CONSULTANCY FOR WRI

ASSESSING IMPACTS OF DEFORESTATION IN ITAIPU'S DAM WATERSHED IN PARAGUAY

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ASSESSING IMPACTS OF DEFORESTATION AND BENEFITS OF REFORESTATION IN THE PARAGUAY'S SECTION OF ITAIPU'S DAM WATERSHED

1. Executive summary

This report presents results from a rapid eco-hydrological assessment to evaluate the impacts of deforestation on the Paraguay section of the Itaipu Dam. Itaipu Binational is one of the most economic and financially efficient hydropower projects in the world (WCD, 2000). However, our assessment qualitatively indicates that recently high deforestation rates in proximity to its multiannual reservoir may have increased substantially the potential amount of soils to be transported to the reservoir.

This study used processed based eco-hydrological models, including the model FIESTA/WaterWorld (Mulligan, 2013; Sáenz and Mulligan, 2013; Saenz *et al*., 2013), and scenario analysis, in order to determine these impacts. These models were also used to identify potential areas for investment in forest restoration in order to mitigate some of those impacts.

Study results indicate that the Itaipu's Dam watershed may have lost around 7.3% of its forests over the 2000 – 2010 decade, with Paraguay losing close to 10% of its forests found within the watershed. These figures represent a substantial forest loss, particularly in Paraguay. Recent forest cover loss may have resulted in greater soil loss and transport to the Itaipu Dam reservoir. The study provides a qualitative indication of the probable economic cost of dredging this potential amount of additional soils available for transport to the reservoir. The cost could be in the order of several million USD per year (between USD $ 7 to USD $23 million per year depending on the cost of dredging applied). Therefore, if forest degradation continues at the rate seen during the 2000 – 2010 period, the Itaipu dam could probably be impacted operationally and economically from the short to middle term. *However, a more detailed economic and operational assessment is needed to confirm this qualitative conclusions. Until then, these numbers and conclusions should be used with caution.*

The study also implemented a priority setting exercise to identify areas of high reforestation value, in terms of avoided dredging. It shows that 2.5% of Paraguay's land within Itaipu's watershed can be consider of high reforestation value (around 30000 ha). These lands largely overlay with recently deforested areas (2000 – 2010 period).

This report could be used to qualitatively illustrate to Itaipu Binational, how substantial recent deforestation can really translate into reservoir operational problems in the short term, and on potential declines in economic performance in the middle term, due to increased dredging. Thus, the report can be used as a tool to indicate to dam owners and operators, as well as local government officials, that deforestation has to be controlled and reforestation activities in targeted areas, as the ones suggested here, should start to be implemented.

2. Itaipu Dam watershed area and forest cover

2.1 Area estimates

Using the Itaipu Dam Watershed, extracted from Sáenz and Mulligan (2013) (Figure 1), we delineated all areas contributing flow and sediments to the Itaipu dam reservoir. What we can see from this area assessment is that out of 93.1 million hectares, only 1.3% (around 1.2 million hectares) are found in Paraguay (Table 1).

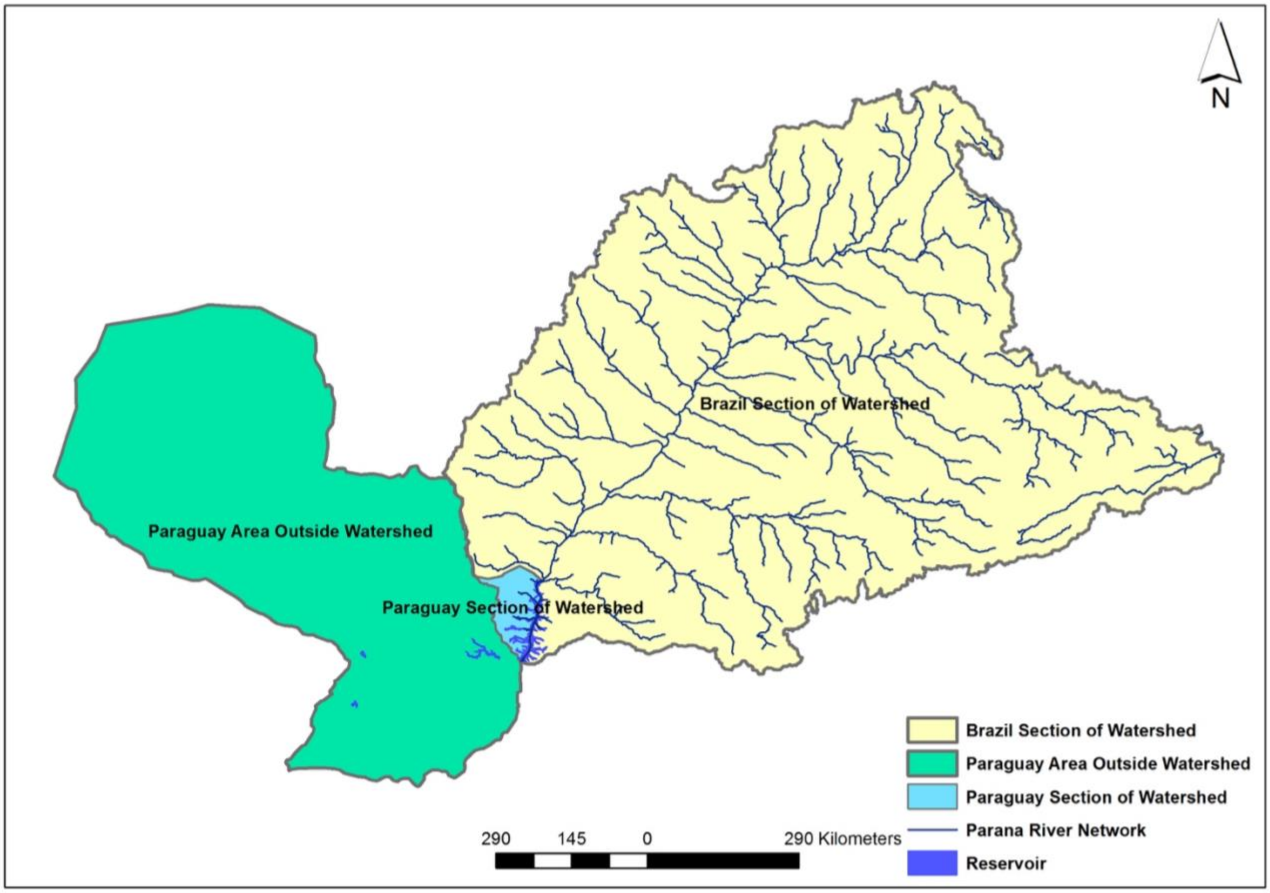

Figure 1. Study area including: a. Area of the Itaipu Dam Watershed; b. Section of the watershed within Paraguay; c. Section of the watershed within Brazil; and d. Area of Paraguay outside of the Watershed. ***Sources: Itaipu Dam Watershed, extracted from Sáenz, L. and Mulligan, M. (2013); HydroSHEDS, HydroBasins_v1b.***

Table 1. Area estimates of Itaipu Dam Watershed in total numbers as well as in percentage for Brazil and Paraguay sections. ***Sources: Itaipu Dam Watershed, extracted from Sáenz, L. and Mulligan, M. (2013); HydroSHEDS, HydroBasins_v1b.***

Variable	Value	Value in km2	Value in Million Hectares
Area			
Dam Watershed (Mm2)	931465.1	931465.1	93.1
Brazil Section (Mm2)	919813.0	919813.0	92.0
Paraguay Section (Mm2)	11643.6	11643.6	1.2
Dam Watershed (%)	100.0	--	--
Brazil Section (%)	98.7	--	--
Paraguay Section (%)	1.3	--	--

2.2 Forest cover year 2000

Using Vegetation Continuous Fields MODIS tree cover data produced by Hansen et al., (2006), analysis indicate that Paraguay only contained around 2.31% of the forest cover of Itaipu's Dam watershed in the year 2000 (around 322200 hectares) (Table 2). Itaipu had a forest extension of around 13.9 million ha in the year 2000, with around 97.7% of these forests found in Brazil. Most forested parts of Itaipu in Brazil are in the headwaters and steepest slopes of the Atlantic forest, and in some parts of the states of Mato Grosso del Sur and Goias (Figure 2).

It can be noted that Paraguay held a greater proportion of Itaipu's forests than land area. While Paraguay accounted for only around 1.3% of Itaipu's land area, it contained almost twice as much percentage of Itaipu's forests (Table 2). This indicates that Paraguay held an important concentration of Itaipu's forest in the lower watershed in proximity to the reservoir, of likely significant value for mitigating sedimentation and probably landslides in embankments around the large Itaipu's reservoir (Figure 2).

