UNIVERSIDADE FEDERAL RURAL DO RIO DE JANEIRO
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PRIORITY AREAS FOR NATURAL REGENERATION AND REDUCTION OF SEDIMENTS IN THE ATIBAINHA BASIN

PhD CLAUDIA MOSTER
Advisor

SEROPÉDICA, RJ
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Monograph presented to the Forest Engineering Course, as a partial requirement to obtain the Degree of Forestry Engineer, Forestry Institute of the Federal Rural University of Rio de Janeiro.

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ABSTRACT

Erosion is a physical process generated by the action of rainwater causing disaggregation, transport and deposition of soil particles. This process is natural and occurs in all terrestrial surface. However, erosion has been intensified by inadequate anthropogenic action. The presence of vegetation cover on the soil reduces the possibility of erosion, slope collapse and siltation of water bodies, that is, it contributes to the protection and preservation of soil and other environmental systems. Since the summers of 2013-2014 and 2014-2015, there have been news reports regarding the low level in the reservoirs of the Cantareira System. The combination of inadequate soil use, low rainfall rates due to a drought period and temperatures above the normal conditions, high demand of water and lack of collective conscience of Brazilian consumers for the rational use of water are factors that have caused a water crisis. The global overexploitation of ecosystems is causing impacts on ecosystem services provision, bringing out the importance of adequately conceptualize, quantify, map and monitor water ecosystem services. Satellite images can be used to evaluate and monitor the delivery of water ecosystem services. The evaluation of water supply and water damage mitigation services can greatly benefit from the use of satellite products, contributing to a better understanding of the processes and functions that underlie its provision to guide decision makers. InVEST and RIOS, used in the present study, are tools for spatial and temporal analysis of the provision of ecosystem services in the ecological-economic context. The present work aims to define priority areas with high potential for natural regeneration that promote reduction of sediment exports at the lowest cost in the Atibainha Basin, in the Cantareira System, São Paulo. The output from the scenarios indicate that, for the Atibainha basin, areas with regeneration potential above 70% can also contribute to the reduction of sediment supply. Thus, it is considered that, by indicating the areas with regeneration potential above 90%, it is possible to obtain the provision of this hydrological ecosystem service at the lowest investment cost and greater probability of success in the restoration. The provision of hydrological ecosystem services for sediment reduction and the regeneration potential of the Atibainha basin are spatially related. Thus, it is concluded that it is possible to apply the natural regeneration, at the lowest cost, to the restoration of priority areas that promote the improvement of water quality in the basin.

Keywords: SPATIAL-ANALYSIS, WATER ECOSYSTEM SERVICES, UNASSISTED REGENERATION, REGENERATION POTENTIAL.

RESUMO

A erosão é um processo físico gerado pela ação da água da chuva causando desagregação, transporte e deposição de partículas do solo. Este processo é natural e ocorre em toda a superfície terrestre. No entanto, a erosão foi intensificada por ação antropogênica inadequada. A presença de cobertura vegetal no solo reduz a possibilidade de erosão, colapso da encosta e assoreamento dos corpos d'água, ou seja, contribui para a proteção e preservação do solo e demais sistemas ambientais. Desde os verões de 2013-2014 e 2014-2015, há relatos de notícias sobre o baixo nível dos reservatórios do Sistema Cantareira. A combinação de uso inadequado do solo, baixas taxas de chuvas devido ao período de seca e temperaturas acima das condições normais, alta demanda de água e falta de consciência coletiva dos consumidores brasileiros para o uso racional da água são fatores que provocaram uma crise hídrica. A superexploração global dos ecossistemas está causando impactos na provisão de serviços ecossistêmicos, destacando a importância de conceber, quantificar, mapear e monitorar adequadamente os serviços ecossistêmicos hidrológicos. Imagens de satélite podem ser usadas para avaliar e monitorar a prestação de destes serviços. A avaliação dos serviços de abastecimento de água e de mitigação de danos causados pela água pode se beneficiar enormemente do uso de imagens de satélite, contribuindo para uma melhor compreensão dos processos e funções subjacentes à sua provisão para orientar gestores. InVEST e RIOS, utilizados no presente estudo, são ferramentas para análise espacial e temporal da prestação de serviços ecossistêmicos no contexto ecológico-econômico. O presente trabalho tem como objetivo definir áreas prioritárias com alto potencial de regeneração natural que promovam a redução das exportações de sedimentos ao menor custo na Bacia de Atibainha, no Sistema Cantareira, em São Paulo. Os resultados dos cenários indicam que, para a bacia de Atibainha, áreas com potencial de regeneração acima de 70% também podem contribuir para a redução da oferta de sedimentos. Assim, considera-se que, ao indicar as áreas com potencial de regeneração acima de 90%, é possível obter a prestação desse serviço ecossistêmico hidrológico ao menor custo de investimento e maior probabilidade de sucesso na restauração. A provisão de serviços ecossistêmicos hidrológicos para redução de sedimentos e o potencial de regeneração da bacia de Atibainha estão espacialmente relacionados. Assim, conclui-se que é possível aplicar a regeneração natural, ao menor custo, ao restabelecimento de áreas prioritárias que promovam a melhoria da qualidade da água na bacia.

