1 Introduction

Numerous hydroelectric plants have been constructed in drainage basins in order to meet countries' energy needs. However, part of the literature affirms that the economic benefits caused by the implantation and operation of such hydroelectric plants are overestimated, while the negative effects on biodiversity, water quality, and the riverside communities are underestimated. Another evidence of such overestimation is the shortening of the foreseen lifespan of hydroelectric undertakings when those are placed downstream others, as the latter ones lose their former ability of trapping sediments as time passes (Mendes, 2020).

Many hydroelectric power plants develop their sustainability programmes, guided by economic and socioenvironmental issues, aiming to act in environment compensations, as well as to reduce impacts, and to support the socioenvironmental development of the region where it is being installed (Moreira *et al.,* 2015). The process of defining how to prioritize investments in sustainability programmes, as well as the magnitude of these investments, still represents a challenge in such a way that one of the types of study that may contribute to this endeavour consists in the evaluation of ecosystem services (Arias *et al,* 2011; Vogl *et al.,*2016).

After having economically measured the services provided by the environment, governments and organizations are able to establish a benchmark to their expenses concerning the preservation, and also to eventual payments for environmental services (Winemiller *et al.*, 2016). The term "ecosystem services" describes a relatively new approach, which directly associates the environment to the provision of human wellbeing, a concept to which the generation of renewable energy is intrinsically connected with (Espécie *et al.*, 2019).

Faber *et al*. (2012) defend that the ecosystem evaluation studies represent an extensive line of research inside ecological economics, affirming that the "monetization of the environment" is essential to balance the costs of maintaining it with the benefits it provides. Costanza *et al*. (1997) affirm that ecosystem services are not totally captured in commercial markets or adequately quantified on a comparable basis regarding the economically measurable services.

Espécie *et al.* (2019) reinforce the existence of dependence of the hydroelectric plants on ecosystem services. The relation between the generation of hydroelectric power and conservation of the ecosystem in the water basin is emphasized in terms of supply and demand for ecosystem services of regulation of water flow and sediment retention (Guo *et al.*, 2007). The usage of the soil of the upstream drainage basin might extend the lifespan of the reservoirs (Schleiss *et al.*, 2016). With this in mind, hydroelectric plants may be considered beneficiaries of ecosystem services, insofar as they are positively affected by benefits that the environment provides, which may help in the water provision, as well as regulate the water quality and the soil erosion, etc. (Guo *et al*. 2007; Vogl *et al*., 2016).

In view of the above, the aim of this research consists in measuring the ecosystem service of regulation of soil erosion for the Itaipu hydroelectric plant. It is understood that the protection zone vegetation prevents sediments from being discharged into the reservoir, maintaining their operation conditions and its lifespan (Capeche, 2005; Harrington *et al.*, 2010). Measuring the value of these ecosystem services is an opportunity to comprehend the risks caused by the shortage of natural resources (water and soil), as well as to dimension and evaluate the magnitude of investments (costs and benefits) and act preventively in areas of interest, aiming to maintain the lifespan of the venture.

It constitutes an opportunity for research, since in the preliminary review of the literature on this topic few studies discuss the provision of ecosystem services and their benefits for hydroelectric plants in the Brazilian scenario. This research can contribute to a potential replication methodology for assessing environmental investments and prospecting scenarios for land use and conservation activities, in line with the objectives of preserving the capacity of hydroelectric reservoirs and also enable ecosystem valuation as another reference for evaluating investments in environmental preservation. In this paper, it was estimated that, for each US$ 1 invested in environmental preservation activities, the hydroelectric plant avoids expenses – as a result of the process of dredging – that range from US$ 4.53 (lowest cost) to US$ 520.65 (highest cost). It also differs from most environmental studies on hydroelectric plants in that it focuses on the discussion of how ecosystem services for soil erosion regulation are relevant and economically viable to ensure reservoir storage capacity, rather than addressing impact of hydroelectric plants and of their management of environmental resources.

The article begins with the theoretical reference, and in sequence, the methodological procedures and findings are presented. Finally, the final considerations are discussed.

2 Theoretical Background

2.1 The electric sector and the hydroelectric plants

The electric sector is considered to be fundamental for the good functioning of practically all of the other sectors of an economy, in such a way that the energy availability determines the country's capacity to provide its population various services and to prosper economically (Yüksel, 2010; Mayumi & Tanikawa, 2012; Purwanto & Afifah, 2016; Vogl *et al.*, 2016). For comparison purposes, 64% of Brazil's energy matrix comes from hydroelectricity, whereas it represents 16.4% of the world's power generation mix (EPE, 2019).

