Anthropogenic impacts to the sediment budget of São Francisco River navigation channel using SWAT

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Abstract: The São Francisco River Basin, located in eastern Brazil, has undergone a significant amount of anthropogenic changes in the last several decades, such as agricultural expansion, irrigation activities, mining, and the construction of large dams. Together, these changes have altered the historic sediment budget and have led to an aggradation of sediments in the navigation channel, impacting the ability to efficiently ship agricultural commodities to regional ports. In an effort to aid decision makers in future waterway navigation planning, an international partnership between the Brazilian government agency CODEVASF and the US Army Corps of Engineers (USACE) was created. Through this partnership a SWAT model of the 630 000 km^2 São Francisco River basin was developed to better understand both the historic and current sediment budget within the navigation channel. The SWAT model of the São Francisco River Basin was calibrated for hydrology and sediment loads. Monthly discharges were calibrated at 17 Agência Nacional de Águas (ANA) gages, with Nash-Sutcliffe efficiency (NSE) values ranging from 0.42 to 0.75 for an eleven year simulation. Sediment loads were calibrated to an ANA sediment gage located in the Middle São Francisco River Navigation Channel, with a PBIAS (Percent Bias) of 11.6. Based on model results, the aggradation rate of sediment in the São Francisco River and major tributaries has increased by approximately 20 Mt since Pre-European settlement of the basin (from approximately 7 Mt/a to 27 Mt/a). This increase has contributed to an impaired navigation channel due to shoaling of sandy sediments in the navigation channel.

Keywords: sediment budget, aggradation rate, São Francisco River, anthropogenic impact, SWAT

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1 Introduction

The São Francisco River – located in eastern Brazil – is a historically important north-south corridor of navigation linking the important agricultural and mining activities that occur in the states of Minas Gerais and Bahia to the northeast part of the country. The São Francisco River Basin has undergone substantial landuse changes over the previous few decades. A significant amount of land has been converted from native vegetation to either grazing or intense row crop farming. In addition, dams and large-scale irrigation projects have been constructed, and the expansion of row crop farming, irrigation, and dam construction is expected to continue in the watershed. The impacts associated with these watershed changes are currently not well understood, thus the Soil and Water Assessment Tool (SWAT) ecohydrological model[1-4] was applied to calculate both the modern and historic sediment budgets as well as improve the overall understanding of the sediment dynamics in the São Francisco River Basin.

SWAT is a physical-based continuous (daily time-step) watershed model which has been extensively

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used to evaluate watershed hydrology, sediment yield, and nutrient dynamics (among other processes)[5-9]. Numerous processes within SWAT were applied to determine the modern and historic sediment budget for the São Francisco River Watershed, including hydrology and water balance calibration, reservoir sedimentation, in-stream sediment processes, and irrigation. The sediment yield capabilities of SWAT have been utilized in numerous studies to understand sediment dynamics and sediment delivery at the basin scale in watersheds throughout the world[10-14]. The SWAT sediment yield capabilities have also been specifically applied in some Brazilian watersheds[15-17] (also summarized in Bressiani et al.[18]). In addition, the irrigation algorithms in SWAT have been used in numerous studies for a variety of applications including irrigation optimization, basin-wide water allocations, and Best Management Practices (BMPs)[19-22].

Although numerous studies have successfully demonstrated the robustness of SWAT to address hydrologic modeling, irrigation and sediment yield applications, fewer studies have directly addressed the applications of reservoir sedimentation and in-stream sediment dynamics, which are important sediment budget components in this study. Few studies have investigated SWAT's ability to represent sedimentation in reservoirs directly; however, many studies have investigated nutrient settling and concentrations in reservoirs using SWAT[23,24]. One study that did investigate the robustness of SWAT to measure sedimentation rates in reservoirs directly was conducted on a small watershed (17 km^2) in India[25]. The authors used a sediment concentration value of 450 mg/L to initiate sedimentation (but did not provide justification for using that value) and simulated three in-stream reservoirs with storage capacity ranging from 0.18 to 0.27 million m^3. The model was calibrated for both daily and monthly sediment yields, and achieved an R^2 value of 0.99 (monthly yields) and 0.82 (daily yields). This study showed that SWAT accurately represented the sediment dynamics within the 17 km^2 watershed system and demonstrated the robustness of the reservoir sedimentation routines in SWAT.

SWAT has also been applied to evaluate in-stream sediment processes in a limited number of studies. For example, an evaluation of climate change impacts on in-stream sediment concentrations and dynamics was performed in the Sierra Nevada mountains in California[26]. It was demonstrated that in-stream temperatures are predicted to rise and that sediment concentrations are predicted to decrease by 50% by 2100 based on the A2 emission scenario. The authors of the Sierra Nevada study note that sediment calibration data was limited and that higher uncertainties are associated with the results of the sediment loads and sediment concentration results. A second study for a small watershed (4.3 km^2) in Denmark investigated the robustness of using various sediment transport equations in SWAT[27]. This study found that the default Bagnold sediment routing method did not sufficiently predict in-stream sediment processes when compared to other sediment routing options such as the modified Bagnold equation. A third study, conducted in the Lamar River watershed in Yellowstone National Park, demonstrated the ability for SWAT to accurately model in-stream sediment processes including bank erosion for a mountainous stream, yielding a Nash-Sutcliffe efficiency[28,29] (NSE) value of 0.78 for sediment loads[30].

SWAT has further been used to evaluate anthropogenic impacts, including the effects of impoundments, on hydrology and sediment yields at various scales. The anthropogenic impacts on the hydrology of the Kangsabati River basin (5 796 km^2) in eastern India were evaluated by specifically investigating the impacts associated with the construction of dams in the watershed[31]. In another study, six watersheds within the Lake Erie basin were modeled in SWAT in order to develop BMP strategies aimed at non-point source pollution reductions[32]. In the Lake Erie study, a pristine condition scenario was modeled in SWAT by returning all agricultural and urban land uses to wetland and forest associated with the pre-European settlement condition for the Maumee River watershed. The results of the Maumee SWAT modeling showed that prior to anthropogenic alterations, sediment loads from the watershed were 84% less than the modern sediment yields. Thus, the overall objective of the present study is to build on these previous studies by developing an understanding of the scale of sediment load changes since pre-European settlement of the São Francisco River basin using SWAT. As the São Francisco River navigation channel experiences shoaling, the knowledge of the extent and magnitude of sediment loads due to anthropogenic changes in the watershed will provide insight into how much mitigation of sediment loads may be possible if Best Management Practices (BMPs) or other measures are implemented in the basin. Overall, the specific study objectives include: (1) Develop a calibrated SWAT sediment yield model of the São Francisco River basin under baseline conditions. (2) Model pre-European settlement conditions by developing a SWAT historic scenario model with native vegetation and without anthropogenic activities such as dams and irrigation. (3) Determine the magnitude of sediment loads associated with anthropogenic changes by comparing existing and historic sediment budgets.

2 Basin description

The São Francisco River is located in the Brazilian states of Minas Gerais, Bahia, Pernambuco, Alagoas, and Sergipe (with a small area in the state of Goiás and the Federal District – see Figure 1). The São Francisco River is approximately 2 900 km in length with a watershed area of approximately 630 000 km^2. The navigation channel extends from Pirapora, Minas Gerais to the twin port cities of Juazeiro, Bahia and Petrolina, Pernambuco (1,371 km downstream). Approximately 13 million people live in the basin, with the highest density living in the south (headwaters), especially near the Belo Horizonte metropolitan area. The climate ranges from humid in the headwaters (south) to semi-arid in the Lower São Francisco River (north). Vegetation includes a cerrado (savannah) system in the headwaters with a high diversity of mixed forest as well as Caatinga vegetation, which is a sparse and stunt-growth vegetation associated with the semi-arid region of the watershed in the north and east.

Landuse in the basin is currently dominated by agriculture (46%) and rangeland (43%). Remaining landuses consist of forest with small amounts of urban land, among others. The agriculture is primarily soy beans with other large crops consisting of corn, wheat, and cotton (often crops are rotated between soy and corn, with two harvests per year). Other smaller agriculture includes various fruit crops. Soils in the basin are generally highly fertile latosols (41% of the basin) and to a lesser extent podzols (11%), and less fertile arenosols (10%) and cambisols (7%). The agricultural goods are primarily shipped in trucks within the basin to regional or coastal ports. Historically, cargo, agricultural goods and passengers used the São Francisco River for transportation and in the 1970s transportation by barge of corn, soy, grain, tomato pulp and other goods were transported regularly. Since 1999 only a single transportation company has been transporting a small amount of cotton by barge on the river with no more than 50 000 t shipped per year. Transportation by barge has been declining due to the shoals preventing efficient shipping in the river[33].