Palavras-chave: ANÁLISE ESPACIAL, SERVIÇOS ECOSSISTÊMICOS HIDROLÓGICOS, REGENERAÇÃO PASSIVA, POTENCIAL DE REGENERAÇÃO.

SUMMARY

1. INTRODUCTION

Erosion is a physical process, generated by the action of rainwater causing disaggregation, transport and deposition of soil particles. According to Bertoni and Lombardi Neto (1990), the rainwater that enters in contact with the soil exerts an erosive action generating surface runoff in which they transport sediments and deposit them near to drainage channels. This process is natural and occurs in all terrestrial surface. However, erosion is intensified by inadequate anthropogenic action, since areas with inadequate soil use suffer greater impacts with erosion. Thus, it leads to serious environmental problems such as silting rivers, water eutrophication and the killing of organisms (CARVALHO et al., 2010).

The presence of vegetation cover on the soil reduces the possibility of erosion, slope collapse and siltation of water bodies, that is, it contributes to the protection and preservation of soil and other environmental systems (MONTEBELO, 2005). Forests can help to prevent flood-and-drought regimes in downstream territories, protect soils and help to retain sediments (EHRLICH and EHRLICH, 1992). They are also responsible for different water ecosystem services, including provision of water supply, water damage mitigation, provision of water cultural services, climate regulation, among others (BRAUMAN, 2007).

Since the summers of 2013-2014 and 2014-2015, there have been news reports regarding the low level in the reservoirs of the Cantareira System. The combination of inadequate soil use, low rainfall rates due to a drought period and temperatures above the normal conditions, high demand of water and lack of collective conscience of Brazilian consumers for the rational use of water are factors that have caused a water crisis. This crisis reflects the lack of strategic planning that has affected the region's supply system in recent years (CORTES, 2015; MARENGO, 2015). Therefore, it is important to conduct studies that show the feasibility of low cost and easily implemented mitigation techniques, like unattended restoration to promote natural regeneration.

Pressures such as land-use change, overexploitation, pollution, conversion of forests into agricultural land, the spread of invasive species, air pollution and climate change are causing impacts on water ecosystem services provision (ROUNSEVELL et al., 2010; LOUMAN et al., 2010). Increases in sediment yield are observed in many places of the world, dramatically affecting water quality and reservoir management. That’s why it is important to adequately conceptualize, quantify, map and monitor water ecosystem services (CARVALHO-SANTOS et. al., 2014).

Satellite images can be used to evaluate and monitor the delivery of water ecosystem services. The evaluation of water supply and water damage mitigation services can greatly benefit from the use of satellite products, contributing to a better understanding of the processes and functions that underlie its provision (CARVALHO-SANTOS, 2014). We can count on a variety of software capable of processing data from satellite images, by doing so they generate information to understand how the production and the delivery of sediments works to design strategies for reducing sediment loads (SHARP et al., 2015). InVEST and RIOS, used in the present study, are tools for spatial and temporal analysis of the provision of ecosystem services in the ecological-economic context.

In this context, the present work aims to define priority areas with high potential for natural regeneration that promote reduction of sediment exports in the Atibainha Basin at the lowest cost.

Specific objectives:

a. Identify the priority areas for sediment reduction.

b. Verify association between priority areas for sediment reduction and areas with high regeneration potential.

2. LITERATURE REVIEW

1.1 WATER ECOSYSTEM SERVICES

According to Costanza et al. (1997), ecosystem functions are responsible, directly or indirectly, for the supply of ecosystem services, that is, production of goods and services. They sustain the production of ecosystem goods, such as water, seafood, forage, timber, biomass fuels, natural fiber, and many pharmaceuticals, industrial products, as well as many intangible aesthetic and cultural benefits (DAILY, 1997). The provision of ecosystem services related to water include purification of water, mitigation of peak floods and droughts, contribution to the basin flow and erosion control (CICES, 2017).

