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From waste to resource: cost-benefit analysis of reservoir sediment reuse for soil fertilization in a semiarid catchment

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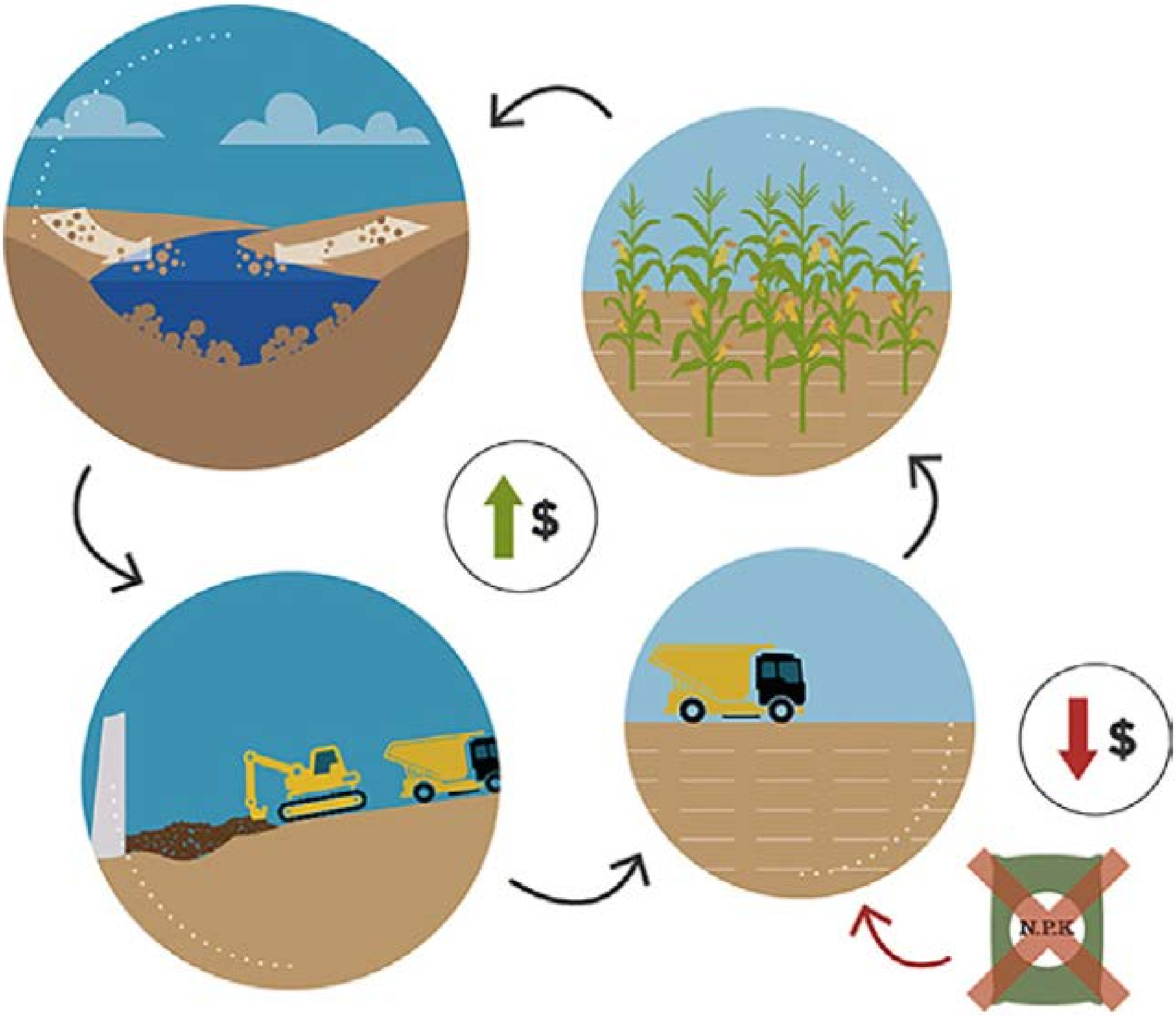
Graphical abstract:



Highlights:

- Nutrient enrichment is observed in reservoirs' sediments in relation to soils
- Sediment from surface reservoirs may be reused as nutrient source for agriculture
- Sediment reuse was shown feasible in a dry region with high density of reservoirs
- Savings with sediment-based soil fertilization can be as high as 29 %
- Transference of nutrient-enriched sediment helps turning a problem into benefits

Abstract: Reservoir networks have been established worldwide to ensure water supply, but water availability is endangered quantitatively and qualitatively by sedimentation. Reuse of sediment silted in reservoirs as fertilizer has been proposed, thus transforming nutrient-enriched sediments from waste into resource. The aim of this study is to assess the potential of reusing sediment as a nutrient source for agriculture a semiarid basin in Brazil, where 1029 reservoirs were identified. Sedimentation was modelled for the entire reservoir network, accounting for 7×10^5 tons y^{-1} of sediment deposition. Nutrients contents in reservoir sediments was analysed and compared to nutrients contents of agricultural soils in the catchment. The potential of reusing sediment as fertilizer was assessed for maize crops (*Zea mays* L.) and the sediment mass required to fertilize the soil was computed considering that the crop nitrogen requirement would be fully provided by the sediment. Economic feasibility was analysed by comparing the costs of the proposed practice to those obtained if the area was fertilized by traditional means. Results showed that, where reservoirs fall dry frequently and sediments can be removed by excavation, soil fertilization with sediment presents lower costs than those observed for application of commercial chemical fertilizers. Compared to conventional fertilization, when using sediments with high nutrient content, 29% of costs could be saved, while when using sediments with low nutrient content costs are 6% higher. According to the local conditions, sediments with nitrogen content above 1.5 g kg^{-1} are cost efficient as nitrogen source. However, physical and chemical analyses are recommended to define the sediment mass to be used and to identify any constraint to the application of the practice, like the high sodium adsorption ratio observed in one of the studied reservoirs, which can contribute to soil salinization.

Keywords: Reservoir sedimentation; Sediment reuse; Fertilizer; Semiarid; Cost-benefit analysis

1. INTRODUCTION

Water supply is largely accomplished by damming rivers, which promotes water storage during the excess periods to meet the demands during shortages. This practice gained particular importance in regions presenting high temporal variability of the hydrological processes, historically enabling the establishment of societies (Kuil et al., 2016, Abeywardana et al., 2018).

The success of reservoir construction led to widespread implementation of dense networks of reservoirs worldwide (de Araújo and Medeiros, 2013), the deployment of such infrastructure helping humans to inhabit water scarce regions and to cope with droughts (de Araújo and Bronstert, 2016). However, environmental impacts have been reported (Owens et al., 2005), mainly caused by the reduction of stream flow (Habets et al., 2018) and sediment retention (Lima Neto et al., 2011; Mamede et al., 2018).

Sedimentation of reservoirs also impacts quantitative water availability and water quality. Accumulation of sediments reduces reservoirs' storage capacities and increases evaporation losses as a result of the modified morphology (de Araújo et al., 2006). Qualitatively, fine suspended sediments represent an important source of adsorbed nutrients (Maavara et al., 2015) accelerating eutrophication processes (Owens et al., 2005).

To extend reservoirs' life time and keep water availability at acceptable levels, control of reservoir sedimentation is usually proposed (Kondolf et al., 2014), which can be accomplished by a reduction in sediment input through soil conservation practices (Santos et al., 2017). However, erosion control has shown to be a difficult task especially in developing countries, due to large territorial extensions and remoteness of fields, coupled with limited operational capacity of environmental agencies. Therefore, an alternative or complementary practice would be the removal of sediment from reservoirs, but disposal of the dredged sediments may be challenging.

Several studies have proposed the reuse of sediment silted in reservoirs as fertilizer for the agricultural sector (Fonseca et al. 1998; Sigua 2009; Braga et al. 2017) and for soil restoration (Yozzo et al. 2004; Capra et al., 2015; Bondi et al. 2016). Since the late 1990's the idea of using reservoir sediments as fertilizer and agriculture soils has propagated (Fonseca et al., 1998), with several studies demonstrating that the addition of sediment to soils improves its physicochemical properties, resulting in higher total dry matter production by plants (for instance, Fonseca et al., 2003; Capra et al., 2015; Braga et al., 2017).

