COUPLED SEDIMENT YIELD AND SEDIMENT TRANSPORT MODELING TO SUPPORT WATERWAY NAVIGATION PLANNING IN NORTHEAST BRAZIL

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Abstract

The São Francisco River Basin - located in northeast Brazil - has undergone a significant amount of anthropogenic changes in the last several decades, including 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 commodities to regional ports. In an effort to aid decision makers in future waterway navigation planning, a SWAT model of the 630,000 km^2 São Francisco River basin was developed and used to calculate a basin-wide sediment budget.

The SWAT model of the São Francisco River Basin was calibrated for hydrology and sediment loads. Monthly discharges were calibrated at ten Agência Nacional de Águas (ANA) gages, with NSE values ranging from 0.52 to 0.72 for a six-year simulation. An additional seven ANA gages were used to validate the model, resulting in NSE values between 0.51 and 0.88 for these additional gages. Sediment loads were calibrated to an ANA sediment gage located in the Middle São Francisco River Navigation Channel, with a PBIAS of -12.6. A sediment budget was calculated and approximately 94% of the sediment that is shoaling in the navigation channels originates from overland sources. A total of approximately 23 million tonnes of net sediment is deposited in the bed of the São Francisco River and major tributaries annually. This net deposition has contributed to an impaired navigation channel due to shoaling of sandy sediments in the navigation channel.

Combining a geomorphology study with the SWAT model, conceptual designs for navigation improvements were developed for the São Francisco River navigation channel. A HEC-RAS sediment transport model was built for the navigation channel to predict long-term navigation sustainability using spur dikes and cut-off dikes at the critical shoals. This conceptual design was shown to be a viable long-term alternative to maintaining a sustainable, economically feasible navigation channel when compared to the current practices of maintenance dredging alone.

Keywords: Sediment Budget, Waterway Navigation, Sediment Transport, Sediment Yield

INTRODUCTION

The Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba (CODEVASF) and the US Army Corps of Engineers (USACE) engaged in an intergovernmental partnership agreement to support river engineering, navigation improvements, and bank stabilization projects along the São Francisco River in northeast Brazil. The São Francisco River is an important north-south corridor of navigation in Brazil, which links the important agricultural and mining activities that occur in the southern states of Minas Gerais and Bahia to the northeast part of the country. The São Francisco River Basin has undergone significant landuse changes over the previous few decades. Large percentages of the watershed have been converted from native vegetation to either grazing or intense row crop agriculture. In addition, hydropower dams and large-scale irrigation projects have been constructed and the expansion of row crop farming as well as dam and pumping plant construction is expected to continue in the basin. The impacts associated with these watershed changes are currently not well understood, and a numerical watershed yield model and navigation sediment transport model were developed to improve the overall understanding of the sediment dynamics (yield and transport) in the São Francisco River Basin and navigation channel.

The São Francisco River is approximately 2,900 kilometers in length with a watershed area of 630,000 km^2 (see Figure 1). It is the longest river that is entirely contained within Brazil and includes portions of the states of

Alagoas, Bahia, Goiás, Minas Gerais, Pernambuco, Sergipe, and the Federal District. The upstream boundary of the navigation channel begins at a small port city – Pirapora, Minas Gerais. The navigation channel then continues through a low sinuosity alluvial river valley for 1,015 km until it reaches the upstream end of a large reservoir, the Sobradinho reservoir. Navigation continues approximately 200 kilometers through the Sobradinho reservoir (which includes a navigation lock), and then another 42 kilometers downstream of the reservoir through a rock controlled section of river. The navigation channel terminates at the twin port cities of Juazeiro, Bahia, and Petrolina, Pernambuco. The São Francisco River continues downstream of Petrolina/Juazeiro for an additional 675 river kilometers through three large hydropower dam systems (which do not include any navigation locks) to its outlet in the Atlantic Ocean. There is no commercial navigation downstream of Petrolina/Juazeiro.

Figure 1 Location Map and Boundary of the São Francisco River Basin

Approximately 13 million people live in the São Francisco River 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 associated with a cerrado ecosystem is present in the headwaters with a high diversity of mixed forest, and a caatinga ecosystem (sparse and stunted vegetation) is associated with the semi-arid region of the watershed to the north. More information regarding physical characteristics of the São Francisco Basin is found in CODEVASF & ANA (2002) and Biswas et al. (1999), which presents an overview of the site location, weather, vegetation, hydrology, navigation, dams, development, geomorphology, geology, and other watershed feature information.

METHODS

Modeling Framework

A decision support system is necessary for planning the waterway development within the São Francisco River Basin. The primary navigation impedance in the São Francisco River waterway is shoaled alluvial sediment (primarily medium sand), which reduces the navigation draft and prohibits year-round commercial transport of agricultural goods and mining commodities. To address these concerns, a numerical modeling framework to support navigation planning was developed and then applied to the São Francisco River in Northeast Brazil. This modeling framework includes the development of a hydrology and sediment yield model of the São Francisco River Watershed, coupled with a sediment transport model of the navigable waterway. The results of this watershed model were used for determining sub-watersheds that are primary sources of sediment and also used as input values for the sediment transport model. The sediment transport model was developed for the Middle São Francisco River, where the current alluvial navigation channel is defined.