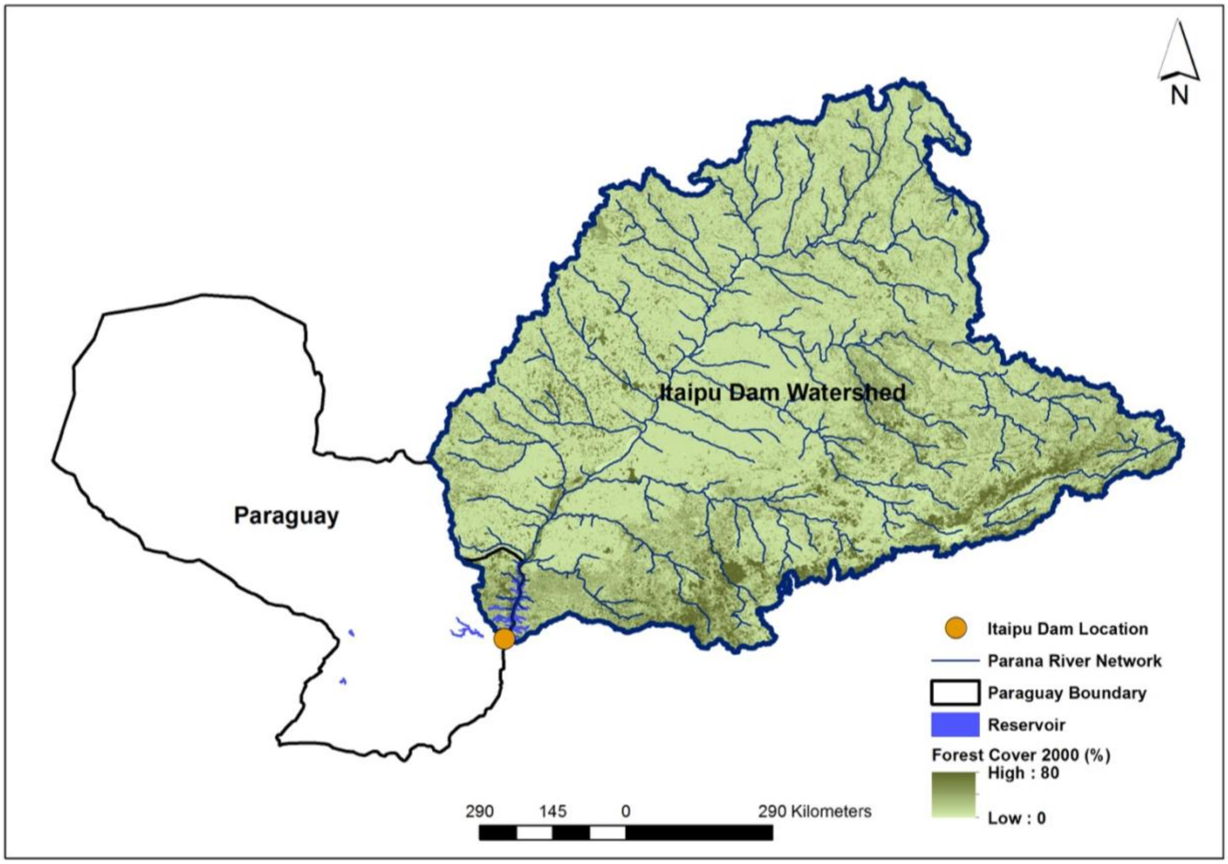

Figure 2. Forest cover in the watershed of the Itaipu Dam in the year 2000. 13.7 million ha of forests of which 97.7% were located in Brazil and the remainder in Paraguay. *Sources: Mulligan, M. (2017); Hansen, et al., (2006).*

Table 2. Forest Cover in Itaipu Dam Watershed in year 2000. Total numbers for watershed as well as in percentage for Brazil and Paraguay sections. *Sources: Mulligan, M. (2017); Hansen, et al., (2006).*

Variable	Value	Value in Million Hectares
Forest Cover		
Dam Waterhsed (ha)	13951533.0	14.0
Brazil Section (ha)	13629106.2	13.6
Paraguay Section (ha)	322195.9	0.3
Dam Watershed (%)	100.0	
Brazil Section (%)	97.7	
Paraguay Section (%)	2.3	

2.3 Forest cover change 2000 – 2010

Using Vegetation Continuous Fields MODIS tree cover data for years 2000 and 2010, produced according to the methodology described by Hansen et al., (2006), difference detection analysis indicate that the Itaipu Dam watershed lost around 7.3% of its forest during this period (around 1.02 million ha) (Table 3). 97% of these forests were lost in Brazil and around 3% in Paraguay (Table 3).

This figure shows that Paraguay lost almost 10% of its forests found within the watershed, with a forest loss rate that was greater than that in the Brazil's section, in percentage terms (Table 3). Therefore, Paraguay underwent the greatest forest loss rate within the Itaipu Dam watershed, over the 2000 – 2010 period, highlighting an important pressure for deforestation over that decade.

Figure 3 shows the MODIS tree cover data for years 2000 and 2010. I can be noted the thinning of the forest in the Paraguay's part of the watershed in the 2010 map, as well as in some sections of the Atlantic forests in Brazil.

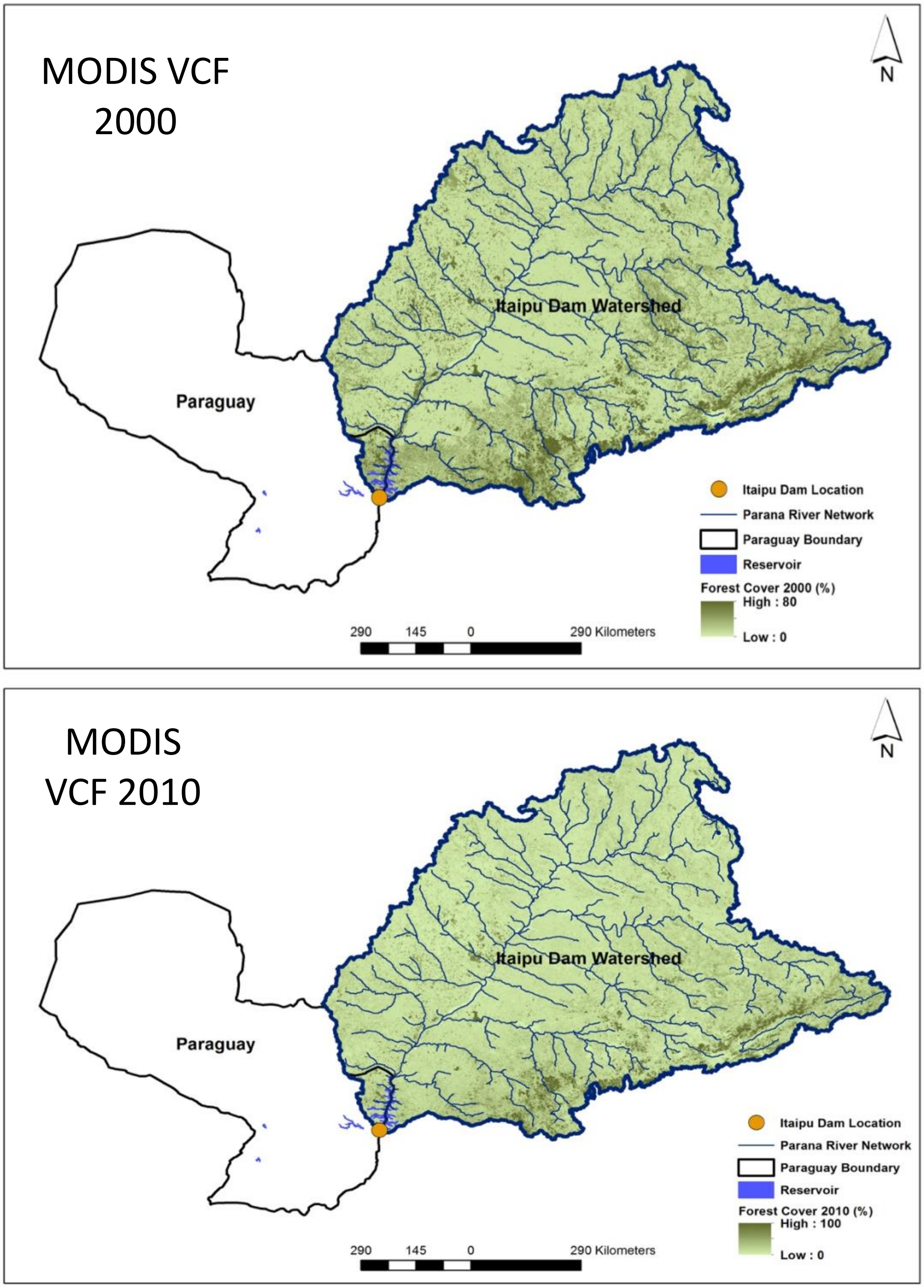

Figure 3. Forest Cover loss in Itaipu Dam Watershed over the 2000 – 2010 decade. 1.02 million ha of forests were lost in the whole watershed, with Paraguay showing a greater forest loss rate, relative to 2000 forest cover. *Sources: Mulligan, M. (2017); Hansen, et al., (2006).*

Table 3. Forest Cover loss in Itaipu Dam Watershed over the 2000 – 2010 decade. Total numbers in ha for the watershed as well as in percentage terms for Brazil and Paraguay sections. Change also presented relative to initial forest cover per country. *Sources: Mulligan, M. (2017); Hansen, et al., (2006).*

Variable	Value	Value in Million Hectares
Forest Loss		
Dam Waterhsed (ha)	1019384.0	1.02
Brazil Section (ha)	988405.0	0.99
Paraguay Section (ha)	30979.0	0.03
Dam Watershed (%)	100.0	
Brazil Section (%)	97.0	
Paraguay Section (%)	3.0	
Forest Loss (% of 2000 cover)		
Dam Watershed (%)	7.3	
Brazil Section (%)	7.3	
Paraguay Section (%)	9.6	

3. Eco-hydrological modelling and baseline results

We then applied the model FIESTA/WaterWorld, Version 3, 2017 (Mulligan, 2017) with the best secondary data for climate (WorldClim, Hijmans, et al., 2005), and land cover (MODIS VCF 2010), according to Mulligan (2013) and Saenz et al., 2014; and produced a representation of the baseline eco-hydrology of the Itaipu Dam Watershed to the year 2010. We used MODIS VCF 2010 data to re-create the baseline eco-hydrology for that year, to then run a scenario analysis and compared changes due to deforestation since the year 2000.

