Coupled Sediment Yield And Sediment Transport Model To Support Navigation Planning In Northeast Brazil

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

by

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DISSERTATION

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of Wayne State University,

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CHAPTER 1.0 INTRODUCTION

1.1 Background and Project Location

Waterway navigation for transportation of bulk goods (agricultural and mining commodities) is an underutilized means of transportation in Brazil (DNIT, 2012). The Brazilian Department of Transportation (DNIT) has developed a transportation plan that seeks to equally balance road, rail, and waterway transportation by the year 2025 (DNIT, 2012) by significantly increasing transportation associated with waterways (and to a lesser extent increasing railway transportation). DNIT and other agencies are focusing resources on waterway development in order to improve this economically efficient means of transportation of bulk goods. The Sao Francisco River – located in Northeastern Brazil – is one of the waterways that is a current focus area of DNIT and other agencies due to its strategic importance of a major north-south transportation corridor. This natural waterway corridor links the humid and agriculturally rich areas in the southern portion of the watershed, to the economically stressed, semi-arid areas in the northern part of the watershed.

The research associated with this dissertation consists of the development of a numerical modeling framework to support the navigation planning, which is then demonstrated in the case study of the Sao Francisco River in Northeast Brazil. This modeling framework includes the development of a hydrology and sediment yield model of the Sao Francisco River Watershed coupled with a sediment transport model of the navigable waterway. The results of this watershed model was used for determining sub-watersheds that are primary sources of sediment and also used as input values for the river hydraulics and sediment transport model. The sediment transport model was
developed for the Middle Sao Francisco River, where the current alluvial navigation channel is defined (approximately 1,015 kilometers in length).

The entire Sao Francisco River is approximately 2,900 kilometers in length with a watershed area of approximately 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, Goias, 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 for 1,015 km until 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 Sobradinho reservoir through a rock controlled section of river. The navigation channel terminates at the twin port cities of Juazeiro, Bahia, and Petrolina, Pernambuco. The Sao Francisco River continues downstream of Petrolina/Juazeiro for an addition 675 river kilometers through 3 large hydropower dam systems (which do not include any navigation locks) to its outlet in the Atlantic Ocean. There is no major commercial navigation downstream of Petrolina/Juazeiro.

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 Sao Francisco River (north). Vegetation includes cerrado systems in the headwaters with a high diversity of mixed forest as well as caatinga vegetation (a sparse and stunt vegetation associated with the semi-arid region of the watershed). More information
regarding physical characteristics of the Sao 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.
Figure 1: Location of the Sao Francisco River Watershed
1.2 Problem Statement

As with typical watersheds, the rate of sediment delivery in the Sao Francisco River Watershed has been non-uniform through both geologic and modern time scales (Kothyari et al., 1997). Sediment delivery rates are affected by a variety of geologic processes, hydrologic and climate variability, fluvial geomorphic evolution of the landscape, and anthropogenic alterations in the tributary watersheds.

The specific modern anthropogenic modifications of the Sao Francisco River are noteworthy. A significant amount of the Sao Francisco basin has been converted from native vegetation to grazing or intense row crop farming. These anthropogenic landscape changes have altered the rate of sediment delivery over and above the natural variation of historic sediment loads that occur due to geologic and geomorphic processes. In addition, dams have been constructed and both the expansion of row crop farming and dam construction is expected to continue in the watershed. The construction of dams have increased the amount of storage of sediment within the basin. Together, the combined impacts associated with these watershed changes (landuse development leading to increased sediment yields, and dams leading to increased sediment storage) are currently not well understood. As a result a sediment yield model was proposed to be developed in order to improve the overall understanding of the sediment dynamics in the Sao Francisco River watershed basin and its potential future impacts to navigation.

The objective of this research consists of the development of a baseline model of the existing sediment conditions by building a watershed model that can calculate a sediment budget for the watershed. Outputs from the sediment yield model were coupled with a sediment transport and analysis model in order to determine conceptual planning
approaches to improve the navigation channel between Pirapora, MG and the terminus of the alluvial navigation channel at the Sobradinho reservoir (approximately 1,015 km). Planning approaches can include dredging, engineering works (such as dikes to create a self-scouring channel) or a combination of both. The model assisted in determining feasible alternatives to achieve an economically viable navigation draft (in the case study of the Sao Francisco River this navigation draft consist of a 2.0 meters channel between Pirapora, MG and the Sobradinho Reservoir).

1.3 **Hypothesis**

The hypothesis of this research consists of the following statement:

The development of a navigation plan consisting of river training structures, which promote a self-scouring navigation channel, is a feasible alternative to traditional dredging approaches alone for an alluvial system where depositional shoals currently hinder navigation.

A case study of the Sao Francisco River was used to test this hypothesis, and the model was designed to demonstrate that the construction of self-scouring structures will provide a sustainable, reliable navigation channel for the Sao Francisco River for a minimum project life of 50-years. The output of the sediment yield model is used as an input into the sediment transport model in order to accurately capture and apply the sediment dynamics within the watershed to the navigation channel for both existing and future planning efforts that are on-going in Brazil.
CHAPTER 2.0 LITERATURE REVIEW

This research includes the development of a hydrologic and sediment yield model of the Sao Francisco River Watershed, coupled with a sediment transport model. A rigorous selection process was conducted to determine the most appropriate sediment yield model to be coupled with the Hydrologic Engineer Center – River Analysis System (HEC-RAS), which is the sediment transport model. The numerical model of the watershed basin was selected based on the ability to address the following objectives:

1. The model shall be used to develop a Watershed Sediment Budget of the case study – the Sao Francisco River Watershed.
2. The current and potential future sediment delivery to the Sao Francisco River shall be able to be calculated using the selected sediment yield model. This will assist in determining the future navigation conditions of the river.
3. The model shall be able to determine which sub-watersheds are primary sources of sediment in order to recommend areas of prioritization for best management practices.
4. The output of the model (sediment yields from each sub-basin) shall be able to be used as the input values for the 1-dimensional hydraulics and sediment transport model.

2.1 Sediment Budget

A watershed sediment budget identifies sources and sinks as well as transport mechanisms in order to understand the sediment yields and sediment delivery rates within a watershed. The major erosion sources of the sediment budget include 1) overland
runoff; 2) rill and gully erosion; 3) mass wasting; 4) river bank erosion; 5) river bed erosion; and 6) wind erosion. Sediment sinks consist of 1) wetlands; 2) floodplains; 3) upland storage; 4) in-channel storage; and 5) reservoirs. Figure 2, modified from Reid and Dunne (1996), provide a graphic of how the sediment sources, sinks and transport mechanisms are related within a watershed. The sediment yield model was used to calculate the components of the sediment budget (described in Chapter 6).

Several terms associated with the sediment budget are defined below, which will be used throughout this report:

**Erosion (also Gross Erosion)** – the gross detachment and mobilization of sediment from an individual source. Most of the sediment that is mobilized in a given event
(precipitation or wind) on the landscape is not transported to streams, but instead is moved from one upland location to another.

**Sediment Delivery** – the total sediment load transported to a specific location in the stream network (such as a gage, lake, dam, etc.). Sediment Delivery is often expressed in annual terms by weight, such as tons/year.

**Sediment Yield** – the annualized sediment delivery normalized by the contributing drainage basin area, often expressed in tons/km²/year or tons/acre/year.

**Anthropogenic** – conditions that have been influenced by human activity such as landuse change and construction of reservoirs.

**Baseline** – the current or modern sediment delivery, yield, and storage conditions.

**Natural (as in Natural Sediment Loads)** – the component of sediment delivery, yield, or storage that is not associated with human activity. This is also assumed to be equivalent to the Pre-European settlement sediment delivery, yield, and/or storage.

The rate of erosion from each of the sediment budget sources has been impacted by human modifications of the landscape, which has led to a general increase in sediment yield for each source. For example, the clear cutting of the native vegetation, which covered the majority of the Sao Francisco River basin, and the subsequent conversion to agricultural landuses had the following general consequences:

- Sediment erosion associated with overland flow has likely increased due to the greater percentage of exposed soils eroding at a higher rate during precipitation events.
• The exposed sediment in agricultural landuses also caused an increase in aeolian (wind generated) sediment erosion.

• Removal of native vegetation weakened the soil structure along natural swales, leading to rill erosion and, ultimately, gully erosion.

• The removal of vegetation on the landscape decreased plant interception and transpiration, increased impervious surface area, and consequently led to a change in hydrology (generally greater peak flows).

Numerous other human alterations such as irrigation, urbanization, infrastructure projects (water, wastewater, and stormwater), etc., have impacted a large percentage of the Sao Francisco River tributary watersheds. The combined effect of these changes to the natural landscape have likely caused a significant increase in the gross sediment erosion rates within the Sao Francisco River basin.

Storage and sink components of the sediment budget include many natural geomorphic features (such as fluvial floodplains, point bars, mid-channel bars, wetlands, and lakes). Storage also occurs in man-made features such as the reservoirs behind dams. The construction of dams in modern history has had little effect on sediment erosion (most notable impacts to sediment erosion occur immediately downstream of a dam where a “hungry water” situation results in bank erosion and downcutting). However, dams have had a dramatic effect on the amount of sediment delivered downstream due to the capturing and storage of sediment (Syvitski, et al., 2005). Therefore, although the landuse changes have increased gross sediment erosion, there has also been an increase in the sediment storage, which mitigates some of the increases associated with the landuse
change. The selection of the sediment yield model is based upon ensuring that these processes can accurately be represented in order to make information planning decisions within a watershed in transition.

2.2 Comparison of Sediment Yield Models

Watershed models that simulate the hydrologic and sediment yield processes can provide watershed managers a better understanding of the watershed. Many watershed models can predict hydrologic runoff, sediment yield, upland soil and stream erosion, and transportation and deposition of sediment. For the Sao Francisco River basin, an understanding of the sediment dynamics can assist in determining potential long-term impacts to navigation in the river.

Several numerical modeling tools have been considered to be used for the development of the hydrology and sediment yield model. These models are listed in Table 1. Each model is considered for its relative use in supporting the numerical modeling required to assist navigation planning in the following sections.
Table 1: Watershed and Sediment Yield Models Considered

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Acronym</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areal Nonpoint Source Watershed Environment Response Simulation</td>
<td>ANSWERS</td>
<td>Beasley et al. 1980</td>
</tr>
<tr>
<td>Precipitation-Runoff Modeling System</td>
<td>PRMS</td>
<td>Leavesley et al. 1983</td>
</tr>
<tr>
<td>Agricultural Non-Point Source Pollution Model</td>
<td>AGnPS</td>
<td>Young et al. 1987</td>
</tr>
<tr>
<td>KINematic runoff and EROSion model</td>
<td>KINEROS</td>
<td>Woolhiser et al. 1990</td>
</tr>
<tr>
<td>Hydrological Simulation Program - Fortran</td>
<td>HSPF</td>
<td>Bicknell et al. 1993</td>
</tr>
<tr>
<td>European Hydrological System model</td>
<td>MIKE SHE</td>
<td>Refsgaard and Storm 1995</td>
</tr>
<tr>
<td>Soil and Water Assessment Tool</td>
<td>SWAT</td>
<td>Arnold et al. 1998</td>
</tr>
<tr>
<td>Annualized Agricultural Non-Point Source model</td>
<td>AnnAGNPS</td>
<td>Bingner and Theurer 2001</td>
</tr>
<tr>
<td>Dynamic Watershed Simulation Model</td>
<td>DWSM</td>
<td>Borah et al. 2002</td>
</tr>
<tr>
<td>ANSWERS-Continuous Hydrologic Engineering Center - Hydrologic Model System 4.0 Alpha Gridded Surface Subsurface Hydrologic Analysis</td>
<td>ANNSWERS-Continuous</td>
<td>Bouraoui et al. 2002</td>
</tr>
<tr>
<td></td>
<td>HEC-HMS</td>
<td>USACE 2010d</td>
</tr>
<tr>
<td></td>
<td>GSSHA</td>
<td>Downer and Ogden 2006</td>
</tr>
</tbody>
</table>

2.2.1 Technical Capabilities of Various Sediment Yield Models

The various numerical models considered to be used to analyze the Sao Francisco hydrology and sediment dynamics have a wide range of complexity. Simple models are easy to build and use, but may not capture the various activities in a watershed, and may be incapable of providing desired detailed results. Complex models can be computationally demanding and challenging to construct and calibrate. Therefore, an appropriate model should be selected based on the question(s) to be answered by the model. In addition, the model selected for the Sao Francisco River should be based on
the available data, desired accuracy of output, complexity of the modeling, and other factors.

The watershed models listed in Table 1 can generally be divided into either long-term continuous models or watershed-scale storm-event models. Only long-term continuous models were considered for the Sao Francisco River basin because the objective of the model is to determine the baseline annual sediment budget, and not the dynamics associated with an individual storm. Of the models listed in Table 1 AGNPS, ANSWERS, DWSM, KINEROS, and PRMS model sediment yield based on individual storms only, and therefore will not be considered in the comparison.

The remaining models have been compared based on the technical mechanisms to address various hydrologic and sediment processes. Borah et al. (2008) compared many of these models based on technical criteria and a summary of the findings is described in Table 2 and Table 3. In order to calculate the baseline sediment budget for the Sao Francisco River Watershed, the major processes that must be included in the model include hydrology, sediment yield, reservoirs, and irrigation. Future uses of the model (outside of this research) may include nutrient modeling and Best Management Practices. It is important that the selected model can address each of the processes.

Based on Table 3, ANSWERS-Continuous and GSSHA cannot address the relevant channel or reservoir sediment routing. SWAT, HSPF, MIKE SHE, and HEC-HMS 4.0 Alpha can address the relevant processes that will be required for the model based on a technical review of the model capabilities. Borah et al. (2008) notes that SWAT is most appropriate for primarily agricultural watersheds (such as the Sao Francisco River) and HSPF is more appropriate for mixed agricultural and urban
watersheds. Borah et al. (2008) also notes that MIKE SHE is generally too complicated for efficient applications in large watersheds. GSSHA is also noted to be too complex for large watersheds and cannot support BMPs, which may be a future need of the model. AnnAGNPS is a model similar to SWAT; however, it is not used in as many applications as the SWAT model. HEC-HMS 4.0 Alpha is a new model and is still in the research and testing phase to address sediment yields. HEC-HMS 4.0 Alpha also cannot address BMPs, which may be a future need of the model. Therefore, based on a technical review the models may be ranked in the following order: 1) SWAT; 2) AnnAGNPS; 3) HSPF; 4) HEC-HMS Alpha 4.0; 5) MIKE SHE; 6) GSSHA; and 7) ANSWERS-Continuous.
<table>
<thead>
<tr>
<th>Description/ Criteria</th>
<th>AnnAGNPS</th>
<th>ANSWERS-Continuous</th>
<th>HSPF</th>
<th>MIKE SHE</th>
<th>SWAT</th>
<th>GSSHA</th>
<th>HEC-HMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model components/ capabilities</td>
<td>Hydrology, transport of sediment, nutrients, and pesticides resulting from snow-melt, precipitation and irrigation, source accounting capability, and user interactive programs including TO-PAGNPS generating cells and stream network from DEM.</td>
<td>Daily water balance, infiltration, runoff and surface water routing, drainage, river routing, ET, sediment detachment, sediment transport, nitrogen and phosphorous transformations, nutrient losses through uptake, runoff, and sediment</td>
<td>Runoff and water quality constituents on pervious and impervious land areas, movement of water and constituents in stream channels and mixed reservoirs, and part of the USEPA BASINS modeling system with user interface and ArcView GIS platform.</td>
<td>Interception-ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen process in the root zone, soil erosion, dual porosity, and irrigation.</td>
<td>Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the USEPA BASINS modeling system with user interface and ArcView GIS platform.</td>
<td>Spatially varying rainfall inputs including radar estimates, rainfall excess and two-dimensional flow routing on cascading over-land grids, continuous soil moisture accounting, diffusive wave or full-dynamic channel routing, upland erosion, sediment transport in channels.</td>
<td>Hydrology, transport of sediment, sedimentation, channel and reservoir routing.</td>
</tr>
<tr>
<td>Temporal scale</td>
<td>Long term; daily or sub-daily steps.</td>
<td>Long term; dual time steps: daily for dry days and 30 seconds for days with precipitation.</td>
<td>Long term; variable constant steps (hourly).</td>
<td>Long term and storm event; variable steps depending on numerical stability.</td>
<td>Long term; daily steps.</td>
<td>Long-term and storm event; variable steps depending on numerical stability.</td>
<td>Long-term and storm event; variable time steps.</td>
</tr>
<tr>
<td>Watershed representation</td>
<td>Homogeneous land areas (cells), reaches, and impoundments.</td>
<td>Square grids with uniform hydrologic characteristics, some having companion channel elements; 1-D simulations.</td>
<td>Pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D simulations.</td>
<td>2-D rectangular / square overland grids, 1-D channels, 1-D unsaturated and 3-D saturated flow layers.</td>
<td>Sub-basins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management); ponds, groundwater, reservoirs and main channel.</td>
<td>Two-dimensional square overland grids and one-dimensional channels.</td>
<td>Sub-basins grouped based on hydrologic (lumped areas with same cover, soil, and management), reservoirs and main channel.</td>
</tr>
<tr>
<td>Runoff on overland</td>
<td>Runoff curve number generating daily runoff following SWRRB and EPIC procedures and SCS TR-55 method for peak flow.</td>
<td>Manning and continuity equations (temporarily variable and spatially uniform) solved by explicit numerical scheme.</td>
<td>Empirical unit hydrograph equations solved by Chezy-Manning equation.</td>
<td>2-D diffusive wave equations solved by explicit finite-difference scheme.</td>
<td>Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.</td>
<td>Two-dimensional diffusive wave equations solved by explicit finite-difference scheme.</td>
<td>Several functions including Clark Unit hydrograph, kinematic wave, modClark, SCS Unit Hydrograph, Snyder Unit Hydrograph, or User-specified hydrograph.</td>
</tr>
<tr>
<td>Description/ Category</td>
<td>AnnAGNPS</td>
<td>ANSWERS-</td>
<td>MIKE SHE</td>
<td>SWAT</td>
<td>GSSHA</td>
<td>HEC-HMS</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------</td>
<td>----------</td>
<td>----------</td>
<td>------</td>
<td>-------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>Reservoir Reservoir sediment</td>
<td>Sediment deposition based on constant deposition rate, flow velocity, and pool water.</td>
<td>Sediment deposition based on constant deposition rate, flow velocity, and pool water.</td>
<td>Not simulated.</td>
<td>Not simulated.</td>
<td>No information.</td>
<td>No information.</td>
<td></td>
</tr>
</tbody>
</table>

Impact of watershed management practices on nonpoint source losses.
2.2.2  **Sediment Yield Model Ease of Use**

GSSHA and MIKE SHE are both physically based models using multidimensional flow-governing equations with approximate numerical solutions schemes, which make the models computationally intensive and subject to numerical instabilities. Therefore, these models are the most complex and difficult to use. The remaining models are empirical models that do not require approximate solutions to any partial differential equations. HSPF and SWAT are commonly used models and have numerous documentation, on-line support and training opportunities. AnnAGNPS and ANSWERS-Continuous are less commonly used models and have less documentation and on-line support. HEC-HMS Alpha 4.0 is a promising new software package that handles sediment yield and has a user-friendly interface. Therefore, based on an ease of use basis, the models can be ranked in the following order: 1) HEC-HMS Alpha 4.0; 2) HSPF; 2) SWAT; 4) AnnAGNPS; 4) ANSWERS-Continuous; 1); 6) GSSHA; and 6) MIKE SHE.

2.2.3  **Sediment Yield Model Selection**

Both long-term continuous and storm-event hydrologic and sediment yield models were investigated and compared. The long-term continuous models were compared in an alternative analysis based on the technical basis to calculate a watershed-scale sediment budget and an ease of use. The results of this comparison are shown in Table 4. Based on this comparison, the SWAT model has the highest ranking and, therefore, is the selected model to compute the sediment budget for the Sao Francisco River watershed.
2.3 The Soil & Water Assessment Tool (SWAT) Model

The Soil and Water Assessment Tool (SWAT) is the selected tool to develop the sediment yield dynamics in the modeling framework (and is demonstrated in an application of the Sao Francisco River Watershed). SWAT is a physically-based continuous (daily time-step) watershed model used to evaluate watershed hydrology, sediment yield, and nutrient dynamics, among other processes. SWAT divides a watershed into several sub-basins, and each sub-basin is further divided into Hydrologic Response Units (HRUs). These HRUs are relatively small sub-catchments that are assumed to have uniform properties of soil, management, slope, and landuse; thus the model is a lumped Parameter model at the subwatershed scale (HRU scale), but a distributed model at the watershed scale. HRUs are determined by overlaying several input GIS layers into the model. These layers consist of soil data, landuse (with management), DEM, and weather. The slope, soils and landuse data are intersected and unique combined landuse-soil-slope data are generated as the basis of the HRUs. The

Table 4: Model Comparison

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Technical Basis</th>
<th>Ease of Use</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AnnAGNPS</td>
<td>5</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>ANSWERS-Continuous</td>
<td>0</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>HSPF</td>
<td>4</td>
<td>4.5</td>
<td>8.5</td>
</tr>
<tr>
<td>MIKE SHE</td>
<td>2</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>SWAT</td>
<td>6</td>
<td>4.5</td>
<td>10.5</td>
</tr>
<tr>
<td>GSSHA</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>HEC-HMS Alpha 4.0</td>
<td>3</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

Sum of the Criteria: 21

(0 = worst; 6 = best. Rankings are normalized to add up to 21 total points per category)
sub-basins are linked together through a stream network, and both water and sediments are routed through the watershed via this stream network. Reservoirs are applied at the downstream end of a sub-basin to both attenuate the flow, as well as store sediments. Additional storage can be captured in the model by adding wetlands and ponds into sub-basins. Irrigation can be added at reservoirs or along rivers.

2.3.1 Hydrology in SWAT

The input climate data in SWAT includes daily precipitation, minimum temperature, maximum temperature, solar radiation, relatively humidity, and wind speed. SWAT simulates the hydrology of a watershed using a simple water balance equation (Equation 1):

\[
SW_t = SW_0 + \sum_{i=1}^{t} (R_{\text{day}} - Q_{\text{surf}} - E_a - w_{\text{seep}} - Q_{\text{gw}})
\]

Where:

- \(SW_t\) = final soil water content (mm H2O)
- \(SW_0\) = initial soil water content on day \(i\) (mm H2O)
- \(R_{\text{day}}\) = precipitation on day \(i\) (mm H2O)
- \(Q_{\text{surf}}\) = surface runoff on day \(i\) (mm H2O). Calculated using the SCS curve number method (USDA Soil Conservation Service, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911).
- \(E_a\) = evapotranspiration on day \(i\) (mm H2O).
- \(w_{\text{seep}}\) = water entering the vadose zone from the soil profile on day \(i\) (mm H2O)
- \(Q_{\text{gw}}\) = return flow or base flow on day \(i\) (mm H2O)
2.3.2  Upland Sediment Erosion, Yield, and Delivery in SWAT

Erosion caused by rainfall and runoff is computed using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965). The USLE model provides estimates of long-term (annual) sediment erosion associated with rill and sheet-flow erosion, whereas MUSLE provides estimates of total sediment yield on a daily timestep by incorporating a variable flowrate ($Q_{surf}$). The MUSLE equation is shown in Equation 2.

\[
\text{sed} = 11.8 \left( Q_{surf} \cdot q_{peak} \cdot area_{hru} \right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG
\]  

Where:

- $\text{sed}$ = sediment yield on a given day (metric tons)
- $Q_{surf}$ = surface runoff volume (mm H$_2$O/ha)
- $q_{peak}$ = peak runoff rate (m$^3$/s)
- $area_{hru}$ = area of the HRU (ha)
- $K_{USLE}$ = USLE soil erodability factor
- $C_{USLE}$ = USLE cover and management factor
- $P_{USLE}$ = USLE support practice factor
- $LS_{USLE}$ = USLE topographic factor
- $CFRG$ = coarse fragment factor

Not all of the sediment that is eroded from an upland source is delivered to a stream. The gross erosion associated with precipitation and overland flow processes may be calculated using MUSLE for agricultural watersheds; however, the sediment yield will
be a function of the ratio of eroded sediment that is delivered to the stream divided by the eroded sediment that stays in upland fields (see Equation 3).

\[
SDR = \frac{\text{sediment delivery to stream}}{\text{sediment eroded from upland}}
\]  \hspace{1cm} (3)

Where:

\[SDR = \text{Sediment Delivery Ratio}\]

This sediment delivery ratio is dependent on the watershed drainage area, topography, stream lengths, soil texture, etc. (Borah et al., 2008). The United States Soil Conservation Service (SCS) (1971) estimated sediment delivery ratios as a function of watershed size alone (see Table 5). Due to the single variable used to develop these ratios, a large amount of scatter exists in the original data.

<table>
<thead>
<tr>
<th>Drainage Area, ( km^2 )</th>
<th>Sediment Delivery Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.58</td>
</tr>
<tr>
<td>0.1</td>
<td>0.52</td>
</tr>
<tr>
<td>0.5</td>
<td>0.39</td>
</tr>
<tr>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>10</td>
<td>0.22</td>
</tr>
<tr>
<td>50</td>
<td>0.153</td>
</tr>
<tr>
<td>100</td>
<td>0.127</td>
</tr>
<tr>
<td>500</td>
<td>0.079</td>
</tr>
<tr>
<td>1000</td>
<td>0.059</td>
</tr>
</tbody>
</table>
2.3.3 Channel and Bank Erosion in SWAT

River bed erosion is often computed using a sediment transport model. Dozens of sediment transport models have been developed to calculate total bed-material load (see for example Engelund and Hansen, 1967; Ackers and White, 1973; Yang, 1973; Brownlie, 1981; and Karim and Kennedy, 1981). These equations, among others, can be used to calculate suspended sediment loads, bed loads, wash loads, or total loads. Many stable channels have erodible beds; however, the channel morphology maintains its general dimensions overtime, which leads to no net erosion or increase in sediment delivery downstream (i.e., the load of sediment entering a stable reach is equivalent to the sediment leaving the stable reach, and therefore the bed does not contribute any additional net delivery). Incising channels do add to the net sediment delivery downstream and should be accounted for in a sediment budget. Numerical modeling software such as HEC-RAS (Hydraulic Engineering Center, 2008) incorporates a number of sediment transport equations to calculate the bed erosion rates as well as bed incision, which is used as the sediment transport model for the coupled sediment modeling for this research.

The SWAT model calculates both bank erosion and bed erosion using similar methods. For erosion to occur two processes must be present. In the first process, the stream power (or capacity of the river to transport sediment) must be higher than the amount of sediment being transported. If there is more sediment being transported than the transport capacity no erosion will occur and instead the excess sediment will be deposited. 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 based on the excess shear stress equation from Hanson and Simon (2001) in SWAT. See Equation 4 and 5.

\[ \xi_{bank} = k_{d,bank} \cdot (\tau_{e,\text{bank}} - \tau_{c,\text{bank}}) \cdot 10^{-6} \]  
(4)

\[ \xi_{bed} = k_{d,\text{bed}} \cdot (\tau_{e,\text{bed}} - \tau_{c,\text{bed}}) \cdot 10^{-6} \]  
(5)

Where:
\[ \xi \] = erosion rates of the bank or bed (m/s)
\[ k_d \] = erodability coefficient of bank or bed (cm$^3$ N$^{-1}$ s$^{-1}$)
\[ \tau_e \] = effective shear stress acting on the bank or bed (N s$^{-1}$)
\[ \tau_c \] = critical shear stress acting on the bank or bed (N s$^{-1}$)

The effective shear stress (\( \tau_e \)) is calculated in SWAT using Equations 6, 7, and 8 from Eaton and Millar (2004):

\[ \frac{\tau_{e,\text{bank}}}{\gamma_w \cdot \text{depth} \cdot \text{slp}_{ch}} = \frac{SF_{\text{bank}}}{100} \cdot \left( \frac{(W + P_{\text{bed}}) \cdot \sin \theta}{4 \cdot \text{depth}} \right) \]  
(6)

\[ \frac{\tau_{e,\text{bed}}}{\gamma_w \cdot \text{depth} \cdot \text{slp}_{ch}} = \left( 1 - \frac{SF_{\text{bank}}}{100} \right) \cdot \left( \frac{W}{2 \cdot P_{\text{bed}}} + 0.5 \right) \]  
(7)

\[ \log SF_{\text{bank}} = -1.4026 \cdot \log \left( \frac{P_{\text{bed}}}{P_{\text{bank}}} + 1.5 \right) + 2.247 \]  
(8)

Where:
\[ SF_{\text{bank}} \] = proportion of shear stress acting on the bank (dimensionless)
\[ \gamma_w \] = specific weight of water (N m$^{-3}$)
\[ \text{depth} \] = depth of water in the channel (m)
\[ \text{slp}_{ch} \] = channel bed slope (m m$^{-1}$)
\[ W \] = top width of channel (m)
\( P = \) wetted perimeter of bed or banks (m)

\( \theta = \) angle of the channel bank from horizontal

In SWAT, a Digital Elevation Model (DEM) is used to calculate channel slope and the in-stream flow routing algorithm provides channel velocity.

When the input concentration from an upstream reach is greater than the capacity of sediment that can be transported, then aggradation occurs in SWAT. 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 9) and a shear stress (expressed in the depth and slope of the channel terms) as shown in (Equation 10).

\[
K_{CH} = 0.003 \cdot e^{385 \cdot J_i}
\]

(9)

Where:

\( K_{CH} = \) channel erodability coefficient (cm/h/Pa)

\( J_i = \) Jet Index from ASTM standard D 5852-95

\[
depth_{cut} = 358.6 \cdot depth \cdot slp_{ch} \cdot K_{CH}
\]

(10)

Where:

\( depth_{cut} = \) amount of channel downcutting (m)

\( depth = \) depth of water in the channel (m)

\( slp_{ch} = \) channel slope (m/m)

\( K_{CH} = \) channel erodability coefficient (cm/h/Pa)
2.3.4 Sediment Sinks (Reservoirs) in SWAT

The major sediment sinks that will be addressed in the Sao Francisco River watershed model are the reservoirs in the basin. Channel sinks have already been described. Additional sinks included in the SWAT model consists of deposition of sediment in wetlands and floodplains. Each sediment budget sink has a significant body of research associated with depositional rates for each feature. This section describes these sediment sinks and methods that are currently in practice to estimate sedimentation rates.

A number of studies have investigated the gross rate of reservoir sedimentation as a function of storage lost per year. Mahmood (1987) calculated that the storage capacity of reservoirs is being lost at a rate of 1% per year world-wide. Crowder (1987) estimated the rate of storage lost in the lower 48 United States as 0.22% per year. A similar value of 0.2% was calculated by White (2001) for the inventory of storage lost per year in all of North America. The rate of storage lost for individual reservoirs is highly variable and is a function of the total storage capacity, inflow sediment delivery, and sediment trap efficiency.

A reservoir fills with sediment in three phases according to Morris, Annandale and Hotchkiss (2008). In the first phase, immediately following construction, continuous sediment trapping occurs. In this phase, a large percentage of fine sediments are retained within the reservoir and fill submerged depressions throughout the reservoir until the sediment deposits are essentially flat across a given cross section (although there is still a slope to the bottom of the reservoir in the longitudinal direction). In this phase, coarse sediments deposit at the upstream end, forming a delta that slowly propagates
downstream. Turbidity currents of suspended sediments form in larger reservoirs in this phase as well. See Figure 3, from Sloff (1997) for a representation of the reservoir morphology in the first phase of deposition. In the second phase a submerged channel-floodplain pattern forms in the reservoir, and most of the suspended sediments are able to be transported through the reservoir and over the dam. Only coarse material is able to deposit in the reservoir during the phase. In the third and final stage, a long-term balance of sediment inflow and outflow is achieved, and both suspended sediments and coarse sediments are able to be transported through the reservoir and dam. Sediment trapping efficiency, therefore, is determined as a function of individual grain sizes (usually divided into suspended sediments and bed-load sediment categories) and is variable through time and space in the reservoir.

**Figure 3: Sedimentation Regimes in Reservoirs. From Sloff (1997)**
Researchers have employed many methods to calculate reservoir sedimentation rates. These methods range in complexity and include approaches such as one-dimensional numerical models of sediment deposition based on settling velocity (Toniolo and Parker, 2003); shock-capturing numerical modeling of delta front (Garcia, 2008); two-dimensional morphodynamic modeling of a fan-delta (Garcia, 2008); and a calculation based on sediment trapping efficiency (Brune, 1953; Churchill, 1948). The appropriate method to use in calculating sedimentation rates is dependent upon the question of interest. For this study, the modeling efforts are focused on the gross effects that reservoirs have as sediment sinks in the overall sediment budget. Since longitudinal or two-dimensional effects are not of primary interest, a sediment trapping efficiency calculation will be utilized on the reservoirs included in this study.

Trapping efficiency models have been proposed to correlate suspended sediment retention to watershed and reservoir characteristics. The most common trapping efficiency model was developed by Brune (1953). This model is a curve that relates the trapping efficiency of sediments retained in a reservoir to the capacity-inflow ratio (capacity of the reservoir divided by the average annual inflow). Since the capacity of the reservoir is continually reduced due to filling, the trapping efficiency is a variable Parameter. The Brune curve is replicated in Figure 4.

The Brune curve does not account for the concentration of sediment in the inflow, and does not include any watershed specific variables to determine trapping efficiency. Other researchers and models do take into account additional considerations such as the influence of upstream dams on sediment delivery to a downstream dam (Minear and Kondolf, 2009), and accounting for sediment settling based on concentrations of the
sediment in the reservoir water column (Neitsch et al., 2005). SWAT accounts for the influence of upstream dams on sediment delivery by calculating the sediment balance at each reservoir. The sediment mass balance equation is listed in Equation 11.

\[
\text{sed}_{wb} = \text{sed}_{wb,i} + \text{sed}_{\text{flowin}} - \text{sed}_{\text{stl}} - \text{sed}_{\text{flowout}}
\]

(11)

Where:

- \(\text{sed}_{wb}\) = amount of sediment in the water body at the end of a daily time-step (metric tons)
- \(\text{sed}_{wb,i}\) = amount of sediment in the water body at the beginning of time-step \(i\) (metric tons)
- \(\text{sed}_{\text{flowin}}\) = amount of sediment added to the water body with inflow (metric tons)
- \(\text{sed}_{\text{stl}}\) = amount of sediment removed from the water body by settling (metric tons)
- \(\text{sed}_{\text{flowout}}\) = amount of sediment transported out of the water body with outflow (metric tons)
Figure 4: Sediment Trapping Efficiency Curve from Brune (1953)
The settling of the suspended solids is calculated using a first order decay of the concentration to represent the sediment settling. The initial suspended sediment concentration in the reservoir at time-step $i$ is given in Equation 12.

$$conc_{sed.i} = \frac{(sed_{wb.i} + sed_{flowin})}{(V_{stored} + V_{flowin})}$$  \hspace{1cm} (12)

Where:

$conc_{sed,i} =$ initial concentration of suspended sediments in the reservoir (mg/m$^3$)

$sed_{wb,i} =$ amount of sediment in the water body at the beginning of time-step $i$ (metric tons)

$sed_{flowin} =$ amount of sediment added to the reservoir with the inflow (metric tons)

$V_{stored} =$ volume of water stored in the reservoir at the beginning of time-step $i$ (m$^3$)

$V_{flowin} =$ volume of water entering the reservoir within the time-step (m$^3$)

SWAT initiates sediment settling when an equilibrium sediment concentration (set by the user) is exceeded. The final sediment concentration at the end of a time step is based on Equations 13 and 14.

$$if \ conc_{sed.i} > conc_{sed.eq}$$

$$conc_{sed.f} = conc_{sed.eq} + (conc_{sed.i} - conc_{sed.eq}) \cdot e^{-k_s \cdot t \cdot d_{50}}$$  \hspace{1cm} (13)
\[ \begin{align*}
&\text{if } \text{conc}_{\text{sed},i} \leq \text{conc}_{\text{sed},eq} \\
&\text{conc}_{\text{sed},f} = \text{conc}_{\text{sed},i} \quad (14)
\end{align*} \]

Where:

- conc\textsubscript{sed,f} = final concentration of sediment in the water body (mg/m\textsuperscript{3})
- conc\textsubscript{sed,eq} = equilibrium concentration of sediment in the water body (mg/m\textsuperscript{3})
- k\textsubscript{s} = first order decay constant (day\textsuperscript{-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 days.
- t = length of the time step (1 day)
- d\textsubscript{50} = median particle size of the inflow sediment (µm)

The amount of settling of the suspended sediment on a given day is calculated using Equation 15.

\[ \text{sed}_{\text{stl}} = (\text{conc}_{\text{sed},i} - \text{conc}_{\text{sed},f}) \cdot V \quad (15) \]

Where:

- \text{sed}_{\text{stl}} = amount of sediment removed from the water by settling (metric tons)
- V = volume of water in the impoundment (m\textsuperscript{3})

The trapping efficiency (on a daily time-step) may be calculated by applying Equation 16.

\[ \text{Trapping Efficiency}_i = \frac{\text{sed}_{\text{stl}}}{\text{sed}_{\text{flowin}}} \quad (16) \]
SWAT assumes a well-mixed reservoir, and therefore, the concentration of the sediment that flows out of the reservoir is equal to the concentration of the sediment in the well-mixed system. In order to achieve close to 100% trapping efficiency in large reservoirs, sedimentation must be initiated at a low concentration, and the first order decay constant must settle most of the sediment within a single time step of 1 day. Therefore, both the equilibrium concentration may need to be artificially lowered in large reservoirs to near zero, and the decay constant may need to be raised artificially high to settle out most of the suspended solids within the time step of the model.

