Chapter 5

Monitoring Water Siltation Caused by Small-Scale Gold Mining in Amazonian Rivers Using Multi-Satellite Images

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Abstract

The small-scale mining techniques applied all over the Amazon river basin use water from streams, including digging and riverbed suctioning, rarely preventing environmental impacts or recovery of the impacted areas. As a consequence, thousands of tons of inorganic sediment (which can contain mercury) have been discharged directly into the rivers creating sediment plumes that travel hundreds of kilometers downstream with unknown consequences to the water quality and aquatic biota. We hypothesize that because of intensification of mining activities in the Brazilian Amazon, clear water rivers such as the Tapajós and Xingu rivers and its tributaries are becoming permanently turbid waters (so-called white waters in the Amazonian context). To investigate this hypothesis, satellite images have been used to monitor the sediment plume caused by gold mining in Amazonian rivers. Given the threat of intense water siltation of the Amazonian rivers combined with the technological capacity of detecting it from satellite images, the objective of this chapter is to inform the main activities carried out to develop a monitoring system for quantifying water siltation caused by small-scale gold mining (SSGM) in the Amazon rivers using multi-satellite data.

Keywords: total suspended solids, water quality change, remote sensing

1. Introduction

The Amazon river basin is the largest in the world, draining approximately 7,500,000 km^2 and discharging 20% of the global riverine waters into the ocean [1]. Within this territory, which includes eight countries in South America (Brazil, Bolivia, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela), several economic activities are threatening water quality. The three activities with the most impact are hydropower dams, agribusiness expansion (deforestation) and, mostly, mining activities [2–5]. The political and economic context in Brazil is even more concerning, given the construction of several hydropower dams and the recent changes in environmental laws to benefit agribusiness and mining activities in the Amazon region. With regard to mining, although it usually takes place in small areas compared to cattle and soybean production, for example, the environmental impacts such as area degradation, water siltation, and metal contamination are more severe and intense than those of other land use changes [6].

In the Amazon, substantial small-scale gold mining (SSGM) activities started in the 1950s at a few sites, called "garimpos." In the 1980s, encouraged by the high gold price, hundreds of thousands of people migrated to mining sites, causing an intense "gold rush" in order to escape complete social downgrading [7]. The SSGM decreased in the 1990s due to overexploitation of superficial gold, gold price stagnation, and national economic crises. However, within recent years, the gold price has risen from US$ 400 per ounce (28.3 grams) in 2005 to US$ 1300 in 2016 encouraging a new gold rush in the Amazon region [8]. In Brazil alone, approximately 130,000 small-scale gold miners are responsible for 30 tons per year [9, 10]. This production generates at least R$ 26 million per month for the regional economy [11].

Despite its financial contribution, the semi-mechanized nature of small-scale gold mining activities often generates a legacy of extensive environmental degradation, both during operations and well after mining activities have ceased [7]. SSGM takes place mostly over alluvial deposits (river network) using either dredges or water-jet systems that cause dislodging of bottom or topsoil, respectively [11, 12]. The discharge of sediment into the water has severe impacts on the water quality, such as decreasing light availability for primary production [13] and changing benthic [14] and fish communities [15]. Currently, these socio-environmental impacts can be intensified since legislation is currently being debated in the Brazilian congress, which would weaken existing environmental/indigenous laws and to slash funding for environmental protection agencies.

Technically, monitoring of environmental impacts caused by SSGM, such as quantification of water siltation using satellite images, is rarely performed either due to lack of water quality data [e.g., total suspended solids (TSS)] or because of limitation of satellite image specifications such spatial resolution [16, 17]. Today, with the availability of 10 m images such as MSI/Sentinel-2, even narrow rivers (up to 30 m width) can be monitored.

2. Scientific hypothesis and objective

The scientific hypothesis of this research is that naturally low-turbid rivers (clear and black waters, based on the Sioli [18] and Junk [19] classification of the Amazonian water types) and some tributaries that are heavily impacted by SSGM tailing discharge are becoming "white" waters (naturally turbid waters), directly affecting the aquatic and benthic ecosystems.

To test the hypothesis of whether or not SSGM activities are responsible for the "whitening" process in some Amazonian rivers, we need to investigate the spatial-temporal TSS distribution along these rivers throughout the years.

Recently, Lobo et al. [20] have estimated TSS in the Tapajós river using an empirical model based on measured TSS and radiometric data. The effects of TSS derived from mining activities on both the inherent and apparent optical properties were quantified. The authors concluded that the inorganic nature of mine tailings is the main component affecting the underwater scalar irradiance in the Tapajós river basin. For tributaries with low or no influence of mine tailings, waters are relatively more absorbent. On the other hand, with TSS loadings from mining operations, the scattering process prevails over the absorption coefficient at the green and red wavelengths. This change in load and seasonality might affect, in the long run, biota composition of a previous clear water environment to a distinct light availability regime as the river becomes subjected to mining operations.

