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Reversing desertification by using dam reservoir sediments as agriculture soils

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Bottom sediments from two reservoirs in South Portugal were subject to chemical, physical and mineralogical study to test their suitability for agricultural use. In spite of large differences in geomorphic characteristics and lithology of the drainage basin, they have high levels of total, exchangeable and soluble forms of nutritional elements much needed for sustainable food-fibre production. Comparing our results with natural soils, we conclude that sandy sediments could be good agricultural soils on their own and the more clayey varieties, fertilizers for low quality soils. If sediment removal from the reservoirs becomes economically feasible, the suitability for agricultural use may eventually solve some classical problems such as: (1) the period of life of dam reservoirs filled with sediments, (2) the water quality, and (3) the scarcity of soils in some regions, turning a global problem into a global resource.

Introduction

Today one of the major problems of planet Earth is the progressive degradation of soils. It is interesting to note the words used in the Oxford dictionary for definition of desert, words such as uninhabited, desolate, uncultivated, and barren. Deserts can be present in all climates. According to the World Watch Institute, topsoil loss globally is approaching 1% per year, while natural remediation can take hundreds of years (Fyfe, 1989, 1997; UNESCO, 1997). The geochemistry and the mineralogy of soils are critical in estimating their capacity for sustainable organic productivity and to improve the chemical and physical properties of these soils. We often need to supply them some additives containing macronutrients and appropriate trace metals. The types of additives should be closely linked to soil type and climate to avoid pollution problems. So, instead of soluble chemical fertilizers often we should use mineral fertilizers with strict quality control (Fyfe, 1997). One of these mineral fertilizers could be the sediments accumulated in the bottom of dam reservoirs, from natural processes and over-erosion in drainage areas, which contain nutritional elements much needed in soils.

Dams have increased in numbers, because many regions depend on surface-water storage. In China, for example, in 1950 there were 2 large dams, while 35 years later there were 18,820! (Abramovitz, 1996, in Fyfe, 1997). Although hydroelectricity is one of the less polluting energy sources, dams are a problem because they represent barriers to the natural sediment transport cycle and today rivers don't flow freely to the oceans. On the other hand, the reservoirs themselves lose value as they become filled with sediment and the quality of water progressively decreases due to nutrients and metals release from bottom sediments. One of the methods to recover eutrophic systems, as managed in Swedish lakes, is dredging superficial nutrient-rich sediments (Ryding, 1982). Once removed, these sediments could be an important resource for agricultural use, if they do not have high levels of toxic elements.

This study was aimed at determining the suitability of reservoir sediments as agricultural soil additives or mineral fertilizers in eroded regions. Thus, we have studied the bottom sediments from 2 reservoirs in South Portugal (Alentejo region), to test their fertility through chemical, physical and mineralogical analysis. These reservoirs belong to distinct hydrological basins and they are very different with relation to geomorphology and geologic characteristics, age and uses (Table 1).

Maranhão is an old dam, largely filled with sediments and is the largest surface water reserve of Alto Alentejo. Its drainage basin has a remarkable geological diversity, very important in relation to geochemical and mineralogical studies of the sediments. There occurs a Cenozoic sedimentary cover over Paleozoic and Precambrian formations of the Variscan Fold Belt. This basement includes a large diversity of metasediments (shales, and pelitic schists, greywackes, quartzites, conglomerates, carbonate rocks), metavolcanic sequences ranging in composition from acid to basic rocks and an intrusive massif (granitic rocks with different geochemical features and mafic and ultramafic intrusive bodies). The Cenozoic sedimentary cover is mainly detrital (Gonçalves, 1971; Carvalho & Carvalhosa, 1982; J.T. Oliveira et al., 1991). Fonseca et al. (1993) have previously studied the sediments of this dam in some detail.

Monte Novo is much more recent and supplies water to Évora, the largest city in the Alentejo region. However, it has many problems related to water quality, due to the excess of N and P which have originated some toxic compounds, e.g. trihalomethane. Its drainage basin has much less geological diversity and includes 2 distinct zones: the North is greatly influenced by intrusive acid rocks (tonalitic and granitic rocks) and South by Paleozoic schists with some basic volcanites and scarce zones of Miocene cover (shales, conglomerates and carbonate rocks) (Oliveira et al., 1992).

Table 1 Hydrological and morphometric characteristics of the Maranhão and Monte Novo reservoirs.

Reservoirs	Year	River	Basin	Surface area (km^2)	Volume (m^3)	Maximum depth (m)	Average depth (m)	Main use
Maranhão	1957	Sorraia	Tagus	19.6	205×10^6	55	16	irrigation
Monte Novo	1982	Degebe	Guadiana	2.8	15×10^6	30	5	domestic

Methods

In both reservoirs we have performed the sampling in winter, because in the annual cycle, this season corresponds to the period when more nutrient deposition takes place (Bostrom & Pettersson, 1982). The sediments were collected from a regular sampling net (60 points in Maranhão, 13 points in Monte Novo) with a Shipeck and a modified Van Veen dredges. The sediments were subjected to most of the chemical and physical studies routinely used for the evaluation of soil fertility (according to Danahue et al., 1983): grain size, organic matter content, pH, Kjeldahl N, available major (P, K) and micronutrients (Fe, Mn, Zn, Cu, B and Mo), cation exchange capacity, and exchangeable cation contents. Total element analysis and clay mineral identification and characterization were also carried out to have a more complete knowledge, regarding the sediments capacity for nutrients retention and their value as a nutrients reserve potentially usable by plants.

