

The Três Marias Reservoir: A sink for sediments outcoming from over-erosion of soils in Minas Gerais, Brazil

Rita Fonseca^{1,2}, Fernando J. A. S. Barriga^{2,3}, Suzi Theodoro⁴, Tiago Canário²,
Maria Manuela Morais⁵

¹University of Évora, Department of Geosciences, Portugal

²University of Lisbon, Campo Grande, Creminer-Faculty of Sciences, Portugal

³University of Lisbon, Campo Grande, Faculty of Sciences, Department of Geology, Portugal

⁴Petrobrás, SAN Quadra 01, Bloco D, Ed. Petrobrás, Brasília, DF

⁵University of Évora, Department of Biology and Center of Ecology and Environment, Portugal

Abstract: The goal of this study is defining the structure and functioning of the Três Marias tropical reservoir, located in the Cerrado region in Brazil, through geological and chemical study of the bottom sediments. Most of these sediments result from over-erosion of soils of the drainage basin. The geochemical behaviour of major elements was used to assess the contribution of the two foremost setting lithologies (sedimentary rocks of the Três Marias Formation and kamafugitic volcanic sequences of the Mata da Corda Formation) and the soils overlying them, as distinct sources of different elements: the first one provides elements of low and very high mobility, while the second is responsible for the inputs of large amounts of Mg and K. Due to the mineralogical composition and fine-grained texture of sediments, nutrient elements are strongly sorbed or fixed, disclosing the evident lack of nutrients in the water column and the low phytoplanktonic primary production.

Keywords: sediments, Três Marias Reservoir, geochemistry, nutrients, clay minerals

1. Introduction

Reservoirs are intrinsically linked to the rivers that feed them, creating a river-reservoir continuum in which water and sediments inputs are a function of the surrounding watershed land use. In the most part of watersheds worldwide, the weathering of soils is very pronounced, specially induced by human activities, through agriculture and practices such as over farming, overgraze, over irrigation and deforestation, causing desertification in some places. Due to over-erosion, the finer particles are easily washed away from soils, which become deficient in a host of components, acquire a coarse texture and get less fertile.

Accumulated on the bottom of a reservoir, sediments are largely composed of fine-grained particles which have an important role due to the properties that their fine grain size and chemistry impart to them (Hillier 1995). These particles are detrital and often recycled from one environment to another. The nature and

contents of the chemical elements of sediments, besides its dependence on the mineralogical composition of the parent rocks and soils of the drainage basin and on the alteration mechanisms occurring during the cycles of erosion-transport-deposition, what means they are related to the dynamic equilibrium between sediments and the water column.

After dam construction, the particles accumulated in the basin are subject to modifications because as soils become submerge, there occur a complex set of chemical and physical transformations and soils are gradually covered by allochthonous and autochthonous deposits with contrasting chemical and physical characteristics. Knowledge of the chemical composition of sediments accumulated in reservoirs allows a better understanding of the evolution processes that occur in this kind of environment.

To define the feasibility of extracting the reservoir sediments, using the fine-grained fractions related to agricultural over-erosion as fertilizers or artificial soils, in the last decade several studies have been carried out to evaluate the characteristics of sediments accumulated in various reservoirs, developed under different climatic conditions and with geologically different drainage basins, thus with much contrasted types and rates of weathering/erosion regimes.

One of the selected systems is Três Marias Reservoir, located in São Francisco River Basin, in Minas Gerais State, Brazil. The purpose of this study is the characterization of the structure and the sedimentological and chemical dynamics of this reservoir, through detailed physical, mineralogical and geochemical analysis of representative sediments collected in sites uniformly distributed along the reservoir and subjected to different conditions of sedimentation. Furthermore, it is aimed to evaluating their significance as weathering products from the drainage basin by relating the spatial distribution with the parent rocks of the studied areas.

2. Characterization of Três Marias Reservoir

This reservoir is set in the Cerrado region, which has been subjected, over the last decades, to a disordered deforestation of native species, with attendant problems on the over-erosion of soils. The eroded particles, transported by river flows as suspended loads, are trapped behind barriers like the Três Marias Dam, and their accumulation involves a number of technical and environmental problems including filling of the reservoir and changing its properties. Três Marias is a large lake, with 1,050 km² of inundation area, volume of 15.3 million m³, extension of the main axe of 150 km and average depth of 16.8 m. It is fed by a large variety of waterways, tributaries of the main watercourse where it is implanted, the São Francisco River (S. Vicente, Paraopeba, Extrema, Sucurúí,

Ribeirão do Boi, Borrachudo and Indaiá, Fig. 1). However, Borrachudo and Indaiá are responsible for most of the input of sediments to the reservoir.

The Três Marias region has a tropical climate of savanna (Aw type, following the classification of Köppen), characterized by severe dry winters and rainy summers, with an average annual precipitation near 1,200 – 1,300 mm (Bezerra 1987). These conditions lead to a high intensity of rock and soil weathering in its drainage basin, followed by extreme leaching of soluble elements, especially between October and April.