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 (see White et al., 2010; and Bosch, 2008). The primary study that investigated the robustness of SWAT to measure sedimentation rates was conducted by Mishra et al. (2007) on a small watershed (17 km²) in India. Mishra used a sediment concentration value of 450 mg/L to initiate sedimentation, although does not provide justification for using that value. The India model had three in-stream reservoirs with storage capacity ranging from 0.18 to 0.27 million cubic meters. 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 the reservoirs in the India watershed model accurately captured and settled the sediment using the reservoir sedimentation routines in SWAT.

Other sources of storage (sinks) in the sediment budget include wetlands, depressions, floodplains, and in-channel storage. Each sediment sink has its own set of procedures (both mathematical and field collection) to estimate sedimentation rates. For
example, Parker (2008) lists eight separate equations that may be used to calculated sedimentation rates in floodplains by grain size. Parker also lists several field methods including tracers, coring, and “Leopold chains” (i.e., scour chains) to estimate floodplain sedimentation. These specific sinks are not of primary interest to this research. It should be noted that SWAT incorporates the same methods as in reservoir sedimentation (a mass balance approach) to calculate sedimentation rates in depressions, wetlands, ponds and lakes. Floodplain and other in-stream sinks are addressed in SWAT using the sediment transport and routing algorithms previously described.

2.3.5 Additional Capabilities in SWAT

Gassman et al. (2007) conducted a comprehensive literature review on the applications where SWAT has been utilized, including:

- Hydrologic Assessments
- Base Flow in Karst-Influenced Systems
- Groundwater recharge and tile flow applications
- Snowmelt applications
- Irrigation
- Influence of wetlands, reservoirs, and other impoundments
- Pollutant loss studies
- Sediment studies
- Nitrogen and Phosphorous Studies
- Pesticide and Surfactant Studies
Gassman found that numerous studies have showed the robustness of SWAT in predicting sediment loads at different watershed scales (see Arnold et al., 1999; Saleh et al., 2000; Srinivasan et al., 1998). Numerous other equations and processes are incorporated into SWAT and were used indirectly in this research, although are not described here. For instance, nitrogen and phosphorous cycling (and availability) was modeled in SWAT in order to calculate crop density; however, these Parameters were not specifically calibrated in the Sao Francisco River SWAT model. Also, groundwater recharge and lateral inflow were modeled in SWAT in order to calculate the water budget at each time step. These intermediate processes were important to be calculated in the overall development of the SWAT model, but are not direct results that are being investigated in this research. More information on the numerous intermediate processes incorporated into SWAT can be found in the SWAT2009 Theoretical Documentation (Neitsch, et al., 2011).
CHAPTER 3.0 WATERSHED MODEL DATA

The primary data that were used to build a hydrology and sediment yield SWAT model included the following:

- Topography
- Soils
- Landuse
- Reservoirs
- Irrigation withdrawals
- Weather (precip, temperature, relative humidity, solar radiation, and wind)
- Gages (streamflow and sediment gages)

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. The properties of an individual HRU are considered to be uniform within each subwatershed. Each subwatershed has many HRUs (the number depends on the size of the watershed, the resolution of the data, and how the data is grouped together).

Additional data added to the model include reservoirs and irrigation. Major reservoirs were added to the model to store both water and sediments. Irrigation was also added as a water withdrawal from the model.

The weather data is the input information that drives the model. Precipitation, temperature, relative humidity, solar radiation, and wind are all variables used to calculate the hydrologic processes occurring in the watershed.
Flow and sediment gages were used for calibration and validation of the model results. Section CHAPTER 4.0 of this report describes the hydrology gages used and Section CHAPTER 5.0 includes a description of the sediment gages used in calibration and validation. More information regarding how the SWAT model uses each type of data can be found in the SWAT references.

3.1 Topography Data

The typography data was initially used to create the SWAT model topology using ArcSWAT. ArcSWAT is a pre-processor to the SWAT model that builds the model geometry, topology, and HRUs. The topography data was 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 (see Figure 5).
Figure 5: Topography Data used in SWAT Model
The Automatic Watershed Delineation tools in ArcSWAT were utilized to divide the watershed into 76 sub-basins. The topography data was also used to divide the watershed into 3 slope categories, which were used to define the first part of the HRU. These categories are:

1. 0% – 2% Slope
2. 2% – 5% Slope
3. Over 5% Slope

See Figure 6 for the distribution of the slopes throughout the basin and the subwatershed classification used in the SWAT model.
Figure 6: Slope and Sub-Classification in SWAT
3.2 Soils

Soils data is available from Embrapa in a digital form entitled the Mapa de Solos Do Brasil (Embrapa, 1981). This map was digitized at the U.S. Geological Survey’s EROS Data Center in Sioux Falls, South Dakota in 1992. There are seventy soil groups defined in the overall Brazil Soil Dataset within the Sao Francisco River watershed. ArcGIS 10.0 was used to clip the soils dataset to the boundary of the Sao Francisco River Watershed. See Figure 7 for a map of the soils data in the watershed.
Figure 7: Soils Map of the Sao Francisco River Basin
The SWAT model requires numerous physical and chemical soil property information for each 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 were 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 following list includes the ISRIC soil information, and the associated name of the SWAT variable is listed in parenthesis:

- Number of layers (NLAYERS)
- Layer thickness, by layer (SOL_Z)
- Hydrologic Soil Group (HYDGRP)
- Maxim 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 % (CLAY, SILT, SAND, & ROCK)
- Moist soil albedo (SOL_ALB)
- Universal Soil Loss Equation (USLE) Erodability (K) factor (USLE_K)
The soil input data can be found in the usersoil table within the SWAT2012.mbd database. This data can also be queried within the ArcSWAT interface. An example of the data for a specific soil layer is shown in Figure 8.

Figure 8: Example Soil Input Database in ArcSWAT

![Soil Input Database in ArcSWAT](image)

3.3 Landuse

Landuse data is necessary in a SWAT model to define activities associated with farming, urban landuses, forests, etc. Each landuse has specific impacts to the hydrology and sediment yield of a watershed. The global dataset – GlobCover 2005 – was used to
assign the landuse to the Sao Francisco River SWAT model. GlobCover 2005 is a global dataset with 300m x 300m resolution of landcover from the year 2005 (European Space Agency, 2006). See Table 6 for the landuse categories associate with the GlobCover 2005 dataset. Figure 9 includes a map of the landuses within the SWAT model.

Table 6: GlobCover 2005 Categories and Associated SWAT Landuses

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
<th>SWAT</th>
<th>SWAT Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Post-flooding or irrigated croplands (or aquatic)</td>
<td>AGRC</td>
<td>Agricultural Land-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Close-grown</td>
</tr>
<tr>
<td>14</td>
<td>Rainfed croplands</td>
<td>AGRR</td>
<td>Agricultural Land-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Row Crops</td>
</tr>
<tr>
<td>20</td>
<td>Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)</td>
<td>AGRL</td>
<td>Agricultural Land-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Generic</td>
</tr>
<tr>
<td>30</td>
<td>Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)</td>
<td>AGRL</td>
<td>Agricultural Land-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Generic</td>
</tr>
<tr>
<td>40</td>
<td>Closed to open (&gt;15%) broadleaved evergreen or semi-deciduous forest (&gt;5m)</td>
<td>FRSE</td>
<td>Forest-Evergreen</td>
</tr>
<tr>
<td>50</td>
<td>Closed (&gt;40%) broadleaved deciduous forest (&gt;5m)</td>
<td>FRSD</td>
<td>Forest-Deciduous</td>
</tr>
<tr>
<td>60</td>
<td>Open (15-40%) broadleaved deciduous forest/woodland (&gt;5m)</td>
<td>FRSD</td>
<td>Forest-Deciduous</td>
</tr>
<tr>
<td>70</td>
<td>Closed (&gt;40%) needleleaved evergreen forest (&gt;5m)</td>
<td>FRSE</td>
<td>Forest-Evergreen</td>
</tr>
<tr>
<td>90</td>
<td>Open (15-40%) needleleaved deciduous or evergreen forest (&gt;5m)</td>
<td>FRST</td>
<td>Forest-Mixed</td>
</tr>
<tr>
<td>100</td>
<td>Closed to open (&gt;15%) mixed broadleaved and needleleaved forest (&gt;5m)</td>
<td>FRST</td>
<td>Forest-Mixed</td>
</tr>
<tr>
<td>110</td>
<td>Mosaic forest or shrubland (50-70%) / grassland (20-50%)</td>
<td>FRST</td>
<td>Forest-Mixed</td>
</tr>
<tr>
<td>120</td>
<td>Mosaic grassland (50-70%) / forest or shrubland (20-50%)</td>
<td>RNGE</td>
<td>Range-Grasses</td>
</tr>
<tr>
<td>130</td>
<td>Closed to open (&gt;15%) (broadleaved or needleleaved, evergreen or deciduous)</td>
<td>RNBG</td>
<td>Range-Brush</td>
</tr>
<tr>
<td></td>
<td>shrubland (&lt;5m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>Closed to open (&gt;15%) herbaceous vegetation (grassland, savannas or lichens / mosses)</td>
<td>RNBG</td>
<td>Range-Brush</td>
</tr>
<tr>
<td>150</td>
<td>Sparse (&lt;15%) vegetation</td>
<td>BARR</td>
<td>Barren</td>
</tr>
<tr>
<td>160</td>
<td>Closed to open (&gt;15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water</td>
<td>WETF</td>
<td>Wetlands-Forest</td>
</tr>
<tr>
<td>170</td>
<td>Closed (&gt;40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water</td>
<td>WETF</td>
<td>Wetlands-Forest</td>
</tr>
<tr>
<td>180</td>
<td>Closed to open (&gt;15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water</td>
<td>WETL</td>
<td>Wetlands-Mixed</td>
</tr>
<tr>
<td>190</td>
<td>Artifical surfaces and associated areas (Urban areas &gt;50%)</td>
<td>URHD</td>
<td>Residential-High Density</td>
</tr>
<tr>
<td>200</td>
<td>Bare areas</td>
<td>BARR</td>
<td>Barren</td>
</tr>
<tr>
<td>210</td>
<td>Water bodies</td>
<td>WATR</td>
<td>Water</td>
</tr>
<tr>
<td>220</td>
<td>Permanent snow and ice</td>
<td>WATR</td>
<td>Water</td>
</tr>
<tr>
<td>230</td>
<td>No data (burnt areas, clouds,....)</td>
<td>BARR</td>
<td>Barren</td>
</tr>
</tbody>
</table>
Figure 9: SWAT Landuses Used in the Sao Francisco River Basin Model
3.4 Weather Data

SWAT requires the following daily weather data to be included in the watershed model:

- Temperature (°C)
- Precipitation (mm)
- Wind (m/s)
- Relative Humidity (fraction)
- Solar Radiation (MJ/m²)

Weather data is available throughout the Sao Francisco River Watershed at the Global Weather Data for SWAT website (http://globalweather.tamu.edu/). This site collects all available weather data within a 5° (Latitude) by 5° (Longitude) limit. The following 4 steps are required to obtain the available weather data:

1. Select a bounding box defining the weather Stations (Figure 10)
2. Define the weather time period (Figure 11)
3. Select which data is to be collected (Figure 12)
4. Select how the data is to be delivered (Figure 13)
The Sao Francisco River Watershed model was designed to be calibrated to recent landuse and hydrology. The model included data from 1995 through 2006 with model output from 2001-2006. Therefore, a twelve-year period of weather data is selected (January 1, 1995 through December 31, 2006). The first six years in the model is a “hotstart” period, meaning that the model will not be calibrated to the first six years’ worth of data.
All of the available weather data was selected and used in the SWAT model. Therefore all options in the Global Weather Data for SWAT website were selected.
There are a total of 1,254 weather stations with daily data for temperature, precipitation, wind, relative humidity, and solar radiation.

### 3.5 Reservoirs Data

Five of the largest reservoirs in the Sao Francisco basin were added to the model.

These reservoirs include the following list, and are shown in Figure 14:

- **Tres Marias** located at: 18° 12’ 51” S, 45° 15’ 46” W
- **Sobradinho** located at: 9° 25’ 54” S, 40° 49’ 40” W
- **Luiz Gonzaga** located at: 9° 8’ 38” S, 38° 18’ 48” W
- **Paulo Afonso** located at: 9° 23’ 49” S, 38° 12’ 08” W
- **Xingo** located at: 9° 37’ 14” S, 37° 47’ 34” W
Figure 14: Major Dams in the Sao Francisco River Watershed
The various properties of the reservoirs were applied to the SWAT model. Table 7 describes the volumes and surface areas for each reservoir's emergency spillway and principal spillway.

**Table 7: Physical Reservoir Parameters Used in SWAT Model**

<table>
<thead>
<tr>
<th>SWAT ID</th>
<th>Reservoir Name</th>
<th>RES_ESA (ha)</th>
<th>RES_EVOL (10^4 \text{ m}^3)</th>
<th>RES_PSA (ha)</th>
<th>RES_PVOL (10^4 \text{ m}^3)</th>
<th>RES_VOL (10^4 \text{ m}^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>Três Marias</td>
<td>115556</td>
<td>2333333</td>
<td>104000</td>
<td>2100000</td>
<td>2100000</td>
</tr>
<tr>
<td>17</td>
<td>Sobradinho</td>
<td>468889</td>
<td>3788889</td>
<td>422000</td>
<td>3410000</td>
<td>3410000</td>
</tr>
<tr>
<td>8</td>
<td>Luiz Gonzaga</td>
<td>92222</td>
<td>1188889</td>
<td>83000</td>
<td>1070000</td>
<td>1070000</td>
</tr>
<tr>
<td>11</td>
<td>Paulo Afonso</td>
<td>11111</td>
<td>133333</td>
<td>10000</td>
<td>120000</td>
<td>120000</td>
</tr>
<tr>
<td>14</td>
<td>Xingó</td>
<td>6667</td>
<td>422222</td>
<td>6000</td>
<td>380000</td>
<td>380000</td>
</tr>
</tbody>
</table>

Where,

RES_ESA = Reservoir surface area when the reservoir is filled to the emergency spillway

RES_EVOL = Volume of water needed to fill the reservoir to the emergency spillway

RES_PSA = Surface area of reservoir when filled to the principal spillway. A 10% reduction of the emergency spillway is assumed.

RES_PVOL = Volume of water needed to fill the reservoir to the principal spillway

RES_VOL = Initial reservoir volume

Note, the threshold values for the RES_ESA, RES_EVOL, RES_PSA, RES_PVOL and RES_VOL had to be increased in the resrng table of the SWAT2012.mdb database because the maximum limits of these variables were less than the volumes and areas of the dams being modeled. RES_ESA and RES_PSA were
increased to 500,000 hectares, and the remaining 3 variables were increased to $5,000,000 \times 10^4$ m$^3$.

The initial sediment properties (among other Parameters) used in the SWAT model for each reservoir are described in Table 8.

### Table 8: Sediment and Other Reservoir Default Parameters

<table>
<thead>
<tr>
<th>SWAT ID</th>
<th>Reservoir Name</th>
<th>RES_SED (mg/L)</th>
<th>RES_NSED (mg/L)</th>
<th>RES_D50 (μm)</th>
<th>RES_K (mm/hr)</th>
<th>EVRSV</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>Três Marias</td>
<td>100</td>
<td>450</td>
<td>10</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>17</td>
<td>Sobradinho</td>
<td>100</td>
<td>450</td>
<td>10</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>Luiz Gonzaga</td>
<td>100</td>
<td>450</td>
<td>10</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>11</td>
<td>Paulo Afonso</td>
<td>100</td>
<td>450</td>
<td>10</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>14</td>
<td>Xingó</td>
<td>100</td>
<td>450</td>
<td>10</td>
<td>0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The default sediment variables that are used in all of the reservoirs are listed below:

- $\text{RES\_SED} =$ The initial sediment concentration in the reservoir
- $\text{RES\_NSED} =$ The equilibrium sediment concentration in the reservoir
- $\text{RES\_D50} =$ The median sediment diameter that is deposited in the reservoir
- $\text{RES\_K} =$ Hydraulic conductivity of the base of the reservoir
- $\text{EVRSV} =$ Reservoir evaporation coefficient.
3.6 Irrigation

Irrigation is permitted throughout the Sao Francisco River watershed. There are a total of 26 major irrigation sources identified by CODEVASF (CODEVASF, 2014). The names, locations, permitted flow and additional information associated with each irrigation operation are listed in Table 9. The locations of the irrigation sources are shown in Figure 15.

Table 9: Permitted Irrigation Activities in the Sao Francisco River Basin

<table>
<thead>
<tr>
<th>SR</th>
<th>Name</th>
<th>Coordinates</th>
<th>Name of Source</th>
<th>Source Type</th>
<th>Intake Type</th>
<th>Permitted Flow m³/h</th>
<th>SWAT Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ª</td>
<td>Gorutuba</td>
<td>15º 49' 55&quot; S 43º 15' 46&quot; W</td>
<td>Gorutuba</td>
<td>Dam</td>
<td>Gravity</td>
<td>8762</td>
<td>55</td>
</tr>
<tr>
<td>2ª</td>
<td>Jaiaba</td>
<td>15º 5' 24.088&quot; S 44º 18' 36&quot; W</td>
<td>São Francisco</td>
<td>River</td>
<td>Pump</td>
<td>8740</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Lagoa Grande</td>
<td>15º 44'55&quot; S 43º18'36&quot; W</td>
<td>Gorutuba</td>
<td>Dam</td>
<td>Gravity</td>
<td>8740</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Pirapora</td>
<td>17º 14' 56&quot; S 44º 51' 14&quot; W</td>
<td>São Francisco</td>
<td>River</td>
<td>Pump</td>
<td>3750</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Barreiras do Norte</td>
<td>12º 4' 47.509&quot; S 44º 51' 14&quot; W</td>
<td>Grande</td>
<td>River</td>
<td>Pump</td>
<td>12642</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Calma</td>
<td>14º 17' 23&quot; S 42º 44' 8&quot; W</td>
<td>Carnaiba de Dentro</td>
<td>Dam</td>
<td>Gravity</td>
<td>539</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Estreito</td>
<td>14º 49' 35&quot; S 42º 48' 27&quot; W</td>
<td>Verde Pequeno</td>
<td>Dam</td>
<td>Gravity</td>
<td>4669</td>
<td>53</td>
</tr>
<tr>
<td></td>
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Figure 15: Location of Irrigation Sources
CHAPTER 4.0 HYDROLOGY CALIBRATION

After the initial model setup, the SWAT model underwent a calibration process. The model was first calibrated to the hydrology (flow gage data) of the watershed at a series of gages, and then calibrated to sediment (obtained from sediment gages).

4.1 Hydrology Variables Used in Calibration

The following Parameters were used to calibrate the model in sequential order. The SWAT database Parameter file is included in parenthesis:

1. Main channel width (CH_W2.rte)
2. Baseflow alpha days (ALPHA_BF.gw)
3. Tributary channel width (CH_W1.sub)
4. Manning’s “n” of main channel (CH_N.rte)
5. Depth of main channel from top of bank to bottom (CH_D.rte)
6. Runoff Curve Number (CN2.mgt)
7. Hydraulic conductivity of the soil (SOL_K.sol)
8. Hydraulic conductivity in main channel (CH_K2.rte)
9. Hydraulic conductivity in sub-basin tributaries (CH_K1.sub)
10. Average slope steepness of HRU (HRU_SLP.hru)
11. Average slope length of HRU (SLSUBBSN.hru)
12. Manning’s “n” for overland flow (OV_N.hru)
13. Deep aquifer percolation fraction (RCHRG_DP.gw)
14. Surface runoff lag coefficient (SURLAG.bsn)
15. Threshold depth of shallow aquifer water for return flow (GWQMN.gw)
16. Groundwater revap coefficient (GW_REVAP.gw)
17. Depth of water in shallow aquifer for percolation (REVAPMN.gw)
18. Groundwater delay time (GW_DELAY.gw)

The items listed above either are sensitive Parameters that can be used for calibration, or are Parameters that generally have known information. Parameters that are known or can be calculated or estimated were adjusted first to develop the most representative model of the watershed possible. Additional Parameters that are unknown were adjusted within a wider range in order to achieve calibration. Automated calibration programs are available (such as SWAT-CUP); however, it was decided to manually calibrate the Sao Francisco River watershed SWAT model in order to develop a deeper understanding of the interaction of various Parameters to the model results. Parameters not included in the above list used the default SWAT values and were not adjusted in the calibration process.

The hydrology was first calibrated to the Morpara Gage (ANA gage 46360000). This gage is located near Morpara, BA approximately 50 km upstream of the confluence of the Sao Francisco River and the Rio Grande. This location is near the middle of the research focus area (the navigation channel), and the location is not influenced significantly by any reservoir operations. This free-flowing river condition makes the location suitable for calibration of watershed wide Parameters, and the location is representative of the area of interest for the SWAT model. After the hydrology was calibrated to the Morpara gage, additional gages were investigated to ensure calibration throughout the basin. Additional localized calibration was required for some sub-watersheds to achieve calibration throughout the Sao Francisco River basin. The following sections describe how default values were adjusted to achieve calibration.
4.1.1 *Main Channel Width (CH_W2.rte)*

The main channel width is a moderately sensitive Parameter to the hydrology (however, this is a very sensitive Parameter to the calibration of sediment). The width of the main channels can be estimated using aerial photos of the streams. This was performed at low water conditions (when the aerials were taken) in order to ensure that floodplain widths are not associated with the channel widths in SWAT. The ArcSWAT pre-processor generally over-estimated the stream widths, and therefore this was the first value adjusted.

At each sub-basin, a representative reach was selected to measure the width (generally near the middle of the reach or sub-basin). Table 10 displays the measured widths associated with each reach. In general, the widths were reduced approximately one order of magnitude from those calculated by ArcSWAT.
Table 10: Estimated Main Channel Widths, Depths and Ratios for each Reach

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<th>Width/Depth Ratio</th>
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4.1.2 Baseflow Alpha Days (ALPHA_BF.gw)

The baseflow alpha days (units of 1/days) is known as the baseflow recession constant. According to the SWAT Manual, “the baseflow recession constant, $\alpha_{gw}$, is a direct index of groundwater flow response to changes in recharge (Smedema and Rycroft, 1983).” The baseflow recession constant is essentially a scaling factor that determines how much groundwater can flow into a nearby stream as a function of the recharge flow. According to the SWAT Theoretical Documentation, these variables are related using equation 17:

$$\frac{dQ_{gw}}{dt} = \alpha_{gw}(w_{rchrg,sh} - Q_{gw})$$

Where:

- $\alpha_{gw}$ = baseflow recession constant
- $Q_{gw}$ = groundwater flow into the main channel on day $i$ (mm H$_2$O)
- $w_{rchrg,sh}$ = the amount of recharge entering the shallow aquifer on day $I$ (mm H$_2$O)

Watersheds that have a slow response to recharge have a low baseflow recession constant, and watersheds that have a fast response to recharge have a high value of the baseflow recession constant. The value of baseflow alpha days can be determined using a baseflow filtering program (Arnold et al., 1995). The baseflow alpha days may be directly calculated if the number of baseflow days for a watershed is known. Baseflow days is the amount of time for baseflow to recede in the absence of groundwater recharge. The baseflow filter program available from the SWAT website was used for the Sao Francisco River model. This program is available at:
The daily Morpara gage data from 2001-2006 was used to calculate the Baseflow Days. The baseflow filter program calculated baseflow days for the Sao Francisco River at the Morpara gage to be 46 days. The baseflow alpha days can be calculated using the Equation 18:

\[
\alpha = \frac{1}{N} \ln \left( \frac{Q_N}{Q_o} \right) = \frac{2.3}{BFD}
\]

Where:
\[
\alpha = \text{alpha baseflow days (1/days)}
\]
\[
N = \text{number of days from the start of the recession}
\]
\[
Q_N = \text{river flow at day N}
\]
\[
Q_o = \text{initial flow}
\]
\[
BFD = \text{baseflow days}
\]

Since the baseflow filter calculated the baseflow days to be 46 days, the alpha baseflow factor used in the SWAT model is 0.05 days\(^{-1}\). This value was initially applied uniformly to all HRUs in the SWAT model.

4.1.3 Tributary Channel Width (CH_W1.sub)

The width of the tributary channels is a moderately sensitive Parameter, and in general an upper bound is known for the various subbasins. This value impacts the amount of percolation through the losing streams, which are present in the watershed (wide streams with a high hydraulic conductivity will have significant percolation to the shallow aquifer). Since virtually all of the tributaries that were not modeled as a main
channel has widths less than 10 meters, a value of 10 meters was applied to the tributary channel width.

4.1.4 Manning’s “n” of the Channel (CH_N2.rte)

Manning’s “n” represents the amount of friction and form losses in the main channel. This Parameter has a low sensitivity in the outcome of the hydrology model, but it can be estimated for the channels in the Sao Francisco River watershed. An initial value 0.030 was supplied to the main reaches throughout the entire SWAT model of the Sao Francisco River. Due to the low sensitivity of the Parameter, uniformly applying this value is appropriate and yielded acceptable calibration.

4.1.5 Depth of the Main Channel from Top of Bank (CH_D.rte)

A maximum depth of 10 meters was applied to the model. This depth was chosen because this was a representative value observed in the field near Barra, Bahia in the Middle Sao Francisco River as well as at Propria, Sergipe (near the mouth of the river). Conditions at both locations had observed banks of up to 4 meters tall, with depths up to 6 meters. Additional data is not available throughout the watershed, however, since these locations are located near the downstream section of the navigation channel (at Barra) and near the mouth (Propria), it is not expected to have significantly deeper channels, and therefore 10 meters was selected as the upper limit.

This depth was reduced for narrow streams, and an assumed width to depth ratio of 10 was applied. This is based on observed channels, such as the Correntes River, that has a width of approximately 20 meters and a maximum depth to the top of bank of 2
meters. Therefore, for streams with widths less than 100 meters, the depth of the channel (to the top of bank) was reduced. For example, Basin 10 has a measured width of 40 meters, and the depth that was supplied to the model was 4 meters. A width to depth ratio that is slightly less than the calculated width/depth ratio was supplied to the model in order for bank erosion to be active (bank erosion is only active if the typical width/depth ratio at a given time step is less than a supplied value). The CH_D.rte depths are listed in Table 10.

4.1.6 Runoff Curve Number (CN2.mgt)

The CN2.mgt variable is the initial Soil Conservation Service (SCS) runoff curve number for a specific moisture condition (moisture condition II). More information regarding the background of the runoff curve number can be found in Wischmeier and Smith (1978) and SCS Engineering Division (1986). SWAT allows the curve number to be updated as a function of agricultural practices (planting, tillage, and harvest/kill operations). For the Sao Francisco River SWAT model, the curve number was not updated and was held constant through the entire simulation.

The curve numbers are a function of the soil types and landuse. Default curve numbers can be found in the SWAT2012.mdb “crop” table. This table lists the agricultural landuses and includes a CNA, CNB, CNC, and CND column (Curve number for hydrologic soil conditions A-D). Additional default CN numbers can be found in the “urban” table of the SWAT2012.mdb database. The curve numbers can also be seen in each HRU when the user edits the Management (.Mgt) Parameters in ArcSWAT (an example is shown in Figure 16). The list of curve numbers for each land cover are shown
in the *Land Cover/Plant Growth Database* which can be accessed through the *Edit SWAT Input* menu and then by selecting the *Land Cover/Plant Grown* option (an example is shown in Figure 17).

**Figure 16: Management (.Mgt) Parameters Example**
The default curve numbers were initially applied to each subbasin in the watershed. During basin specific calibration some basin curve numbers were adjusted and are described in Section 4.3.
4.1.7 **Hydraulic conductivity of the soil (SOL_K.sol)**

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). This database was used to extract all physical properties of soil for the Sao Francisco River watershed. The default values were used for all physical soil properties in the watershed, except for the hydraulic conductivity. The SOL_K.sol values for the soil was used as a calibration Parameter throughout the watershed. During the calibration it was found that the saturated hydraulic conductivity for each soil layer was reduced by a factor of 5 (for example the default hydraulic conductivity value in the ISRIC database for a latosol is 600 mm/hr, and the value used in the SWAT model is 120 mm/hr).

4.1.8 **Hydraulic conductivity in main channel (CH_K2.rte)**

The hydraulic conductivity of the main channel measures how much water is lost to groundwater recharge. The units of the main channel hydraulic conductivity (CH_K.rte) is mm/hr, and therefore the total length of the channel and width of channel are important Parameters to estimate correctly in order for the groundwater recharge to be calculated correctly. A positive hydraulic conductivity of the main channel alluvium categorizes the stream as a “losing stream”, or a stream that loses water to the groundwater (see Figure 18). The losing stream nature of the Sao Francisco River is observed by investigating flow gages. In many locations, the river flow does not increase significantly in the downstream direction, and in some cases the river flow decreases in the downstream direction (this is particular true in the middle Sao Francisco River).
Some of this water loss is due to evaporation, but a component is also due to groundwater recharge in the losing stream.

**Figure 18: Stream-groundwater Relationships (After Dingman, 1994)**

- **(a)** Gaining stream receiving water from groundwater flow
- **(b)** Losing stream connected to groundwater system
- **(c)** Losing stream perched above groundwater system
- **(d)** Flow-through stream

The value of the hydraulic conductivity for each river is not known. The SWAT manual provides some guidance on estimated hydraulic conductivities of natural rivers as a function of the bed material (see Table 11, after Lane, 1983). This Parameter was heavily used in the calibration process. A uniform value of 5 mm/hr was applied to all reaches within the Sao Francisco River watershed.
4.1.9 **Hydraulic conductivity in sub-basin tributaries (CH_K1.sub)**

The hydraulic conductivity of the sub-basin tributaries is similar to the hydraulic conductivity in the main channel. This Parameter measures how much water is lost to groundwater recharge in the tributaries. The units of the main channel hydraulic conductivity (CH_K1.sub) is mm/hr. Initially, a uniform value of 5 mm/hr was applied to all sub-basins within the Sao Francisco River watershed. This value was changed for some sub-basins as described in Section 4.3.

4.1.10 **Average slope steepness of HRU (HRU_SLP.hru)**

The average slope steepness is a value that is calculated by ArcSWAT for each HRU. This is a very sensitive variable to both the water and sediment yield of the watershed. Steeper slopes have significantly higher peak flows, increased runoff percentage, and more sediment yield than flatter slopes. The SWAT calculated values for
the HRU_SLP were applied for the initial calibration at the Morpara gage. Some HRU_SLP values were adjusted for site specific areas in order to achieve calibration at other gages. These changes are described in Section 4.3.

4.1.11 Average slope length of HRU (SLSUBBSN.hru)

The average slope length is defined as the distance that sheet flow is the dominant surface runoff process (as opposed to rill or gully flow). ArcSWAT calculates this length based on the topography, but it was found that this value was over-estimated. The SWAT manual notes that 90 meters is considered to be a very long slope length. Since ArcSWAT calculates all slopes lengths to be longer than 90 meters for each HRU, the SLSUBBSN.hru slopes were reduced to 90 meters for all HRUs.

4.1.12 Manning’s “n” for overland flow (OV_N.hru)

The overland flow Manning’s “n” is a measure of the surface runoff friction value. The overland Manning’s n value is generally higher than the n value in rivers and channels. A range of Manning’s “n” as a function of land use practices is shown in Table 12, from Engman (1983).
The default value of 0.08 was applied to the surface runoff of each basin. This is consistent with dominant landuses such as rangeland and conventional tillage agriculture. Varying the overland Manning’s “n” by landuse did not have a significant effect on the results of the model, and therefore a value of 0.08 was uniformly applied across the overland flow throughout the basin.

4.1.13 Deep aquifer percolation fraction (RCHRG_DP.gw)

The deep aquifer percolation fraction is a measure of the percentage of water that is lost from the hydrologic system to a deep aquifer. The remaining percentage is available to be evaporated through the soil column or to contribute to lateral flow to the streams. This variable is a very sensitive Parameter to balance the hydrology of the Sao Francisco River watershed. During the manual calibration process a value of 0.6 (60%) was found to balance the hydrology and match observed flow records. This value was applied throughout all of the HRUs in the basin, but was modified for specific areas as described in Section 4.3.
4.1.14 *Surface runoff lag coefficient (SURLAG.bsn)*

The SURLAG is a coefficient that is applied uniformly throughout the entire basin (this is in the basin file and is not site specific to sub-basins or HRUs). The SURLAG coefficient controls the fraction of the total water that is allowed to reach a stream on a given day. In large watersheds, the time of concentration will be greater than a single day and therefore more water should be stored in the basin (or “lagged”) before reaching a stream. The default value of SURLAG in SWAT is 4.0. A relationship between the SURLAG coefficient, the time of concentration, and the fraction of surface runoff storage reaching the stream can be seen in Figure 19 and Equation 19.

![Figure 19: Influence of SURLAG on Fraction of Runoff Reach Stream](image)

$$Q_{surf} = \left( Q'_{surf} + Q_{stor,i-1} \right) \left( 1 - \left[ \frac{SURLAG}{t_{conc}} \right] \right) \tag{19}$$

Where:
\[ Q_{\text{surf}} = \text{the amount of surface runoff discharged to the main channel on a given day (mm H}_2\text{O)} \]

\[ Q'_{\text{surf}} = \text{the amount of surface runoff generated in the subbasin on a given day (mm H}_2\text{O)} \]

\[ Q_{\text{stor},i-1} = \text{the surface runoff stored or lagged from the previous day (mm H}_2\text{O)} \]

\[ \text{SURLAG} = \text{the surface runoff lag coefficient} \]

\[ t_{\text{conc}} = \text{time of concentration for the subbasin (hrs)} \]

The SURLAG is a sensitive Parameter to the output of the SWAT model. During the manual calibration process a very low SURLAG value of 0.05 was found to be appropriate. This low value is justified by the very large basins that are being modeled in the Sao Francisco River watershed, yielding significant storage on a given day following a rain event.

4.1.15  Depth of water in shallow aquifer for return flow (GWQMN.gw)

In order for water from the shallow aquifer to flow into a receiving stream, there must be a certain volume or depth in the aquifer. SWAT uses the GWQMN Parameter to apply a threshold depth of water in the shallow aquifer for the return flow to occur. The default depth is 0 mm in SWAT (meaning that return flow is always allowed to occur if there is water in the shallow aquifer). This value was adjusted during calibration, but it was found that maintaining the default value of 0 mm was an appropriate value to achieve acceptable calibration.
4.1.16  Groundwater revap coefficient (GW.REVAP.gw)

The Groundwater revap is a process by which water in the shallow aquifer is allowed to evaporate back into the unsaturated zone. GW.REVAP coefficient dictates whether there is limited revap (a value of 0), or if the revap closely resembles evaporation from a lake (a value of 1). The range of the revap coefficient is 0.02 to 0.2, and the default value is 0.02. During the calibration it was found that the default value of 0.02 was appropriate for all HRUs in the Sao Francisco River watershed.

4.1.17  Depth of water in the shallow aquifer for revap (REVAPMN.gw)

A certain height of water must be available in the shallow aquifer in order for revap to occur. The default value in SWAT is 1 mm. During calibration it was found that an appropriate depth for revap to occur is 100 mm. This was applied to all HRUs in the Sao Francisco River watershed.