Figure 1 Location map of the São Francisco River Basin

Some studies have investigated the anthropogenic changes specifically within the São Francisco River watershed. A consortium of agencies including the Agência Nacional de Energia Elétrica (ANEEL), the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) and the Agência Nacional de Águas (ANA) conducted a study of the sediment loads in the São Francisco River Basin[34]. This study included a summary of the sediment data at the mouth of the Sao Francisco River at ANA gage 49705000 near Propriá, Sergipe. This study showed that there is an overall decrease of sediment loads to the ocean since the late 1970s (and this reduction is assumed to be associated with the sediment capture in the large dams that were constructed upstream of the mouth of the river in the 1980s and 1990s). In a separate study, the geomorphic changes in the in-stream sediment processes of the São Francisco River watershed were evaluated over the 50-year time period between 1950 and 2000[35]. This comprehensive evaluation of the river morphology demonstrated that the river is experiencing net aggradation in the navigable portions of the São Francisco River since the 1950s. In this study, the middle São Francisco River (the length between Pirapora, Minas Gerais and the Sobradinho reservoir) was divided into 73 reaches. An overall increase in mid-channel bars, point bars and islands has been quantified within this stretch by conducting a comparison of historical aerials and cross sectional survey data collected at flow and sediment gages. A total of 78% of these reaches have experienced aggradation since 1950, which was concluded to be a result of the increased sediment loads associated with the agricultural development of the watershed.

3 Methods

3.1 Description of SWAT model

SWAT divides a watershed into several sub-basins, and each sub-basin is usually further divided into Hydrologic Response Units (HRUs). These HRUs are relatively small subareas that are assumed to have uniform properties of soil, management, slope, and landuse, but are not spatially represented in SWAT, and thus are simulated as independent hydrologic units. Thus, the model is a lumped parameter model at the subwatershed scale (HRU scale), but a distributed model at the watershed scale. The sub-basins are linked together through a stream network, and both water and sediments are routed through the watershed via this stream network. The input climate data in SWAT includes daily precipitation, minimum temperature, maximum temperature, solar radiation, relatively humidity, and wind speed, which are the primary hydrologic drivers in the model. Erosion caused by rainfall and runoff is computed using the Modified Universal Soil Loss Equation (MUSLE)[36], which incorporates the soil, landuse, management, and other factors associated with the HRUs to calculate sediment yield. Hydrologic, sediment, and nutrient outputs can be investigated at daily, monthly, or annual scales at any node or reach within the watershed.

3.2 Sediment processes in SWAT

This research leverages some sediment routing and deposition algorithms available in the SWAT suite of processes (specifically reservoir sedimentation and in-stream bank and bed erosion as well as bed deposition). SWAT accounts for the influence of upstream dams on sediment delivery by calculating the sediment balance at each reservoir and applying a sediment settling equation where sediment concentrations are calculated using a first order decay approach. The initial suspended sediment concentration in the reservoir at time-step i is given in Equation (1).

$$conc_{sed,i} = \frac{(sed_{wb,i} + sed_{flowin})}{(V_{stored} + V_{flowin})} \qquad (1)$$

where, $conc_{sed,i}$ is initial concentration of suspended sediments in the reservoir, mg/m^3; $sed_{wb,i}$ is amount of sediment in the water body at the beginning of time-step i, t; sed_{flowin} is amount of sediment added to the water body with inflow, t; V_{stored} is volume of water stored in the reservoir at the beginning of time-step i, m^3; V_{flowin} is volume of water entering the reservoir within the time-step, m^3.

If the sediment concentration is greater than an equilibrium sediment concentration (set by the user), the final concentration at the end of a time step is calculated based on Equation (2).

$$conc_{sed,f} = conc_{sed,eq} + (conc_{sed,i} - conc_{sed,eq}) \cdot e^{(-k_s \cdot t \cdot d_{50})} \quad (2)$$

where, $conc_{sed,f}$ is final concentration of sediment in the water body, mg/m^3); $conc_{sed,eq}$ is equilibrium concentration of sediment in the water body, mg/m^3; k_s is first order decay constant(d^{-1}), default value is set to 0.184, which represents that 99% of the 1 μm size particles settle out of the suspension in 25 d; t is length of the time step (1 d); d_{50} is median particle size of the inflow sediment, μm.

For in-stream sediment processes, both bank erosion and bed erosion as well as bed sedimentation are calculated at each time step within the SWAT model. For erosion to occur two processes must be present. In the first process, the stream power must have sufficient capacity to transport the sediment that is delivered to the stream from overland flow processes and upstream reaches. Second, the shear stress exerted by the water on the bed and bank must be more than the critical shear stress to dislodge a sediment particle. The potential erosion rates are calculated in SWAT based on the excess shear stress equation from Hanson and Simon[37] in SWAT (see Equations (3) and (4)).

$$\xi_{bank} = k_{d,bank} \cdot (\tau_{e,bank} - \tau_{c,bank}) \cdot 10^{-6} \quad (3)$$

$$\xi_{bed} = k_{d,bed} \cdot (\tau_{e,bed} - \tau_{c,bed}) \cdot 10^{-6} \quad (4)$$

where, ξ is erosion rates of the bank or bed, m/s; k_d is erodability coefficient of bank or bed, cm^3/N·s; τ_e is effective shear stress acting on the bank or bed, N/s; τ_c is critical shear stress acting on the bank or bed, N/s;

The effective shear stress (τ_e) is calculated in SWAT using Equations (5)-(7) from Eaton and Miller[38]:

$$\frac{\tau_{e,bank}}{\gamma_w \cdot depth \cdot slp_{ch}} = \frac{SF_{bank}}{100} \cdot \left(\frac{(W + P_{bed}) \cdot \sin\theta}{4 \cdot depth} \right) \quad (5)$$

$$\frac{\tau_{e,bed}}{\gamma_w \cdot depth \cdot slp_{ch}} = \left(1 - \frac{SF_{bank}}{100}\right) \cdot \left(\frac{W}{2 \cdot P_{bed}} + 0.5 \right) \quad (6)$$

$$\log SF_{bank} = -1.4026 \cdot \log\left(\frac{P_{bed}}{P_{bank}} + 1.5 \right) + 2.247 \quad (7)$$

where, SF_{bank} is proportion of shear stress acting on the bank, dimensionless; γ_w is specific weight of water, N/m^3; $depth$ is depth of water in the channel, m; slp_{ch} is channel bed slope, m/m; W is top width of channel, m; P is wetted perimeter of bed or banks, m; θ is angle of the channel bank from horizontal.

When the channel capacity is greater than the sediment input from the upstream reach, then channel erosion occurs. The rate of downcutting (calculated at the same time step as SWAT) is a function of the channel erodability coefficient (Equation (8)) and a shear stress (expressed in the depth and slope of the channel terms) as shown in Equation (9).

$$K_{CH} = 0.003 \cdot e^{385 \cdot J_i} \quad (8)$$

$$depth_{dcut} = 358.6 \cdot depth \cdot slp_{ch} \cdot K_{CH} \quad (9)$$

where, K_{CH} is channel erodability coefficient, cm/h·Pa; J_i is Jet Index from ASTM standard D 5852-95; $depth_{dcut}$ is amount of channel downcutting, m; $depth$ is depth of water in the channel, m; slp_{ch} is channel slope, m/m.

Sedimentation in a given timestep can occur in the channel in SWAT only when the transport capacity in a reach is less than the available sediment entering the reach. No sedimentation along the banks occur, although floodplain sedimentation can also be handled in SWAT. All of these processes are leveraged in the sediment budget calculations performed on the São Francisco River SWAT model.

3.3 Model data

The primary data that was used to build a hydrology and sediment yield model for the São Francisco River basin included the following: topography, soils, landuse, reservoirs, irrigation withdrawals, and weather (precipitation, temperature, relative humidity, solar radiation, and wind). The topography, soils, and landuse layers were overlapped to create Hydrologic Response Units (HRUs). Areas that have similar slopes, soil classification, and landuse were grouped into a single HRU.

Landuse data is necessary in a SWAT model to capture the hydrologic and sediment loss impacts associated with agriculture, urban landuses, forests, and other landuses. Each landuse has specific impacts to the hydrology and sediment yield of a watershed. The GlobCover 2005[39] global dataset was used to assign the landuse to the São Francisco River SWAT model.