Precipitation ties the hydrologic cycle to the sedimentary cycle, that includes the processes of erosion, nutrient transport, and sediment formation. Changes in the global climate may cause changes, increases in temperature and evaporation, in many ecosystem functions, especially those linked to the hydrologic cycle. The expected intensifications in precipitation may further affect runoff and soil moisture and consequently influence vegetation and agriculture patterns (DAILY, 1997). The stock of the global ecosystem services is diminishing and is increasingly threatened by the overexploitation of the environments (MOKONDOKO, 2018).

1.2 VALUATION OF WATER AS NATURAL CAPITAL

In the capitalist system we can highlight the role that the market has in determining prices, but when it comes to ecosystem goods and services, as they are public goods there is not a market for it. The price system only exists for the goods and services produced by the economic system. In this sense, if the allocation of natural resources in the economic system is carried out only under free market conditions, the result will be the environmental degradation (GARCIA and ROMEIRO, 2013). Hydrological services usually provide complex outcomes that are not acknowledge by market specialists. It is hard to determine at which price a given habitat should be sold. As a result, habitats that support complex ecosystems are usually sold too cheaply, since social benefits are not accounted in the price (DAILY, 1997).

The concerns about problems related to water scarcity and quality has intensified the interest in the sustainable management of ecosystems over the years (CARVALHO-SANTOS et. al., 2014). The expansion of the economic system and the deterioration of ecosystems will result in increasing costs to society. Thus, to recover or maintain ecosystem service flows, at some point society will have to pay for the recovery of degraded ecosystems. The information generated by the valuation process can guide the allocation of economic and natural resources in the economic system towards the more efficient and rational use of ecosystem services (MERICO, 2002).

Valuation involves resolving fundamental philosophical issues, the establishment of context, and the defining of objectives and preferences. Since mankind would not be able to thrive without the provision of goods and services, the use value of ecosystem services is infinite. The evaluation of the tradeoffs facing society requires estimating the marginal value of ecosystem services to determine the costs of losing, or the benefits of preserving a given amount or quality services (DAILY, 1997).

The pursuit for rational use of water resources should be evaluated in rural contexts, since economic value is only one of the values that guide the access forms and the decisions about the use of natural resources. Thus, it is common sense that the recognition and appreciation of social, economic and cultural relations of the rural environment should be considered for the management of water resources (CHIODI et al., 2013).

1.3 BASIN MANAGEMENT

Nature's services are vital to human survival and economically important, however is largely ignored in decisions (Daily, 1997). Therefore, the construction of mechanisms that allow the identification of the costs of natural replacement of ecosystem services flow, natural capital and mitigation of environmental impacts can be an important management tool (MERICO, 2002).

The management of water resources is important for the formulation of principles and guidelines for management and decision-making aiming the use, control and protection of water resources. The management of natural resources should incorporate the interdependence between the ecosystem components and the economic system, providing a model of Integrated Management of Natural Resources (GARCIA and ROMEIRO, 2013). Many countries, like France, the United States, Germany and Switzerland adopted this model to promote preservation, improvement of water quality and rational use (PINHATTI, 1998).

According to estimates by OECD1 - Organization for Economic Co-operation and Development (2008), in 2005 around 2.7 billion people lived in areas with severe water stress and the study estimated that by 2030 will be 4 billion people who will be living at the same conditions. With the emergence of new interests related to the use of water, changes in land use and occupation, and international experiences in water management, the Brazilian government instituted in 1997 the National Water Resources Policy - PNRH (BRASIL, 1997). The PNRH provided the principles of participation, integration and decentralization (FELICIDADE, 2003). The policy granted responsibilities to states, municipalities and civil society, in addition the river basin was established as a management unit (PEREIRA and MEDEIROS, 2009), and brought the participation of the public sector, users and community in the space created by the Committees of Hydrographic Basins (CBH) (FELICIDADE, 2003).

According to the national water agency (Agência Nacional de Águas), the management of the Cantareira System is currently the responsibility of ANA itself and the Department of Water and Electric Power of the State of São Paulo (Departamento de Água e de Energia Elétrica). They follow up the data of water levels, flow and stored volume. With the help of the collected data and within their legal attributions, managers create rules that determine the operation of the Cantareira System. The operation is made by the Basic Sanitation Company of the State of São Paulo (Sabesp).

1.4 UNNATENDED RESTORATION

What allows the recovery of degraded environments is the ecological succession, that is, gradual colonization of native species (CARDINELLI, 2016 apud MAGNAGO et al., 2015a). Martins et al. (2009) draws attention to the need to take into account the history of the area to be restored, the landscape, the degree of isolation, the size and the stage of succession of the fragments that serve as seed banks.