The methods used for chemical, physical and mineralogical analysis were 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 (1954) triangular diagram (Pettijohn, 1975) and subsequent classification. According to grain-size distribution, sediments were mapped (Figure 1 A, B) and in the Maranhão reservoir sixteen samples were depicted as representative of the various morphological characteristics.

Clay mineral characterization: Extraction of clay fraction (< 2 µm) by centrifuge sedimentation, saturation with different cations (Mg^{2+}, K^+, Li^+) and preparation of an oriented aggregate (glass slide method) by a procedure described by Moore & Reynolds (1997). Samples were subjected to drying at room temperature, ethylene glycol solvation and heating to 300 °C or 550 °C and submitted to X-ray diffraction analysis (Co-K radiation). Clay minerals identification and characterization were based on Thorez (1976), Wilson (1987) and Moore & Reynolds (1997). Subsequent complementary studies were also performed (at the Macaulay Land Use Research Institute, Aberdeen, Scotland) through a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDX) and an infrared spectrometer (FTIR) (prepared as KBr discs).

Organic matter: Samples were frozen soon after collection at –20 °C and the organic matter content was determined by oxidation with $K_2Cr_2O_7$ and titration with $FeSO_4$ (LNEC, Portugal, standard E201, 1967).

pH: pH (H_2O) was measured in a water-sediment suspension.

Elemental geochemistry: Total abundances of selected elements (P, K, Fe, Mn, Zn, Cu, B and Mo) were determined by IC and DC Plasma at the Bondar-Clegg Laboratories, Canada and the evaluation of the corresponding plant-available contents were based on Egner-Riehm (P, K), Lakanen (Fe, Cu, Mn, Zn) boiling water (B) and thiocinate (Mo) methods (Page et al., 1982). Nitrogen was measured by using the Kjeldahl technique. These analyses were performed in the Laboratório Químico Agricola Rebelo da Silva, Lisbon, Portugal.

Cation exchange capacity (CEC): CEC and the exchangeable cations contents were estimated by using the Mehlich method (Thomas, 1982).

Results and discussion

Grain size analysis

In both reservoirs, grain size analyses (Figure 1 A, B) suggest a remarkable sedimentary diversity, owing to (1) large geological diversity of the drainage basins, and (2) local and seasonal fluctuation of the hydraulic flow that produces distinct energetic conditions inside the lakes. The sedimentary distribution in the bottom coincides with the major contribution of fine material, as observed in other similar systems (Sly, 1978; Keulder, 1982; Duck, 1986). Most sediments fall in the silty clay and clayey silt textural classes and are deposited in the old watercourse bed along the reservoirs which corresponds to the larger depths. Average grain sizes increase to the margins where deposition of the coarser fraction predominantly takes place. In the Monte Novo reservoir, the two main branches have a different grain-size distribution for similar depths, which evidences the important influence of the drainage basin lithology: branch near N-S—finer sediments—schists; branch near NW-SE—coarser sediments—granitic rocks.

Clay mineralogy

The overall study performed by X-ray diffraction (XRD), infrared spectral analysis (FTIR) and electron microprobe analysis (hooked up to a SEM) shows clearly that the mineralogical composition of clay fraction of the sediments is very similar in both reservoirs, with a large variety of clay minerals present in both cases. Only relative abundances vary as a consequence of the geological variation of drainage basins. In Maranhão sediments the main clay mineral is