GlobCover 2005 is a global dataset with 300 m×300 m resolution of landcover from the year 2005. The statistics associated with the SWAT landuse categories for the entire São Francisco River Basin are listed in Table 1, and Figure 2 displays the landuse data used in the SWAT model.

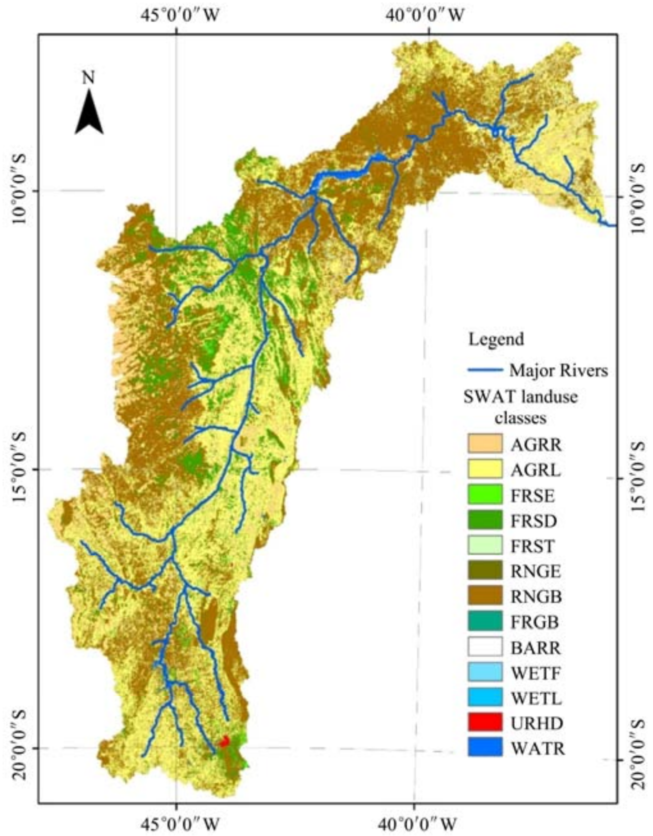


Figure 2 Landuse data of the São Francisco River Watershed

Table 1 Landuse statistics for final HRUs in the baseline SãoFrancisco Basin SWAT model

Assigned SWAT category landuse	SWAT landuse category description	Pre-processed area/hm^2	Final SWAT area/hm^2	SWAT area/%
AGRR	Agricultural Land – Row Crops	6 307 196	6 205 612	9.79
AGRL	Agricultural Land – Generic	22 366 715	22 822 713	35.99
RNGB	Range – Brush	26 545 427	27 038 349	42.63
FRSD	Forest – Deciduous	5 476 216	5 365 425	8.46
FRSE	Forest – Evergreen	347 118	33 290	0.05
FRST	Forest – Mixed	1 974 263	1 553 291	2.45
BARR	Barren	85 679	885	0.0014
URHD	Residential – High Density	41 778	43	0.0001
WATR	Water	617 710	399 320	0.63
	TOTAL	63 762 102	63 418 928	100.00

Soils data were obtained from EMPRAPA[40] in a digital form entitled the Mapa de Solos Do Brasil. There are seventy soil groups defined in the overall Brazil Soil Dataset within the São Francisco River Watershed (Figure 3). Soil physical and chemical property data were not directly available in the EMPRAPA dataset. Therefore, the International Soil Reference and Information Centre (ISRIC)[41] database, which contains soil physical and chemical properties at a 5 arc-minute resolution for the world, was used to extract soil property data that were applied directly to the EMPRAPA soil boundaries. The physical and chemical ISRIC soil information applied to the EMPRAPA boundaries included: Number of layers (NLAYERS); layer thickness, by layer (SOL_Z); hydrologic soil group (HYDGRP); maximum rooting depth of soil (SOL_ZMX); fraction of porosity from which anions are excluded (ANION_EXCL); potential crack volume (SOL_CRK); moist bulk density (SOL_BD); available water capacity (SOL_AWC); saturated hydraulic conductivity (SOL_K); organic carbon content (SOL_CBN); clay, silt, sand, and rock fragment percent (CLAY, SILT, SAND, & ROCK); moist soil albedo (SOL_ALB); and Universal Soil Loss Equation (USLE) Erodibility (K) factor (USLE_K).

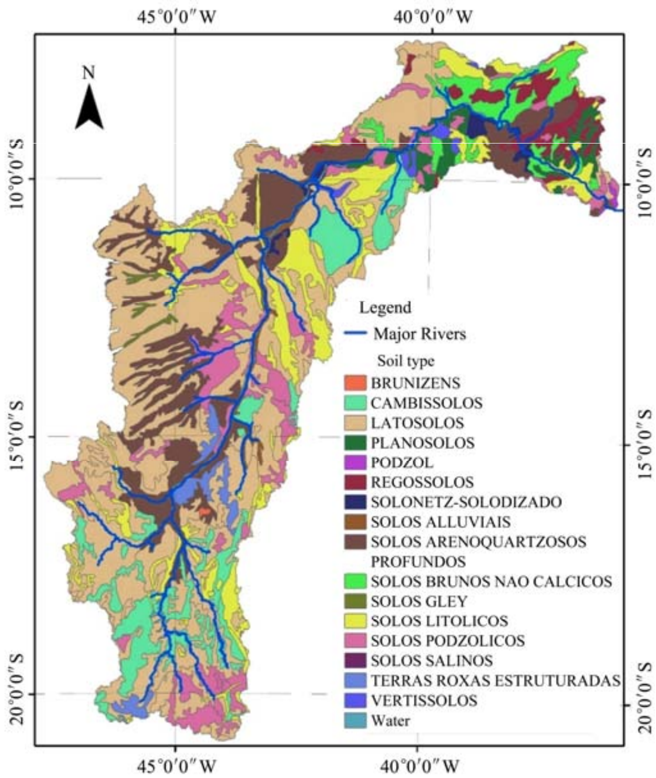


Figure 3 Soils data of the São Francisco River Watershed

The topography data was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) by NASA[42]. This data consists of a 30 m Digital Elevation Model (DEM) for the entire basin (see Figure 4). The DEM data was divided into 3 slope classes: 1) 0-2%; 2) 2%-5%; and 3) Over 5%.

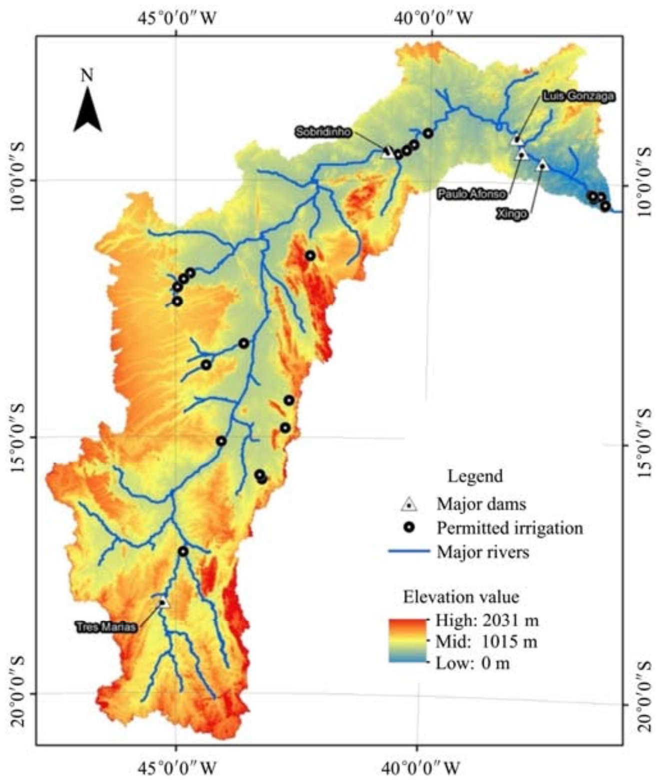


Figure 4 Elevation, major dams and permitted irrigation locations

Five of the largest reservoirs in the São Francisco basin were added to the model: Três Marias, Sobradinho, Luiz Gonzaga, Paulo Afonso and Xingó (Figure 4). Reservoir volume, surface area, and some sediment property information associated with each reservoir are shown in Table 2. No rule-based operation plan was available for the reservoirs modeled in SWAT, although minimum outflows in order to provide environmental flows are listed in Table 2. Also, based on the historic record of outflows, a maximum outflow from each reservoir was determined. In the absence of available rule-based operations of the reservoirs, actual outflow data was supplied to the SWAT model for each reservoir based on the ouflow gages located at each reservoir for the baseline model scenario.