Sediment removal from reservoirs and its application as fertilizer contribute to a circular economy philosophy (Stahel, 2016) by transforming nutrient-enriched sediments from waste (in reservoirs) into resource (in agricultural fields). The main benefits of the sediment reuse practice are: it recovers the reservoir's storage capacity previously lost by siltation (Yozzo et al., 2004; Kondolf et al., 2014); it improves soil physicochemical characteristics, increasing quality and productivity of crops (Fonseca et al., 2003; Capra et al., 2015; Braga et al., 2017); it prevents the addition of external nutrients from commercial chemical fertilizers, which are partially transported to water bodies and contribute to water quality degradation (Kok et al., 2018); it reduces nutrient content in the sediment and thus the reservoir eutrophication level (Lira et al., submitted).

The objective of this work was to assess the potential of reusing sediment deposited in reservoirs as fertilizer for the agricultural sector, in terms of nutrient availability and cost-efficiency. The study was conducted in the semiarid Banabuiú River in Basin in Brazil, where there is a dense network of man-made surface reservoirs.

2. STUDY AREA

The Banabuiú River Basin extends across an area of approximately 19,800 km² in the northeast of Brazil (Fig. 1), a region with semiarid hot tropical climate. Average rainfall is 750 mm y^{-1}, 75 % of which is concentrated in the months of February to May, whereas potential evaporation can reach up to 2,500 mm y^{-1}. Rivers are intermittent, and groundwater is very limited and spatially heterogeneous, resulting in water scarcity.

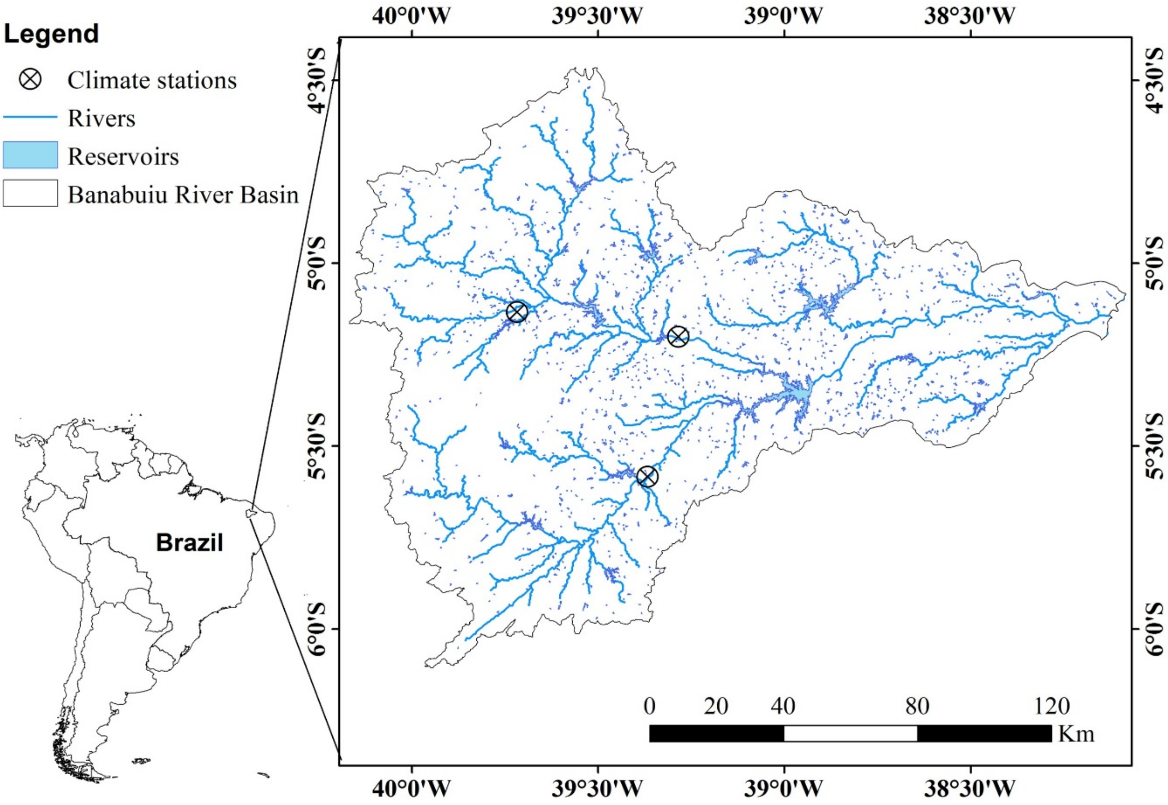


Figure 1. Location of the Banabuiú River Basin and the studied reservoirs

The population living in the basin surpasses 500,000 inhabitants, almost 70 % living in the rural areas. Predominant economic activities are small scale farming, with focus on maize and bean crops, as well as cattle, goat and sheep stock. To adapt to the prolonged drought periods, a dense network of small surface reservoirs was implemented by communities and farmers in addition to the large strategic reservoirs built by the public sector (Pereira et al., 2019). Using the Global Surface Water Explorer developed by Pekel et al. (2016), 1,029 reservoirs with maximum flooded areas larger than 5 ha were identified in the Banabuiú River Basin, resulting in an average direct contributing area of 19 km²/reservoir, reaching as low as 6 km²/reservoir if the reservoirs of all sizes are considered. Such reservoirs are the main sources of water to meet the population's demand in the study area, but very little data is available. Pereira et al. (2019) state that the local water authority of the State of Ceará, where the Banabuiú River Basin is located, monitors 153 reservoirs by in situ measurements, but there are more than 5,500 of such structures. The reservoirs' sample considered in this study includes all 1,029 reservoirs with maximum flooded areas larger than 5 ha identified in the Global Surface Water Explorer by Pekel et al. (2016).

3. METHODS

3.1. Estimation of reservoir's siltation

The volume of sediment deposited in the surface reservoirs in the Banabuiú River Basin was estimated using the model proposed by Lima Neto et al. (2011) (Equation 1).

$$\Delta V = \xi m \frac{V_0 \cdot \Sigma R}{\rho} \quad (1)$$

Where: ΔV is the yearly average reservoir storage capacity reduction (m³ per year), ξm is the sediment retention rate (tons m^{-3} MJ^{-1} mm^{-1} ha h), V_0 is the initial capacity (m³) when the reservoir was built, ΣR is the yearly average rainfall erosivity factor (MJ mm ha^{-1} h^{-1} per year), and ρ is the sediment dry-bulk density (tons m^{-3}).

In this study, non-strategic small reservoirs were considered, for which very little data is available (Zhang et al., 2016). The sediment retention rate used was an average value of 3.65 10^{-7} tons m^{-3} MJ^{-1} mm^{-1} ha h as proposed by Lima Neto et al. (2011). The initial storage capacities of all reservoirs were estimated according to the method proposed by Pereira et al. (2019), based on the maximum flooded areas and perimeters obtained from the dataset by Pekel et al. (2016).

The rainfall erosivity factor was computed according to the method developed by Bertoni and Lombardi Neto (1990) (Equation 2) for the southern region of Brazil. The same procedure was adopted by Lima Neto et al. (2011).

$$R = \sum_{m=1}^{12}\left[67.355\left(\frac{P_m^2}{P}\right)^{0.85}\right] \tag{2}$$

Where: R is the annual rainfall erosivity factor (MJ mm ha^{-1} h^{-1}), P_m the monthly rainfall (mm), and P the annual average rainfall (mm).

Rainfall time series with over 100 years (1913 to 2016) records were available for three rain-gauges in the basin and obtained from the Brazilian Federal Hydrologic Information System (ANA, 2018). Rainfall erosivity was calculated for each rain-gauge and used as input for the estimation of siltation of each reservoir, considering the nearest gauge. Sediment dry-bulk density was measured on samples of four reservoirs in the basin (Fogareiro, Marengo, São Nicolau and São Joaquim – see section 2.3). For all other reservoirs, the average of these values was used.

The mass of sediment available for reuse (M_i, tons y^{-1}) was computed on a yearly basis for each reservoir (Equation 3), as the product of the annual volume of deposited sediment (Equation1) by the sediment dry-bulk density.

$$M_i = \Delta V \cdot \rho \tag{3}$$

The average sediment deposition layer in the reservoirs was estimated based on the total sediment yearly average storage capacity reduction of all reservoirs in the basin by the total flooded area.