This approach worked well for the study area, and it seems a very promising approach for other areas in the Amazon region that are facing the same SSGM impacts in order to provide easy-access information for land use management in very remote areas with little financial support. However, further extension to other study areas in the Brazilian Amazon scale using different satellite data requires improvement on image processing to handle a large database and requires validation of the methods used for SSGM area mapping and TSS estimation prior to extend it to additional areas.

Therefore, the purpose of this chapter is to inform the main activities carried out toward a monitoring system for quantifying water siltation caused by SSGM in the Amazon rivers using multi-satellite data. In the assessment phase, the activities aimed to evaluate the viability of retrieving total suspended solids (TSS) from rivers other than Tapajós using images of several satellite missions.

3. Building a water siltation monitoring system

As a part of the assessment phase, a monitoring system was designed for areas selected according to the following criteria: (i) river basins that naturally present low sediment content (clear and blackwaters according to Junk [19], as opposed to white waters), in which discharge of mining tailings can have a negative impact on biodiversity and on the local economy; (ii) areas where SSGM is actively occurring over topsoils dominated by inorganic fine particles [21]; and (iii) rivers detectable by medium spatial resolution images or high resolution (at least 30 m wide). Considering these criteria, four areas were defined: (A) the Tapajós river, (B) the Amanã river, (C) Peixoto de Azevedo river, and (D) the Xingu river (**Figure 1**).

The first step was to select cloud-free images from the web platforms for each sensor. The images were downloaded from USGS, ESA, or DGI website servers (**Table 1**). In this chapter, few images are used here to illustrate the methodology. The second step was to convert top of the atmosphere (TOA) reflectance into surface reflectance (ρw). Considering the different sensors, the image correction may have different correction approaches (**Table 1**).