Table 2 Reservoir geometry and operation properties

Reservoir name	Year	SWAT ID	Principal spillway volume /10^4 m^3	Surface Area /hm^2	Minimum outflow /($m^3 \cdot s^{-1}$)	Maximum Outflow /($m^3 \cdot s^{-1}$)
Três Marias	1962	71	2 100 000	104 000	500	3 000
Sobradinho	1979	17	3 410 000	422 000	1 500	3 500
Luiz Gonzaga	1988	8	1 070 000	83 000	1 800	4 000
Paulo Afonso	1979	11	120 000	10 000	1 800	4 000
Xingó	1994	14	380 000	6 000	1 800	4 000

Irrigation is permitted throughout the São Francisco River watershed. There are a total of 26 major irrigation sources identified by CODEVASF[43] and these were input into the SWAT model. Actual operation and flow data is not available at the permitted irrigation sources. CODEVASF[43] estimated that each irrigation source is operating at approximately 25% capacity during the dry season (months of April through November). Therefore, the operation of the irrigation systems in the SWAT model included a 25% permitted flow for the months associated with the dry season in the watershed. The names, locations, permitted flow and additional information associated with each irrigation operation are listed in Table 3.

Precipitation data from 60 ANA[44] gages were used in the model. The Climate Forecast System Reanalysis (CFSR)[45] data was obtained at 1 254 locations throughout the basin for all additional weather data including temperature, wind, relative humidity, and solar radiation. Initially, precipitation data from the CFSR was used in the SWAT model, but was replaced with actual rain gage data from ANA due to poor calibration over a sufficient time-period of data using the CFSR data (poor results using the CFSR precipitation data were also reported for a SWAT analysis of the 73 000 km^2 Jaguaribe River watershed located in northeastern Brazil[46]). Weather data was collected from 1995 through 2010 for both the ANA and CFSR data. The year 1995 was used as a warm-up period with all remaining years used for calibration (1996-2006) and validation (2007-2010) of the hydrology within the SWAT model.

The final SWAT delineation is shown in Figure 5. A total of 76 subbasins were delineated. This scale allowed for sufficient analysis of major tributary basins (shown in Figure 5) and is at a scale that is relevant to the coarse analysis of the system wide sediment budget that was analyzed. The two major ecoregions (Cerrado to the south and west, and Caatinga to the north and east of the basin) shown in Figure 5 were used to divide the watershed into two major areas where calibration parameters were adjusted, as necessary.

Table 3 Permitted irrigation activities in the São Francisco Basin

Name	Coordinates		Source	Source type	Intake type	Permitted flow/ ($m^3 \cdot h^{-1}$)	SWAT basin
	Latitude	Longitude					
Gorutuba	15°49'55"S	43°15'46"W	Gorutuba	Dam	Gravity	8762	55
Jaíba	15°5'24"S	44°5'24"W	São Francisco	River	Pump	53529	56
Lagoa Grande	15°44'55"S	43°18'36"W	Gorutuba	Dam	Pump	8740	55
Pirapora	17°14'56"S	44°51'14"W	São Francisco	River	Pump	3750	68
Barreiras do Norte	12°4'48"S	44°57'59"W	Grande	River	Pump	12642	31
Ceraíma	14°17'23"S	42°44'8"W	Carnaíba de Dentro	Dam	Gravity	539	46
Estreito	14°49'35"S	42°48'27"W	Verde Pequeno	Dam	Gravity	4669	53
Formoso A	13°11'7"S	43°38'37"W	Corrente	River	Pump	47160	42
Miroros	11°27'34"S	42°20'34"W	Verde	Dam	Pump	3110	23
Nupeba	11°48'35"S	44°43'0"W	Grande	River	Pump	14196	29
Piloto Formoso	13°36'16"S	44°23'45"W	Formoso	River	Pump	1620	45
Riacho Grande	11°55'28"S	44°50'48"W	Grande	River	Pump	8042	29
São Desidério	12°21'38"S	44°58'20"W	São Desiderio	Dam	Gravity	4700	35
Bebedouro	9°22'45"S	40°26'38"W	São Francisco	River	Pump	13320	12
Nilo Coelho	9°25'37"S	40°49'21"W	São Francisco	River	Pump	83520	13
Betume	10°25'4"S	36°33'34"W	São Francisco	River	Pump	7167	21
Cotinguiba-Pindoba	10°16'30"S	36°46'55"W	São Francisco	River	Pump	6939	21
Propria	10°12'19"S	36°50'4"W	São Francisco	River	Pump	5775	21
Boacica	10°14'04"S	36°38'25"W	São Francisco	River	Pump	9345	21
Itiúba	10°13'13"S	36°4753"W	São Francisco	River	Pump	3373	21
Marituba	10°23'38"S	36°338"W	São Francisco	River	Pump	4817	21
Curaçá	9°3'44"S	40°2'52"W	São Francisco	River	Pump	19675	7
Mandacaru	9°23'3"S	40°26'32"W	São Francisco	River	Pump	5200	12
Maniçoba	9°17'35"S	40°18'57"W	São Francisco	River	Pump	23160	12
Salitre 1	9°28'53"S	40°37'37"W	São Francisco	River	Pump	25200	22
Tourão	9°24'27"S	40°27'31"W	São Francisco	River	Pump	47736	12

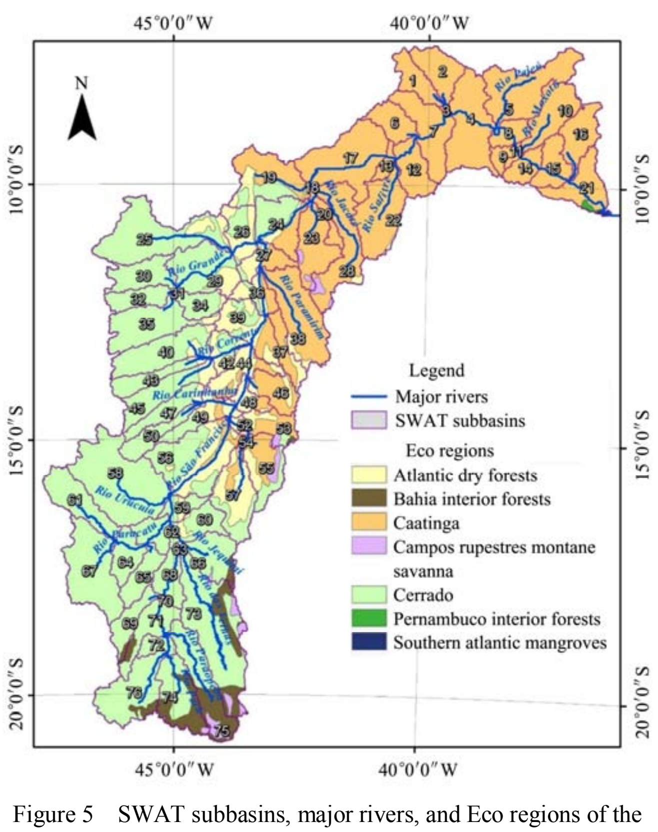


Figure 5 SWAT subbasins, major rivers, and Eco regions of the São Francisco River Watershed

The final SWAT delineation is shown in Figure 5. A total of 76 subbasins were delineated. This scale allowed for sufficient analysis of major tributary basins (shown in Figure 5) and is at a scale that is relevant to the coarse analysis of the system wide sediment budget that was analyzed. The two major ecoregions (Cerrado to the south and west, and Caatinga to the north and east of the basin)[18] were used to divide the watershed into two major areas where calibration parameters were adjusted, as necessary.

3.4 Baseline model calibration

Hydrologic calibration of the São Francisco River baseline conditions was achieved by adjusting 15 variables. These variables and the final values of each are listed in Table 4. Initially, variables with low levels of uncertainty (such as channel geometry information) were fixed, and the automated calibration program SWAT-CUP[47] was used to determine the sensitivity of the variables used in calibration. The P-Value was used to determine parameter sensitivity (lower P-Value signifying higher sensitivity) and each P-Value is listed in Table 4 for all of the parameters analyzed. The baseflow alpha days were computed using the baseflow filter program from Arnold et al.[48]. Next channel widths, depths, and width-depth ratios were estimated using aerial maps and surveyed cross section data at gages. Default SWAT values were applied for all variables not listed in Table 4. The NSE was the primary hydrologic statistical measure used to determine if calibration was achieved. Methods from Moriasi et al.[29] were applied to determine appropriate levels of calibration and validation for the analyzed gages.