4.1.18  Groundwater delay time (GW.DELAY.gw)

The groundwater delay (in days) is a measure of the length of time it takes for water to flow from the bottom of the deepest soil layer through the vadose zone, and into the shallow aquifer. Groundwater flow through the soil is calculated as a function of the hydraulic conductivity of the soil. However, below the soil layer SWAT does not apply a hydraulic conductivity to the parent material that is not a soil. Instead, the groundwater delay Parameter is used to lag the groundwater flow after it has flowed through the soil material but before it reaches the shallow aquifer.
The GW\_DELAY term ranges from 0 to 500 days in SWAT with a default value of 31 days. During the calibration it was determined that an appropriate value for the GW\_DELAY is 0 days. This is justified due to a deep soil layer provided in SWAT (1000 mm in all locations). Therefore, as soon as the groundwater flows through the soil layer it immediately reaches the shallow aquifer.

### 4.2 Hydrologic Calibration to Morpara Gage

The Morpara Gage (ANA Gage 46360000) was selected for the initial basin-wide calibration of the SWAT model. This gage was selected for the following reasons:

1. The gage includes a long daily flow record (since 1954) and is a current gage.
2. The gage includes both flow and sediment records.
3. The gage is in the middle Sao Francisco River. This research focuses on the current sediment dynamics and sediment budget of the middle Sao Francisco River and its impacts on navigation.
4. The gage is not heavily influenced by dams/reservoirs. This allows the natural hydrology of the basin to be observed. (The gage is only slightly influenced by controls at the Tres Marias dam, approximately 900 km upstream).

The Morpara gage is located at S 11°33’30”, W 43°16’57” on the main stem of the Sao Francisco River at the city of Morpara, Bahia. This location corresponds to the inflow into sub-basin 27 of the SWAT model (see Figure 20).

Daily flow records are available at the Morpara gage since 1954. This data was used to calibrate the SWAT model at the inflow into sub-basin 27. The calibration period
of the SWAT model consists of the years 2001 through 2006. This data is plotted in Figure 21.

The Nash Sutcliffe Efficiency (NSE), developed by Nash and Sutcliffe (1970) was the primary hydrologic statistical measure to determine if calibration was achieved. The NSE is a measure of how much better a model predicts hydrologic behaviors better than the mean of the observed data. The NSE model equation is shown in Equation 20.

\[
NSE = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} (Q_o^t - \bar{Q}_o)^2}
\]  

(20)

Where:

\( Q_o^t \) = observed discharge at observation \( t \)

\( Q_m^t \) = hydrologic model discharge at observation \( t \)

\( t \) = time (day) of observation

\( T \) = total number of observations

\( \bar{Q}_o \) = average of all observations
Figure 20: Morpara Gage in the SWAT Model (Inflow to Basin 27)
Moriasi et al. (2007) provides recommendations for determining statistical metrics for calibration of hydrology, sediment yield, and nutrient models such as SWAT. Moriasi et al. (2007) recommends the following performance ratings for a hydrology model with a monthly time-step:

- **Very Good:** \(0.75 < \text{NSE} \leq 1.00\)
- **Good:** \(0.65 < \text{NSE} \leq 0.75\)
- **Satisfactory:** \(0.50 < \text{NSE} \leq 0.65\)
- **Unsatisfactory:** \(\text{NSE} \leq 0.50\)
Moriasi et al. (2007) also notes that lower NSE are acceptable when calibration is conducted at a daily time-step, although the authors do not provide specific recommendations on how much to lower these rankings. Based on these recommendations and the purpose of the model (determine a general sediment budget for the Middle Sao Francisco watershed), it was determined that obtaining a NSE greater than 0.65 (minimum of “Good” calibration) was a reasonable goal to achieve a calibrated model. The recommendations by Moriasi et al. have been widely accepted by the community of practice of hydrologic, sediment yield, and nutrient modeling at the watershed scale.

Using these recommendations and the hydrologic variables described in Section 4.1 calibration was achieved at the Morpara gage. The NSE achieved for the SWAT model at this location is 0.66 for the average monthly flowrates (see Figure 22).
The output of the SWAT model daily flow at the Morpara gage was also compared to the observed daily flow. The NSE associated with the daily calibration from 2001-2006 is 0.56. This also is considered a “Good” calibration based on the fact that the daily flow NSE is generally lower than a monthly calibration (Moriasi et al. recommends to relax the values associated with each category for a daily calibration). The calibrated data is shown in Figure 23.
Figure 23: Daily Flow Calibration at the Morpara Gage (NSE = 0.56)
4.3 Sub-basin specific Calibration

The overall basin calibration provided a basis for average conditions throughout the Sao Francisco basin upstream of the Morpara gage. However, there is significant variability of meteorology, landuse, soils, groundwater behavior, topography, etc. that required additional basin specific calibration of additional gages. Each of the major tributaries were included in this calibration for hydrology. The additional basin-specific calibration was completed at the following major tributaries and associated ANA gages:

1. Rio Para – ANA Gage 40330000 (SWAT Basin 74)
2. Rio Paraopeba – ANA Gage 40850000 (SWAT Basin 75)
3. Rio das Velhas – ANA Gage 41818000 (SWAT Basin 73)
4. Rio Jequitai – ANA Gage 42145498 (SWAT Basin 66)
5. Rio Paracatu – ANA Gage 42980000 (SWAT Basin 62)
6. Rio Urucuia – ANA Gage 43980002 (SWAT Basin 58)
7. Rio Verde Grande – ANA Gage 44670000 (SWAT Basin 57)
8. Rio Carinhanha – ANA Gage 45260000 (SWAT Basin 49)
9. Rio Corrente – ANA Gage 45960001 (SWAT Basin 42)

See Figure 24 for the locations of each of these tributaries.
Figure 24: Major Tributaries Calibrated in SWAT Model
4.3.1 Rio Para – Gage 40330000 (SWAT Basin 74)

The entire Rio Para is captured in a single sub-basin (Basin 74). The outlet of basin 74 corresponds to ANA gage 40330000. This basin has 43 distinct HRUs. The following adjustments were made to Parameters in Basin 74:

1. SLOPE multiplied by 0.5 for each HRU.
2. ALPHA_BF set to 0.0007 for each HRU
3. GW_DELAY set to 30 days for each HRU
4. RCHRG_DP set to 0.8 for each HRU
5. CH_K1 (hydraulic conductivity for tributaries) was set to 0
6. CH_K2 (hydraulic conductivity for main channel) was set to 0
7. CN2 multiplied by 0.75 for each HRU

Using these 6 changes a NSE of 0.66 was obtained for the 2001-2006 monthly flow record (see Figure 25). This is considered to be a “Good” hydrology calibration for this basin.
Figure 25: Monthly Flow Calibration at the Rio Para (NSE = 0.66)
4.3.2 Rio Paraopeba - Gage 40850000 (SWAT Basin 75)

The entire Rio Paraopeba is captured in a single sub-basin (Basin 75). The outlet of basin 75 corresponds to ANA gage 40850000 (although the gage is approximately 120 km upstream of the outlet of the river). This basin has 76 distinct HRUs. The following adjustments were made to Parameters in Basin 75:

1. ALPHA_BF set to 0.0005 for each HRU
2. CN2 multiplied by 0.81 for each HRU
3. CH_K1 (hydraulic conductivity for tributaries) was set to 0
4. CH_K2 (hydraulic conductivity for main channel) was set to 0
5. RCHRG_DP set to 0.7 for each HRU

Using these 5 changes a NSE of 0.72 was obtained for the 2001-2006 monthly flow record (see Figure 26). This is considered to be a “Good” hydrology calibration for this basin.
Figure 26: Monthly Flow Calibration at the Rio Paraopeba (NSE = 0.72)
4.3.3 Rio das Velhas - Gage 41818000 (SWAT Basin 73)

The entire Rio das Velhas is captured in a single sub-basin (Basin 73). The outlet of basin 73 corresponds to ANA gage 41818000 (although the gage is approximately 120 km upstream of the outlet of the river). This basin has 76 distinct HRUs. The following adjustments were made to Parameters in Basin 73:

1. ALPHA_BF set to 0.0005 for each HRU
2. CH_K1 (hydraulic conductivity for tributaries) was set to 0 for each HRU
3. CH_K2 (hydraulic conductivity for main channel) was set to 0 for each Reach
4. RCHRG_DP set to 0.8 for each HRU
5. SLOPE multiplied by 1.5 for each HRU

Using these 5 changes a NSE of 0.63 was obtained for the 2001-2006 monthly flow record (see Figure 27). This is considered to be a “Good” hydrology calibration for this basin.
Figure 27: Monthly Flow Calibration at the Rio das Velhas (NSE = 0.63)
4.3.4 Rio Jequitai - Gage 42145498 (SWAT Basin 66)

The entire Rio Jequitai is captured in a single sub-basin (Basin 66). The outlet of basin 66 corresponds to ANA gage 42145498 (although the gage is approximately 50 km upstream of the outlet of the river). This basin has 64 distinct HRUs. The following adjustments were made to Parameters in Basin 66:

1. RCHRG_DP set to 0.7 for each HRU

Using this changes a NSE of 0.67 was obtained for the 2001-2006 monthly flow record (see Figure 28). This is considered to be a “Good” hydrology calibration for this basin.

Figure 28: Monthly Flow Calibration at the Rio Jequitai (NSE = 0.67)
4.3.5 Rio Paracatu – Gage 42980000 (SWAT Basin 62)

The Rio Paracatu is contained within sub-basins 61, 62, 64, 65, and 67. The outlet of the SWAT basin 62 corresponds to ANA gage 42980000 (although the gage is approximately 45 km upstream of the outlet of the river). This basin has 296 separate HRUs. No adjustments were made to any of the sub-basins or HRUs.

Without changing the default calibration Parameters a NSE of 0.61 was achieved for the 2001-2006 monthly flow record (see Figure 29). This is considered to be a “Satisfactory” hydrology calibration for this basin.

Figure 29: Monthly Flow Calibration at the Rio Paracatu (NSE = 0.61)
4.3.6 Rio Urucuia – Gage 43980002 (SWAT Basin 58)

The entire Rio Urucuia is captured in a single sub-basin (Basin 58). The outlet of basin 58 corresponds to ANA gage 43980002 (although the gage is approximately 31 km upstream of the outlet of the river). This basin has 94 distinct HRUs. The following adjustments were made to Parameters in Basin 66:

1. SLOPE multiplied by 2.0 for each HRU

By adjusting this value, the model achieved a calibration NSE value of 0.57 for the 2001-2006 monthly flow record (see Figure 30). This is considered to be a “Satisfactory” hydrology calibration for this basin.

Figure 30: Monthly Flow Calibration at the Rio Urucuia (NSE = 0.57)
4.3.7  Rio Verde Grande – Gage 44670000 (SWAT Basin 57)

The Rio Verde is contained within the SWAT basins 52, 53, 54, 55, and 57. There is an ANA gage located within the SWAT basin 57 (ANA Gage 44670000), and the calibration of the Rio Verde Grande watershed is based on output from SWAT basin 57 (although all HRUs and Basin data were adjusted for each of the 5 basins that make up the Rio Verde Grande watershed). This basin has 269 distinct HRUs. The following adjustments were made to Parameters in Basins 52, 53, 54, 55 and 57:

1.  SLOPE multiplied by 0.5 for each HRU
2.  RCHRG_DP set to 0.9 for each HRU
3.  ALPHA_BF set to 0.05 for each HRU
4.  CN2 multiplied by 0.5 for each HRU
5.  CH_K1 (hydraulic conductivity for tributaries) was set to 0 for each HRU
6.  CH_K2 (hydraulic conductivity for main channel) was set to 0 for each Reach

By adjusting these calibration Parameters a NSE of 0.60 was achieved for the 2001-2006 monthly flow record (see Figure 31). This is considered to be a “Satisfactory” hydrology calibration for this basin.
Figure 31: Monthly Flow Calibration at the Rio Verde Grande (NSE = 0.60)
4.3.8 Rio Carinhanha – Gage 45260000 (SWAT Basin 49)

The Rio Carinhanha is contained within sub-basins 47, 49, and 50. The outlet of the SWAT basin 49 corresponds to ANA gage 45260000 (although the gage is approximately 45 km upstream of the outlet of the river). This basin has 140 separate HRUs. The following adjustments were made to sub-basins 47, 49, and 50:

1. CN Reduced by 50% for each HRU. This is justified due to the extremely flat farming landuse associated with most HRUs.
2. K of the channel increased to 50 mm/hr.
3. RCHRG_DP recharge set to 0.5 (50%)
4. SLOPE decreased by 50% (0.5) for each HRU.
5. ALPHA_BF set to 0.0005 for each HRU

By adjusting these calibration Parameters a NSE of 0.58 was achieved for the 2001-2006 monthly flow record (see Figure 32). This is considered to be a “Satisfactory” hydrology calibration for this basin.
Figure 32: Monthly Flow Calibration at the Rio Carinhanha (NSE = 0.58)
4.3.9 Rio Corrente – ANA Gage 45960001 (SWAT Basin 42)

The Rio Corrente is contained within sub-basins 40, 41, 42, 43 and 45. The outlet of the SWAT basin 42 corresponds to ANA gage 45960001 (although the gage is approximately 53 km upstream of the outlet of the river). This basin has 137 separate HRUs. The following adjustments were made to sub-basins 40, 41, 42, 43 and 45:

1. CN Reduced by 50% for each HRU. This is justified due to the extremely flat farming landuse associated with most HRUs.
2. K of the channel increased to 50 mm/hr.
3. RCHRG_DP recharge set to 0.4 (40%)
4. SLOPE decreased by 50% (0.5) for each HRU.

By adjusting these calibration Parameters a NSE of 0.67 was achieved for the 2001-2006 monthly flow record (see Figure 33). This is considered to be a “Good” hydrology calibration for this basin.
Figure 33: Monthly Flow Calibration at the Rio Corrente (NSE = 0.67)
4.3.10  *Rio Grande – ANA Gage 45965000 (SWAT Basin 26)*

The Rio Grande is contained within sub-basins 25, 26, and 29-35. The outlet of the SWAT basin 26 corresponds to ANA gage 45965000. This basin has 311 separate HRUs. The following adjustments were made to sub-basins 25, 26, and 29-35:

1. CN Reduced by 50% for each HRU.
2. RCHRG_DP recharge set to 0.7 (70%)
3. SLOPE decreased by 50% (0.5) for each HRU.
4. ALPHA_BF changed to 0.0008

By adjusting these calibration Parameters a NSE of 0.52 was achieved for the 2001-2006 monthly flow record (see Figure 34). This is considered to be a “Satisfactory” hydrology calibration for this basin.
4.4 Validation of Calibrated model using Sao Francisco River Gages

Following the calibration of each of the major tributaries feeding into the Sao Francisco River, a comparison of several gages along the Sao Francisco was completed. The following gages were investigated to validate the calibrated model:

1. Rio Sao Francisco upstream of Para – ANA Gage 40100000 (SWAT Basin 76)
2. Rio Sao Francisco at Manteiga – ANA Gage 42210000 (SWAT Basin 60)
3. Rio Sao Francisco at Manga – ANA Gage 44500000 (SWAT Basin 56)
4. Rio Sao Francisco at Bom Jesus de Lapa – ANA Gage 45480000 (SWAT Basin 44)
5. Rio Sao Francisco at Morpara – ANA Gage 46360000 (SWAT Basin 27)
6. Rio Sao Francisco at Juazeiro – ANA Gage 48015000 (SWAT Basin 12)
7. Rio Sao Francisco at Ibo – ANA Gage 48590000 (SWAT Basin 4)

The comparison of the model data with the observed monthly data (with the Nash-Sutcliffe efficiencies) for these additional 7 validation points are shown in Figure 35 through Figure 41.

**Figure 35: ANA Gage 40100000 (SWAT Basin 76). NSE = 0.51 (Satisfactory)**
Figure 36: ANA Gage 42210000 (SWAT Basin 60). NSE = 0.73 (Good)

Figure 37: ANA Gage 44500000 (SWAT Basin 56). NSE = 0.75 (Very Good)
Figure 38: ANA Gage 45480000 (SWAT Basin 44). NSE = 0.76 (Very Good)

Figure 39: ANA Gage 46360000 (SWAT Basin 27). NSE = 0.66 (Good)
Figure 40: ANA Gage 48015000 (SWAT Basin 12). NSE = 0.88 (Very Good)

Figure 41: ANA Gage 48590000 (SWAT Basin 4). NSE = 0.57 (Satisfactory)
A summary of the 17 gages used for calibration and validation of the Sao Francisco River model is shown in Table 13.

**Table 13: Summary of Calibration and Validation for Hydrology**

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

No calibration or validation gages received an “unsatisfactory” rating, and the distribution of NSE ratings for the hydrology of the basin are summarized as:

- 3 gages rated Very Good
- 6 gages rated Good
- 8 gages rated Satisfactory

The Sao Francisco river model was used to determine course sediment budget characteristics of the basin for both hydrology and sediment. In all of the gages analyzed for calibration and validation, a minimum rating of Satisfactory was achieved and over half of the gages were rated either Good or Very Good. Based on the use of the model and final rankings of the validation/calibration, the SWAT model was considered calibrated for hydrology.
CHAPTER 5.0 SEDIMENT CALIBRATION

5.1 Calibration Parameters

The following variables were used to calibrate the SWAT model for sediment loads in sequential order (the SWAT database Parameter file is included in parenthesis):

1. Width-depth ratio (CH_WDR.rte)
2. Channel erodability factor (CH_COV1.rte)
3. USLE equation support practice factor (USLE_P.mgt)
4. Sediment concentration in lateral and groundwater flow (LAT_SED.hru)
5. Erodability of channel bank sediment (CH_BNK_KD.rte)
6. Erodability of channel bed sediment (CH_BED_KD.rte)
7. Median particle size diameter of channel bank sediment (CH_BNK_D50.rte)
8. Median particle size diameter of channel bed sediment (CH_BED_D50.rte)
9. Critical shear stress of channel bank (CH_BNK_TC.rte)
10. Critical shear stress of channel bed (CH_BED_TC.rte)
11. Channel erodability factor by month (CH_ERODMO.rte)
12. Sediment Transport equation (CH_EQN.rte)

5.1.1 Width-Depth Ratio (CH_WDR.rte)

In the SWAT model, the channel dimensions are allowed to change during the simulation period. When channel degradation (erosion) occurs on a reach a widening of the river will result in order to achieve a new equilibrium condition. This is the mechanism by which bank erosion volumes are calculated. The width-depth ratio is an important Parameter to determine how much widening will occur after the channel down-
cuts. In order to turn on channel downcutting the IREG Parameter must be set to 1 in the .bsn file.

At each sub-basin, a representative reach was selected to measure the width (generally near the middle of the reach or sub-basin). A maximum value of 10 meters was applied to the channel depth, and the width-depth ratio was subsequently calculated. Table 10 displays the measured widths, depths, and width-depth ratio. These were the values used prior to the sediment transport calibration.

5.1.2 Channel erodability factor (CH_COV1.rte)

The channel erodability factor is a Parameter that is applied to the river banks. The value ranges from 0 to approximately 20, where a high value of CH_COV1 representing that the channel material is very resistant to the erosive forces of the river. A low value represents that the bank material is very erodible (however, a value of 0 represents that there is no bank erosion, and therefore completely resists the erosive forces from the river). Due to the often bare bank observed through the Sao Francisco River an initial low value of 0.6 was applied to the channel erodability factor.

5.1.3 USLE equation support practice factor (USLE_P.mgt)

The Universal Soil Loss Equation practice factor (USLE_P.mgt) is a Parameter applied to each HRU within the basin. This factor represents various farming practices and ranges from 0 to 1.0. SWAT guidance notes that the USLE P factor is generally
lower when calculating sediment yield than for typical USLE applications. Table 14 lists a variety of USLE P factors under a range of agricultural applications.

Table 14: USLE P factors for Various Agricultural Applications

<table>
<thead>
<tr>
<th>Land slope (%)</th>
<th>Farm planning</th>
<th>Computing sediment yield&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contour P factor&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Stripcrop P factor</td>
</tr>
<tr>
<td>1 to 2</td>
<td>0.60</td>
<td>0.30</td>
</tr>
<tr>
<td>3 to 8</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>9 to 12</td>
<td>0.60</td>
<td>0.30</td>
</tr>
<tr>
<td>13 to 16</td>
<td>0.70</td>
<td>0.35</td>
</tr>
<tr>
<td>17 to 20</td>
<td>0.80</td>
<td>0.40</td>
</tr>
<tr>
<td>21 to 25</td>
<td>0.90</td>
<td>0.45</td>
</tr>
</tbody>
</table>

<sup>1</sup>Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contouring factor is used in the computation.

<sup>2</sup>Use these values for control of interterrace erosion within specified soil loss tolerances.

<sup>3</sup>These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field’s contribution to watershed sediment yield.

The USLE P factor was set to a low value of 0.15. This is the final value used in the calibrated sediment transport model.

5.1.4 Sediment concentration in lateral and groundwater flow (LAT_SED.hru)

The sediment concentration in the lateral groundwater flow is a very sensitive Parameter in the overall sediment dynamics of the Sao Francisco River watershed. Due to the high degree of return flow (water that enters the groundwater and returns to the river) the sediment concentration associated with this return flow can add a significant load to the river. Although sensitive to the output of the model, the final calibrated model used a sediment concentration of 0 mg/L in the lateral groundwater flow for all HRUs.
5.1.5  Erodability of channel bank sediment (CH_BNK_KD.rte)

The channel bank erodability is a calculated value of erosion based on a submerged jet test on the channel bank. The units of the erodability are cm$^3$/N-s. The value can be calculated based on a method developed by Hanson (1990) using a submerged jet impinging upon the bank and measuring the subsequent scour depth (see Figure 42).

Figure 42: Submerged Jet Test used to Determine Channel Bank Erodability

The channel bank erodability value ranges typically from 0.001 to 3.75 cm$^3$/N-s. Since direct tests were not available, the approximate geometric mean of the range of the values (a value of 0.1 cm$^3$/N-s) was applied to all reaches in the Sao Francisco River. The model was calibrated using this value.
5.1.6 Erodability of channel bed sediment (CH_BED_KD.rte)

The erodability of the channel bed is a similar parameter to the erodability of the channel bank. Since the bed is made of erodible sands, a high value of 3.75 cm³/N-s was applied to all reaches in the Sao Francisco River.

5.1.7 Median particle size diameter of bank sediment (CH_BNK_D50 rte)

The mean particle diameter of the bank is a parameter used in the bank erosion algorithms within SWAT. Bank gradation data is available for the medium Sao Francisco River along the navigation channel, and averages to be approximately 0.5 mm (see Figure 43 for a sample gradation curve for bank gradation data collected at site called Campo de Provas near Barra, Bahia). Although data is not available for the gradation of the banks throughout the Sao Francisco watershed, this average value of 0.5 mm (500 μm) was added to all reaches within the SWAT model, and the model was calibrated using this data.
5.1.8 Median particle size diameter of bed sediment (CH_BED_D50.rte)

The median particle size diameter of the bed is used in the calculations of erosion for the bed of the river. Limited data is available for the gradation of the bed of the Sao Francisco River and the tributaries. However, based visual observations of bed gradation samples collected at the Campo de Provas site, and visual observations of several samples collected by the CODEVASF-USACE team at the Torrinha-Itacoatiara site, the average gradation of the bed is approximately a medium to course sand with a particle diameter of 0.5 mm (500 μm). This value was added to all reaches within the Sao Francisco SWAT model and the final calibrated model used this value.

5.1.9 Critical shear stress of channel bank (CH_BNK_TC.rte)

The critical shear stress of the channel bank is used to calculate the erosion of the bank when a shear stress applied. This value was used as a calibration Parameter, and a calibrated sediment transport model was developed when a value of 0.2 N/m² was applied.
to all banks within the SWAT model. This value was higher than the channel bed due to the cohesive properties of the clays found in the channel banks, which require a higher shear stress to dislodge. This value is also within typical literature values for the channel bank critical shear.

5.1.10 Critical shear stress of channel bed (CH_BED_TC.rte)

The critical shear stress of the channel bed is a measure of when the bed material will begin to erode based on the shear stress applied. This value was used as a calibration Parameter, and a calibrated sediment transport model was developed when a value of 0.08 N/m² was applied to all channel beds within the SWAT model. This is a realistic value (less than the channel bank) due to the more erodible material found in the channel bed.

5.1.11 Channel erodability factor by month (CH_ERODMO.rte)

The channel erodability factor is a value that ranges from 0.0 (for a non-erosive channel) to 1.0 (where no resistance to erosion is applied). A value of 1.0 was applied to all reaches, which indicates that no additional resistance to erosion is applied to the model. Therefore, only the sediment transport function determine the amount of sediment erosion calculated along each reach.

5.1.12 Sediment Transport equation (CH_EQN.rte)

The Yang sediment transport equation was selected for previous sediment transport models (HEC-RAS models) within the watershed, and therefore the Yang
equations was also chosen for all reaches within the SWAT model (the Yang sediment transport function corresponds to a value of 4 in the CH_EQN.rte variable in SWAT). Yang is an appropriate sediment transport function with particles sizes in the sand and gravel categories (0.15 mm to 7.0 mm). It was developed under a wide range of velocities (0.8 to 2.45 m/s) and depths (up to 17 meters) and is applicable for very flat sloped rivers such as the Sao Francisco River. The field tests of Yang were also performed on very wide rivers (up to 1750 meters). All of the Parameters associated with the Sao Francisco River make Yang an appropriate sediment transport function, and therefore Yang was chosen for the SWAT model.
5.2  *Sediment Calibration to the Morpara Gage*

The Morpara Gage (ANA Gage 46360000) was selected for the initial basin-wide calibration of the SWAT model for sediment as well as hydrology. This gage was selected for the following reasons:

1. The gage includes a long daily flow record (since 1954) and is a current gage.
2. The gage includes both flow and sediment records
3. The gage is in the middle Sao Francisco River. This research focuses on the current sediment dynamics and sediment budget of the middle Sao Francisco River and its impacts on navigation.
4. The gage is not heavily influenced by dams/reservoirs. This allows the natural hydrology of the basin to be observed. (The gage is only slightly influenced by controls at the Tres Marias dam).

The Morpara gage is located at S 11°33’30”, W 43°16’57” on the main stem of the Sao Francisco River at the city of Morpara, Bahia. This location corresponds to the inflow into sub-basin 27 of the SWAT model (see Figure 20).

A sediment rating curve is available at the Morpara gage, and this was used to determine the daily sediment loads through the simulation period of the SWAT model (2001-2006). The fraction of the sediment load that is in suspension (i.e., the suspended sediment load) is known as a function of the flowrate in the Sao Francisco River at the Morpara gage (ANA gage 46360000, available at [http://hidroweb.ana.gov.br/](http://hidroweb.ana.gov.br/)). The data is collected by ANA, which uses as USDH-59 sampler (according to Carvalho et al., 2000), which is a hand-line depth-integrated sampler. A power regression of this data was made, which is plotted in log-log scale in Figure 44. There is about one-half to one order of
magnitude of scatter in the data for a given flowrate, which is typical of many suspended sediment rating curves of alluvial rivers.

![Graph showing the relationship between flow and sediment load](image)

In addition to the suspended sediment data that is available, the Sao Francisco River is also transporting bedload that is likely comprised predominately of sand (this assumption is due to the sandy gradation of the active river bed at observed locations during field visits to the site). In a previous study (CODEVASF-USACE, 2013b) a robust sensitivity analysis was performed on a HEC-RAS model of the Sao Francisco River to determine the likely percentage of bedload in the system. This study (the Sambaiba Island sediment transport model), determined that the bedload fraction is approximately 25% of the suspended load. This is a valid assumption to be applied to the
Morpara gage. More information regarding the bedload fraction sensitivity analysis at Sambaiba Island can be found in the Sambaiba Island Final Report prepared by the CODEVASF-USACE (2013b). Therefore, the rating curve regression plus an additional 25% was added to the daily sediment load data. This data was then converted to a monthly load, and was used to calibrated the sediment data for the SWAT model.

The calibration of sediment yield for typical SWAT modeling studies is based on a Percent Bias (PBIAS) statistical technique. The PBIAS of a sediment yield model can be calculated using Equation 21.

\[
PBIAS = \frac{\sum_{i=1}^{n}(Y_{i}^{obs} - Y_{i}^{sim}) \times 100}{\sum_{i=1}^{n}(Y_{i}^{obs})}
\]

Where:

\(Y_{i}^{obs}\) = observed Parameter (sediment) at observation i

\(Y_{i}^{sim}\) = simulated model Parameter (sediment) at observation i

\(i\) = observation number

\(n\) = total number of observations

PBIAS is a statistical measure of the average tendency of the simulated data to be larger or smaller than their observed counterpart. The ideal PBIAS is 0.0, with low absolute values representing accurate model results. Positive PBIAS represents a model underestimated observed data and a negative PBIAS indicates that the model is overestimating observed data. Moriasi et al. (2007) recommends the following performance ratings for a sediment yield model with a monthly time-step based on PBIAS:

**Very Good:** \(PBIAS < \pm 15\)
Good: \[ \pm 15 \leq \text{PBIAS} < \pm 30 \]

Satisfactory: \[ \pm 30 \leq \text{PBIAS} < \pm 55 \]

Unsatisfactory: \[ \text{PBIAS} \geq 55 \]

The PBIAS calculated at the Morpara gage is -12.6, which is considered to be a Very Good sediment calibration according to Moriasi et al. (2007). Figure 45 displays the monthly sediment loads for both the observed data set as well as the calibrated model.

**Figure 45: Calibrated Sediment at Morpara Gage. PBIAS = -12.6 (Very Good)**
5.3  **Sediment Calibration to the Mouth of the Sao Francisco River**

A consortium of agencies including the Agencia Nacional de Energia Eletrica (ANEEL), the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA), and the Agencia Nacional de Aguas (ANA) conducted a study of the sediment loads in the Sao Francisco River (ANEEL, 2001). This study included a summary of the sediment data at the mouth of the Sao Francisco River at gage 497050000 (the Propria gage). This study showed that there is an overall decrease of sediment loads to the ocean since the late 1970’s (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 1980’s and 1990’s. Recent sediment loads (1986-1999) have averaged 1.8 million tonnes of suspended sediment delivered to the Atlantic Ocean from the Sao Francisco River (see Figure 46).

The SWAT model output of the average annual sediment loads to the Atlantic Ocean can be investigated by inspecting the output of the sediment table at SWAT sub-basin 21. The annual sediment loads for both suspended sediments (clays and silts) as well as bed load sediments (sands and all other materials) are shown in Figure 47 and Table 15. The average suspended sediment load is approximately 1,650,000 tonnes per year, which is slightly less than the average delivery observed from the ANEEL report of 1,830,000 tonnes per year. SWAT predicts the total sediment delivery to the ocean to be 2,300,000 tonnes per year. These values closely match observed data, and further validates the sediment delivery predicted by the SWAT model.
**Figure 46: Sediment Loads to the Atlantic Ocean from the Sao Francisco River**

<table>
<thead>
<tr>
<th>Parâmetro</th>
<th>MLT</th>
<th>1986 - 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qss (t/dia)</td>
<td>7.472</td>
<td>5.022</td>
</tr>
<tr>
<td>Qss (t/ano)</td>
<td>2.727170</td>
<td>1.833197</td>
</tr>
<tr>
<td>Área de drenagem (km²)</td>
<td>623.500</td>
<td>623.500</td>
</tr>
<tr>
<td>Qss específico (t/km².ano)</td>
<td>4.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Q (m³/s)</td>
<td>2.528</td>
<td>2.120</td>
</tr>
<tr>
<td>Css (mg/L)</td>
<td>34</td>
<td>27</td>
</tr>
</tbody>
</table>

**ENGLISH TRANSLATION:**
- **ano:** year
- **Estação PropriA:** PropriA Station
- **cod.:** Station Code
- **Qss:** Suspended Sediment Load
- **t:** tonnes
- **dia:** day
- **Area de drenagem:** Drainage Area
- **especifico:** specific
- **Css:** Concentration of suspended sediments
- **Descarga sólida em suspensão média diária por ano:** Average Daily Solid Discharge in suspension per year
Table 15: SWAT Model Sediment Delivery to the Atlantic Ocean

<table>
<thead>
<tr>
<th>Year</th>
<th>Sediment Load, tonnes</th>
<th>Bed Load, tonnes</th>
<th>Total Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>1710200</td>
<td>649400</td>
<td>2359600</td>
</tr>
<tr>
<td>2002</td>
<td>1632830</td>
<td>685770</td>
<td>2318600</td>
</tr>
<tr>
<td>2003</td>
<td>1624960</td>
<td>681640</td>
<td>2306600</td>
</tr>
<tr>
<td>2004</td>
<td>1651338</td>
<td>502062</td>
<td>2153400</td>
</tr>
<tr>
<td>2005</td>
<td>1654710</td>
<td>676890</td>
<td>2331600</td>
</tr>
<tr>
<td>2006</td>
<td>1640860</td>
<td>682140</td>
<td>2323000</td>
</tr>
<tr>
<td>Average</td>
<td>1652483</td>
<td>646317</td>
<td>2298800</td>
</tr>
</tbody>
</table>
5.4 **Annual Loads from Sao Francisco Tributaries**

The sediment loads can also be calibrated by investigating the contribution of loads from each of the major tributaries. All tributaries upstream of the Sobradinho Reservoir were investigated to determine the total percentage of the sediment loads that each tributary contribute to the Sao Francisco River. The SWAT model output of the tributary sediment loads is shown in Figure 48.

**Figure 48: Percent Sediment Load from Major Tributaries**

A similar analysis was conducted in the Analise Multitemporal da Dinâmica de Alteracao da Conformacao do Leito do Rio Sao Francisco – Trecho Medio (CODEVASF-ANA, 2002). This data was compared to the output of the SWAT model and is shown in Table 16 and Figure 49. All tributaries accurately match with the CODEVASF-ANA study, except for possibly the Rio Grande watershed, where the
model over-predicts the sediment loads when compared to the CODEVASF-ANA study. The Rio Grande however is overall a small contribution to the overall sediment loads to the Sao Francisco River watershed. This data can be used to determine relative impacts to sediment loads in individual tributaries (agricultural best management practices, construction of dams, etc.).

Table 16: Percentage of Model Sediment Loads Compared to CODEVASF-ANA

<table>
<thead>
<tr>
<th>Tributary</th>
<th>SWAT Model</th>
<th>2002 ANA Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rio Pará</td>
<td>2.27%</td>
<td>2.00%</td>
</tr>
<tr>
<td>Rio Paraopeba</td>
<td>9.67%</td>
<td>11.00%</td>
</tr>
<tr>
<td>Rio das Velhas</td>
<td>15.08%</td>
<td>17.00%</td>
</tr>
<tr>
<td>Rio Jequitaí</td>
<td>2.70%</td>
<td>2.00%</td>
</tr>
<tr>
<td>Rio Paracatu</td>
<td>17.96%</td>
<td>17.00%</td>
</tr>
<tr>
<td>Rio Urucuia</td>
<td>17.26%</td>
<td>18.00%</td>
</tr>
<tr>
<td>Rio Verde Grande</td>
<td>0.11%</td>
<td>0.50%</td>
</tr>
<tr>
<td>Rio Carinhana</td>
<td>0.82%</td>
<td>2.00%</td>
</tr>
<tr>
<td>Rio Corrente</td>
<td>1.97%</td>
<td>2.00%</td>
</tr>
<tr>
<td>Rio Grande</td>
<td>4.68%</td>
<td>1.00%</td>
</tr>
<tr>
<td>All Others</td>
<td>27.47%</td>
<td>27.50%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Figure 49: Comparison of Model and Observed Sediment Loads (Percentage)
CHAPTER 6.0 CURRENT HYDROLOGY AND SEDIMENT BUDGET

Following the calibration of the hydrology and sediment for the Sao Francisco SWAT model, the results of the water yield and sediment yield can be determined. Hydrology can be investigated in order to determine the percentage of rainfall that infiltrates into the shallow groundwater or deep aquifers, how much is converted to overland flow, and how much is evaporated back to the atmosphere. The sediment budget can be developed in order to gain understanding as to where the sediments originate from within the watershed.