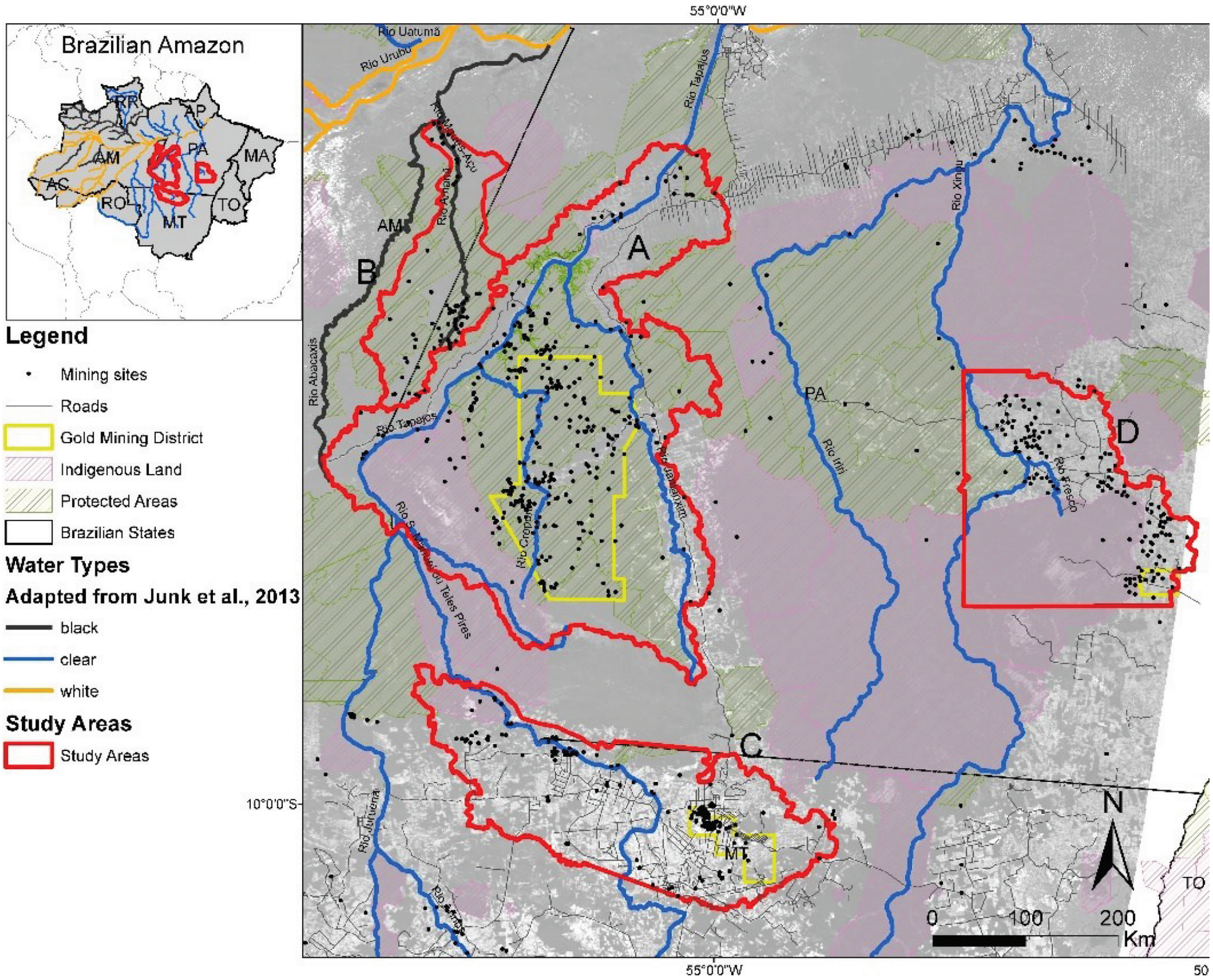

Figure 1. Study areas in the Brazilian Amazon. States of Acre (AC), Amapá (AP), Amazonas (AM), Maranhão (MA), Pará (PA), Rondônia (RO), Roraima (RR), and Tocantins (TO). (A) The Tapajós river basin (PA). (B) The Amanã river (AM). (C) The Teles Pires river, Peixoto Azevedo region (MT). (D) The Fresco river at Xingu river basin (PA).

The second step was to correct the atmospheric effects of original images to surface reflectance. The atmospheric correction (AC) process is necessary for intercalibration of the images in order to compare images from different sensors. The atmospheric correction method for each sensor is chosen according to the output quality and time/processing cost. Only physical-based methods are applied, such as 6S [22], FLAASH [23], ACOLITE [24], and Sen2Cor [25]. For all physical methods, the aerosol optical thickness (AOT) data and water vapor (among other environmental conditions) are required as input to run the model. Some methods retrieve this information from the image (image-based method, such as Sen2Cor and ACOLITE), and others (such as 6S) require the user to indicate this information [26, 27]. The procedure assures that any variation on water-leaving reflectance is due to changes in the water constituents and not to atmospheric effects, neither to intercomparison deviations related to images acquired with different sensors at different times/dates.

The third step was to estimate TSS from corrected satellite images. In this assessment phase, we tested the empirical model developed by Lobo et al. [20] based on in situ radiometric and TSS

Satellite/sensor	Life span	Swath (km)	Resolutions				Atm. correction	Available at
			Spatial	Temperature (days)	Radiometric	Spectral		
Landsat-1&2/MSS	1973–1978	170	60 m	16	8 bit	550, 650, 750, and 900 nm	Corrected	earthexplorer.usgs.gov
Landsat-5/thematic mapper (TM)/	1983–1997	170	30 m	16	8 bit	470, 550, 660, 830, 1600, and 2200 nm	Corrected	earthexplorer.usgs.gov
IRS/LISS-III	2011–	141	23 m	5	10 bit	550, 660, 810, and 1600 nm	FLAASH	www.dgi.inpe.br
RapidEye	2012–2015	77	5 m	6	12 bit	470, 550, 660, 705, and 820 nm	FLAASH	geocatalogo.mma.gov.br
Landsat-8/OLI	2014–	170	30 m	16	12 bit	440, 470, 550, 660, 830, 1600, and 2200 nm	ACOLITE or 6S	earthexplorer.usgs.gov
CBERS-4/MUX	2015–	120	20 m	16	8 bit	470, 550, 660, 705, and 820 nm	6S	www.dgi.inpe.br
Sentinel-2/ESA	2015–	290	10 m	5	12 bit	470, 550, 660, 705, and 820 nm	Sen2Cor	earthexplorer.usgs.gov

Table 1. Satellite/sensor specification in terms of resolution, life span, level of atmospheric correction, and source of data.

Satellite/sensor	Red band (ρ_w)		Parameters for Eq. 1		
	Range (nm)	Centered (nm)	*a*	*b*	*c*
Landsat-1&2/MSS	600–700	650	2.272	2.558	2.230
Landsat-5/Thematic Mapper (TM)	630–690	660	2.272	2.468	2.154
Landsat-5/OLI	640–670	655	2.272	2.516	2.182
CBERS-4/MUX	630–690	660	2.272	2.471	2.156
Sentinel-2	640–680	665	2.272	2.469	2.188
IRS/LISS-III	630–690	660	2.272	2.468	2.154
RapidEye	630–685	658	2.272	2.484	2.163

Table 2. Parameters to retrieve TSS from several satellites/sensors using the atmospherically corrected red band.

measurements taken in April 2011 [23 sample points were taken during high water level (water depth ~8 m)] and September 2012 [16 sample points were taken during low water level (water depth ~3 m)]. The measured in situ reflectance (ρw) was resampled for Landsat-5/TM spectral band. Then, to establish an empirical relationship between measured TSS and measured reflectance data, the TSS concentrations measured at 39 sample points were used. To evaluate the use of satellite images on TSS retrieving, this empirical algorithm was applied on two satellite image sets acquired at the same period of field campaigns: Landsat-5/TM (April, 2011) and IRS/LISS-III (September, 2012). To do so, the algorithm was inverted so the user can extract TSS from ρw. In the case of Landsat-5/TM and LISS-III, the following algorithm is applied:

$$TSS \ = \ a + (\rho w / b)\ c \tag{1}$$

where ρw is the surface reflectance at red band, $a = 2.272$, $b = 2.468$, and $c = 2.154$.

