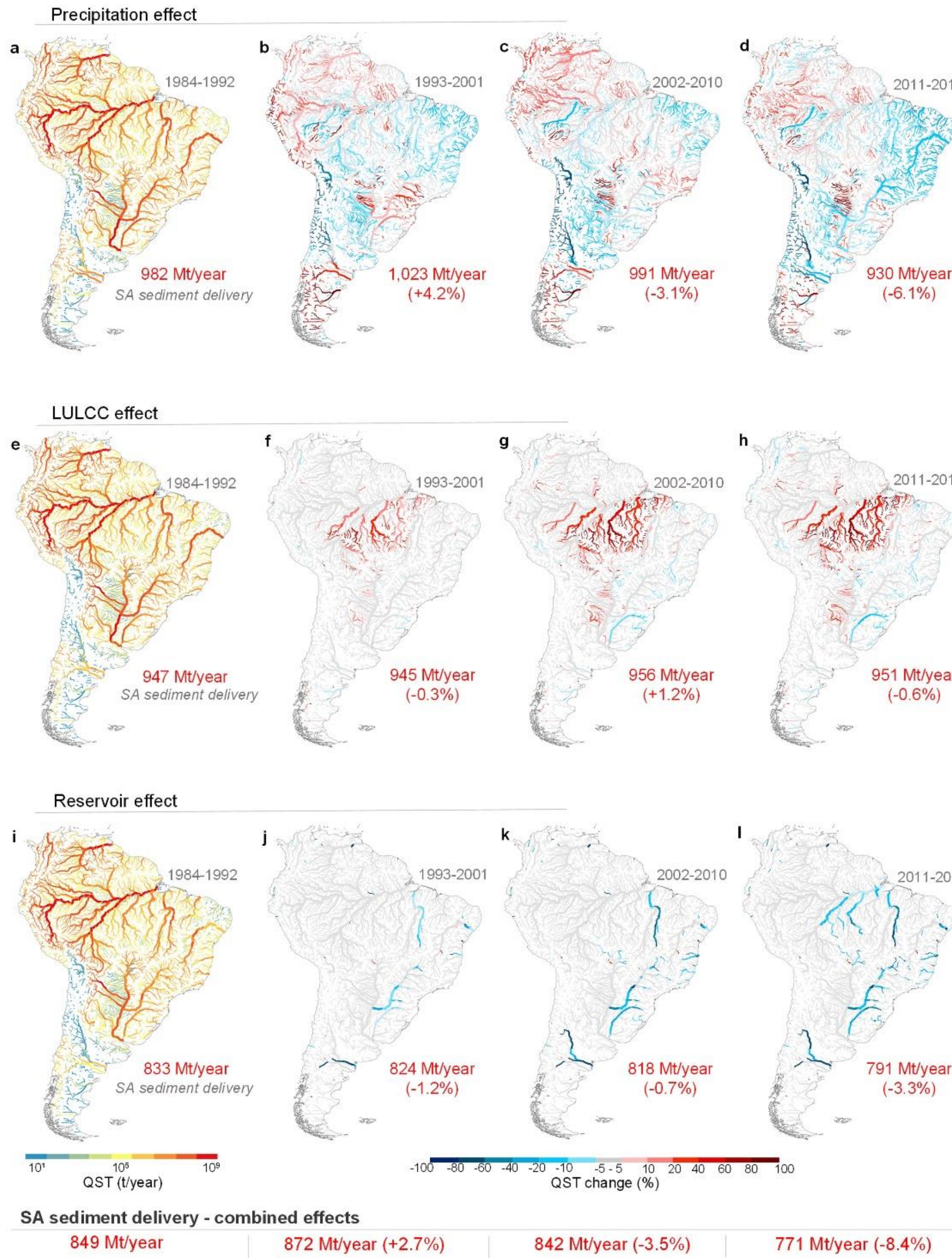

Figure 2. Temporal changes in sediment fluxes in South American rivers between 1984–2019. Maps show the QST and their changes (%) considering the isolated effect of precipitation changes (**a–d**), land use and land cover changes (LULCC, **e–h**), and existing reservoirs (**i–l**). Maps **a**, **e,** and **i** show QST values for the baseline period (1984–1992). The other maps present the sediment flow changes compared with the baseline period. Numbers in red indicate the average sediment

delivery from South America (SA) to the oceans in each period. Percentage values indicate the increase or decrease of sediment delivery compared with the previous period. These values are presented at the bottom (SA sediment delivery - combined effects) for the combined effect of each driver, i.e., when simulations were performed considering the synergic effect of precipitation, LULCC, and reservoirs on sediment flows.