The modeling approach consists of nine steps (graphically presented in Figure 2). First, an understanding of the existing sediment dynamics of the basin is developed using the Soil and Water Assessment Tool (SWAT) as the sediment yield model. Next, this information is used to develop a sediment budget for the watershed, which indicates the primary sediment sources and sinks. The sediment budget allows for decision makers to prioritize sediment mitigation measures (either focusing on upland sediment management, bank stabilization, or other mitigation areas). The sediment mitigation measures then can be applied into a watershed development plan. The future conditions of the watershed plan are then modeled in a future sediment yield model (using SWAT) to understand the future sediment dynamics of the system.

In parallel to the sediment management planning and modeling, an understanding of the fluvial system is necessary for navigation planning purposes. A geomorphology study of the waterway allows for a determination of what types of measures may be suitable for improvement of the shoaling issues. The geomorphology study feeds into a conceptual design of a navigation plan that can consist of dredging, and riverine training structures, such as spur dikes, cutoff dikes, and other navigation structures. The sediment dynamics of the future watershed plan and the conceptual design of the waterway can then be modeled in a sediment transport model to predict the effectiveness of the proposed conceptual designs and to make iterative revisions in order to finalize a proposed navigation plan.

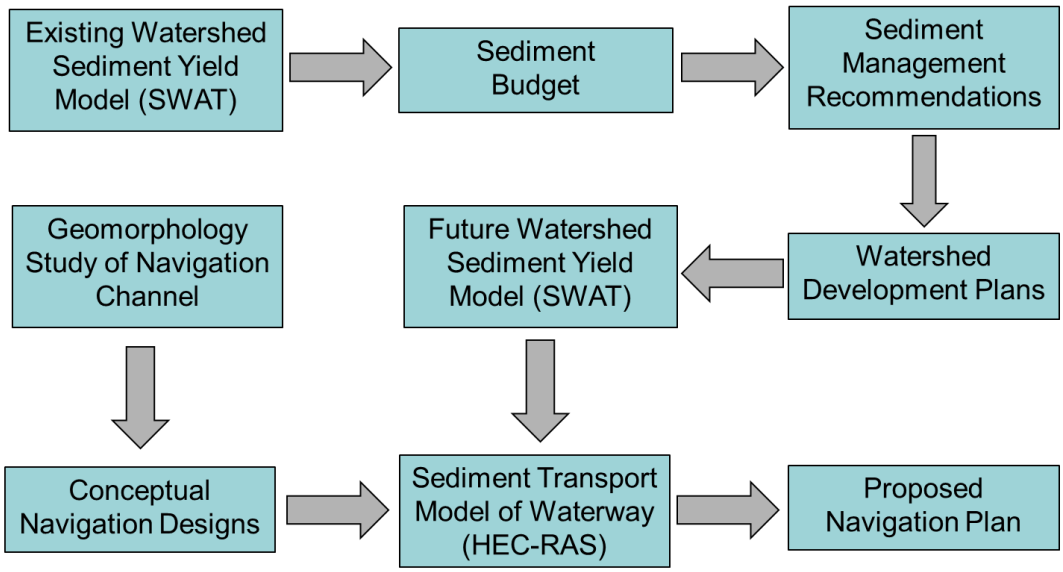

Figure 2 Waterway Modeling and Planning Framework

Hydrology and Sediment Yield Model

The Soil and Water Assessment Tool (SWAT) was the model selected to evaluate the sediment dynamics of the São Francisco River Basin. The primary data that was used to build a hydrology and sediment yield model in SWAT include the following: topography, soils, landuse, reservoirs, irrigation withdrawals, weather (precipitation, temperature, relative humidity, solar radiation, and wind), and river gages (streamflow and sediment gages). The topography, soils, and landuse layers were overlaid in ArcSWAT and were used to create Hydrologic Response Units (HRUs). Areas that have similar slopes, soil classification, and landuse were grouped into a single HRU, with each subwatershed consisting of numerous HRUs.

The topography data were obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) by NASA (NASA, 2013). This data consists of a 30m Digital Elevation Model (DEM) for the entire basin. The DEM data was divided into three slope classes 1) 0-1%; 2) 1-2%; and 3) Over 2% (see Figure 3a for derived slope classes).

Soils data were obtained from the Empresa Brasileira de Pesquisa Agropecuária (Emprapa, 1981), which had previously been converted to a digital format by the U.S. Geological Survey's EROS Data Center. There are seventy soil groups defined in the overall Brazil Soil Dataset within the São Francisco River watershed. See Figure 3b for a map of the soils in the watershed. Soil physical and chemical property data were not directly available in the Embrapa dataset; therefore, a second soil dataset was used to extract soil property information and was applied directly to the Embrapa soil boundaries. The International Soil Reference and Information Centre (ISRIC) provides a soil data set at a 5 arc-minute resolution for the world, including soil physical and chemical properties (Batjes, 2012).