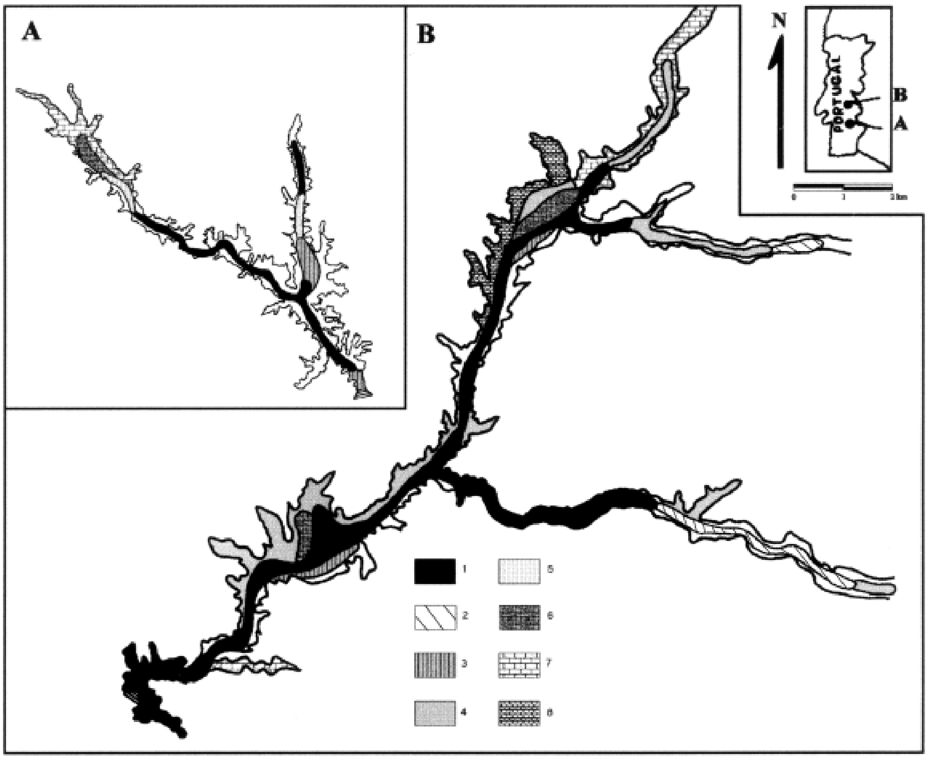


Figure 1 (A, B) Textural facies map of bottom sediments from Monte Novo (A) and Maranhão (B) reservoirs. 1 –silty clay / clayey silt, 2 –silt, 3 –sand-silt-clay, 4 –sandy silt, 5 –silty sand, 6 - sand, 7 –coarse sand-gravel / silty coarse sand, 8 –silty gravel / gravel.

montmorillonite whereas in Monte Novo it is illite. In the latter reservoir chlorite is more abundant, probably as a result of the large influence of schists in the surrounding area. The large variety of clay minerals is as follows, which plays a fundamental role in plant nutrition. Their nature and structure explain the geochemical composition found in the sediments:

(1) Smectites: dioctahedral calcium smectites, montmorillonite variety, more abundant in the Maranhão reservoir (sometimes over 60%), often associated with illite-montmorillonite mixed-layered, well to medium crystallized in Maranhão and with medium to poor crystallinity in Monte Novo, where there appear some Fe^{3+} rich smectites (nearly nontronite).

(2) Illites: potassium illites with a variable K/Na ratio in the Monte Novo reservoir, Al^{3+}, Fe^{3+} or Al^{3+}+Fe^{3+} rich in the octahedral sheet. Aluminous illites are more abundant and the substituition of Al^{3+} for Fe^{3+} is less common in Monte Novo sediments. According to the position and shape of the (001) peak on XRD patterns (Lucas, 1962; Chamley, 1967; Moore & Reynolds, 1997), illites vary from well to medium crystallized and, in a few samples, the asymmetry of some basal reflections is indicative of a transition to mixed layer systems (‘open’ or degraded illites—IM, IC, IV).

(3) Kaolinites and chlorites: medium to highly disordered kaolinites and chlorites. Chlorites are trioctahedral and mainly Fe-rich. The difference in the resolution of kaolinite peaks shown by infrared diagrams denotes that in the Maranhão sediments the disordering is lower. Beside, in this latter reservoir, the various groups of minerals show a crystallinity increase.

(4) Vermiculite: vermiculite occurs in almost all sediments in both reservoirs, with an abundance of about 5% of the clay fraction.

(5) Randomly interstratified or mixed layers and structures (chlorite-vermiculite, illite-montmorillonite, illite-chlorite): these are moderately abundant in both reservoirs.

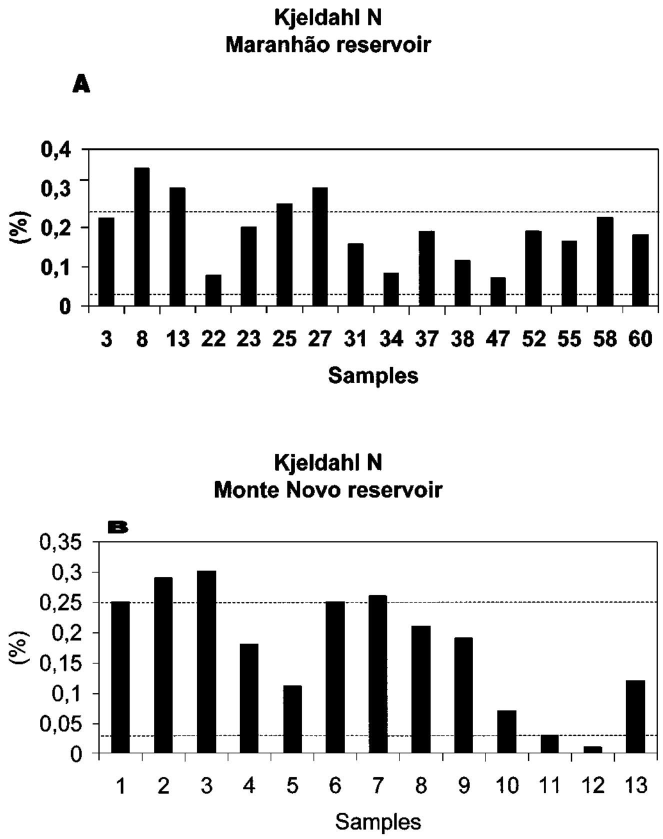


Figure 2 (A, B) Nitrogen levels of Maranhão and Monte Novo sediments. Dashed-lines delimit medium range of total nitrogen for soils in general (after Bear, 1964; Donahue et al., 1983).

