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PROGRESS IN EROSION AND SEDIMENTATION IN LATIN AMERICA

Assessing the use of erosion modeling to support payment for environmental services programs

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Abstract
Purpose Payment for environmental services (PES) has assumed increasing importance in discussions about sustainable development strategies. Many of the PES programs are based on water erosion control and the corresponding environmental and economic benefits generated in the basins where they are implemented. The main objective of this study was to show how erosion susceptibility models can support PES programs.
Materials and methods The application of the Universal Soil Loss Equation (USLE) in the Sarandi Experimental River Basin (32.7 km^2), located in the Federal District, Brazil, was used as a study case. Then a scheme for organizing knowledge about ecosystem services related to erosion control and water resources was performed. Considering the generated scheme, the USLE results, the land use map, and the water use in the region, we evaluated how erosion modeling could support PES programs.
Results and discussion The results show that a large part of the study basin (90%) presents "low" susceptibility to erosion, which is significant in terms of the use and conservation of ecosystem services, as well as being a limitation regarding the need for the implantation of PES programs for erosion control. Incentives for maintaining the natural vegetation in areas with higher erosion susceptibility have the greatest potential to justify PES programs in the study basin, and the sanitation company is the potential payer for erosion control in the Sarandi River Basin.
Conclusions The application of the USLE in a spatially distributed form proved to be an important support tool for land management and the implementation of PES policies.

Keywords Brazil · Land use management · Sediment control · Soil erosion

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1 Introduction

Payment for environmental services (PES) has assumed increasing importance in discussions of strategies for environmentally sustainable development in the world. In Brazil, the topic has generated discussions and actions such as the Water Producer Program (WPP, "Programa Produtor de Águas") coordinated by the National Water Agency ("Agência Nacional de Águas," ANA), and that has been replicated or adapted in small urban and rural watersheds in various regions of the country. The primary purpose of these programs is the preservation and/or restoration of ecosystem services related to water resources, which are regulation, support, provision, and cultural services. To this end, through economic mechanisms, actions are encouraged so that humans can work toward maintaining or improving the quantity and quality of surface and groundwater, such as controlling erosion, sedimentation, flooding, runoff, water infiltration into the soil, nutrient flow, and other hydrological processes at the catchment scale.

In the WPP, for example, financial incentives are proportional to the environmental benefits related to reducing erosion arising from the implementation of soil and water management and conservation projects on farms and surrounding areas. Among these actions, there are construction of terraces and infiltration basins, readjustment of roads, restoration and protection of springs, reforestation of protected areas and legal reserves, and environmental sanitation. In the USA, there are

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also important PES programs related to erosion control in agricultural areas such as the Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP), both with the purpose of improving the conditions of water resources in lakes, rivers, reservoirs, springs, and underground, by reducing runoff and erosion in agricultural areas. In the CRP, the landowner receives financial incentives to change the use of areas with high potential for erosion, for example, from crops to natural vegetation. In EQIP, the payment is for farmers to adopt conservation practices in the crop areas that are more susceptible to erosion. These are just three examples of PES programs based on erosion control. In the Brazilian case, the parameters C (crop) and P (practice) of the Universal Soil Loss Equation (USLE) are used to calculate the PES values (Chaves et al. 2004), while in the US cases, the USLE is mainly used to define areas that can be incorporated in the programs (Claassen et al. 2008).

Despite its recognized limitations, discussed by Cohen et al. (2005), the USLE (developed by Wischmeier and Smith 1978) remains a very useful tool in modeling the potential and rate of erosion in watersheds. Undoubtedly, the simplicity of applying this equation in a geographic information system (GIS) environment significantly contributes to its popularity. Another important factor is the difficulty that still exists in estimating erosion processes through more structured mathematical models. Besides the large amount of data and information needed for the simulation of erosion, transport, and deposition of sediments with physically based mathematical models, their results are still not satisfactory enough to replace the use of USLE for supporting territorial management.