Resilience determines the degree and magnitude in which the natural rate of recovery occurs after a disturbance, enabling the natural system to resume its ecological functions and increase its biodiversity (WESTMAN, 1978). Benayas et al. (2009) thru a meta-analysis of 89 restoration assessments with a variety of ecosystem types concluded that ecological restoration increased the provision of ecosystem services and biodiversity.

Unattended restoration is a low-cost practice, since it requires less manpower and inputs compared to artificial regeneration methods, that produces great benefits related to the provision of ecosystem services (BIRCH, 2010; BOTELHO et al., 2001).

3. METHODOLOGY

3.1. AREA OF STUDY

The Cantareira System (Figure 1) is largely responsible for human water supply in the metropolitan region of São Paulo. The System is composed by five hydrographic sub-basins Jaguari, Jacareí, Cachoeira, Atibainha and Juquery, which are connected by underground artificial tunnels and canals.

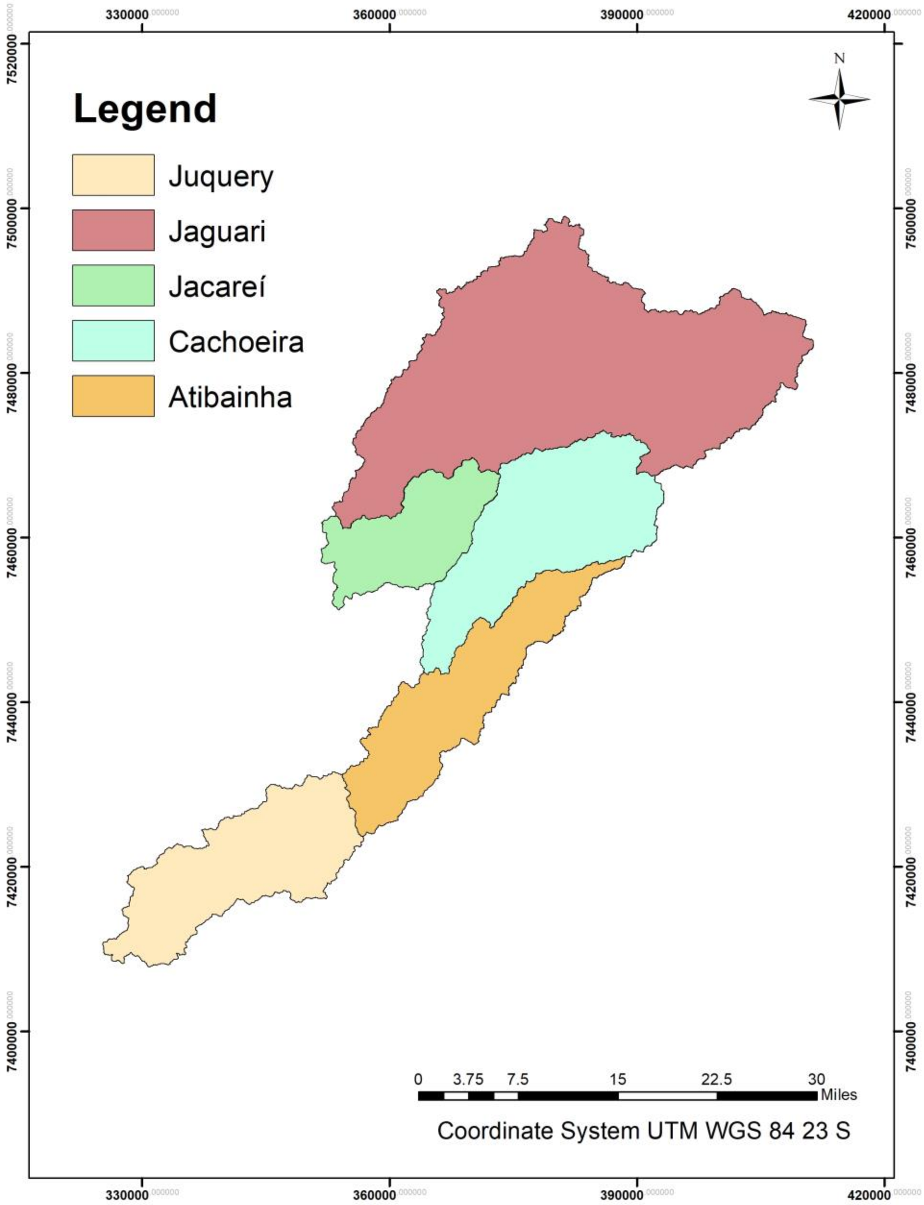

Figure 1: The Cantareira System, composed by five hydrographic sub-basins Juquery, Jaguari, Jacareí, Cachoeira and Atibainha, in the metropolitan region of São Paulo.