The low degree of crystallinity is based on (1) asymmetric, low-intensity and broad reflections in XRD patterns, (2) broad bands and little inflections in IR spectra and (3) diffuse clay crystal morphology on SEM images. This indicates an allochtonous origin for most of the clay minerals in the sediments. Besides, the disorder in the stacking of layers shown by degraded and interstratified structures and the non-dependence of the various clay minerals in spatial distribution in the bottom of reservoirs from the lithology of drainage basins, denotes important transformation mechanisms inside the reservoirs or in the surrounding soils. The main domain of expanding clays (montmorillonite) in the sediments and the fact that illite and chlorite are the preponderant minerals in the parent material of the drainage basins formations suggest a classical transformation sequence: illite, chlorite–vermiculite–montmorillonite.

Organic matter content

In both reservoirs organic matter contents are usually within the medium interval for soils in general (2%–7%, Bear, 1964, Donahue et al., 1983) except in sandy sediments where values are low (< 2%). However, the values in Maranhão sediments (clay-silt sediments: 2.5%–6%, medium value: 3.7%) are slightly higher than those in Monte Novo (clay-silt sediments: 2.2%–3.3%, medium value: 2.8%). This difference is probably due to the lower energy level of the latter reservoir, which implies a lower entrance of allochtonous organic material into the system. Besides, other probable sources of this organic material (plankton, organisms in the bottom and margins, vegetation) could be quite different in the two reservoirs. Organic compounds are concentrated in clay and silt fractions .

Chemical study of sediments

The chemical composition of sediments is fundamental in relation to their suitability for agricultural use. As for soils in general, it is important to study the nutrients levels and the conditions that enhance their release and availability to plants. According to Twinch & Breen (1982) the nature and levels of chemical elements in the sediments of the reservoirs are related to: (1) mineralogical composition of sources in the drainage basin, (2) weathering processes during material transport to the reservoirs, and (3) dynamic equilibrium between sediments and water.

pH values

In the Monte Novo reservoir and in most sediments of Maranhão, pH values are neutral or near neutral (5.5–7.2) which, according to Donahue et al. (1983), are in the range considered most advantageous for the ready availability of most nutrients in soils. A few samples in the deeper zones of Maranhão are near acid, probably due to the acid nature of organic matter and/or the high levels of Al_2O_3 (20%) and Fe_2O_3 (8%–9%). These oxides, under some conditions (Bohn et al., 1985), enhance the release of H^+ and high contents of exchangeable H^+ and Al^{3+}, which show higher levels in those samples (5.4–6.6 meq/100g).

Total and available elemental geochemistry

Representative element levels are presented in figures 2, 3, 4 and 5, which show the total and the available form of each element and the difference between their abundances, giving a measure of the existing reserve nutrients, provided that these elements are contained in minerals susceptible to weathering. To test the fertility level of the sediments, each parameter was compared with the corresponding medium interval as defined for various mineral soils after Bear (1964), Donahue et al. (1983) and Santos (1991).

(1) *Nitrogen*: In both reservoirs, except in sandy sediments where values are low (< 0.1%), Kjeldahl nitrogen has a high level (Maranhão: 0.115%–0.35%; Monte Novo: 0.12%–0.30%) and sometimes exceeds average values for mineral soils (0.02%–0.25%). According to Henriques (1989), major nitrogen sources are basically