It is believed that big hydroelectric ventures impact locations where they are installed and that there is a need to observe them, especially in the social, economic, and environmental spheres. With this in mind, there has been an extensive discussion regarding the need for companies to approach sustainability not only as a secondary issue, but integrating it to the strategic decision processes (Engert; Rauter & Baumgartner, 2016; Moreira *et al.*, 2015).

Based on a systematic review concerning hydroelectric plants, Jiang, Quiang, and Lin (2016) utilized a bibliometric analysis of scientific production from 1994 to 2013, evaluating 1,726 papers related to the topic (*highly related to hydropower*). The main findings were: (i) most topics were linked to the periods of post-construction and to the beginning of the operation, rather than to the construction projects and to the utilized technologies; (ii) multidisciplinary topics; and (iii) the rapid and vertiginous increase in issues on hydroelectric plants.

In a similar study, Han *et al.* (2014) analysed 434 scientific papers from 1991 to 2012. Besides the aforementioned findings, the authors identified the most important journals that mention this topic (*Renewable and Sustainable Energy Reviews*, *Renewable Energy*, *Energy Policy*). The main countries where publications about sustainability in hydroelectric plants are found include the United States of America, Turkey, Brazil, and China. The main keywords were "*Turquia*" (Turkey), "eco" (eco-tourism, ecosystems, ecosystem services, ecosystem rehabilitation, ecosystem-mapping, ecosystem index for sustainability, ecosystem goods and services, eco-labelling, ecological land classification, ecological services), "small hydro", and "fish."

In this connection, hydroelectric plants are considered to be relevant, in comparison to other potential sources, given that it is a relatively low-cost source of renewable energy (Liu *et al.*, 2013). Its capacity of generation, especially in countries with broad flooded areas, has been helping them offer a greater amount of electricity. Compared to other sources, the benefits of using hydroelectric plants are related to (Yüksel, 2010; Liu et al., 2013): (i) efficiency of energy conversion, with low operation costs and an already consolidated technology; (ii) low maintenance costs; (iii) stability of its main input (water) in face of the market conditions; (iv) possibility of operating generation flexibly; (v) capacity of promoting improvements in the living conditions of communities that are near big ventures; and (vi) high level of reliability.

In Brazil, this has been the main alternative for energy supply (EPE, 2019). Moreira *et al.* (2015) affirm that the year-on-year growth rate of the energy sector in Brazil is of 4%, taking into account the increase of the participation of other sources of energy in its electricity mix. The Brazilian energy matrix is constituted by: hydroelectricity, 64%; biomass, 8.5%; natural gas, 8.6%; wind power, 7.6%; mineral coal, 3.2%; nuclear energy, 2.5%; and others, 5.6% (EPE, 2019).

Brazil's hydroelectric capacity becomes apparent when we observe the availability of hydric resources in regions with potential for power generation: the second most important Brazilian basin in terms of hydroelectricity, Parana Basin, uses 72% of its total potential, while São Francisco Basin uses 65%. The percentage of countries such as France and Germany are 100% and 83%, respectively (MME, 2020).

2.2 Sustainability and ecosystem services

Given the size of the hydroelectric projects and their impact in the environments where they were installed, it is often discussed the actions for sustainability carried out by the hydroelectric plants. The majority of studies consider evaluations of an economic, social, and environmental nature (Liu *et al.*, 2013; Kumar; Katoch, 2016). Taken into account are: local impact, restrictions that such ventures may generate in ecosystems and in nearby communities, changes in dynamics of land and aquatic habitats, deposition of sediments in riverbeds, decrease in biodiversity, degradation of water quality, etc. (Wang *et al*., 2010; Yuksel, 2010; Schleiss *et al.,* 2016).

Jager and Smith (2008), in turn, affirm that reservoirs of big hydroelectric plants operate in systems that aim at maximizing revenues obtained by selling the generated energy, while respecting some licenses for the use of the reservoir. However, these optimization systems usually do not consider the health of the aquatic ecosystem. According to these authors, both situations should be conciliated, ruling out the existing trade-off between maximization of the generation revenue and the reservoir´s preservation. Harmonizing both, generation efficiency and environmental preservation would become more reasonable, considering the provision of water valuation.