3.1 FIESTA/WaterWorld

FIESTAFD/WaterWorld is a model designed to better-understand spatial and seasonal changes in water inputs, evaporative and soil losses associated with the conversion of tropical forests to pasture in data-sparse environments (Mulligan, 2013). The model implements significant innovations in our understanding of tropical eco-hydrological processes, including wind driven precipitation and fog intercepted by trees, as well as actual evapo-transpiration (AET) losses in tropical areas (Mulligan and Burke, 2005; Sáenz and Mulligan, 2007; Bruijnzeel *et al.,* 2010; Mulligan, 2013). It also implements soil erosion and sediment transport sub-models that are suitable for tropical roughed terrain, where the energy of runoff inducing wash-sheet erosion in steep terrain as well as gully erosion, becomes the dominant processes (Saenz, 2011).

- **Selection of FIESTA/WaterWorld**

FIESTA/WaterWorld was chosen because it is a model that has been widely reported for ecosystem service mapping and quantification in tropical areas; and for policy support, which is the purpose of this rapid assessment (Bruijnzeel *et al.,* 2010; Mulligan *et al.,* 2010; Mulligan, 2013; Sáenz and Mulligan, 2013; Sáenz *et al.,* 2013; Sáenz *et al.,* 2014; Sáenz *et al.,* 2016). The model has been applied and tested widely throughout the tropics with particular applications in the watersheds of tropical dams (Mulligan, 2013; Sáenz and Mulligan, 2013; Sáenz et al., 2014).

In terms of model features useful for this study, FIESTA/WaterWorld was chosen because the model particularly allows for the interpretation of forest ecosystem services beyond hydrology, which helps us make a stronger case for forest protection. For instance, significant innovations in the treatment of wind driven precipitation processes and their interception by trees are incorporated into the model. These innovations are very relevant for tropical mountainous areas such as in the Atlantic forest of Brazil, to produce more accurate water balances in the headwaters of tropical dams (Saenz, et al., 2014; Saenz, et al., 2016). This is first, because rainfall is highly underestimated in tropical mountains, and thus FIESTA/WaterWorld helps to correct for those underestimations, achieving sounder water balances (Bruijnzeel *et al.,* 2010); and second, because part of wind driven rain volumes are intercepted by trees, preventing its loss to neighbouring watersheds, and thus helping dams, like Itaipu, maintain its performance. FIESTA/WaterWorld allows us to filter this process to assess the role of forests in keeping this extra rainfall in the watersheds of dams. Moreover, FIESTA/WaterWorld, allows for the estimate of fog interception by trees which in tropical areas can represent between 5% to 25% of annual water balances in tropical mountainous watersheds (Giambelluca, et al., 2011).

In terms of soil loss and sediment generation, FIESTA/WaterWorld implements a physically based modelling approach of wash-sheet runoff based erosion and sediment transport/deposition in hillslopes and along river streams based upon the empirical work of Thornes (1990), Kirkby (1976) and Morgan (2001), which have been reported to be more representative of soil erosion and sediment transport processes in tropical roughed terrain (Mulligan, et al., 2010). The Thornes (1990) model, in particular, has been widely used (Mulligan, 1998; Diodato, 2006). When forests are lost, denuded soils in steep slopes are more susceptible to soil loss when high intensity rainfall transforms into rapid runoff. This is the dominant process for soil loss and transport in steep tropical mountains (Bruijnzeel, 2004). The model was chosen to reproduce these processes because it represents them well from empirical physically based research (Saenz, 2011).

Finally, the model has been developed with input from water practitioners around the world, to improve its applicability for rapid assessments and policy support, which is mainly the focus of its application here. For instance, hydrological assessments in tropical regions are hindered by the lack of quality controlled local meteorological data and data sparsity (Vorosmarty et al., 2010). FIESTA/WaterWorld was designed to overcome that challenge in mind, by concentrating one of the most complete global database of quality controlled meteorological and biophysical variables (around 200), for seamless applications in data sparse regions and through process based methods as the ones described above, in order to improve the performance of the model when using global datasets (Saenz, 2011). Some of the projects that have funded the development of the model for tropical applications include FIESTA (Bruijnzeel et al., 2006), CGIAR CPWF Andes Focal Project (Mulligan, et al., 2009), CGIAR CPWF COMANDES (2012), and CGIAR Northern Volta Basin project (Mulligan and van Soesbergen, 2017), are some of those projects.

The main variables calculated with the model were annual water yield, evapo-transpiration, fog interception (in the highest parts), wash-runoff soil erosion and sediment transport patterns in rivers (Figure 4 to Figure 7). Expanded methods and main assumptions and caveats that went in to the modelling exercise are described in Appendix 1.

3.2 Rainfall

Paraguay only receives around 1.4% of the Itaipu's Dam watershed rainfall (around 19000 million m3) (Table 4). On average intensities per hectare though, rainfall is greater in the Paraguay's section (1626 mm/year compared to 1419mm/year) (Table 4). Yet, the areas that receive the most rainfall intensities are found in Brazil's Atlantic forests, where they can reach up to 3000 mm/year (Figure 4).

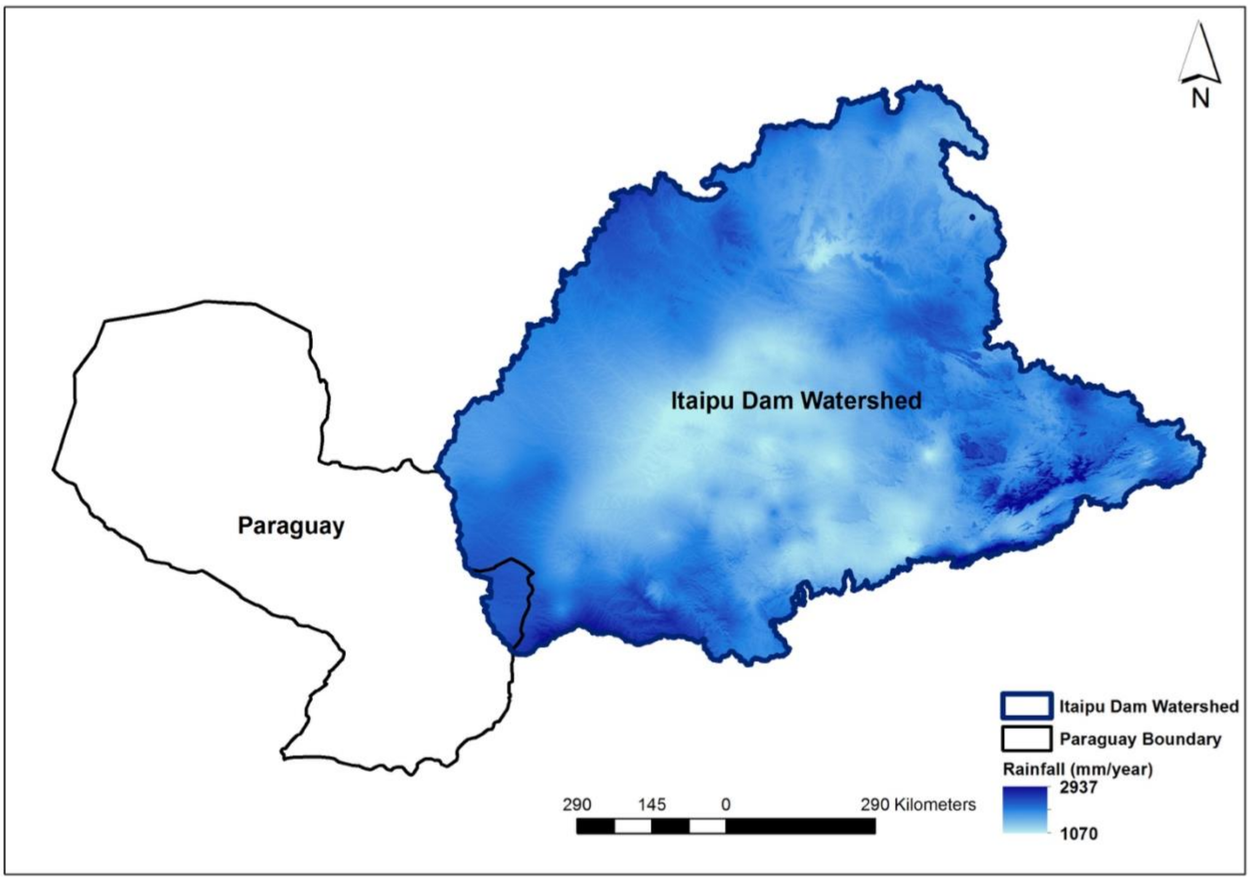

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Table 4. Rainfall intensities and volumes in Itaipu Dam Watershed. Average annual rainfall intensities in mm/year; volumes in million m3; as well as in percentage terms for Brazil and Paraguay sections. Using w*ind corrected rainfall data modeled with FIESTA/WaterWorld V 3.31, using WorldClim 2000 rainfall surfaces interpolated from rainfall stations.*