The GlobCover 2005 (European Space Agency, 2006) was used to assign the landuse to the São Francisco River SWAT model. GlobCover 2005 is a global dataset with 300m x 300m resolution of landcover from the year 2005. Figure 3c includes the landuse data used in the SWAT model.

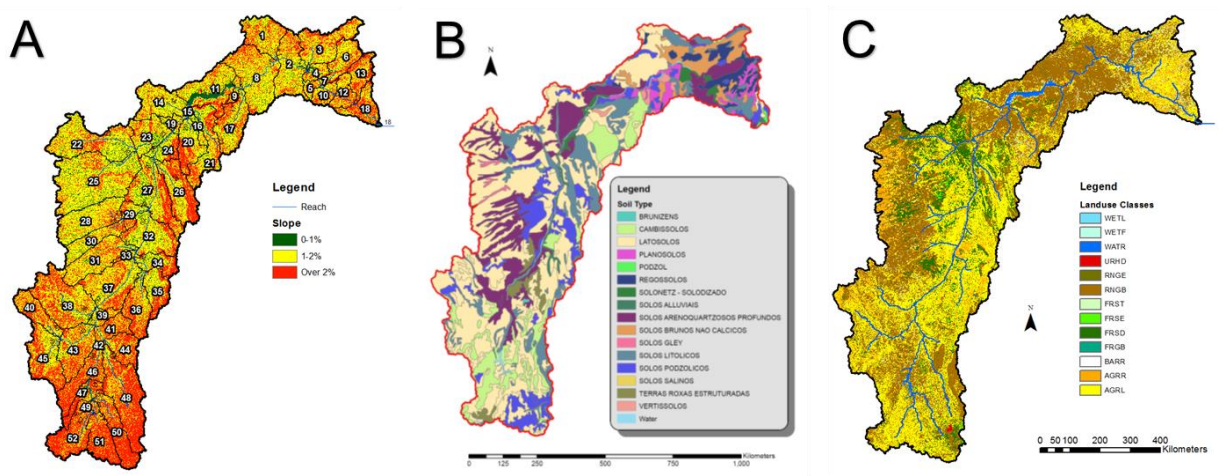

Figure 3 HRUs Built from A – Slope (ASTER, 2013); B – Soils (Embrapa, 1981); and C – Landuse (European Space Agency, 2006)

Five of the largest reservoirs in the São Francisco Basin were added to the model. These reservoirs include the Três Marias, Sobradinho, Luiz Gonzaga, Paulo Afonso and Xingó reservoirs. Irrigation practices were also added to the SWAT model. Irrigation within the basin is permitted throughout the São Francisco River watershed, with most projects owned and constructed by CODEVASF. There are a total of 26 major irrigation sources identified by CODEVASF (2013) and these were input into the SWAT model.

Weather data for the São Francisco River Basin were obtained from the Global Weather Data website http://globalweather.tamu.edu/. These data includes temperature, precipitation, wind, relative humidity, and solar radiation weather. Weather data were collected from 1995 through 2006 at 1,254 locations throughout the basin.

Although the modeling was designed to include daily output from 2001-2006, all data from 1995 through 2006 were collected in order for the model to have a sufficient "hotstart" period (from January 1, 1995 through December 31, 2000). Existing conditions, historic conditions (using pre-European settlement landuse data and the removal of anthropogenic activities such as hydropower and irrigation), as well as future conditions of the hydrology and sediment were modeled using the developed SWAT model.

The Nash Sutcliffe Efficiency (NSE), developed by Nash and Sutcliffe (1970) was the primary hydrological statistical measure to determine if calibration was achieved. The NSE is a measure of how much better a model predicts hydrologic behaviors compared to the mean of the observed data. The calibration of sediment yield for typical SWAT modeling studies is based on a Percent Bias (PBIAS) statistical technique, which was applied to this study. The São Francisco Basin SWAT model was first calibrated to the hydrology of a gage in the Middle São Francisco basin at Morpará (ANA gage 46360000). Monthly flow simulations yielded a NSE = 0.66 and daily flow simulations yielded a NSE = 0.56 for a simulation from 2001-2006 (Figure 4).