Moreover, reservoirs need maintenance to guarantee its lifespan. According to Yüksel (2009), reservoirs lose storage capacity when sediments accumulate in streams that maintain them, impacting their operation and longevity. Sycitski *et al.* (2005) estimate that approximately 100 billion tons of sediments were stuck in the reservoirs built in the last 50 years. Excessive sedimentation and sediments trapping are concerning problems in the operation of dams and in power production, besides their impact on hydroecologic processes, such as the supply of nutrients for species of fish and reconstruction of downstream deltas. In regards to individual dams, the World Commission on Dams (WCD) discovered that 10% of the studied projects lost 50% of their active storage as a result of sedimentation (WCD, 2000).

In this respect, around 20% of the sedimentation in the reservoir comes from natural processes, such as weathering of rocks, and 80% comes from bad usage and irregular occupation of the soil, lack of crop rotation, lack of terracing, construction of inadequate rural roads, lack of riparian forest, and destruction of forest cover (Arias *et al.*, 2011). Actions for maintenance of upstream forest cover on a drainage basin contribute for the economic and operational life of a hydroelectric plant (Hajramurni 2010; Arias *et al.*, 2011) and constitute a monetary benchmark for the allocation of investments and/or for the establishment of partnerships for the payment of environmental services. In the words of Arias *et al.* (2011, p.475):

> The above suggests that (1) sedimentation is a critical issue for the operation and longevity of hydropower dams; (2) forest conservation in a watershed can significantly prevent excessive sediment yields to downstream dams; and (3) erosion control is an ecosystem service provided by forested watersheds and it offers value to downstream hydropower generation. Hence, a regulatory or market-based system that monetizes the value from ecosystem services could generate revenues to finance upstream forest conservation and management. A standardized methodological tool that allows land managers and dam operators to evaluate the potential economic benefits from forest conservation in the context of reservoir sedimentation and the useful lifespan of a hydropower facility is thus needed.

Based on the aforementioned arguments, it is possible to affirm that one important aspect to be improved for the maintenance of the reservoir lifespan is associated with the preservation of the surrounding vegetation – especially in the protection zones (Guo et al., 2007; Schleiss *et al*., 2016). From an ecologic perspective (Faber *et al.*, 2012), the use of soil condition ensures the regulation of soil erosion, that is, it enables the environment to provide its ecosystem service. This ecosystem service, in turn, consists in one of the main associates of hydroelectric plants both in construction and operational phases (GVces, 2018). The assessment of ecosystem services is relevant for the correct measurement of benefits and environmental impact in the regions where the hydroelectric plants are installed.

Intralawan *et al.* (2018), in the evaluation of the potential benefits and environmental costs resulting from the installation of the hydroelectric projects in the Mekong river (Vietnam), considering the ecosystem services in the region, concluded that the forecast of loss with fishing, discharge of sediments in the river, and loss of nutrients for local biodiversity outweigh the benefits of generating electricity and controlling floods. In the view of these authors, these facts – if analysed in anticipation – could definitely have stopped the very installation of the hydroelectric projects. Stephenson and Shabman (2019), in turn, analysed 17 cases of hydroelectric projects relicensing in the USA, noting that none of these requests took into account the assessment of local ecosystem services for comparison with monetary estimates of hydroelectric energy benefits. The incompleteness of information for decision-making when ecosystems services are not in these assessments is pointed.

In order to homogenize the concepts, the definition of "ecosystem services" offered by Costanza *et al.* (1997) is adopted, by which such services consist of human populations benefits, directly or indirectly obtained from ecosystem functions. Given the relevance of hydropower for the energy supply, the main ecosystem services and their potential relations with hydroelectric plants are presented in the following figure:

Ecosystem utility services	**Concept**	**Relation with hydroelectric plants**
General provision	Production of tangible goods (food or inputs) that generate wellbeing.	Fish supply/monitoring
Water supply	Contribution in terms of quantity of water	Dependence for generation/impact on downstream users

Water quality regulation	Water quality control	Influence turbine operation
Regulation of soil erosion	Role of ecosystems in the control of soil erosion processes	Control and monitoring, depending on the impact on the life of the reservoir
Regulation of global climate	Influence on emissions of relevant greenhouse gases	Maintenance and restauration of surrounding areas
Cultural services	Natural benefits	Modification of landscapes and interaction with ecosystems
Leisure and tourism	Role of ecosystems in relaxation and leisure	Influence in touristic activities

Figure 1: Main ecosystem services and interfaces with hydroelectric plants
Source: Adapted from GV'ces (2018).

In this research, the soil erosion regulation was considered as the primary ecosystem service, for its impact in the operative and economic life of a power plant. However, it is necessary to acknowledge that the presence of sediments also impacts the quality of the water in the reservoir and may increase turbine maintenance costs.