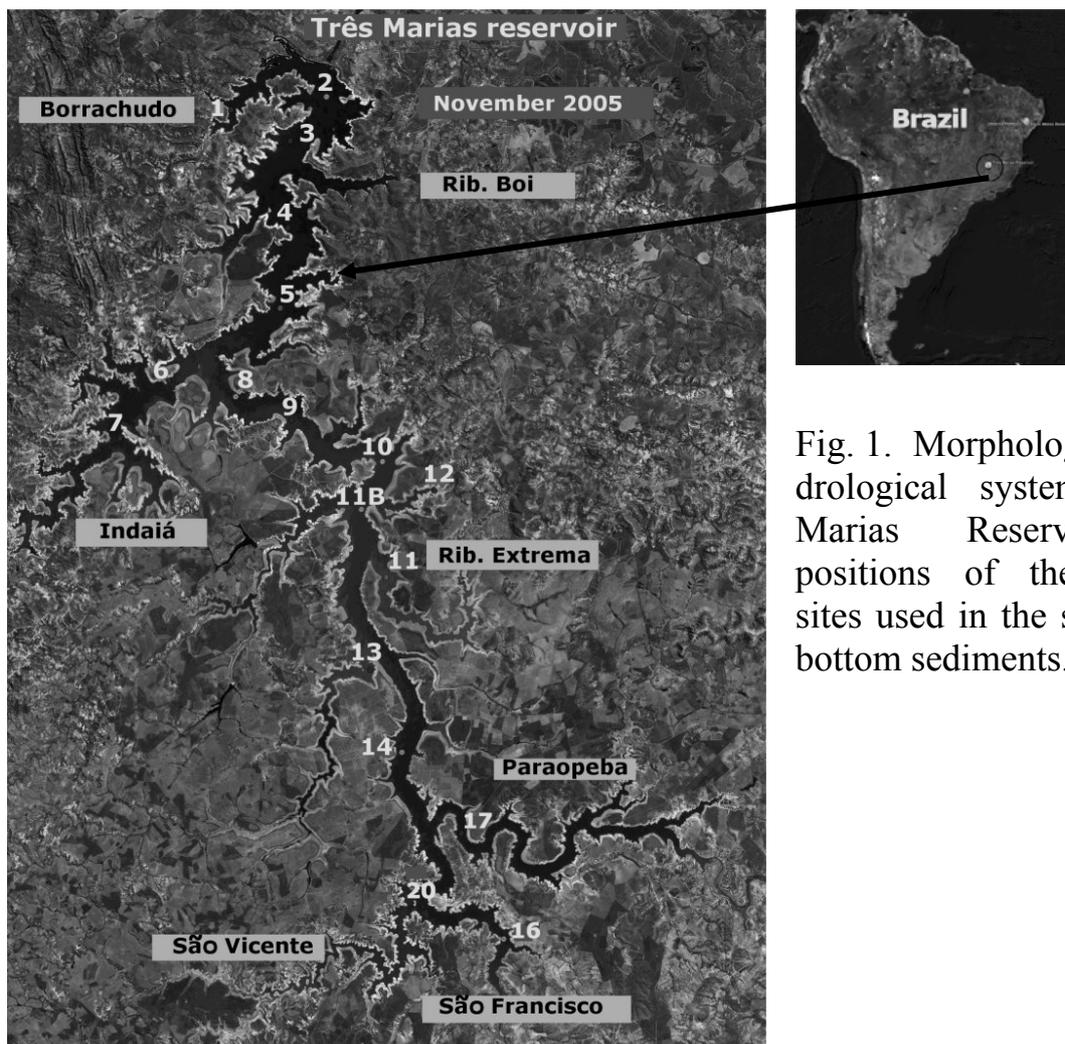


Fig. 1. Morphology and hydrological system of Três Marias Reservoir with positions of the sampling sites used in the study of the bottom sediments.

3. Lithology of the drainage basin

One of the most important features concerning the study of this reservoir is the two distinct groups of rocks in the catchment area, which enhance a significant array of mineralogical, textural and geochemical characteristics of the accumulated sediments. The geological setting is dominated by the Três Marias Formation which belongs to the ‘Série Bambúí’ group, mainly composed of

detrital sedimentary rocks consisting of micaceous and clayey siltstones with calcareous matrix, arkoses, ferruginous shales and metamorphic limestones. Plentiful zones of alluvial cover occur in the West sector (Fig. 2). This sector is also under the influence of the Mata da Corda Formation, which is responsible for the inputs of a large variety of nutrient elements, due to its composition represented by kamafugitic volcanic rocks. These are intrusive and extrusive ultrabasic, potassic rocks, mainly lavas, volcanic breccias, tuffs and ash, with a strongly weathered mineralogical composition consisting of olivine, pyroxene, amphibole, phlogopite, magnetite, ilmenite, diopside and glass, poor in silica and alumina and rich in titanium, magnesium and potassium (Leonardos et al. 1991).