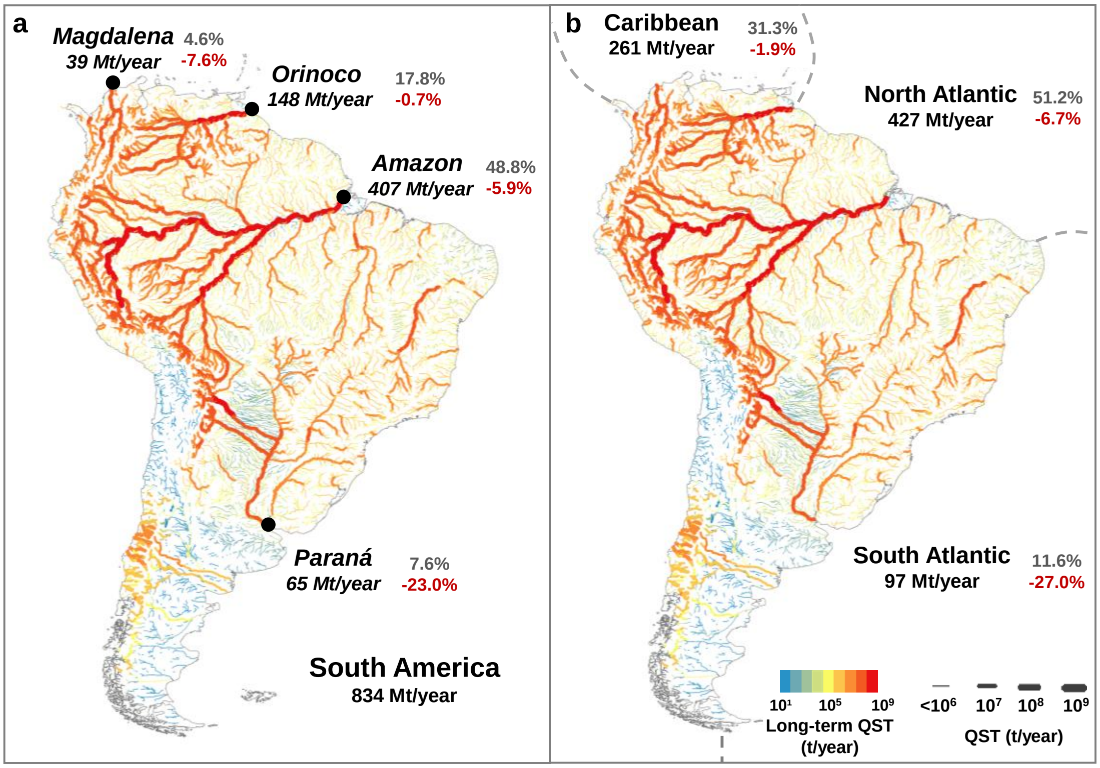

Figure 3. Long-term average of total simulated sediment discharge (QST) and the impact in the supply to the Caribbean, North and South Atlantic oceans. **a**, Main rivers responsible for the sediment supply to the oceans. **b**, Amount of sediment load reaching the oceans. Gray numbers indicate the relative percentage of the sediment load in comparison with the total reaching the oceans. Red numbers indicate the relative reduction in 2011-2019 in comparison with 1984-1992.

By contrast, LULCC resulted in local but more substantial effects, with several rivers showing simulated QST changes above 80% (Figure 2-**h**). In addition, LULCC effects were progressive over time, and the Amazon arc of the deforestation region is the main affected area (Figure 2). This region has been deforested (1,424 ha/year, INPE - Instituto Nacional de Pesquisas Espaciais, 2021) for livestock, soybean planting, and other crops(Song et al., 2021, 2018; Zalles et al., 2021). Since 1984, we observed that deforestation mostly increased the sediment flux in some Amazon sub-basins such as Juruá, Japurá, Magdalena and Branco ones, as well as along the headwaters of

Magdalena and Orinoco rivers (Figure 2). At the same time, more significant reforestation (natural or non-natural) was observed in the Uruguay River basin, in the headwaters of the Upper Paraná, São Francisco, and in some small rivers on the right bank of the Paraguay River (Figure 2).