ANA manages the hydrology and sediment gage data throughout the São Francisco basin (and throughout Brazil). The hydrology of the São Francisco River basin SWAT model was first calibrated to ANA gage 46360000 located near Morpará, BA, approximately 50 km upstream of the confluence of the São Francisco River and the Rio Grande. This location is near the middle of the project's focus area (the navigation channel), and the location is not influenced significantly by any reservoir operations.

Table 4 Calibration parameters for baseline SWAT model (Hydrology)

Parameter	Table	Description	Sensitivity (P-value)	Initial estimated value	Value used
ALPHA_BF ($days^{-1}$)	.gw	Baseflow alpha days	0.0173	0.0095	0.0095
OV_N	.hru	Manning's "n" value of overland flow	0.120	0.08	0.096
SOL_K (mm/hr)	.sol	Saturated hydraulic conductivity	0.125	Varies	R: -0.15
RCHRG_DP	.gw	Deep aquifer percolation fraction	0.207	0.10	0.02
ESCO	.hru	Soil evaporation compensation factor	0.366	0.95	0.88
CH_K1 (mm/hr)	.sub	Hydraulic conductivity in tributaries	0.378	5	5
SLSUBBSN (m)	.hru	Average slope length	0.453	90	113
CH_K2 (mm/hr)	.rte	Hydraulic conductivity in main channel	0.498	5	3
REVAPMN (mm)	.gw	Depth of water in shallow aquifer for revap	0.503	100	58
CN2	.mgt	Runoff curve number	0.508	Varies	R: -0.09
CH_N2	.rte	Manning's "n" value for main channels	0.601	0.03	0.022
GW_DELAY (days)	.gw	Groundwater Delay	0.618	30	32
SOL_AWC	.sol	Available Water Capacity of the Soil Layer	0.627	Varies	R: -0.14
CH_N1	.sub	Manning's "n" value for tributary channels	0.771	0.03	0.05
GW_REVAP	.gw	Groundwater revap coefficient	0.880	0.02	0.038

Note: R: Relative Change from Default Values (multiply default value by 1 + R).

The simulated hydrology was then calibrated and validated at 16 additional gages throughout the São Francisco River basin located at the outlet of 10 major tributaries as well as 6 locations along the São Francisco River main channel (the Morpará gage is the seventh gage location on the main channel). Calibration could not be achieved by fixing all of the variables listed in Table 4 constant throughout the watershed due to the heterogeneity of the characteristics of the basin. Calibration parameters were adjusted for the subbasins associated with the Caatinga ecosystem (separated calibration from the Cerrado ecosystem). The ALPHA_BF.gw was adjusted to 0.005 for each HRU within the Caatinga ecosystem. Also the CH_K1.sub and CH_K2.rte were adjusted to 10 mm/h and 50 mm/h respectively for the Caatinga sub-basins. Finally, deep water recharge (SWAT parameter RCHRG_DP.gw) was adjusted to 10% for the Caatinga subbasins.

3.5 Baseline model sediment calibration

SWAT is able to calculate sediment sources and sinks at a variety of time scales in the output files. Table 5 includes the variables, units and output file names used for each of the parameters used in the sediment budget calculation. The sediment output was evaluated at the average annual scale to determine the sediment sources and sinks for the overall watershed. Since the sources and sinks are calculated at an annual scale, much of the sediment that is delivered to a river will not be transported to a final sink (reservoirs, floodplains, or the ocean) within an annual timescale. Therefore, the bed (or channel) was considered both a source and a sink of the sediment budget at the annual scale in order to demonstrate how much sediment is in mobilization in a given year.

Table 5 Output variables at monthly scale used to calculate annual sediment budget

Output Variable	Output File	Description	Units	Type
CH_BNKtons	output.sed	Bank Erosion	t	Source
CH_BEDtons	output.sed	Bed Erosion	t	Source
SYLDt_ha	output.sub	Overland Sediment Yield	$t \cdot hm^{-2}$	Source
CH_DEPtons	output.sed	Bed Deposition	t	Sink
SED_INtons – SED_OUTtons	output.rsv	Reservoir Sedimentation	t	Sink
FP_DEPtons	output.sed	Floodplain Deposition	t	Sink
SED_OUTtons at SWAT ID 21	output.sed	Sediment Load to Atlantic Ocean	t	Sink

The calibration of sediment yield for typical SWAT modeling studies is based on a Percent Bias (PBIAS) statistical technique and is a recommended method by Moriasi et al.[29]. The Morpará Gage (ANA Gage 46360000) was selected for the initial basin-wide calibration of the SWAT model for sediment as well as hydrology. Suspended sediment data is collected at the Morpará gage 4 times per year using a USDH-59 sampler as described by Carvalho et al.[49], which collects only suspended sediment loads. A joint CODEVASF-USACE[50] study found that the bedload in this reach is approximately 25% of the suspended load. This data was compiled into a flow-sediment load rating curve and monthly sediment loads were calculated for the years 2001-2010. The years 1996-2000 were removed from the sediment budget calculation in order to calculate average annual sediment budget variables for the baseline conditions which include the current landuse conditions and current reservoir trapping efficiency rates. The SED_INtons monthly output from the output.sed table at the Morpará gage (SWAT ID 27) was used to compare and calibrate/validate to the observed data. Fourteen sediment calibration parameters (listed in Table 6) were adjusted to achieve calibration of sediment.

3.6 Historic conditions scenario model

In order to understand the impacts to the sediment budget and navigation channel due to anthropogenic changes in the watershed, a pseudo Pre-European SWAT model of the basin was developed. The historic conditions SWAT model scenario attempted to achieve a physical representation of the landuse activities prior to European settlement, without adjusting any of the hydrologic inputs to the model. The primary sources of pre-development morphological conditions of the river are described in a previous survey conducted in the early 1850s by Henrique Guilherme Fernando Halfeld[51]. These Halfeld maps provide significant insight into the conditions of the São Francisco River prior to major development in the basin. After reviewing these maps it was shown that there is very little difference between current widths of the river and the river widths in 1852-1854 when the survey was conducted.

Table 6 Calibration parameters for baseline SWAT model (Sediment)

Parameter	Table	Description	Value used
CH_WDR/$m \cdot m^{-1}$	.rte	Channel width/depth ratio	10
CH_COV1	.rte	Channel erodability factor	0.6
USLE_P	.mgt	Universal Soil Loss Equation Support Practice Factor	0.15
LAT_SED/$mg \cdot L^{-1}$	.hru	Sediment concentration in lateral flow	0
CH_BNK_KD/$cm^3 \cdot N^{-1} \cdot s^{-1}$	.rte	Erodability of Channel Bank Material	0.1
CH_BED_KD/$cm^3 \cdot N^{-1} \cdot s^{-1}$	.rte	Erodability of Channel Bed Material	1
CH_BNK_D50/μm	.rte	Median particle size of bank material	500
CH_BED_D50/μm	.rte	Median particle size of bed material	500
CH_BNK_TC/$N \cdot m^{-2}$	.rte	Critical Shear Stress of Channel Bank	0.2
CH_BED_TC/$N \cdot m^{-2}$	.rte	Critical Shear Stress of Channel Bed	0.08
CH_ERODMO1-12	.rte	Erodability Factor by Month	1
CH_EQN	.rte	Sediment Transport Equation	1
RES_SED/$mg \cdot L^{-1}$	.res	Initial Sediment Concentration in Reservoir	1
RES_NSED/$mg \cdot L^{-1}$	.res	Normal Sediment Concentration in Reservoir	1

Figure 6 demonstrates the similar morphology of the river at a location near Paratinga, Bahia in 1852 and 1999. This is a typical result when comparing the majority of the maps that have not been influenced by dams. Although the typical river conditions and morphology have not significantly changed in the last 150 years, there have been significant changes in the areas where dams have been constructed. The construction of the dams has created a sediment sink, which captures sediment that would have historically flowed downstream. The SWAT model associated with the pre-European development scenario includes the removal of all existing dams. The stream widths in the currently impounded areas were updated using the Halfeld[51] widths in these locations.

a

b

Figure 6 River morphology near Paratinga, Bahia (formerly Urubú) in 1852 (a) and in 1999 (b)

Another major anthropogenic change to the watershed includes the conversion of native vegetation to agriculture and urban cities. All of the agricultural and urban landuses were converted to mixed forest throughout the watershed in the "pre-European development SWAT model". This is based on the forest vegetation associated with the native Cerrado and Caatinga ecosystems that would have covered the majority of the watershed prior to European settlement. In addition, the USLE equation support practice factor was lowered to 0.05 for all landuse categories to simulate the sediment loads associated with the native vegetation, and irrigation was turned off at all sub-basins.