6.1 Hydrology Results

The hydrology of the watershed can be summarized at the basin scale by looking at the average annual water budget for the following Parameters:

1. Precipitation
2. Evapotranspiration
3. Surface Runoff
4. Percolation to the Shallow Aquifer
5. Re-evaporation (revap) from the Shallow Aquifer to the Vadose Zone
6. Lateral Flow to the Rivers from the Vadose Zone
7. Return Flow to the Rivers from the Shallow Aquifer
8. Recharge to the Deep Aquifer

These average, annual, basin-wide Parameters are shown in Figure 50. Units for each Parameter in Figure 50 are mm, and therefore are multiplied by the area of the basin
to calculate a volume for each Parameter. The following hydrologic dimensionless ratios can be extracted from this figure:

- Streamflow / Precipitation: 21%
- Baseflow / Total Flow: 77%
- Surface Runoff / Total Flow: 23%
- Percolation / Precipitation: 26%
- Deep Recharge / Precipitation: 16%
- Evapotranspiration / Precipitation: 65%

Overall, the Sao Francisco basin has a relatively low percentage of surface runoff compared to the precipitation. This is a result of the very flat basin with sandy soils and significant evapotranspiration. All results from the water budget are expected given the conditions of the Sao Francisco River basin.
Figure 50: Average Annual Hydrology Budget for the Sao Francisco River Basin

(Note: PET = Potential Evapotranspiration)

The distribution of the water yield throughout the basin can also be extracted from the results of the SWAT model. Figure 51 shows the sub-basin specific average annual water yield. The water yield is defined as the sum of the surface water and groundwater (both return flow and lateral flow) that is delivered to the streamflow of the Sao Francisco River. Evapotranspiration and deep aquifer recharge (which are both removed from the water budget) are not included in the water yield.
From the output of the water yield it is observed that 29 out of the 76 basins (38%) yield less than 50 mm of water per year (actual yearly volume is based on the multiplication of the water yield depth and the area of an individual basin). In addition, it is observed that the majority of the water is yielded from the headwater basins where over 400 mm of water is yielded per year. These observations regarding the geographic distribution of water yield are consistent with known data (the majority of the flow of the Sao Francisco River comes from the headwaters) and expected results (areas where little yield occur are consistent with areas of minimal precipitation).
Figure 51: Average Annual Water Yield by Basin of the Sao Francisco River Basin
6.2  **Basin-Wide Sediment Budget**

A sediment budget is of particular interest to this research, as the results help guide how a sediment management strategy could be developed for the watershed and to assist in future navigation planning. A sediment budget is a calculation of the sediment sources and sediment sinks as described in Section 2.1 and displayed in Figure 2.

The basin wide sediment characteristics can be displayed in terms of the net sediment yield and compared with the net in-stream sediment processes (see Figure 52). This figure shows that there is approximately 1.39 Mg (or metric tonnes) yielded per hectare across the Sao Francisco Basin annually. Much of this yielded sediment stays within the watershed (is not delivered to a stream), but a percentage is delivered to the bed of the river or in reservoirs. Overall, the river channel is noted to be a net sediment sink and not a source (there is more sediment deposition in the Sao Francisco River than erosion of the river banks). This is a consistent observation when compared with other CODEVASF and ANA studies.
SWAT is able to calculate the specific bank erosion, bed erosion, overland sediment sources, reservoir sedimentation, and outlet to the Atlantic Ocean at the watershed scale. These data are available at daily, monthly, or yearly timesteps. Since this research is investigating average annual conditions, the six-year annual data were averaged and compared to determine the sediment sources and sinks for the overall watershed (i.e., an annual sediment budget). The daily channel erosion source was added together for each year to determine the total tonnes associated with this source of sediment. Also, the daily deposition of the sediment was also summed over each year and then averaged to calculate the total annual sink of sediment in the channel. Therefore, the channel can either act as a net source or a net sink based on the gross
values of deposition or erosion associated with the main channels. Each of the gross sediment source and sink data are summarized in Table 17.

Table 17: Overall Watershed Average Annual Sediment Budget (2001-2006)

<table>
<thead>
<tr>
<th>EROSION SOURCES (tonnes per year)</th>
<th>DEPOSITION SINKS (tonnes per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Bank</td>
<td>Floodplain</td>
</tr>
<tr>
<td>Upland/Tributaries</td>
<td>Reservoirs</td>
</tr>
<tr>
<td>51,000,000</td>
<td>74,000,000</td>
</tr>
<tr>
<td>5,200,000</td>
<td>300,000</td>
</tr>
<tr>
<td>88,000,000</td>
<td>68,000,000</td>
</tr>
<tr>
<td>2,300,000</td>
<td>2,300,000</td>
</tr>
<tr>
<td>TOTAL</td>
<td>TOTAL</td>
</tr>
<tr>
<td>144,000,000</td>
<td>144,000,000</td>
</tr>
</tbody>
</table>

The data in Table 17 are shown in Figure 53 and Figure 54. These figures indicate that a small percentage of the gross sediment erosion comes from the banks of the Sao Francisco River and the major tributaries. The much larger contribution of the sediment to the Sao Francisco River is from the upland overland flow and small tributaries (approximately 60% of the gross erosion). Most of the sediment that is delivered to the Sao Francisco River is deposited in the 5 major reservoirs modeled in the basin. Only a small percentage is permanently deposited in the Sao Francisco River floodplain (0.2%).

Approximately 2.8% of the deposition sinks is associated with the delivery to the Atlantic Ocean at the 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. Syvitsky and Milliman (2007) 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 (2007) calculated that the Sao Francisco River should have approximately 6.4 million tonnes of sediment being delivered to the ocean per year (compared to the 2.3 million tonnes that the SWAT model
calculated). A suspended sediment gage at Propria, Sergipe (ANA gage 497050000, located approximately 69km from the Sao Francisco River mouth) shows the long-term suspended sediment load (from 1977-1999) is 2.7 million tonnes per year (see Table 18). The Propria gage is located in the Sao Francisco River estuary and is tidally influenced without any major tributaries between Propria and the Sao Francisco River mouth. It is therefore a reasonable gage to use to represent the total suspended sediment load to the Atlantic Ocean. The SWAT model matches the long-term sediment load at the Propria gage better than the predictions by Syvitsky and Milliman (2007) model. The overestimation from Syvitsky and Milliman (2007) may be due to the reservoir trapping factor of 0.30 (representing a 70% reservoir trapping efficiency) in their model. Due to the three major dams just upstream of mouth, a trapping efficiency of 85-90% may be more appropriate, which would bring the Syvitsky and Milliman reservoir trapping factor to 0.15. This would change their prediction of sediment loads to the Atlantic Ocean from the Sao Francisco River to 3.2 million tonnes per year, which is much closer to the observed long-term average at the Propria gage.

### Table 18: Suspended Sediment Loads at Propria Gage (497050000)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended Sediment Load, tonnes/day</td>
<td>7,472</td>
<td>5,022</td>
</tr>
<tr>
<td>Suspended Sediment Load, tonnes/year</td>
<td>2,727,170</td>
<td>1,833,197</td>
</tr>
<tr>
<td>Drainage Area km²</td>
<td>623,500</td>
<td>623,500</td>
</tr>
<tr>
<td>Specific Suspended Sediment Load, tonnes/km²/year</td>
<td>4.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Flow, cms</td>
<td>2,528</td>
<td>2,120</td>
</tr>
<tr>
<td>Concentration of Suspended Sediment, mg/L</td>
<td>34</td>
<td>27</td>
</tr>
</tbody>
</table>

(from ANEEL, 2001)
The bed erosion is also a major sediment source (36% of the total load in the river was previously stored in the bed). However, the bed deposition is also a major sediment sink. Overall, the model calculates approximately 23,000,000 tonnes of sediment per year is deposited within the channel, leading to an aggrading system. This is consistent with the findings of a recent study by CODEVASF & ANA (2002) which demonstrated that 59 out of 73 reaches that were studied experienced net deposition (aggradation) in the channels. This was evidenced in the CODEVASF & ANA study by comparing aerials from 1946 to 2000, and identifying areas of increased mid-channel bars, islands, point bars, and other sand deposits (see Figure 55).
Figure 53: Gross Sediment Budget of Erosion Sources for All Basins
Figure 54: Gross Sediment Budget of Deposition Sinks for All Basins
Figure 55: Aggradation and Degradational Reaches in the Sao Francisco River

Net depositional reaches are shown as red bars (on the left) and net erosion is shown as blue bars on the left. The distribution of deposition and erosion (by areas) is shown in the bars on the right.

Sedimentacao = Sedimentation; Erosao = Erosion; Manutencao = Maintenance
Due to the offsetting erosion and deposition of the bed component of the sediment budget, it is useful to visualize the data in terms of the net sediment sources and sinks instead of the gross sediment sources and sinks. Table 19 lists the net sediment sources and sinks. This table removes any sediment that is both eroded and deposited in the same source, which in this case is the bed source. From this table it is noted that there is a net aggradation of sediment in the channel, which is evidenced from an increase in island formation, and additional longitudinal and transverse bars.

Table 19: Net Sediment Sources and Sinks

<table>
<thead>
<tr>
<th>EROSION SOURCES (tonnes per year)</th>
<th>DEPOSITION SINKS (tonnes per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Bank</td>
<td>Floodplain</td>
</tr>
<tr>
<td>Upland/Tributaries</td>
<td>Reservoirs</td>
</tr>
<tr>
<td></td>
<td>Ocean</td>
</tr>
<tr>
<td>TOTAL</td>
<td>TOTAL</td>
</tr>
<tr>
<td>0</td>
<td>23,000,000</td>
</tr>
<tr>
<td>5,200,000</td>
<td>300,000</td>
</tr>
<tr>
<td>88,000,000</td>
<td>68,000,000</td>
</tr>
<tr>
<td></td>
<td>2,300,000</td>
</tr>
<tr>
<td>93,000,000</td>
<td>93,000,000</td>
</tr>
</tbody>
</table>

Figure 56 and Figure 57 display this data in a graphical format.
Figure 56: Net Sediment Budget of Erosion Sources for All Basins
Figure 57: Net Sediment Budget of Deposition Sinks for All Basins
The total average annual load of sediments that are trapped in reservoirs is calculated as approximately 67.5 million tonnes. Assuming a specific gravity of sediment of 2.65, the total volume of sediment entering the reservoir is 25.5 million m$^3$ per year (note that porosity is not included in this calculation, since the reservoir water fills the gaps between sediment particles). 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 (1987) and an order of magnitude less than the average of storage lost in North America (0.2% was calculated by White, 2001). A major reason that percentage of storage lost per year is less than other estimates for similar regions is that the 5 reservoirs modeled for the Sao Francisco basin include extremely large volume reservoirs including Sobradinho (34.1 km$^3$) and Tres Marias (21 km$^3$), (by comparison, Lake Mead in the United States has a volume of 37 km$^3$). Due to the very large volumes associated with the dams in the Sao Francisco River Basin, the overall percentage volume lost per year is smaller than the world average.

The overall trapping efficiency of each of the reservoirs was also calculated from the SWAT model (see Figure 58). The five primary dams on the main stem of the Sao Francisco River were modeled as previously described. The trapping efficiency is a calculation that determines the percentage of sediment that is trapped in the reservoir (based on the amount of sediment entering the reservoir). The trapping efficiencies are very high, especially in the Sobradinho, Luiz Gonzaga, and Xingo reservoirs. The Sobradinho reservoir is approximately 200 km long, and it is expected that virtually all of the sediments entering this reservoir are settled in the impounded area (model predicts
98.3%). Comparatively, only small loads of sediments enter into the 3 reservoirs downstream of Sobradinho, and the majority of these sediments also deposit in the reservoirs. The upstream reservoir (Tres Marias) receives a significant suspended sediment load, and due to the shorter distance that the sediment travels, a portion of this load (63%) is predicted to stay in suspension and flow through the reservoir impoundment. Although there is a significant suspended sediment load to Tres Marias, the actual trapping efficiency may be higher than predicted in the model.

**Figure 58: Trapping Efficiency of Each Reservoir**
6.3 Distribution of Sediment Yields in the Sao Francisco Watershed

The temporal and geographic distribution of the sediment yield from the Sao Francisco River watershed was investigated using ArcGIS and VIZSWAT. VIZSWAT is a proprietary software that maps the output of various SWAT Parameters across the basin in either map or animation form. An animation of the 6-year SWAT simulation of the sediment yield was developed using this software (named SaoFranciscoSedYield.avi). Typical conditions of the daily sediment yield for the rainy season can be observed in Figure 59 (this represents a daily output that is typical of the rainy season). Typical conditions of the daily sediment yield for the dry season can be observed in Figure 60 (this represents a daily output that is typical of the dry season). Both figures were extracted from the VIZSAT animation of the 6-year simulation of the sediment yield.
Figure 59: Sediment Yield Model Typical Rainy Season Conditions

São Francisco Sediment Yield Model

Flow, cms

Sediment Yield

tonnes/ha

24/01/2003

This movie was created by SDA.
The average annual sediment yield for each sub-basin was also investigated using the output from SWAT. Figure 61 displays the geographic distribution of the average specific sediment yield per acre per year. The major sources of sediments within the watershed are focused in the headwaters, although other notable sources occur in the Middle Sao Francisco River and the northern part of the watershed as well. Western Bahia has a low sediment production due to the flat, sandy characteristics of the basin in this area. Figure 61 can also be used to prioritize best management practices within the watershed to reduce sediment loads in areas where high sediment yields persist.
The output from the SWAT model on a daily time-step is available for the main step and each of the major tributaries. This daily sediment output data was used as input into the HEC-RAS model of the navigation channel (described in Section CHAPTER 9.0).
CHAPTER 7.0  ADDITIONAL SWAT SCENARIOS

The calibrated SWAT model was additionally used to determine both the historical and future sediment conditions of the Sao Francisco watershed. The historical conditions of the sediment yields in the watershed can be useful in determining the amount of impacts associated with landuse activities. The future sediment load conditions are important to understand in order to plan for future navigation conditions (associated with sediment loads). Both of these alternatives were analyzed in the calibrated SWAT model.

7.1  Historical Sediment Conditions

The major historical human influences to the Sao Francisco River watershed include 1) the construction of dams; 2) the conversion of native vegetation to agriculture; and 3) the development of cities. Population increases have been significant in the watershed (especially in major cities such as Belo Horizonte, MG), but the urban growth does not impact a significant amount of area in the watershed, as compared to the agricultural development.

In order to understand the pre-European settlement conditions of the watershed, historical information was gathered and analyzed. The primary source of pre-development conditions of the river are described in a survey by Halfeld (1860). In the early 1850s, Henrique Guilherme Fernando Halfeld was commissioned by Dom Pedro II, the Emperor of Brazil, to survey the Sao Francisco River from Pirapora, Minas Gerais to the Atlantic Ocean. Halfeld collected all of the survey data in 1852-1854 and published these maps in 1860. These detailed Halfeld maps provide significant insight into the conditions of the Sao Francisco River prior to major development in the basin.
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. See Figure 62 for a comparison of the river morphology near Paratinga, Bahia in 1852 and 1999. From Figure 62 it is shown that the river has a similar morphology, width, and location of islands, although there is some changes to the shape and size of some of the islands. This is a typical result when comparing the majority of the maps that have not been influenced by dams.

Figure 62: Comparison of Halfeld (1860, left) and LANDSAT (1999, right)

Although the typical river conditions and morphology have not significantly changed in the last 150 years for most of the navigation channel, there have been
significant changes in the areas where dams have been constructed. See Figure 63 for an example of the historic and current conditions within an existing impoundment (Sobradinho Reservoir). The construction of the dams have created a sediment sink, which captures sediment that would have historically flowed downstream.

**Figure 63: 1860 Halfeld Map (left) and Current Sobradinho Reservoir (right)**

The anthropogenic alterations to the Sao Francisco watershed were removed in order to simulate the historic (pre-European settlement) conditions. First, the SWAT model associated with the Pre-European development scenario includes the removal of all existing dams. 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 the historically mixed forest throughout the watershed at the beginning of the historic SWAT simulation. This landuse is based on the forest vegetation associated with the native Cerrado, Caatinga and Atlantic Forest ecosystem that would have covered the majority of the watershed prior to European settlement. Finally, the irrigation practices were turned off in the Pre-European development SWAT model. This was updated in the water use table (.WUS) within the SaoFranciscoSWAT database. The results of the historical sediment budget are shown in Figure 64 and Figure 65.
Figure 64: Historical Sediment Sources (Compared with Existing Conditions)
Figure 65: Historical Sediment Sinks (Compared with Existing Conditions)
The SWAT model was used to calculate the pre-European settlement and current conditions of sediment loads (and overall sediment budget parameters). Table 20 summarizes the anthropogenic impacts on the Sao Francisco River sediment budget. Overall, the SWAT model shows that there have been a significant increase in erosion sources including bed erosion (82% increase), bank erosion (593% increase), and upland / minor tributary contributions (182% increase) since pre-European settlement. Anthropogenic development has also led to an increase in sediment sinks including the bed of the river (153% increase) and floodplains (683% increase). Reservoirs are the most significant increase as a sediment sink with an absolute increase of 67.5 million tonnes per year of trapped sediment.

### Table 20: Anthropogenic Impacts on the Sao Francisco Sediment Budget

<table>
<thead>
<tr>
<th>Erosion (Sources)</th>
<th>Pre-European Settlement Loads (tonnes/year)</th>
<th>Current Condition Sediment Loads (tonnes/year)</th>
<th>Change, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>28,000,000</td>
<td>51,000,000</td>
<td>82%</td>
</tr>
<tr>
<td>Bank</td>
<td>800,000</td>
<td>5,200,000</td>
<td>593%</td>
</tr>
<tr>
<td>Upland / Tributaries</td>
<td>31,000,000</td>
<td>88,000,000</td>
<td>182%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deposition (Sinks)</th>
<th>Pre-European Settlement Loads (tonnes/year)</th>
<th>Current Condition Sediment Loads (tonnes/year)</th>
<th>Change, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>29,000,000</td>
<td>74,000,000</td>
<td>153%</td>
</tr>
<tr>
<td>Floodplains</td>
<td>38,000</td>
<td>300,000</td>
<td>683%</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>0</td>
<td>68,000,000</td>
<td>∞</td>
</tr>
<tr>
<td>Oceans</td>
<td>3,900,000</td>
<td>2,300,000</td>
<td>-41%</td>
</tr>
</tbody>
</table>

Due to development (primarily the construction of dams) there is a notable decrease in the overall sediment loads to the ocean (41% decrease). This observation is consistent with other researchers such as Syvitski et. al (2005) and Syvitski and Milliman (2007), which have noted an overall global reduction in sediment yields to the oceans. The reduction in sediment loads following the dam construction may also be evidenced through the recent beach erosion that is occurring near the Sao Francisco mouth. Due to
a reduction in sediment loads to the mouth, there may not be the historic replenishment of sediment from the river, possibly leading to the littoral transport forces to erode the beach. This may also be influenced by other factors such as updrift, changes in the wave climate and other natural or anthropogenic changes in the littoral sediment supply. Only a coastal sediment budget study will be able to develop an understanding of the cause(s) of the recent coastal erosion near the mouth of the Sao Francisco River. Approximately 190 meters of erosion have occurred between 2004 and 2011 at this location (see Figure 66). The lighthouse, which was originally constructed along the shore, is now approximately 400 meters from the shoreline (see Figure 67).
Figure 66: Coastal Erosion at Sao Francisco Mouth

2004 aerial (left), and 2011 aerial (right). Lighthouse highlighted in both aerials.
Figure 67: Lighthouse and Eroded Beach at Sao Francisco River Mouth
7.2  **Future Watershed Conditions**

A future conditions scenario was modeled in SWAT to analyze the future sediment loads and determine future impacts to the navigation channel. These future changes are associated directly with planning efforts that are being conducted by CODEVASF (the agency responsible for regional development of the Sao Francisco Basin). These proposed changes, which were added as the primary assumptions in the future conditions scenario, include the following watershed changes:

1. Three large diversion projects are proposed to divert flow from outside the basin into the Sao Francisco basin at the headwaters.
2. Five additional dams are proposed on major Sao Francisco Tributaries. These dams are located in the Velhas, Paracatu, and Uruçuia watersheds.
3. Some of the flow in the Lower Sao Francisco River is diverted to the semi-arid Northeast (outside the basin) for irrigation and water supply purposes.
4. Twenty-five percent (25%) of the existing rangeland is converted to high intensity row crops (a response to the increased availability of irrigation)

7.2.1  **Flow Diversion into the Basin in the Headwaters**

There are three proposed diversions into the Sao Francisco Basin that have been considered and are in the planning stages at CODEVASF. These are:

1. Empreendimento Tunel de Sao Marcos
2. Empreendimento Bebedouro do Paranaiba
3. Empreendimento Vertedor de Furnas
A fourth project was considered by CODEVASF to divert water from the Tocantins basin to the Sao Francisco basin, but is not being considered in this report.

The Empreendimento Tunel de Sao Marcos consists of a transfer of 70 cms (2,207,520,000 m³ per year) from the Bacia do Rio Sao Marcos to the Paracatu River (see Figure 68). This location corresponds to SWAT basin 67 in the model.

The Empreendimento Bebedouro do Paranaiba consists of a transfer of 120 cms (3,784,320,000 m³ per year) from the Bacia do Rio Paranaiba to the Paracatu River (see Figure 68). This location also corresponds to SWAT basin 67 in the model, which brings the total diversion to the Paracatu River of 190 cms.

The Empreendimento Vertedor de Furnas consists of a transfer of 62 cms (1,955,232,000 m³) from the Bacia do Rio Grande to the Rio Sao Francisco (see Figure 68). The location of the diversion corresponds to SWAT basin 76.
There are numerous methods available in SWAT in order to simulate additional flow in the basins. The Point Source Discharge option was selected, and the associated daily flow rates were added to the Future Conditions Model.

### 7.2.2 Proposed Dams

CODEVASF is currently proposing 3 new dams within the Paracatu watershed, and one dam in both of the Urucuia and Velhas watersheds. Figure 69 shows the area that ultimately contributes to each of the proposed reservoirs. The storage and area of the reservoir, as well as the dam height, and corresponding SWAT Basin ID are shown in Table 21.
These dams were added into the SWAT model using the “Add Reservoir” option under the “Watershed Delineator” tool. Since both the Caatinga and Sono2 reservoirs are located in the same basin, the volumes (and areas) were added together and simulated as one impoundment.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Reservoir Name</th>
<th>SWAT Basin</th>
<th>Normal Volume (RES_VOL) (10^4 m^3)</th>
<th>Emergency Volume (RES_EVOL) (10^4 m^3)</th>
<th>Normal Reservoir Area (RES_PSA) (ha)</th>
<th>Emergency Reservoir Area (RES_ESA) (ha)</th>
<th>Dam Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velhas</td>
<td>Santo Hipólito</td>
<td>73</td>
<td>440200</td>
<td>484220</td>
<td>29350</td>
<td>32285</td>
<td>46</td>
</tr>
<tr>
<td>Paracatu</td>
<td>Paracatu</td>
<td>67</td>
<td>155600</td>
<td>171160</td>
<td>19030</td>
<td>20933</td>
<td>11</td>
</tr>
<tr>
<td>Paracatu</td>
<td>Caatinga</td>
<td>65</td>
<td>255500</td>
<td>281050</td>
<td>21670</td>
<td>23837</td>
<td>45</td>
</tr>
<tr>
<td>Paracatu</td>
<td>Sono2</td>
<td>65</td>
<td>206700</td>
<td>227370</td>
<td>10990</td>
<td>12089</td>
<td>57</td>
</tr>
<tr>
<td>Urucua</td>
<td>Urucua</td>
<td>58</td>
<td>320300</td>
<td>352330</td>
<td>19620</td>
<td>21582</td>
<td>50</td>
</tr>
</tbody>
</table>
Figure 69: Proposed Reservoirs to Manage Headwater Discharges
7.2.3  Landuse Conversion

The current trend of landuse conversion within the Sao Francisco River is from rangeland to high intensity row crops (such as corn, soy, and cotton). Although the specific amount of development of the rangeland is not currently predicted in the future landuse plans at CODEVASF, it is assumed that the trend will continue. An assumed value of 25% of the rangeland was converted to row crops in the Future Conditions model of the Sao Francisco River watershed.

7.2.4  Proposed Water Withdrawals from the System

CODEVASF has developed a future conditions plan to divert water through irrigation canals throughout the northeast of Brazil. This project is called the Projeto Semi-Arido and currently consists of 11 distinct water withdrawal locations. Many of the withdrawals are directly from the Sobradinho Reservoir (corresponding to SWAT Basin 17). Additional withdrawals are located at locations downstream of the Sobradinho Dam. The total operational flow of all of the proposed projects is 252 cms (equivalent to the flow diversions into the basin). A conceptual layout of the projects is shown in Figure 70. The data associated with the projects are included in Table 22. These additional water withdrawals were added to the SWAT model by adjusting the Parameters in the Water Use Table (i.e., the .wus table in SWAT).
Figure 70: Conceptual Layout of Proposed Irrigation Projects

Proposed Irrigation Channels are shown in Red. Specific Irrigation Projects names are labeled T1-A through T4. Project names are listed in Table 22.

Table 22: Proposed Water Withdrawals (Irrigation Projects)

<table>
<thead>
<tr>
<th>Name</th>
<th>Code</th>
<th>SWAT Basin</th>
<th>Min Flow, cms</th>
<th>Operational Flow, cms</th>
<th>Max Flow, cms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahia Norte</td>
<td>T1-A</td>
<td>17</td>
<td>10</td>
<td>29</td>
<td>120</td>
</tr>
<tr>
<td>Sertão Pernambucano</td>
<td>T1-B</td>
<td>17</td>
<td>10</td>
<td>17</td>
<td>70</td>
</tr>
<tr>
<td>Jacaré Verde</td>
<td>T1-C</td>
<td>17</td>
<td>10</td>
<td>17</td>
<td>70</td>
</tr>
<tr>
<td>Terra Nova</td>
<td>T1-D</td>
<td>17</td>
<td>10</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td>Piauí Canindé</td>
<td>T1-E</td>
<td>17</td>
<td>10</td>
<td>19</td>
<td>80</td>
</tr>
<tr>
<td>Arco Íris</td>
<td>T2-A</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Eixo Norte</td>
<td>E-N</td>
<td>7</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Eixo Leste</td>
<td>E-L</td>
<td>7</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Sertão Alagoano</td>
<td>T3-A</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Dois Irmãos</td>
<td>T3-B</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Xingó</td>
<td>T-4</td>
<td>14</td>
<td>10</td>
<td>10</td>
<td>41</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>211</strong></td>
<td><strong>252</strong></td>
<td></td>
<td><strong>648</strong></td>
</tr>
</tbody>
</table>
7.2.5  Results of Future Landuse Scenario

The future conditions scenario was developed in order to evaluate impacts to the sediment budget, and to the hydrology of the system. A map of the hydrology impacts (outflows) is included in Figure 71. This map shows a major increase in flow outputs in the basin where proposed diversions bring water into the basin, and significant decreases in flows associated with the basins downstream of the major withdrawals (to irrigate the Northeast portion of Brazil). The model also shows a positive increase to the flows in the Middle Sao Francisco River navigation channel, which will be a positive benefit to navigation through this reach.

The focus of this manuscript is to determine the potential future impacts to the navigation channel in order to determine future navigation impacts associated with the proposed landuse changes. Initially the overall sediment budget was calculated. The total sediment sources can be seen in Figure 72 and the total sediment sinks may be seen in Figure 73.
Figure 71: Impacts to Annual Basin Outflows of the Future Conditions Scenario
Figure 72: Gross Erosion Sources of Future Conditions Scenario

GROSS EROSION SOURCES

- Bed: 19.0%
- Bank: 4.1%
- Upland/Tributaries: 76.9%

<table>
<thead>
<tr>
<th>Source</th>
<th>Existing Conditions</th>
<th>Future Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>50,700,317</td>
<td>87,970,369</td>
</tr>
<tr>
<td>Bank</td>
<td>23,761,114</td>
<td>5,094,537</td>
</tr>
<tr>
<td>Upland/Tributaries</td>
<td>5,236,226</td>
<td>95,877,235</td>
</tr>
</tbody>
</table>

Existing Conditions vs Future Conditions
Figure 73: Gross Deposition Sinks of Future Conditions Scenario
Table 23 summarizes the overall sediment budget results. The overall future sediment budget shows that there is an expected net increase in sediment yields from the overland flow, and small tributaries. This can be accounted for due to the conversion of range landuse to high-intensity row crops, which typically yield more sediment than rangeland. There is also an increase of approximately 39% of storage of sediment in future proposed reservoirs. The future bank erosion and floodplain storage are not significantly impacted by the future conditions. Both the bed sources and the bed storage are reduced. This is a result of there being less sediment delivered to the Sao Francisco River because of the 5 proposed upstream dams. This results in less sediment aggrading in the system. Since most of the sediment being transported in the navigation channel experiences both erosion and deposition at an annual scale, the reduction of sediment being delivered to the navigation channel may also reduce the amount of sediment available for erosion, leading to the reduction in erosion. Also, some of the reduction in erosion is due to the conversion of erosive headwater rivers to a depositional reservoir area, leading to less sediment erosion in these headwater rivers.

**Table 23: Comparison of Existing and Future Sediment Budget Conditions**

<table>
<thead>
<tr>
<th>Erosion (Sources)</th>
<th>Current Conditions Sediment Loads (tonnes/year)</th>
<th>Future Conditions Sediment Loads (tonnes/year)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>51,000,000</td>
<td>24,000,000</td>
<td>-53%</td>
</tr>
<tr>
<td>Bank</td>
<td>5,200,000</td>
<td>5,100,000</td>
<td>-3%</td>
</tr>
<tr>
<td>Upland / Tribararies</td>
<td>88,000,000</td>
<td>96,000,000</td>
<td>9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deposition (Sinks)</th>
<th>Current Conditions Sediment Loads (tonnes/year)</th>
<th>Future Conditions Sediment Loads (tonnes/year)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed</td>
<td>74,000,000</td>
<td>30,000,000</td>
<td>-59%</td>
</tr>
<tr>
<td>Floodplain</td>
<td>300,000</td>
<td>290,000</td>
<td>-3%</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>68,000,000</td>
<td>94,000,000</td>
<td>39%</td>
</tr>
<tr>
<td>Ocean</td>
<td>2,300,000</td>
<td>200,000</td>
<td>-91%</td>
</tr>
</tbody>
</table>
Therefore, the future landuse scenario will likely improve navigation conditions and not degrade navigation conditions. This is specifically due to the capturing of sediments in dams in the headwaters, which is a more dominate process than the increase in overland runoff due to landuse conversions. The scope of this analysis only considers impacts to the navigation channel, although it is recognized that there are multiple users, which are expected to be impacted in a variety of ways due to any proposed plans made by CODEVASF or other stakeholders in the watershed. The SWAT tool that was developed for this research may also be used by other stakeholders to determine potential impacts to other areas of interest, or CODEVASF may use the model to analyze a variety of alternative future landuse scenarios.
CHAPTER 8.0  EXISTING NAVIGATION CHANNEL MORPHOLOGY

8.1  Overall Conditions

The study reach for this research consists of the Middle Sao Francisco River between Pirapora, MG (upper boundary) and the delta of the Sobradinho Reservoir (downstream boundary). This section of the Sao Francisco River navigation channel is the case study that applies the methods developed in this research, which consists of coupling a sediment yield and a sediment transport model to aid in navigation planning. The case study reach of the Sao Francisco River is approximately 1015 kilometers long through this segment. Limited samples are available for the bed gradation; however based on these samples and visual observations during field visits, the Sao Francisco River within the study reach is primarily a sandy, alluvial river (see Figure 74 for an example bed gradation of the Middle Sao Francisco River near Morpara, BA).

The river has a very mild slope (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 wide in the upper reaches of the navigation channel to approximately 1 km wide 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 Administracao da Hidrovia do Rio Sao Francisco (AHSFRA). AHSFRA is responsible for the operations and maintenance of the navigable portion of the waterway. AHSFRA provided a survey of the bathymetry
from 2011 and 2012, which was used to support the sediment transport modeling associated with this research.

Prior to the sediment transport modeling, an analysis of the fluvial geomorphology of the river was conducted. The Middle Sao 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 will contribute a significant load of sediment and flow to the Sao 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 define reaches. Therefore, the geomorphic reaches are defined based only on the confluences of major tributaries. In fact, most of the reaches exhibits similar width/depth ratios and sinuosity, and have a similar pattern consisting of islands followed by a narrow, deep section throughout the entire study area. The major tributaries that define the upper and lower sections of each sub-reach are listed in Table 24. Figure 75 includes the location of each tributary, which divides the river into its separate geomorphic reaches.

<table>
<thead>
<tr>
<th>Reach No.</th>
<th>Reach Description</th>
<th>AHSFRA Upstream Station, km</th>
<th>AHSFRA Downstream Station, km</th>
<th>Total Length, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pirapora to Rio das Velhas</td>
<td>1982</td>
<td>1958</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>Rio das Velhas to Rio Jequitaí</td>
<td>1958</td>
<td>1938</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Rio Jequitaí to Rio Paracatu</td>
<td>1938</td>
<td>1868</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>Rio Paracatu to Rio Urucuía</td>
<td>1868</td>
<td>1810</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>Rio Urucuía to Rio Verde Grande</td>
<td>1810</td>
<td>1572</td>
<td>238</td>
</tr>
<tr>
<td>6</td>
<td>Rio Verde Grande to Rio Carinhanka</td>
<td>1572</td>
<td>1545</td>
<td>27</td>
</tr>
<tr>
<td>7</td>
<td>Rio Carinhanka to Rio Corrente</td>
<td>1545</td>
<td>1395</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>Rio Corrente to Rio Grande</td>
<td>1395</td>
<td>1123</td>
<td>272</td>
</tr>
<tr>
<td>9</td>
<td>Rio Grande to Sobradinho Reservoir</td>
<td>1123</td>
<td>967</td>
<td>156</td>
</tr>
</tbody>
</table>

Total Length: 1015

AHSFRA also provided a list of 60 critical (shallow) reaches within the Middle Sao Francisco River, which is analyzed in the following sections of this report. A critical site is defined by AHSFRA as a historical, consistent impedance to navigation. These
sites are either dredged periodically, or have a consistent need for dredging or rock excavation. The locations of these sites are shown in Figure 75, and the data associated with each site are listed in Table 25.