This study is focused on the Atibainha sub-basin that covers an area of 314.5 km². The sub-basin is in the eastern headwaters of the Piracicaba River Basin. The region became susceptible to environmental impacts since the implementation and subsequent duplication of an important highway - "Fernão Dias" (JESUS, 2011). The dense ombrophilous forest that originally occupied the whole basin was replaced by pastures, silviculture and secondary vegetation in the most varied stages of development. The dense ombrophilous forest can still be found with greater occurrence to the northeast (Serra da Mantiqueira) and southwest (Serra da Cantareira) of the Atibainha Reservoir basin (JESUS, 2011).

3.2 RIOS MODEL

The Resource Investment Optimization System (RIOS) is a software tool that makes it possible to prioritize watershed investments in areas with larger potential for providing ecosystem services to yield the greatest benefits for both people and nature at the lowest cost. This tool empowers managers to define the location and set of actions that will produce the greatest returns of ecosystem services (VOGL et al., 2015).

According to VOGL et al. (2015) in the RIOS user guide, the tool facilitates the design of investments for a single management goal or a whole set of goals, such as soil erosion control, water quality improvement (for nitrogen and phosphorus), flood regulation, groundwater recharge, dry season water supply, and terrestrial and freshwater biodiversity.

The Sediment Production module uses algorithms for each analyzed objective enabling the creation of scenarios based on the input data provided by the user. Three categories of activities can be considered for the transitions: assisted restoration (planting reforestation), unattended restoration (conduction of natural or induced regeneration) and agroforestry in consortium with cattle run (alteration of management in agriculture). The model produces scenarios, according to the proposed land use activities for payment for ecosystem services, that allows the evaluation of the effect of land use and land cover transitions. The tool combines several of the core components to create investment portfolios intended to maximize the ecosystem service return from those investments. The portfolio is a map of activities, indicating where investments in each activity will give the best returns across all water fund objectives (VOGL et al., 2015).

3.3 THE InVEST "SEDIMENT DELIVERY RATIO MODEL"

InVEST has been enhanced to allow simulations of how land use and land cover (LULC) might contribute to hydrological services provisioning (BHAGABATI, 2014). It maps, evaluates, and economically value ecosystem services to support natural resource use decisions (BAI, 2011).

According to Sharp et al. (2015) in the InVEST user guide, the ultimate goal of InVEST Sediment Delivery model is to map generation of overland sediment and the delivery to the stream. It provides information about how changes in ecosystems are likely to lead to changes in the benefits to people, helping managers to make decisions about natural resource management. The conversion of land use and changes in land management practices may dramatically modify the amount of sediment running off a catchment. In case of deposition in the reservoir, the sediment rate leads to a decrease in the useful life of the reservoir, besides changing the quality characteristics of the water, leading to higher treatment costs.

3.4 INPUT DATA FOR RIOS AND InVEST

The flowchart (Figure 2) display the data collected by Moster (2018) from their respective database source. These files were processed and transformed into specific complementary files required to run RIOS and InVEST models.