4 Results

4.1 Baseline model results

The hydrologic budget of the São Francisco River basin was calculated to ensure that hydrologic conditions are accurately represented in the baseline condition. Average annual precipitation over the modeled timescale (1996-2010) was 630 mm (of which 77% or 485 mm returned to the atmosphere due to evapotranspiration). Of the remaining 145 mm of water, the SWAT model output demonstrates that approximately 19 mm is in the form of surface water runoff, 53 mm in lateral flow, and 65 in return flow, and 7 mm is lost to recharge of the deep aquifer. This water budget is within reasonable values for a semi-arid watershed with very sandy soils and a high baseflow ratio.

The predicted versus measured monthly flows over the entire 15-year simulation period, at ANA gage 46360000 located near Morpará (Figure 7), are shown in Figure 8. Figure 9 displays a second comparison between the simulated and measured flows at ANA gage 43980002 (Figure 7), located at an example major tributary (the Rio Urucuia), which has been identified as a major source of sediment loads to the São Francisco River navigation channel[52]. In general, SWAT replicated flow measured trends well, although some peaks were underestimated, especially at gage 43980002

(Figure 9). The underestimation of the peaks in Figure 9 may be attributed to uncertainties with weather data and possibly uncontrolled reservoir releases within the Urucuia basin. The comparison of the monthly simulated and measured flow simulations at gage 46360000 yielded NSE values of 0.75 and 0.77 for the calibration (1996-2005) and validation (2006-2010) periods, respectively, which equate to a model evaluation status of "very good" based on previous suggested criteria[29]. The overall statistical evaluation for the 17 gages (Table 7) confirms that SWAT adequately replicated measured flow patterns across the basin.

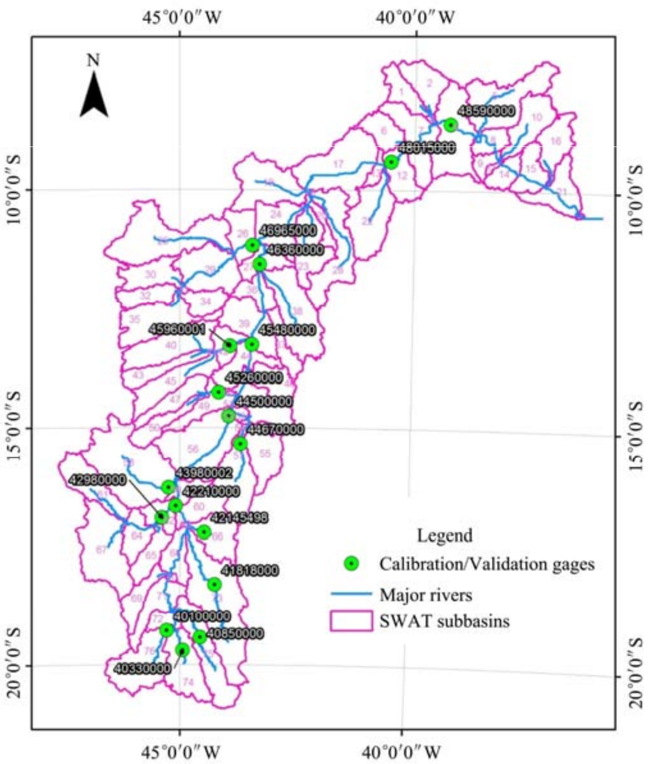


Figure 7 Calibration/validation gages within the São Francisco River SWAT model

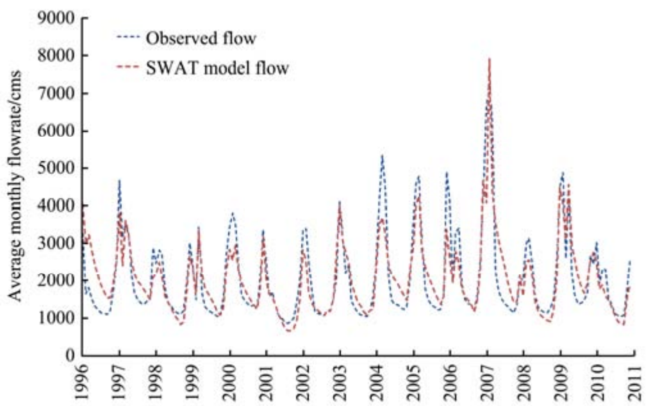


Figure 8 Hydrologic calibration (1996-2005; NSE=0.75) and validation (2006-2010; NSE=0.77) at ANA gage 46360000 located near Morpará (Figure 7)

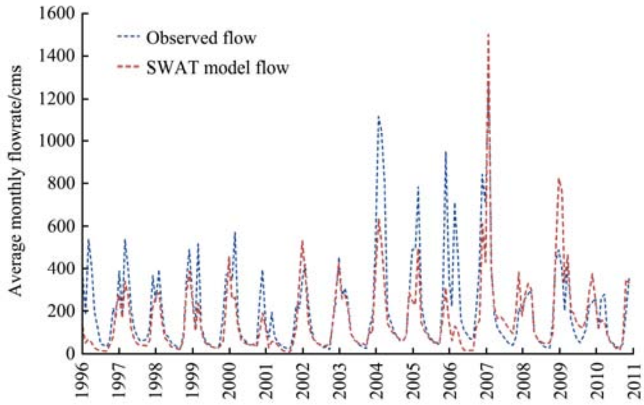


Figure 9 Hydrologic calibration (1996-2005; NSE=0.55) and validation (2006-2010; NSE=0.60) at ANA gage 43980002 at the confluence of the Urucuia River and the São Francisco River (Figure 7)

Table 7 Hydrology Calibration and Validation at 17 ANA Gages within the São Francisco River Basin

ANA Name	Gage	SWAT Basin	NSE Calibration 1996-2005	NSE Validation 2006-2010	Description
Rio Pará	40330000	74	0.52	0.42	Satisfactory
Rio Paraopeba	40850000	75	0.42	0.59	Satisfactory
Rio das Velhas	41818000	73	0.53	0.67	Satisfactory
Rio Jequitai	42145498	66	0.68	0.70	Good
Rio Paracatu	42980000	62	0.65	0.65	Good
Rio Urucuia	43980002	58	0.55	0.60	Satisfactory
Rio Verde Grande	44670000	57	0.49	0.57	Satisfactory
Rio Carinhanha	45260000	49	0.61	0.72	Satisfactory
Rio Corrente	45960001	42	0.59	0.58	Satisfactory
Rio Grande	46965000	26	0.72	0.70	Good
Rio São Francisco upstream of Pará	40100000	76	0.65	0.66	Good
Rio São Francisco at Manteiga	42210000	60	0.48	0.60	Satisfactory
Rio São Francisco at Manga	44500000	56	0.66	0.67	Good
Rio São Francisco at Bom Jesus de Lapa	45480000	44	0.74	0.74	Good
Rio São Francisco at Morpará	46360000	27	0.75	0.77	Very Good
Rio São Francisco at Juazeiro	48015000	12	0.69	0.53	Satisfactory
Rio São Francisco at Ibó	48590000	4	0.60	0.65	Satisfactory

Note: Locations of gages displayed in Figure 10. General criteria for determining Satisfactory, Good, and Very Good Calibration/Validation from Moriasi et al.[29].

Following hydrologic calibration, the SWAT output was compared to the observed sediment loads, (Figure 10) and a PBIAS of 11.6 was calculated for the calibration period of 2001-2006 and -22.6 for the validation period of

2007-2010. According to Moriasi et al.[29] this is considered a “Good” calibration of monthly sediment loads. In some years the model under predicts the observed peak sediment loads (specifically 2003, 2005, and 2006) although matches well under low flows and sediment loads. Possible reasons for some of the discrepancies between the observed data and model output include uncertainty in the observed data (associated with the scatter in the flow-sediment load rating curve), the episodic nature associated with sediment erosion (landscape and bank erosion), as well as inherent uncertainties with the model input parameters at the watershed scale.