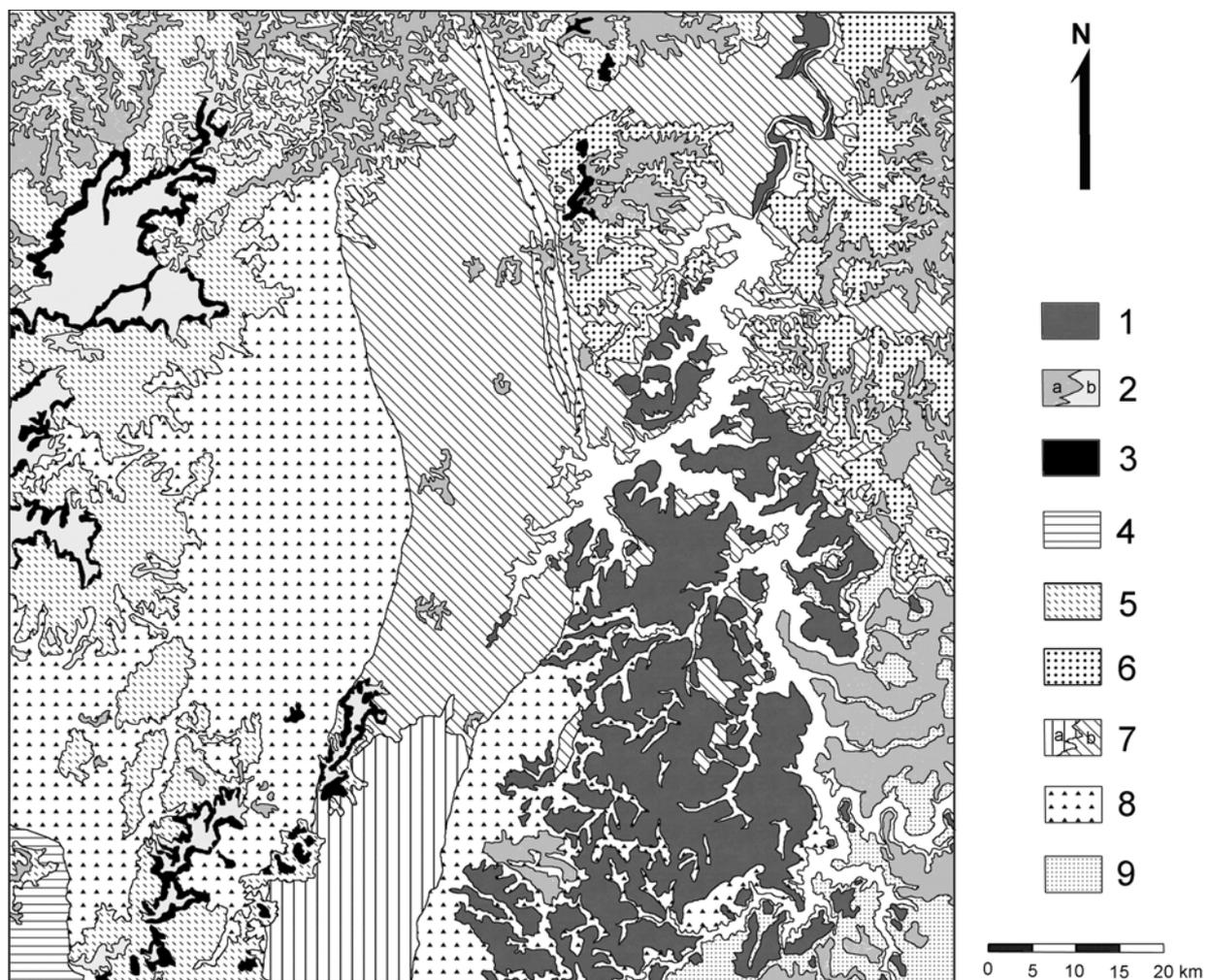


Fig. 2. Geological setting of the Três Marias basin drainage. Legend: 1 = Alluvium; 2 = Terraces, 2a = Sandy sediments, 2b = Laterites; 3 = Mata da Corda Formation; 4 = Sandstones (Areado Group); 5 = Carbonated/detrital sediments; 6 = Impure sandstones; 7a = Siltstones and mudstones, 7b = siltstones and arkoses; 8 = Layered siltstones and subordinated mudstones; 9 = mudstones and subordinated siltstones.

The dry tropical climatic conditions and the high water/rock ratio over a dominant detrital lithology associated with fewer zones of ultramafic volcanic rocks, provide soils characterized by thick surface layers enriched in fine-sized particles. Although the existence of spread areas of a few soil classes such as Argisoils, haplic Cambisoils and litholic Neosoils, the soils having higher influence on the sedimentation within the reservoir belong to the red and yellow-red dystrophic Latosoil group. These are deeply weathered soils, well drained and having high leaching of soluble elements, medium to high clay contents and frequently protected by a thick lateritic crust.

4. Materials and methods

To have a broad knowledge on the structure and functioning of this reservoir, the distribution of sediments was mapped from a regular sampling net with 18 points, relating this distribution not only to distance to the dam wall, but also to the position and importance of the various water streams that feed the reservoir and to the different conditions of sedimentation. Sediments were collected with a modified Shipeck dredge and were subjected to chemical, physical and mineralogical analysis, as follows:

Grain-size analysis: Separation of grain size classes (Wentworth Lane scale, Pettijohn 1975) by wet sieving (gravel-sand-silt clay, Buller & McManus 1979), dry sieving (grain-size sand distribution) and measurement of clay and silt distribution by a laser sedimentometer. Representation of clay, silt and sand proportions in a Shepard triangular diagram (Pettijohn 1975) and subsequent classification; according to grain-size distribution, sediments were mapped (Fig. 3).

Characterization of clay minerals: Clay mineralogy was studied not only in the sediments collected in the reservoir, but also in a few representative soils collected in the drainage basin. The clay fraction ($< 2 \mu\text{m}$) was extracted by centrifuge sedimentation and oriented aggregates (glass slide method) were prepared by a procedure described by Moore & Reynolds (1997). Samples were subjected to drying at room temperature, ethylene glycol solvation and heating to 550°C and submitted to X-ray diffraction analysis (Co-K radiation). Clay minerals identification and characterization were based on the procedures of Thorez (1976), Moore & Reynolds (1997) and Wilson (1999). pH (H_2O) was measured by a potentiometer in a water-sediment suspension.