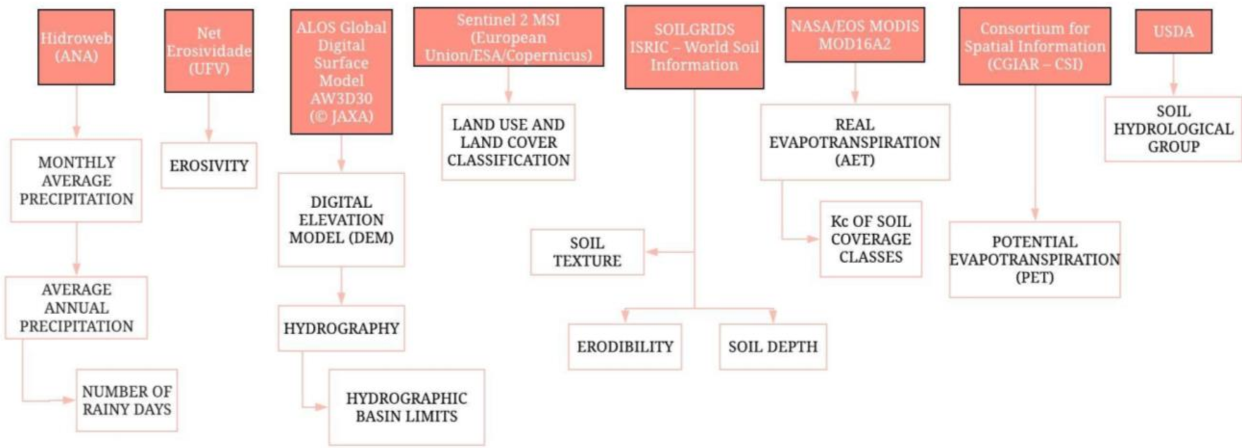

Figure 2: Flowchart of database sources and the generated input data used for modeling.

The following table (Table 1) lists the specific complementary files used for modeling, both for RIOS and InVEST (SDR). The preprocessing data was generated regarding the climatic and edaphic conditions of the hydrographic basin. The results were used for the simulation of the scenarios.

Table 1: Input data for RIOS and InVEST modeling.

INPUT DATA	**RIOS**	**InVEST (SDR)**
1. Digital Elevation Model (.tif)	X	X
2. Rain Erosivity (.tif)	X	X
3. Soil erodibility (.tif)	X	X
4. Soil Depth (.tif)	X	
5. Land use and land cover (.tif)	X	X
6. Relationship between land classes and transition activities (.csv)	X	
7. Table of biophysical coefficients (.csv)	X	X
8. Hydrographic Basin (.shp)	X	X
9. Flow accumulation limit		10.000 cells
10. Beneficiaries (.tif)	X	
11. Riparian distance	30 m	
12. Erosion retention index downstream (.tif)	X	
13. Erosion retention index upstream (.tif)	X	
14. Riparian continuity (.tif)	X	
15. Regeneration Potential (.tif)	X	

Moster (2018) processed and provided the data from Item 1 to 14 (Table 1). The spatial data with the “Natural Regeneration Potential” (Item 15) was estimated and provided by Crouzeilles et al. (2019). The Regeneration Potential was set as the preferred areas for the transition.

3.5 MODELING PREPROCESSING

Regarding the RIOS modeling, different weights can be assigned to the proposed activities and correlating to the ecosystem services evaluated, to indicate the preferred areas and those not available for the transition. The preferred areas for transition were stablished using different probability classes of the natural regeneration potential provided by Crouzeilles et al. (2019).

To obtain Erosion Control results, the SDR model considers the primary factors that influence erosion and sedimentation processes. Thus, the components of the universal soil loss equation (USLE), rain erosivity, soil erodibility and soil depth together represent the potential impact of the activities. The sediment delivery module works at the spatial resolution of the input DEM raster. For each cell, the model first computes the amount of eroded sediment, then the sediment delivery ratio (SDR), which is the proportion of soil loss reaching the basin.

The ecosystem services carefully chosen for the estimation of the impact of afforestation investments in relation to water ecosystem services were erosion control, flood peak mitigation and contribution to base flow. In this way, the modeling of the areas considered spatial information of the sediment production and the water infiltration capacity in the soil, related to the class of use and coverage and soil characteristics, besides the precipitation and Digital Elevation Model (DEM).

Adjusting the parameters of the InVEST biophysical table, it was considered that natural regeneration represents 50% of the characteristics similar to the remaining forest and 50% to the agricultural areas, because the process of alteration of the soil cover characteristics is slow and gradual. In the period of one-year, natural regeneration usually grants good soil cover, but still with dominant grass and shrub species. From the current land cover and land use map it was possible to estimate sediment retention, sediment export and soil loss.

ArcGis was another important tool used for data processing. The interface between RIOS and ArcGis allows pre-processing raster files. RIOS provides an activity portfolio output (processed to turn into inputs for InVEST SDR model).

3.6 PROPOSED SCENARIOS

The proposed scenarios for simulation considered as a transition activity the unattended restoration using as a preferred area for simulation the natural regeneration potential, provided by Crouzeilles et al. (2019) in different probability classes (50%, 60%, 70%, 80% and 90%).

These scenarios were compared with the circumstances of land use and land cover in 2018 (baseline scenario) and the scenario proposed by Moster (2018) that considered transition of areas through the conduction of unattended restoration without setting the natural regeneration potential as preferred areas (scenario 4).

4. RESULTS AND DISCUSSION

The outputs (Table 2) from InVEST include the amount of sediment retention, sediment exportation and the amount of annual soil loss on pixel (USLE) for each simulated scenario using the regeneration potential proposed by Crouzeilles et al. (2019) in different probability classes. Table 2 also show the size of the area indicated for transition generated using RIOS model.