Each of the net average annual sediment source and sink data are summarized in Figure 11. Thisoutput demonstrates that a small percentage of the net sediment erosion comes from the banks of the São Francisco River and the major tributaries (6.1%). The much larger contribution of the net sediment to the São Francisco River is from the upland overland flow and small tributaries (approximately 93.9% of the net erosion). Most of the sediment that is delivered to the São Francisco River is deposited in the 5 major reservoirs modeled in the basin (61.9%). Only a small percentage is deposited in the São Francisco River floodplain (3.4%). This may be due to the limited over-bank flooding that occurs due to regulation of the major reservoirs. The bed erosion is also a major sediment sink (30.9%). Overall, the model calculates approximately 27 Mt/a is deposited within the main São Francisco River and major tributaries, leading to a net aggradation in the navigation channel. This is consistent with the conclusions of the ANEEL et al.[34] and CODEVASF and ANA[35] studies.

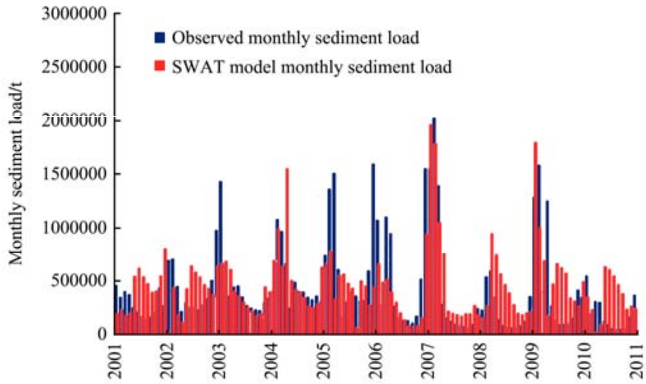


Figure 10 Calibrated (2001-2006) Monthly Sediment Load (PBIAS = 11.6) and Validated (2007-2010) Sediment Load (PBIAS = -22.6) at ANA Gage 46360000located near Morpará (Figure 7)

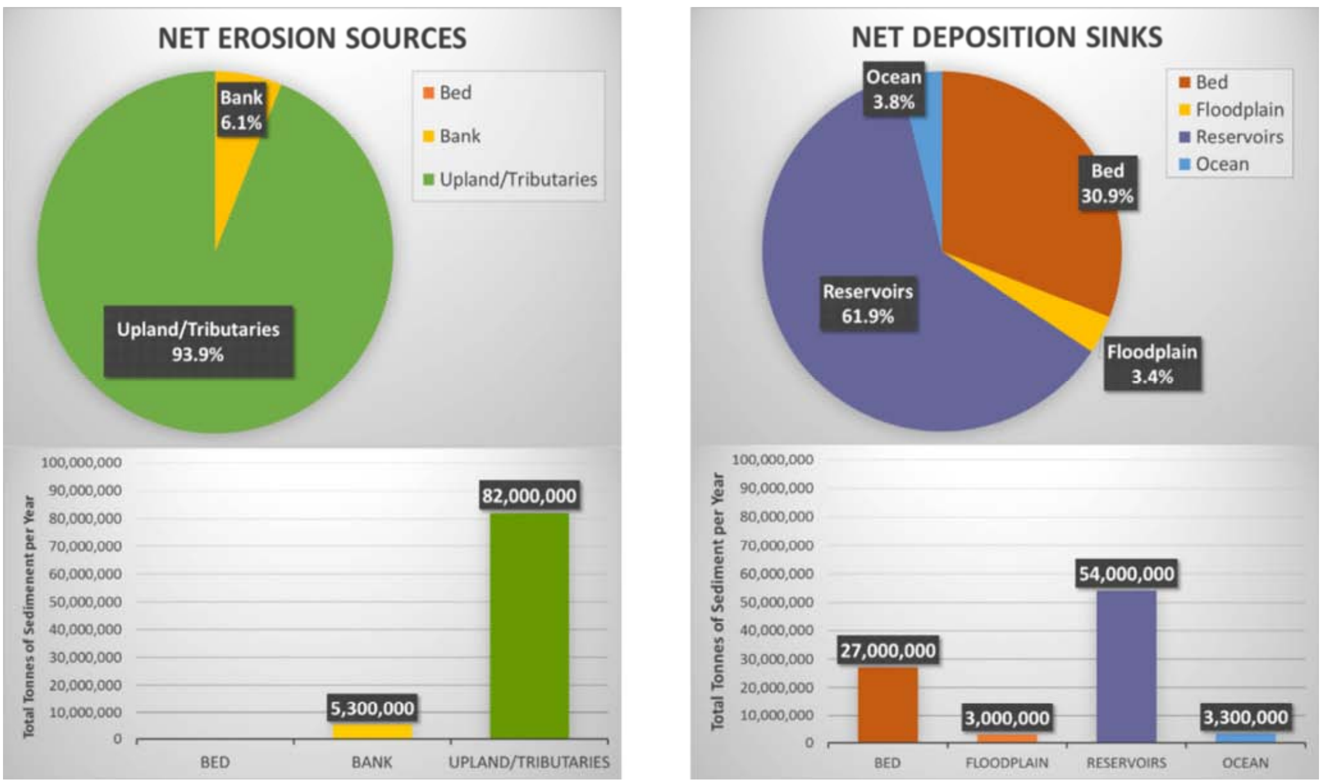


Figure 11 SWAT output of net sediment sources (left) and net sediment sinks (right) for baseline scenario (2001-2010)

Approximately 3.3 Mt (or 3.8% of the deposition sinks) of sediment is calculated to be delivered to the Atlantic Ocean at the São Francisco River mouth. A suspended sediment gage at Propriá, Sergipe (ANA gage 49705000, located approximately 69 km from the São Francisco River mouth) shows the long-term suspended sediment load (from 1977-1999) is 2.7 Mt/a. The Propriá gage is located in the São Francisco River estuary without any major tributaries between Propriá and the São Francisco River mouth, and may be used to represent the sediment load to the Atlantic Ocean. The SWAT model annual average sediment load results are similar to the long-term sediment load at the Propriá gage.

Syvitsky and Milliman[53] developed a predictive model for suspended sediment delivery of major rivers to the oceans using dimensional analysis of the sediment load, area, topographic relief, fluid density, and gravity. Syvitsky and Milliman[53] corrected the mathematical model results by using a glacier erosion factor, basin-wide lithology factor, reservoir trapping factor, and soil erosion factor. Using this model, Syvitsky and Milliman[53] calculated that the São Francisco River delivers approximately 6.4 Mt of sediment per year to the Atlantic Ocean (compared to the 3.3 Mt that the SWAT model calculated). The overestimation by Syvitsky and Milliman[53] may be due to the selected reservoir trapping factor of 0.30 (representing a 70% reservoir trapping efficiency). Due to the three major dams just upstream of mouth, a larger trapping efficiency value may be more appropriate.