3.2. Physical and chemical characteristics of the basin's soils and the reservoirs' sediments

The physical and chemical soil characteristics used in this study were obtained from the soil study carried out by Jacomine et al. (1973). Despite its coarse scale, the study from Jacomine et al. (1973) is the most complete soil database covering the entire Banabuiú River Basin. Geology in the region is predominantly a crystalline basement (covering over 90 % of the basin), represented by gneisses and diverse migmatites. The soil types found in the Banabuiú River Basin are luvisols, planosols, chernosols and latolsols (Figure 2), on which the endemic xerophytic Caatinga vegetation developed. Except for the planosols, a deep medium-texture soil that occurs in a small area in the northeast portion of the basin, soils in the Banabuiú River Basin are shallow, presenting advanced stages of weathering and/or high base saturation.The agricultural suitability of the lands in the Banabuiú River Basin was assessed by Lima (2019) considering soil and environmental limiting factors: nutrient availability, water availability and susceptibility to erosion. The author estimated nutrient availability from the data presented by Jacomine et al. (1973) (see Figure 2), whereas water availability was assessed from annual rainfall recorded in the three rain-gauges used in this work, too. Susceptibility to erosion was evaluated based on terrain slope gradient, calculated from the Shuttle Radar Topography Mission (SRTM) database (Farr et al. 2007).

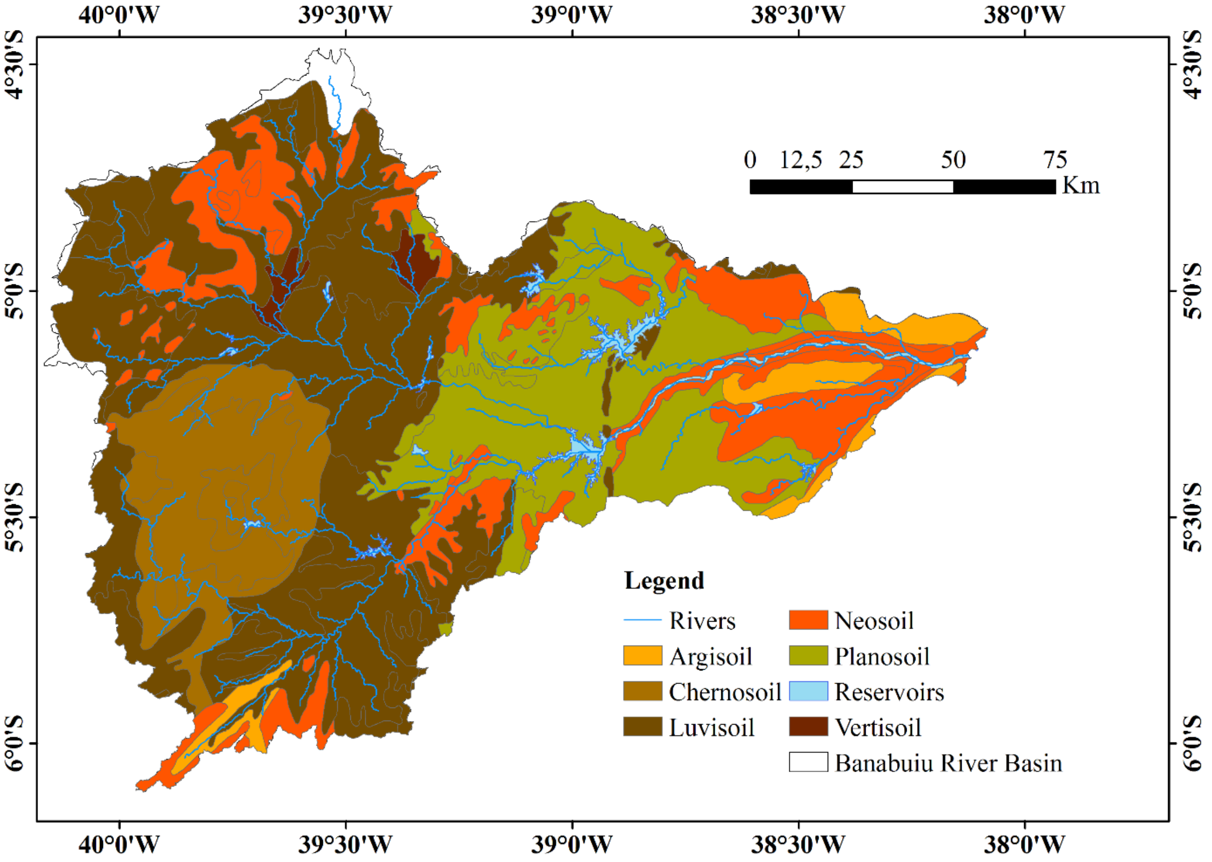


Figure 2. Soil types of the Banabuiú River Basin (adapted from Jacomine et al., 1973)

The characteristics of the sediments deposited in reservoirs were estimated based on data of four reservoirs (see Figure 3) studied in more detail: 20 sediment samples per reservoir were collected in November 2016, during the dry season when the reservoirs were empty and the sediments were accessible.

The sediment was collected at a depth of 0 to 10 cm from the surface, dried completely at 60 °C and sieved to 2 mm. Subsequently, pH, electrical conductivity (EC), concentration of ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), organic matter (OM), nitrogen (N), assimilable phosphorus (P) and potassium (K) were determined, along with granulometric analyses. From the concentrations of Ca^{2+}, Mg^{2+} and Na^{+}, the Sodium Adsorption Ratio (SAR) was calculated as a measure of soil salinization (Equation 4).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{4}$$

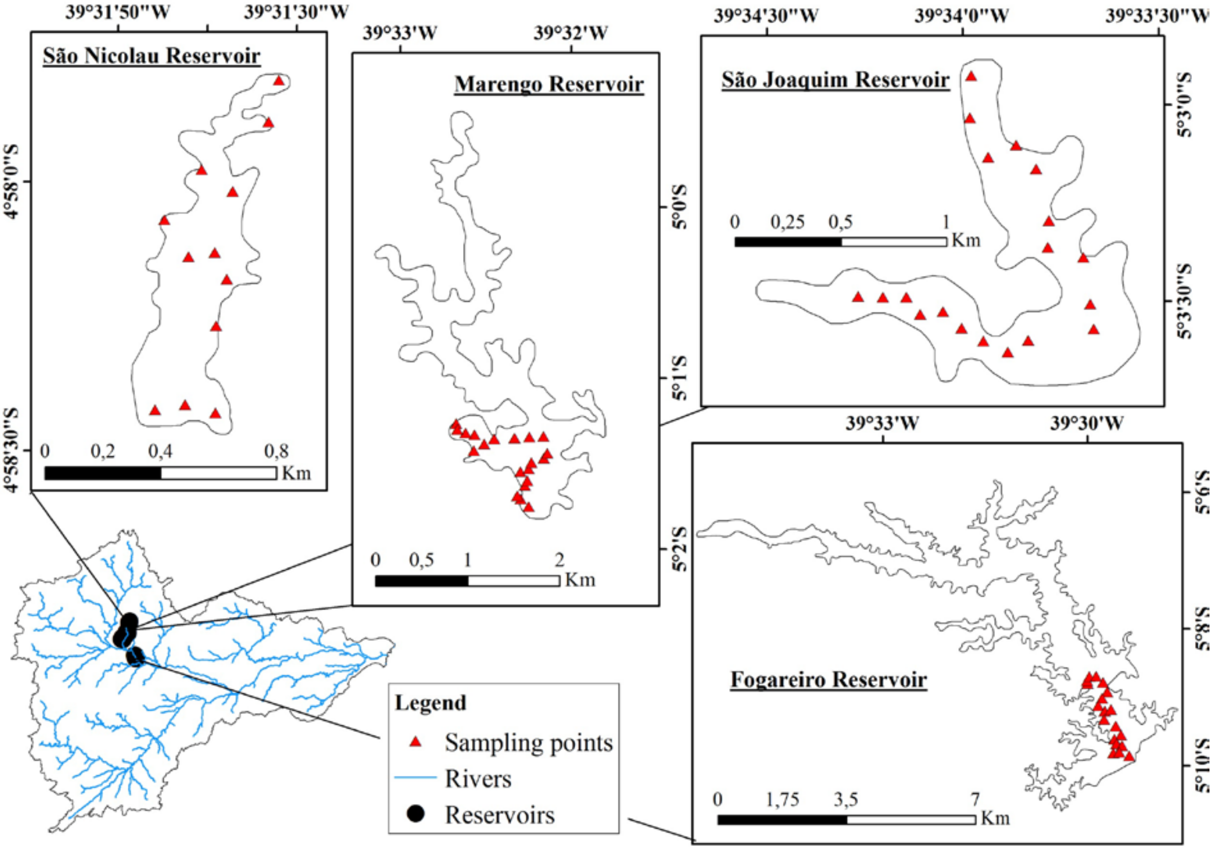


Figure 3. Location of the four reservoirs studied in detail and the sediment sampling points in the Banabuiú River Basin