Considering the different spectral resolution of the orbital sensors, the radiometric measurements were resampled to the sensor's specification during the assessment phase. As a result, specific empirical curves were generated for each sensor (**Table 2**).

After estimating TSS from satellite images, the values were clustered into six TSS concentration classes ranging from 0 to 5, 10, 20, 50, 120, and >120 mgL^{-1}. Finally, the water surface area for each TSS class was tabulated (in km^2) in order to evaluate the amount of water surface with increased TSS values (>20 mgL^{-1}), as opposed to pristine conditions (<20 mgL^{-1}) of clear waters.

4. Estimating TSS concentration from satellite imagery

Results of TSS estimation for study areas A–D (**Figure 1**), from the assessment phase, are presented along with relevant information to characterize SSGM activities and their discharge of sediment into the water.

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4.1. The Tapajós river and tributaries

The lower section of the Tapajós river basin (study area A) located in the State of Pará (Brazil) covers about 130,370 km^2. In terms of SSGM, more than 300 small-scale gold mines with more than 50,000 miners cover approximately 230 km^2 [28]. As a result of SSGM activities, the TSS distribution over the Tapajós river and the main tributaries (Crepori and Jamanxim rivers) was extensively presented by Lobo et al. [20]. The authors indicated that the upstream section of the Tapajós river is naturally classified as "clear water" [16, 18, 29]. This class presented relatively low TSS (~5.0 mgL^{-1}), low dissolved organic matter (absorption coefficient for colored dissolved organic matter, a_{cdom} < 2.5 m^{-1}), and low chlorophyll-a concentration (*chl-a* < 1.0 μgL^{-1}), thus resulting in a relatively deep euphotic zone at 1% of total income irradiance ($Z_{1\%}$ ~6.0 m). In these waters, the suspended sediment has a considerable amount of organic matter (~30% of TSS), composed mostly of allochthonous plant debris [30]. The characteristics and concentration of the suspended sediments change abruptly as the Tapajós river receives clay-rich tributaries, such as the heavily mined Crepori river (TSS ~111.3 mgL^{-1}, particulate organic matter <3%, and euphotic depth ~2.0 m). The sediment plume from the Crepori river only fully mixes with the Tapajós river waters at about 200 km downstream after passing through rapids [16, 20]. After these rapids, as the water velocity decreases, the fine suspended solids sink, and concentrations decrease to values similar to those of the upstream Tapajós river (see Telmer et al. [16]). Similar to the Tapajós river, TSS at the Jamanxim river increases as it receives a sediment-rich discharge from the Novo and the Tocantins sub-basins subject to mining operations. In the low water level season (IRS/LISS-III acquired on September 16, 2012), for example, TSS values of about 115.0 mgL^{-1} were estimated for the Crepori river (**Figure 2**).