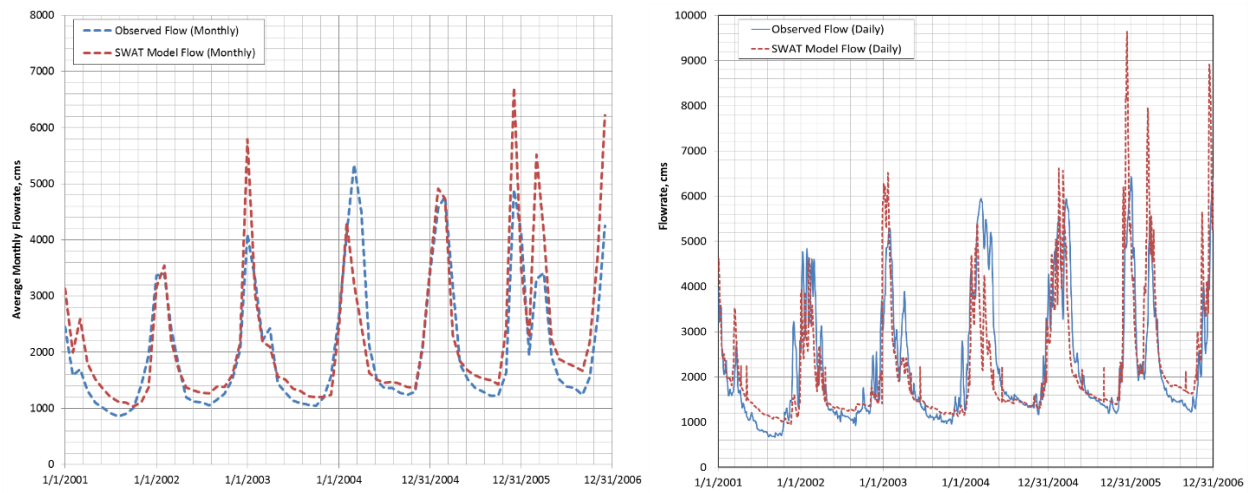

Figure 4 Monthly (left) and Daily (right) Hydrology Calibration at Morpará Gage

The hydrology was calibrated at ten locations throughout the basin and validated at seven additional gages along the São Francisco River's main channel. All calibration and validation yielded a minimum of satisfactory results based on recommended procedures from Moriasi et al (2007), and is presented in Table 1.

The Morpará Gage (ANA Gage 46360000) was selected for the initial basin-wide calibration of the SWAT model for sediment. This gage was selected for the following reasons: 1) the gage includes a long daily flow record (since 1954) and is still an active gage; 2) the gage includes both flow and sediment records; 3) the gage is in the middle São Francisco River (the focus area of navigation impacts); and 4) the gage is not heavily influenced by dams/reservoirs. Suspended sediment data are collected at the Morpará gage four times per year using a USDH-59 sampler, which collects suspended sediment loads. Previous studies have found that the bedload in this reach is approximately 25% of the suspended load (Creech, 2014). These data were compiled into a flow-sediment load rating curve and monthly sediment loads were calculated for the duration of the SWAT simulation (2001-2006). The SWAT output was compared to the observed sediment loads, and a PBIAS of -12.6 was calculated for the length of the simulation (Figure 5). According to Moriasi et al. (2007) this is considered a "Very Good" calibration of monthly sediment loads.

Calibration of the hydrology and sediment for the São Francisco River baseline conditions was achieved by adjusting 15 variables for the hydrology, and 14 additional variables for sediment loads. These variables and the final values of each are listed in Table 2 and 3. Calibration was achieved combining manual methods and utilizing the automated calibration programs SWAT-CUP. All other variables not listed in Table 2 and 3 applied default SWAT values.

Table 1 Hydrology Calibration and Validation within the São Francisco and Major Tributaries

ANA Name	Gage	SWAT Basin	Type	NSE	Description
Rio Pará	40330000	74	Calibration	0.66	Good
Rio Paraopeba	40850000	75	Calibration	0.72	Good
Rio das Velhas	41818000	73	Calibration	0.63	Satisfactory
Rio Jequitaí	42145498	66	Calibration	0.67	Good
Rio Paracatu	42980000	62	Calibration	0.61	Satisfactory
Rio Urucuia	43980002	58	Calibration	0.57	Satisfactory
Rio Verde Grande	44670000	57	Calibration	0.6	Satisfactory
Rio Carinhanha	45260000	49	Calibration	0.58	Satisfactory
Rio Corrente	45960001	42	Calibration	0.67	Good
Rio Grande	45965000	26	Calibration	0.52	Satisfactory
Rio São Francisco upstream of Pará	40100000	76	Validation	0.51	Satisfactory
Rio São Francisco at Manteiga	42210000	60	Validation	0.73	Good
Rio São Francisco at Manga	44500000	56	Validation	0.75	Very Good
Rio São Francisco at Bom Jesus de Lapa	45480000	44	Validation	0.76	Very Good
Rio São Francisco at Morpara	46360000	27	Validation	0.66	Good
Rio São Francisco at Juazeiro	48015000	12	Validation	0.88	Very Good
Rio São Francisco at Ibó	48590000	4	Validation	0.57	Satisfactory