The application of USLE with the assistance of GIS results in a map that indicates the potential or the rate of erosion in the study area, which is an important tool to support land use and land cover planning, as shown by Mellerowicz et al. (1994) and Ha (2011). Thus, the information generated is very useful for the implementation of hydrological PES programs on a river basin scale, allowing the identification of erosion risk areas or the analysis of some policies from the perspective of PES, where the replacement of natural vegetation and the new form of land use can result in a reduction in ecosystem services related to erosion control and other environment associated processes. In this context, PES programs may induce actions and practices for the maintenance of ecosystem services.

The Sarandi Experimental Basin Stream is in the agricultural region of the Federal District, Brazil, but with most of its area still preserved with natural Cerrado (Brazilian Savanna) vegetation. It is noteworthy that, due to the proximity of Brasília and the high value of land in the region, the basin is subjected to strong pressure for urban and agricultural occupation. In addition to the uses of land and water for agricultural development in the basin (rain-fed, irrigation, fish farming, and livestock), just downstream of the confluence of the Sarandi Stream with Mestre D'Armas Stream, there is an uptake of water for human consumption by the Sanitation Company from the Federal District (CAESB), which makes this basin a Source Protection Area. In this case, the generation of the erosion map of this basin can be useful to define which areas should be prioritized for the implementation of conservation practices, to preserve natural areas or even to recover land with native vegetation, thus representing a first reference for the implementation of PES policies. A similar experience is being implemented in the Pipiripau River Basin, also located in the Federal District, Brazil (Lorz et al. 2012; Lima et al. 2013).

Thus, this study aimed to assess the use of erosion modeling to support payment for hydrological environmental services programs, thus demonstrating an approach of how to apply known technologies to implement new land management strategies in a savanna river basin in Brazil.

2 Materials and methods

2.1 Study area

The Sarandi River Basin is located in the northern part of the Federal District, between the cities of Sobradinho and Planaltina, and the mouth of the main river is at coordinates 15°35′58.76″S and 47°41′48.91″W, with a total drainage area of 32.7 km^2. In addition to the location of the study area, based on the image available on Google Earth ®, land cover, land use, and information on major water uses in the Sarandi Basin are given (Fig. 1). Based on the analysis of the satellite image and field work, the current land cover in the Sarandi River Basin was determined: 20.0% agriculture, 22.0% pasture, 55.0% natural vegetation, 2.5% roads, and 0.5% water bodies.

Many of the agricultural activities in the basin are developed in the experimental fields of Embrapa Cerrados (Savanna Agricultural Research Center of the Brazilian Agricultural Research Corporation), which occupies almost the entire area lying on the right bank of the Sarandi Stream (southern portion of the basin) (Fig. 1). The main land uses in the area of Embrapa are pasture, soybeans, wheat, coffee, sugarcane, jatropha, palm, corn, sorghum, various fruits, and native plants. It is noteworthy that the native Cerrado areas in the basin are still well preserved due to maintenance overseen by Embrapa. As can be seen in Fig. 1, both in the east and in the west part of the basin, urban, and agricultural areas are already putting pressure on the remaining areas of natural vegetation. At Embrapa Cerrados, agricultural areas downstream of the dam are nearly all irrigated, supplied by channel 1 (Fig. 1) and four pumping systems, while the experiments conducted in the highest part of the basin are predominantly rain-fed. There are two other significant water uses in the basin, through channels (channel 2 and channel 3—Fig. 1), which supply various small farmers. In two of the properties, the main use of water is for fish farming, while the other part has small irrigated areas.