The assumptions that justify the evaluation of the ecosystem services are related to the absence of Market prices for certain natural resources, in addition to the fact that often the utility function and the indirect benefits that the ecosystem provides are not considered (Arias *et al.*, 2011; Pavani, 2018). These are issues that help to prioritize investments in environmental preservation and for the design and delimitation of policies aimed at paying environmental services (Fu *et al*., 2014). According to Guo *et al*. (2007, p.1558):

> The forest vegetation cover in watersheds provides two important ecosystem services. It provides river water flow regulation. It also provides sediment retention, which acts as a ''sponge'' to regulate and stabilize water runoff to balance river flow over the seasons; further, it retains soil and decreases silt run off into rivers. Hydroelectricity production relies on natural systems of watersheds to provide the ecosystem services, including river water flow regulation and sediment retention […].

Studies focused on the evaluation of the ecosystem service for regulating soil erosion are among the most widespread when analysing the literature on ecosystem services related to hydroelectric power plants (Fu *et al.*, 2014; Espécie et al., 2019). Most of these try to estimate the tons of sediments that enter the reservoir in a given period in the conditions in which the vegetation was. This information is then compared with data on the sedimentation avoided when improvements to soil and vegetation care were implemented in the same area. Sedimentation avoided is interpreted as a cost that will no longer be disbursed by the hydroelectric power plant, related to the cost of dredging to remove this sediment (in tons or cubic meters) from the reservoir bed (Capeche, 2005; Pavani, 2018; GVces, 2018). In this context, erosion regulation is interpreted as an ecosystem service provided by nature, and the costs avoided with dredging make up one of the benchmarks for evaluating environmental investments and payments for environmental services to residents of areas of interest to the hydroelectric power plants. In the words of Oliveira *et al*. (2013, p.160)

> Several researches have reported the influence of soil management systems and preparation methods concerning erosion rates. In general terms, the higher the aggregate soil breakdown caused by the soil preparation method or less conservation management systems, the higher soil losses occur. Studies also show that better soil protection provides lower soil losses due to less soil exposure to erosive agents. This way, the more the crops develop, the less soil areas are unprotected.

Cruz *et al*. (1988) present a methodology for assessing the economic impact of river basin erosion in a hydroelectric reservoir in Philippines. They quantified 3 different costs associated with the impact of soil erosion on the vegetation surrounding the reservoirs: (a) reduced useful life; (b) reduced storage capacity; and (c) increased construction costs of the dam´s physical structure. The results are used to establish a baseline for an eventual payment scheme for the environmental service of forest conservation in the upstream part of the hydrographic basin supplying water to the hydroelectric plant. These authors try to demonstrate how future loss of revenue can be avoided by investing a small amount of money in hydrographic basin management.

Arias *et al.* (2011) indicate the sequence of steps to estimate payments for forest conservation near a hydroelectric plant in Cambodia. This model, in the authors´ interpretation, ensures the conservation of an area of interest to the hydroelectric plant, protecting the reservoir from eventual sediment discharge, so that the cost of conserving the surrounding vegetation can be seen as an investment in hydroelectric energy, as it prevents the reservoir from losing its water storage capacity. It should be noted that the forest vegetation plays a role in regulating the availability of water based on the following possibilities: (i) making rainwater storage via forest vegetation feasible, and redistributing these waters by the tree canopies, branches, and trunks; (ii) mitigating the runoff due to the existence of the humus layer, herbaceous layer, and tree roots; (iii) reinvigorating soil permeability through the presence of macropores due to the system of roots; (iv) limiting soil water through the process of plant transpiration preventing landslides (Medeiros; Young, 2011). The following figure exemplifies the interface between the evaluation of ecosystem services and its application as a reference proposed by the authors.

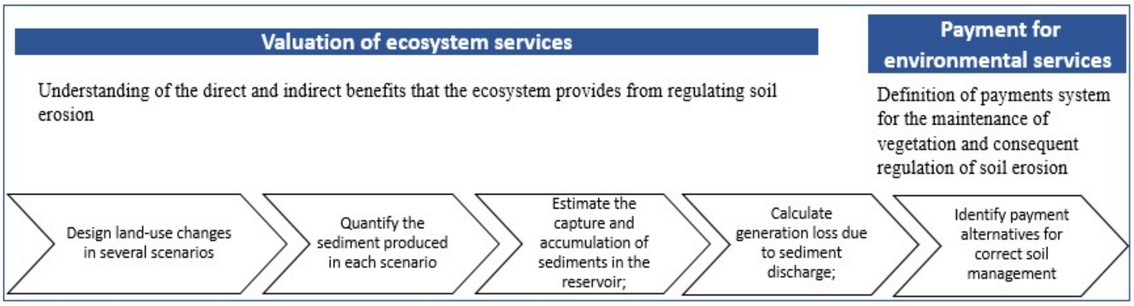

Figure 2: Interface between the evaluation of ecosystem services and payment for environmental services.
Source: Prepared upon literature review.