3.3. Sediment as soil fertilizer for maize crops

Fertility is the most important property in determining the agronomic value of soils, as it defines the ability of a soil to provide nutrients in appropriate quantities and proportions to obtain large crop yields. Soil nutrients are naturally lost by leaching through the soil profile and erosion (Capra et al., 2015), therefore crop yields tend to decrease along time due to changes in soil fertility as a reduction in organic matter, nitrogen, phosphorus, potassium, calcium and magnesium.

To meet crop requirements and recover soil fertility, artificial fertilization is a common practice in agriculture, in which nutrients are added at an amount accounting for the difference of the crop requirement to that potentially supplied by the soil. Acknowledging that man-made surface reservoirs resulting from river damming retain nutrients (Maavara et al., 2015) and that nutrients are well adsorbed by sediments (Owens et al., 2005), reuse of deposited sediment as fertilizer was evaluated. In addition to fertilization with nutrients, sediment reuse may also contribute to improve soil structure. For instance, sandy soils may benefit from the fine particles of sediment by improving their of soil water holding and nutrient binding capacity.

In this study, the potential of reusing sediment was assessed for maize crops (*Zea mays L.*), a species traditionally cultivated in the study region for both human and cattle consumption. The nutrient extraction of maize from the soil for different productivity levels is presented in Table 1, the highest productivity (10 tons ha^{-1}) being considered in this study for the calculation of fertilization requirements. Maize crops present high nitrogen requirements, but in the soil, nitrogen is present in a very unstable form and is subject to leave the system (Coelho and Resende, 2008). The transformation of organic nitrogen into nitrate occurs at high rates, making nitrogen very mobile in the soil and susceptible to leaching by surface runoff. In addition, denitrification may occur in environments with low oxygen tension, promoting nitrogen loss to the atmosphere. Because of this mobility and ease of nitrogen output from the soil-plant system, it is a common practice to consider the nitrogen content in natural soils zero.

Table 1. Average nutrient extraction by maize from the soil for grain production at different productivity levels (Coelho and Resende, 2008)

Productivity (ton.ha^{-1})	**Nutrient requirement (kg.ha^{-1})**				
	N	**P**	**K**	**Ca**	**Mg**
4	77	9	83	10	10
6	100	19	95	17	17
8	167	33	113	27	25
10	217	42	157	32	33

The total sediment mass required to fertilize the soil was computed considering nitrogen as the limiting nutrient, so that the crop requirement of 217 tons of N per ha^{-1} would be fully provided by the sediment. This is a common practice as nitrogen is very volatile (Coelho 2007). Additional information used for the computation of the required sediment mass were: ploughing depth of 20 cm to which the sediment is mixed to the soil, plant spacing of 0.4 m and distance among planting lines of 0.9 m.

The sediment mass required for fertilization was assessed for different soil types of the Banabuiú River Basin and for sediments sampled in the four reservoirs studied in detail (Marengo, São Nicolau, São Joaquim and Fogareiro – Figure 3). In case the requirement of the other macronutrients (P, K, Ca and Mg) was not met by the sediment mass computed for nitrogen supply, addition of mineral fertilizers was considered.

3.4. Cost-benefit analysis of sediment reuse

In order to analyse the economic feasibility of the sediment reuse, the costs resulting from the application of this technique were compared to those obtained if the area was fertilized by traditional means, i.e. using commercial mineral fertilizers. Reservoir storage capacity recovery (Kondolf et al., 2014) and water quality improvement (Lira et al., submitted) were not computed in this study, but represent additional benefits of the sediment reuse practice. All values obtained in Brazilian Reais were converted to US dollars adopting an exchange rate of 3.83 R$/US$.

The costs generated by the sediment reuse consist of physicochemical analysis of the sediment, excavation for machines (including rent, fuel and operation) of the material from the dry reservoir, load, transport and discharge in the crop field. The total cost to assess the sediment properties of a reservoir depends on its size. In this study, a density of 1 sample per ha was fixed. The volume of required sediment was computed as the ratio of the sediment mass requirement to the sediment density, assumed as 1.3 $t.m^{-3}$.

The services of soil/sediment excavation and transport are regulated in the study region by the Infrastructure Secretary of Ceará State (SEINFRA/CE) and the values vary according to the Average Transport Distance of the material. To determine Average Transport Distance in the Banabuiú River Basin, we calculated distances to the nearest reservoir (areas of sediment extraction) assuming that the farmers will obtain the sediment where it is more readily available.

The costs of commercial fertilizers consist of purchase and transport to the crop field. The costs for acquiring the required fertilizers, i.e. urea (N), simple superphosphate (P) and potassium chloride (K), were obtained at local sellers (Table 2). Costs to transport the chemical fertilizers depend on the distance from the place of purchase to the cultivation area. The Brazilian Transportation Agency establishes, through Resolution n° 5820/2018 (Brazil 2018), the freight minimum prices for various types of cargo. For distances of up to 100 km, the transport is charged as US$ 0.56 per kilometre.

Table 2. Costs of acquisition of commercial chemical fertilizers for agricultural fertilization (Quotation in 2018)

Fertilizer	Mass of content (kg)	Element concentration (%)	Cost (US$)
Urea (N)	25	44	13.91
Simple superphosphate (P)	25	18	8.43
Potassium chloride (K)	25	58	13.40

4. RESULTS AND DISCUSSION

4.1. Siltation of reservoirs in the Banabuiú River Basin

The total sediment mass retained in the 1,029 reservoirs with surface areas larger than 5 ha in the Banabuiú River Basin was estimated as approximately 7 x 10^5 tons per year, resulting in sedimentation rates in the range of 1.6 to 1.8 % of the reservoirs' storage capacities per decade. Although no sedimentation has been measured in the studied reservoirs to validate our estimates, the sedimentation rates computed in this work are in agreement with the average value of 1.8 % per decade (ranging from 1.1 % to 3.1 % per decade) measured by de Araújo (2003) in 7 rural reservoirs in the Federal State of Ceará, where the Banabuiú River Basin is located. The smaller ranges of sedimentation rates found in this study are probably caused by the fixed value used for the sediment retention rate in this study (see Equation 1) in the absence of more detailed data. Therefore, it seems that the adopted method is compatible with this study's basin scale, but may produce significant errors for individual reservoirs. If a field or remote sensing based (Zhang et al., 2016) bathymetric survey is possible and the initial storage capacity of the reservoir is known, this source of uncertainty can be overcome.

In their review about sediment management in reservoirs, Kondolf et al. (2014) state that sedimentation reduces reservoir storage capacity at the global scale at a rate of 0.5 % per year (approximately 5 % per decade), thus much higher than those observed in the study area. Nonetheless, local features may considerably impact erosion, sediment transport and deposition in reservoirs, for instance, the same authors list cases in which reservoirs were completely filled by sediments. Lima Neto et al. (2011) studied the Upper Jaguaribe Basin, with an area of 24,600 km² neighbouring to the Banabuiú River Basin with similar environmental characteristics, and found that the reservoir network retained 62 % of the sediment upstream of a large strategic reservoir, with retention reaching 98 % of the sediment yield immediately downstream of that reservoir. The authors conclude that sediment retention in upstream reservoirs reduces the sedimentation rates of the ones located at downstream positions in the basin. Furthermore, Medeiros et al. (2014) argue that the low runoff observed in the Upper Jaguaribe Basin, but also in the Banabuiú River Basin, reduces sediment connectivity and represents a constraint for sediment propagation from the hillslopes to the streams. The authors demonstrate that roughly 60 % of the eroded sediment is retained in the landscape before reaching the reservoirs, which should contribute to the relatively low sedimentation rates observed in the region.