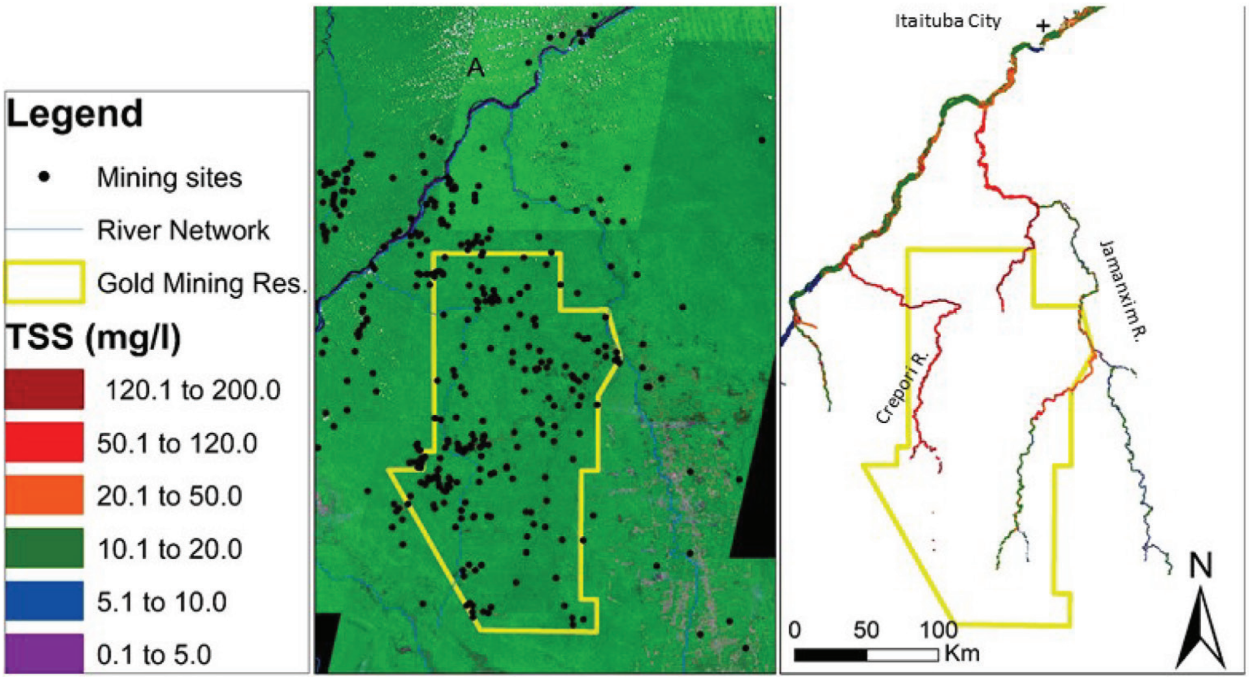

Figure 2. Study area A. TSS concentration with classes ranging from 0.1 to 200 mg L^{-1} using Eq. 1 along the Tapajós river derived from IRS/LISS-III (September 16, 2012).

In terms of surface water impacted by water siltation, **Table 3** shows that Jamanxim river and tributaries present 54% of total surface water (174.3 km^2) with increased TSS levels (>20 mgL^{-1}), mostly because its tributaries Novo and Tocantinzinho rivers present high TSS levels (**Figure 2**). The Crepori river also presents elevated TSS values for 91% of total water surface (31.1 km^2). The discharge of these tributaries into the Tapajós river affects 30% of total surface water (1208.8 km^2) of the Tapajós main channel. These results confirm that Tapajós river and tributaries have been subject to intense water siltation derived from small-scale gold mining that are changing water quality conditions from clear water (<20 mgL^{-1}) in pristine conditions to white waters (TSS levels higher than 20 mgL^{-1}).

Moreover, the recent research applied a sediment modeling approach on Crepori basin to simulate the impacts of past land use-cover change (LUCC) on TSS in the river, comparing these impacts to the effects of gold mining activity in TSS [31]. When comparing the TSS simulated with the 1998–2012 scenario and the estimates conducted by Lobo et al. [20] for the same period, on average, about 14% of TSS estimated by Lobo et al. [20] for high water season is derived by diffuse soil erosion, whereas this proportion is about 6%, on average, for the low water period. Therefore, this suggests that the remaining proportion of TSS measured and estimated by Lobo et al. [20], that is, over 86% of TSS estimated/measured, can be attributed to the gold mining activity.

4.2. The Amanã river

The Amanã river (study area B) is located between the state of Pará and Amazonas, and most of the SSGM is related to Tapajós gold domain as well (Santos et al. [30]). The inclusion of

Study area	River	Extension (km)	Percentage (%) of surface area per class of TSS (mgL^{-1}) from total							Total km^2
			0–5	10	20	50	120	>120	TSS > 20	
A	Tapajos main channel	483.3	27%	43%	27%	3%	0%	0%	30%	1280.8
	Jamanxim and tributaries	707.2	21%	25%	14%	21%	17%	1%	54%	174.3
	Crepori river	228.7	7%	2%	2%	9%	70%	11%	91%	31.1
B	Amana river	95.1	40%	29%	5%	6%	14%	5%	31%	15.1
C	Xingu main channel	185.5	87%	11%	2%	0%	0%	0%	2%	229.6
	Fresco and tributaries	266.7	43%	5%	2%	47%	0%	4%	53%	39.2
D	Teles Pires main channel	120.5	87%	12%	0%	0%	0%	0%	1%	50.2
	Peixoto de Azevedo river	140.4	20%	64%	16%	1%	0%	0%	16%	14.2

Indication of percentage of surface area per class of TSS (mgL^{-1}) from total area mapped.

Table 3. Total water surface mapped for four study areas in the Brazilian Amazon.

this area holds on the need for information about SSGM impacts on aquatic systems by the Environmental Protection Agency (ICMBio) for a better management of protected areas in the Amazon region. Recently, a federal police operation shuts down a group of about hundred miners that used to exploit gold illegally for the past 10 years. Local police agents estimate that approximately US$ 10,000 were generated with small-scale gold mining; they also claim that illegal activities caused intense area degradation for more than 70 hectares as well as mercury and cyanide contamination (both used in the gold extraction process) [32].