The effect of reservoirs was cumulative along the rivers, and greater reservoir storage capacity caused more sediment retention. Sediment modeling show that from 1984 to 2010, hydropower expansion le led to a greater reduction of sediment flows (as high as 80-100%) in the Tocantins, Uruguay, Upper Paraná, lower São Francisco, Desaguadero, and Negro rivers (Figure 2-**k**). In the last decade, hydropower expansion has largely affected the Amazon region (Fig 2-**l**), resulting in a significant change in the sediment flows in this region. By comparing the current (2011–2019) and baseline (1984–1992) periods, river impoundments were responsible for a 5% reduction in total sediment delivery to the oceans. Several reservoirs were built for the Brazilian hydropower expansion, especially after its energy crisis at the beginning of the 21st century. However, many dams existed in SA rivers before 1984 (Figure 1). We found a 25% reduction in sediment delivery to the oceans caused by the reservoirs operating in 2019 compared with a scenario without reservoirs (Figure 4). It is well known that sediment trapping in reservoir lakes can induce downstream sediment erosion, but in general, the sediment volume trapped upstream greatly overcomes the sediment volume eroded in downstream.

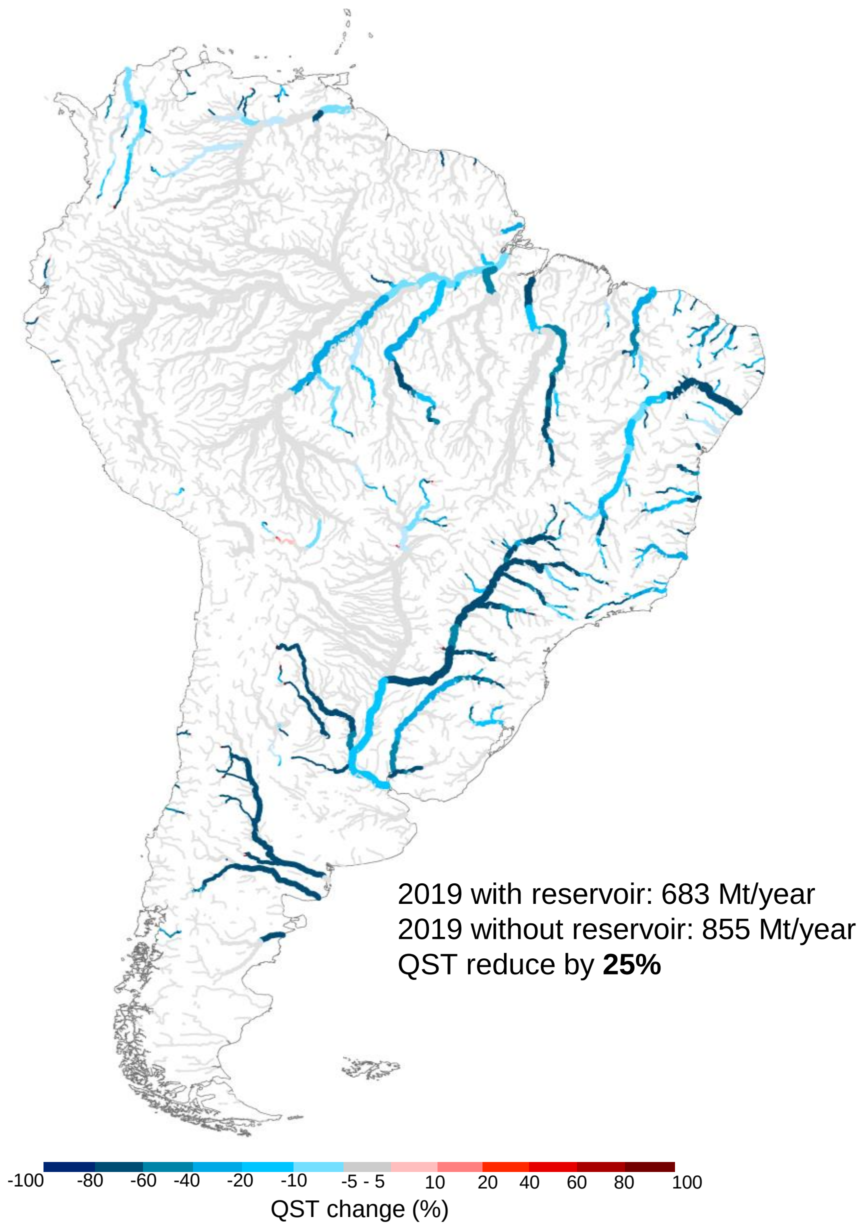

Figure 4. QST change due to reservoir effect considering the year of 2019. Two simulations were performed: one with presence and other with absence of the 234 large reservoirs presented in Extended Data Figure 1. These changes indicate not only the effect of reservoir in the simulated period but also those one existing before 1984.