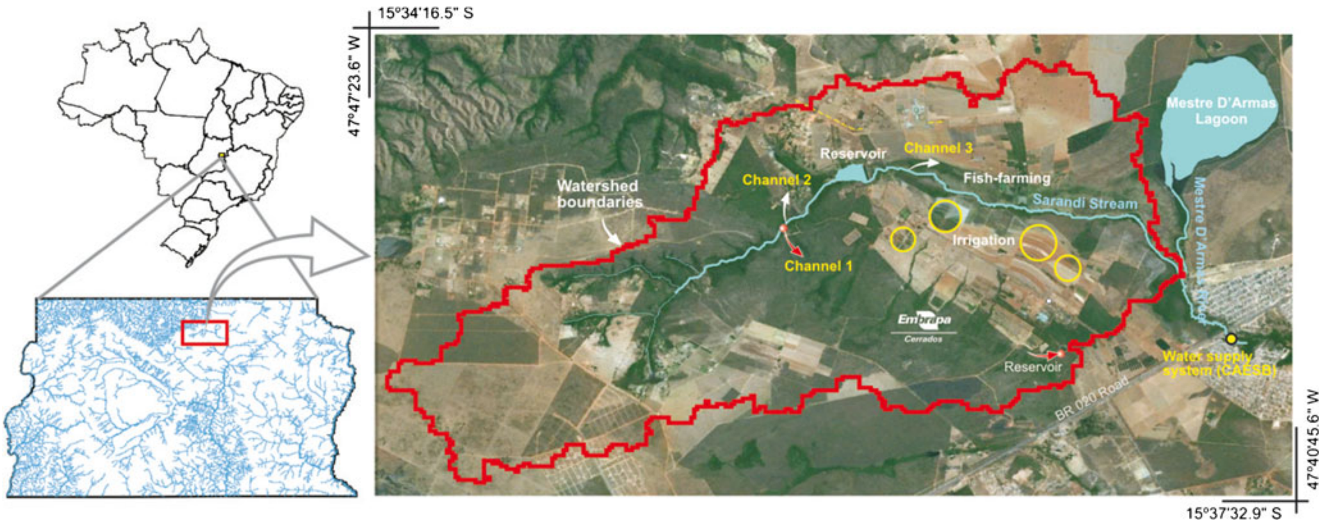

Fig. 1 Location, land cover, land use, and the main water extractions in the Sarandi Experimental River Basin study area, Federal District, Brazil (based partly on Google Earth, 30 August 2011)

Just downstream of the confluence of the Sarandi with the Mestre D'Armas Stream, there is a water withdrawal system for human consumption. Due to the recent urbanization of the region around this pumping system and the consequent impact on water quality at this location, the water supply company (CAESB) is looking for alternatives to increase the technical and economic feasibility of this extraction site. The Sarandi Stream is a tributary of the Mestre D'Armas Stream, releasing its waters into the São Bartolomeu River, in the part of the Federal District that contributes to the Paraná River Basin.

The climatic characteristics of the basin are typical of the Brazilian Central Plateau, in the Cerrado biome, with two well-defined seasons: a rainy one, which begins from September to October and extends until March to April, and a dry season comprising the remaining months of the year. The soil map of the Sarandi Experimental River Basin (scale 1:100,000) is shown in Fig. 2. The soils of the region are generally clayey, but due to their structure, the Oxisols have high permeability and low erodibility (Dedecek et al. 1986).

Figure 3 shows the digital elevation model (DEM) of the study area, obtained through the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite (ERSDAC 2011). Figure 3 shows that the lowest part of the study area, at the mouth of the Sarandi Stream, is at a height of ~953 m, while the maximum altitude in the basin, close to its springs, is ~1,262 m.