Not all of the critical sites defined by AHSFRA are restrictive to navigation in a given year due to the sediment dynamics of the system. However, the geomorphic conditions at these named sites generally contribute to a navigation problem or difficulty based on a shallow draft during the late dry season (August until November). A typical site may have multiple shoals, and therefore more than 60 conceptual designs were necessary to improve the navigation of the Sao Francisco River. Previous studies by the World Bank (INTC, 2012) have identified that a 2.0 meter depth at low water conditions is an economically feasible navigation depth for the Middle Sao Francisco River. Therefore, the necessary 2.0 meter navigation depth is used to identify locations where engineering structures or dredging may be required in order to achieve a sustainable, reliable, navigation channel year-round.
Figure 75: Major Rivers and Critical Sites

Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Reach 7
Reach 8
Reach 9

Upper end of Sobradinho Reservoir
172

Table 25: AHSFRA Critical Sites with Coordinates (UTM, m Zone 23 S)
No
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60

Nome
FRANAVE
BANCO DA RAQUEL
PACO PACO
CASCALHO VERMELHO
BAIXIO DA PORCAS
BAIXIO DA CABRAINHA
COROA DA EMA
VOLTA DO SOBRADO
BAIXIO DO IBIAÍ
CANABRAVA
BAIXIO DA CRIOULAS
BARRA DO JABURU
CACHOEIRA DA MANTEIGA
PONTO CHIQUE
COROA BRANCA
BARREIRA DA MARTINHA
VARGINHA
BARRA DOS VALADARES
ANGICOS
AGRICIO
BARRA DO AFUNDÁ
PORTO DAS BALSAS (S. FRANCISCO)
CABO CHICO
REMANSINHO
ILHA DO BALAEIRO
JANUÁRIA
VENDA
AMARGOSO
JATOBÁ
ILHA DO VALERIM
ITACARAMBÍ
REGIÃO DOS PEDRAIS NA DIVA MG/BA
ILHA DA MELÂNCIA
BARRA DA PARATECA
BARREIRA DO BICHIGUENTO
BARRA DA PITUBA
BOA VISTA DOS GUIMARÃES
ILHA DO REMO
SITIO DO MATO
GAMELEIRA
ILHA DE PARATINGA
QUEBRA LINHA
CACHOEIRINHA DE IBOTIRAMA
CABEÇA LEVANTADA
LIMOEIRO
BOA VISTA DO LAGAMAR
CARNE ASSADA
MELEIRO
IGARITÉ
TOCA DE SANTA LUZIA
TORRINHA
ILHA DE ITACOATIARA
ILHA DO ANGICAL
CURRALINHO
ILHA DA SAMAMBAIA
GOIABEIRA
AMARRA COURO
RODRIGO
UMBUZEIRO
RIO VERDE

Station(s), km
1982
1980‐1978
1960
1950‐1946
1942‐1937
1933‐1929
1922
1920‐1915
1913‐1910
1906
1900‐1895
1885‐1880
1879‐1887
1874
1866
1855
1842
1830‐1825
1824‐1818
1815‐1810
1807‐1800
1780‐1778
1775‐1770
1735‐1725
1719
1700
1690‐1685
1675
1670
1665
1643
1629‐1535
1530
1497
1490‐1484
1460‐1455
1435‐1430
1420‐1410
1392‐1385
1365‐1360
1330‐1225
1300
1260‐1255
1252‐1247
1232
1220
1213
1210‐1205
1194‐1191
1185
1175
1155‐1152
1141
1135‐1126
1010‐1095
1062
1050‐1040
1022‐1020
995‐992
965

X1
504745
507500
517500
517500
522371
520436
512500
512500
507500
507500
505000
497500
492500
492500
490000
490000
492500
495000
495120
492500
492500
512500
515000
547500
557500
570000
577500
587500
590000
587500
597500
605000
638750
647500
650000
655000
667500
666250
667500
673750
692500
691250
690000
685000
678750
683750
681250
681250
676250
682755
690000
696250
697500
700000
767500
747500
750000
765000
780000
782500

Y1
8083034
8085000
8097500
8102500
8108050
8118330
8125000
8130000
8133750
8140000
8142500
8155000
8157500
8161250
8172500
8178750
8187500
8197500
8203842
8215000
8222500
8235000
8237500
8264247
8272500
8287500
8292500
8300000
8307500
8301250
8330000
8338750
8426250
8460000
8467500
8491250
8510000
8525000
8551250
8573750
8597500
8620000
8655000
8661250
8678750
8690000
8696250
8698750
8712500
8719060
8727500
8745000
8755000
8760000
8842500
8807500
8812500
8832500
8855000
8877500

X2
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507279
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517500
520629
517500
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508750
507500
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497500
492500
491512
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495000
493197
492500
495000
513750
517500
556250
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580000
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636250
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650000
657500
670000
667500
666250
675292
697500
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686250
685000
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680000
677500
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696250
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702482
720000
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752500
765000
778750
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Y2
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8086313
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8107500
8115000
8121250
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5132500
8135000
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8147500
8155000
8157710
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8202500
8210669
8217500
8228750
8236250
8242500
8271250
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8296250
‐
‐
‐
‐
8422500
‐
‐
8471250
8493750
8537500
8527500
8557500
8576912
8601250
‐
8657500
8667500
‐
‐
‐
8702500
8717500
‐
‐
8746250
‐
8769913
8795000
‐
8823750
8835000
8857500
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Reach
1
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In addition to the AHSFRA sites, the Departamento Nacional de Infraestrutura de Transportes (DNIT) has identified 16 locations where emergency dredging was necessary during the 2013 dredging season (DNIT, 2013), although this emergency dredging did not occur (except at the Cabeca Levantada site). Many of the sites are also listed in the AHSFRA 60 critical sites list. The DNIT emergency dredging sites are listed in Table 26.

Table 26: DNIT Emergency Dredging Sites

<table>
<thead>
<tr>
<th>Name</th>
<th>Station, km</th>
<th>Coordinates, UTM Zone 23 South (X, Y)</th>
<th>Shoal Length, m</th>
<th>Estimated Volume, m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabeça Levantada</td>
<td>1247</td>
<td>686094 8659829</td>
<td>2784</td>
<td>-</td>
</tr>
<tr>
<td>Limoeiro</td>
<td>1233</td>
<td>678729 8678077</td>
<td>706</td>
<td>-</td>
</tr>
<tr>
<td>Caraíbas</td>
<td>1216</td>
<td>682106 8692383</td>
<td>511</td>
<td>55300</td>
</tr>
<tr>
<td>Meleiro</td>
<td>1205</td>
<td>680246 8702019</td>
<td>612</td>
<td>6100</td>
</tr>
<tr>
<td>Sabonete</td>
<td>1203</td>
<td>678579 8704008</td>
<td>2468</td>
<td>-</td>
</tr>
<tr>
<td>Torrinha</td>
<td>1175</td>
<td>689032 8727981</td>
<td>575</td>
<td>14800</td>
</tr>
<tr>
<td>Curralinho</td>
<td>1135</td>
<td>697800 8760373</td>
<td>1201</td>
<td>7100</td>
</tr>
<tr>
<td>Ilha da Sambaiba</td>
<td>1106</td>
<td>712602 8782560</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Icatú</td>
<td>1070</td>
<td>739753 8802952</td>
<td>313</td>
<td>6730</td>
</tr>
<tr>
<td>Capricho</td>
<td>1060</td>
<td>746387 8806643</td>
<td>789</td>
<td>-</td>
</tr>
<tr>
<td>Amarra Couro</td>
<td>1050</td>
<td>750006 8812511</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ilha do Mendonça</td>
<td>1047</td>
<td>751653 8815994</td>
<td>1334</td>
<td>410</td>
</tr>
<tr>
<td>Papconha</td>
<td>1043</td>
<td>753213 8820391</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rodrigo</td>
<td>1022</td>
<td>763464 8833330</td>
<td>1713</td>
<td>20845</td>
</tr>
<tr>
<td>Umbuzeiro</td>
<td>995</td>
<td>778556 8855008</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Taquari</td>
<td>990</td>
<td>779168 8861216</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

AHFSFRA collects the bathymetry data using a single-beam bathymetry data collection technology. The river is crossed perpendicularly to the navigation channel for a width of approximately 200 meters. Next, the single beam bathymetry data is collected in the upstream direction along the edge of the navigational channel for approximately
200 meters and the boat crosses the river again (creating a saw tooth pattern of data in the upstream direction). A longitudinal profile of the channel bottom is also collected along the approximate centerline of the navigation channel. Typical locations of the bathymetry data are shown in Figure 76.

Navigation channel depth maps were created using ArcGIS 10 using the AHSFRA data. A polygon was created around the outside of the navigation channel depth soundings. However, since this polygon is often significantly outside of the limits of the navigation channel, the centerline of the polygon was established. The centerline was then offset to create a 100 meter wide navigation channel (see Figure 76).
The following sections identify the conditions of the navigation channel at the 60 critical reach sites and the DNIT emergency dredge sites in order to determine the geomorphic processes which cause shoals and navigation restrictions. These sites are also analyzed to determine which sites will require measures to deepen the navigation channel. An investigation of the general geomorphic conditions of each reach is used to determine necessary widths of the river to achieve a self-scouring depth. This analysis is used to develop the preliminary recommendations of channel lengths at each site where navigation drafts need to be improved.
8.2 Reach One Navigation Channel Conditions

Reach One consists of the navigation channel between the AHSFRA Harbor at Pirapora, Minas Gerais (km 1982) to the confluence of the Rio das Velhas (km 1958) near Paco Paco, Minas Gerais. An overview of Reach One is shown in Figure 77. There are 3 AHSFRA critical sites identified in this reach:

1. Franave (Figure 78)
2. Banco da Raquel (Figure 79)
3. Paco Paco (Figure 80)

A total of 10 locations (shoals) were observed where the 2012 navigation channel is less than 2 meters deep within Reach One. All of the shoals occur within the three critical reaches. The average width of the channel from bank to bank associated with these 10 shoal locations is 317 meters (additional statistics may be found in Figure 81).

The Sao Francisco River is predominantly single threaded with only a few islands. A few sand bars are observed in aerial photos of this reach. The length of the channel according to the AHSFRA stationing is 24 km.
Figure 77: Reach One Critical Sites

Legend
- AHSFRA Critical Sites
- Flow Direction

(AHSFRA Stationing: Pirapora = 1982 km; Rio das Velhas = 1958 km)
Figure 78: Franave

| Site Number: | 1 | Number of Shoals: | 3 |
| Site Name:   | Franave | Total Length of Shoals: | 957 |
| Year of Aerial: | 4/29/2008 |
Figure 79: Banco da Raquel

- Site Number: 2
- Site Name: Banco da Raquel
- Year of Aerial: 4/1/2012
- Number of Shoals: 3
- Total Length of Shoals: 1124
Figure 80: Paco Paco

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>3</th>
<th>Number of Shoals:</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Name:</td>
<td>Paco Paco</td>
<td>Total Length of Shoals:</td>
<td>2306</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>May-08 &amp; Apr.-12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 81: Channel Width Statistics of Shoals in Reach 1
8.3 Reach Two Navigation Channel Conditions

Reach Two consists of the navigation channel between the confluence of the Rio das Velhas (km 1958) and the confluence of the Rio Jequitai (km 1938). An overview map of this reach is shown in Figure 82. There are 2 AHSRFA critical sites identified in this reach:

1. Cascalho Vermelho (Figure 83)
2. Baixo da Porcas (Figure 84)

A total of 4 locations were observed where the 2012 navigation channel is less than 2 meters deep. All 4 locations are within the two AHSFRA critical sites. The average width of the channel from bank to bank associated with these 4 shoal locations is 445 meters (additional statistics may be found in Figure 85).

The Sao Francisco River is predominantly single threaded with only a few islands. A few sand bars are observed in aerial photos of this reach. The length of the channel according to the AHSFRA stationing is 20 km.
Figure 82: Reach Two Critical Sites

Legend
- AHSFRA Critical Sites
- Flow Direction

(AHSFRA Stationing: Rio das Velhas = 1958km; Rio Jequitai = 1938km)
Figure 83: Cascalho Vermelho

Site Number: 4  
Site Name: Cascalho Vermelho  
Year of Aerial: 5/1/2008  
Number of Shoals: 2  
Total Length of Shoals: 1163
Figure 84: Baixo da Porcas

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>5</th>
<th>Number of Shoals:</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Name:</td>
<td>Baixo da Porcas</td>
<td>Total Length of Shoals:</td>
<td>1548</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>5/1/2008</td>
<td>Depth</td>
<td></td>
</tr>
</tbody>
</table>

- Over 2m
- Less than 2m

Coordinates: UTM (m) Zone 25, South (WGS 1984)
Figure 85: Channel Width Statistics of Shoals in Reach 2
8.4 Reach Three Navigation Channel Conditions

Reach Three consists of the navigation channel between the confluence of the Rio Jequitai (km 1938) and the confluence of the Rio Paracatu (km 1868). An overview map of Reach 3 is shown in Figure 86. There are 9 AHSFRA critical sites identified in this reach:

1. Baixo da Cabrainha (Figure 87)
2. Coroa da Ema (Figure 88)
3. Volta do Sobrado (Figure 89)
4. Vaixio do Ibiai (Figure 90)
5. Canabrava (Figure 91)
6. Baixio da Crioulas (Figure 92)
7. Barra do Jaburu (Figure 93)
8. Cachoeira da Manteiga (Figure 94)
9. Ponto Chique (Figure 95)

A total of 17 locations were observed where the 2012 navigation channel is less than 2 meters deep. All 17 locations are located within the 9 AHSFRA critical sites. The average width of the channel from bank to bank associated with these 17 shoal locations is 468.7 meters (additional statistics may be found in Figure 96).

The Sao Francisco River is predominantly single threaded with only a few islands. A few sand bars are observed in aerial photos of this reach. The length of the channel according to the AHSFRA stationing is 70 km.
Figure 86: Reach Three Critical Sites

(AHSFRA Stationing: Rio Jequitai = 1938km; Rio Paracatu = 1868km)
Figure 87: Baixo da Cabrainha

<table>
<thead>
<tr>
<th>Site Number</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>Site Name</td>
<td>Baixo da Cabrainha</td>
</tr>
<tr>
<td>Year of Aerial</td>
<td>4/1/2012</td>
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<tr>
<td>Number of Shoals</td>
<td>0</td>
</tr>
<tr>
<td>Total Length of Shoals</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 88: Coroa da Ema

Site Number: 7
Site Name: Coroa da Ema
Year of Aerial: May-06 & Apr-12

Number of Shoals: 2
Total Length of Shoals: 2052
Figure 89: Volta do Sobrado

Site Number: 8  
Site Name: Volta do Sobrado  
Year of Aerial: May-06 & July-09  
Number of Shoals: 2  
Total Length of Shoals: 2814
Site Number: 9
Site Name: Baixio do Ibiaí
Year of Aerial: May-06 & July-09

Number of Shoals: 3
Total Length of Shoals: 3620
Figure 91: Canabrava

**Site Number:** 10  
**Number of Shoals:** 3  
**Site Name:** Canabrava  
**Total Length of Shoals:** 1487  
**Year of Aerial:** May-06 & July-09
<table>
<thead>
<tr>
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<th>11</th>
<th>Number of Shoals:</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>Site Name:</td>
<td>Baixio da Crioulas</td>
<td>Total Length of Shoals:</td>
<td>5104</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>05/07/10 &amp; 08/08/10</td>
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<td></td>
</tr>
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</table>
Figure 93: Barra do Jaburu

Site Number: 12
Site Name: Barra do Jaburu
Year of Aerial: 2/21/2010
Number of Shoals: 2
Total Length of Shoals: 3279
Figure 94: Cachoeira da Manteiga

<table>
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<tr>
<td>Site Name:</td>
<td>Cachoeira da Manteiga</td>
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<td>Year of Aerial:</td>
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Figure 95: Ponto Chique

<table>
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<tr>
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<td>Ponto Chique</td>
<td>Total Length of Shoals:</td>
<td>2196</td>
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<td>Year of Aerial:</td>
<td>2/21/2010</td>
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</table>
Figure 96: Channel Width Statistics of Shoals in Reach 3
8.5 Reach Four Navigation Channel Conditions

Reach Four consists of the navigation channel between the confluence of the Rio Paracatu (km 1868) and the confluence of the Rio Urucuia (km 1810). An overview map of Reach 4 is shown in Figure 97. There are a total of 6 critical sites identified in this reach:

1. Coroa Branca (Figure 98)
2. Barreira da Martinha (Figure 99)
3. Varginha (Figure 100)
4. Barra dos Valadares (Figure 101)
5. Angicos (Figure 102)
6. Agricio (Figure 103)

A total of 15 locations were observed where the 2012 navigation channel is less than 2 meters deep. All 15 shoals are located within the 6 AHSFRA critical sites within Reach Four (the Agricio site includes 2 shoals that are located within Reach 4 and one shoal that is located in Reach Five, and therefore there are a total of 16 shoals within the 6 AHSFRA critical sites). The average width of the channel from bank to bank associated with these 15 shoal locations is 578.3 meters (additional statistics may be found in Figure 104).

The Sao Francisco River is predominantly single threaded with only a few islands. A few sand bars are observed in aerial photos of this reach. The length of the channel according to the AHSFRA stationing is 58 km.
Figure 97: Reach Four Critical Sites

(AHSFRA Stationing: Rio Paracatu = 1868km; Rio Urucuia = 1810km)
Figure 98: Coroa Branca

- Site Number: 15
- Site Name: Coroa Branca
- Year of Aerial: 2/21/2010
- Number of Shoals: 2
- Total Length of Shoals: 772
Figure 99: Barreira da Martinha

Site Number: 16
Site Name: Barreira da Martinha
Year of Aerial: 2/21/2010

Number of Shoals: 3
Total Length of Shoals: 2329
Figure 100: Varginha

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>17</th>
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<tr>
<td>Site Name:</td>
<td>Varginha</td>
<td>Total Length of Shoals:</td>
<td>1512</td>
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<tr>
<td>Year of Aerial:</td>
<td>3/15/2010</td>
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<td></td>
</tr>
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</table>
Figure 101: Barra dos Valadares

Site Number: 18
Site Name: Barra Dos Valadares
Year of Aerial: 2/21/2010 & 3/15/2010

Number of Shoals: 3
Total Length of Shoals: 2926
Figure 102: Angicos

Site Number: 19           Number of Shoals: 3
Site Name: Angicos        Total Length of Shoals: 1276
Year of Aerial: 2/21/2010
Figure 103: Agricio

<table>
<thead>
<tr>
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<tr>
<td>Site Name:</td>
<td>Agricio</td>
<td>Total Length of Shoals:</td>
<td>3011</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>2/21/2010</td>
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<td></td>
</tr>
</tbody>
</table>
Figure 104: Channel Width Statistics of Shoals in Reach 4
8.6 Reach Five Navigation Channel Conditions

Reach Five consists of the navigation channel between the confluence of the Rio Urucuia (km 1810) and the confluence of the Rio Verde Grande (km 1572). An overview map of Reach 5 is shown in Figure 105. There are a total of 12 critical sites identified in this reach:

1. Barra do Afunda (Figure 106)
2. Porto da Balsa (S. Francisco) (Figure 107)
3. Cabo Chico (Figure 108)
4. Remansinho (Figure 109)
5. Ilha do Balaeiro (Figure 110)
6. Januaria (Figure 111)
7. Venda (Figure 112)
8. Amargoso (Figure 113)
9. Ilha do Valerim (Figure 113)
10. Jatoba (Figure 114)
11. Itacarambi (Figure 115)
12. Regiao dos Pedrais na Diva MG/BA (Figure 116 - Figure 120)

A total of 41 locations were observed where the 2012 navigation channel is less than 2 meters deep. Of the 41 locations, 28 are located within these 12 identified AHSFRA critical sites. One shoal is located in the Agricio site (which extends into
Reach Five), and 12 shoals are located outside of these sites. The Regiao dos Pedrais na Diva NG/BA area includes 7 total shoals within Reach Five and 4 shoals within reach Six (11 total shoals for the region). The average width of the channel from bank to bank associated with these 41 shoal locations is 696.3 meters (additional statistics may be found in Figure 121).

The Sao Francisco River is predominantly single threaded channel, however the density of islands and sandbars are higher than in the upstream reaches. The morphology often includes a pattern of a narrow, deep section of the river followed by an island or sand bars. Shoals are typically associated with locations either just upstream or downstream of an island. The length of the channel according to the AHSFRA stationing is 58 km.
Figure 105: Reach Five Critical Sites

(AHSFRA Stationing: Rio Uruçuia = 1810km; Rio Verde Grande = 1572km)
Figure 106: Barra do Afunda

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>21</th>
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<th>2</th>
</tr>
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<tbody>
<tr>
<td>Site Name:</td>
<td>Barra do Afundá</td>
<td>Total Length of Shoals:</td>
<td>1916</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>2/21/2010 &amp; 3/15/2010</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Site Number: 22  
Site Name: Porto da Balsa (S. Francisco)  
Year of Aerial: 8/21/2010 & 11/14/2009  
Number of Shoals: 2  
Total Length of Shoals: 4122
Figure 108: Cabo Chico

Site Number: 23  
Site Name: Cabo Chico  
Year of Aerial: 7/21/2010 & 8/21/2010  
Number of Shoals: 2  
Total Length of Shoals: 1012
Site Number: 24  
Site Name: Remansinho  
Number of Shoals: 3  
Total Length of Shoals: 2677  
Site Number: 25
Site Name: Ilha do Balaeiro
Year of Aerial: 8/4/2008

Number of Shoals: 3
Total Length of Shoals: 2702
Figure 111: Januaria

Site Number: 26
Site Name: Januária
Year of Aerial: 8/4/2008

Number of Shoals: 1
Total Length of Shoals: 581
Figure 112: Venda

Site Number: 27
Site Name: Venda
Year of Aerial: 8/4/2008

Number of Shoals: 3
Total Length of Shoals: 1828
Figure 113: Amargoso and Ilha do Valerim

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>Amargoso and Ilha do Valerim</td>
</tr>
<tr>
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<tr>
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<tr>
<td>Total Length of Shoals</td>
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Figure 114: Jatoba

Site Number: 29
Site Name: Jatobá
Year of Aerial: 6/16/2010

Number of Shoals: 3
Total Length of Shoals: 2299
Figure 115: Itacarambi

Site Number: 31
Site Name: Itacarambi
Year of Aerial: 6/16/2010 & 09/12/2010

Number of Shoals: 1
Total Length of Shoals: 487

Depth
- Over 2m
- Less than 2m
Figure 116: Regiao dos Pedrais na Diva MG/BA (A)

Site Number: 32  
Site Name: Regiao dos Pedrais na Diva MG-BA  
Year of Aerial: 9/11/2011 & 2/10/2012  
Number of Shoals: 11  
Total Length of Shoals: 6009
Figure 117: Região dos Pedrais na Diva MG/BA (B)

Site Number: 32
Site Name: Região dos Pedrais na Diva MG-BA
Year of Aerial: 9/11/2011 & 2/10/2012

Number of Shoals: 11
Total Length of Shoals: 6009
Figure 118: Regiao dos Pedrais na Diva MG/BA (C)

Site Number: 32
Number of Shoals: 11
Site Name: Regiao dos Pedrais na Diva MG-BA
Total Length of Shoals: 6009
Year of Aerial: 9/11/2011 & 2/10/2012
**Figure 119: Regiao dos Pedrais na Diva MG/BA (D)**

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<th>Site Name:</th>
<th>Regiao dos Pedrais na Diva MG-BA</th>
<th>Number of Shoals:</th>
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<tbody>
<tr>
<td>Year of Aerial:</td>
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</tbody>
</table>
Figure 120: Regiao dos Pedrais na Diva MG/BA (E)

<table>
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</thead>
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<tr>
<td>Year of Aerial:</td>
<td>9/11/2011 &amp; 2/10/2012</td>
<td></td>
<td></td>
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</table>
Figure 121: Channel Width Statistics of Shoals in Reach 5
8.7 Reach Six Navigation Channel Conditions

Reach Six consists of the navigation channel between the confluence of the Rio Verde Grande (km 1572) and the confluence of the Rio Carinhanha (km 11545) and the extents of the reach are shown in Figure 122. There are only 4 locations observed where the 2012 navigation channel is less than 2 meters deep in this reach (widths are 687m, 668m, 806m, and 862m).

Only the general area of Regiao dos Pedrais na Diva is an identified critical AHSFRA site in this reach. There are three shoals within the Regiao dos Pedrais na Diva in Reach Six and these shoals are shown in Figure 123. Figure 124 and Figure 125 also include the remaining stretch of the Regiao dos Pedrais na Diva in Reach Six, although there are no shoals located in either of these two figures.

The Sao Francisco River is predominantly single threaded with only a few islands. A few sand bars are observed in aerial photos of this reach. The length of the channel according to the AHSFRA stationing is 58 km.
Figure 122: Reach Six Critical Sites

(AHSFRA Stationing: Rio Verde Grande = 1572km; Rio Carinhana = 1545km)
Figure 123: Regiao dos Pedrais na Diva MG/BA (F)

AHSFRA Trecho No. 32F - Região dos Pedrais na Diva MG/BA

<table>
<thead>
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<th>Number of Shoals:</th>
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<tbody>
<tr>
<td>Site Name:</td>
<td>Regiao dos Pedrais na Diva MG-BA</td>
<td>Total Length of Shoals:</td>
<td>6009</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>9/11/2011 &amp; 2/10/2012</td>
<td></td>
<td></td>
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</table>
Figure 124: Regiao dos Pedrais na Diva MG/BA (G)

<table>
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<tbody>
<tr>
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<td>Regiao dos Pedrais na Diva MG-BA</td>
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<td>Year of Aerial:</td>
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Figure 125: Regiao dos Pedrais na Diva MG/BA (H)

<table>
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<tbody>
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<td>Site Name:</td>
<td>Regiao dos Pedrais na Diva MG-BA</td>
<td>Total Length of Shoals:</td>
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<tr>
<td>Year of Aerial:</td>
<td>9/11/2011 &amp; 2/10/2012</td>
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</table>
8.8 Reach Seven Navigation Channel Conditions

Reach Seven consists of the navigation channel between the confluence of the Rio Carinhanha (km 1545) and the confluence of the Rio Corrente (km 1395). An overview map of Reach 7 is found in Figure 126. There are a total of 7 critical sites identified in this reach:

1. Regiao dos Pedrais na Diva (partial) (Figure 127)
2. Ilha da Melancia (Figure 128)
3. Barra da Parateca (Figure 129)
4. Barreira do Bichiguento (Figure 130)
5. Barra da Pituba (Figure 131)
6. Boa Vista dos Guimaraes (Figure 132)
7. Ilha do Remo (Figure 133)

A total of 20 locations were observed where the 2012 navigation channel is less than 2 meters deep. Seven of these shoals are located within the defined AHSFRA critical sites, and 13 shoals are located outside the boundaries of these defined sites. There are no shoals within the Regiao dos Pedrais na Diva in Reach Seven. The average width of the channel from bank to bank associated with these 21 shoal locations is 812.6 meters (additional statistics may be found in Figure 134).

The Sao Francisco River is predominantly single threaded channel, however the density of islands and sandbars are higher than in the upstream reaches. The morphology often includes a pattern of a narrow, deep section of the river followed by an island or
sand bars. Shoals are typically associated with locations either just upstream or downstream of an island. The length of the channel according to the AHSFRA stationing is 150 km.
Figure 126: Reach Seven Critical Sites

(AHSFRA Stationing: Rio Carinhana = 1545km; Rio Corrente = 1395km)
Figure 127: Regiao dos Pedrais na Diva MG/BA (I)

Site Number: 32
Site Name: Regiao dos Pedrais na Diva MG-BA
Year of Aerial: 9/11/2011 & 2/10/2012

Number of Shoals: 11
Total Length of Shoals: 6009
Figure 128: Ilha da Melancia

Site Number: 33
Site Name: Ilha da Melância
Year of Aerial: Dec.-09 & Feb.-11

Number of Shoals: 1
Total Length of Shoals: 500
Figure 129: Barra da Parateca

Site Number: 34  
Site Name: Barra da Parateca  
Year of Aerial: May-10 & Sept.-11  
Number of Shoals: 1  
Total Length of Shoals: 497
Site Number: 35
Site Name: Barreira do Bichigueno
Year of Aerial: May-10 & Sept.-11
Number of Shoals: 0
Total Length of Shoals: 0
Figure 131: Barra da Pituba

Site Number: 36  
Site Name: Barra da Pituba  
Year of Aerial: May-10 & Sept.-11  

Number of Shoals: 2  
Total Length of Shoals: 1648
Figure 132: Boa Vista dos Guimaraes

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<tr>
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<tr>
<td>Site Name: Boa Vista dos Guimaraes</td>
<td>Total Length of Shoals: 738.9</td>
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<tr>
<td>Year of Aerial: May-10 &amp; Sept.-11</td>
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</table>
Figure 133: Ilha do Remo

Site Number: 38
Site Name: Ilha do Remo
Year of Aerial: May-10 & Sept.-11
Number of Shoals: 2
Total Length of Shoals: 701.1
Figure 134: Channel Width Statistics of Shoals in Reach 7
8.9  Reach Eight Navigation Channel Conditions

Reach Eight consists of the navigation channel between the confluence of the Rio Corrente (km 1395) and the confluence of the Rio Grande (km 1123). An overview map of Reach 8 is displayed in Figure 135. There are a total of 16 critical sites identified in this reach:

1. Sitio do Mato (Figure 136)
2. Gameleira (Figure 137)
3. Paratinga (Figure 138)
4. Quebra Linha (Figure 139)
5. Cachoeirinha de Ibotirama (Figure 140)
6. Cabeca Levantada (Figure 141)
7. Limoeiro (Figure 142)
8. Boa Vista do Lagamar (Figure 143)
9. Carne Assada (Figure 144)
10. Meleiro (Figure 145)
11. Igarite (Figure 146)
12. Toca de Santa Luzia (Figure 147)
13. Torrinha (Figure 148)
14. Ilha de Itacoatiara (Figure 149)
15. Ilha do Angical (Figure 150)
16. Curralinho (Figure 151)

A total of 30 locations were observed where the 2012 navigation channel is less than 2 meters deep. Of these 30 shoals, 21 are located within the defined AHSFRA critical sites, and 9 are located in areas not defined as a critical site by AHSFRA. The average width of the channel from bank to bank associated with these 30 shoal locations is 778 meters (additional statistics may be found in Figure 153).

This reach includes a segment of river between Ibotirama, Bahia and Barra, Bahia. The current navigation activities by ICOFORT occur between the cities of Ibotirama (upstream) and Petrolina (downstream end of navigation channel located approximately 42 kilometers downstream of the Sobradinho Reservoir). Cachoeirinha de Ibotirama is the first restrictive location (critical site) identified by AHSFRA downstream of Ibotirama, and the remaining sites downstream of Ibotirama are prioritized in this study for investigating the feasibility of self-scouring channels.

The Sao Francisco River is predominantly single threaded channel, however the density of islands and sandbars are higher than in the upstream reaches. Some islands through this reach are very large, and are likely formed by chutes rather than recent depositional features. The morphology often includes a pattern of a narrow, deep section of the river followed by an island or sand bars. Shoals are typically associated with locations either just upstream or downstream of an island. The length of the channel according to the AHSFRA stationing is 272 km.
Figure 135: Reach Eight Critical Sites

(AHSFRA Stationing: Rio Corrente = 1395km; Rio Grande = 1123km)
Figure 136: Sitio do Mato

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>39</th>
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<tr>
<td>Site Name:</td>
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<td>Total Length of Shoals:</td>
<td>936</td>
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<td>May-10 &amp; Sept.-11</td>
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</table>
Figure 137: Gameleira

Site Number: 40
Site Name: Gameleira
Year of Aerial: 4/29/2008

Number of Shoals: 1
Total Length of Shoals: 523
Figure 138: Ilha de Paratinga

Site Number: 41
Site Name: Ilha De Paratinga
Year of Aerial: 11/9/2009

Number of Shoals: 5
Total Length of Shoals: 1949
Figure 139: Quebra Linha

<table>
<thead>
<tr>
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<th>42</th>
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<tr>
<td>Site Name:</td>
<td>Quebra Linha</td>
<td>Total Length of Shoals:</td>
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<tr>
<td>Year of Aerial:</td>
<td>11/9/2009</td>
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Figure 140: Cachoeirinha de Ibotirama

AHSFRA Trecho No 43 - Cachoeirinha de Ibotirama

<table>
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<tr>
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<th>43</th>
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Figure 141: Cabeca Levantada

Site Number: 44
Site Name: Cabaça Levantada
Year of Aerial: 4/29/2008
Number of Shoals: 2
Total Length of Shoals: 1074
Figure 142: Limoeiro

Site Name: Limoeiro
Year of Aerial: 9/9/2008
Number of Shoals: 0
Total Length of Shoals: 0
### Figure 143: Boa Vista do Lagamar

**AHSFRA Trecho No. 46 - Boa Vista do Lagamar**  
**Emergency Dredge Site - Caraíbas**

<table>
<thead>
<tr>
<th>Site Number</th>
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<tbody>
<tr>
<td>46</td>
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<td>0</td>
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</tbody>
</table>

**Site Name:** Boa Vista do Lagamar Caraíbas  
**Year of Aerial:** Jan.-99 & Dec.-03
Figure 144: Carne Assada

Site Number: 47
Site Name: Carne Assada
Year of Aerial: Jan.-99 & Dec.-03

Number of Shoals: 0
Total Length of Shoals: 0
Site Number: 48
Site Name: Meleiro_Sabonete
Year of Aerial: Jan.-99 & Dec.-03
Number of Shoals: 2
Total Length of Shoals: 1895
Figure 146: Igarite

Site Number: 49
Site Name: Igarité
Year of Aerial: 9/9/2008
Number of Shoals: 1
Total Length of Shoals: 312
Figure 147: Toca de Santa Luzia

**Site Number:** 50  
**Site Name:** Toca de Santa Luzia  
**Year of Aerial:** Jan.-99 & Dec.-03  
**Number of Shoals:** 0  
**Total Length of Shoals:** 0

<table>
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<th>Depth</th>
<th>Over 2m</th>
<th>Less than 2m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth map</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 148: Torrinha

Site Number: 51
Site Name: Torrinha
Year of Aerial: 9/9/2008

Number of Shoals: 2
Total Length of Shoals: 933
Figure 149: Ilha de Itacoatiara

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>52</th>
<th>Number of Shoals:</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Name:</td>
<td>Ilha de Itacoatiara</td>
<td>Total Length of Shoals:</td>
<td>972</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>Dec.-02 - Sept.-09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 150: Ilha do Angical

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>53</th>
<th>Number of Shoals:</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Name:</td>
<td>Ilha do Angical</td>
<td>Total Length of Shoals:</td>
<td>0</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>Dec.-02 - Sept.-09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 151: Curralinho

Site Number: 54  
Site Name: Curralinho  
Year of Aerial: Dec.-02 - Sept.-09  
Number of Shoals: 1  
Total Length of Shoals: 497

<table>
<thead>
<tr>
<th>Coordinates: UTM (m Zone 25, South (WGS 1984)</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 2m</td>
<td></td>
</tr>
<tr>
<td>Less than 2m</td>
<td></td>
</tr>
</tbody>
</table>
Figure 152: Ilha da Sambaíba

| Site Number:  | 54A                  | Number of Shoals: | 0           |
| Site Name:    | Ilha da Sambaíba      | Total Length of Shoals: | 0          |
Figure 153: Channel Width Statistics of Shoals in Reach 8
### 8.10 Reach Nine Navigation Channel Conditions

Reach Nine consists of the navigation channel between the confluence of the Rio Grande (km 1123) to the delta at the Sobradinho Reservoir (km 967). An overview map of Reach 9 is included in Figure 154. There are a total of 8 critical sites identified in this reach:

1. Ilha da Samambaia (Figure 155)
2. Icatu (Figure 156)
3. Goiabeira (Figure 157)
4. Amarra Couro (Figure 158)
5. Rodrigo (Figure 159)
6. Umbuzeiro (Figure 160)
7. Taquari (Figure 161)
8. Rio Verde (Figure 162)

A total of 8 locations were observed where the 2012 navigation channel is less than 2 meters deep. Seven of the eight shoals are located within the defined AHSFRA critical sites and one shoal is located outside of a location defined as critical by AHSFRA. The average width of the channel from bank to bank associated with these 8 shoal locations is 948.5 meters (additional statistics may be found in Figure 163).

All of the sites located within Reach Nine are within the priority section (Ibotirama to Petrolina).
The Sao Francisco River is influenced by the backwater of the Sobradinho Reservoir in the most downstream locations of this reach. This channel is multi-braided in some locations with numerous islands throughout. Sand bars and other depositional features are also observed in aerial photos of this reach. The length of the channel according to the AHSFRA stationing is 156 km.
Figure 154: Reach Nine Critical Sites

(AHSFRA Stationing: Rio Grande = 1123km; Sobradinho Reservoir Upstream End = 967km)
Figure 155: Ilha da Samambaia

Site Number: 55
Site Name: Ilha da Samambaia
Year of Aerial: Dec.-02 - Sept.-09

Number of Shoals: 0
Total Length of Shoals: 0
Figure 156: Icatu

<table>
<thead>
<tr>
<th>Site Number:</th>
<th>55A</th>
<th>Number of Shoals:</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Name:</td>
<td>Icatu</td>
<td>Total Length of Shoals:</td>
<td>0</td>
</tr>
<tr>
<td>Year of Aerial:</td>
<td>Dec.-02 - Sept.-09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 157: Goiabeira and Capricho

AHSFRA Trecho No 56 - Goiabeira
Emergency Dredge Site - Capricho

Site Number: 56
Site Name: Goiabeira_and_Capricho
Year of Aerial: Dec.-02 - Sept.-09

Number of Shoals: 2
Total Length of Shoals: 1848
Figure 158: Amarra Couro, Ilha do Mendonca, and Papaconha

AHSFRA Trecho No. 57 & Emergency Dredge Site - Amarra Couro Emergency Dredge Sites - Ilha do Mendonça & Papaconha

<table>
<thead>
<tr>
<th>Site Number</th>
<th>57</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Name</td>
<td>Amarra Couro &amp; Ilha do Mendonça &amp; Papaconha</td>
</tr>
<tr>
<td>Year of Aerial</td>
<td>Dec.-02 - Sept.-09</td>
</tr>
<tr>
<td>Number of Shoals</td>
<td>3</td>
</tr>
<tr>
<td>Total Length of Shoals</td>
<td>1468</td>
</tr>
</tbody>
</table>
Figure 159: Rodrigo

AHSFRA Trecho No. 58 & Emergency Dredge Site - Rodrigo

Site Number: 58
Site Name: Rodrigo
Year of Aerial: 2/27/2009
Number of Shoals: 2
Total Length of Shoals: 1896
Figure 160: Umbuzeiro

AHSFRA Trecho No. 59 & Emergency Dredge Site - Umbuzeiro

Site Number: 59
Site Name: Umbuzeiro
Year of Aerial: Jan.-99 & Dec.-03

Number of Shoals: 0
Total Length of Shoals: 0
Site Number: 59A  
Site Name: Taquari  
Year of Aerial: Jan.-99 & Dec.-03  
Number of Shoals: 0  
Total Length of Shoals: 0
Figure 162: Rio Verde

Site Number: 60
Site Name: Rio Verde
Year of Aerial: Jan.-99 & Dec.-03

Number of Shoals: 0
Total Length of Shoals: 0
Figure 163: Channel Width Statistics of Shoals in Reach 9
CHAPTER 9.0  SEDIMENT TRANSPORT MODEL

A hydraulic and sediment transport model using HEC-RAS was developed to assist in navigation planning for the Sao Francisco River navigation channel. The purpose of this model is to run various scenarios (primarily a self-scouring structure scenario and a dredging scenario) to assist decision makers in navigation planning. A proposed alternative can be analyzed using this tool in a systematic way in order to ensure that a combination of navigation improvement designs will develop a sustainable, reliable, navigable system, as intended.