Elemental geochemistry: Total abundances of selected major elements (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , Na_2O and K_2O) were determined by IC and DC Plasma at the Bondar-Clegg Laboratories, Canada. Values were compared with the corresponding chemical composition of parent rocks/soils that develop on them by weathering. The relation or association of 2 or more parameters (covariance) was addressed by using (a) the Pearson coefficient of correlation (r),

significant for $p < 0.05$ and (b) the multiple regressions with variance test (ANOVA). These analyses were performed through the SPSS (version 13.0).

Soluble phosphorus: Evaluation of the soluble contents of phosphorus (orthophosphate) was based on the spectrophotometry method using molybdenum blue (Pansu & Gautheyrou 2006).

Nitrogen and carbon: Nitrogen and carbon were determined using an elemental analyzer for CHNS-O based on the principle of dynamic flush combustion coupled with gas chromatography (Pansu & Gautheyrou 2006).

5. Sedimentary, chemical and mineralogical functioning of the Três Marias Reservoir

The main factors that determine the sedimentation within the reservoir are: (a) a dry tropical climate responsible for a high intensity of rock and soil weathering followed by extreme leaching of soluble elements (Ca, Na, K, Mg) and preferential accumulation of stable elements (Si, Al, Fe); (b) a homogeneous geological setting, dominated by easily erodible detrital sedimentary rocks with scarce zones of ultramafic volcanic rocks; (c) a selective erosion of soil particles that leads to a preponderance of colloidal minerals and organic compounds with high cationic exchange capacity; and (d) mineralogical and chemical transformations occurring during the cycles of erosion-transport-accumulation of particles from the weathering rock/soil profile to the bottom of the reservoir.

5.1. Texture

The sedimentary distribution in the bottom (Fig. 3) coincides with the major contribution of fine material, disclosing the important influence of the drainage basin lithology, characterized by fine-grained detrital sedimentary rocks, associated to selective erosion processes. Most sediments fall in the silt, silty clay and clayey silt textural classes and average grain size increases to the margins where deposition of the coarser fraction predominantly takes place. The slight textural variations displayed along the reservoir reflect local fluctuations of the hydraulic flow, which produces distinct energetic conditions inside the lake.

5.2. Mineralogy of the clay fraction

The sediments of Três Marias have a simple clay assemblage, which denotes a high mineralogical evolution, characteristic of an environment dominated by a high intensity of rock weathering, due to a high water/rock ratio, which promotes high leaching rates and salt movement during soil erosion. Furthermore, the low activity and partial dissolution of Si and the high accumulation of stable elements

Al-Fe in the accumulated material, according to Righi and Meunier (1995), is accelerated by the low pH of sediments ($4.85 < \text{pH} < 5.65$). These mechanisms, coupled with a homogeneous composition of the parent rocks produce:

- a small variety of minerals dominated by kaolinite (mean = 59.0 %) and illite (mean = 38.2 %), followed by lesser amounts of chlorite (mean = 2.7 %),
- an uniform distribution of abundances and chemical/structural characteristics of minerals along the reservoir (Fig. 4).

The variations observed in the relative abundances and in some structural and chemical aspects of minerals disclose either inheritance from distinct parent rocks and distinct soils or the existence of diverse chemical conditions in the deposition environment. The comparative study between the weathering mineralogy of soils of the drainage basin and the clay mineralogy of the reservoir sediments indicates that, from the erosion of the basin upstream to the deposition into the reservoir, the clay-size weathered particles mainly composed of clay minerals, unlike other studied systems (Fonseca et al. 2006) have not transformed significantly.

The presence of illite as one of the most important minerals in the clayey fraction of sediments is in accordance with its medium-high abundances in the soils of the drainage basin, which corresponds to the major source of the most part of the accumulated material in this system, coupled with its probable selective erosion in relation to kaolinite particles, as a consequence of its lower dimensions. Though the low abundances of disordered illite in the red dystrophic Latosol, the group having higher influence on the sedimentation in the central-south region of the reservoir, the sectors where this mineral attain the higher contents are setting by Cambisoils, where illite percentages are very similar to those of kaolinite.

The medium to high values of kaolinite and the absence or the presence of low contents of chlorite, suggests incorporation of residual weathering products in the bottom sediments, reflecting the contribution of an intensely weathered lithology.

In each mineral, the intensities ratio and the shape of the corresponding reflections in the diffraction patterns, reflect the preponderance of Fe over Mg or Al, denoting the Fe-rich nature of the setting clastic sedimentary lithology.

5.3. Elemental total geochemistry

The diversity of basic factors that determine the sedimentation within this hydric system are

- the maximum, medium and minimum values of the major elements in sediments (Fig. 5),
- the comparison between the chemical composition of sediments and of a few representative soils of the drainage basin and