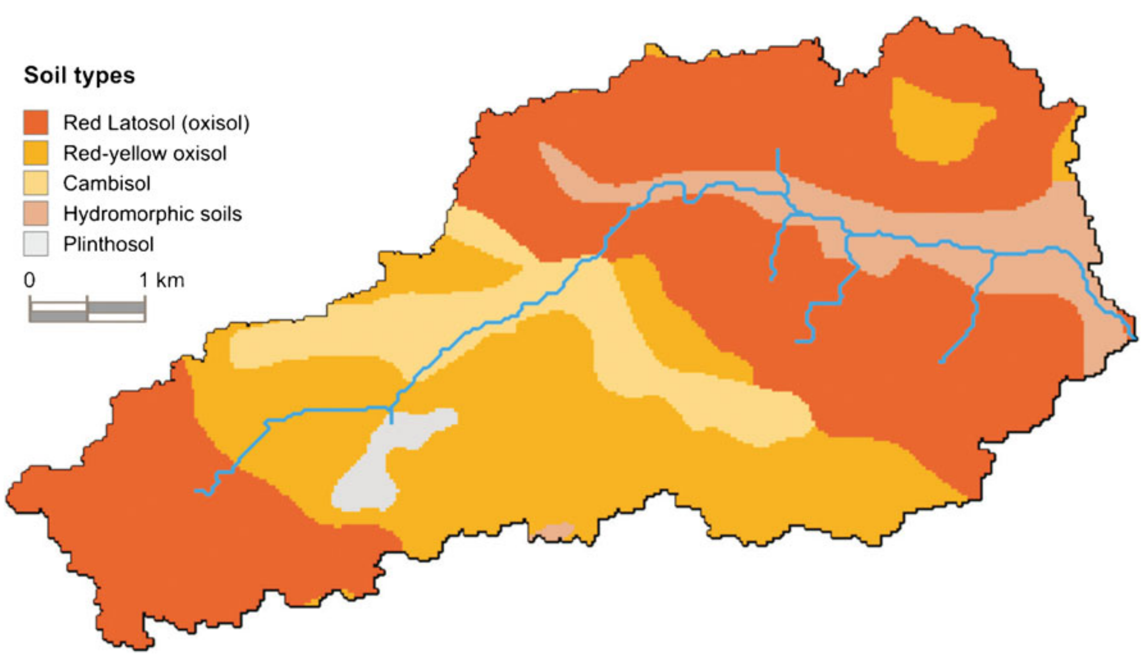

Fig. 2 Soil map of the Sarandi Experimental River Basin (based on Embrapa 1978)

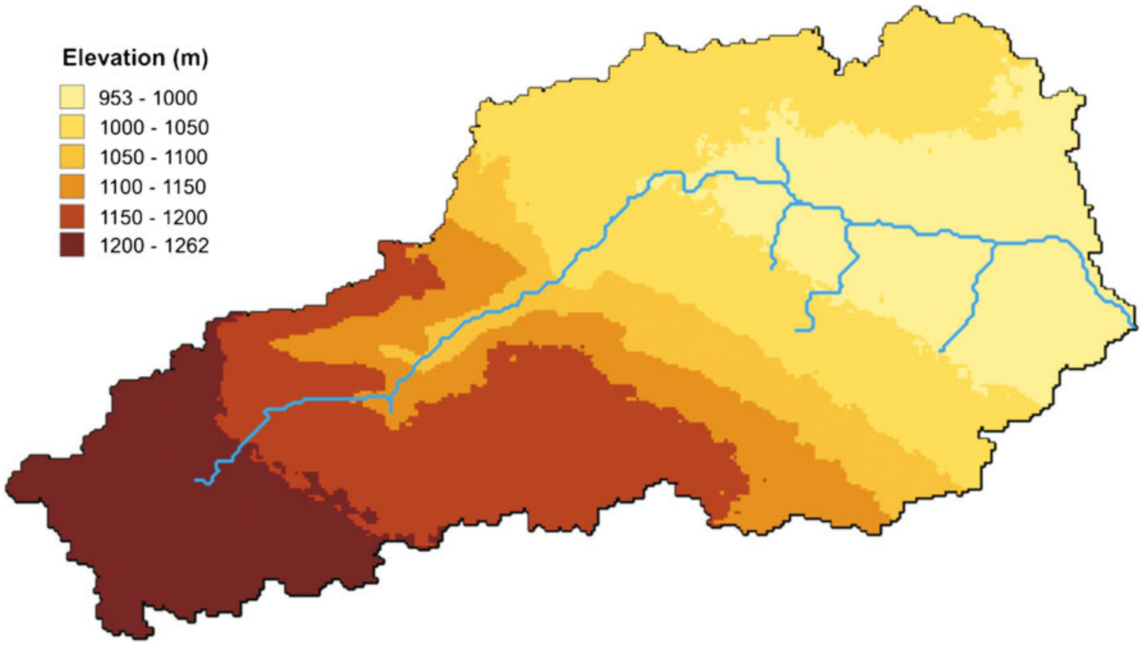

Fig. 3 Digital elevation model (DEM) of the Sarandi Experimental River Basin

2.2 The erosion model

The soil erosion potential in the basin was estimated using the USLE:

$$A = R\,K\,LS\,C\,P \quad (1)$$

where A is the annual average soil loss (t ha^{-1}), R is the rainfall erosivity index (MJ mm ha^{-1} h^{-1} $year^{-1}$), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), L is the slope length factor (dimensionless), S is the slope steepness factor (dimensionless), C is the cropping factor (dimensionless), and P is the conservation practice factor (dimensionless).