According to figure 2, Vogl *et al*. (2016) still argue that land management based on ecosystem services, in line with environmental and regional goals, can benefit the hydroelectric sector and support economic growth. The authors defend the opportunity to direct environmental investments to ensure the provision for ecosystem services based on the quantification of the benefits of soil and water conservation. The economic viability of this model is exemplified with five hydroelectric plants built in India.

3 Methodological Procedures

The proposal for the integration of topics is illustrated here in the form of the Itaipu hydroelectric plant and its particular *Sustainability Programme*. The choice was intentional, since the corporation is considered the largest hydroelectric power generating in the world, with its sustainability programme in force for over a decade, being internationally recognized for its contribution to the socio-economic development of the Western region of the Parana State, for its participation in the energy supply to Brazil (approximately 11% of the country), and for its water management and soil conservation practices.

The operation of that plant began in 1984. Its reservoir is 170 km long, and 20 power units, generating 700MW each, were installed. The Itaipu Reservoir, with its 1,350 km² of flooded area, is the seventh largest in Brazil in surface, and has the best indicator of water usage for the energy production among big Brazilian reservoirs. In Itaipu, the production rate is 10.4 MW per km² (that is, each 0.1 km² of flooded area can generate 1 MW) (Itaipu, 2019). The reservoir was constituted in 1982, relying on 1,350 km² in surface area, 163 km in length, 29 billion m³ in volume, and average flow rate of 11,200 m³/s. The following figure shows the Itaipu Reservoir:

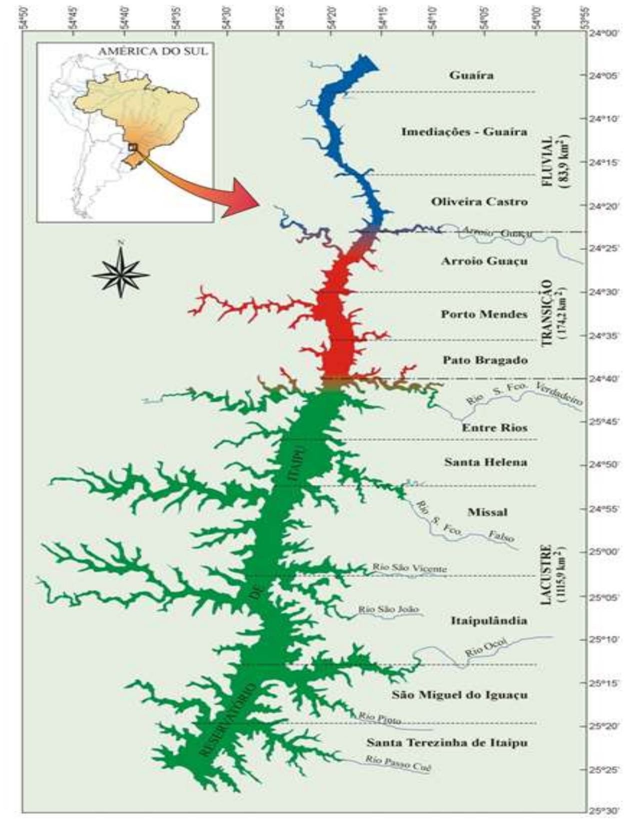

Figure 3: Itaipu Reservoir
Source: Secondary data

This research was conducted assessing documents such as the Ten-Year Energy Plan (Brazil, 2020), the Plant´s annual sustainability reports, and other documents such as technical reports. The purpose of this phase was to obtain information about the actions that were encompassed by the sustainability programme related to the ecosystem service of soil regulation. Aware that erosion interferes on the reservoir´s storage capacity, a perspective to quantify the value of the cubic meter used in power generation was sought. This exercise is justified by the fact that water conservation cannot be achieved without due care with other natural resources, as the hydrological cycle reflects the conditions, uses, and land cover from which the water comes. The water cycle depends from the benefits of vegetation cover (Lima, 1996).