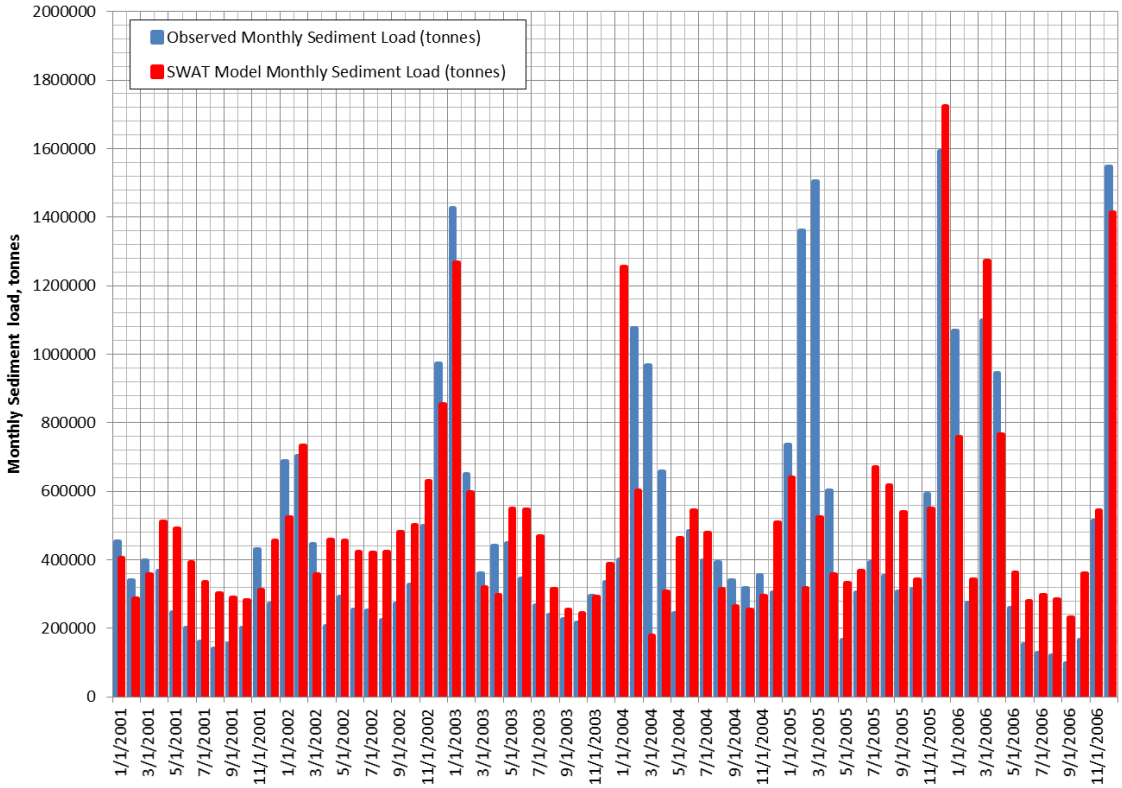

Figure 5 Monthly Suspended Sediment Load Calibration at Morpará Gage

Table 2 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

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

Table 3 Calibration Parameters for Baseline SWAT Model (Sediment)

Parameter	Table	Description	Value Used
CH_WDR (m/m)	.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/l)	.hru	Sediment concentration in lateral flow	0
CH_BNK_KD (cm^3/N-s)	.rte	Erodability of Channel Bank Material	0.1
CH_BED_KD (cm^3/N-s)	.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/m^2)	.rte	Critical Shear Stress of Channel Bank	0.2
CH_BED_TC (N/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/l)	.res	Initial Sediment Concentration in Reservoir	1
RES_NSED (mg/l)	.res	Normal Sediment Concentration in Reservoir	1

Geomorphology Study and Sediment Transport Model

The São Francisco River has a very mild slope (ranging from approximately 0.00006 m/m at the downstream reaches to 0.00013 m/m at the upstream reaches). The width of the river ranges from approximately 200 meters in the upper reaches of the navigation channel to approximately 1 km in the lower reaches (upstream of the Sobradinho Reservoir). Widths can be much larger and in some locations the bank to bank width is over 2 km where islands are present. Depths are on average 2-3 meters deep; however, the navigation channel ranges from 0.3 meters to over 18 meters according to a survey of the navigation channel conducted in 2012 by the Administração da Hidrovia do Rio

Sao Francisco (AHSFRA, 2012). AHSFRA is responsible for the operation and maintenance of the navigable portion of the waterway.