Table 2: RIOS and InVEST SDR outputs for the Atibainha Basin in the metropolitan region of São Paulo.

Scenarios (Transitions)	Sediment Retention (t)	Sediment Exportation (t)	USLE* (ton/ha/yr)	Area (ha)
Baseline	9492822.094	11988.80058	1408993.396	
Scenario 4	9498209.829	6601.065204	1032025.851	5506.28
50%	9496492.454	8318.440741	1221434.213	1895.38
60%	9496831.978	7978.916987	1186287.959	2628.85
70%	9498209.829	6601.065204	1032025.851	5506.28
80%	9498209.829	6601.065204	1032025.851	5506.28
90%	9498209.672	6601.221743	1032044.333	5506.15

*Universal Soil Loss Equation: The amount of annual soil loss on pixel.

The sediment exportation (Table 2), which represent the sediment load delivered to the stream at an annual time scale, decreases as the transition area increases. Different from the sediment retention (Table 2), which represents the avoided soil loss by the current land use compared to bare soil, that does not present significant changes. The amount of annual soil loss on pixel (Table 2), which is the proportion of soil loss actually reaching the catchment outlet in one year, also decreases as the transition area increases.

Comparing the baseline scenario and scenario 4, we can observe a reduction of 44.9% in the sediments exported to the basin. The classes considering a percentage of 70%, 80% e 90% of regeneration potential present similar results from those obtained in the scenario 4, that is, 44.9% of reduction of sediments exportation to the stream. The class of 50% and 60% reduces sediments exportation in 30,6% and 33,4%, respectively.

The scenario 4 (Figure 3), that considered as transition the conduction of unattended restoration without setting the natural regeneration potential as preferred areas, overlaps with the location of areas with regeneration potential proposed by Crouzeilles et al. (2019). Likewise, the areas indicated with regeneration potential by Crouzeilles et al. (2019) are also related to the provision of water ecosystem services, especially sediment production. The natural regeneration of agricultural areas can improve the provision of ecosystem services (STRASSBURG, 2016).