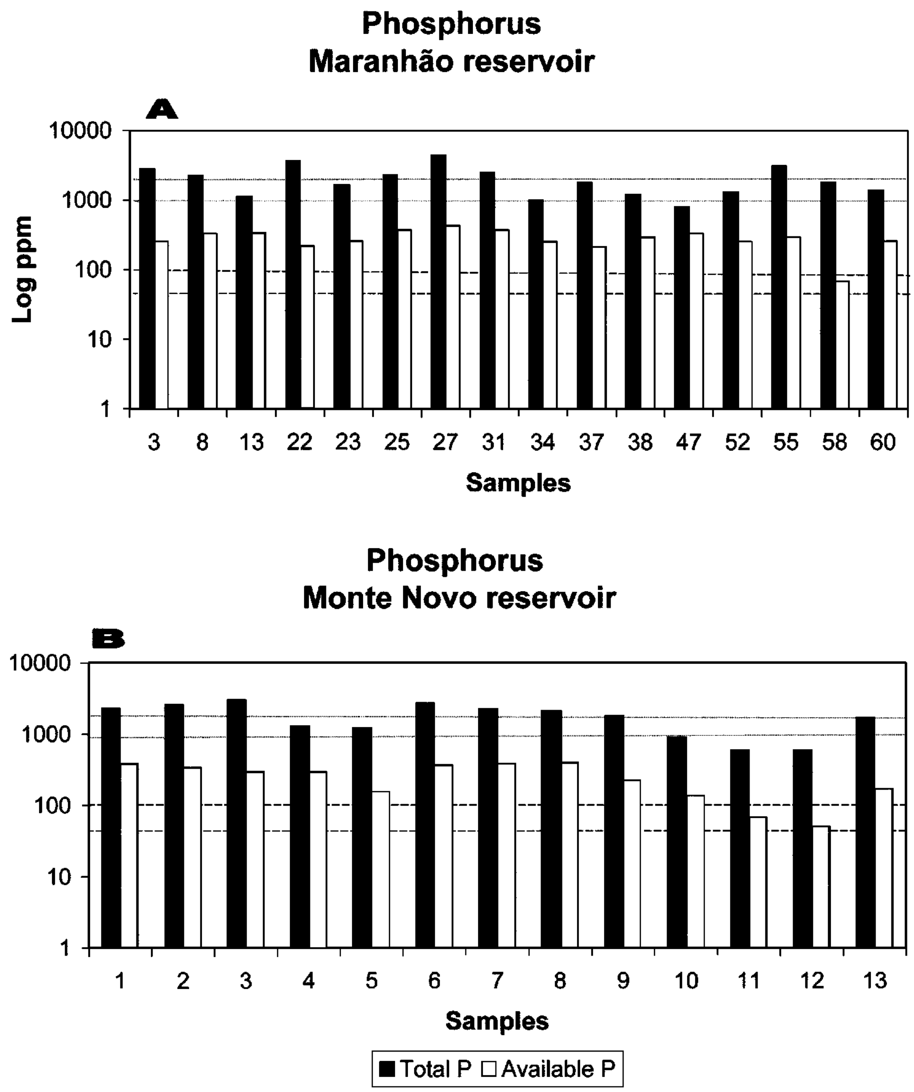


Figure 3 Phosphorus levels of Maranhão and Monte Novo sediments. Dotted-lines and dashed-lines delimit medium intervals of total and available abundances for soils in general (after Donahue et al., 1983; Santos, 1991).

top draining and subsoil affluents. The linear correlation between organic matter and nitrogen levels in the Maranhão sediments (r = 0.9; n = 16), and the Kjeldahl nitrogen always > 95% with respect to ammonia+nitrate in the Monte Novo sediments (Figure 2B), denotes that organic nitrogen is largely dominant in both dams.

In spite of the immediate unavailability of the organic nitrogen, our sediments have advantageous characteristics (fine-grained texture, mineralogy superposed by expanding clays, high K levels) to enhance the mineralization and further availability of organic forms and the adsorption of ammonia on clay minerals and humic molecules exchange complexes (which provide a reserve nutrient).

(2) *Phosphorus and potassium*: phosphorus (Figure 3 A, 3B) and potassium (not graphically represented) have an identical distribution pattern. Total element levels compare well with medium values for mineral soils and sometimes exceed them in the clayey and silty sediments.

In the Maranhão reservoir, organic and inorganic forms of phosphorus have been studied and unlike nitrogen, inorganic forms prevail with average values ranging from 87.6% in sandy sediments to 93.6% in clayey-silty sediments. The linear correlation between total abundances of this element and Fe_2O_3 (r = 0.56, n = 57) and Al_2O_3 (r = 0.40, n = 57) levels enable to conclude that Fe-P and Al-P are the major phosphorus combinations in the bottom sediments of this reservoir. According to some authors (Bear, 1964; Donahue et al., 1983), these fractions are the main sources of available phosphorus, which explains (together with other chemical and physical characteristics) the high and very high levels of the available contents of this nutrient. Monte Novo sediments have similar available phosphorus abundances (see Figure 3 B), showing the suitability of these dam sediments, especially the more clayey varieties, as phosphorus fertilizers. The high levels of this nutrient are also very important to the availability increase of metallic micronutrients, because, according to Shuman (1988), such high values enhance the release of micronutrients from exchange or interlayer positions to the soluble phase.

The availability of potassium for plant uptake has been studied through soluble (available) and exchangeable forms because due to the dynamic equilibrium between both, exchangeable potassium can be easily released by exchanging with other cations in solution or can be directly absorbed by plants. In our sediments the evidence of this equilibrium is the high linear correlation between both forms (e.g. Maranhão: r = 0.8, n = 16). The contents of available potassium are high or very high (Maranhão: 60 ppm–285 ppm; Monte Novo: 40 ppm–392 ppm) comparing with medium values for mineral soils (51 ppm–100 ppm) and they increase in proportion to both clay and montmorillonite contents (Fonseca, 1995). This soluble phase is slightly higher than the exchangeable one, the ratio between both increases in Monte Novo and the ratios K_{avail}/K_{total} and K_{exch}/K_{total} increase as grain sizes decreases (Fonseca, 1995). Exchangeable potassium levels, according to cationic exchange capacity (CEC), are within the medium interval for soils (100–175 meq/100 g, after Cottenie, 1980) and the slightly lower values of Monte Novo sediments are in accordance with the lower organic matter and montmorillonite contents (the main colloid particles that retain exchangeable cations on surface, after Bear, 1964 and Donahue et al., 1983). As for soils in general (Bear, 1964), the proportion of total potassium held in soluble and exchangeable forms is relatively small (< 2%), denoting that the majority of this element resides (1) in potassium-bearing feldspars and micas (reserve form) and (2) fixed in illitic clay minerals.