Upon evaluation of the current morphological conditions of the navigation channel a pattern of the plan-form was observed. The São Francisco River within the boundaries of the navigation channel generally consists of a narrow and deep section of the river which is horizontally controlled by a rocky bank, with extremely low bank erosion rates. Downstream of the horizontally controlled section, the river begins to widen and in many cases an island may be present in the wide portions of the river. Navigation is typically impeded most significantly either downstream or upstream of the islands in the wider portions, and where the transport capacity of the river is low. Due to the rocky knick points that control many sections of the river, the river evolutionary rates are extremely low. The slow evolutionary patterns are evidenced by comparing historic 19th century surveys of the river to the present day morphology. In the early 1850s, Henrique Guilherme Fernando Halfeld was commissioned by Dom Pedro II, the Emperor of Brazil, to survey the São Francisco River from Pirapora, Minas Gerais to the Atlantic Ocean (Halfeld, 1860). These detailed 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 originally surveys were conducted. See Figure 6 for a comparison of the river morphology near Paratinga, Bahia in 1852 and 1999, which demonstrates that the river has a similar morphology, width, and location of islands between these time periods (although there are some changes to the shape and size of some of the islands). This is a typical result when comparing the majority of the locations of the navigation channel that have not been influenced by reservoirs associated with dams.

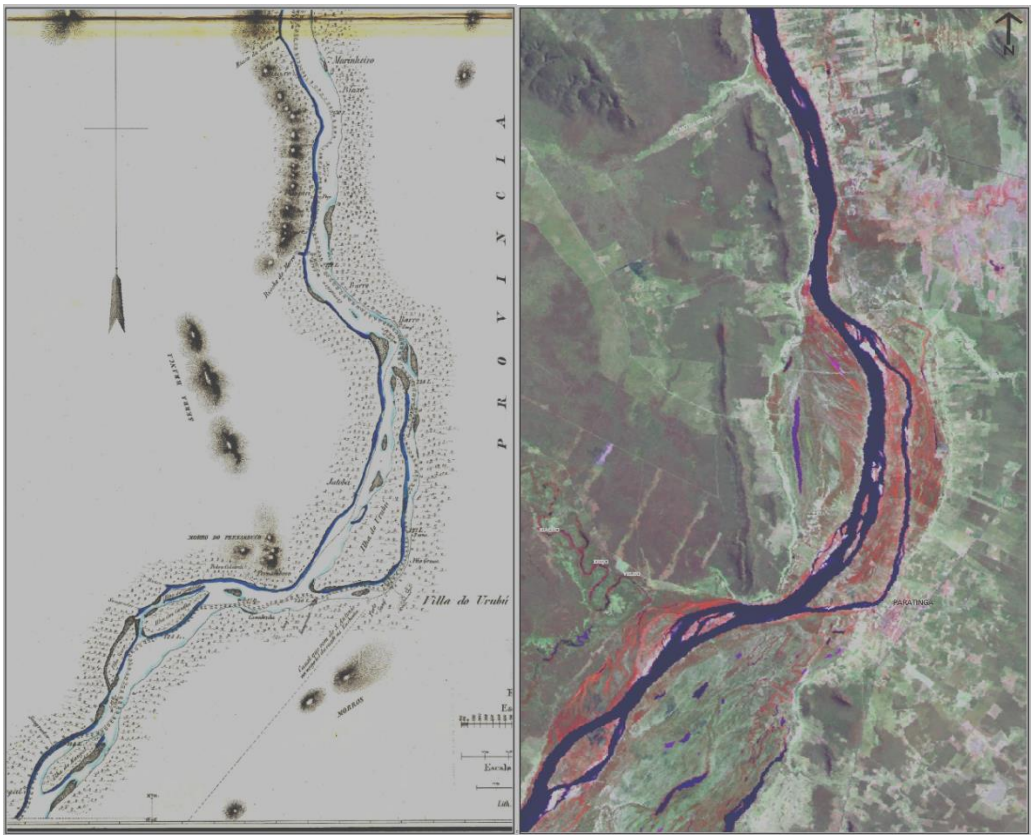

Figure 6 São Francisco River Morphology Surveyed in 1852 (left) and from aerial survey in 1999 (right) at Paratinga, Bahia, Brazil

Prior to the sediment transport modeling, an analysis of the fluvial geomorphology of the river was conducted. The Middle São Francisco River was first divided into sub-reaches based on hydrologic and geomorphic characteristics. The upper and lower limits of each reach are defined at confluences of major tributaries (i.e., where significant increases in flow and sediment exist). Major tributaries contribute a significant load of sediment and flow to the São

Francisco River, leading to potentially differing geomorphic conditions. Between the major tributaries, it was assumed that there is limited hydrologic or geomorphic changes to the slopes, width/depth ratios, sinuosity, etc. The assumption of similar geomorphic characteristics between major tributaries was qualitatively validated by investigating maps of each defined segment. The widths, depths, sinuosity and other dimensionless characteristics were verified to be similar for each defined reach. No major geologic conditions were noted to contribute to a major geomorphic changes in any of the defined reaches. Therefore, the geomorphic reaches are defined based only on the confluences of major tributaries. For each geomorphic reach a specific width of the river is necessary in order to maintain a sustainable self-scouring channel. In locations where the identified width is exceeded navigation shoals may persist. Therefore, a reduction in the effective width (using river training structures) was identified and applied for a conceptual design to be tested and modeled in the HEC-RAS sediment transport model.