4.2. Physicochemical characteristics of soil and sediments

The physicochemical characteristics of both soil and sediments are presented in Figure 4, from which high variability can be observed for most characteristics investigated.

Low pH values were observed for the sediments of the Fogareiro, São Joaquim and São Nicolau reservoirs (Figure 4a), whereas sediment of the Marengo reservoir was slightly alkaline (pH 7.3) and the basin soils presented nearly neutral pH. Previous studies had already reported high spatial variability of pH (for instance, Yuan et al., 2014) on deposited sediment. According to Illés and Tombácz (2006), pH variation may change the aggregation / cohesion behaviour of sediment particles, and Wetzel (2001) states that phosphate adsorption by sediment is favoured by pH values in the range of 5 to 6. Sediment pH has also been pointed to as an important factor controlling phosphorus transference at the water-sediment interface in lakes (Jin et al., 2006).

Two main sources of organic matter (OM) in sediments deposited in reservoirs are: (1) plant and soil residues from outside the lake and (2) the decomposition of organisms living in aquatic systems (Röske et al., 2008). Thus, climatic conditions and land use type in the catchment significantly influence the OM content in sediments, that can vary from 0.5 to 20 % (Fonseca et al., 2011; Hur et al., 2014). In this study, average OM content of sediments analysed were 3 %, with the concentrations ranging from 22.4 g kg^{-1} to 36.2 g kg^{-1} (Figure 4b), with the reservoir with higher OM (São Joaquim) also presenting higher values of nitrogen and potassium (Figures 4g and h, respectively). Previous studies have reported high spatial variability of OM (Szczuciński et al., 2013; Yuan et al., 2014) in sediments of surface reservoirs, as well.

Overall, electrical conductivity (EC) ranged between 0.5 and 4.2 dS m^{-1} with high variability within reservoirs (Figure 4c). Electrical conductivity is an important parameter to determine soil salinity and the agronomic quality of a substrate. When evaluating the growth of plants in substrate with electrical conductivities above 2 dS m^{-1}, lower growth rates were observed due to the high amount of salt in this material (e.g. Rhoades et al. 1992, Braga et al. 2017). In this study, such high concentrations were found on average only in the Fogareiro reservoir (4.2 dS m^{-1}).

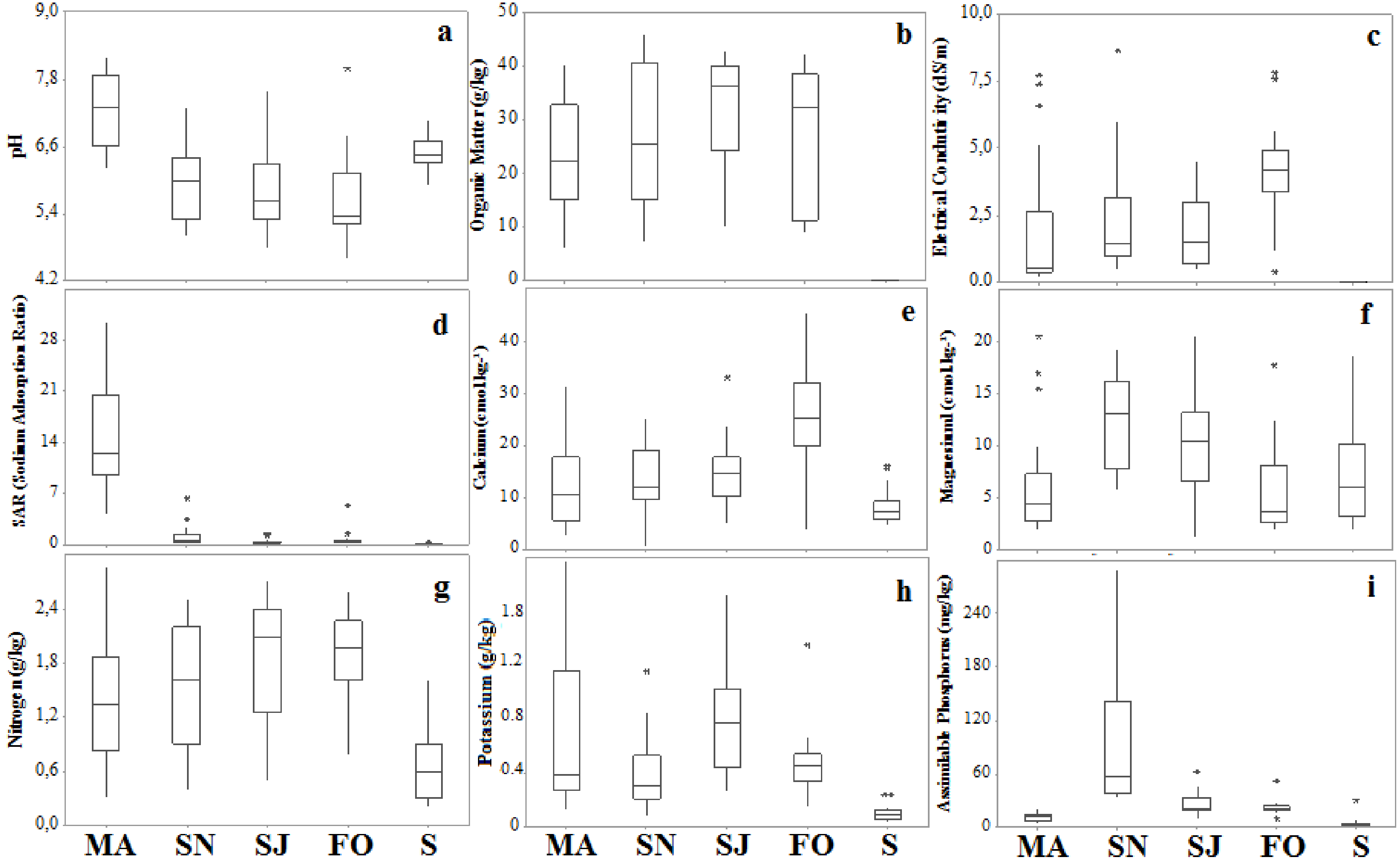


Figure 4. Boxplots of physicochemical characteristics of soils and sediments: a) pH; b) organic matter; c) electrical conductivity; d) sodium adsorption ratio; e) calcium; f) magnesium; g) nitrogen; h) potassium; i) assimilable phosphorus. MA, SN, SJ and FO refer to sediments of Marengo, São Nicolau, São Joaquim and Fogareiro, respectively, and S is for soil in the basin. Measures of organic matter and electrical conductivity are not available for the soils

High SAR results in waterproofing and hardening of the soil, reducing its hydraulic conductivity and penetrability for plant roots (da Costa, 2004). High values of SAR were found only in the Marengo reservoir (Figure 4d), with a median of 12.5 and high variability, resulting from the high residence time of the water (higher than 3 years, whereas the other reservoirs presented residence timer lower than 2 years) and the consequent accumulation of sodium. In such situations, sediment is not recommended as substrate for agricultural production.

Calcium (Ca) and magnesium (Mg) ions are used in the determination of SAR, but are also important macronutrients for plants. In this study, Ca and Mg values were found to range between 10.6 and 25.2 cmol kg^{-1} in sediments and 3.7 and 13.1 cmol kg^{-1} in soils, pointing to an enrichment of the nutrients in most sediment samples (Figure 4e and f). However, concentrations were lower in Marengo sediments, which caused the higher SAR values.

High concentrations of total nitrogen (N) were found in sediments as compared to the soils (Figure 4g), but all under the limit of 4.8 g kg^{-1} established for sediment by the Brazilian Environment Council in its 454/2012 Resolution (Brazil, 2012). The dynamics of N in sediments are difficult to predict (Wu et al., 2008), even though it is known that 80 to 90 % of the denitrification process occurs in sediments (Shaffer and Ronner, 1984).