The main hotspots for simulated QST increases driven by LULCC and precipitation were in the Amazon region (Figure 5). These sediment flow disturbances can require more fertilizers (Borrelli et al., 2017) for food production, affecting the meander migration and generating social and economic damage to riverine communities (Nagel et al., 2022). Increases in Amazon sediment flows can also be accompanied by higher mercury concentrations in rivers (Benefice et al., 2010; Webb et al., 2004; Yokoo et al., 2003), wetlands (Roulet et al., 2001) and fishes (Lino et al., 2019). These increases can be related to changes in the neurobehavioral capacities of adults observed in parts of Brazil, Ecuador, and Bolivia (Benefice et al., 2010; Webb et al., 2004; Yokoo et al., 2003).

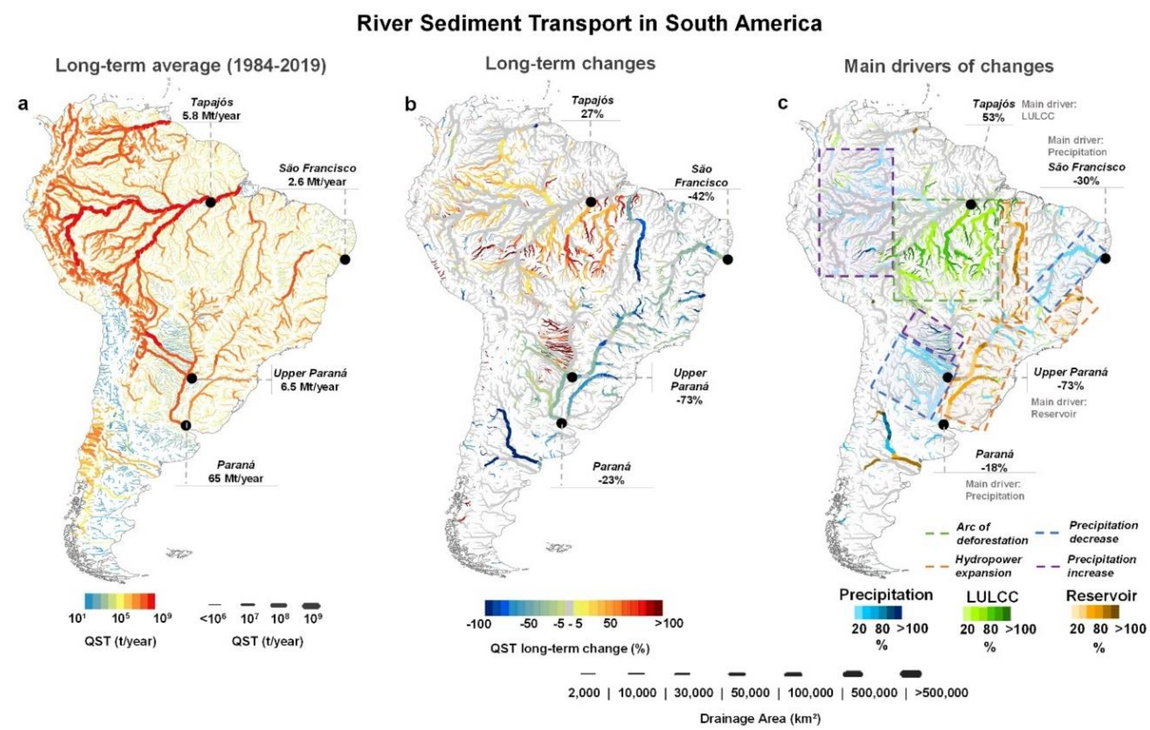

Figure 5. Spatial overview of trends, magnitude, and main drivers of changes in sediment transport of South American rivers between 1984-2019. a) map of the long-term average of total simulated sediment discharge (QST) considering the precipitation and human-induced changes by land use and land cover changes (LULCC) and reservoirs constructions. **b**) Statistically significant QST long-term changes to the level of 5% considering the Mann Kendall test (M-K test). **c**) Magnitude of sediment flow changes considering the main driver (precipitation, LULCC, or reservoir) in each river reach. Hotspots of changes are highlighted in rectangles. For example, it is observed that Tapajós River transported 5.8 Mt/year on average from 1984-2019, with an increasing trend of 27%, in which the LULCC (main) driver was responsible for an increase of 53%.