The equation was simulated in a raster GIS environment, based on spatial information from the Sarandi Experimental River Basin organized in thematic maps of the USLE factors with a spatial resolution (pixel) of 30 m. The quality of the results is limited by the scale of the soil map (1:100,000).

2.2.1 Rainfall erosivity (R factor)

In this work, a constant value of R was used for the entire study area. The adopted value was equal to the one measured by Dedecek et al. (1986), of 8,050 MJ ha^{-1} mm h^{-1} obtained by using data from the rainfall station at Embrapa Cerrados, within the Sarandi River Basin. Recent publications (e.g., Silva 2004; Oliveira et al. 2012) indicate that the erosivity value determined by Dedecek et al. (1986) remains representative for the region.

2.2.2 Soil erodibility (K factor)

The K-factor values were obtained based on the soil map shown in Fig. 2 and bibliographic data (e.g., Dedecek et al. 1986; Bertoni and Lombardi Neto 1990; Denardin 1990; SiIva et al. 1994; Farinasso et al. 2006; Lima et al. 2007; Silva et al. 2009; Lima and Lopes 2009). The K factor values adopted in the present study are shown in Table 1.

2.2.3 Topographic factors (LS)

The LS factor map was derived from the ASTER-GDEM. There are several methods for determining the topographic LS factor (e.g., Williams and Berndt 1976; Wischmeier and Smith 1978; Moore and Burch 1986; Desmet and Grovers 1996; Kinnell 2001, 2005). In this study, the model proposed by Moore and Burch (1986) was used:

$$LS = \left(\frac{Flow\,acumulation * Grid\,size}{22.13}\right)^{0.4} * \left(\frac{\sin(Slope)}{0.0896}\right)^{1.3} \quad (2)$$

2.2.4 Cropping and conservation practices factors (CP)

In order to estimate potential erosion susceptibility in the basin, the values of CP were not considered in this analysis, which means they were considered equal to 1 (bare soil plowed toward the maximum slope direction).

Table 1 Erodibility (K factor) values assigned to different soil classes

Soil class	K factor
Red oxisol	0.013
Red yellow oxisol	0.033
Typic Quartzipsamment	0.032
Cambisol	0.037
Plinthosol	0.057
Hydromorphic soils	0.038

2.3 Calculation procedures

After obtaining all USLE parameters as digital thematic maps, in grid format, the calculation of the soil erosion potential in each cell (30 m×30 m) of the Sarandi Experimental River Basin was performed using the ArcGIS "Raster Calculator" tool.

2.4 The development of an assessment scheme

At this stage, the erosion susceptibility map obtained by applying the USLE, the land cover map of the basin, and knowledge about the main water users in the study area were all used in an integrated way. The erosion susceptibility map allowed the identification of the percentage of the basin area with greater or lesser potential to provide erosion control services. After that, an analysis of the relationship between erosion control and other environmental services was performed. From the maps of erosion susceptibility and land cover, the main providers/maintainers of environmental services in the water basin were identified. The survey of the main water users in the study basin and just downstream of its mouth allowed the identification of potential payers for environmental services directly or indirectly related to erosion control. Based on the above information, a critical analysis of the technical and economic feasibility of a PES program for erosion control in the area was performed as a way to guide the use of economic instruments for land and water use planning at the watershed scale.

3 Results and discussion

3.1 Simulation of the soil erosion potential in the basin

By applying the USLE to determine soil erosion potential—by multiplying the R, K, and LS factors—the soil erosion potential map of the Sarandi Experimental River Basin was obtained (Fig. 4), which shows the areas of the basin with more or less soil erosion susceptibility, spatially distributed into cells of 30 m×30 m. As noted on Fig. 4, the areas near the river in the highest part of the basin and in the transition between the plateau and the lower part of the basin presented high erosion susceptibility. Table 2 shows the data extracted from Fig. 4 regarding the watershed areas classified by low, moderate, or high susceptibility to erosion, which shows that most of the Sarandi Basin (~90%) has low susceptibility to erosion and that only 5% of its area has high susceptibility.