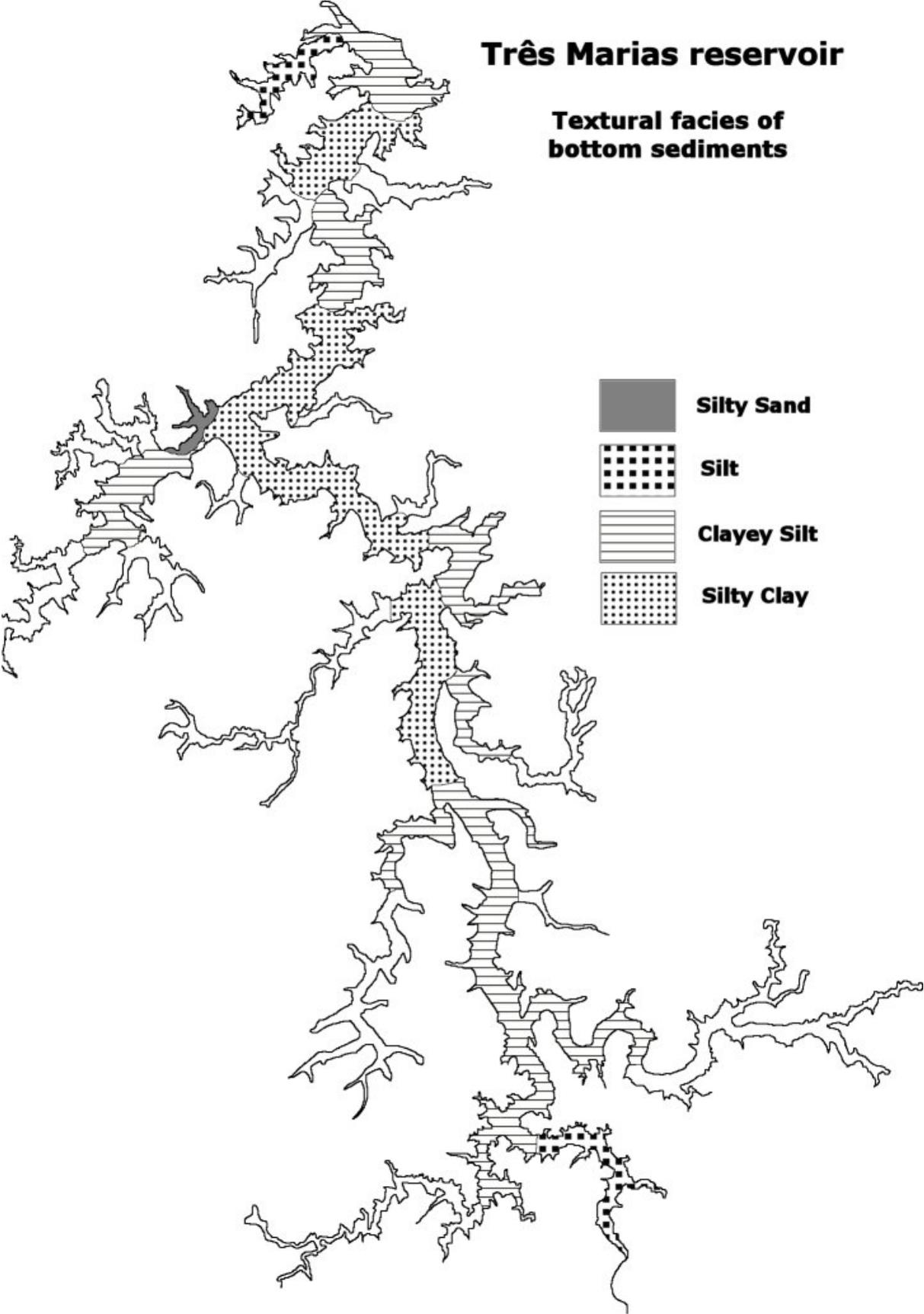


Fig. 3. Textural facies map of bottom sediments from Três Marias Reservoir.