Over time, the implementation of many reservoirs caused substantial simulated QST reductions (> 50%) in the Tocantins, Upper Paraná, Uruguay, and Lower São Francisco rivers (Figure 5-**c**). Ecological and geomorphological implications have already been reported for some of these rivers

(Bandeira et al., 2013; da Silva et al., 2020; Maavara et al., 2015). Lower sediment supply to downstream reservoirs can lead to the loss of riparian vegetation, affecting the water quality, local biodiversity (Naiman et al., 1993), and other wetland vegetation species (Swanson and Bohlman, 2021). Reduced sediment flows can also lead to fewer nutrients and decreased fishery yields, as reported for the São Francisco (Cavali et al., 2020) and Paraná (Maavara et al., 2015) rivers. Hydropower expansion has recently reached the Amazon region, resulting in a statistically significant change in sediment flows. By comparing pre- and post-construction of Santo Antônio and Jirau dams, we estimated a 43% decline in the Madeira River's QST. This remarkable change affected the Amazon River, which experienced a 19% reduction in sediment load over the same period. The coastal region between the mouths of the Amazon and Orinoco rivers is the largest mud beach complex on Earth (Anthony et al., 2014), and may be seriously affected by substantial reductions in sediment supply by Amazon River (Forsberg et al., 2017; Latrubesse et al., 2017). This reduction could also affect the ability of mangroves to act as a carbon sink. These forests account for approximately 10–15% of total carbon sequestration while covering only around 0.5% of the total global coastal area (Ezcurra et al., 2019).

Regarding the impacts on simulated QST from precipitation decreases, the most significant changes were found in the Bermejo River (-31%). This river provides approximately 90% of the Lower Paraná sediment load (Amsler and Drago, 2009), playing a major role in maintaining its ecosystems (Thorp et al., 2006). Climate change projections (Figure S1 - Supporting Information S1) suggest that the Bermejo River will likely experience average precipitation and river discharge reductions in the future. Consequently, the sediment supply to the Lower Paraná River is expected to decline, increasing the vulnerability of the ecosystems that depend on it.

4.3 Implications for the ecosystem, water, and land management

When sediment flows are changing, other aspects of the environment can also be affected. In South America, planned reservoirs (Figure S1 - Supporting Information S1) are particularly concerning, especially those in the Pantanal and Amazon basin. Even if only some of them are built, irreversible environmental consequences could occur (Forsberg et al., 2017). Sediments from uplands carried to the Pantanal wetlands support geomorphological dynamics, wildlife habitats, and biological productivity. However, existing reservoirs have reduced the sediment supply by around 20% in these environments (Fantin-Cruz et al., 2020 and Figure 5). In addition, Andean reservoirs can dramatically change the sediment and nutrient inflows to the Amazon rivers and floodplains and the North Atlantic Ocean. An earlier study showed that six planned dams accounting for only 7% of the total drainage area of the Amazon Basin could reduce the basin-wide sediment supply by 64% (Forsberg et al., 2017).

Both increasing changes in simulated QST due to LULCC or precipitation changes in SA require measures to minimize their impacts. From our results, hotspots include the Amazon, where efforts should focus on reducing deforestation. However, the Brazilian Cerrado, Caatinga, Atlantic Rainforest, and Pampa biomes were also severely degraded in the past and would benefit significantly from erosion control practices. Our results can assist in the delineation of ecosystem restoration strategies by identifying the main areas needing recovery (Zalles et al., 2021), through policies such as payment for ecosystem services, for example (Latrubesse et al., 2019; Song et al., 2018). Sustainable agriculture by farmers must be encouraged, providing practices aimed at soil erosion reduction and improving both terrestrial and aquatic ecosystems quality (Borrelli et al., 2017). Concerning mercury impacts associated with deforestation, consider that (i) Brazilian Amazon riverine populations have a per capita fish consumption of up to 94 kg/year, which is 5.8

times the world average (Isaac and de Almeida, 2011), and (ii) our results showed that QST increase rates reached more than 80%. Therefore, the creation of programs and actions to monitor fishes and prevent damage to the health of the riverine population, such as providing solutions and better diet alternatives (Benefice et al., 2010), is also important.