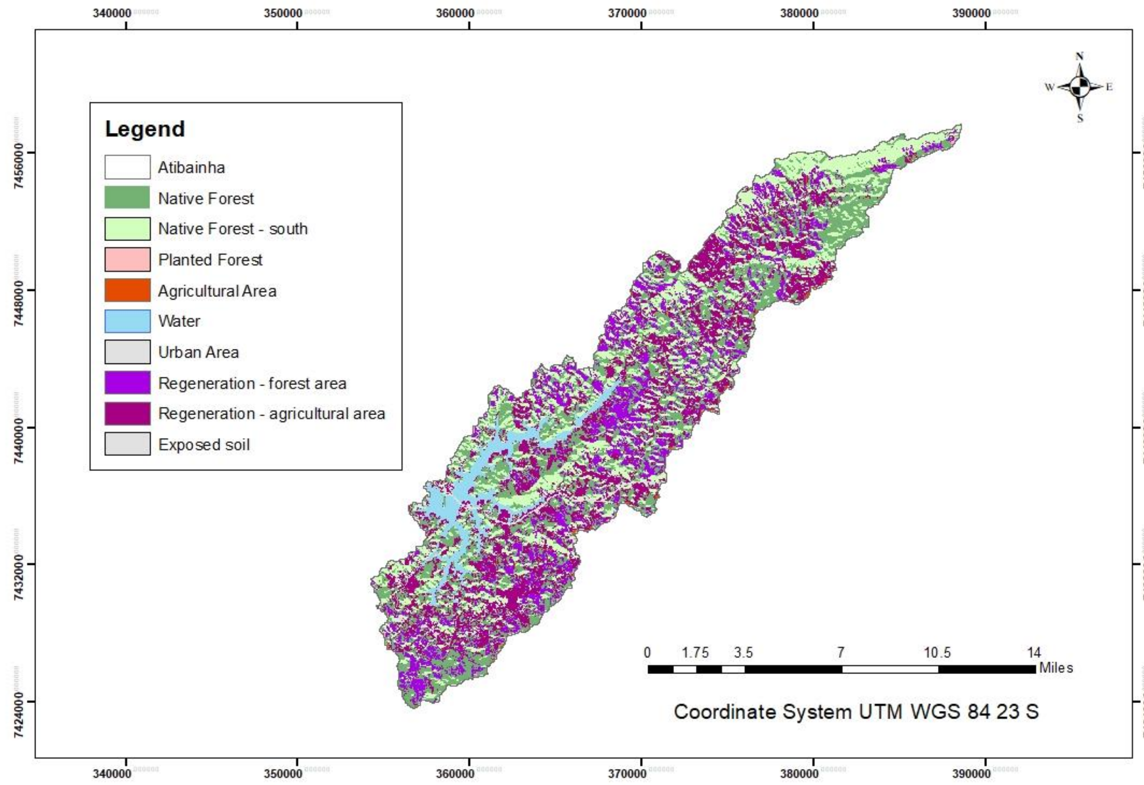

Figure 3: Scenario that considered the transition of areas through the conduction of unattended restoration without setting the natural regeneration potential as preferred areas (Scenario 4).

The output from the scenarios indicate that, for the Atibainha basin, areas with regeneration potential of 70% can also contribute to the reduction of sediment supply (Table 2). However, by indicating the areas with regeneration potential of 90% (Figure 4), it is possible to obtain the provision of water ecosystem service at the lowest investment cost ensuring greater probability of success in the restoration.

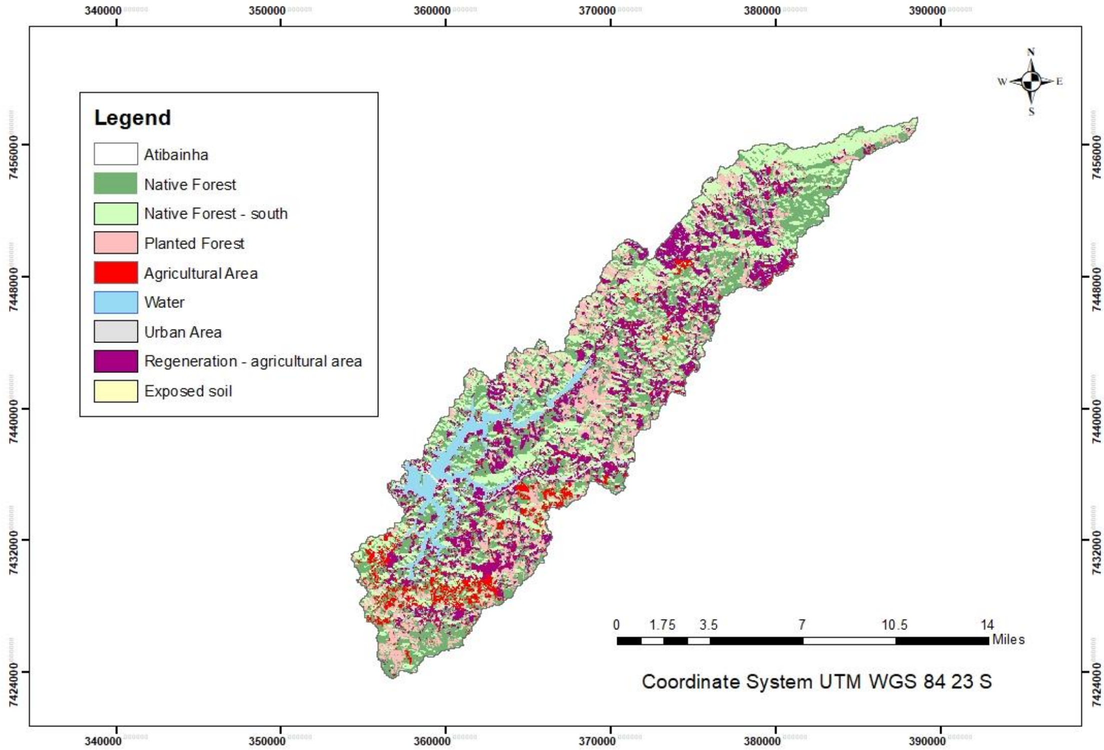

Figure 4: Scenario that considered as a transition activity the unattended restoration and as preferred areas with 90% of natural regeneration potential, provided by Crouzeilles et al. (2019).

The simulated scenarios are used to help managers to apply financial resources, aiming at the better provision of several ecosystem services and establishing priorities for low-budgets projects. Is important to contribute to the evaluation and awareness of the need for investments in alternative practices in areas intended to provide multiple services (SAAD et al., 2011; VOGL et al., 2015).

5. CONCLUSIONS

- The provision of water ecosystem services for sediment reduction and the regeneration potential of the Atibainha basin are spatially related.
- It is concluded that it is possible to apply the natural regeneration, at the lowest cost, to the restoration of priority areas with 90% of regeneration potential, that promote the improvement of water quality in the basin.

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