Next, an evaluation exercise was carried out based on the recommended methodology found in the literature (Arias *et al*., 2011; GVces, 2018). Considering the reposition costs, the expenses that would be necessary to recover the reservoir due to sediment discharge were estimated. According to GVces (2019, p. 99):

> Replacement Cost Method (RCM) is based on the premise that incurred (or estimated) costs for replacement, restauration, or substitution of the quantity or quality of an ecosystem service constitute a valid estimation of the values of the benefits that such ecosystem service provides for the company or the society. Thus, the loss of this ecosystem service would represent a burden to the company's or society's activity, which would partially reflect on the monetary value that should be paid for the replacement of this service […]. Costs related to environmental compensations are also considered in this method […] and it may be used to estimate values that are associated to losses that may occur in the future (*ex-ante*), or to estimate values that are associated to losses that happened in the past (*ex-post*).

In the sequence of the research, the following steps were taken: alterations were projected considering three scenarios of soil usage (pasture, conventional seeding and no-till system); the avoided sediment accumulation in the reservoir was quantified; the costs that resulted from the dredging of those sediments were calculated. Finally, as recommended by Arias *et al*. (2011), the valuation of the eventual non-disbursed revenue due to the accumulation of sediments was proceeded, using the average value of the cubic meter of water used in power generation as a reference unit.

In order to obtain the avoided cost, the following were analysed:

i. Total area covered by the vegetation of the reservoir protection zone;
ii. The history of investments and actions that were carried out in the region of the reservoir protection zone;
iii. The current standard soil loss in the region, as a result of the advanced conservation stage in which the protection zone currently is;
iv. Potential soil losses in different types of land usage: without vegetation cover; with conventional seeding; and with no-till system;
v. Assessment of dredging costs – maximum and minimum – for the sediment withdrawal of the reservoir;
vi. Quantification of any unearned revenue due to the accumulation of sediments.

Next, a comparison between these costs and the investments that were made by the hydroelectric power plant in the region, including reforestation, planting of seedlings, and soil conservation, was conducted. The representability of the investments was defined considering the dredging costs. Finally, the data was presented to the managers of the hydroelectric power plant in order to be validated.

4 Results Presentation

The following figure presents the environmental actions that were considered in this evaluation, taking into consideration their objectives and the justification for their development.

Environmental Action	Objective	Justification
Protection zone vegetation management	- Recovery, protection, and conservation of the protected areas (vegetation area near the reservoir); - Recovery and conservation of permanent preservation areas, by creating ecological corridors	To conserve and recover the protected areas that belong to the Itaipu power

	which allow the gene flow of the regional flora and fauna.	plant, guaranteeing their biological integrity.
Integrated management of water and soil	- Conservation practices, such as agricultural terracing, gully control, rural roads adequacy, construction of isolation fence of the riparian forest, reforestation, recovery of river springs, plantation of seedlings, and protection and recovery of sources.	To reduce the sediment yield in order to maintain the availability of water in good quality and in enough quantity for the energy production and other uses.

Figure 4: Itaipu environmental actions
Source: Based on secondary data

Regarding the evaluation of sediment discharge, three common scenarios of soil usage in nearby areas of the reservoirs were considered, as well as the standard soil loss acknowledged by the hydroelectric plant, considering the soil quality of that region and the advanced stage of the areas conservation.

Table 1:
Evaluation of sediment discharge

Total area evaluated in the erosion estimation of the reservoir protection zone	28,000 ha		
Different uses of soil	Pasture	Conventional seeding	Direct seeding
Soil erosion pattern (reference: universal soil loss equation)	175.80 t/ha/year	26 t/ha/year	13 t/ha/year
Soil erosion of the protection zone region (acknowledged by the hydroelectric plant)	1.7 t/ha/year		

Source: Based on secondary data

Based on this information, a cost simulation was held considering the sediment withdrawal from the reservoir bed. In this step, maximum and minimum cost references, identified in the literature, were used (Carvalho *et al.*, 2000; Bidone *et al*. 2009; Bueno, 2010; GVces, 2016).

Table 2:
Cost calculation

Erosion	**Erosion (t/ha/year) x hectares of the protection zone**	**Erosion x Dredging cost per ton**	**Dredging cost/year**	
175.8 – 1.7 (tons)	174.10*28000	4,874,800*US$ 650	US$ 3.168 Bi	Maximum cost
26-1.7 (tons)	24.30*28000	680,400*US$ 650	US$ 442.26 Mi	
13 – 1.7 (tons)	11.30*28000	316,400*US$ 650	US$ 205.66 Mi	
Erosion	**Erosion (t/ha/year) x hectares of the protection zone**	**Erosion x Dredging cost per m^3**	**Dredging cost/year**	
(175.8 – 1.7)/2.65 (converting tons to m^3)	65.698*28000	1,839,5440 * US$ 15	US$ 27.59 Mi	Minimum cost
(26-1.7)/2.65 (converting tons to m^3)	9.169*28000	256,754 * US$ 15	US$ 3.85 Mi	
(13 – 1.7)/2.65 (converting tons to m^3)	4.264*28000	119.396 * US$ 15	US$ 1.79 Mi	

Source: Based on secondary data

As described on Itaipu’s annual reports, the predominant use of the soil by the riparian agriculturists of the region occurs applying no-till techniques. These techniques are encouraged by the hydroelectric plant sustainability program, by means of actions that have been executed for over a decade, connected to the rural technique assistance and to the sustainable rural development amongst local communities.