Variable	Value	Value in km3
Rain		
Dam Waterhsed (mm)	1422.0	--
Brazil Section (mm)	1419.0	--
Paraguay Section (mm)	1626.0	--
Dam Watershed (Mm3)	1324543.4	1324.5
Brazil Section (Mm3)	1305214.6	1305.2
Paraguay Section (Mm3)	18932.5	18.9
Dam Watershed (%)	100.0	--
Brazil Section (%)	98.5	--
Paraguay Section (%)	1.4	--

3.3 Water Balance

Paraguay only contains around 1.4% of the water balance volume in the watershed (around 15200 million m3) (Table 5). On average depth (mm/year) per hectare though, the water balance is greater in the Paraguay's section by more than 100 mm/year, with 802 mm/year compared to 698 mm/year in the Brazilian section. Yet, the areas that show highest water balances within the watershed, are found in Brazil's Atlantic forests, where they can reach up to 2700 mm/year.
Mountains in the Atlantic forest region enjoy higher rainfall intensities as the block moisture travelling from the Atlantic Ocean and promote condensation, cloud formation and rainfall. Cloud forests in these areas also help promote higher water balances thanks to their fog trapping capacity which increases water balances on average by 3%, but that can reach up to 12% of the water balance in some areas of the Atlantic forest.

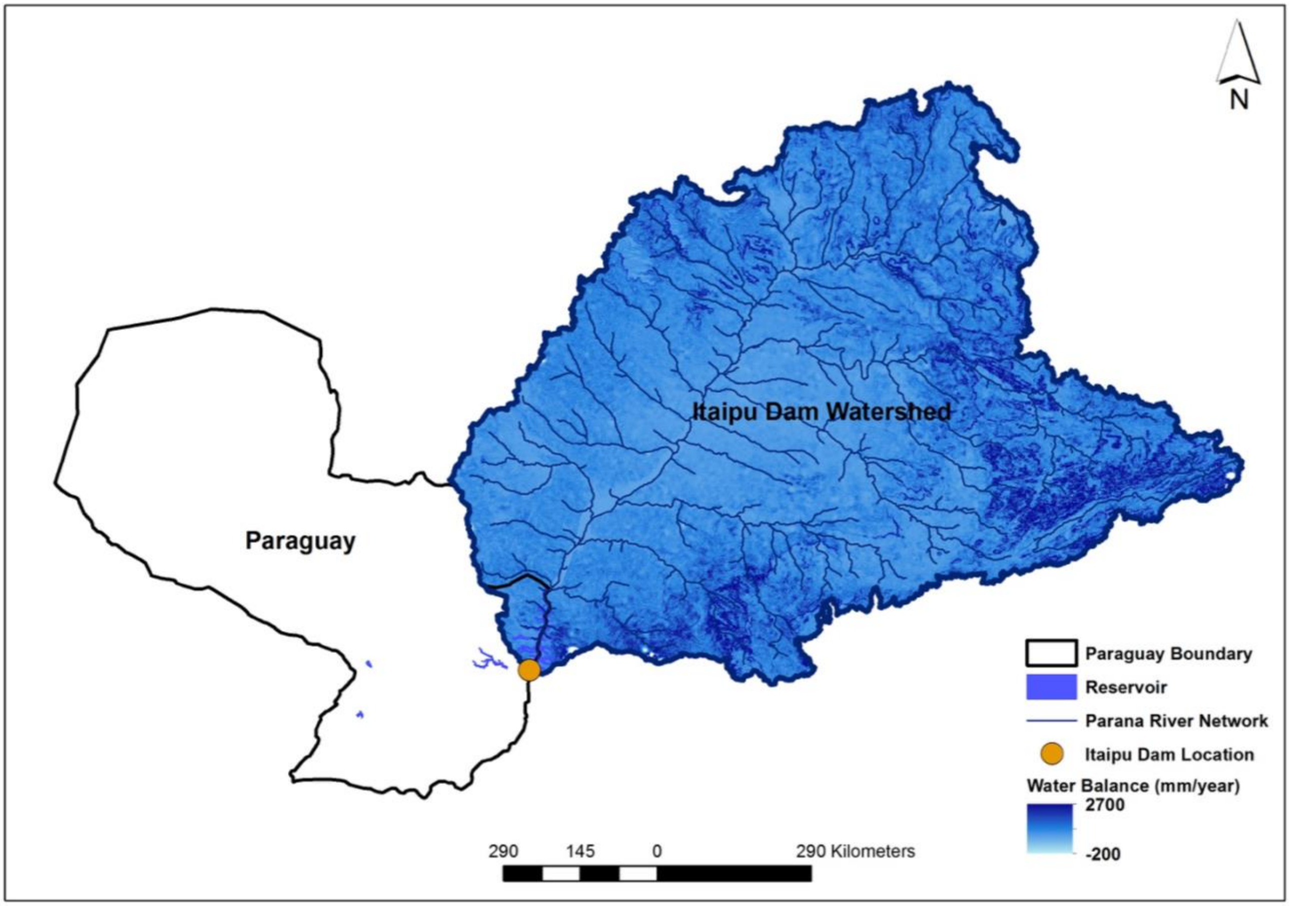

Figure 5. Distribution of water balance (mm/year) in the Itaipu Dam Watershed. ***Modeled with FIESTA/WaterWorld V 3.31, using WorldClim 2000 rainfall surfaces interpolated from rainfall stations and land cover data according to MODIS VCF 2010.***

Table 5. Water Balance in depth and volume for the Itaipu Dam Watershed. Average annual water balance depths are presented in mm/year; volumes in million m3; as well as in percentage terms for Brazil and Paraguay sections. ***Modeled with FIESTA/WaterWorld V 3.31, using WorldClim 2000 rainfall surfaces interpolated from rainfall stations and land cover data according to MODIS VCF 2010.***

Variable	Value	Value in km3
Water Balance		
Dam Waterhsed (mm)	699.0	--
Brazil Section (mm)	698.0	--
Paraguay Section (mm)	802.0	--
Dam Watershed (Mm3)	925855.8	925.9
Brazil Section (Mm3)	911039.8	911.0
Paraguay Section (Mm3)	15183.9	15.2
Dam Watershed (%)	100.0	--
Brazil Section (%)	98.4	--
Paraguay Section (%)	1.6	--

3.4 Fog Interception by the forest vegetation

Some parts of the Atlantic forests in Brazil capture up to 300 mm/year of water from travelling clouds (13% of the water balance of those areas) (Figure 6). These forests are likely important locally for this hydrological service and contribute to the greater water balances of these areas. No fog interception by forests occur in Paraguay though, as this section of the watershed is dominated by lowlands where fog persistence is low throughout the year.

Water inputs from fog amount to around 3200 million m3 of additional water per year, but mostly generated in the Atlantic forest in Brazil. If these forests in Brazil are lost, this water will also be lost for hydropower generation in Itaipu. Calculating the economic impact of this loss for Itaipu is outside the scope of this rapid analysis, which focuses on assessing the impacts of forest loss in Paraguay and the benefits of reforestation in this country for the Itaipu Dam.