Potassium (K) concentrations in sediments were also significantly higher than in the soils of origin (Figure 4h), ranging from 0.5 to 0.8 g kg^{-1} and 0.3 to 0.7 g kg^{-1}, respectively. Sediments of the São Joaquim reservoir presented a median 9 times higher than the median of the soil of the region whereas Marengo sediment showed highest variability between samples with a standard deviation of 0.52 g kg^{-1}.

The concentration of assimilable phosphorus in the basin soils was on average 1 mg kg^{-1}, while concentrations in the sediments ranged from 11 to 57 mg kg^{-1} except for São Nicolau, which presented much higher P concentrations and the highest variability between samples (Figure 4i). This observation suggests the enrichment of P in the sediment by assimilation / adsorption of P dissolved in water: several studies (e.g. Fonseca et al., 2011; Kosten et al., 2012) have shown a linear correlation between the P content in sediment with fine-grained particles. The adsorption also depends on the environmental conditions of the aquatic system, such as pH, redox potential and P concentrations in the water column. For instance, low pH values favour P adsorption by sediment, whereas high pH favours the transfer of P from sediment to the water column. This pattern can be observed in this study by comparing Figures 4a and i: the reservoir with the highest P concentration (São Nicolau) presented average pH of 6 while the one with the lowest P concentration (Marengo) presented pH mostly in the range of 6.5 to 8.0.

It was noticed that the São Nicolau reservoirs is also among those with highest content of natural clay (Figure 5), i.e. the clay fraction that can be dispersed in water, possibly due to the favouring of phosphorus adsorption by the fine particles. The particle size distributions of sediments sampled in the studied reservoirs are presented in Figure 5.

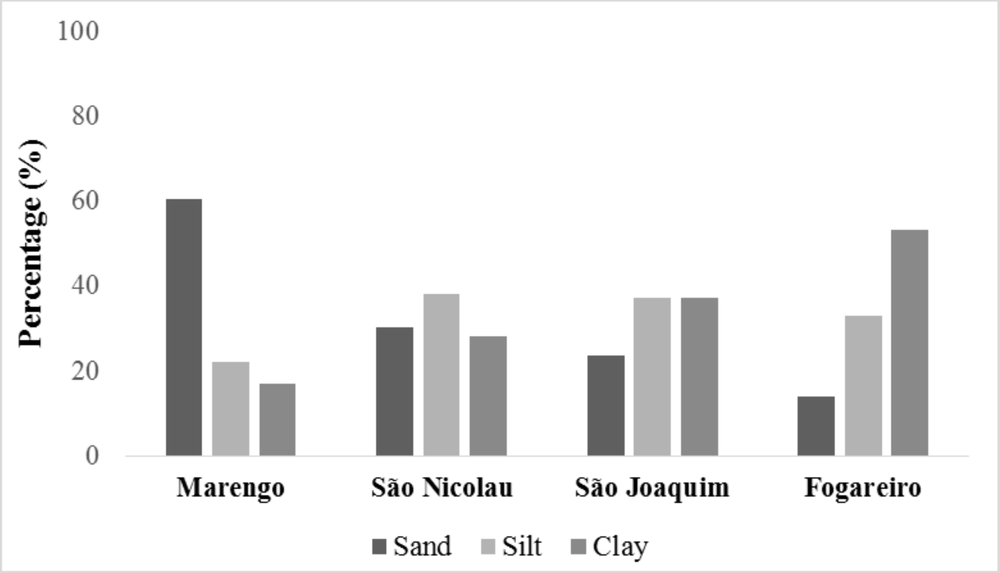


Figure 5. Sediment particle size distribution of the studied reservoirs

In general, enrichment of nutrients from soils to sediments was also observed, in agreement with Young et al. (1989) that found about three times as much nutrients per unit weight of soil eroded particles as the original soil. In water bodies, Frazen (2009) argues that nutrient contents are higher in lentic systems (such as reservoirs) than in lotic systems, as the formers store a larger fraction of the biomass production that decants at the end of its life cycle, contributing to nutrient accumulation.

As for the suitability for agriculture in the Banabuiú River Basin, Lima (2019) classified the soils in seven levels (Figure 6) and found out that 9 % (approximately 1,800 km²) and 12 % (approximately 2,400 km²) of the basin are unsuitable and partly suitable for agriculture, respectively, according to the soil susceptibility to erosion. In the area suitable for agriculture, most of it (43 % of the total basin) was classified as presenting good fertility, located along the streams near the basin outlet as well as on the north and south borders and at the foot of mountains situated in the west portion. The region with low soil fertility but still suitable for agriculture, where the sediment reuse practice should be more advantageous, covers 36 % of the basin with an area of approximately 7,100 km² spread in the central-north portion of the Banabuiú River Basin.

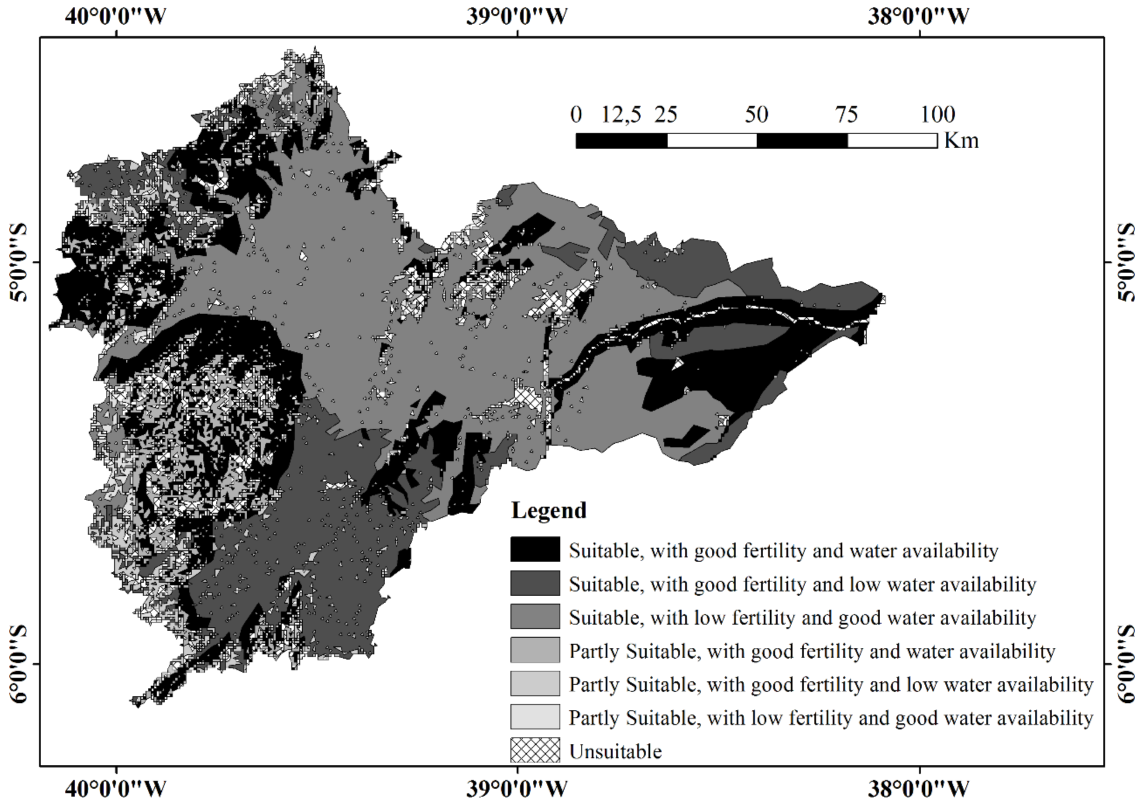


Figure 6. Agriculture suitability of soils in the Banabuiú River Basin (Lima, 2019)

4.3. Sediment as soil fertilizer for maize crops

The mass of sediment from the four studied reservoirs needed to fertilize the soils of the study area was computed (Table 3) based on the ratio between the nutritional requirement of maize (Table 1) and the nutrients concentration in sediment (Figure 4).