In view of the above, in table 2, it is possible to infer that annual costs of approximately US$ 1.79 million are avoided when we consider the lowest verified cost of dredging in the literature. It is noted that the costs with the withdrawal of sediments from the reservoir would be greater in the eventual use of the soil for pasture or conventional seeding techniques.

When the eventual non-invoiced revenue for accumulation of sediments was verified, using the value of the cubic meter as a reference unit, the water consumption, generation (gigawatts-hour), and revenue in the last 11 years was then analysed. The following table presents the information that shows dependency on water availability as an input, once its decline may cause a decrease in generation. In this case, it is suggested that the economic evaluation reflects the loss of equivalent billing (GVces, 2018) in the eventual loss of storage capacity of the reservoir due to the discharge of sediments.

Table 3:
History of water consumption, generation, and revenue.

Year	Total m^3(to turbine and cool the generating units)	Generation (GWh)	Revenue (US$)	US$/$m^3$
2010	302,463,122,458	85,303	3,450,500,000	0.01141
2011	326,072,700,058	91,523	3,384,400,000	0.01038
2012	344,836,101,658	97,533	3,703,500,000	0.01074
2013	349,534,447,258	97,878	3,760,100,000	0.01076
2014	309,180,808,858	87,165	3,680,400,000	0.01190
2015	314,828,344,858	88,575	3,680,800,000	0.01169
2016	369,998,719,258	102,335	3,811,500,000	0.01030
2017	336,476,556,058	95,682	3,729,703,000	0.01108
2018	333,253,836,058	96,586	3,699,900,000	0.01110
2019	265,395,069,057	79,445	3,586,800,000	0.01351
2020	252,101,869,083	76,842	3,566,800,000	0.01414

Source: Based on secondary data

Based on table 3, it appears that the average value of the cubic meter is US$ 0.0115, so that the average daily water consumption is 872,762,534.16 m^3 and the average daily revenue is US$ 9,976 million. In this context, any loss of water storage capacity that compromises the availability of this input for generation can directly affect the hydroelectric plant´s revenues. Although the loss of revenue is not the central point of this work, as highlighted by the literature (Lima, 1996; Medeiros & Young, 2011), the strong interface between the ecosystem service for regulating soil erosion and the water supply stands out.

The data in table 3 also reveals similar trajectories between water consumption and energy generation, a finding reinforced by the correlation index verified in this historical series ($r = 0.986554$). In view of the above, it can be affirmed that, in addition to the preservation of the reservoir, it is necessary to envision the positive developments for water availability when the vegetation and adjacent soil are preserved. It is also important to note that water, as the main input for hydropower generation, is going through a time of scarcity due to a series of factors (rainfall regime, precarious conditions of vegetation close to the reservoirs, and others) which have caused the reduction in generation hydroelectric power in recent years and the consequent rise in tariffs due to the increased participation of other sources (thermal, wind power and others) for the national supply (ANA, 2019). The next graphs highlight the water flow and energy generation trajectory in recent years for the Itaipu plant.