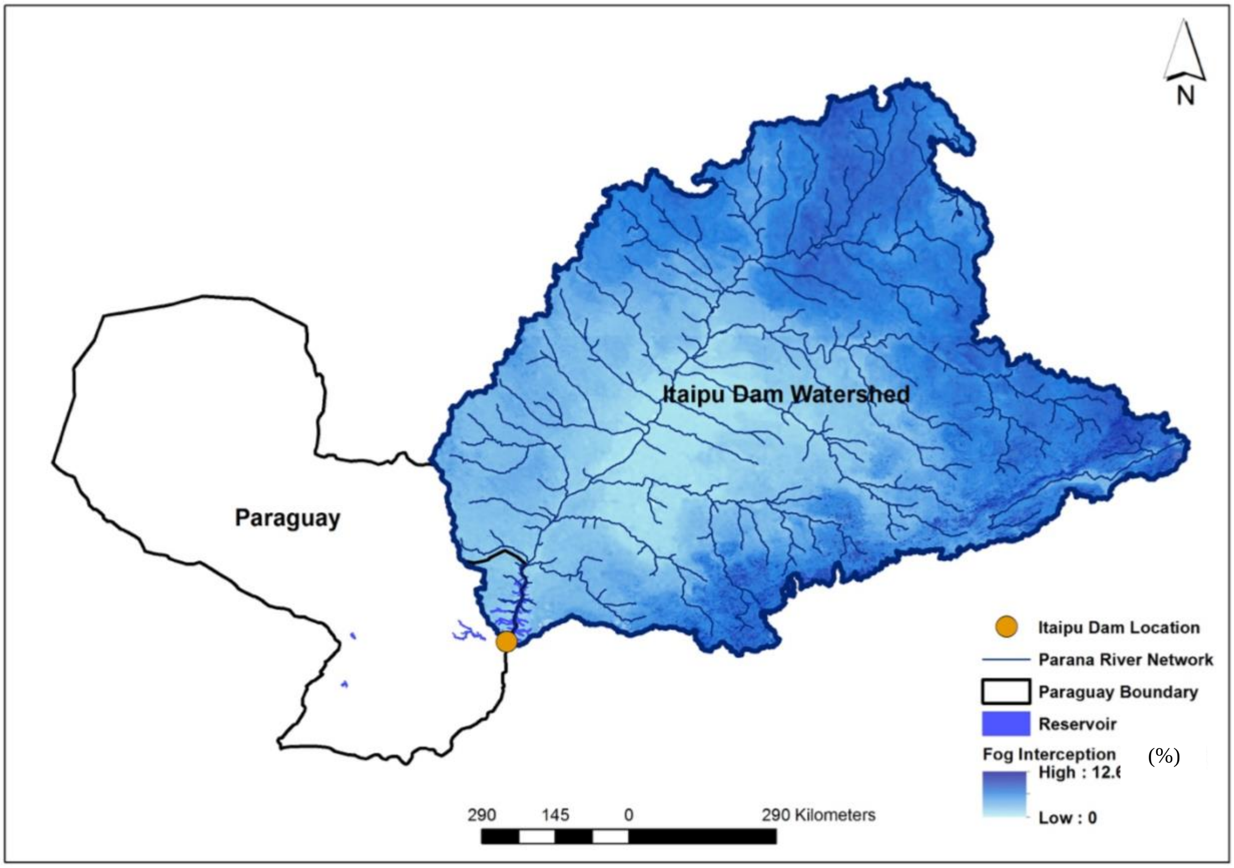

Figure 6. Distribution of fog interception (mm/year) in the Itaipu Dam Watershed. *Modeled with FIESTA/WaterWorld V 3.31.*

3.5 Soil Erosion

Paraguay is responsible for around 1.25% of the soil loss per year from hillslopes that occurs in the Itaipu's watershed (around 92400 m3 of soil loss) (Table 6). However, soil loss should be tackled in the Paraguay's part of the watershed due to recent larger deforestation rates than in the Brazilian section. In total numbers (m3), soil loss is greater in Brazil though, particularly in headwaters and steep slopes of the Atlantic forest, and in some parts of the states of Mato Grosso del Sur and Goias (Figure 7).

However, soil erosion in Paraguay is likely to affect the dam reservoir more directly because newly deforested areas are closer to the reservoir than Brazil's headwaters, and thus sediments are likely to deposit more directly.

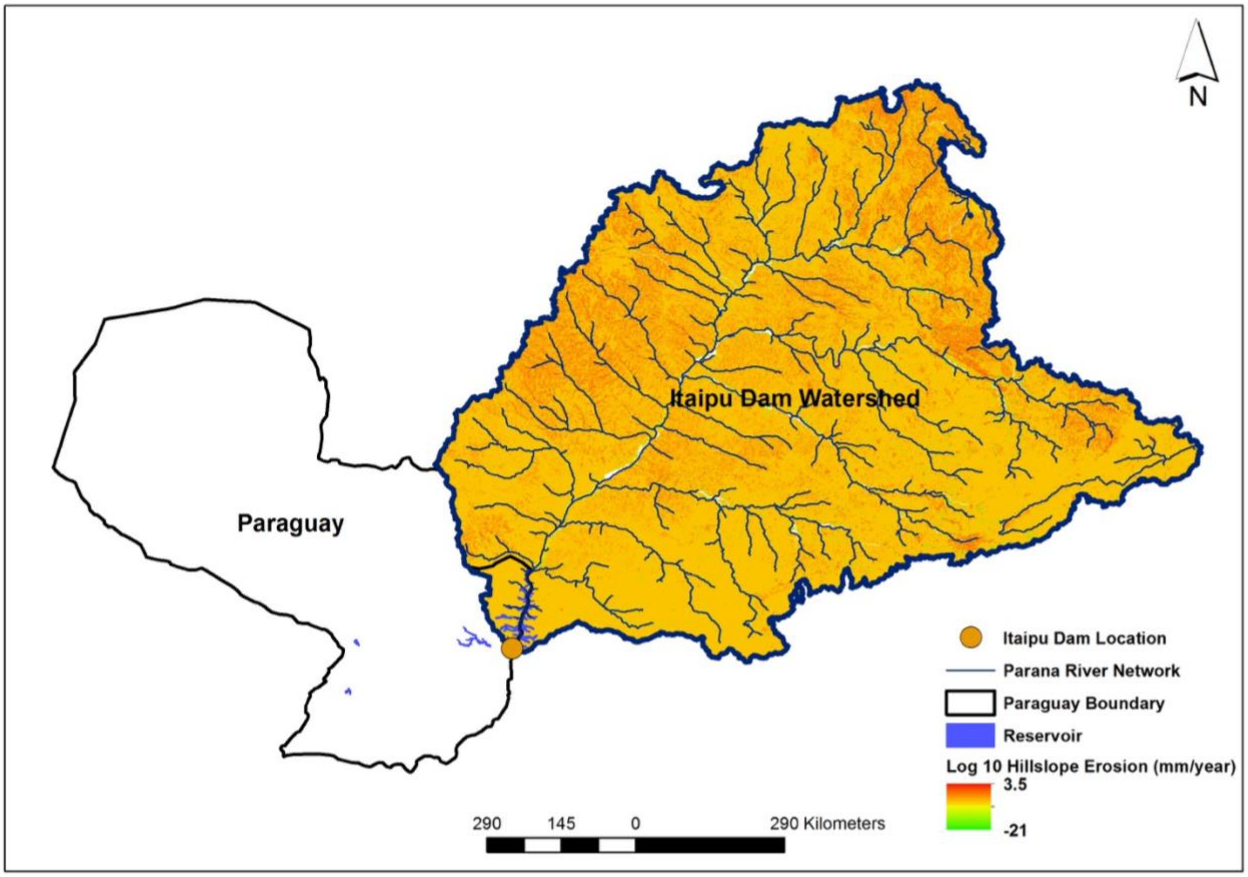

Figure 7. Distribution of Soil Erosion (mm/year) in the Itaipu Dam Watershed. *Modeled with FIESTA/WaterWorld V 3.31.*

Table 6. Soil Erosion depth and volume for the Itaipu Dam Watershed. Soil Erosion depths are presented in mm/year; volumes in million m3; as well as in percentage terms for Brazil and Paraguay sections. ***Modeled with FIESTA/WaterWorld V 3.31.***

Variable	Value
Soil Erosion	
Dam Waterhsed (mm)	0.007920
Brazil Section (mm)	0.007920
Paraguay Section (mm)	0.007930
Dam Watershed (Mm3)	7.377
Brazil Section (Mm3)	7.285
Paraguay Section (Mm3)	0.092
Dam Watershed (%)	100.0
Brazil Section (%)	98.7
Paraguay Section (%)	1.3

3.6 Conclusions: Forest cover, forest cover change and baseline eco-hydrology

Although Paraguay only accounts for 1.3% of the Itaipu's watershed area, its section shows an important concentration of forests likely relevant for maintaining the performance of the Itaipu Dam Reservoir. These forests in hillslopes and riparian buffers are likely important for mitigating sedimentation of the reservoir and its impacts on hydropower outputs and economic performance. In addition, some of these forests can be important to regulate storm flows, which can induce landslides in steep reservoir embankments during exceptionally wet seasons, thus reducing its lifespan.

However, deforestation rates over the 2000 – 2010 decade were worryingly greater in the Paraguay's part of the watershed than in the Brazilian part. Paraguay lost close to 10% of its forest located in the watershed. This forest loss is worrisome because, it may have resulted in greater sediments transported to the reservoir from nearby areas. Impacts of deforestation on the eco-hydrology of the watershed, in its Paraguay's section, are likely to be significant for the dam reservoir, although were not quantified here due to operational data constraints. The significance of these impacts is because rainfall intensities and water budgets, which transform into surface runoff, are relatively greater in Paraguay than the average for the whole watershed. This means that surface runoff from deforested areas close to the reservoir, or from riparian buffers of rivers feeding the reservoir, has a greater ability to transport more sediments to the reservoir.

In contrast, impacts of deforestation in Paraguay on total water flows reaching the reservoir are likely to be relatively small though, since Paraguay already only contributes around 1.6% of Itaipu's annual water volumes. Impacts of deforestation on infiltration, and therefore seasonality of flows, should be

studied in the future but these are beyond the scope of this rapid assessment.
At this stage, economic analysis of the impacts of deforestation or the benefits of reforestation in Paraguay should focus on reservoir silting.

Next steps in the analysis include first: to run a scenario of forest cover to the year 2000, and interrogate the model for differences in soil loss, which may have resulted from deforestation over the 2000 – 2010 period. Second, identify areas of greater soil loss and likely transport to the reservoir as targets for reforestation projects. Third, input into the economic analysis calculating annual dredging costs and potential savings due to reforestation. With this information, a subsequent discussion of implications for reservoir management and likely economic benefits of reforestation will be presented, together with some recommendations and general conclusions.

4. Scenario analysis

For the scenario analysis, the model FIESTA/WaterWorld, Version 3, 2017 (Mulligan, 2017) was run with MODIS VCF 2000 data to re-create the eco-hydrology for that year. Subsequently, a change detection analysis was implemented to interrogate model results for changes in soil erosion and water yield, which may have impacted the Itaipu Dam reservoir over the 2000 – 2010 period. The scenario serves to improve our understanding of the sensitivity of the reservoir to potential changes in forest vegetation in the Paraguay part of the watershed. For this scenario, we assumed that forests underwent change according to MODIS VCF data over the 2000 – 2010 period (no protected areas or nature reserves existed or changed within the area).