A sediment transport model requires numerous data including channel geometry, flow, sediment loads, bed gradation, hydraulic Parameters, and numerous others. The development of the sediment transport model leveraged several existing data sources including:

1. ANA gage data (flow and stage rating curves)
2. AHSFRA low water datum plane
4. AHSFRA navigation bathymetry depths (2012)
5. Sediment samples collected within the navigation channel

The following sections describe how these data sets were used to construct the hydraulic and sediment transport model.
9.1 Geometry Files

AHSFRA contracted HIDROTOPO (a Brazilian hydrographic and topographic engineering firm) in 1999 to develop a benchmark network along the navigation channel of the Sao Francisco River. A total of 59 benchmarks were established along the navigation channel between Pirapora and Pilao Arcado (approximately 1015 km). An example of the data collected at each of the benchmarks is shown in Figure 164 and Figure 165. A stage gage was installed at the locations of each of these benchmarks, and both the elevation of the benchmark and the elevation of the stage gage are recorded for each of the sites.

Of these 59 benchmarks 39 had sufficient data to build a low-water datum plane (data is listed in Table 27). This low water datum plane is the same plane used by AHSFRA to calculate low water depths during bathymetry collection each year.
Figure 164: Example Elevation Data Associated with Transverse Section

<table>
<thead>
<tr>
<th>Ponto Inicial</th>
<th>Ponto Final</th>
<th>Norte</th>
<th>ESTE</th>
<th>Distância</th>
<th>Azimute</th>
<th>Observação</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN13A</td>
<td>RN2</td>
<td>52.248</td>
<td>0.044</td>
<td>633 MM SS</td>
<td>352 11 37</td>
<td>RN13A = 470,602</td>
</tr>
<tr>
<td>RN2</td>
<td>RN3</td>
<td>27.333</td>
<td>3.457</td>
<td>25.128</td>
<td>372 11 37</td>
<td>RN2(11.188) = 470,542</td>
</tr>
<tr>
<td>RN3</td>
<td>RG 100</td>
<td>27.471</td>
<td>0.914</td>
<td>4.373</td>
<td>271 38 42</td>
<td>RN3(11.214) = 470,517</td>
</tr>
<tr>
<td>RG 100</td>
<td>NA - ME</td>
<td>8.578</td>
<td>17.938</td>
<td>20.860</td>
<td>315 03 16</td>
<td>REGUA 1,00 (PEDRAL) = 461,782</td>
</tr>
<tr>
<td>NA - ME</td>
<td>NA - MD</td>
<td>-41.249</td>
<td>400.281</td>
<td>385.576</td>
<td>277 25 28</td>
<td>NA - MD = 461,560</td>
</tr>
</tbody>
</table>

Observação

- ZERO REGUA
- COTA = 460,762
Figure 165: Example Topographic Section by HIDROTOPO
AHSFRA collects navigation channel bathymetry annually from Pirapora to the Sobradinho Reservoir. This bathymetry data is collected using single beam depths and is corrected to the low-water datum plane. In order to use the depth data to construct the

<table>
<thead>
<tr>
<th>Name</th>
<th>Number</th>
<th>Left Bank</th>
<th>Right Bank</th>
<th>Datum, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pirapora</td>
<td>RN-02</td>
<td>506384.2</td>
<td>507156</td>
<td>474.043</td>
</tr>
<tr>
<td>Três Coqueiros</td>
<td>RN-03</td>
<td>513430.2</td>
<td>513433.5</td>
<td>472.234</td>
</tr>
<tr>
<td>Rio Das Velhas</td>
<td>RN-04</td>
<td>517631.4</td>
<td>517770.6</td>
<td>470.687</td>
</tr>
<tr>
<td>Passa Val</td>
<td>RN-05</td>
<td>519331.2</td>
<td>519330.9</td>
<td>470.497</td>
</tr>
<tr>
<td>Barreira Das Ciganas</td>
<td>RN-06</td>
<td>522207.8</td>
<td>522505.3</td>
<td>469.762</td>
</tr>
<tr>
<td>Baluarte</td>
<td>RN-07</td>
<td>520074.2</td>
<td>520457</td>
<td>468.26</td>
</tr>
<tr>
<td>Cana Brava</td>
<td>RN-08</td>
<td>513037.2</td>
<td>513511.8</td>
<td>467.972</td>
</tr>
<tr>
<td>Sobrado</td>
<td>RN-09</td>
<td>510859.8</td>
<td>510686.6</td>
<td>466.276</td>
</tr>
<tr>
<td>Loje</td>
<td>RN-10</td>
<td>508850.4</td>
<td>509300.7</td>
<td>466.074</td>
</tr>
<tr>
<td>Pé do Morro</td>
<td>RN-11</td>
<td>498653</td>
<td>498506.9</td>
<td>461.214</td>
</tr>
<tr>
<td>Bica Grande</td>
<td>RN-12</td>
<td>499594.9</td>
<td>500048.9</td>
<td>461.033</td>
</tr>
<tr>
<td>Cachoeira do Manteiga</td>
<td>RN-13</td>
<td>491374.6</td>
<td>491819.4</td>
<td>460.782</td>
</tr>
<tr>
<td>Angico de Cima</td>
<td>RN-17</td>
<td>494875.6</td>
<td>495193.1</td>
<td>460.317</td>
</tr>
<tr>
<td>Bom Jardim</td>
<td>RN-19</td>
<td>508039.9</td>
<td>508610.2</td>
<td>456.09</td>
</tr>
<tr>
<td>São Francisco</td>
<td>RN-20</td>
<td>513784.5</td>
<td>514182.6</td>
<td>450.952</td>
</tr>
<tr>
<td>Lajedo</td>
<td>RN-21</td>
<td>522164.2</td>
<td>522158.7</td>
<td>451.403</td>
</tr>
<tr>
<td>Cano Verde</td>
<td>RN-22</td>
<td>543216.6</td>
<td>543619.7</td>
<td>449.151</td>
</tr>
<tr>
<td>Capivara</td>
<td>RN-23</td>
<td>553628.1</td>
<td>553921.6</td>
<td>448.846</td>
</tr>
<tr>
<td>Maria da Cruz</td>
<td>RN-24</td>
<td>563419.4</td>
<td>563322.1</td>
<td>447.23</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>RN-27</td>
<td>609105</td>
<td>609613.1</td>
<td>437.727</td>
</tr>
<tr>
<td>Coroa Branca</td>
<td>RN-30</td>
<td>635191.8</td>
<td>635524.8</td>
<td>431.055</td>
</tr>
<tr>
<td>Barreiro Grande</td>
<td>RN-31</td>
<td>652802.1</td>
<td>653113.4</td>
<td>426.776</td>
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<tr>
<td>Pituba</td>
<td>RN-32</td>
<td>656396.8</td>
<td>657003.2</td>
<td>426.234</td>
</tr>
<tr>
<td>Campinhos</td>
<td>RN-33</td>
<td>657242.6</td>
<td>657946.6</td>
<td>425.684</td>
</tr>
<tr>
<td>Piranhas</td>
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<td>667477.9</td>
<td>667985.3</td>
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<tr>
<td>Cachoeira do Araçá</td>
<td>RN-37</td>
<td>669952.3</td>
<td>670177.5</td>
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<tr>
<td>Gameleira</td>
<td>RN-39</td>
<td>675559.8</td>
<td>675657.3</td>
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<tr>
<td>Pernambuco</td>
<td>RN-40</td>
<td>692539.1</td>
<td>692661.8</td>
<td>414.275</td>
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<tr>
<td>Manga</td>
<td>RN-42</td>
<td>694428.5</td>
<td>695054.3</td>
<td>412.217</td>
</tr>
<tr>
<td>Quebra Linha</td>
<td>RN-43</td>
<td>691440.1</td>
<td>692052.7</td>
<td>412.584</td>
</tr>
<tr>
<td>Serra Branca</td>
<td>RN-44</td>
<td>689093.2</td>
<td>689661.6</td>
<td>411.398</td>
</tr>
<tr>
<td>Cachoeirinha do Ibotirama</td>
<td>RN-46</td>
<td>691909.6</td>
<td>692547.8</td>
<td>410.141</td>
</tr>
<tr>
<td>Limoeiro</td>
<td>RN-47</td>
<td>678423.7</td>
<td>679220.4</td>
<td>407.812</td>
</tr>
<tr>
<td>Meleiro</td>
<td>RN-48</td>
<td>679500.8</td>
<td>679797.7</td>
<td>405.763</td>
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<tr>
<td>Sta. Luzia</td>
<td>RN-49</td>
<td>682731.8</td>
<td>682738.4</td>
<td>403.915</td>
</tr>
<tr>
<td>Boa Vista do Sakunio</td>
<td>RN-55</td>
<td>764818.8</td>
<td>765327.4</td>
<td>392.79</td>
</tr>
<tr>
<td>Tapera</td>
<td>RN-56</td>
<td>771019.4</td>
<td>771309.2</td>
<td>392.08</td>
</tr>
<tr>
<td>Pedras do Raul</td>
<td>RN-57</td>
<td>775602.8</td>
<td>775914.8</td>
<td>392.507</td>
</tr>
<tr>
<td>Pilão Arcado Velho</td>
<td>RN-59</td>
<td>782362.7</td>
<td>783031.1</td>
<td>391.311</td>
</tr>
</tbody>
</table>
sediment transport model, depths were converted to elevations by subtracting the elevations from the low water datum plane.

AHSFRA also provided the electronic chart data that included the locations of islands and banks. Each island polygon was set to an elevation equivalent to the low water datum at the location of the island. The top of the island and top of banks were assigned elevations based on an existing 30m Digital Elevation Model of the system. The toe of the island was set 1.0 meters below the low-water datum and then a surface was built, which interpolated these elevations to the navigation channel. A Triangular Irregular Network (TIN) which leveraged all existing geometry data was then developed (for an example of the surface, see Figure 166). HEC-GeoRAS (USACE, 2012a) was used to develop the cross sections along the TIN. Average spacing of the cross sections were approximately 500 meters; however, additional cross sections were added at each shoal in order to capture all local low points along the channel.
The geometry data developed for the model (including cross sections) is a coarse representation of the Sao Francisco River throughout the entire navigation channel. The coarseness of the model is appropriate due to the general questions that the model was used to answer. Any future site-specific designs will need to update the channel geometry using refined data and ensure that all cross sections within a given boundary.

The geometry file for the existing conditions of the navigation channel (based on the 2012 AHSFRA bathymetry) is named Sao_Francisco_Nav in the HEC-RAS model. A screen shot of the geometry file associated with the existing conditions and an example cross section at each reach is shown in Figure 167 through Figure 184.
Figure 167: Navigation Channel Geometry File – Reach 1

Figure 168: Example Cross Section from Reach 1 (Station 2031321)
Figure 169: Navigation Channel Geometry File – Reach 2

Figure 170: Example Cross Section from Reach 2 (Station 1997509)
Figure 171: Navigation Channel Geometry File – Reach 3

Figure 172: Example Cross Section from Reach 3 (Station 1943321)
Figure 173: Navigation Channel Geometry File – Reach 4

Figure 174: Example Cross Section from Reach 4 (Station 1877321)
Figure 175: Navigation Channel Geometry File – Reach 5

Figure 176: Example Cross Section from Reach 5 (Station 1751821)
Figure 177: Navigation Channel Geometry File – Reach 6

Figure 178: Example Cross Section from Reach 6 (Station 1589321)
Figure 179: Navigation Channel Geometry File – Reach 7

Figure 180: Example Cross Section from Reach 7 (Station 1488321)
Figure 181: Navigation Channel Geometry File – Reach 8

Figure 182: Example Cross Section from Reach 8 (Station 1236689)
Figure 183: Navigation Channel Geometry File – Reach 9

Figure 184: Example Cross Section from Reach 9 (Station 1077842)
9.2 Hydrology Files

AHSFRA provided the gage elevations at various ANA gages that correspond to the 90% Exceedance Stage (which is defined as the low water datum for the Sao Francisco River navigation channel). These stages at the various gages are shown in Table 28. Using the historical flow measurement and elevation data available from ANA, a rating curve was developed for each of flow gages along the Sao Francisco River within the study limits. These rating curves were used to determine the hydrology (flowrate) at each of the gage locations at the low water datum. Figure 185 through Figure 197 includes the rating curves and calculations to determine the associated flowrate at each of these stage-flow gages. Several regressions were used on the various gages including a power regression, standard quadratic polynomial regression, and a cubic polynomial regression. R² values for the rating curve regressions are very high at values of 0.95 and above. The hydrology data was used in the hydraulic model to define the low-water datum plane. A map of the locations of the gages is included in Figure 198.

Table 28: Gages Used to Construct Hydrology of Low Water Datum

<table>
<thead>
<tr>
<th>Gage Name</th>
<th>ANA Gage Number</th>
<th>Station, km</th>
<th>Start Date</th>
<th>End Date</th>
<th>Model Station, km</th>
<th>90% Gage Stage, m</th>
<th>90% Exceedence Flow, cms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pirapora - Barreiro</td>
<td>41130000</td>
<td>1985</td>
<td>6/1/1968</td>
<td>1/1/2013</td>
<td>2033821</td>
<td>1.88</td>
<td>551.4</td>
</tr>
<tr>
<td>Montante Barra Jequitai</td>
<td>42030000</td>
<td>1937</td>
<td>1/1/1963</td>
<td>5/1/1991</td>
<td>1988821</td>
<td>2.03</td>
<td>574.4</td>
</tr>
<tr>
<td>Cachoeira da Manteiga</td>
<td>42210000</td>
<td>1878</td>
<td>1/1/1959</td>
<td>1/1/2013</td>
<td>1920821</td>
<td>2.01</td>
<td>589</td>
</tr>
<tr>
<td>São Romão</td>
<td>43200000</td>
<td>1837</td>
<td>10/1/1952</td>
<td>1/1/2013</td>
<td>1887821</td>
<td>2.39</td>
<td>857.6</td>
</tr>
<tr>
<td>São Francisco</td>
<td>44200000</td>
<td>1778</td>
<td>1/1/1994</td>
<td>1/1/2013</td>
<td>1810821</td>
<td>2.55</td>
<td>814.5</td>
</tr>
<tr>
<td>Manga</td>
<td>44500000</td>
<td>1595</td>
<td>10/1/1932</td>
<td>1/1/2013</td>
<td>1617321</td>
<td>1.48</td>
<td>929.8</td>
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<tr>
<td>Carinhanka</td>
<td>45298000</td>
<td>1540</td>
<td>9/1/1927</td>
<td>1/1/2013</td>
<td>1561321</td>
<td>1.03</td>
<td>993.7</td>
</tr>
<tr>
<td>Bom Jesus da Lapa</td>
<td>45480000</td>
<td>1409</td>
<td>8/1/1940</td>
<td>3/1/2013</td>
<td>1423339</td>
<td>1.6</td>
<td>1012.8</td>
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<tr>
<td>Gameleira</td>
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<td>1360</td>
<td>9/1/1927</td>
<td>1/1/2013</td>
<td>1371339</td>
<td>1.6</td>
<td>1124.1</td>
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<td>1327</td>
<td>1/1/1977</td>
<td>3/1/2013</td>
<td>1342339</td>
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<td>Ibotirama</td>
<td>46150000</td>
<td>1263</td>
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<td>3/1/2013</td>
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<td>1126.6</td>
</tr>
<tr>
<td>Morpará</td>
<td>46360000</td>
<td>1180</td>
<td>6/1/1954</td>
<td>3/1/2013</td>
<td>1187519</td>
<td>0.97</td>
<td>1247</td>
</tr>
<tr>
<td>Barra</td>
<td>46998000</td>
<td>1123</td>
<td>10/1/1925</td>
<td>12/1/1977</td>
<td>1123500</td>
<td>1.29</td>
<td>1363.5</td>
</tr>
</tbody>
</table>
The 90% exceedance stage at the Pirapora – Barreiro gage is 1.88 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ Q = \left( \frac{y}{0.2421} \right)^{1/0.3247} \]

\[ Q = \left( \frac{1.88}{0.2421} \right)^{1/0.3247} = 551.4 \text{ cms} \]
The 90% exceedance stage at the Jequitai gage is 2.03 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ Q = \left( \frac{y}{0.026} \right)^{1/0.6859} \]

\[ Q = \left( \frac{2.03}{0.026} \right)^{1/0.6859} = 574.4 \text{ cms} \]
The 90% exceedance stage at the Cachoeira da Manteiga gage is 2.01 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[
Q = \left( \frac{y}{0.0174} \right)^{1/0.7446}
\]

\[
Q = \left( \frac{2.01}{0.0174} \right)^{1/0.7446} = 589.0 \text{ cms}
\]
Figure 188: Stage-Discharge Rating Curve for Sao Romao (43200000)

The 90% exceedance stage at the Sao Romao gage is 2.39 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ Q = \left( \frac{y}{0.0274} \right)^{1/0.6616} \]

\[ Q = \left( \frac{2.39}{0.0274} \right)^{1/0.6616} = 857.6 \text{ cms} \]
The 90% exceedance stage at the Sao Francisco gage is 2.55 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

$$2.55 = 3.0 \times 10^{-12} Q^3 - 1.0 \times 10^{-7} Q^2 + 0.0018Q + 1.1486$$

Using an equation solver, the flowrate associated with a 2.55 meter stage is 814.5 cms.
The 90% exceedance stage at the Magna gage is 1.48 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

$$1.48 = -4.0 \times 10^{-7} Q^2 + 0.0016Q + 0.3381$$

Using an equation solver, the flowrate associated with a 1.60 meter stage is 929.8 cms.
The 90% exceedance stage at the Carinhana gage is 1.03 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ 1.03 = 1.0 \times 10^{-12} Q^3 - 7.0 \times 10^{-8} Q^2 + 0.0014Q - 0.293 \]

Using an equation solver, the flowrate associated with a 1.03 meter stage is 993.7 cms.
The 90% exceedance stage at the Bom Jesus da Lapa gage is 1.60 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

$$1.60 = -5.0 \times 10^{-8} Q^2 + 0.0013 Q + 0.3346$$

Using an equation solver, the flowrate associated with a 1.60 meter stage is 1012.8 cms.
The 90% exceedance stage at the Gameleira gage is 1.60 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ 1.60 = -6.0 \times 10^{-8} Q^2 + 0.0015Q - 0.0104 \]

Using an equation solver, the flowrate associated with a 1.60 meter stage is 1124.1 cms.
The 90% exceedance stage at the Gameleira gage is 1.95 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ 1.95 = -4.0 \times 10^{-8}Q^2 + 0.0013Q + 0.4732 \]

Using an equation solver, the flowrate associated with a 1.95 meter stage is 1178.8 cms.
The 90% exceedance stage at the Ibotirama gage is 1.96 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[
1.96 = -6.0 \times 10^{-8} Q^2 + 0.0014Q + 0.4589
\]

Using an equation solver, the flowrate associated with a 1.96 meter stage is 1126.6 cms.
The 90% exceedance stage at the Morpara gage is 2.97 meters according to the historical stage record at the ANA gage. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ 2.97 = -6.0 \times 10^{-8} Q^2 + 0.0014 Q + 0.4589 \]

Using an equation solver, the flowrate associated with a 2.97 meter stage is 1247.0 cms.
The 90% exceedance stage at the Barra gage is 1.29 meters according to AHSFRA. Therefore, the flow associated with the low water datum at this gage can be calculated using the following equation:

\[ 1.29 = -2.0 \times 10^{-7} Q^2 + 0.0022Q - 1.3378 \]

Using an equation solver, the flowrate associated with a 1.29 meter stage is 1363.5 cms.
Figure 198: Locations of Gages in used in Stage-Discharge Rating Curves
A steady state flow file was created to represent this low flow data throughout the navigation channel. This steady state flow file is named *Low_Flow_Steady* in the HEC-RAS model. The data associated with this steady flow file is shown in Figure 199.

**Figure 199: Low Flow Steady Flow File (Low Water Datum Flows)**

![Steady Flow Data - Low_Flow_Steady](image)

In addition to the low flow steady state file (associated with conditions of the low water datum), a quasi-unsteady state file was developed and used in the sediment transport model (both existing conditions and future scenarios). Hydrology data at each of the gages were input into the quasi-unsteady state file. The quasi-unsteady state file is named *Sao_Francisco_Quasi_Unsteady*. 
A six-year simulation from January 1, 2001 through December 31, 2006 was selected to represent the hydrology for the sediment transport model. This period of record was chosen because it is the same period of record used for the Soil and Water Assessment Tool (SWAT) model developed for the system. The SWAT model provided the sediment input data into the sediment transport model. In addition, this period of record was chosen because it is a recent period of record that is representative of current hydrologic conditions (post dam construction, and post agricultural expansion in the watershed). Previous studies by the CODEVASF and USACE such as the Curralinho project (CODEVASF-USACE, 2013a) and the Sambaiba Island project (CODEVASF-USACE, 2013b) have shown that the sediment transport model reaches a dynamic equilibrium condition within the first 3-4 years after a structure is constructed. Therefore, the 6-year simulation is sufficient to evaluate the impacts associated with proposed structures and dredging in order to improve navigation on the Sao Francisco River Navigation Channel. Figure 200 shows the flow hydrograph for the upstream boundary at the Pirapora gage (model cross section 2033821). Additional gage data was added to the quasi-unsteady state file at each of the major tributaries. The additional flow was added to the model using the lateral flow series Boundary Condition Type. The downstream boundary condition was set to a normal depth with a slope of 0.00006 m/m. The Sao_Francisco_Quasi_Unsteady flow file is shown in Figure 201.
Figure 200: Upstream Boundary Flow Series Boundary Condition (Pirarpora)
The water temperature for the entire simulation was set to 27.9°C. This value was used in a previous study (see Curralinho, CODEVASF-USACE, 2013a). This study found that the sediment transport model is not sensitive to the temperature, and therefore, the average water temperature at a selected gage (the Morpara gage) was used for the entire simulation.
9.3 Sediment Files

A sediment file was created for the existing conditions sediment transport model. This file is named *Sao_Francisco_Nav* in the HEC-RAS sediment transport model. Data and lessons learned from other sediment transport models completed by both CODEVASF and USACE were leveraged in the sediment transport model of the navigation channel (see CODEVASF-USACE, 2013a and CODEVASF-USACE, 2013b). Both of these models used the Yang sediment transport function, which was selected for the sediment transport calculations. The Yang sediment transport function is applicable for sandy bed streams with medium particle sizes of 0.0137 – 1.71 mm and depths of 0.011 – 15.2 m (although the majority of the field data used to develop the Yang model was less than 0.91m).

The sediment transport equation given by Yang (1996) is a total load equation based on the stream power at each cross section (stream power is defined as the product of the velocity and shear stress).

In metric units, the final sediment discharge is converted into metric tonnes. These equations are solved for an individual cross section. If, after the sediment transport equations are solved, there is less sediment entering the cross section from upstream than the sediment capacity, the cross section will erode. The sediment transport capacity is defined as the amount of sediment that the river can transport under the given hydraulic conditions. HEC-RAS calculates the stream power at each cross section in the model, and if there is more stream power than the mass of incoming sediment, the bed will erode an amount of sediment to meet the capacity of the stream. If there is more sediment
entering the cross section, then the excess fraction of the sediment will deposit. See USACE (2010b) for more information on the Yang sediment transport function.

The Yang sediment transport function simultaneously solves the following six equations at each cross section:

1. Shear Velocity:

   \[ u_s = \sqrt{g \cdot R \cdot S} \]

2. Reynold’s Number:

   \[ R_s = \frac{u_s \cdot d_w}{v} \]

3. Particle Fall Velocity (Ruby Equation):

   \[ F_i = \sqrt{3 \cdot \frac{36 \cdot v^2}{g \cdot d_w^3 \cdot (s-1)}} - \sqrt{\frac{36 \cdot v^2}{g \cdot d_w^3 \cdot (s-1)}} \]

   \[ \omega = F_i \cdot \sqrt{(s-1) \cdot g \cdot d_w} \]

   \[ V_{ct} = \begin{cases} \omega \cdot \left( \frac{2.5}{\log \left( \frac{u_s \cdot d_w}{v} \right) - 0.06} + 0.66 \right) & \text{if } 0 < R_s < 70 \\ \omega \cdot 2.05 & \text{if } R_s \geq 70 \end{cases} \]

4. Log of Concentration:

   \[ \log C_t = \begin{cases} 5.435 - 0.286 \cdot \log \left( \frac{\omega \cdot d_w}{v} \right) - 0.457 \cdot \log \left( \frac{u_s}{\omega} \right) & \text{if } d_{wi} < 0.00656 \text{ Sand} \\ + \left( 1.799 - 0.409 \cdot \log \left( \frac{\omega \cdot d_w}{v} \right) - 0.314 \cdot \log \left( \frac{u_s}{\omega} \right) \right) \cdot \log \left( \frac{V \cdot S}{\omega} - \frac{V_{ct} \cdot S}{\omega} \right) & \text{if } d_{wi} \geq 0.00656 \text{ Gravel} \end{cases} \]
5. Sediment Discharge, lbs/s:

\[ G = \frac{\gamma_w \cdot Q \cdot C_t}{1000000} \]

6. Sediment Discharge, tons/day:

\[ G_s = \frac{86400}{2000} \cdot G \]

Where,

- \( u^* \) = shear velocity, ft/s
- \( g \) = gravity, ft/s²
- \( R \) = Hydraulic Radius, ft
- \( S \) = Slope
- \( R_s \) = Reynolds Number
- \( d_{si} \) = Median Particle Diameter, ft
- \( \nu \) = Kinematic Viscosity, ft²/s
- \( s \) = specific gravity of sediment
- \( V_{cr} \) = Critical Velocity
- \( C_t \) = Sediment Concentration, ppm
- \( \gamma_w \) = Unit Weight of Water, lb/ft³
- \( G \) = Sediment Discharge, lbs/s
- \( Q \) = Discharge, ft³/s
- \( G_s \) = Sediment Discharge, tons/day
The Exner 5 sorting method and Ruby Fall Velocity Method were applied to the model of the navigation channel. Also, a large maximum depth (10 meters) was applied to each cross section to ensure that each section has the opportunity to erode. This assumption should be refined where known rock outcrops exist along the Sao Francisco River or for other reaches outside the study area. In addition, other refinements may also be necessary to analyze site specific applications. These refinements may include the sediment transport function to be selected based on the physical characteristics (such as width, depth, slope, or bed particle size) of a reach. A portion of the Sao_Francisco_Nav sediment transport file (GUI) is shown in Figure 202.
Limited gradation data is available for the Sao Francisco River. A previous study by a consultant to CODEVASF – Fundacao de Estudos e Pesquisas Aquaticas (FUNDESPA, 2005) includes a collected gradation analysis of bed material along the Sao Francisco River. This gradation shows that the approximate median particle size, $d_{50}$, of the stream bed is 550 μm or 0.55 mm (equivalent to a coarse sand). Although bed gradation is not available throughout the Sao Francisco River, the collected FUNDESPA gradation was used throughout the model domain (see Figure 203).
Sediment boundary condition data was added to the model at all major tributaries. The sediment transport model used the output of a sediment yield model that was developed in the Soil and Water Assessment Tool (SWAT) as input into the sediment transport boundary. Therefore, the sediment yield model output from SWAT was coupled with the sediment transport input in HEC-RAS. This approach provides more realistic boundary conditions at major tributaries that are unmonitored, but have sufficient (daily) sediment data at the tributary confluence based on the calibrated sediment yield model output.

The SWAT model was calibrated to both hydrology and sediment yields throughout the Sao Francisco basin. Each of the major tributaries contribute a hydrologic flow and a sediment load. The SWAT model was used to accurately represent the daily sediment loads associated with each tributary. The SWAT model consists of 76
subwatersheds, and at the downstream boundary of each subwatershed a daily time-series of sediment loads can be extracted from the output of the SWAT model. Table 29 identifies the SWAT model sub-watershed basin ID and the corresponding HEC-RAS cross section (the HEC-RAS cross sections represent the first cross section downstream of the confluence of each major tributary). The daily sediment load for each of the major tributaries were added to HEC-RAS using the sediment series option. An example of the Sediment Load Series input to the Sediment Transport Model can be found in Figure 204.

### Table 29: SWAT Output and Sediment Input Table

<table>
<thead>
<tr>
<th>Tributary Name</th>
<th>SWAT Model Sub-watershed</th>
<th>Sediment Transport Model Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>São Francisco River (Upstream boundary)</td>
<td>68</td>
<td>2033821</td>
</tr>
<tr>
<td>Rio das Velhas</td>
<td>63</td>
<td>1975321</td>
</tr>
<tr>
<td>Rio Jequitai</td>
<td>60</td>
<td>1915821</td>
</tr>
<tr>
<td>Rio Paracatu</td>
<td>59</td>
<td>1843321</td>
</tr>
<tr>
<td>Rio Urucua</td>
<td>56</td>
<td>1593321</td>
</tr>
<tr>
<td>Rio Verde Grande</td>
<td>51</td>
<td>1573821</td>
</tr>
<tr>
<td>Rio Carinhanga</td>
<td>48</td>
<td>1489321</td>
</tr>
<tr>
<td>Rio das Rãs</td>
<td>44</td>
<td>1406234</td>
</tr>
<tr>
<td>Rio Corrente</td>
<td>39</td>
<td>1325339</td>
</tr>
<tr>
<td>Rio Santo Onofre</td>
<td>36</td>
<td>1190472</td>
</tr>
<tr>
<td>Rio Paramirim</td>
<td>27</td>
<td>1132000</td>
</tr>
<tr>
<td>Rio Grande</td>
<td>24</td>
<td>994505</td>
</tr>
</tbody>
</table>
Figure 204: Example Sediment Load Series Input at Cross Section 1489321
9.4 Project Setup

Two existing conditions models were developed using the files previously described. These projects include a low flow steady state model (to calibrate the hydraulics to low-flow conditions) and a 6-year sediment transport simulation (to be used to analyze navigation planning alternatives).

The steady state low flow hydraulic model includes the following files:

- Project: Sao_Francisco_Nav (.prj)
- Plan: Sao_Francisco_Low_Flow (.p02)
- Geometry: Sao_Francisco_Nav (.g02)
- Steady Flow: Low_Flow_Steady (.f02)

The existing conditions sediment transport model includes the following files:

- Project: Sao_Francisco_Nav (.prj)
- Plan: Sao_Francisco_Sediment (.p04)
- Geometry: Sao_Francisco_Nav (.g02)
- Quasi Unsteady: Sao_Francisco_Quasi_Unsteady (.q02)
- Sediment: Sao_Francisco_Nav (.s02)
CHAPTER 10.0 VALIDATION OF EXISTING CONDITIONS MODELS

10.1 Steady State Model Calibration

The low-flow steady state model was first used to validate the predicted water surface profiles of the low-flow simulation. The elevations at thirteen ANA gages along the navigation channel were used to calibrate the model’s water surface profile. The model achieved calibration of the low-flow water surface profile despite significant breaks in slopes along the channel. The results of the low-flow calibration are shown in Figure 205. The results of the calibrated low-flow model are also shown in Table 30. Table 30 shows that at each of the gages there is less than 10 cm of error associated with the HEC-RAS low water surface profile. This is sufficient accuracy for the modeling being conducted, and therefore the low-flow model was considered calibrated.
Figure 205: Calibrated Hydraulic Model Profile

Table 30: Low-Flow Model Calibration

<table>
<thead>
<tr>
<th>Station</th>
<th>Gage Elevation, m</th>
<th>Low-Flow Elevation from HEC-RAS, m</th>
<th>Difference, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030100</td>
<td>475.933</td>
<td>475.92</td>
<td>0.013</td>
</tr>
<tr>
<td>1920700</td>
<td>461.491</td>
<td>461.51</td>
<td>-0.019</td>
</tr>
<tr>
<td>1878400</td>
<td>458.91</td>
<td>458.87</td>
<td>0.04</td>
</tr>
<tr>
<td>1811200</td>
<td>453.579</td>
<td>453.55</td>
<td>0.029</td>
</tr>
<tr>
<td>1617200</td>
<td>436.275</td>
<td>436.23</td>
<td>0.045</td>
</tr>
<tr>
<td>1561100</td>
<td>432.473</td>
<td>432.45</td>
<td>0.023</td>
</tr>
<tr>
<td>1422400</td>
<td>421.927</td>
<td>421.92</td>
<td>0.007</td>
</tr>
<tr>
<td>1371300</td>
<td>417.142</td>
<td>417.24</td>
<td>-0.098</td>
</tr>
<tr>
<td>1342400</td>
<td>415.561</td>
<td>415.62</td>
<td>-0.059</td>
</tr>
<tr>
<td>1275900</td>
<td>411.141</td>
<td>411.14</td>
<td>0.001</td>
</tr>
<tr>
<td>1187300</td>
<td>405.72</td>
<td>405.75</td>
<td>-0.03</td>
</tr>
<tr>
<td>1123300</td>
<td>401.374</td>
<td>401.46</td>
<td>-0.086</td>
</tr>
<tr>
<td>967000</td>
<td>390.875</td>
<td>390.89</td>
<td>-0.015</td>
</tr>
</tbody>
</table>
The HEC-RAS model includes a total of 2,623 cross sections. The depth of the thalweg at each cross section was calculated by subtracting the thalweg elevation from the modeled low-water datum water surface profile. These depths to the thalweg are plotted in Figure 206. From the tabulated data, there are a total of 56 locations where the thalweg is less than 2.0 meters. This is consistent with the approximate 60 critical sites (as defined by AHSFRA). A shoal may encroach upon the navigation channel in some cases in the Sao Francisco River causing a portion of the cross-section to be less than 2.0 meters, but there may still remain some portion of the navigation channel deeper than 2.0 meters. Subtracting the thalweg from the low-water datum will not display these locations. However, these 56 sites will be investigated to determine if the shoals are successfully addressed using the structure designs in the Self-Scouring Structures Alternative (Section CHAPTER 11.0).
Figure 206: Depth of Thalweg at Each HEC-RAS Cross Section
10.2 Sediment Transport Model Validation

The validation of the sediment transport model was based on whether the model predicted similar amounts (depths) of deposition and erosion that have been observed in comparisons of historical navigation charts, and that it is a robust model that behaves similar to other models (and other observations) noted within the system. To this end, the model was validated using the following process and considerations:

1. Calibration data (such as sediment transport function, gradation of the bed, computation time-steps, sorting and fall methods, etc.) were set equal to the previous CODEVASF and USACE (high resolution) navigation models that achieved a high level of calibration at specific sites of typically approximately 10 km in length.

2. The model was then verified to be robust, meaning that during the simulation the behavior of erosion and deposition is realistic. A robust model will not have a single trend of erosion only or deposition only throughout the entire simulation as this is not an observed pattern in the Sao Francisco River. Any cross sections that continue to only erode (or only aggrade) should be limited to very small amounts of erosion or deposition.

3. The model results of the sedimentation/erosion are within an expected range of approximately (+/-) 1 meter (m) over the course of a long-term simulation. This value is the upper limit observed when comparing AHSFRA bathymetry surveys at a location over-time.
The six-year simulation (2001 through 2006) was run on an 64-bit, 8 core 3.60 GHz, 24.0 GB RAM desktop computer. One simulation of the sediment transport model run took approximately 1 hour and 20 minutes to fully execute.