(3) *Micronutrients*: The two reservoirs have a similar distribution pattern of metallic elements. Zn and Mn data are depicted as representative examples in Figure 4 (A to D).

In general, the typical concentration of total forms for soils is : Fe: 2%–10%; Mn: 500 ppm–1000 ppm; Cu: 15 ppm–40 ppm; Zn: 50 ppm–100 ppm; and Mo: 1 ppm–2 ppm (after Donahue et al., 1983). In the Maranhão reservoir, total abundances of metallic micronutrients (average total abundances: Fe: 3.85%; Mn: 800 ppm; Cu: 27 ppm; Zn: 69 ppm) are within the normal ranges, whereas Mo is slighly higher (Mo: 2.5 ppm). In Monte Novo, metallic and nonmetallic elements have always higher values (average total abundances: Fe: 4.9%; Mn: 1139 ppm; Cu: 26.1 ppm; Zn: 75 ppm; B: 73 ppm) and except in sandy sediments, Mn and B levels could represent a pollution problem because they exceed the concentration levels considered toxic to the majority of soils (Mn > 1000 ppm, B > 50 ppm, after Donahue et al., 1983). However, the most part of B concentration is a non-soluble form and not prejudicial to the environment, because its available (soluble) contents (B: 0.30 ppm–1.06

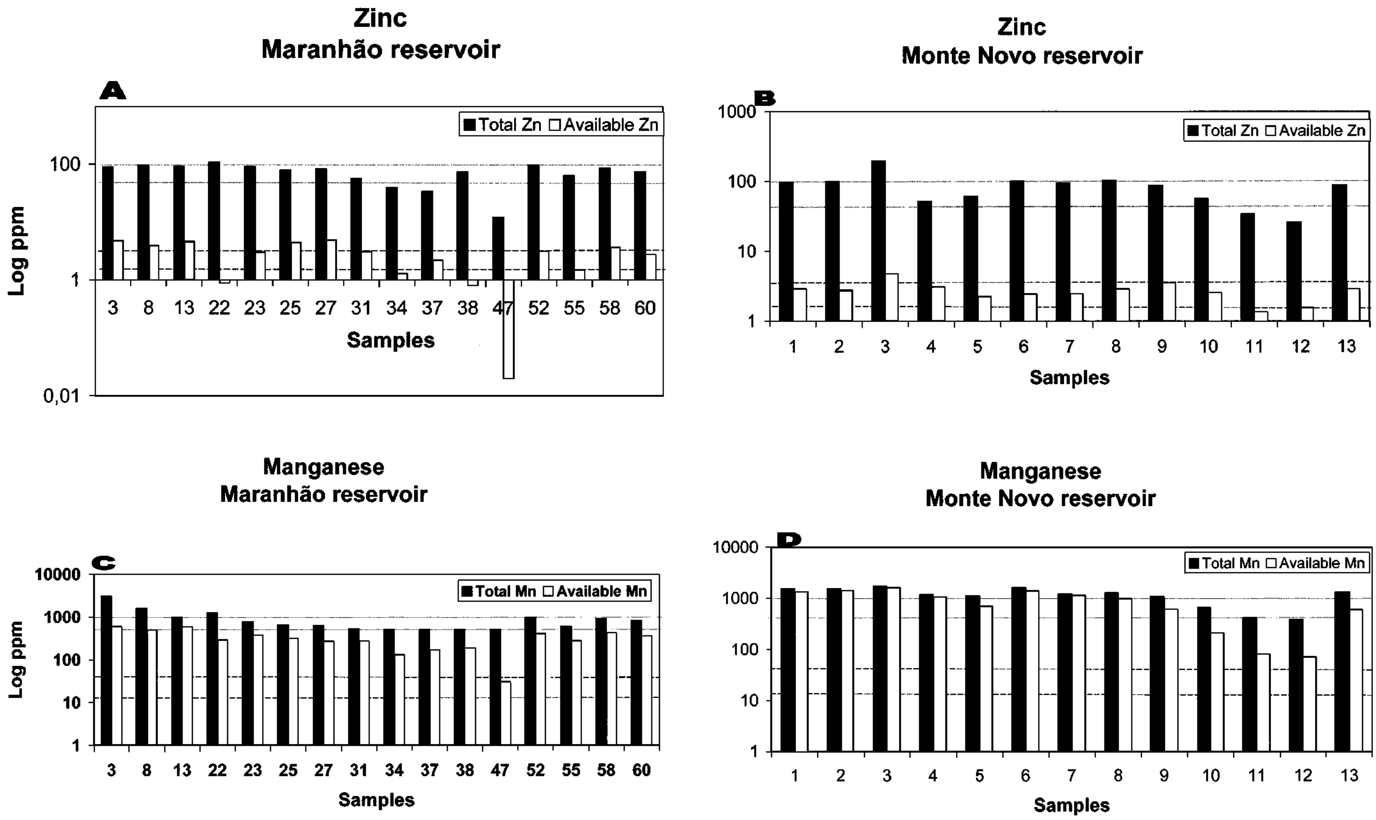


Figure 4 (A to D) Metallic micronutrients levels of Maranhão and Monte Novo sediments. Dotted-lines and dashed-lines delimit medium intervals of total and available abundances for soils in general (after Bear, 1964; Donahue et al., 1983).