4.1 Recap of forest loss statistics

The watershed lost around 31000 ha of forests in the Paraguay's part, over the 2000 – 2010 decade. This is close to 10% (9.62%) of forests lost within section of Itaipú Watershed in Paraguay. This loss is likely very impacting to the reservoir, in terms of sediment generation and transport, due to its proximity.

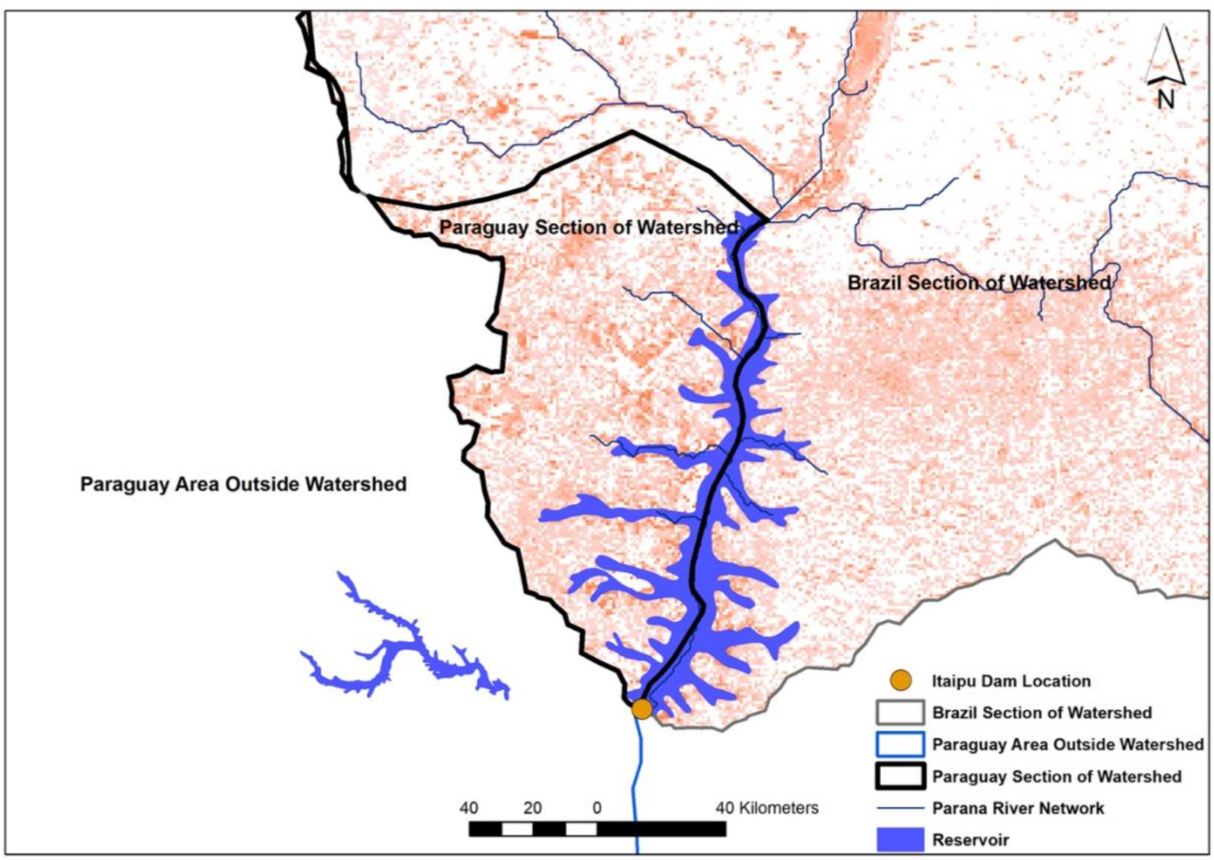

Figure 8. Forest Cover loss in Paraguay section of Itaipu over the 2000 – 2010 period. Extracted from Figure 3 above. Gradients of red show variability in forest loss.

4.2 Change in Water Balance

Analysis indicates that some hectares lost up to 300mm/year of water yield due to forest loss, because of declines in fog interception by trees and loss of infiltration volumes. Other sections gained up to 266 mm/year due to evapotranspiration declines due to lower water consumption by trees. However, the difference in water yield is not significant though for the area (average increase below 0.4%), and no direction of change can be attributed as figures are in the margin of data uncertainty.

It can be concluded that deforestation, over the 2000 – 2010 period, may not have changed annual flows reaching the Itaipu's reservoir significantly, but it may have affected hydrological processes such as fog interception and infiltration locally. These processes are important for the seasonality of flows that local communities or businesses may depend upon. Although these seasonal impacts are not likely affecting the annual or multiannual reservoir storage in the short term, because of the large reservoir capacity, they may in the future, if seasonality changes mean water diversions from the main channels feeding the reservoir. But this is in only an assumption offered here to present with a case which may likely happen depending on patterns of local water allocation and use. Nonetheless, assessing those potential socio-economic scenarios of hydrological change were beyond the scope of this rapid analysis, and should be part of future studies in case a correlation between deforestation and changes in water use can be proven.

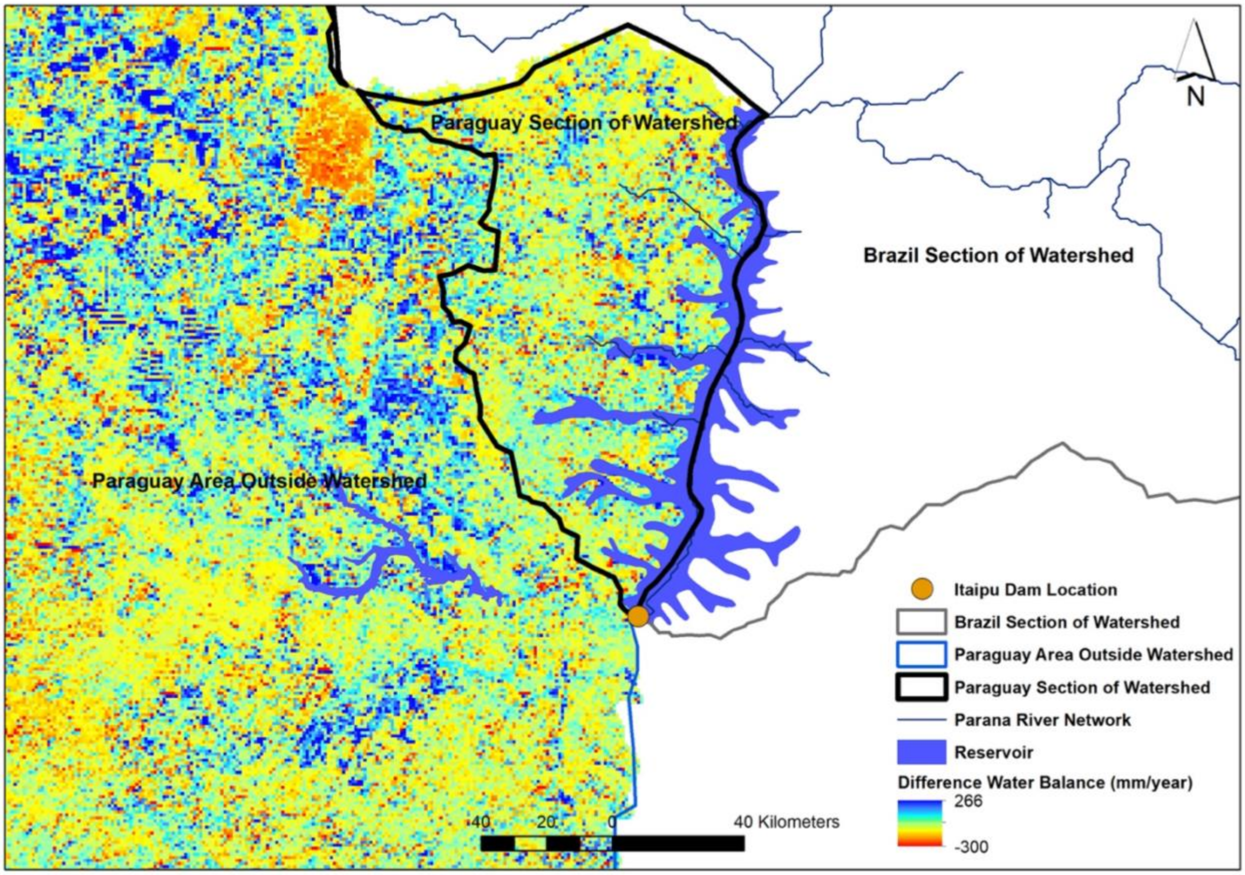

Figure 9. Differences in Water Balance (mm/year) in the Itaipu Dam Watershed. ***Modeled with FIESTA/WaterWorld V 3.31, using WorldClim 2000 rainfall surfaces interpolated from rainfall stations and land cover data according to MODIS VCF 2000 - 2010.***

4.3 Change in Soil Erosion

The modelling indicates a soil loss of around 3 m3/year per hectare on average for the watershed, due to forest loss over the 2000 – 2010 decade; with some isolated and unstable hectares around the lake (probably steep gullies) losing a disproportionate amount of up to 3000 m3/year of soil (Figure 10). Totalizing for the area of the Itaipu watershed in Paraguay, this average soil loss per hectare amounts to around 3.83 million of m3/year.