In terms of water siltation, preliminary results from Landsat-8/OLI (July 29, 2016) indicate TSS values higher than 120 mgL^{-1} where mining sites are present (**Figure 3**). TSS concentration decreases as the river enters the protected area (Flona de Pau-Rosa). In terms of surface water with increased TSS levels, **Table 3** indicates that 31% of 15.1 km^2 presents elevated TSS, mostly located in the upstream section of the river, as shown in **Figure 3**. The TSS values only decrease when the river reaches a more stable and wider section downstream. Overall, these results confirm that the Amanã river has also been subject to intense water siltation derived from small-scale gold mining that are changing water quality conditions from clear water (<20 mgL^{-1}) in pristine conditions to white waters (TSS levels higher than 20 mgL^{-1}).

4.3. Peixoto de Azevedo/Teles Pires river

The Peixoto de Azevedo river (study area C) is located upstream of the Tapajós (so-called Teles Pires river), characterized by natural clear water (TSS < 20 mgL^{-1}). This region is marked also by high deforestation rate, mostly due to the conversion of forest into pasture and agriculture fields [33]. SSGM was intense from 1970 to 1998, but recently the activity is not as intense as it had been before [30]. However, the sediment plume caused either by current mining activity or by degraded areas is still detectable by satellite images (**Figure 4**). The TSS estimation using Landsat-8/OLI (August 06, 2016) for the Peixoto de Azevedo river was up to 20 mgL^{-1} as opposed to the water from the Tapajós upstream (Teles Pires), with TSS lower than 20 mgL^{-1}. The water surface with increased TSS (>20 mgL^{-1}), however, was only 16% for Peixoto de Azevedo (out of 14.2 km^2 mapped) and 1% of Teles Pires river (out of 50.2 km^2). The

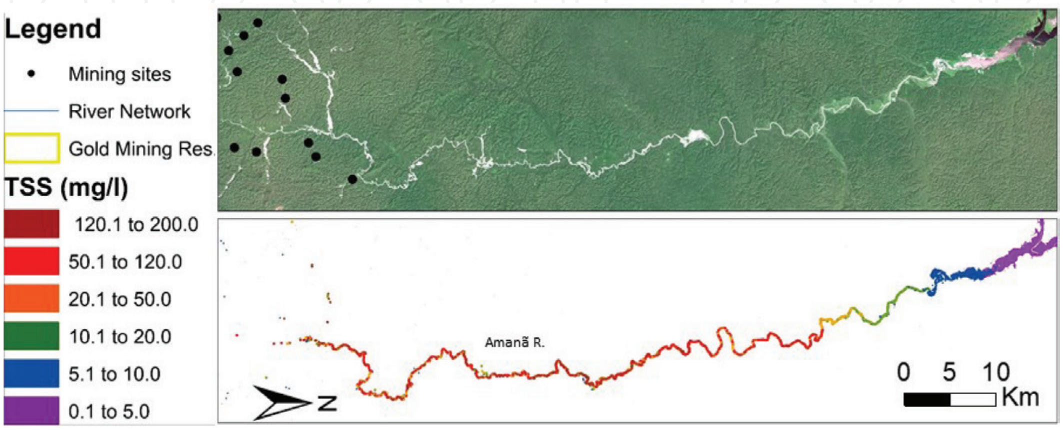

Figure 3. Study Area B (Amanã river). TSS concentration with classes ranging from 0.1 to 200 mgL^{-1} using Eq. 1 along the Amanã river located in the border between Pará and Amazonas states derived from Landsat-8/OLI (July 29, 2016).