ppm) are within the medium range for mineral soils (0.4 ppm–1 ppm). A linear correlation between total Mn and Fe_2O_3, Al_2O_3 and clay abundances (n = 13: Mn_{tot} - Fe_2O_3 = 0.93, Mn_{tot} - Al_2O_3= 0.83, Mn_{tot} - %clay= 0.92) suggest that this element can be adsorbed or coating fine grained particles (clay minerals, iron and aluminum oxides) or co-precipitaded by these oxides. Identical correlations were found in Maranhão sediments (Fonseca, 1995).

As for total forms, in the Monte Novo reservoir, available levels of metallic micronutrients are very high (average available values: Fe: 1119 ppm; Mn: 797 ppm; Cu: 7.1 ppm; Zn: 2.7 ppm), compared with normal levels for mineral soils (Fe:100 ppm–300 ppm; Mn: 16 ppm–45 ppm; Cu: 0.9 ppm–7 ppm; Zn: 1.5 ppm–3.5 ppm, after Bear, 1964; Donahue et al., 1983). In Maranhão, only Fe and Mn in the more clayey sediments are up to these limits. The high available levels of these latter elements in both systems can be explained by the reduced conditions of the environment and the pH values from acid to neutral, which enhance a decrease of the nutrients retention on the exchange complex and a subsequent availability increase. For concentration levels considered toxic, only Mn in the clayey sediments of Monte Novo reservoir exceed these limits. According to Bohn et al. (1985), the abundance of Mn could be related to the prevailing redox conditions and reduced forms are more soluble. Therefore, if we use these sediments as agricultural soils or additives, under aerial conditions, Mn will be more oxidized, decreasing its availability to plants.

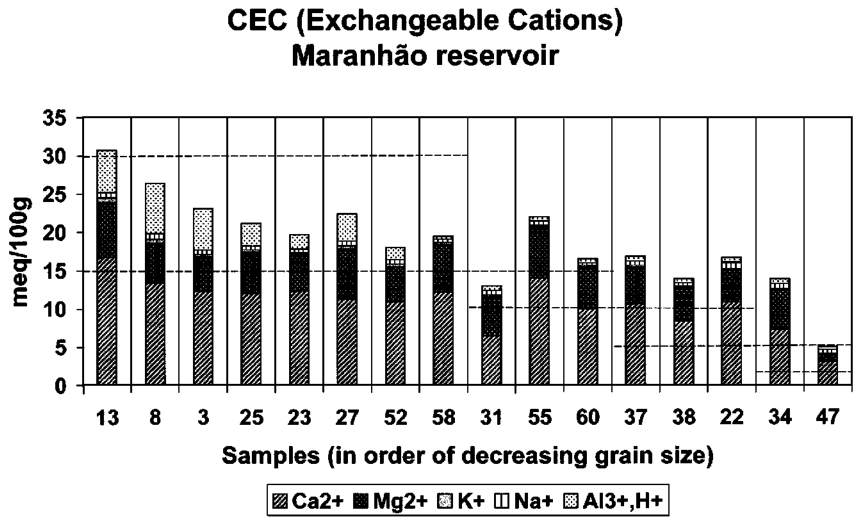
Metallic nutrients levels and the ratio available/total element increase in proportion to increased clay and organic matter and Fe_2O_3 and Al_2O_3 contents. Distribution patterns of total and available B and Mo differ from that of the remaining nutrients and no correlation was found between their abundances and any other sediment characteristics.

(4) *Cationic exchange capacity (CEC)*: According to textural characteristics of sediments, CEC values are from medium to high, relatively to medium intervals fixed for different granulometric groups of soils (Cottenie, 1980) (Figure 5).

CEC values decrease in proportion to increased particles size (Figure 5). Adsorption and cationic exchange phenomena depend mainly on clay size (e.g. Maranhão— linear correlation CEC-%clay: r = 0.73, n = 16) and organic particles (e.g. Maranhão—linear correlation CEC - %O.M.: r = 0.65, n =16). The high levels present in the sediments are probably due to the high contents of both the total clay fraction and montmorillonic minerals and significant amounts of vermiculite and mixed layer structures of this latter mineral. According to some authors (Bear, 1964; Donahue et al., 1983; Bohn et al., 1985, Sposito, 1989), these two clay minerals have the higher CEC values, being only slightly pH-dependent.