Not all detached soils may be transported to the reservoir though. Assessing the amounts of sediments reaching the reservoir requires much deeper modelling of soil loss and transport in river channels and from unstable areas around the reservoir, as well as on the ground verification and ground truthing, which were beyond the scope of this rapid analysis.

Problem areas though are clearly those along riparian buffers and hillslopes surrounding the reservoir, where forest loss has likely increased erosion (Figure 11).

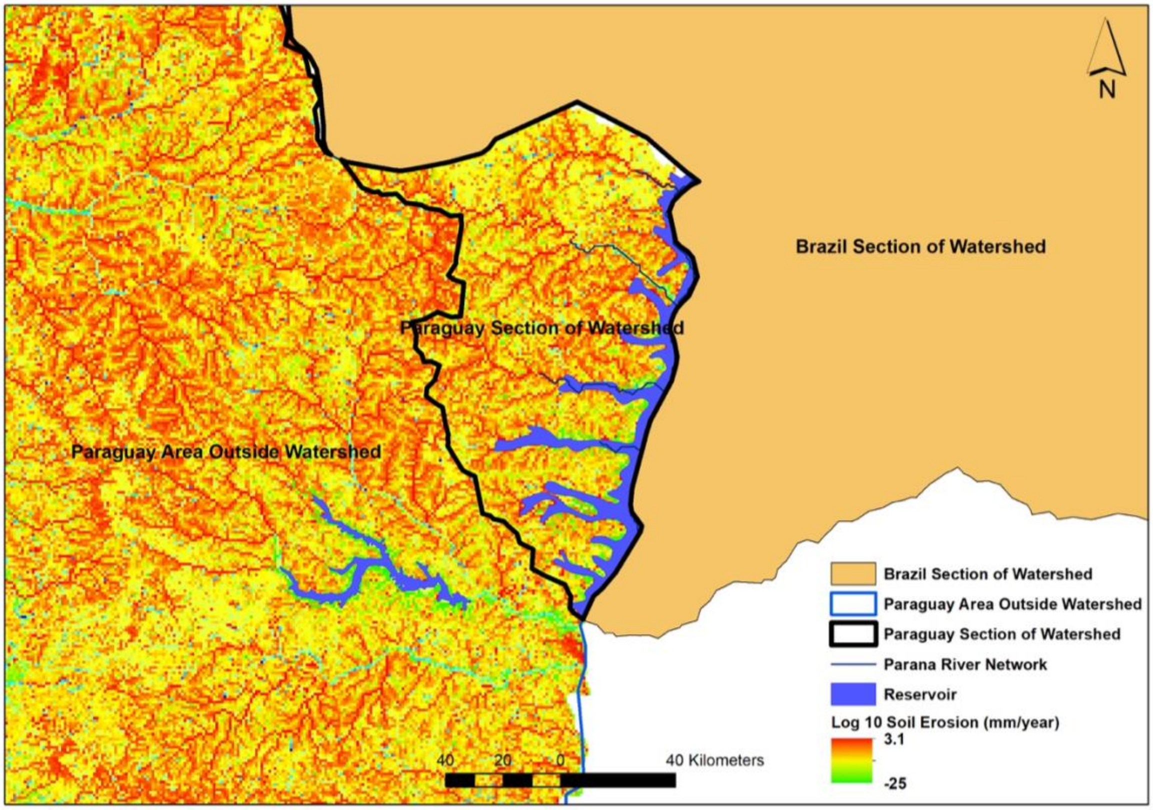

Figure 10. Differences in Soil Erosion (mm/year) in the Itaipu Dam Watershed. ***Modeled with FIESTA/WaterWorld V 3.31, Thornes (1990) wash erosion model and land cover data according to MODIS VCF 2000 - 2010.***

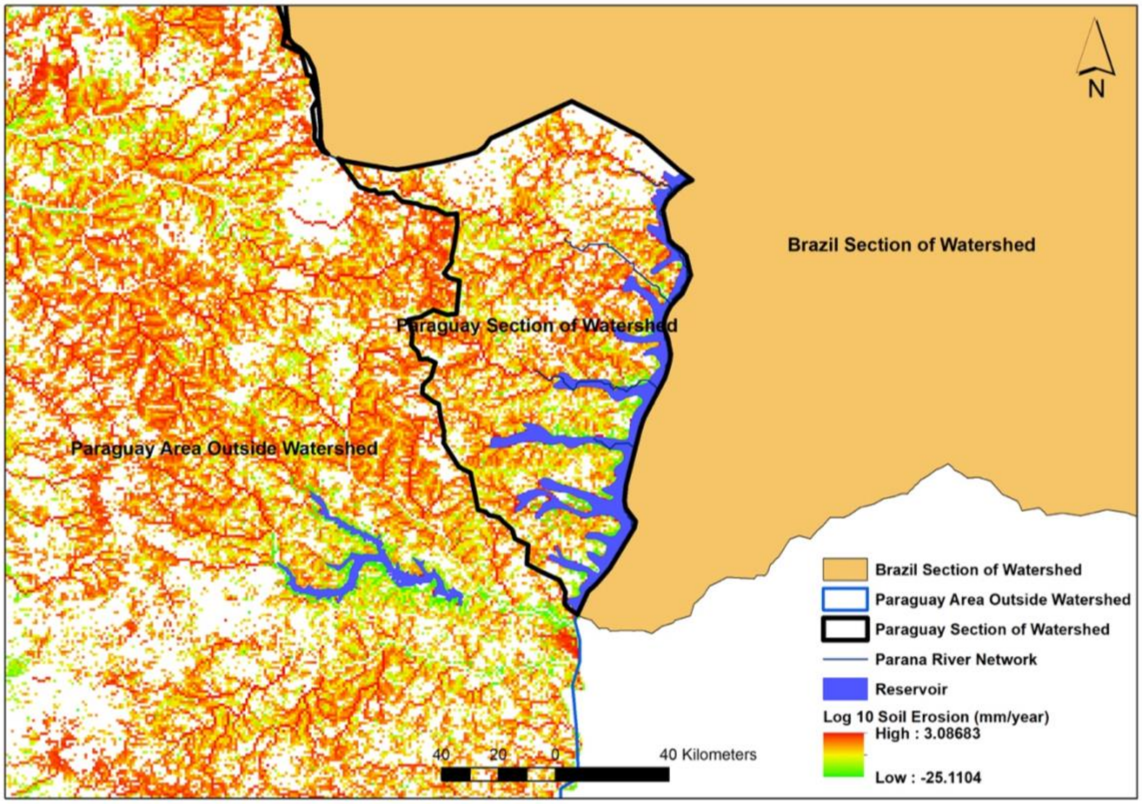

Figure 11. Areas of Soil Erosion (mm/year) of greater potential for sediment transport in the Itaipu Dam Watershed. ***Modeled with FIESTA/WaterWorld V 3.31, Thornes (1990) wash erosion model and Beven and Kirkby (1979) transport and deposition model.***

4.4 Potential economic impacts of soil erosion due to recent deforestation

Dredging the amount of material described above, in the case of being transported to the reservoir, could cost Itaipu around 7.7 million USD/year at a cost of 2 USD per m3. If we apply a dredging cost of 6 USD per m3, total annual dredging costs could go up to 23 million USD/year. Costs may vary depending on country and region. We used dredging costs reported by Saenz, et. Al. 2013 and 2014, for some dams in Colombia and Ecuador.

However, we don't know how much of this soil loss is entering the reservoir and therefore these numbers only can be used as indication of potential impacts. Determining accurately the amount of sediments to be dredged from the reservoir requires a more detail study of sediment transport and deposition to the reservoir from rivers and channels as well as an assessment of reservoir silting with on-site verification with technical personnel. Thus this numbers should be used with caution.

5. Priority areas for reforestation

Using a statistical analysis of soil production areas, it was determined that the areas of great priority for reforestation are those presented in Figure 12 in light green. These areas are likely to help mitigate the majority of soil loss (around 80%) produced by the watershed in the Paraguay's section. They are also capable of helping mitigate an important amount of sediments transport to the reservoir, since these areas coincide with riparian buffers of major channels and reservoir boundaries.

Most of these areas are found in riparian buffers along major river streams draining to the reservoir, which are likely to carry greater sediment loads from the watershed. Other problem areas are around the reservoir's boundary itself, which may have a greater slope, thus making them more susceptible to soil loss and even landslides (depending on embankment slope and management). Unstable areas can generate greater sediment loads more directly deposited to the reservoir, especially in the event of landslides. These processes are common in reservoir access roads and unstable areas around dam reservoirs. Their impact depends on the management though and may not be the case for Itaipu. An assessment of unstable areas around the dam reservoir escapes the scope of this study, but should be the focus of future assessments in case the problem is reported by plant operators.

The total reforestation area calculated here is of around 30000 ha distributed along these buffers (Figure 12). Not all pixels in the map are fully deforested though, and it may be that only a fraction of the pixel should be reforested. Future studies should verify priority areas for reforestation on the ground and contrast them with recently deforested areas (2000 - 2010), as well as earlier deforestation records.