Table 3. Mass of sediment needed to meet the nutritional requirements of maize with high yield

Type of required fertilization	**Soil type**	**Sediment mass (kg.ha^{-1}) from reservoir**			
		Marengo	**São Nicolau**	**São Joaquim**	**Fogareiro**
Nitrogen from sediment	All types	161,940	135,625	103,333	109,873
Additional potassium	Natric Planosoil	27.8	42.4	4.9	34.3
Additional phosphate	Hypochromic Luvisoil	34.9	34.0	34.6	30.5
	Natric Planosoil	33.8	32.9	33.4	29.4
	Chromic Luvisoil	37.6	36.8	37.3	33.2
	Litolic Neosoil	36.6	35.5	36.1	32.0

Sediment masses from the studied reservoirs in the range of roughly 100 to 140 tons are required, per hectare, to fertilize the soils in the Banabuiú River Basin to meet the maize crop requirement for nitrogen. Only Marengo reservoir would demand larger sediment amounts for fertilization, but this is also the reservoir with high SAR and, therefore, unsuitable for the use of sediment as fertilizer. This finding gives rise for the need of conducting sediment analysis before adopting the sediment reuse practice indistinctly. Thereby, costly and time-consuming laboratory analysis could be complemented by remote-sensing techniques, at least for the assessment of the top soil and sediment characteristics (e.g. Viscarra Rossel et al., 2006). The potassium content was sufficient to meet the nutritional need of maize, except for the Natric Planosoil, for which the addition of chemical fertilizer (potassium chloride) is needed.

Phosphorus content in the sediment mass used for nitrogen supply is not enough to provide maize crop with its needs, and additional chemically fertilization, in the form of simple superphosphate, is suggested for the soils in the study area, except Eutrophic Luvisoils. The other macronutrients, Ca^{2+} and Mg^{2+}, can be supplied in adequate quantity by the soil. The ratio of the total sediment mass deposited annually in the 1,029 reservoirs (almost 7 x 10^5 $t.y^{-1}$) and the sediment mass required to supply the nitrogen demand of maize, gives the area that can be potentially fertilized in the Banabuiú River Basin, assuming that the sediment of the sampled reservoirs is representative of the basin (Table 4).

Table 4. Area potentially fertilized with the sediment reuse technique considering the sediment mass of all reservoirs in the Banabuiú River Basin and the sediment characteristics of the four studied reservoirs

Sediment characteristics	**Required sediment mass ($kg.ha^{-1}$)**	**Area potentially fertilized ($ha.y^{-1}$)**
Marengo	161,940	4,310
São Nicolau	135,625	5,146
São Joaquim	103,333	6,755
Fogareiro	109,873	6,352

4.4. Cost-benefit analysis of sediment reuse

The main shortcoming to the sediment reuse practice seems to be the sediment extraction, as dredging requires some effort and is usually costly. In dry environments like in the study region, small reservoirs fall completely dry with high frequency, at least every other year in the Banabuiú River Basin. This feature contributes to the feasibility of the proposed practice, as sediments are exposed towards the end of the dry season and can be easily accessed and presumably extracted by excavation at high cost-efficiency.

The costs of nitrogen fertilization with sediments depends on the transport distance and the required sediment volume. The Average Transport Distance was considered as 2.33 km, the average value obtained from the reservoirs to any part of the basin (Figure 7). According to SEINFRA, the unit cost of excavation, loading, transport and discharge of sediment at distances of 2 to 3 km is US$ 3.15 m^{-3}, therefore the total cost of fertilization was computed as the product of the unit cost indicated by SEINFRA (US$ 3.15 m^{-3}) by the sediment volume required for fertilization (Table 5).

Table 5. Costs with sediment-based nitrogen fertilization of the soils to meet the nutritional requirement of maize

Sediment characteristics	Required sediment mass (kg ha^{-1})	Required sediment volume (m^3 ha^{-1})	Total cost (US$.ha^{-1})
Marengo	161,940	124.6	392.49
São Nicolau	135,625	104.3	328.55
São Joaquim	103,333	79.5	250.43
Fogareiro	109,873	84.5	266.18

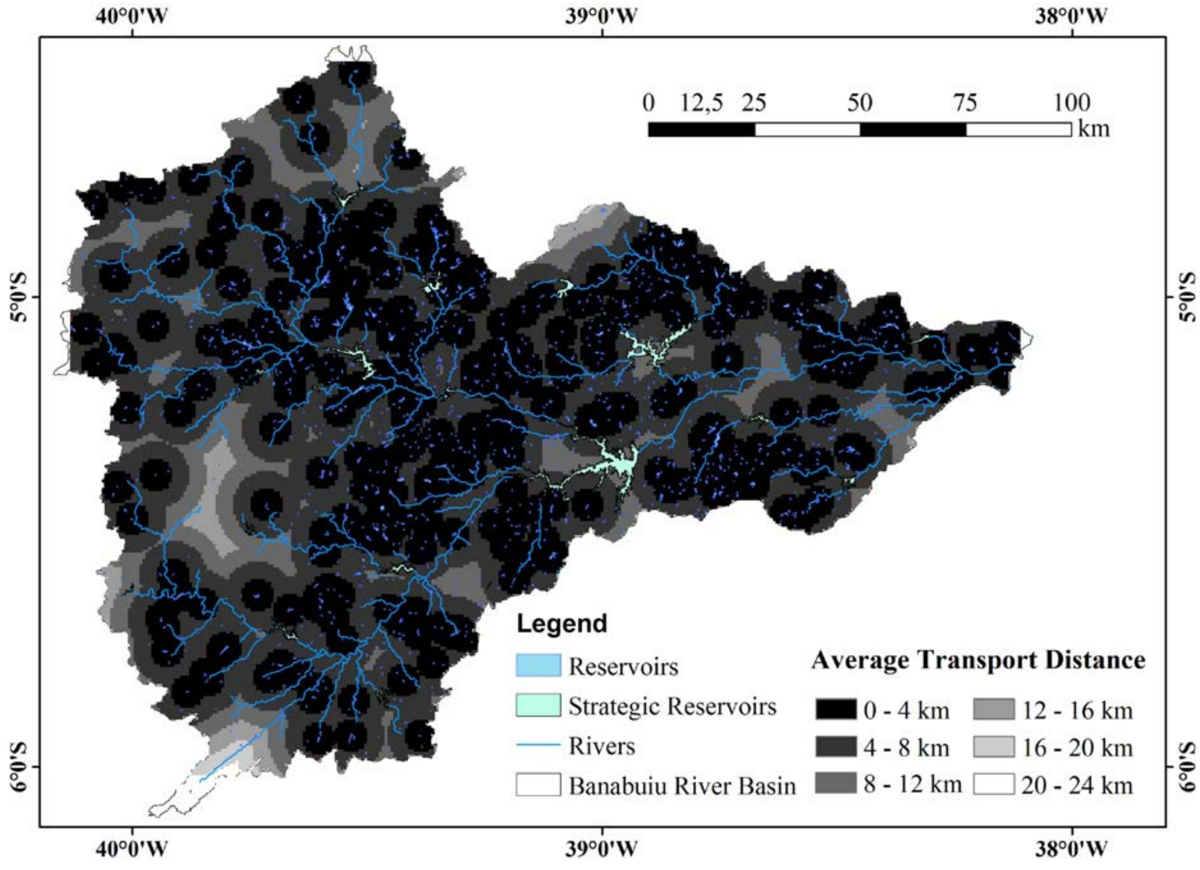


Figure 7. Transport distances from reservoirs in the Banabuiú River Basin

To completely meet the nutritional requirements of maize in relation to macronutrients, it was verified that additional phosphorus and potassium should be provided, according to the soil type (Table 6). The purchase and transport of the commercial fertilizers produce an extra cost of the sediment reuse practice and were considered in the total cost computation.

The physicochemical sediment analysis account for US$ 23.5 per sample. Considering the siltation rate in the basin (7×10^5 m³ per year), the total area flooded by the reservoirs (approximately 14,000 ha) and the sediment density (1.3 tons m^{-3}), we estimate a sediment deposition layer of 3.8 mm per year. The sediment mass required for soil fertilization ranges from 103 to 162 tons (see Table 3), thus a reservoir area between 2.1 and 3.3 ha, depending on the sediment characteristics, is required to fertilize one hectare of soil. Therefore, the costs of a single survey regarding sediment analysis are estimated as US$ 24.45 to US$ 38.32 per hectare of soil to be fertilized, and if a survey is conducted once every five years, the final cost of the sediment analysis are in the range of 9.78 to 15.33 US$.$ha^{-1}$ (Table 6).