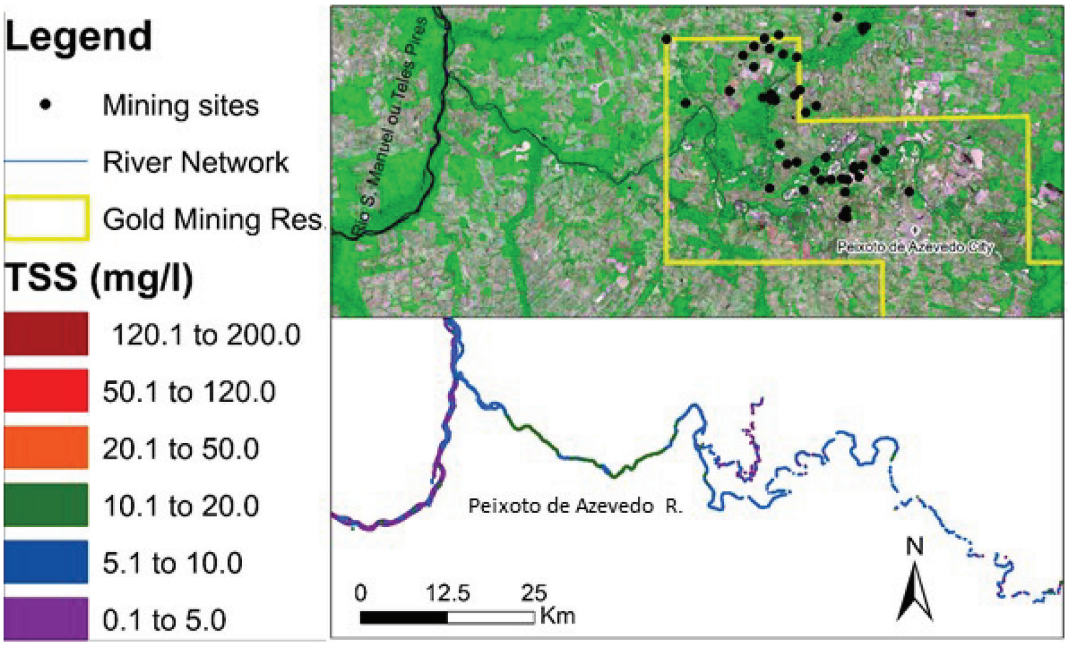

Figure 4. Study area C (Peixoto de Azevedo river/Teles Pires). TSS concentration using Eq. 1 along the Peixoto Azevedo river derived from Landsat-8/OLI (August 06, 2016).

water siltation in the Peixoto de Azevedo river is not too high, indicating that the sediment discharged by current small-scale gold mining is not enough to change the water quality as it occurs in the Tapajós and Amanã rivers.

4.4. Fresco and Xingu river

The Xingu river, likewise the Tapajós river, has its headwaters in the Brazilian central shield, and as a consequence, it also has clear water characterized by low TSS concentration [19]. The Xingu river basin presents several indigenous lands and protected areas that have been threatened by SSGM for decades [34]. Today, intense SSGM is taking place in the Fresco river (**Figure 5**) at the borders of the Kayapó territory. As mining activities within indigenous land are prohibited in Brazil, a recent federal police operation had closed an illegal mining activity in the Kayapó land where drafts, dredges, guns, and mercury were apprehended [35].

As a result of intense SSGM in this region, the TSS estimation using Sentinel-2 image (July 18, 2016) shows TSS higher than 200 mgL^{-1} in the Branco river, which in turn discharges into the Fresco river. At the São Félix do Xingu region, the Fresco river presented TSS concentration of up to 50 mgL^{-1}. For the Xingu Main channel, only 2% of total water surface (229.6 km^2) shows TSS above 10 mgL^{-1}, which corresponds to the sediment-rich Fresco river discharge area. In fact, 39.2 km^2 of the Fresco river and tributaries is analyzed in this study (**Figure 5**); 53% presents TSS above 10 mgL^{-1} (**Table 3**). Once more, the results confirm that Fresco river and tributaries have been subject to intense water siltation derived from small-scale gold mining that are changing water quality conditions from clear water (<20 mgL^{-1}), in pristine conditions, to white waters (TSS levels higher than 20 mgL^{-1}).