3.2 Analysis of the results from the perspective of PES programs

The soil erosion susceptibility map of the Sarandi Experimental River Basin (Fig. 4) and data detailed in Table 2 provide

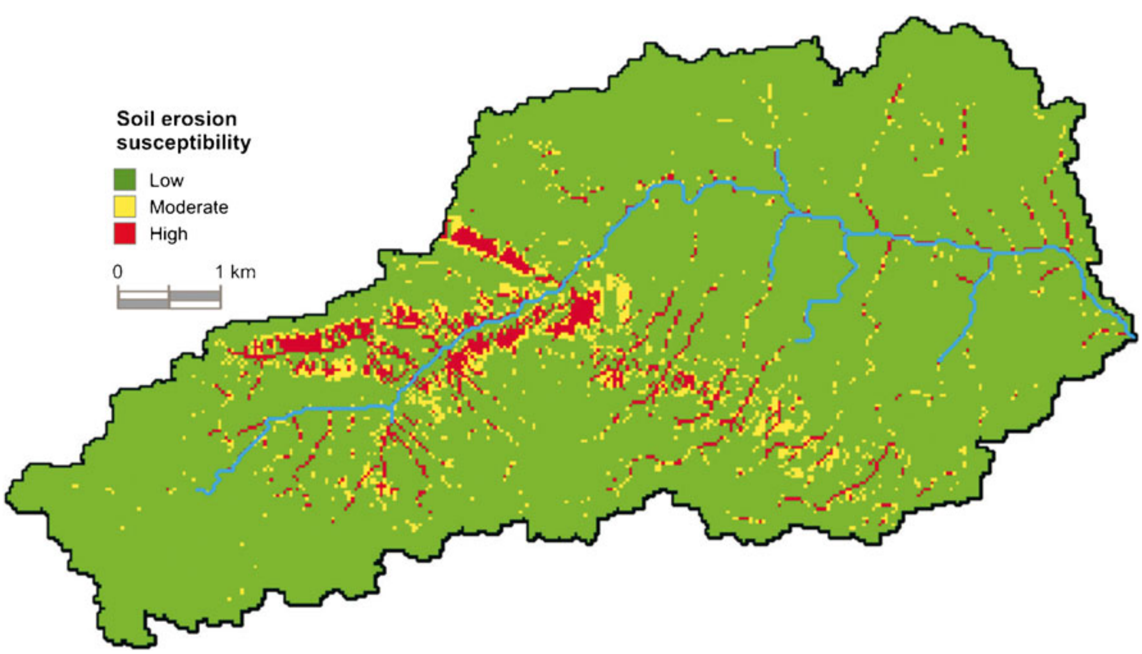

Fig. 4 Soil erosion susceptibility map of the Sarandi Experimental River Basin

Table 2 Quantification of the areas within the Sarandi Experimental River Basin, Brazil, with low, moderate, or high soil erosion susceptibility

Classification	Soil loss potential (t ha^{-1} year^{-1})	Number of cells	Area (km^2)	Area (%)
Low	0–1,000	32,482	29.2	89.3
Moderate	1,000–2,000	1,977	1.8	5.5
High	>2,000	1,895	1.7	5.2
Σ		36,354	32.7	100.0

important information to help develop improved land use management in the area. Sites that are more susceptible to erosion can also be understood as those areas with greater sensitivity or risk for generating negative effects on ecosystem services, such as erosion control, retention of sediments, soil formation, nutrient cycling, maintaining the natural hydrologic cycle, water supply, energy, fibers, food, and land productivity. Thus, where there is a choice, it is better not to change these fragile environments, maintaining their natural balance and their full potential for providing ecosystem services. However, once the decision to change the cover and land use in these locations has been taken, the use of soil conservation practices is fundamental. This involves higher costs related to land use, to maintain both the productivity and viability of the activity (economic, social, and environmental) and to avoid generating negative externalities for the other beneficiaries of ecosystem services provided by these natural environments.