RESULTS

SWAT is able to calculate the bank erosion, bed erosion, overland sediment sources, reservoir sedimentation, and net annual sediment loads to the Atlantic Ocean at the watershed scale. Together, these variables make up the São Francisco Basin's sediment budget. The sediment output was evaluated at the average annual scale to determine the sediment sources and sinks for the overall watershed. Each of the net average annual sediment source and sink data are summarized in Figure 7 based on the six-year SWAT simulation. This figure shows that a small percentage of the gross sediment erosion comes from the banks of the São Francisco River and the major tributaries (approximately 6%). The much larger contribution of the net sediment to the shoaling navigation channel is from the upland overland sources and small tributaries (approximately 94% of the net erosion). Most of the sediment that is delivered to the São Francisco River is deposited in the five major reservoirs modeled in the basin (approximately 72%). Only a small percentage is deposited in the São Francisco River floodplain (less than 1%). This may be due to the limited over-bank flooding that occurs due to regulation of the major reservoirs. Overall, the model predicts approximately 23 million tonnes of sediment per year (approximately 25% of the sinks) is deposited within the São Francisco River navigation channel and major tributaries, leading to a net aggradation in the system.

Figure 7 Sediment Budget: Net Sources (Left) and Sinks (Right) of Sediment in the São Francisco River Basin

Approximately 2.5% of the sediment sinks is associated with the delivery of sediment to the Atlantic Ocean at the São Francisco River mouth. Syvitsky and Milliman (2007) 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. Using this model, Syvitsky and Milliman (2007) calculated that the São Francisco River should deliver approximately 6.4 million tonnes of sediment per year to the Atlantic Ocean (compared to the 2.3 million tonnes that the SWAT model calculated). A suspended sediment gage at Propriá, Sergipe (ANA gage 49705000, located approximately 69 km upstream from the São Francisco River mouth) shows the long-term suspended sediment load (from 1977-1999) is approximately 2.7 million tonnes per year. 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. The overestimation by Syvitsky and Milliman (2007) 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 the mouth, a trapping efficiency of 85% may be more appropriate, which would bring the Syvitsky and Milliman reservoir trapping factor to 0.15. This would change their prediction of sediment delivery to the Atlantic Ocean from the São Francisco River to 3.2 million tonnes per year; a value closely resembling the observed long-term average at the Propriá gage.

Based on the required reductions in width of the São Francisco River navigation channel for each geomorphic reach, conceptual river training structure designs were developed and analyzed in a sediment transport model. An example of a conceptual design is shown in Figure 8. After the structures were input into the sediment transport model, the results of a six-year simulation were analyzed. The primary analysis consisted of investigating the depths of the thalweg along the navigation channel. This provided confirmation that the proposed design (based on geomorphic characteristics of each reach) would provide a sufficient amount of self-scour along the navigation channel. In several instances the self-scouring goal of 2.0 meters at the low water datum (an economically viable navigation draft) was not achieved, and the structures were revised. After the revised structures were added to the model, the channel was able to maintain a self-scour depth of at least 2.0 meters along the channel for each geomorphic reach. The results of the final navigation depths are shown in Figure 9.

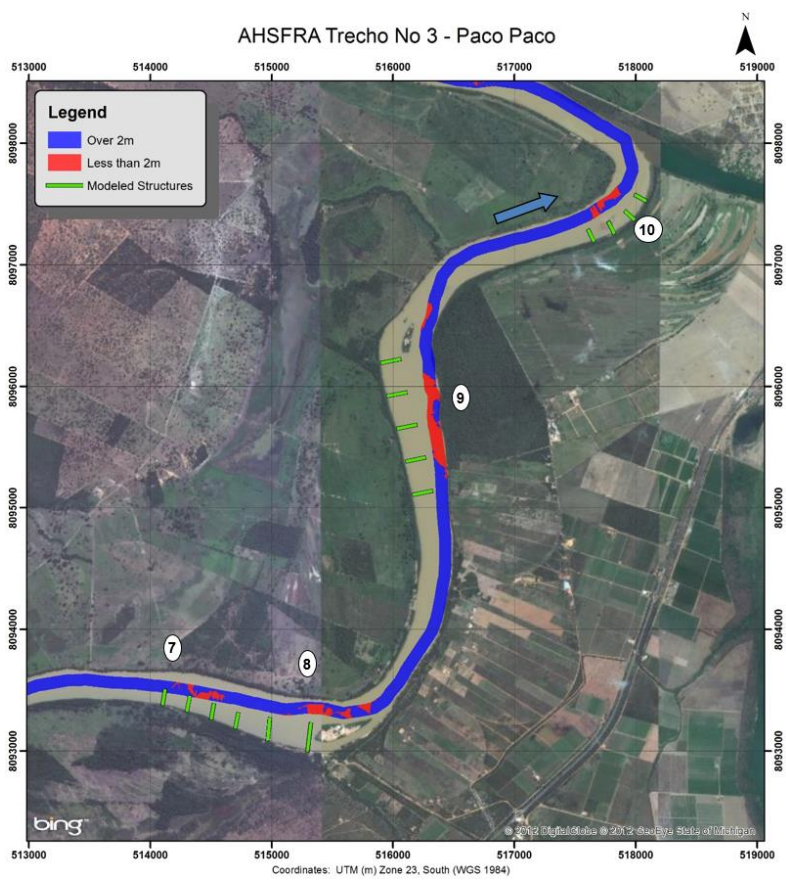

Figure 8 Typical Structure Design for Improved Navigation in the São Francisco River