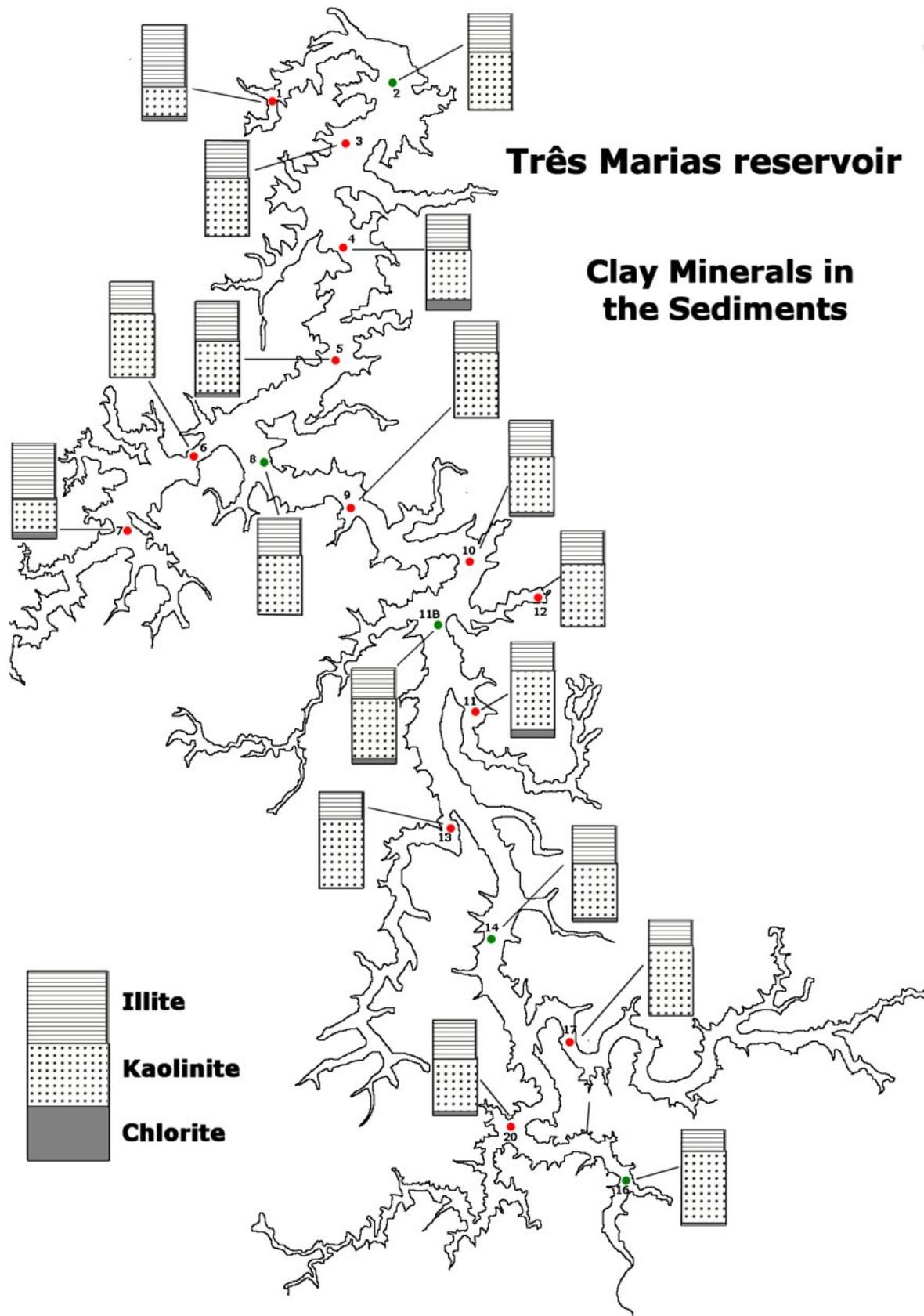


Fig. 4. Spatial distribution of the clay mineral groups in the clayey fraction of sediments from Três Marias Reservoir.

- the ratio between abundances of elements (Si/Al, Fe/Mg, Fe/Al, Na/K and Ca/Na).

They disclose the chemical weathering of the two distinct groups of rocks in the catchment area (detrital rocks of Três Marias Formation and sequence of intrusive and extrusive rocks of Mata da Corda Formation), as the major sources of the sediments accumulated in the bottom of the lake.

The distribution of elements along the reservoir, much more uniform than in other Mediterranean systems previously studied (e.g. Fonseca et al. 1998, Fonseca 2002, Fonseca et al. 2003), emphasizes the chemical homogeneity of the setting geology.

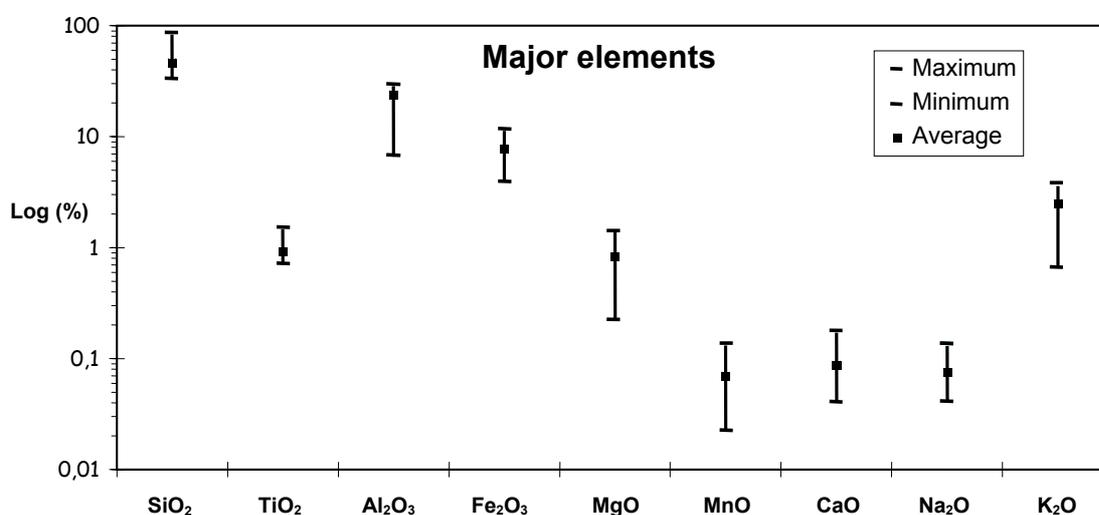


Fig. 5. Representation of the maximum, medium and minimum values of the major elements in sediments of Três Marias Reservoir (n = 18).

Magnesium and potassium are the elements showing higher dispersion in the reservoir and higher contents when compared with the values observed in red Latosols, the soil class having higher influence on the sedimentation. This difference is much pronounced in the branch of Indaiá River, sector of the reservoir under higher influence of rocks from Mata da Corda Formation, characterized by ultrabasic and ultrapotassic composition with Mg-rich minerals. Given the geochemical mobility of these elements, especially in a climate characterized by intense leaching rates of salts, Mg and K should probably be the only elements proceeding from this source which reach the reservoir with significant amounts. The provenance of these elements from the same source could be assessed through the high correlation coefficients between them, as shown in Table 1.

The influence of the geology of the catchment area on the chemical composition of sediments, deduced from the comparative study between values of the major

elements in sediments and in rocks/soils of the drainage basin, has an accurate definition from the association of different elements using analysis of linear correlation. This analysis allows the deduction about the main mineralogical sources of each element. In general, the medium-high correlation between major elements, suggests a lithogenic contribution from the weathering of rocks and soils of the drainage area. Among values of positive correlation, the higher ones correspond to elements having identical geochemical mobility.