In many cases, by either choice or from lack of knowledge, these sensitive areas are changed by human use and the necessary precautions are neglected, causing problems to the proprietors themselves, to other users of the watershed, and to the environment. Therefore, the soil erosion potential map represents an important tool for managing land use; prioritizing areas for conservation or to use a priori; helping to identify the causes of economic, social, and environmental problems; and underpinning actions to solve these problems (a posteriori), either through command and control instruments, or economic ones, such as the PES programs. As noted by Bennet et al. (2005), the first step toward the adoption of policies for sustainable management of ecosystems must be to increase our knowledge about the ecological dynamics and complexities surrounding ecosystems. Figure 5 shows a schema that seeks to organize knowledge about ecosystem services that can be generated through erosion control, an action that may be backed by the results derived from the application of the USLE in a GIS environment.

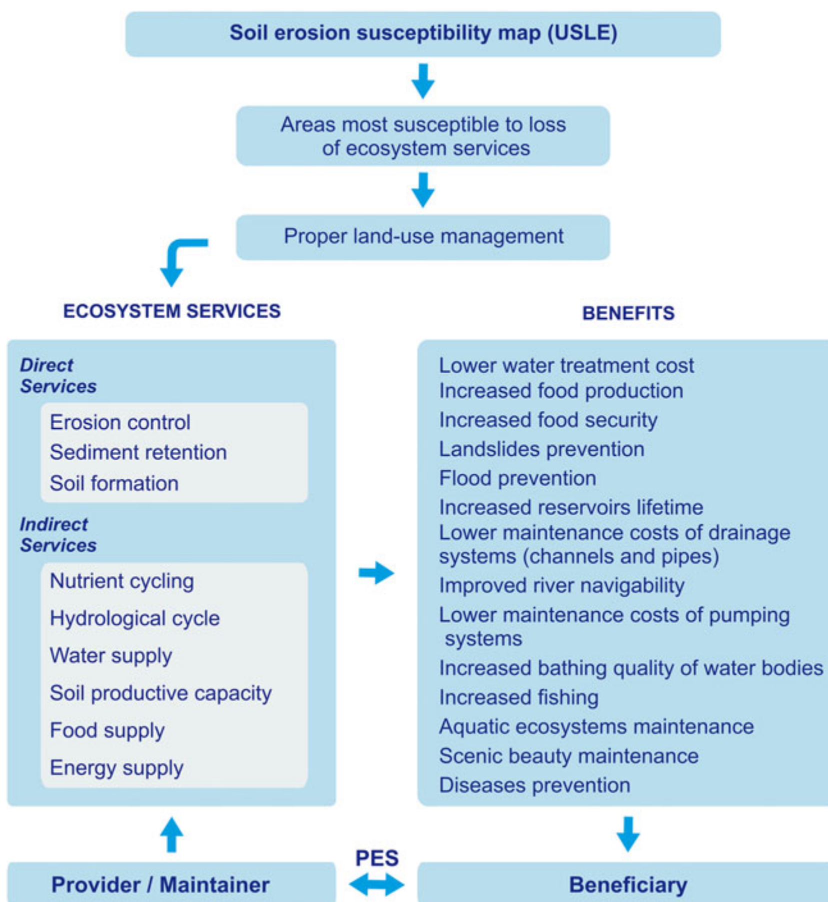

Fig. 5 Schematic model of the relationship among erosive processes, ecosystem services related to water resources, and the integration of tools that can be used for territorial management, such as USLE and PES programs

Through an integrated analysis of data and information regarding the use of soil and water in the study area, the results of the soil erosion susceptibility simulation in the Sarandi Basin, and possibilities for establishment of PES programs based on the relationships between ecosystem service providers/maintainers and those who benefit from these services, some basic questions must be answered. The first question is whether the erosive processes constitute a significant problem in the Sarandi Basin. The USLE results for assessing the soil erosion susceptibility in the basin (see Fig. 4 and Table 2) show that ~90% of the basin presents a low risk and that only 5% presents a high risk. Comparing the erosion susceptibility map (Fig. 4) with information about the land cover obtained from the satellite image shown in Fig. 1, it is possible to note that the areas with greatest potential for erosion still have preserved natural vegetation. So, with the available information, in principle, it can be said that the present risk of significant problems with the issue of erosion and sediments in the basin is small.