Although dams can cause several negative impacts on sediment flows and ecosystems, they also have contributed to worldwide water and energy security, supporting economic and social development (Hogeboom et al., 2018; Tilmant et al., 2014). In 2018, reservoirs used for hydropower generation, irrigation, industrial and domestic water supply, flood protection, fishing, and recreation were valued at US$265 billion per year (Hogeboom et al., 2018). Because of these factors, trade-offs and the adoption of sustainable management practices in reservoir operation are essential (Best, 2019), including for major areas requiring new dam construction, such as the Amazon and Pantanal (Randle et al., 2021). Such practices would permit sediment passage through reservoirs to provide environmental benefits (Randle et al., 2021) and minimize environmental impacts.

5 Conclusions

Sediment flow changes in SA induced by human activities such as deforestation and river damming are a consequence of demands from local populations and other. Both increases and decreases in sediment flows can be problematic for the environment and society because each ecosystem is unique. Thus, in this study we aimed to comprehend the spatiotemporal changes in sediment fluxes in SA over the last 36 years (1984-2019). We found that 51% of the main SA rivers experienced statistically significant changes in simulated sediment transport over this period, with 36% due to Amazon deforestation and river damming and 15% due to precipitation changes. We also estimated a 10% reduction in the average sediment delivery to the oceans.

Amazon, Orinoco, Paraná and Magdalena were the main SA rivers delivering sediments to the oceans, and these rivers experienced a reduction in simulated sediment flux of 5.9%, 0.7%, 23.0%, and 7.6%, respectively. Precipitation was the main driver responsible for reducing total simulated sediment discharge (QST) in SA rivers. By contrast, LULCC resulted in local but more substantial effects, with several rivers showing simulated QST changes above 80%. Similarly, to LULCC, hydropower expansion led to a greater reduction of sediment flows (as high as 80-100%) in the Tocantins, Uruguay, Upper Paraná, lower São Francisco, Desaguadero, and Negro rivers. Our results of simulation also show that Amazon region is the most affected one due to deforestation, and, especially in the last decade, also by reservoirs.

Our study is the first to provide a thorough and consistent analysis of the synergistic effects of LULCC, river damming, and precipitation change on sediment flows for the entire SA continent from 1984 to 2019. Our modeling outputs provide unprecedented information about the status of sediment dynamics in SA, and a means to develop evidence-based strategies and transboundary policies related to continental-wide sediment dynamics and the conservation and restoration of ecosystems. This understanding of the evolution of sediment flow changes across space and time can help mitigate impacts on people and nature, based on our identification of the most sediment-affected regions. The approach used here can also be useful as described next for applications in other locations. Furthermore, the findings and data provided in this study may be useful in future investigations of carbon fluxes, nutrient transport, biological productivity, human food and energy safety, and other studies related to ecosystem maintenance and soil conservation.

The MGB-SED AS model has shown ability to properly simulate sediment fluxes in several sites of South America. However, large-scale modeling is not free of uncertainties, which requires that the results and conclusions be understand from this perspective. In the future, we intend to perform sensitivity/uncertainties analyses to improve our knowledge about continental sediment modeling, which also constitutes part of our continental modeling research agenda, started with the work of Siqueira et al. (2018). Future works could also use different methods and approaches to represent other processes like gully and lateral erosions; different particle sizes distribution; new schemes for dam operation. In addition, the model could be updated and re-calibrated using new databases of soil, land use, climate and precipitation data.

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Data availability

Data supporting the findings of this study are available in the references cited in the main text, methods, and Supporting Information S1. Also, any data can be provided from the corresponding author upon reasonable request. Simulated Suspended Sediment Discharge for South America Rivers (MGB-SED AS) - V2.0 dataset is available in: doi.org/10.17632/ncr6d42tx5.1. This dataset provides both annual long-term average and daily simulated data. More information and datasets can be found in https://www.ufrgs.br/samewater/.

Code availability

The source code of the MGB-SED AS model is available at https://www.ufrgs.br/samewater/produtos/south-america-sediment-model/

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