Table 1. Matrix of linear correlation among major elements of sediments from Três Marias Reservoir (n = 18).

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O
SiO ₂	1.000 < 0.000	-	-0.874 < 0.001	-0.668 < 0.001	-0.431 < 0.05	-	-	-0.497 < 0.05
TiO ₂	-	1.000 < 0.000	-	-	0.595 < 0.005	0.401 < 0.05	0.827 < 0.000	0.579 < 0.006
Al ₂ O ₃	-0.874 < 0.001	-	1.000 < 0.000	0.540 < 0.05	0.415 < 0.05	-	-	0.543 < 0.01
Fe ₂ O ₃	-0.668 < 0.001	-	0.540 < 0.05	1.000 < 0.000	0.422 < 0.05	-	-	0.481 < 0.05
MgO	-0.431 < 0.05	0.595 < 0.005	0.415 < 0.05	0.422 < 0.05	1.000 < 0.000	0.446 < 0.05	0.629 < 0.003	0.935 < 0.000
CaO	-	0.401 < 0.05	-	-	0.446 < 0.05	1.000 < 0.000	0.625 < 0.003	0.423 < 0.04
Na ₂ O	-	0.827 < 0.000	-	-	0.629 < 0.003	0.625 < 0.003	1.000 < 0.000	0.679 < 0.001
K ₂ O	-0.497 < 0.05	0.579 < 0.006	0.543 < 0.01	0.481 < 0.05	0.935 < 0.000	0.423 < 0.04	0.679 < 0.001	1.000 < 0.000

SiO₂ and Al₂O₃, two key components in sedimentation processes, show negative correlations, implying origins from distinct sources. Silica does not show positive correlation with any other elements, thus it corresponds mostly to quartz, a common mineral in the detrital rocks of the Três Marias Formation. Aluminum, a major component of particulate matter, remains immobile during the transformation processes occurring under the Três Marias climatic conditions. This behavior could explain the uniform distribution of Al along the reservoir. The significant (but not high) correlation between Al and elements such as Fe, Mg and K, reflect a heterogeneous origin, probably from minerals like K-feldspar, muscovite and biotite, the first two minerals with strong presence in the nearest detrital lithologies and the latter, a major component of the volcanic rocks of Mata da Corda Formation.

High levels of Al₂O₃ and very low of CaO and Na₂O in the sediments, along with Na/K (0.020 – 0.060) and Ca/Na (0.750 - 1.800) ratios markedly lower than in the

most representatively soils and rocks of the drainage area, disclose the immobility of the first element, in opposition to the high mobility of Ca and Na during the chemical and mineralogical transformations occurred in the cycles of erosion-transport-deposition from the basin upstream to the reservoir. Very mobile elements such as Ca and Na are easily leached from the weathered rocks and soils and dissolved, entering without any difficulty in the percolation waters which flow to the reservoir. Although the most part of these ions stay in solution in the water column, they may be fixed or adsorbed in the structure of a few mineral and organic components of the accumulated products. The low content of Ca in sediments, when comparing with the pattern rocks and soils, only show significant correlation with Na, element with identical mobility, which may suggest the provenance of both elements from Ca-Na-minerals, like plagioclases, the major mineralogical components of some lithotypes of Três Marias Formation (e.g. arkoses). Calcium could also derive from the cement of a few siltitic rocks belonging to the same formation.

The medium-high contents of Fe along the reservoir and the low correlation between Fe and the other major elements, disclose its origin mainly from Fe-oxides, very common components of the setting lateric soils and of the cement of a large number of detrital rocks. The Fe/Al ratio (0.150 - 0.593) much lower than in the sequence of volcanic rocks of Mata da Corda Formation (Fe/Al = 2 - 3) and its low geochemical mobility, remove the possibility of its provenance from these lithologies.

5.4. Geochemistry of nutrients

In the likeness of other aquatic systems (e.g. Bloesch et al. 1988), the phosphorus found in the sediments has a mostly allochthonous origin, it enters into the reservoir under a particulate form and only a slight proportion is transported in solution. Considering the medium interval defined for various pattern soils (0.12 % P₂O₅), sediments show medium values (0.11 % P₂O₅), lower than in other similar systems previously study (Fonseca 2002; Fonseca et al. 2006), which reflect its inheritance from detrital rocks having low clayey components and from red Latosols and haplic Cambisols, generally depleted in this element.

The statistical analyses of linear correlation and multiple regression with variance test (ANOVA), performed on total phosphorous contents and a few other components of sediments, assessed that (a) the Al- and Fe-oxides are well correlated with this element (Fe₂O₃ - P₂O₅: $r = 0.877$; Al₂O₃ - P₂O₅: $r = 0.578$) and (b) only Fe₂O₃ explain 96 - 98% of the total variation of phosphorus, which clearly define as predominant P fraction, the P bonded to Fe followed by P bonded to Al. This association P-Al and P-Fe, along with the low pH (average pH = 5.17) and the prevailing mineralogy of sediments mainly composed by kaolinite and Fe-

oxides, can easily explain the much low levels of readily available P (soluble P), always less than 10 µg/L, despite the total P levels that compare well with the soils of the drainage basin (Fig.6, dotted-lines delimit the medium interval of soluble abundances for soils in general after Bear (1964) and Donahue et al. (1983). These inorganic components assure a strong retention and immobilization of P because they are variable-charged minerals and, in opposition to the majority of minerals having permanent surface charge, they are positively charged and have a high surface area, suitable for anions (orthophosphate) adsorption (Sparks 1995). Also, in minerals like kaolinite, the outer surfaces are layered by OH⁻. In an acid or near acid environment like this of Três Marias Reservoir, oxidriles can be partial or total replaced by anions existing in solution, like ortophosphates, which can be strongly adsorbed, inducing its evident decrease of solubility.