The validation tests were confirmed by investigating the invert change at the 2,624 cross sections in the model (see Figure 207). The vast majority of the cross sections resulted in less than 0.5 m of deposition or erosion over the simulation. A total of 73 cross sections had between 0.5 and 1.0 m of deposition or erosion, and 9 cross sections resulted in greater than 1.0 m of deposition or erosion. The largest erosion depth simulated is 1.37 m, and the largest amount of deposition at a single cross section is 1.13 m. Only approximately 0.3% of the cross sections are outside of the expected range of erosion/deposition and the extremes are not significantly greater than expected. Therefore, the model is considered validated for the general purposes it was used for in this study.
In addition, typical cross sections (see Figure 208) show both deposition and erosion over various seasons. This is a typical, expected response in a river that is in a state of dynamic equilibrium. Where cross sections experience a continual trend of either deposition or erosion over time, the rate or amount is very small (i.e., there is very little change over-time). There are no cross sections that exhibit a significant amount of continual erosion or deposition over time at a high rate.

Based on the robustness and the reasonable results provided by the output of the sediment transport model, this tool was determined to have an appropriate level of accuracy for use in general planning purposes (i.e., to confirm general behavior of the system with conceptual layouts of structures or dredging). For detailed designs it is recommended that a more focused model be developed at individual locations.
Figure 208: Typical Cross Section Exhibiting Deposition/Erosion Over Time

Figure 209: Typical Trending Cross Section with Small Rates of Erosion
10.3 Model Uncertainty and Sensitivity

Sediment transport models require a significant amount of data to develop. Sediment data, by nature, is dynamic and surveys of the river bottom only represent a single moment in time. Sediment data can also be difficult and expensive to collect under the range of conditions that are being analyzed. When data does not exist or the quality of the data is low, either new data should be collected, or assumptions regarding the value of the data are required. If assumptions regarding sediment or geometry data are made, it is very important to test these assumptions to determine how sensitive the model is to a change in the variable. This sensitivity analysis should also be extended to data that is of poor or uncertain quality.

For the sediment transport model of the navigation channel the following data are lacking or of low quality and were included in a sensitivity analysis:

1. Bedload sediment transport
2. Sediment gradation along the navigation channel
3. Bed geometry

10.3.1 Bedload Sediment Transport

Bedload is the sediment that is transported along the bed by rolling, saltation (small discrete jumps), and sliding. A characteristic difference between bedload and suspended load is that the bedload remains almost entirely within a thin layer along the surface of the bed. No data exists for the bedload as a function of flowrate for the Sao
Francisco River within the model domain. This is a typical situation for many alluvial rivers, as bed load is a very difficult and expensive parameter to collect.

However, many studies have investigated the relationship between the bedload and the suspended load, or the bedload as a function of the total load. Maddock & Borland (1950) generally classifies the percentage of bedload as a function of the suspended sediment concentration and the riverbed material (see Table 31). By applying the known suspended load characteristics to Table 31, an estimate can be made regarding the percentage of bedload as a fraction of the suspended load. For example, the average concentration of the suspended load from the 102 samples collected from ANA at the Morpara sediment gage is 128 mg/L. Combined with the sandy nature of the riverbed at this location, the Maddock table estimates a large range associated with the bedload fraction (from 25% to 150% of the suspended load). An initial estimate of 50% of the suspended load was applied to the sediment transport model (for example, when the suspended load is 10,000 tonnes per day, the bedload is assumed to be 5,000 tonnes per day). However, several scenarios were compared to determine the impact of adjusting the bedload fraction in the sensitivity analysis (see Table 32). For all scenarios the loads for each sand fraction were evenly distributed across all sand categories of very fine sand, fine sand, medium sand, coarse sand, and very coarse sand (see Table 32).

In a previous study (CODEVASF-USACE, 2013b) a sensitivity analysis was performed on the 6-year simulation for the Sambaiba Island project. This project consisted of a model of the Campo de Provas and Sambaiba Island site, which is a representative reach of the Sao Francisco River navigation channel. The Campo de Provas reach was selected to perform the sensitivity analysis in order to analyze the
results within a site specific reach. The Campo de Provas and Sambaiba Island project has a zero station (0+000) at the navigation channel station 1106+500. The results of the previous sensitivity analysis for the bedload fraction are shown in Figure 210.

**Table 31: Maddock's Classification of Estimating the Bedload Fraction**

<table>
<thead>
<tr>
<th>Suspended sediment concentration mg/L</th>
<th>River bed material</th>
<th>Bedload discharge expressed as % of suspended sediment discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 1000</td>
<td>sand</td>
<td>25-150</td>
</tr>
<tr>
<td>less than 1000</td>
<td>gravel, rocks, hard clay</td>
<td>5-12</td>
</tr>
<tr>
<td>1000 - 7500</td>
<td>sand</td>
<td>10-35</td>
</tr>
<tr>
<td>1000 - 7500</td>
<td>gravel, rocks, hard clay</td>
<td>5-12</td>
</tr>
<tr>
<td>more than 7500</td>
<td>sand</td>
<td>5-15</td>
</tr>
<tr>
<td>more than 7500</td>
<td>gravel, rocks, hard clay</td>
<td>2-8</td>
</tr>
<tr>
<td>Scenario</td>
<td>Flow, cms</td>
<td>Total Load, tonnes/day</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-----------</td>
<td>------------------------</td>
</tr>
<tr>
<td><strong>Suspended Load Only</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>1537</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>3427</td>
<td>100</td>
</tr>
<tr>
<td>1500</td>
<td>8524</td>
<td>100</td>
</tr>
<tr>
<td>3000</td>
<td>40478</td>
<td>100</td>
</tr>
<tr>
<td>6000</td>
<td>192215</td>
<td>100</td>
</tr>
<tr>
<td>10000</td>
<td>605887</td>
<td>100</td>
</tr>
<tr>
<td><strong>Bedload = 10% of Suspended Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>1691</td>
<td>90.9</td>
</tr>
<tr>
<td>1000</td>
<td>3770</td>
<td>90.9</td>
</tr>
<tr>
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<td>9377</td>
<td>90.9</td>
</tr>
<tr>
<td>3000</td>
<td>44526</td>
<td>90.9</td>
</tr>
<tr>
<td>6000</td>
<td>211436</td>
<td>90.9</td>
</tr>
<tr>
<td>10000</td>
<td>666476</td>
<td>90.9</td>
</tr>
<tr>
<td><strong>Bedload = 25% of Suspended Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>1922</td>
<td>80</td>
</tr>
<tr>
<td>1000</td>
<td>4284</td>
<td>80</td>
</tr>
<tr>
<td>1500</td>
<td>10655</td>
<td>80</td>
</tr>
<tr>
<td>3000</td>
<td>50598</td>
<td>80</td>
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<tr>
<td>6000</td>
<td>240268</td>
<td>80</td>
</tr>
<tr>
<td>10000</td>
<td>757359</td>
<td>80</td>
</tr>
<tr>
<td><strong>Bedload = 50% of Suspended Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>2306</td>
<td>66.7</td>
</tr>
<tr>
<td>1000</td>
<td>5140</td>
<td>66.7</td>
</tr>
<tr>
<td>1500</td>
<td>12786</td>
<td>66.7</td>
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<tr>
<td>3000</td>
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<td>66.7</td>
</tr>
<tr>
<td>10000</td>
<td>908831</td>
<td>66.7</td>
</tr>
<tr>
<td><strong>Bedload = 100% of Suspended Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>3075</td>
<td>50</td>
</tr>
<tr>
<td>1000</td>
<td>6854</td>
<td>50</td>
</tr>
<tr>
<td>1500</td>
<td>17049</td>
<td>50</td>
</tr>
<tr>
<td>3000</td>
<td>80956</td>
<td>50</td>
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<tr>
<td>6000</td>
<td>384429</td>
<td>50</td>
</tr>
<tr>
<td>10000</td>
<td>121774</td>
<td>50</td>
</tr>
<tr>
<td><strong>Bedload = 150% of Suspended Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>3843</td>
<td>40</td>
</tr>
<tr>
<td>1000</td>
<td>8567</td>
<td>40</td>
</tr>
<tr>
<td>1500</td>
<td>21311</td>
<td>40</td>
</tr>
<tr>
<td>3000</td>
<td>101915</td>
<td>40</td>
</tr>
<tr>
<td>6000</td>
<td>480537</td>
<td>40</td>
</tr>
<tr>
<td>10000</td>
<td>1514718</td>
<td>40</td>
</tr>
</tbody>
</table>
Figure 210: Model Sensitivity to Bedload over 6-Year Sediment Transport Simulation
The sensitivity analysis of the bedload shows that after the 6-year sediment transport simulation the amount of bedload only impacts the elevation of the bed within the upper 1 kilometer of the upstream boundary (see Figure 211). The model is simulating excess sedimentation in the upper cross sections when too much bedload is supplied, and simulating excess erosion in the upper cross sections when too little bedload is supplied within the first kilometer downstream of the upper boundary. The model solutions converge approximately 1 km downstream of the upper boundary. Therefore, the initial bedload fraction is not a sensitive Parameter in the model. This general conclusion was applied to the overall Sao Francisco River navigation channel model as well.

Figure 211: 6-year Simulated Bed under Various Bedload Conditions
10.3.2 Sediment Gradation

The sediment gradation of the river bed is another variable that is under-sampled within the Sao Francisco River navigation channel boundary. It is recommended that additional bed gradation samples be collected prior to any designs beyond a conceptual level to verify the bed gradation used in the sediment transport model.

The gradation associated with a sample collected by FUNDESPA (2005) was used in the validated sediment transport model as the bed gradation throughout the length of the navigation channel. A sensitivity analysis varied the bed gradation under three scenarios:

1. All Bed Gradations are \( \frac{1}{4} \) of the size of the FUNDESPA sample

2. All Bed Gradations are 2 times the size of the FUNDESPA sample

3. All Bed Gradations are 4 times the size of the FUNDESPA sample

The bed gradations supplied to the model for the sensitivity analysis are shown in Table 33.

<table>
<thead>
<tr>
<th>Particle Size, diam (mm)</th>
<th>FUNDESPA Sample % Finer</th>
<th>( \frac{1}{4} ) x FUNDESPA % Finer</th>
<th>2 x FUNDESPA % Finer</th>
<th>4 x FUNDESPA % Finer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0625</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.125</td>
<td>0</td>
<td>4.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.25</td>
<td>0</td>
<td>48.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>4.2</td>
<td>98.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>48.8</td>
<td>100</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>98.3</td>
<td>100</td>
<td>48.8</td>
<td>4.2</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>100</td>
<td>98.3</td>
<td>48.8</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>98.3</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

The results of the sensitivity analysis are shown in Figure 212.
Within the representative site (selected as a site called Campo de Provas near Barra, Bahia) boundary, when the bed is assumed to be \( \frac{1}{4} \) the size of the FUNDESPA sample, there is little change to the overall results (in some cross sections there is slightly more erosion of the bed when compared with the calibrated model). When the bed gradation is 4 times as large as the FUNDESPA sample, the simulated bed does not change from the initial conditions. There is very little sedimentation, and even less erosion due to the large particles making up the bed. At 2 times the size of the FUNDESPA sample there is a moderate decrease in the amount of erosion when compared with the calibration simulation, but this decrease is not as pronounced as the nearly un-erodible bed that results when the samples are 4 times the size as the FUNDESPA sample. Since the model calibrates well using the FUNDESPA sample, this sample is used throughout the final calibrated model.

Although calibration was achieved using the FUNDESPA sample, the uncertainty associated with the bed gradation at any given location is very high. The model also showed that the bed gradation is a sensitive factor in the overall outcome of the model. Therefore, it is recommended that new bed gradations in the navigation channel within the model boundary be collected, especially within any site where a proposed basic or executive design is proposed. It is recommended that the sediment transport model be updated with revised bed sediment gradation data and the output reanalyzed for the effectiveness of the proposed conceptual designs.
Figure 212: 6-year Simulated Bed under Various Bed Gradation Conditions
10.3.3 Bed Geometry

The initial bed geometry was also varied to determine the sensitivity of the model results to varying bed elevations. A section of the river within the representative Campo de Provas site was adjusted vertically up 0.5 meters and down 0.5 meters to determine the impacts to the simulation results. No other cross sections were adjusted for this sensitivity analysis. The results of the 6-year simulation for all three scenarios are shown in Table 34 and Figure 213.

<table>
<thead>
<tr>
<th>Campo de Provas Model Station</th>
<th>Initial Conditions, m</th>
<th>Calibrated Model, m</th>
<th>Simulated bed with initial conditions 0.5 m higher</th>
<th>Simulated bed with initial conditions 0.5 m lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>2496.146</td>
<td>393.84</td>
<td>393.51</td>
<td>393.53</td>
<td>393.46</td>
</tr>
<tr>
<td>2457.7</td>
<td>394.08</td>
<td>393.83</td>
<td>393.80</td>
<td>393.85</td>
</tr>
<tr>
<td>2419.26</td>
<td>394.32</td>
<td>394.08</td>
<td>394.12</td>
<td>394.01</td>
</tr>
<tr>
<td>2380.83</td>
<td>394.56</td>
<td>394.33</td>
<td>394.30</td>
<td>394.35</td>
</tr>
<tr>
<td>2342.392</td>
<td>394.80</td>
<td>394.56</td>
<td>394.60</td>
<td>394.48</td>
</tr>
<tr>
<td>2303.31</td>
<td>394.54</td>
<td>394.21</td>
<td>394.19</td>
<td>394.23</td>
</tr>
<tr>
<td>2264.23</td>
<td>394.28</td>
<td>393.93</td>
<td>393.98</td>
<td>393.84</td>
</tr>
<tr>
<td>2225.15</td>
<td>394.02</td>
<td>393.56</td>
<td>393.53</td>
<td>393.56</td>
</tr>
<tr>
<td>2186.073</td>
<td>393.76</td>
<td>393.36</td>
<td>393.43</td>
<td>393.28</td>
</tr>
</tbody>
</table>

The final bed elevations for each of the three 6-year simulations are similar. Many of the cross sections in this shallow section of the Rio Sao Francisco are within 0.05 meters of each other and all are within 0.15 meters, despite having a range of initial condition elevation of 1 meter. This shows that in the shallow section that the results converge temporarily within the period of simulation and the modeled deposition/erosion dynamics control the results, not the initial conditions.

However, the cross sections that were raised 0.5 meters lead to additional sediment erosion in the model, which deposit in cross sections downstream. Also the
simulation where cross sections were lowered 0.5 meters leads to lower bed elevations downstream (because less sediment is available to deposit downstream). Therefore, although the bed solutions converge within the area that was adjusted, the elevation of the bed downstream is significantly sensitive to the geometry (see Figure 213).

Since the model is sensitive to the bed elevations for the initial conditions, it is recommended that a new bathymetry of the Sao Francisco River is collected from bank to bank (not just the navigation channel). The resurvey shall consist of both a bathymetry of the channel bed from bank to bank and shall meet USACE minimum accuracy standards defined in Table 3-1 of *EM 1110-2-1003 (Hydrographic Surveying)*, USACE (2004).

**Figure 213: Sensitivity of Sediment Transport Model to Initial Bed Elevation**

![Figure 213](image)
10.3.4 Sensitivity Analysis and Uncertainty Conclusions

Other Parameters used in the navigation channel model were also analyzed for their sensitivity or uncertainty. For example, the temperature of the water column (a Parameter used in the settling velocity of sediment) was adjusted under a range of conditions, which yielded limited changes to model results. Similar negligible changes to the model output occurred when altering numerous other Parameters (such as settling depth concentration, time steps, among others). Other Parameters are moderately sensitive to the model results but have a higher degree of certainty (such as expansion and contraction coefficients) and these were not altered in the sensitivity analysis because the confidence of the selected numeric values are relatively high. It is recognized that there is a high degree of uncertainty in the geometry and sediment gradation information, which are expected to be two of the most sensitive Parameters in the model. Therefore, the model is limited in its application to predict scouring depths or depositional rates without a higher resolution bathymetry and sediment samples throughout the boundary of the model.

The model is a course model that was designed to be used for planning purposes only, and not specific engineering design at a site-specific scale. The validation of the model has a relatively high degree of uncertainty since the model was not calibrated to two known bathymetry surveys. Instead the behavior of the model was validated based on an expected range of approximately (+/-) 1 meter of change (erosion or deposition) throughout the simulation that was modeled. This validation approach results in a similar scale of uncertainty with the model results. Therefore, the model is not intended to predict the final elevation of the bed with a high degree of certainty, but instead is used
for a comparative analysis of how the river is likely to generally respond under the alternatives being analyzed (self-scouring structures and dredging). Sections CHAPTER 11.0 and CHAPTER 12.0 discuss the two main alternatives analyzed in the model.
CHAPTER 11.0 SELF-SCOURING STRUCTURES ALTERNATIVE

Self-scouring structures have been used in rivers in the United States in order to maintain navigation channels and reduce the need for dredging. A common design includes the use of spur dikes made of rock to reduce the effective width of the river, and promote a scouring effect along the bed of the river, due to the focusing of shear stresses on a narrower section.

The length of the spur dike structures is determined by the required reduction of the river width in order to achieve the self-scour through a critical section. This is determined from geomorphologic studies or from modeling. In this project, a combination of using a geomorphological approach as well as sediment transport modeling was used to determine the required river widths. After the length of a required spur dike is found, the distance between spur dikes can be determined using a variety of guidance from USACE (USACE, 1980) as well as other guidance (Julien, 2002). Some approaches determine the distance between structures using a combination of some or all of the following variables: spur dike length, angle, permeability, and degree of curvature of the river. In general, reducing the spacing results in a reduction of the scour at the spur tip and stabilizes the thalweg farther away from the concave bank (Julien, 2002). Specific approaches found to be effective to determine the length between structures include:

1. Rule of thumb of 3-5 times the spur dike length

2. 1-1/2 to 2-1/2 times the length of the upstream structure (when structures are about 300 meters)
3. 2 to 2-1/2 times the structure length (based on USACE experience on the Missouri River)

4. Spacing (S) is a function of the length (L), the length to channel width ratio (L/W) and the channel radius of curvature to channel width ratio (R/W) using the following equations:
   a.  \( S = 1.5 \ (L) \ (R/W)^{0.8} \ (L/W)^{0.3} \)
   b.  \( S = (4 \text{ to } 5) \ (L) \)
   c.  \( S_{\text{max}} = R(1-(1-L/R)^2)^{0.5} \)

5. Assuming the flow expands at a ratio of 5 to 1 in the longitudinal direction, with the next downstream structure being placed just upstream of the intersection of the flow expansion and the bank. This was used on the Missouri River in some cases and creates a dike spacing of almost 5 times the structure length on straight sections of river.

The width of the Missouri River and the required length of self-scouring structures have similar scales as the Sao Francisco River. The sandy morphology of the Missouri River is another important similarity between the two systems. The guidance of using 2 times the spur dike length that has been applied to the Missouri River will also be applied to the conceptual layout of self-scouring structures required to improve navigation in the 60 noted critical sites (as well as other unnamed shoals). This is a conservative distance between structures due to the very straight nature of the Sao Francisco River through the majority of the navigation channel. Therefore, although longer distances between structures may be applicable (especially for straight sections) an
initial distance between structures will be calculated as 2 times the spur dike length. This is the spacing used in the modeling as well as the basis for estimating costs of the structures. The first upstream dike was placed upstream of the beginning of the shoal (typically a distance equivalent to the structure length) and the downstream structure was placed a minimum of a structure length downstream of the end of the shoal.

Figure 214: Example Self-Scouring Channels Constructed on Missouri River

To test the feasibility and estimate quantities of (primarily) spur dike structures to achieve the self-scouring channel depths the following steps were performed:

1. Determine necessary stable width of channel based on morphology equilibrium of the reach.

2. Determine average channel width at the project site.

3. Determine length of spur dike field to achieve stable self-scouring channel based on the necessary stable width found in Step 1.
4. Determine distance between structures (2 times the structure length)

5. Determine number of structures to fully address the shoaled area.

6. Test the conceptual design using the sediment transport model.

The following assumptions were applied to develop the conceptual design of the self-scouring structure spur dike fields at each site:

1. The length of the spur dike field is a function of the local morphology of the larger reach. The minimum width where shoals less than 2 meters deep occur was determined (excluding any outliers). Where shoals are present, this minimum width was applied.

2. A minimum of 3 structures was applied to address any specific shoal.

3. Distances between spur dike fields was set to 2 times the spur dike length. This value was used for the general coarse layout of the structures, although during basic designs, distances will be based on site-specific conditions.

HEC-GeoRAS was used to input all of the structures into the HEC-RAS model. Blocked obstructions were digitized around the footprint of all proposed dike field areas, and ineffective flow areas were digitized on the backside of any island cutoffs. A TIN was developed at an elevation equivalent to the tops of the islands, such that the dike fields or island cut-offs would be over-topped when the water surface elevation is greater than the elevation of the island. Figure 215 shows an example of the dike fields and ineffective flow areas that were added to a typical site in HEC-GeoRAS.
Figure 215: Example Dike Fields and Ineffective Flow Areas in HEC-GeoRAS
11.1 Reach One Conceptual Structures

Reach One consists of the navigation channel between the AHSFRA Harbor at Pirapora (km 1982) to the confluence of the Rio das Velhas (km 1958) or 24 kilometers according to AHSFRA. The sediment transport model of this reach includes 79 cross sections from stationing 2,033,821m (upstream) to 2,008,821m (downstream), or 25 HEC-RAS model kilometers along the thalweg.

From Section 8.2 a total of 10 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach One. The average width of the channel from bank to bank associated with these 10 shoal locations is 316.8 meters. The minimum width of the shoaled section through this reach is 241.6 meters. The design width selected for this reach is approximately 10% less than the minimum channel width. A 10% reduction (based on the minimum width of river in a shoaled location) was chosen in order to ensure that there is a reduction in channel width at the shoal in the narrowest section of the river. The modeling verified that the 10% reduction is a valid assumption for this reach. Therefore, the design width of 220 meters was selected for Reach One.

Table 35 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach One. The design width was subtracted from the channel width in order to determine the length of each spur dike structure. However, a minimum structure length of 50 meters was applied to all locations. The distance between structures was then calculated by multiplying the structure length by 2. The number of structures was calculated based on the distance between structures and the total length of the shoal to ensure that the dike field covers the entire length of the shoal. The estimated structure length was then calculated by multiplying the required structure
length by the number of structures. This is the conceptual length required for a dike field only. However, at each shoal location, it was investigated to determine if another structure such as an island cut-off or longitudinal dike would reduce the total structure length. In locations where other structures were used in the layout a “Final Concept Length” was determined. This calculation process applies for all of the reaches.

An estimated total of 42 structures are necessary to address the 10 shoals in Reach One with a total estimated length of 3,808 meters.

Table 35: Reach One Required Structures for Self-Scour

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Franave</td>
<td>220</td>
<td>250.6</td>
<td>232</td>
<td>50</td>
<td>100</td>
<td>4</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Franave</td>
<td>220</td>
<td>299.7</td>
<td>198</td>
<td>79.7</td>
<td>159.4</td>
<td>3</td>
<td>239.1</td>
<td>239.1</td>
</tr>
<tr>
<td>3</td>
<td>Franave</td>
<td>220</td>
<td>342.6</td>
<td>527</td>
<td>122.6</td>
<td>245.2</td>
<td>4</td>
<td>490.4</td>
<td>490.4</td>
</tr>
<tr>
<td>4</td>
<td>Banco da Raquel</td>
<td>220</td>
<td>297.4</td>
<td>605</td>
<td>77.4</td>
<td>154.8</td>
<td>6</td>
<td>464.4</td>
<td>464.4</td>
</tr>
<tr>
<td>5</td>
<td>Banco da Raquel</td>
<td>220</td>
<td>318.4</td>
<td>154</td>
<td>98.4</td>
<td>196.8</td>
<td>3</td>
<td>295.2</td>
<td>295.2</td>
</tr>
<tr>
<td>6</td>
<td>Banco da Raquel</td>
<td>220</td>
<td>244.4</td>
<td>365</td>
<td>50</td>
<td>100</td>
<td>6</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>Paco Paco</td>
<td>220</td>
<td>324.2</td>
<td>444</td>
<td>104.2</td>
<td>208.4</td>
<td>4</td>
<td>416.8</td>
<td>416.8</td>
</tr>
<tr>
<td>8</td>
<td>Paco Paco</td>
<td>220</td>
<td>430.6</td>
<td>699</td>
<td>210.6</td>
<td>421.2</td>
<td>3</td>
<td>631.8</td>
<td>370</td>
</tr>
<tr>
<td>9</td>
<td>Paco Paco</td>
<td>220</td>
<td>359.3</td>
<td>825</td>
<td>139.3</td>
<td>278.6</td>
<td>5</td>
<td>696.5</td>
<td>696.5</td>
</tr>
<tr>
<td>10</td>
<td>Paco Paco</td>
<td>220</td>
<td>304</td>
<td>338</td>
<td>84</td>
<td>168</td>
<td>4</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td></td>
<td><strong>TOTAL</strong></td>
<td><strong>42</strong></td>
<td><strong>4070.2</strong></td>
<td><strong>3808.4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These 10 sites were added to the sediment transport model. An example of the structures added to the model is shown in Figure 216. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.
Figure 216: Example Conceptual Structures in Reach One (Shoals 9 and 10)
11.2 Reach Two Conceptual Structures

Reach Two consists of the navigation channel between the confluence of the Rio das Velhas (km 1958) and the confluence of the Rio Jequitai (km 1938) or 20 kilometers according to AHSFRA. The sediment transport model of this reach includes 60 cross sections from stationing 2,008,321m (upstream) to 1,985,321m (downstream), or 23 HEC-RAS model kilometers along the thalweg.

From Section 8.3 a total of 4 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Two. The average width of the channel from bank to bank associated with these 4 shoal locations is 445 meters. The minimum width of the shoaled section through this reach is 415.9 meters. Due to the shortness of the reach, the design width was combined with the statistics of the morphology of Reach Three (which had a minimum width of channel at a shoal of 403.1). The design width selected for this reach was 333 meters (or approximately 17.5% less than the minimum channel width). The reduction of 17.5% was used because this value was determined to be effective to maintain a self-scouring channel in the sediment transport model (a value of 10% did not achieve the results).

Table 36 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Two. An estimated total of 22 structures are necessary to address the 4 shoals in Reach Two with a total estimated length of 2,302 meters.
Table 36: Reach Two Required Structures for Self-Scour

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Cascalho Vermelho</td>
<td>333</td>
<td>475.7</td>
<td>854</td>
<td>142.7</td>
<td>285.4</td>
<td>5</td>
<td>713.5</td>
<td>713.5</td>
</tr>
<tr>
<td>12</td>
<td>Cascalho Vermelho</td>
<td>333</td>
<td>471.9</td>
<td>309</td>
<td>138.9</td>
<td>277.8</td>
<td>3</td>
<td>416.7</td>
<td>416.7</td>
</tr>
<tr>
<td>13</td>
<td>Baixo da Porcas</td>
<td>333</td>
<td>418.1</td>
<td>438</td>
<td>85.1</td>
<td>170.2</td>
<td>5</td>
<td>425.5</td>
<td>425.5</td>
</tr>
<tr>
<td>14</td>
<td>Baixo da Porcas</td>
<td>333</td>
<td>415.9</td>
<td>1110</td>
<td>82.9</td>
<td>165.8</td>
<td>9</td>
<td>746.1</td>
<td>746.1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>22</strong></td>
<td><strong>2301.8</strong></td>
<td><strong>2301.8</strong></td>
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</tr>
</tbody>
</table>

These 4 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.

11.3 Reach Three Conceptual Structures

Reach Three consists of the navigation channel between the confluence of the Rio Jequitai (km 1938) and the confluence of the Rio Paracatu (km 1868) or 70 kilometers according to AHSFRA. The sediment transport model of this reach includes 249 cross sections from stationing 1,985,321m (upstream) to 1,909,821m (downstream), or 75.5 HEC-RAS model kilometers along the thalweg.

From Section 8.4 a total of 17 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Three. The average width of the channel from bank to bank associated with these 17 shoal locations is 468.7 meters. The minimum width of the shoaled section through this reach is 403.1 meters. The design width selected for this reach was 333 meters (or approximately 17.5% less than the minimum channel width). The reduction of 17.5% was used because this value was determined to be effective to maintain a self-scouring channel in the sediment transport model (a value of 10% did not achieve the results).
Table 37 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Three. An estimated total of 121 structures are necessary to address the 17 shoals in Reach Three with a total estimated length of 14,061 meters.

Table 37: Reach Three Required Structures for Self-Scour

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
</tr>
</thead>
<tbody>
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<td>644</td>
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<td>238.8</td>
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<tr>
<td>16</td>
<td>Coroa da Ema</td>
<td>333</td>
<td>496.2</td>
<td>1388</td>
<td>163.2</td>
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<td>979.2</td>
<td>721</td>
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<tr>
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<td>529.7</td>
<td>493</td>
<td>196.7</td>
<td>393.4</td>
<td>3</td>
<td>590.1</td>
<td>475</td>
</tr>
<tr>
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<td>Volta do Sobrado</td>
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<td>2321</td>
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<td>18</td>
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<td>1346.4</td>
</tr>
<tr>
<td>19</td>
<td>Vaixio do Ibiai</td>
<td>333</td>
<td>493</td>
<td>1566</td>
<td>160</td>
<td>320</td>
<td>7</td>
<td>1120</td>
<td>1120</td>
</tr>
<tr>
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<td>Vaixio do Ibiai</td>
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<td>139.8</td>
<td>279.6</td>
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<tr>
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<td>Canabrava</td>
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<td>502</td>
<td>208.1</td>
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<td>Baixio da Crioulas</td>
<td>333</td>
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<td>218.4</td>
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<td>Baixio da Crioulas</td>
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<td>16</td>
<td>1312</td>
<td>1312</td>
</tr>
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<td>923</td>
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<td>1300</td>
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</tbody>
</table>

TOTAL: 121 14822.8 14061

These 17 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.
11.4  Reach Four Conceptual Structures

Reach Four consists of the navigation channel between the confluence of the Rio Paracatu (km 1868) and the confluence of the Rio Urucuia (km 1810) or 58 kilometers according to AHSFRA. The sediment transport model of this reach includes 174 cross sections from stationing 1,909,821m (upstream) to 1,848,821m (downstream), or 61.5 HEC-RAS model kilometers along the thalweg.

From Section 8.5 a total of 15 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Four. The average width of the channel from bank to bank associated with these 15 shoal locations is 578.3 meters. The minimum width of the shoaled section through this reach is 493.8 meters. The design width selected for this reach was 395 meters (or approximately 20% less than the minimum channel width). The reduction of 20% was used because this value was determined to be effective to maintain a self-scouring channel in the sediment transport model (a value of 10% did not achieve the results).

Table 38 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Four. An estimated total of 71 structures are necessary to address the 15 shoals in Reach Four with a total estimated length of 8,809 meters.
Table 38: Reach Four Required Structures for Self-Scour

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
</tr>
</thead>
<tbody>
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<td>143.5</td>
<td>287</td>
<td>4</td>
<td>574</td>
<td>574</td>
</tr>
<tr>
<td>33</td>
<td>Coroa Branca</td>
<td>395</td>
<td>498.4</td>
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<td>103.4</td>
<td>206.8</td>
<td>3</td>
<td>310.2</td>
<td>310.2</td>
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<tr>
<td>34</td>
<td>Barreira da Martinha</td>
<td>395</td>
<td>619.2</td>
<td>1519</td>
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<td>11</td>
<td>926.2</td>
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<tr>
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<td>Barreira da Martinha</td>
<td>395</td>
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<td>377</td>
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<tr>
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<td>395.2</td>
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<td>641.4</td>
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<tr>
<td>38</td>
<td>Varginha</td>
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<td>50</td>
<td>100</td>
<td>11</td>
<td>550</td>
<td>443</td>
</tr>
<tr>
<td>39</td>
<td>Barra Dos Valadares</td>
<td>395</td>
<td>663</td>
<td>602</td>
<td>268</td>
<td>536</td>
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<td>804</td>
<td>536</td>
</tr>
<tr>
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<td>Barra Dos Valadares</td>
<td>395</td>
<td>566.5</td>
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<td>833.5</td>
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</tr>
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<tr>
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<td>624.5</td>
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<td>312.6</td>
<td>312.6</td>
</tr>
<tr>
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<td>Agricio</td>
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<td>223.3</td>
<td>446.6</td>
<td>4</td>
<td>893.2</td>
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</tr>
<tr>
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<td>Agricio</td>
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</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>71</strong></td>
<td><strong>10009</strong></td>
<td><strong>8809</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These 15 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.

11.5 Reach Five Conceptual Structures

Reach Five consists of the navigation channel between the confluence of the Rio Urucuia (km 1810) and the confluence of the Rio Verde Grande (km 1572) or 238 kilometers according to AHSFRA. The sediment transport model of this reach includes 658 cross sections from stationing 1,848,321m (upstream) to 1,593,821m (downstream), or 254.5 HEC-RAS model kilometers along the thalweg.

From Section 8.6 a total of 41 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Five. The average width of the channel from bank to bank associated with these 41 shoal locations is 696.3 meters. The minimum
The width of the shoaled section through this reach is 537.6 meters. The design width selected for this reach was 450 meters (or approximately 16% less than the minimum channel width). The reduction of 16% was used because this value was determined to be effective to maintain a self-scouring channel in the sediment transport model (a value of 10% did not achieve the results).

Table 39 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Five. An estimated total of 167 structures are necessary to address the 41 shoals in Reach Five with a total estimated length of 30,453 meters.

These 41 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.
### Table 39: Reach Five Required Structures for Self-Scour

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
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</thead>
<tbody>
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<td>702.2</td>
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<td>835.2</td>
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**Total** 167 36455.6 30453.4
11.6 Reach Six Conceptual Structures

Reach Six consists of the navigation channel between the confluence of the Rio Verde Grande (km 1572) and the confluence of the Rio Carinhanha (km 11545) or 27 kilometers according to AHSFRA. The sediment transport model of this reach includes 66 cross sections from stationing 1,593,821m (upstream) to 1,565,821 (downstream), or 28 HEC-RAS model kilometers along the thalweg.

A total of 3 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Six. The minimum width of the 3 shoals reach is 668 meters. The design width selected for this reach was 550 meters (or approximately 17.5% less than the minimum channel width). The reduction of 17.5% was used because this value was determined to be effective to maintain a self-scouring channel in the sediment transport model (a value of 10% did not achieve the results).

Table 40 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Six. An estimated total of 12 structures are necessary to address the 4 shoals in Reach Six with a total estimated length of 1,766 meters.

Table 40: Reach Six Required Structures for Self-Scour

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
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<td>668</td>
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<td>708</td>
<td>708</td>
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</table>
These 4 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.

11.7 Reach Seven Conceptual Structures

Reach Seven consists of the navigation channel between the confluence of the Rio Carinhanha (km 1545) and the confluence of the Rio Corrente (km 1395) or 150 kilometers according to AHSFRA. The sediment transport model of this reach includes 366 cross sections from stationing 1,565,821 m (upstream) to 1,406,754 (downstream), or 159 HEC-RAS model kilometers along the thalweg.

From Section 8.8 a total of 20 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Seven. The average width of the channel from bank to bank associated with these 21 shoal locations is 812.6 meters. The minimum width of the shoaled section through this reach is 611.4 meters. The design width selected for this reach was 550 meters (or approximately 10% less than the minimum channel width).

Table 41 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Seven. An estimated total of 87 structures are necessary to address the 20 shoals in Reach Seven with a total estimated length of 14,583 meters.
Table 41: Reach Seven Required Structures for Self-Scour

<table>
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<tr>
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<th>Design Width, m</th>
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<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures</th>
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<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
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<td>885</td>
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These 20 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.

11.8 Reach Eight Conceptual Structures

Reach Eight consists of the navigation channel between the confluence of the Rio Corrente (km 1395) and the confluence of the Rio Grande (km 1123) or 272 kilometers according to AHSFRA. The sediment transport model of this reach includes 366 cross sections from stationing 1,406,754m (upstream) to 1,126,536 (downstream), or 280.2 HEC-RAS model kilometers along the thalweg.

A total of 30 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Eight. The average width of the channel from bank to bank
associated with these 30 shoal locations is 778 meters. The minimum width of the shoaled section through this reach is 603.4 meters. The design width selected for this reach was 550 meters (or approximately 10% less than the minimum channel width).

Table 42 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Eight. An estimated total of 108 structures are necessary to address the 30 shoals in Reach Eight with a total estimated length of 18,844 meters.