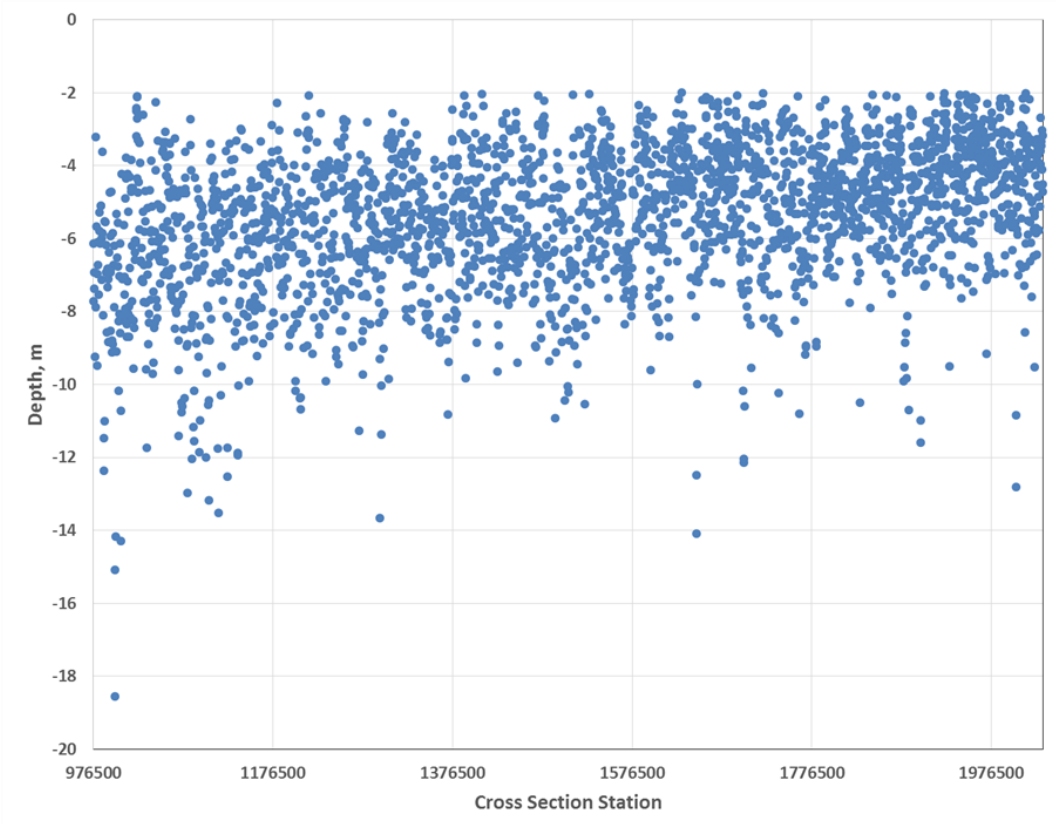

Figure 9 Predicted Navigation Channel Depths following a Six-Year Sediment Transport Simulation

CONCLUSIONS

A SWAT model of the São Francisco Basin was developed to calculate a modern sediment budget for the watershed and to analyze the changes to the sediment budget since Pre-European settlement. Based on the SWAT model results, currently only a small component of the existing sediment budget is due to bank erosion of the São Francisco River. Approximately 5.6% 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 94.4% 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 the existing shoals in the São Francisco River navigation channel, and an improved navigation channel will only result from minimizing sediment yields at upland sources and by projects designed to improve navigation at the shoal locations.

The sediment transport model confirms the effectiveness of the conceptual layout of self-scouring structures, and the proposed alignments of structures can be used as a guide for planning long-term structural solutions for improving navigation of the Sao Francisco River. The linked sediment yield and sediment transport modeling is a system wide model, which characterizes likely future conditions throughout the entire system, and the modeling demonstrates that the layouts and approaches used will likely not create new navigation hazards. The modeling conducted in this alternative analysis should only be used as a guide for general structure layouts and planning purposes. Any specific project will need to develop a site-specific model or analysis in order to verify the effectiveness of the proposed self-scouring structures. In addition, other concerns such as bank erosion associated with the proposed designs (particularly on the opposite bank) will need to be investigated for any site-specific project that will be developed into a basic or executive design. Therefore, although the model will not support detailed analysis at the site-specific level, the modeling results can be used for general planning purposes such as calculating costs to efficiently develop the Sao Francisco River navigation channel.

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