Another important question is who the providers/maintainers of the basin ecosystem services are and who benefits from the services. In the Sarandi River Basin, most of the land is under the supervision and management of Embrapa Cerrados, a federal agricultural research center, and the rest is shared between: *Águas Emendadas* Ecological Station (ESECAE), which is controlled by the Federal District Government; UPIS, a private university; and many small farmers. In the upper part of the basin subdivisions of land for the establishment of urban settlements are beginning to appear (Fig. 1). Both urban and agricultural uses, depending on where and how they are conducted, can pose a threat to the maintenance of ecosystem services.

Among the most direct beneficiaries of these services are the actual users of land and water resources of the basin; CAESB; and part of the community of the town of Planaltina, who receives the water collected by CAESB. In the case of Embrapa, the direct benefits are lower maintenance cost of its channel pumping systems; improved quality and quantity of water for continuous supply of its headquarters, laboratories, irrigated areas, and areas of animal production; lower cost of its research projects (fewer conservation practices and less soil loss caused by erosion); and longer lifetime and water availability of its reservoir installed in the Sarandi Stream.

Regarding ESECAE, maintenance of aquatic ecosystems and scenic beauty fit in perfectly with the goals related to their existence. Moreover, the Sarandi Stream is a source of water for wildlife that still lives in this ecological station, which is under extreme pressure from the expansion of agricultural activities and urbanization of its surroundings.

The private university (UPIS), due to its greater distance from the watercourse, is supplied mainly by groundwater. However, it is important to highlight the relationship between erosion and soil water infiltration/recharge of aquifers, which can compromise the ecosystem service of water supply (quantity and quality) in cases like that.

Regarding farmers, as well as the issues of water quality and quantity for human and animal consumption, there is the question of maintaining the cost of its channels and pumping systems for irrigation and the provision of a suitable environment for developing aquaculture projects in the basin.

Although the water collection area Mestre D'Armas (managed by CAESB) is located outside of the Sarandi River Basin, the water from this area is the main input for this water supply system, because in the dry season, the water flow of the Sarandi Stream is much higher than the water discharge in the Mestre D'Armas River. Besides the quantitative relevance, the waters of the Sarandi Stream have the important function of diluting the effluents that the Mestre D'Armas community releases upstream from the CAESB water withdrawal (see Fig. 1), which has hindered the technical and economic viability of this activity. This impact directly affects the operating and maintenance costs of the system and sometimes makes use of this resource for water supply unviable.

The downstream communities supplied by the Mestre D'Armas River, including the users of the water derived by CAESB, are direct beneficiaries of the ecosystem services generated in the Sarandi River Basin, highlighting questions of water safety and disease prevention.

Based on the foregoing, considering the carrying capacity, the current land and water uses in the Sarandi River Basin, the water use downstream of its confluence with the Mestre D'Armas River, and the problems related to erosion processes and their consequences in terms of land use and water in the region, the following should be pointed out:

- Erosion does not yet represent a significant problem for the related ecosystem services in the Sarandi Experimental River Basin.
- The soils of the Sarandi Basin have been adequately used considering their erosive potential, which can be encouraged and maintained through economic mechanisms such as PES, mainly due to the strong pressure for land use by urban and agriculture development of the region.
- Presently, due to the technical and economic problems experienced in the Mestre D'armas water supply system, CAESB is a potential payer for environmental services related to erosion control in the Sarandi Basin. However, in the scenario presented above, environmental sanitation and urban drainage actions in the Mestre D'armas community, as well as actions aiming to reduce or optimize the water use of the Sarandi Stream, would bring a more immediate and direct return to improve the situation.

4 Conclusions

Based on the application of the USLE, 90% of the Sarandi Experimental River Basin has low susceptibility to erosion, which is very significant in terms of provision and conservation of ecosystem services. Considering the USLE results and local conditions in terms of land owners and water users, there is no need to implement PES programs to control erosion in the Sarandi Experimental River Basin. Maintaining natural vegetation in areas with greater susceptibility to erosion in the Sarandi Experimental River Basin is recommended so as to avoid an increase of soil erosion rates to undesirable levels.

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