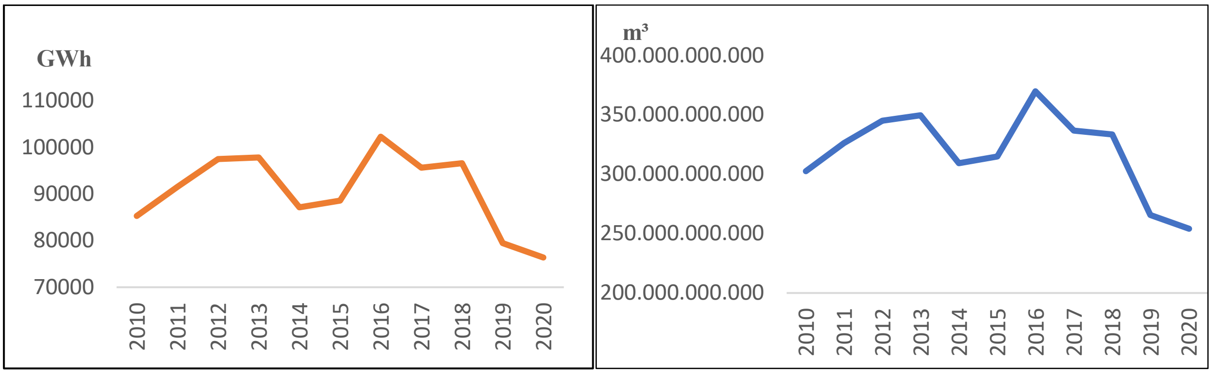

Figure 5: Energy generation and water flow.
Source: Based on secondary data

Another aspect which was not considered in the average figures of the topic study, although stoutly important, is the impact of other undertakings upstream Itaipu Reservoir. The last survey accomplished has signaled that there are other 156 man-made reservoirs of several sizes and purposes upstream Itaipu (Mendes, 2020). Throughout time, as those reservoirs become silted, they gradually lose their project design of trapping sediments, thus releasing more and more sediment discharge to downstream undertakings. As a consequence, the downstream reservoirs become silted faster than predicted, and thereby also lose their trapping efficiency beforehand. Such phenomenon is synergic and occurs in all the reservoirs of the watershed at the same time like a domino effect.

Next, investments of the hydroelectric power plant sustainability program were evaluated, focusing on activities that directly impact the maintenance of the vegetation and the soil conservation, which are perceived as directly avoiding the inflow of sediments into the reservoir. The average annual values are US$ 312,500 and US$ 82,500, respectively, and their sum represents approximately 22,04% of the lowest avoided annual cost due to dredging, and 0.011% of the average annual revenue. With this information in mind, it is estimated that, for each US$ 1 invested in these activities, the hydroelectric plant avoids expenses – as a result of the process of dredging – that range from US$ 4.53 (lowest cost) to US$ 520.65 (highest cost).

5 Final Remarks

The objective of this work is to measure the ecosystem service of regulation of soil erosion for the Itaipu hydroelectric plant. It was found that the ecosystem service provided by the soil and vegetation surrounding the reservoir has prevented high sediment discharges from entering the reservoir, corroborating previous studies (Arias *et al*., 2011; Vogl *et al*. 2016). This benefit allows the storage capacity of the reservoir to be maintained, avoiding reduction of its useful life. The annual costs avoided for removing sediment from the reservoir, using soil for no-till farming range from US$ 1.79 million to US$ 205.66 million.

With this information in mind, and considering the average of annual disbursements of the hydroelectric power plant in the conservation of the vegetation in protected areas and integrated management of water and soil, the economic viability of maintaining the developed actions was confirmed, representing an investment in the preservation of the storage capacity of the reservoir, with water being the main input for hydroelectric generation. These activities, although not the only ones, were interpreted in this research as being decisive – according to the specialized literature (Oliveira, 2003; Capeche, 2005; Vogl *et al*. 2016) – to prevent the progress of erosion in the site.

Among the contributions for the evaluation exercise, stand out the possibility of expanding the understanding of risks arising from sedimentation and eventual scarcity of water for the generation of hydroelectricity; the continuous loss of storage capacity of the more than 150 other reservoirs placed upstream the Itaipu Reservoir, thus increasing the sediment discharge into it as time passes; the dimensioning of investments in view of the magnitude of services provided by the environment; and the opportunity for the organization to act preventively in areas of interest, such as those around the reservoir in order to ensure its integrity.

In addition, with this information, new research fronts can be open, such as the use of monetary measurements carried out as a reference for projects including payments for environmental services to local surrounding farmers interested in preserving the vegetation. In this context, initiatives of this nature carried out by hydroelectric power plants in Costa Rica, Venezuela, and Colombia stand out. These plants pay for the conservation of the hydroelectric basins from where comes the water for power generation (Pagiola; Von Glehn &Taffarello, 2013). Another opportunity for future research consists in replicating this study in other large hydroelectric power plant, in order to obtain comparative data on environmental investments, conservation status of vegetation areas, and measurement of ecosystem services, always by bearing in mind the variables which may be taken into account in studies of such magnitude.

It is recognized that this evaluation exercise points out relevant data to support an organization´s decision-making process, as regards its environmental performance, although aspects such as settling rate, disposal of sediments upstream ~~of~~ the reservoir, interference of other reservoirs upstream and the specific characteristics of the location were not considered. These topics can be relevant for sedimentation estimates, and can constitute an opportunity for further future study.

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