These 30 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.
Table 42: Reach Eight Required Structures for Self-Scour

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<th>Shoal Site</th>
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<td>405.6</td>
<td>3</td>
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<tr>
<td>123  Ilha de Paratinga</td>
<td>550</td>
<td>760.8</td>
<td>377</td>
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<td>421.6</td>
<td>3</td>
<td>632.4</td>
<td>709</td>
</tr>
<tr>
<td>124  Ilha de Paratinga</td>
<td>550</td>
<td>615.9</td>
<td>307</td>
<td>65.9</td>
<td>131.8</td>
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<td>263.6</td>
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</tr>
<tr>
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<td>831.7</td>
<td>597</td>
<td>281.7</td>
<td>563.4</td>
<td>3</td>
<td>845.1</td>
<td>845.1</td>
</tr>
<tr>
<td>126  Unnamed</td>
<td>550</td>
<td>852.2</td>
<td>347</td>
<td>302.2</td>
<td>604.4</td>
<td>3</td>
<td>906.6</td>
<td>906.6</td>
</tr>
<tr>
<td>127  Unnamed</td>
<td>550</td>
<td>853.3</td>
<td>323</td>
<td>303.3</td>
<td>606.6</td>
<td>3</td>
<td>909.9</td>
<td>606.6</td>
</tr>
<tr>
<td>128  Quebra Linha</td>
<td>550</td>
<td>852.8</td>
<td>674</td>
<td>302.8</td>
<td>605.6</td>
<td>3</td>
<td>908.4</td>
<td>621</td>
</tr>
<tr>
<td>129  Quebra Linha</td>
<td>550</td>
<td>776.3</td>
<td>357</td>
<td>226.3</td>
<td>452.6</td>
<td>3</td>
<td>678.9</td>
<td>678.9</td>
</tr>
<tr>
<td>130  Quebra Linha</td>
<td>550</td>
<td>785.7</td>
<td>2462</td>
<td>235.7</td>
<td>471.4</td>
<td>7</td>
<td>1469.9</td>
<td>1414.2</td>
</tr>
<tr>
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<td>756.6</td>
<td>197</td>
<td>206.6</td>
<td>413.2</td>
<td>3</td>
<td>619.8</td>
<td>523</td>
</tr>
<tr>
<td>132  Cabeça Levantada</td>
<td>550</td>
<td>783.8</td>
<td>816</td>
<td>233.8</td>
<td>467.6</td>
<td>4</td>
<td>935.2</td>
<td>701.4</td>
</tr>
<tr>
<td>133  Cabeça Levantada</td>
<td>550</td>
<td>745.8</td>
<td>258</td>
<td>195.8</td>
<td>391.6</td>
<td>3</td>
<td>587.4</td>
<td>587.4</td>
</tr>
<tr>
<td>134  Meleiro</td>
<td>550</td>
<td>821.7</td>
<td>1235</td>
<td>271.7</td>
<td>543.4</td>
<td>4</td>
<td>1086.8</td>
<td>986.1</td>
</tr>
<tr>
<td>135  Meleiro</td>
<td>550</td>
<td>884.4</td>
<td>660</td>
<td>334.4</td>
<td>668.8</td>
<td>3</td>
<td>1003.2</td>
<td>1003.2</td>
</tr>
<tr>
<td>136  Igarité</td>
<td>550</td>
<td>849.7</td>
<td>312</td>
<td>299.7</td>
<td>599.4</td>
<td>3</td>
<td>899.1</td>
<td>599.4</td>
</tr>
<tr>
<td>137  Torrinha</td>
<td>550</td>
<td>613.8</td>
<td>494</td>
<td>63.8</td>
<td>127.6</td>
<td>6</td>
<td>382.8</td>
<td>382.8</td>
</tr>
<tr>
<td>138  Torrinha</td>
<td>550</td>
<td>657.6</td>
<td>439</td>
<td>107.6</td>
<td>215.2</td>
<td>4</td>
<td>430.4</td>
<td>310</td>
</tr>
<tr>
<td>139  Ilha de Itacoatiara</td>
<td>550</td>
<td>876.5</td>
<td>690</td>
<td>326.5</td>
<td>653</td>
<td>3</td>
<td>979.5</td>
<td>979.5</td>
</tr>
<tr>
<td>140  Ilha de Itacoatiara</td>
<td>550</td>
<td>668.4</td>
<td>282</td>
<td>18.4</td>
<td>236.8</td>
<td>3</td>
<td>355.2</td>
<td>355.2</td>
</tr>
<tr>
<td>141  Curralinho</td>
<td>550</td>
<td>996.5</td>
<td>497</td>
<td>446.5</td>
<td>893</td>
<td>3</td>
<td>1339.5</td>
<td>551</td>
</tr>
</tbody>
</table>

TOTAL 108 21461.5 18844
11.9 Reach Nine Conceptual Structures

Reach Nine consists of the navigation channel between the confluence of the Rio Grande (km 1123) to the delta at the Sobradinho Reservoir (km 967) or 156 kilometers according to AHSFRA. The sediment transport model of this reach includes 366 cross sections from stationing 1,126,536m (upstream) to 967,500m (downstream), or 159 HEC-RAS model kilometers along the thalweg.

From Section 8.10 a total of 8 locations were observed where the 2012 navigation channel is less than 2 meters deep in Reach Nine. The average width of the channel from bank to bank associated with these 30 shoal locations is 948.5 meters. The minimum width of the shoaled section through this reach is 789.8 meters. The design width selected for this reach was 700 meters (or approximately 10% less than the minimum channel width).

Table 43 provides a calculation of the required structure lengths in order to achieve a self-scouring channel in Reach Nine. An estimated total of 34 structures are necessary to address the 8 shoals in Reach Nine with a total estimated length of 5,439 meters.

<table>
<thead>
<tr>
<th>Shoal</th>
<th>Site</th>
<th>Design Width, m</th>
<th>Total Channel Width, m</th>
<th>Shoal Length, m</th>
<th>Individual Structure Length, m</th>
<th>Distance Between Structures, m</th>
<th>Number of Structures</th>
<th>Total Estimated Structure Length, m</th>
<th>Final Concept Length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>Unnamed</td>
<td>700</td>
<td>924.9</td>
<td>538</td>
<td>224.9</td>
<td>449.8</td>
<td>3</td>
<td>674.7</td>
<td>674.7</td>
</tr>
<tr>
<td>143</td>
<td>Goiabeira</td>
<td>700</td>
<td>898.2</td>
<td>570</td>
<td>196.2</td>
<td>396.4</td>
<td>4</td>
<td>792.8</td>
<td>673.2</td>
</tr>
<tr>
<td>144</td>
<td>Goiabeira</td>
<td>700</td>
<td>843.1</td>
<td>1178</td>
<td>143.1</td>
<td>286.2</td>
<td>6</td>
<td>858.6</td>
<td>715.5</td>
</tr>
<tr>
<td>145</td>
<td>Amarra Couro</td>
<td>700</td>
<td>789.8</td>
<td>520</td>
<td>89.8</td>
<td>179.6</td>
<td>5</td>
<td>449</td>
<td>449</td>
</tr>
<tr>
<td>146</td>
<td>Amarra Couro</td>
<td>700</td>
<td>998.7</td>
<td>583</td>
<td>96.7</td>
<td>193.4</td>
<td>5</td>
<td>483.5</td>
<td>483.5</td>
</tr>
<tr>
<td>147</td>
<td>Amarra Couro</td>
<td>700</td>
<td>864.4</td>
<td>365</td>
<td>164.4</td>
<td>328.8</td>
<td>3</td>
<td>493.2</td>
<td>493.2</td>
</tr>
<tr>
<td>148</td>
<td>Rodrigo</td>
<td>700</td>
<td>962.8</td>
<td>321</td>
<td>150</td>
<td>300</td>
<td>3</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>149</td>
<td>Rodrigo</td>
<td>700</td>
<td>1306.3</td>
<td>1575</td>
<td>300</td>
<td>600</td>
<td>5</td>
<td>1500</td>
<td>1500</td>
</tr>
</tbody>
</table>

**TOTAL 34** 5701.8 5439.1
These 8 sites were added to the sediment transport model. Attachment One includes Figures associated with each of the conceptual layouts required to maintain a self-scouring channel through these identified shoals.

11.10 Validation of Self-Scour Effectiveness – Sediment Transport Results

After the structures were input into the sediment transport model, the results of a 6-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 a few instances the self-scouring goal of 2.0 meters was not achieved, and the structures were revised slightly. After the revised structures (currently version shown in Attachment One) were added to the model, the channel was able to maintain a self-scour depth of at least 2.0 meters along the channel. The depths of the cross sections are plotted in Figure 121.
The sediment transport model, therefore, 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 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, as demonstrated in Figure 217. 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 (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.
11.11 **Self-Scouring Structure Costs Template**

As described in previous sections (11.1 through 11.9), a total length of structures was estimated for each reach. It is recommended that a cost engineer develop a detailed, reach specific estimate of costs associated with the proposed conceptual plans.

A CODEVASF cost engineer has provided a cost estimating template to assist in estimating costs for the proposed conceptual plans. The cost estimate template is based on the detailed cost estimate prepared for the Curralinho Project (CODEVASF-USACE, 2013a), and is shown below in Figure 218. The cost estimate template is shown in Figure 219.

**Figure 218: Cost Estimate Associated with Curralinho Project**

**ABSTRACT - Costs estimate for Curralinho Project**

1 - Total costs using rock transportation only BY ROAD

<table>
<thead>
<tr>
<th>Service</th>
<th>Percentage</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary Services</td>
<td>16.59%</td>
<td>R$ 6,179,610.93 in January 2013</td>
</tr>
<tr>
<td>Dike Construction</td>
<td>83.41%</td>
<td>R$ 8,828.02 per meter</td>
</tr>
</tbody>
</table>

Length of dike: 700 meter

2 - Total costs using rock transportation BY ROAD and BY WATERWAY

<table>
<thead>
<tr>
<th>Service</th>
<th>Percentage</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary Services</td>
<td>22.69%</td>
<td>R$ 3,854,716.05 in January 2013</td>
</tr>
<tr>
<td>Dike Construction</td>
<td>77.31%</td>
<td>R$ 5,506.74 per meter</td>
</tr>
</tbody>
</table>

Length of dike: 700 meter
The implementation of construction or dredging is recommended to be completed based on a demand basis, and not based on the geomorphologic reaches developed for the sediment transport model. The first priority area for maintaining a navigation channel is the stretch from Ibotirama down to the Sobradinho Reservoir. This stretch is prioritized
due to the on-going activity between Ibotirama and the twin cities of Petrolina/Juazeiro.

Additional transportation hubs could be developed and addressed as the demand for waterway transportation continues to increase in the upstream direction. Table 44 lists the lengths of structures, volumes, and a coarse estimate based on the (CODEVASF) provided cost estimate template. Costs are based only on the amount of volume of the structures estimated and do not include any projects that require rock excavation, bank stabilization, maintenance, operation, or other project design features.

**Table 44: Estimated Self-Scouring Structures by Demand Hubs**

<table>
<thead>
<tr>
<th>Reach</th>
<th>Total Structure Length, m</th>
<th>Total Structure Volume, m³</th>
<th>Estimated Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pirapora to São Francisco</td>
<td>34,991</td>
<td>1,837,012</td>
<td>R$ 449,597,604</td>
</tr>
<tr>
<td>São Francisco to Carinhanga</td>
<td>27,324</td>
<td>1,434,521</td>
<td>R$ 351,090,285</td>
</tr>
<tr>
<td>Carinhanga to Bom Jesus de Lapa</td>
<td>11,882</td>
<td>623,800</td>
<td>R$ 152,671,246</td>
</tr>
<tr>
<td>Bom Jesus de Lapa to Ibotirama</td>
<td>12,388</td>
<td>650,370</td>
<td>R$ 159,174,155</td>
</tr>
<tr>
<td>Ibotirama to Pilão Arcado</td>
<td>11,895</td>
<td>624,493</td>
<td>R$ 152,840,854</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>98,480</strong></td>
<td><strong>5,170,195</strong></td>
<td><strong>R$ 1,265,374,144</strong></td>
</tr>
</tbody>
</table>

Based on these costs, the priority reach (between Ibotirama and Pilao Arcado) would require approximately R$ 150,000,000 to construct the navigation dikes. Also, the entire navigation channel would cost approximately R$ 1,250,000,000 to construct the navigation dikes. All estimated costs are in 2013 Brazilian Reais units.
CHAPTER 12.0  DREDGING ALTERNATIVE

The sediment transport model was also used to determine the magnitude of dredging required to maintain a stable navigation channel. The dredging alternative focused on the stretch of river between Ibotirama and the upstream end of the Sobradinho reservoir. The primary purpose of the sediment transport model was to determine the amount of time necessary between dredging events to maintain a sustainable, reliable navigation channel.

12.1  Previous Studies

The Curralinho Project, CODEVASF-USACE, (2013a), investigated dredging as an alternative to improve navigation at the Curralinho shoal. The Curralinho site has a single shoal at the downstream (northern) boundary of the site (see Figure 220). Two dredging scenarios were developed for the Curralinho project. These scenarios are described below:

1. Dredge the shoal to 2.0 meters (1.8 meters of draft with 0.2 meters of over-dredge)

2. Dredge the shoal to 2.5 meters (2.0 meters of draft with 0.5 meters of over-dredge)

In the first scenario (1.8 meters with 0.2 meters of over-dredge) the sediment transport model was used to determine how much time is necessary for the over-dredge to shoal back in. In this scenario, the sediment transport model showed that the channel will begin to fill in 0.2 meters after approximately 2 years (see Figure 221). This analysis
shows that there is a short-term gain on the dredging, which would be required to be re-
dredged every other year to maintain even a 1.8 meter (minimum) channel depth at low
water datum.

In the second scenario (2.0 meters with 0.5 meters of over-dredge) the sediment
transport model was again used to determine how much time is necessary for the over-
dredge to shoal back in. In this scenario, the sediment transport model showed that the
channel will begin to fill in 0.5 meters after approximately 5 years (see Figure 222). This
analysis shows that rate of shoaling is consistent (about 10 centimeters per year for this
site) as the first scenario. After 5 years, a minimum of 0.5 meters would need to be
dredged through the critical shoal at Curralinho again.
Depths are referenced from Low Water Datum (LWD)
Source: AHSFRA (2011)
Figure 221: Curralinho Scenario 1.8 meters with 0.2 meters Over-Dredge
A second study at the Torrinha site (CODEVASF-USACE, 2014) shows a similar rate of re-filling in dredged areas. At the ferry crossing in the Torrinha site, a shoal was dredged in 2009. The 2011 AHSFRA navigation charts (see Figure 223) show that this shoal had reappeared by 2011 (within 2 years). This site is in a nearby location as the Curralinho site, and has a similar morphology as Curralinho. The rate of 2 years for a dredged site to refill can be considered to be a realistic result of the Curralinho model, due to the observed in-filling within 2 years that resulted at Torrinha.
Figure 223: AHSFRA Chart of Torrinha-Itacoatiara Site (2011)

Source: AHSFRA (2011), Depths are referenced from Low Water Datum (LWD)

Previous Dredging in 2009
12.2  **Dredging Scenario in the Sediment Transport Model**

The sediment transport model developed for the Sao Francisco River was used to
determine rates of infilling at the critical sites between Ibotirama and the Sobradinho
Reservoir. The infilling rates can be used to determine the frequency of dredging
requirements (and the subsequent long-term costs associated with a dredging plan). A
2.5-meter dredge channel was added to the sediment transport model at the critical shoals
in order to calculate general infilling rates through this prioritized section of the river.
The main purpose to use the sediment transport model is to confirm the infilling rates that
have been observed following actual dredging events or predicted using a detailed
sediment transport model.

CODEVASF let a contract in 2013 to conduct emergency dredging from
Ibotirama to the upstream end of the Sobradinho Reservoir. In the contract, a total of 21
sites were identified to be dredged with an estimated volume of 251,285 m$^3$ of dredge
material (although only one site (Cachoeirinha) was actually dredged in 2013). These
volumes were originally estimated by the Department of Transportation (DNIT). The
CODEVASF-USACE team obtained the official 2012 bathymetry data of the Sao
Francisco River between Ibotirama and the Sobradinho reservoir. This data was used in
ArcGIS to calculate the actual volumes at each of these sites. If all of the sites are
dredged to 2.0 meters, the total volume is approximately 248,000 m$^3$ (very similar to the
DNIT estimate). However, if over-dredge of 0.5 meters is included, the total volume to
be dredged is approximately 775,000 cubic meters (see Table 45).
A sample of these sites were added to the sediment transport model. These sites include:

1. Cachoeirinha (station 1256153)
2. Cabeca Levantada (station 1254732)
3. Caraibas (station 1215785)
4. Meleiro (station 1213339)
5. Papaconha (station 1061506)
6. Rodrigo (stations 1025559, 1025411, and 1024795 – 3 cross sections)

The dredge events were added to the sediment transport model at these stations by creating a new geometry file in HEC-RAS. This file is named
Sao_Francisco_Dredge.g03. The dredge bottom was set to 2.5 meters below the Low Water Datum (LWD) elevation for each of these sites. The data used to set the elevation are shown in Table 46, and an example updated cross section is shown in Figure 224.

### Table 46: Example site Data used in Sediment Transport Model

<table>
<thead>
<tr>
<th>Site</th>
<th>Station, m</th>
<th>Low Water Datum Elevation, m</th>
<th>Navigation Channel Bottom, m</th>
<th>Dredge Bottom, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cachoeirinha</td>
<td>1256153</td>
<td>409.89</td>
<td>407.44</td>
<td>407.39</td>
</tr>
<tr>
<td>Cabeça Levantada</td>
<td>1254732</td>
<td>409.59</td>
<td>407.38</td>
<td>407.09</td>
</tr>
<tr>
<td>Caraíbas</td>
<td>1215785</td>
<td>407.14</td>
<td>404.7</td>
<td>404.64</td>
</tr>
<tr>
<td>Meleiro</td>
<td>1213339</td>
<td>406.95</td>
<td>404.98</td>
<td>404.45</td>
</tr>
<tr>
<td>Papaconha</td>
<td>1061506</td>
<td>398.26</td>
<td>395.82</td>
<td>395.76</td>
</tr>
<tr>
<td>Rodrigo</td>
<td>1025559</td>
<td>395.66</td>
<td>393.88</td>
<td>393.16</td>
</tr>
<tr>
<td>Rodrigo</td>
<td>1025411</td>
<td>395.6</td>
<td>393.83</td>
<td>393.1</td>
</tr>
<tr>
<td>Rodrigo</td>
<td>1024795</td>
<td>395.42</td>
<td>392.97</td>
<td>392.92</td>
</tr>
</tbody>
</table>

### Figure 224: Example Dredge at Cabeca Levantada

![Dredging cross section](image)
The 6-year simulation of the sediment transport model was run at each of the example sites, and the infilling rate (invert change) was investigated over time at each location. These data are shown in Figure 225. From this figure, it is observed that the infilling rate is not uniform for each cross section. This is an expected result due to the amount of dredging (depth) varies for each cross section, and the local morphology of the river will dictate actual infilling rates at a particular dredged shoal. However, it is noted that the infilling rates vary between 0.05 meters per year to 0.4 meters per year immediately following the dredge. The average infilling rate is approximately 0.2 meters per year. This confirms the previous rates noted of approximately 0.1 meters per year. This further validates the sediment transport model and also provides additional confidence in the estimated infilling rates of potential dredge sites.
12.3 **Dredging Costs**

Based on the sediment transport modeling of these example shoals, it can be confirmed that any dredging conducted is expected to fill in within a few years (depending on the dredge depth). Previous studies as well as the sediment transport modeling conducted in this study have shown that a dredged shoal is likely to refill between 2-5 years. For planning purposes, it is recommended to use a dredged shoal refill time of 2 years to estimate the cost of future dredging and to compare the dredging alternative with the alternative of self-scouring structures. It is recommended that a
CODEVASF cost engineer evaluate the life-cycle costs of dredging these shoals on a reach-by-reach basis with a priority on the Ibotirama to Sobradinho Reservoir reach. These costs should also be compared against the self-scouring channel structural costs to assist in determining the least cost alternative.

A general cost estimate for the amount of dredging necessary to achieve a sustainable, reliable, navigation channel was also estimated. A Geographic Information System (GIS) was used to calculate the necessary dredging volumes for each transportation reach (based on hubs instead of geomorphic reaches). Using the assumption that overdredging of 0.5 meters will be employed, the total volumes were determined. These volumes were multiplied by 25 cycles (every 2 years dredging is required over a 50-year life cycle of the project). Inflation is not included in the cost estimate, and a general unit cost of R$ 11 per cubic meter was applied to all of the dredging volumes (excludes mobilization, profit, etc.). The results of the coarse dredging cost estimate are shown in Table 47.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Volume, m³</th>
<th>Unit Cost per cubic meter</th>
<th>Dredge Event Cost</th>
<th>Estimated Number of Dredge Events in 50-years</th>
<th>Total Estimated Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pirapora to São Francisco</td>
<td>2,903,259</td>
<td>R$ 11</td>
<td>R$ 31,935,849</td>
<td>25</td>
<td>R$ 798,396,225</td>
</tr>
<tr>
<td>São Francisco to Carinhana</td>
<td>1,993,617</td>
<td>R$ 11</td>
<td>R$ 21,929,787</td>
<td>25</td>
<td>R$ 548,244,675</td>
</tr>
<tr>
<td>Carinhana to Bom Jesus de Lapa</td>
<td>923,621</td>
<td>R$ 11</td>
<td>R$ 10,159,831</td>
<td>25</td>
<td>R$ 253,995,775</td>
</tr>
<tr>
<td>Bom Jesus de Lapa to Ibotirama</td>
<td>833,706</td>
<td>R$ 11</td>
<td>R$ 9,170,766</td>
<td>25</td>
<td>R$ 229,269,150</td>
</tr>
<tr>
<td>Ibotirama to Pilão Arcado</td>
<td>1,101,088</td>
<td>R$ 11</td>
<td>R$ 12,111,968</td>
<td>25</td>
<td>R$ 302,799,200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7,755,291</strong></td>
<td><strong>Total</strong></td>
<td><strong>R$ 85,308,201</strong></td>
<td><strong>Total</strong></td>
<td><strong>R$ 2,132,705,025</strong></td>
</tr>
</tbody>
</table>

Based on these costs, the priority reach (between Ibotirama and Pilao Arcado) would require approximately R$ 300,000,000 to maintain the navigation channel using
dredging over a 50-year life cycle. Also, the entire navigation channel would cost approximately R$2,130,000,000 to maintain a dredged channel. All estimated costs are in 2013 Brazilian Reais units.

Based on the comparison of costs associated with each transportation reach, an approach that utilizes self-scouring structures is likely to be a cost effective alternative to maintenance dredging.
CHAPTER 13.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

13.1 Summary

A hydrology and sediment yield model of the Sao Francisco was developed in order to analyze the sediment budget of the Sao Francisco basin. Following a model selection task, the Soil and Water Assessment Tool (SWAT) was selected for the modeling of the basin. This tool uses a concept called Hydrologic Response Units (HRUs), which are composed of the soil characteristics, landuse, and slope characteristics of small units of area within a sub-watershed. The SWAT model is a powerful tool that allows the user to analyze reservoirs, irrigation, groundwater and surface hydrology, sediment yields, and contaminants (amongst others).

The SWAT model was calibrated to eighteen different flow gages, one sediment gage, and eleven sediment loads from tributary inflows. Calibration achieved Satisfactory to Very Good ratings for all gages analyzed.

The SWAT model was used to calculate a sediment budget for the watershed. After the SWAT model was calibrated, it was used to analyze two additional scenarios. These scenarios are the pre-European settlement conditions (before major landuse conversions and the construction of dams) and a proposed future landuse condition. Insight into the sediment dynamics of the system was developed based on the investigation of the results of these three scenarios.

The sediment loads (output) of the SWAT model were then applied as sediment loads (inputs) into a sediment transport model. This coupled approach ensured that the dynamic nature of the sediment loads are accurately represented throughout the model.
domain of the sediment transport model. The sediment transport model was developed as a tool to be for analyzing planning alternatives to improve navigation of the Sao Francisco River from Pirapora to the Sobradinho Reservoir.

An investigation of the hydrologic and geomorphic conditions of the river was determined to support planning efforts using the HEC-RAS sediment transport model. Specifically, the geomorphic conditions generally led to shoaling within the navigation channel were determined. To this end, the Sao Francisco River was divided into 9 geomorphic reaches with upstream and downstream boundaries located at major tributaries. This approach assisted in determining what channel widths are necessary for each reach in order to achieve a self-scouring channel.

In order to analyze the hydraulics of the Sao Francisco River at the low water conditions a 1-dimensional numerical hydraulic model (using HEC-RAS) was developed. A low flow rate (defined as a 90% exceedance flowrate) was input into the model, and the stage of the river was calibrated to the low water datum at 13 ANA gages. The hydraulic model was then converted to a sediment transport model using data from a variety of sources including ANA, AHSFRA, CODEVASF, FUNDESPA, and USACE. These data were leveraged in order to develop a calibrated sediment transport model of the existing conditions of the river.

Following the development of the existing conditions sediment transport model, two conceptual approaches (alternatives) were analyzed to assist with long-term navigation planning. The alternatives were designed to address and assess the planning level approaches to achieve a sustainable, reliable, navigation channel with a minimum of 2.0 meters of draft. The specific alternatives consisted of:
**Alternative 1**: Self-scouring structures from Pirapora to the Sobradinho Reservoir

**Alternative 2**: Dredging scenario from Ibotirama to the Sobradinho Reservoir

In both cases an estimate of quantities (structures and dredging) can assist decision makers in determining feasible alternatives for navigation improvement on a reach-by-reach basis. This can be leveraged by CODEVASF and other agencies within Brazil to determine the feasibility of waterway development for the Sao Francisco River. Based on the alternative analysis comparison, it was shown that over the course of a 50-year life cycle, developing self-scouring navigation structures is likely a more cost effective approach than maintenance dredging.
13.2 Conclusions

The Sao Francisco River is an important north-south corridor in northeastern Brazil. The river has the potential to be further developed into a waterway connecting the humid southern state of Minas Gerais in the headwaters to the semi-arid portions of the region in Bahia and Pernambuco in the Middle Sao Francisco basin. Agricultural expansion (and to a lesser extent mining) is a significant demand in the watershed. Current commodities and agricultural goods are primarily transported by road due to the lack of railroad and waterway in the region. The increase in transportation demand in the northeast of Brazil and the lack of an inexpensive means of transportation warrants investigation into the feasibility of developing a reliable, sustainable navigation channel within this region.

Numerous observations were made regarding the sediment dynamics of the Sao Francisco River watershed using the coupled SWAT sediment yield model and HEC-RAS sediment transport model. The following are a list of conclusions made from this study:

- It was shown that the SWAT model is a tool that can be used to analyze the sediment and hydrology within the Sao Francisco River watershed (the case study used to demonstrate the couple sediment modeling framework). This tool was also used to develop insights into the historic, present, and potentially future conditions of the Sao Francisco River basin.

- Decision makers may now use the guidance from this report and to model additional scenarios. Questions such as “what would occur if proposed dams were constructed?” or “what impacts would result from diverting flow into the basin
from outside sources?” may be analyzed directly by CODEVASF using the SWAT tool.

- Overall, a small component of the existing sediment budget is due to bank erosion of the Sao Francisco River. Approximately 6% of the sediment that is causing shoals in the Sao Francisco River may have originated in the banks of the Sao Francisco River or the banks of the major tributaries. Approximately 94% of the sediments that are causing shoals originated from overland sediment sources such as agricultural runoff or erosion of the beds/banks of small tributaries.

- Due the high percentage of sediments that originated in the uplands and minor tributaries, bank erosion measures alone on the Sao Francisco River will have a negligible effect on the existing shoals in the Sao Francisco River navigation channel.

- The water yield in the Sao Francisco River basin is generally concentrated in the headwaters, which is a consistent finding with previous CODEVASF and ANA studies.

- The sediment yield in the Sao Francisco River basin is generally concentrated in the headwaters, which is a consistent observation with previous CODEVASF and ANA studies.

- The output of the Sao Francisco River sediment yield can be effectively used as an input into the Sao Francisco River sediment transport model. The coupled sediment modeling approach was confirmed through the Sao Francisco River case study.
The SWAT model predicted a baseline condition of the sediment sources and sinks of the Sao Francisco River watershed. These conditions may have existed prior to major anthropogenic alterations of the basin such as conversion of native landuse to rangeland and row crops, and the construction of dams. The model predicts that all but one source and sink have increased since pre-European settlement. Bank erosion, bed erosion, and overland loads of settlement have all increased. Bed storage, floodplain storage, and reservoir storage have also increased since the historic conditions. The only sink that has decreased since Pre-European settlement was shown to be the sediment loads to the Atlantic Ocean. This is an expected result due to the construction of major dams upstream of the mouth, which has led to capturing of sediments.

The SWAT model was used to analyze future conditions for the stakeholders in the basin under a wide range of scenarios. The future conditions model shows that conditions to navigation may improve due to the construction of the proposed dams. In addition to navigation impacts, it is recognized that there are multiple users, which are expected to be impacted in a variety of ways due to any proposed plans made by decision makers in the watershed. The SWAT tool that was developed may also be used by other stakeholders to determine potential impacts to other areas of interest, or CODEVASF may use the model to analyze a variety of alternative future landuse scenarios.

The SWAT model developed is a tool that can assist landuse managers in understanding the watershed response (hydrologic and sediment) to various landuse activities. The scale of the SWAT model is very coarse, meaning that
only general conclusions related to watershed responses can be extracted from the model under large-scale changes. General trends of watershed responses can be extracted from the model, but the decision maker should use the exact numeric values from the model cautiously and these should not be over-interpreted. The model is a powerful tool to generally understand the current and potential impacts associated with changes to the Sao Francisco River watershed.

- It was determined that dividing the Sao Francisco River into 9 geomorphic reaches (bounded at major tributaries) developed an understanding of the geomorphological conditions that lead to navigation obstacles such as shoaling of sand in critical reaches. By leveraging this geomorphological information within each reach, maximum river widths were determined in order to maintain a self-scouring channel. In many cases when the existing river width exceeds a reach-specific value, shoaling often occurs. This shoaling presents a restriction to navigation within the navigation channel during the dry season (and especially during the late dry season when the river recedes to its minimum levels in September through November).

- The sediment transport model verified the viability of using self-scouring structures (primarily spur dikes) to reduce the width of the Sao Francisco River and focus the energy of the river to a narrower cross section. In addition to the river engineering structure conceptual designs, the model was used to estimate dredge volumes over time to maintain the navigation channel. The sediment transport model showed that dredging locations may fill in at a rate of...
approximately every 2 years. This information can also be used to determine the feasibility of developing a long-term dredging plan to address navigation impairments.

- The sediment transport model demonstrated the viability of achieving a reliable, sustainable, navigation channel using navigation structures (primarily spur dikes) on the Sao Francisco River. A coarse cost estimate comparing navigation structures to maintenance dredging demonstrated that constructing navigation structures alone will likely be a cost effective alternative to maintenance dredging.

13.3 Further Study

Based on the outcome of this project the following recommendations for further study are made:

1. The bedload is a very important variable that impacts the navigation channel, and yet is currently not well understood. It is recommended that bedload values are collected throughout the watershed to confirm the assumption that 20% of the sediment being transported in the Sao Francisco River is in the bedload, and 80% is in suspension. This will also assist in validating the reservoir infilling rates, and how much sandy material is actively moving in the navigation channel.

2. Radionuclide dating of sediments in the reservoir may provide an alternative method of determining reservoir in-filling rates and sediment transport rates. This methodology should be considered to more accurately determine the total sediment loads in the Sao Francisco River system.
3. The Sao Francisco River, Pirapora to the Sobradinho Reservoir sediment transport model should be used to make planning level decisions only. The model was not developed to an appropriate scale to assist with analyzing specific designs to a high degree of certainty.

4. Future project designs can be added to the sediment transport model to determine the effectiveness of additional alternatives and to assess impacts to other projects. However, it is recommended that any future project that is added to the model by CODEVASF use higher resolution data than the available data used to create the model.

5. It is recommended that each conceptual layout be re-analyzed in a detailed, systematic feasibility study to develop the alternative with the highest benefit-cost ratio. The conceptual layouts shown in Attachment One provide an estimate of the number of structures required to achieve a self-scouring channel. However, each design will need to be analyzed with more rigorous analysis and modeling to optimize the required site specific layout and design.

6. It is recommended that additional bathymetry data be collected from bank to bank (not only in the navigation channel) throughout the Sao Francisco River in order to refine and reduce the uncertainty associated with the existing sediment transport model.

7. It is recommended that additional sediment samples be collected along the Sao Francisco River and that the sediment transport model is updated with this
information to provide additional information for model calibration and to reduce the uncertainty of the results of the sediment transport model.

8. It is recommended that CODEVASF cost engineers calculate the costs associated with the self-scouring plan and the dredging plan on a reach-by-reach basis. The priority of this cost estimate should be focused on the stretch of the Sao Francisco River between Ibotirama and the Sobradinho Reservoir.

9. It is recommended that CODEVASF or other Brazil government agencies consider self-scouring structures to be compared with dredging in order to determine a cost effective alternative to developing a reliable, sustainable navigation channel for the Sao Francisco River.

10. Finally, it is recommended that this modeling framework of coupling a sediment yield and sediment transport model be applied in future navigation projects within the developing world. This will allow decision makers to determine the sediment dynamics from source to sink and assist in informed planning of navigation improvements for both existing and future conditions in similar watersheds.
REFERENCES


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Deposition of sediment (shoaling) in commercial waterways is a major obstacle to maintaining sustainable riverine transportation of bulk goods (primarily agricultural and mining commodities). The rate of aggradation of sediment in a waterway is directly related to both the rate of sediment erosion from upland and river bank sources (sediment yield) and the energy in the river to effectively transport the sediment through the waterway system (sediment transport). Historically, methods used for waterway development have included trial and error or rules of thumb associated with river training structures and chute cut-off canals or engineering of navigation locks and dams. More recently, hydraulic and sediment transport modeling techniques have been developed and applied in designs of specific waterway development features within discrete reaches of a system. However, previous large scale waterway development planning has not incorporated both the sediment yield and sediment transport modeling necessary to develop engineering solutions based on a comprehensive understanding of the interrelated sediment dynamics of the system under both current and planned future conditions.
To advance waterway development planning, this research developed a coupled sediment yield and sediment transport modeling framework. The coupled sediment modeling approach was applied within a case study in a waterway that is being developed in Northeast Brazil - the Sao Francisco River waterway. A Soil and Water Assessment Tool (SWAT) sediment yield model was developed and linked to a Hydraulic Engineering Center – River Analysis System (HEC-RAS) sediment transport model to develop a feasibility study of navigation improvements on the Sao Francisco River. A geomorphology analysis was performed to segment the geomorphological conditions leading to shoalings amongst nine reaches in the waterway. The coupled modeling was leveraged to develop river training structure conceptual designs, which were compared against long-term dredging solutions to find an economically feasible and sustainable navigation channel. The coupled sediment yield and sediment transport modeling framework demonstrated in this research can be applied to gain the necessary understanding of the sediment dynamics of a system for better decision support in the area of navigation planning in other waterway development projects.
AUTOBIOGRAPHICAL STATEMENT

As a civil engineer with a passion for water and a desire to understand the physical world, my objective is to see water resources developed sustainably and efficiently throughout the world. I believe that numerical models can provide decision makers tools that can determine physical, environmental, and economic impacts associated with various development scenarios.

My educational and professional background has greatly influenced my approach to solving water resources and civil engineering problems. I received my Bachelor of Science in Civil Engineering from Lawrence Technological University in 2002 and my Master of Science in Civil Engineering from the University of Michigan in 2003. Since that time I have had the privilege to work with leaders in the field of sediment transport, hydraulic modeling, and geomorphology at the United States Army Corps of Engineers in Detroit. This background prepared a course for me to live and work in Brazil to assist with the development of the Sao Francisco waterway, which will lead to a betterment of shipping commodities (agricultural and mining goods) with a reduction in environmental impacts when compared with current road-based transportation approaches.

My personal mission statement is to make a positive impact in my professional relationships and the world within my sphere of influence. With a strong moral character I seek to lead, serve, and work hard every day to improve life quality in international and developing sectors, reduce environmental impacts, and lead teams that will provide solutions to complex international engineering problems. My goal is to look back on my career and be proud of the relationships that I have built, the positive impacts that I have
left to society, and to be fond of the adventure of working in diverse multi-cultural settings.