The remaining elements of major importance to the chemical and biological functioning of this system, organic carbon and nitrogen, are carried into the reservoir by flowing waters like streams and watercourses. In this sort of system (Fonseca 2002) major nitrogen sources are usually effluent discharges from top draining and excessive use of fertilizers in soils. The high linear correlation between both elements (N - C_{org}: r = 0.827, p < 0.01), denotes the predominance of the organic form of nitrogen over ammonia and nitrate. Also, the close relation between their abundances and the nature of the clay fraction explains the medium-high levels and the uniform distribution along the reservoir, where sediments are

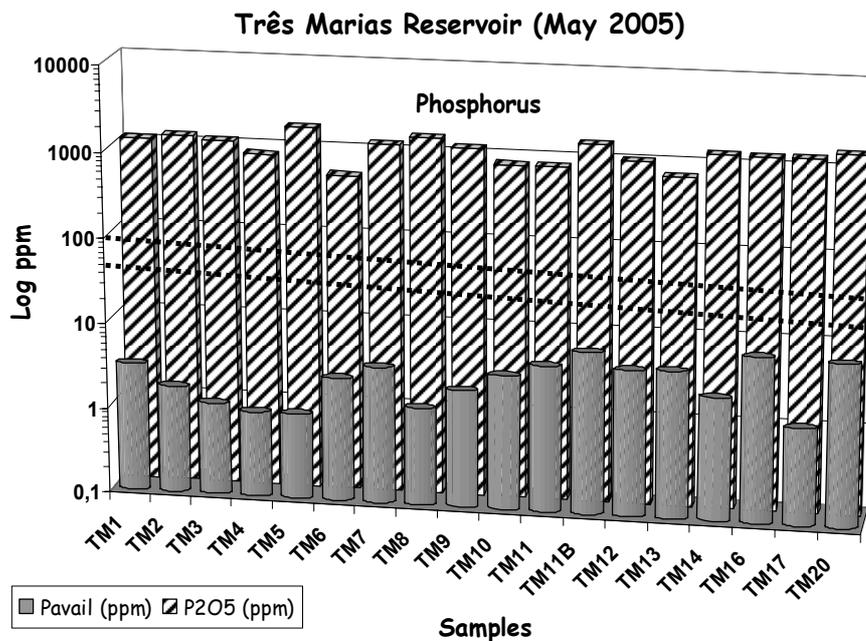


Fig. 6. Average phosphorus levels of sediments from Três Marias Reservoir (May 2005).

near homogeneous and mainly clayey: (N: mean = 0.17 %, max. 0.21 %, min. 0.07 %. Organic C: mean = 1.34 %, max. 2.31 %, min. 0.57 %.) With the exception of the most coarse-grained sample dredged near the margins of the reservoir, the C and N values are higher than average for mineral soils and far higher than in the soils of the drainage basin, showing that the sediments accumulated in the bottom of the reservoir represent an efficient sink for nutrients out coming from the over-erosion of soils in the catchment area.

6. Conclusions

The abundances of chemical elements in the sediments of the Três Marias Dam and their relation with the average values of the soils upstream outcome from their geochemical mobility. This results from a very strong chemical weathering environment. Among the studied elements, only Mg and K seem to derive from the sequence of volcanic rocks of the Mata da Corda Formation, which feeds directly the Indaiá River, taken as one of the main suppliers of clastic elements into the system.

The bulk physical, chemical and biological factors inside the reservoir, such as the physical and chemical conditions of the water and the acidity, bacteria activity, organic matter state and content, particulate size and the mineralogy of bottom sediments are factors which influence the mobilization, dispersion, distribution and concentration of nutrients. Most of the nutrients have a predominantly allochthonous origin and are strongly sorbed or fixed in the sediments. The latter act as a strong retainer, releasing nutrients to the reservoir water only when their levels in the water decrease, because of their mineralogical composition and fine-grained texture. This produces a general lack of nutrients in the aqueous environment, thus explaining the low phytoplanktonic primary production characteristic of Três Marias Reservoir.

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Contact address

Rita Fonseca, University of Évora, Department of Geosciences, Apartado 94, 7002-554 Évora, Portugal. Fon: ++351 266 745301 (Ext. 5325), e-mail: rfonseca@uevora.pt

Adress of the editors:

Priv. Doz. Dr. Günter Gunkel

Technische Universität Berlin, FG Wasserreinhaltung, Sekr. KF 4, Strasse des
17. Juni 135, 10623 Berlin. e-mail: guenter.gunkel@tu-berlin.de

Prof. Dr. Maria do Carmo Sobral

Universidade Federal de Pernambuco (UFPE), Departamento de Engenharia
Civil, Av. Acadêmico Hélio Ramos, s/n Cidade Universitária, 50.740-530,
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Cover figures:

Itaparica Reservoir, front: fisherman boots and irrigated agriculture of palm trees,
back: remaining vegetation 21 years after dam close.

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