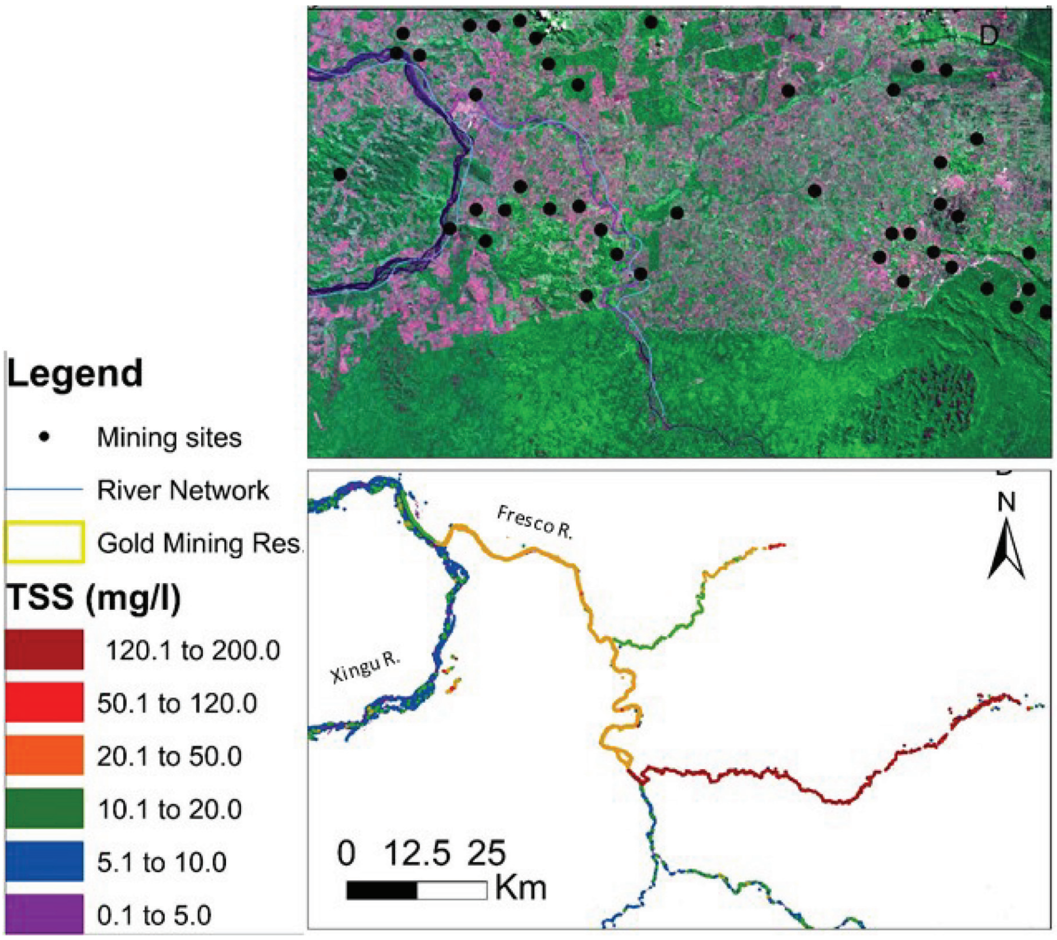

Figure 5. Study area D (Fresco and Xingu rivers). TSS concentration using Eq. 1 along the Fresco river derived from Sentinel-2 (July 18, 2016).

5. Future research

Given the favorable results derived from the first phase of assessment of the methodology, the next steps of this research (second phase) include the establishment of an image-processing framework to correct a large imagery base of multiple sensors in order to build a time series from the 1970s to present, and validation of the empirical model designed by Lobo et al. [20] with field campaigns in the selected areas to estimate TSS from the corrected imagery.

The approach that will be used in the viability assessment for building a time series follows the method applied by Lobo et al. [20], which takes dark dense vegetation (DDV) as reference for atmospheric correction. The main input parameters such as AOT, ozone, and water vapor will be optimized until the forest spectra match those from the imagery calibrated with radiometric measurements (Landsat-5/TM and IRS/LISS-III calibrated with in situ radiometric measurements in April 2011 and September 2012).

Once all images are atmospherically corrected and organized into a database, they are ready for TSS estimation using the parameters in **Table 2**. The challenge here is to validate the application of empirical model designed by Lobo et al. [20] into the additional areas to estimate TSS from the corrected imagery. Although the selected areas present similar characteristics of river basin conditions and mining techniques, slight variation of sediment composition or even the presence of dissolved organic matter can be observed among these areas. Therefore, an effort to sample water in the extended areas (B–D) in order to validate the empirical model is key for a broader application and water quality monitoring purposes. The application of the empirical model to other areas needs a validation process that includes TSS and radiometry acquisition.

Products derived from historical Landsat-1&2/MSS and Landsat-5/TM data (1973–2011) as well as current data from Sentinel-2, Landsat-8/OLI, and RapidEye will be available online at INPE (www.dpi.inpe.br/labisa). One of the main users, and actually who claimed for TSS information within protected areas, is the ICMBio (Chico Mendes Institute for Biodiversity). They have expressed direct interest concerning the SSGM impacts in rivers to support the territory management plan and to indicate areas where urgent action to control illegal activities is needed.

In addition to the direct use for SSGM controlling and monitoring by these national agencies, the applicability of these products for aquatic research is enormous. In fact, evaluation of light attenuation caused by mining tailing has shown that, in general, the euphotic zone in impacted rivers has decreased to at least half of nonimpacted rivers [36]. Several studies can use TSS distribution as an input for hydrological and sediment transportation models; studies on light attenuation and consequences to the biota, as well as socioeconomic studies, will benefit from this research.

6. Conclusions

We hypothesize that because of intensification of mining activities in the Brazilian Amazon, clear water rivers such as Tapajós and Xingu rivers and its tributaries are becoming or may become permanently turbid waters (so-called white waters in the Amazonian context). This chapter informs the main activities carried out to develop a monitoring system for quantifying water siltation caused by SSGM in the Amazon rivers using multi-satellite data in order to investigate this hypothesis.

As a result of the first assessment phase, a multi-satellite approach was developed based on TSS algorithm proposed by Lobo et al. [20]. To do so, radiometric in situ data were resampled to several sensors' specifications, such as Landsat-8/OLI and Sentinel-2, and applied to clear water rivers subject to intense sediment discharged by small-scale gold mining in order to recover TSS concentration. Except for Peixoto de Azevedo (study area C), the results confirm that Tapajós (A), Amanã (B), and Fresco river and tributaries (D) have been subject to intense water siltation derived from small-scale gold mining that are changing water quality conditions from clear water (<20 mgL^{-1}), in pristine conditions, to white waters (TSS levels higher than 20 mgL^{-1}).

In order to establish a monitoring system of water siltation, the next steps of this research (second phase) include an image-processing framework to correct a large imagery base of

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multiple sensors and validation of the empirical model designed by Lobo et al. [20] with field campaigns in the selected areas to estimate TSS from the corrected imagery.

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Conflict of interest

The authors declare no conflict of interest.

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