In both reservoirs, sediments have a relatively uniform exchangeable cation distribution. Ca^{2+} represents more than 50% of total CEC and its abundances are within the medium interval proposed by Cottenie (1980) for mineral soils. The slightly higher ratio Mg^{2+}/CEC in Maranhão may reflect the ferromagnesian parent material found in this reservoir's drainage basin.

Concerning the fertility of the sediments, the high values of available macronutrients and CEC, and the clay mineralogy are very advantageous. The high level of montmorillonite and the presence of vermiculite (as a proper mineral and mixed layer), due to their high cation exchange capacity, enhance the availability of nutrients (Bear, 1964; Donahue et al., 1983; Santos, 1991). Furthermore, the crystallinity of most clay minerals is not high and there occur significant amounts of randomly interstratified structures which are favourable to the use of nutrients by plants through slow release of components. Also, as adsorption and cationic exchange phenomena allow colloidal particles to be a nutrient ions reserve, these dam sediments offer very good conditions for agricultural use. Preliminary work in some Maranhão sediments (Fonseca et al., 1993) produced excellent results with tulip growth. These sediments compare well with top



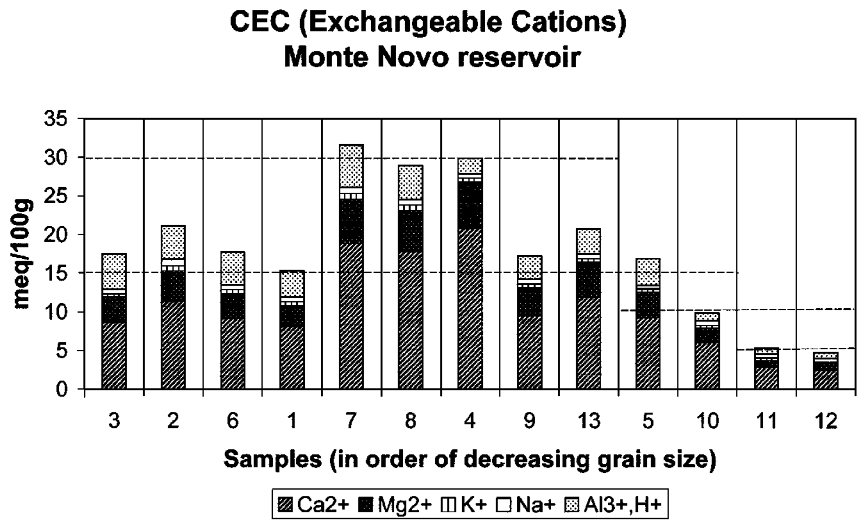


Figure 5 CEC (total bars) and exchangeable cations distribution (within each bar) in Maranhão and Monte Novo sediments plotted in order of increasing abundance of the clay fraction. Dashed lines indicate the medium intervals for CEC fixed for different granulometric groups of soils, according to the granulometric characteristics of the sediments.

quality potting soil. Work in both the Maranhão and Monte Novo sediments, under more controlled conditions, is under way.

Conclusions

We have studied the bottom sediments from two reservoirs in South Portugal to test their suitability for agricultural use. In spite of large differences in geomorphic characteristics and basin drainage lithology, our results clearly show that for most variables, the sediments compare well or even exceed the corresponding values for soils in general. The high contribution of fine-grained elements (mainly in the deeper zones) are associated with: (1) high abundances of clay minerals with high cationic exchange capacity and expansive structure (montmorillonite), (2) occurrence of vermiculite, (3) medium to low crystallinity of clay minerals, and (4) pH values in the range considered optimal for the ready availability of most nutrients. These enhance good physical and chemical characteristics to the sediments concerning their fertility, such as:

1 High levels of total and available forms of macronutrients. Total N, available P and K are usually up to medium interval for soils in general.

2 High contents of available micronutrients. Only for Mn in the clayey sediments of the Monte Novo reservoir do levels approach near toxic levels, prejudicial to plant roots growth. However, these levels could probably decrease after aerial exposure of sediments due to agriculture use, because these new conditions may induce further transformations from reduced to oxidized forms, much more insoluble. Nevertheless, it would be more convenient to use this kind of sediments for crops less sensitive to this element excess.

3 Medium to high cationic adsorption and exchange capacity with very high levels of exchangeable Ca^{2+} and Mg^{2+}.

4 Fertility tests have already shown that these sediments compare well with quality soils (Fonseca et al., 1993).

This study shows that it is worth evaluating the economic feasibility of removing reservoir sediments and using them for agricultural purposes in areas with scarce soils. Sandy sediments could eventually yield better results because they can be used as soils on their own but the more clayey varieties, due to its high nutrient abundances, can be used as fertilizers for poor quality soils. In the economic study, we could also evaluate the possibility of enabling the coarser fractions to travel beyond dams to permit much needed sediment transport and accumulation in coastal zones. If the sediment removal becomes economically feasible, it may eventually resolve some classical problems in world dams: (1) the period of life of dam reservoirs filling with sediments, (2) the water quality, (3) the scarcity of soils in some regions and (4) the sediment scarcity in coastal areas.

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