Table 6 also presents the costs of acquisition of the chemical commercial fertilizers to meet the nutritional requirement of maize for nitrogen, phosphorus and potassium and the transport of this material. Considering purchase of the fertilizers in the municipality of Quixeramobim, in the centre of the basin, the average distance in the Banabuiú River Basin is 34.5 km, which result in a transport cost of 3.22 US$ $tons^{-1}$ if a 6-tons capacity truck is used. In general, relatively high costs are observed for chemical fertilization in the study area, particularly in soils with low fertility like the Natric Planosoil.

The total costs for soil fertilization with sediment and complementary commercial fertilizers ranges from 260 to 500 US$.$ha^{-1}$, depending on sediment characteristics and soil nutritional deficit, while the costs with conventional fertilizer ranges from 323 to 474 US$.$ha^{-1}$. Thereby, sediment from the Marengo reservoir presents the highest costs, especially on Planosoils, whereas the high SAR values observed in this reservoir can lead to soil salinization. Therefore, the sediment from Marengo reservoir is not recommended for reuse. For the other three reservoirs, the highest cost for fertilization with the sediment reuse technique is 444 US$.$ha^{-1}$ (São Nicolau on Planosoils) and the lowest costs were observed for sediment of the São Joaquim reservoir, in which high contents of nitrogen and potassium were found.

Table 6. Costs of conventional fertilizer and sediment reuse practice to meet the nutritional requirement of maize

Type of fertilization	**Soil type**	**Costs (US\$.ha^{-1}) according to the sediment characteristics***				**Costs (US\$.ha^{-1}) of conventional fertilizer**	**Difference between sediment reuse practice and conventional fertilization (%)****			
		MA	**SN**	**SJ**	**FO**		**MA**	**SN**	**SJ**	**FO**
Sediment nitrogen fertilization	All soil types	392	329	250	266	320	23	3	-22	-17
Chemical phosphate fertilization	Hypochromic Luvisoil	67	66	67	59	77	-13	-14	-13	-23
	Natric Planosoil	65	61	61	52	69	-6	-12	-12	-25
	Chromic Luvisoil	72	69	69	61	77	-6	-10	-10	-21
	Litolic Neosoil	70	61	69	61	77	-9	-21	-10	-21
Chemical potassium fertilization	Natric Planosoil	28	41	14	41	82	-66	-50	-83	-50
Physicochemical sediment analysis	All soil types	15	13	10	10	0	-	-	-	-
Transport of material	All soil types	0	0	0	0	3	-100	-100	-100	-100
Total cost	**Hypochromic Luvisoil**	474	408	327	335	400	**19**	**2**	**-18**	**-16**
	Natric Planosoil	500	444	335	369	474	**5**	**-6**	**-29**	**-22**
	Chromic Luvisoil	479	411	329	337	400	**20**	**3**	**-18**	**-16**
	Litolic Neosoil	477	403	329	337	400	**19**	**1**	**-18**	**-16**
	Eutrophic Luvisoil	407	342	260	276	323	**26**	**6**	**-20**	**-15**

**MA, SN, SJ and FO are Marengo, São Nicolau, São Joaquim and Fogareiro reservoirs, respectively*

*** We apologize for an error in the calculation of the "Difference between sediment reuse practice and conventional fertilization (%)", originally published in Science of the Total Environment in March 2019. The numbers are corrected here and might differ from those in (an early version of) the published article*

In general, soil fertilization with the sediment reuse technique in the Banabuiú River Basin presents costs compatible with those observed for application of commercial chemical fertilizers, therefore representing a source of macronutrients with economic feasibility for the agriculture sector. If sediment with high nutrient content is used, like that from the São Joaquim reservoir, savings with soil fertilization with the sediment reuse technique can be as high as 18 % to 29 % depending on the soil type. Sediment reuse from reservoirs with lower nutrient content, such as São Nicolau, may be up to 7 % more expensive than traditional fertilization.

Economic feasibility of the sediment reuse practice can be assessed as a function of nitrogen content in the sediment. By comparing the costs of sediment reuse according to the nitrogen content with those generated by nitrogen fertilization with commercial fertilizers (320 US$.ha^{-1}), it is observed that sediments with nitrogen contents above 1.5 g.kg^{-1} are cost efficient as nitrogen source.

The cost efficiency of the sediment reuse technique in the Banabuiú River Basin seems to be remarkable to increase profitability of small-scale farming. Nutrient obtainment from different wastes has been proposed worldwide, but the costs are usually a constraint. For example, Kok et al. (2018) assessed the phosphorus recovery from wastewater for agriculture reuse at a global scale and realized that, although wastewater can potentially satisfy 20 % of the global phosphorus demand, only 4 % of the wastewater discharge is technologically and economically usable.

Before to the adoption of sediment as nutrient source, physicochemical analyses are recommended, representing roughly 3 % of the total cost as estimated in this study (Table 6). The use of hyperspectral satellite imagery to map nutrient content in the soils and sediments (Viscarra Rossel et al., 2006) can not only reduce those costs, but also turn the practice more appealing by avoiding the time-consuming laboratory analysis. Remote sensing approaches for the identification of areas with soil nutritional deficit and reservoirs with highest nutrient content help optimization of the nutrient balance at the regional scale through the sediment reuse technique, helping the development of agricultural policies.

Additional benefit resulting from the reuse of sediment consists of water quality improvement. Recycling of nutrients within the catchment where they are generated prevents the addition of external chemical fertilizers in agricultural fields, which has been pointed out as a major anthropogenic source of nutrient contributing to eutrophication globally (Maavara et al., 2015). Also, nutrient-enriched sediments represent a potential source of phosphorus to the water in reservoirs, and the removal of such layers helps keeping the water quality at more acceptable levels (Lira et al., submitted).

Despite the feasibility for reuse of sediments as nutrient source, demonstrated in this work, caution should be taken to avoid potential problems. For instance, high sodium content observed in the sediment of one reservoir surveyed in this study may lead to soil salinization and negatively impact plant growth (Braga et al., 2017). Also, heavy metals and/or other toxic elements in the sediments (Yun et al., 2014) could potentially contaminate soils if present in high concentrations (Fonseca et al., 2003; Mattei et al., 2017).

The sediment reuse technique was assessed in this study in a semiarid basin where most reservoirs often get completely dry, exposing the sediments and enabling their obtainment by excavation. In environments where the sediment removal requires dredging, environmental impacts of such practices should be assessed, such as water quality degradation caused by the resuspension of sediments from the anoxic zone.

5. CONCLUSIONS

Sedimentation of surface reservoirs in the semiarid Banabuiú River Basin, with 19.800 km² in northeast Brazil, accounts for storage capacity reduction of 1.6 to 1.8 % per decade, with a total sediment accumulation of 7 x 10^5 tons per year in the 1,029 non-strategic reservoirs with surface areas larger than 5 ha.

In general, a nutrient enrichment is observed in the sediments in relation to the soils of the basin, the former potentially representing an important source of nutrients to the agricultural sector by the sediment reuse technique. Due to the high spatial variability of sediment characteristics, physicochemical analyses are recommended not only to define the mass of sediment to be used as fertilizer, but also to identify any constraint to the sediment reuse as fertilizer. For instance, the Marengo reservoir in the study area presented high sodium adsorption ratios, which can contribute to soil salinization.

In the Banabuiú River Basin, where reservoirs fall dry frequently and sediment can be removed by regular excavation, soil fertilization with the proposed technique presents lower costs than those observed for application of commercial chemical fertilizers. Savings with soil fertilization through the sediment reuse technique can be as high as 29 %, but in reservoirs with low nutrient content in the sediment, adoption of the practice may generate costs up to 6 % higher than traditional fertilization. According to the local conditions and fertilization costs, sediments with nitrogen content above 1.5 $g.kg^{-1}$ are cost efficient as nitrogen source.

As an outlook, we propose further investigations regarding additional benefits of the sediment reuse practice not assessed in this study, like the reduction of chemical nutrients used in agriculture introduced to the water bodies, as well as the water quality improvement by the removal of nutrient-enriched sediments. Furthermore, mapping the nutrient content in soils and sediments using hyperspectral satellite imagery should contribute not only to the cost reduction of the sediment reuse technique, but also assist planning at the regional scale by geographically identifying the nutrient sources (reservoirs) and the soils with nutritional deficit.

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