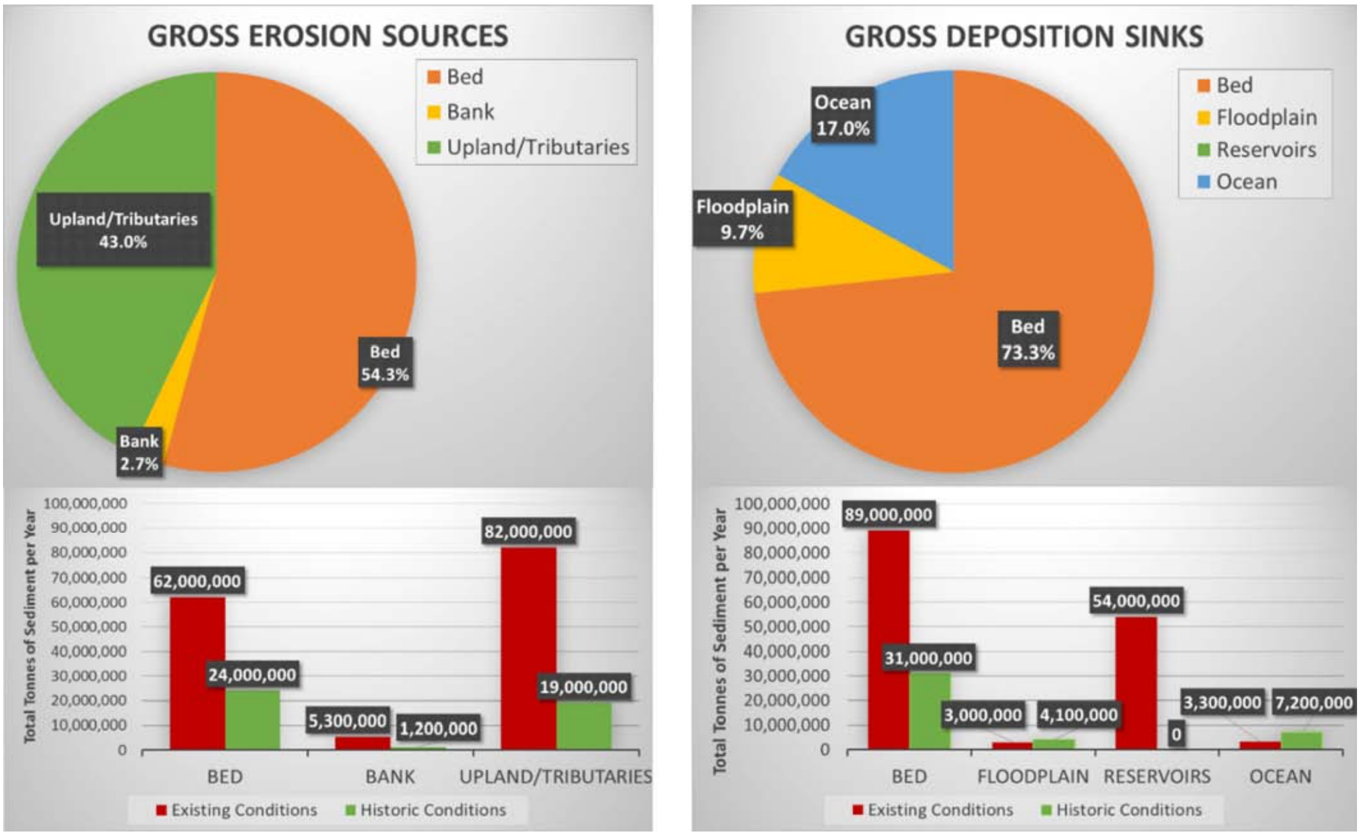
The SWAT model predicts that the total average annual load of sediment that is trapped in reservoirs is approximately 54 Mt based on the 2001-2010 simulation. Assuming a specific gravity of 2.65, the total volume of sediment entering the reservoir is 20.4 Mt/a. The total volume of the 5 reservoirs being modeled is 70.8 billion m^3, and the volume lost represents about 0.03% per year. This is significantly less than the world average of 1% lost per year according to Mahmood[54] and an order of magnitude less than the average of storage lost in North America (0.2% was calculated by White[55]). A major reason that percentage of storage lost per year is less than other estimates for large regions is that the 5 reservoirs modeled include extremely large volume reservoirs including Sobradinho (34.1 km^3) and Três Marias (21 km^3). Due to the very large volumes associated with the dams in the São Francisco River Basin, the overall percentage volume lost per year is smaller than the world average rate.

4.2 Historic conditions scenario results

The SWAT model was used to calculate the historic conditions scenario sediment budget by adjusting landuse and management parameters to pre-European conditions. Table 8 and Figure 12 summarize the anthropogenic impacts on the São Francisco River sediment budget. Overall, the SWAT model shows that there have been a significant increase in erosion sources including bed erosion (158% increase), bank erosion (342% increase), and upland / minor tributary contributions (332% increase) since European settlement. Following agricultural and urban development (and the construction of dams), there has been a corresponding increase in sediment deposition in the river bed (187% increase) and a small decrease in floodplain deposition (27% decrease). Reservoirs are the most significant sink increase with an absolute increase of 54 Mt/a of trapped sediment.

Table 8 Comparison of gross sediment sources and sinks for historic and baseline scenarios

Erosion (Sources)	Pre-European Settlement Loads/($t \cdot a^{-1}$)	Baseline Conditions Sediment Loads/($t \cdot a^{-1}$)	Change/%
Bed	24,000,000	62,000,000	158%
Bank	1,200,000	5,300,000	342%
Upland / Tributaries	19,000,000	82,000,000	332%
Deposition (Sinks)	Pre-European Settlement Loads/($t \cdot a^{-1}$)	Baseline Conditions Sediment Loads/($t \cdot a^{-1}$)	Change/%
Bed	31,000,000	89,000,000	187%
Floodplains	4,100,000	3,000,000	-27%
Reservoirs	0	54,000,000	∞
Ocean	7,200,000	3,300,000	-54%



a b

Figure 12 SWAT output of historic scenario sediment sources (a) and sediment sinks (b)

Due to development (primarily the construction of dams) there is a notable decrease in the overall sediment loads to the ocean (54% decrease). This observation is consistent with other researchers such as Syvitski et al[53,56], which have noted an overall global reduction in sediment yields to oceans. The reduction in sediment loads following the dam construction may also be evidenced through the recent beach erosion that is occurring near the São Francisco River mouth. Due to a reduction in sediment loads to the mouth, there may not be the historic replenishment of sediment from the river in order to replace the sediment lost due to the long-shore littoral transport forces. This phenomenon has been described at other major river outlets including the Mississippi River in Louisiana, where wetland losses have occurred due to the placement of dams and levees that resulted in a reduction in sediment to the coastal delta[57].

Based on model results, the aggradation rate of sediment in the São Francisco River and major tributaries has increased by 20 Mt since pre-European settlement of the basin (from approximately 7 Mt/a to over 27 Mt/a). This has contributed to the current navigation impairments of sediment shoals in the São Francisco River navigation channel. Although large volumes of sediment are captured in the Três Marias dam upstream of the navigation channel, there is a significant increase in sediment loads due to development that has occurred in the major tributaries and along the main stem of the São Francisco River.

5 Summary and conclusions

A hydrology and sediment yield SWAT model was developed in order to analyze the historic and modern sediment budget of the São Francisco River basin. The SWAT model was calibrated and validated to seventeen different flow gages, and two sediment gages. Calibration achieved Satisfactory to Very Good ratings for all gages analyzed.

The SWAT model was used to calculate a sediment budget for the watershed and to analyze the changes to the sediment budget since pre-European settlement. The major changes to the basin since Pre-European settlement include significant landuse conversions, construction of dams, and changes to hydrology associated with irrigation. No attempt was made to replicate historic climate (precipitation, temperature, etc) conditions in the historic conditions model. Instead, modern hydrology was applied in order to compare overall impacts to the sediment budget using the same hydrologic inputs. Insight into the sediment dynamics of the system was developed based on the investigation of the results of these two scenarios.

Overall, the baseline conditions model demonstrated that a small component of the existing sediment budget is due to bank erosion of the São Francisco River. Approximately 6.1% of the sediment that is causing shoals in the São Francisco River may have originated in the banks of the São Francisco River or the banks of the major tributaries. The remaining 93.9% of the sediments that are causing shoals originated from overland sediment sources or sediment erosion occurring in minor tributaries. Due to the high percentage of sediments that originated in the uplands and minor tributaries, bank erosion measures alone will have a negligible effect on mitigating the existing shoals in the São Francisco River navigation channel.

The baseline condition SWAT model was compared to the pre-European settlement conditions model to determine major changes to the historic sediment budget associated with the construction of dams, and the conversion of native vegetation to current landuse, which is dominated by agriculture. The historic conditions model demonstrates that most sources and sinks have increased since Pre-European settlement. Bank erosion, bed erosion, and overland loads of settlement have all increased. Bed storage and reservoir storage have also increased since the pre-settlement conditions. Deposition in floodplains was shown to have slightly decreased since pre-European settlement (-27%) and this may be due to the reduction in peak flows associated with the regulation of dams. The most notable decrease to a sediment source or sink was exhibited in the sediment load to the Atlantic Ocean, where the model results demonstrated a 54% decrease since pre-European settlement. This is an expected result due to the construction of major dams upstream of the mouth, which has led to capturing of sediments.

Based on model results, the aggradation rate of sediment in the São Francisco River and major tributaries has increased by approximately 20 Mt since pre-European settlement of the basin (from approximately 7 Mt/a to 27 Mt/a). This has contributed to the current navigation impairments of sediment shoals in the São Francisco River navigation channel.

The SWAT model may also be used to analyze future conditions for the stakeholders in the basin under a wide range of scenarios. A future conditions model may demonstrate impacts due to proposed mitigation measures in the basin or responses to environmental conditions, navigation, power generation, climate change, etc. The SWAT model developed is a tool that can assist landuse managers in understanding the watershed response (hydrologic and sediment) to various landuse activities.

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