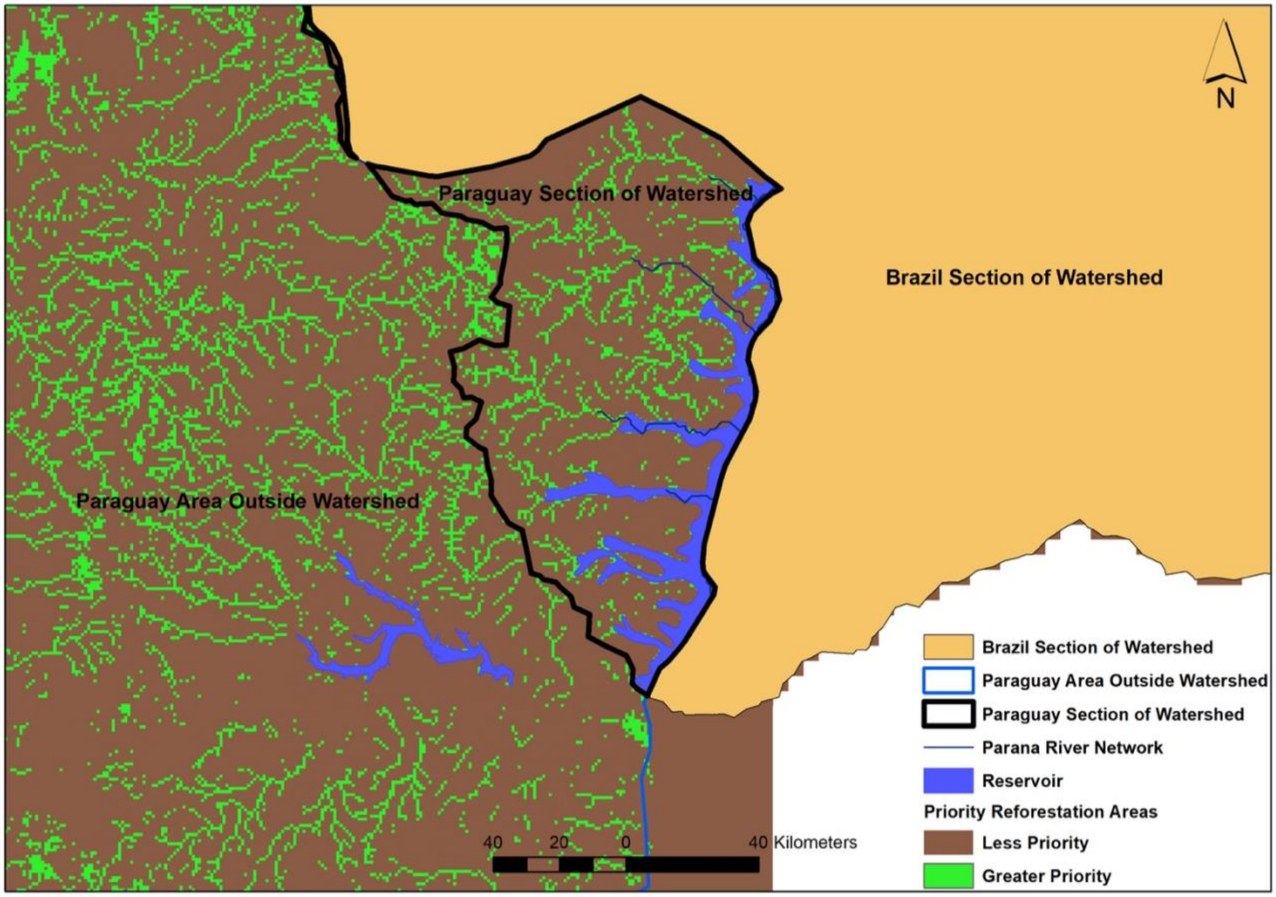

Figure 12. Areas of priority for reforestation to mitigate soil erosion and likely sediment transport to the Itaipu Dam Reservoir.

6. Limitations and caveats of the rapid assessment

The application of FIESTA/WaterWorld was done for rapid assessment and policy support, thus quantities reported should be used with caution, and only as an indication of potential impacts. *If FIESTA/WaterWorld estimates wanted to be used for economic valuation of services to design investments and to verify those values with Itaipu Binational, then a more detailed study using local climatic and operational data should be commissioned*. A detailed study of this sort should be a type of feasibility study of the benefits of reforestation for the operational and economic performance of the Itaipu Dam.

Taking into account the previous limitation of this rapid assessment, the following caveats have to be taken into consideration when reporting its results:

- The study does not provide estimates of changes in energy potentials due to deforestation, because essential data to calculate this was not available, including: water head, reservoir storages and turbined discharge, among others.

- *No estimate of useful life can be inferred from this results due to lack of information on operational storage*.
- The study does not incorporate impacts of deforestation in the Brazilian part of the Parana River basin, as this assessment is much more demanding and beyond the scope of analysis proposed here.
- Rainfall estimates have not been adjusted to reflect a more deforested watershed over the 2000 – 2010 period. This is because we used a standard climatology to the year 2000 provided by Hijmans et al., 2005. This climatology is quality controlled for seamless application of models that require not just rainfall, but also relative humidity, atmospheric pressure as well as other meteorological variables over the same periods of time. Since there was no local meteorological information that fulfills this requirement, such estimates were not possible to be carried out here. Some recommendations on how to implement this type of assessments will be provided in the recommendations section.
- *Our assessment for impacts of deforestation on water yield only focuses on the Paraguay's part of the watershed and not the watershed as a whole*, thus no runoff was accumulated at the multiple inlets of the reservoir. If an assessment is required to explore the spectrum of impacts of deforestation on the accumulated runoff to the dam, a modeling assessment for the whole watershed is required, including the vast watershed sections in Brazil and not just the Paraguay's section.
- The study shows that the impacts of deforestation on soil erosion are likely significant. However, the study does not conclude how significant these impacts are regarding the reservoir storage and its operational rules, due to lack of local data.
- The study indicates that economic impacts of dredging additional sediments resulting from deforestation over the 2000 – 2010 period could be potentially significant depending on dredging costs. However, the assessment was done at the spatial grid scale of a terrain dataset of 1km.
- *Since a 1km dataset smooths the slope of the terrain and thus the energy of runoff to detach soils, it is likely that soil erosion estimates are larger than the present estimate.*
- The study has identified around 30000 ha in riparian buffers and reservoir boundaries, where potential reforestation activities can take place in the Paraguay's section of Itaipu. It is likely that this figure changes if the assessment is done at a higher spatial scale than the 1km used here.

7. Conclusions and recommendations

Soil loss and sediment generation are likely to be important problems for the operation of the Itaipu Dam reservoir, especially due to recent significant deforestation in the Paraguay's part of the watershed. Paraguay lost close to 10% of its forests in the watershed during the 2000 – 2010 decade. The economic impact for Itaipu of these additional sediments, if needed to be dredged, could potentially be in the order of million USD. Our sensitivity analysis pointed to a range of dredging costs between USD $7.7 million to USD $23 million a year depending on the cost of dredging used (from USD $2 to USD $6 per m3).

Sedimentation impacts and costs resulting from deforestation in Paraguay can be exacerbated by important rainfall intensities and water balances that are higher in the Paraguay's part. These factors can intensify the processes that promote soil erosion and transport, and thus the operational and economic impacts for Itaipu. This is why preventing further deforestation and as much as possible implementing reforestation activities is likely to be fundamental to maintain its operational and economic performance and ensure plant longevity.

Impacts of deforestation on water flows are likely to be minimal at the watershed scale though. Our analysis did not find a clear trend, with some areas facing water yield declines and others gaining water availability. These impacts may be significant locally though, for communities or businesses, but they are smoothed at the watershed scale and are likely regulated by the large annual reservoir storage of Itaipu. Although these seasonal impacts are not likely affecting the annual or multiannual reservoir storage in the short term, they may in the future, if seasonality changes mean future water diversions from main channels reaching the reservoir or changes in land use to compensate for seasonality changes. Nonetheless, assessing those potential socio-economic scenarios of hydrological change were beyond the scope of this rapid analysis, and should be part of future studies in case a correlation between deforestation and changes in water use is demonstrated.

Targeted reforestation with native species along riparian buffers of main river channels reaching the reservoir can help to mitigate a significant amount of the sediments that may result from deforested areas. Our study has identified around 30000 ha in riparian buffers and reservoir boundaries, where such activities can take place, with potential to mitigate 80% of the soil loss that have resulted from deforestation over the 2000 – 2010 decade. This area is equivalent to 9.3% of the forests found in the Paraguay's part of Itaipu in the year 2000, and represent 2.5% of Paraguay's the land area within Itaipu' watershed.

These numbers should be used with caution though, as determining accurately the amount of sediments to be dredged from reservoirs requires a more detailed study of sediment transport and deposition from rivers and channels as well as reservoir sedimentation assessments, with on-site verification with technical personnel. In addition, further analysis should filter out the priority areas for reforestation identified here using higher resolution remote sensing products such as Landsat based Hansen et al., (2013), and as much as possible implement on the ground verification campaigns with plant operators and watershed management authorities. Land tenure status and risks should also be assessed in order to identify the set of areas more suitable for long term reforestation and forest protection.

7.1 Recommendations for future assessments

This report could be used to qualitatively illustrate to Itaipu Binational, how deforestation can really translate into more soil loss silting the reservoir in the short term, and on how those problems can impact economic performance in the middle term, if increased dredging operations were needed to be implemented from scratch. Thus, the report can be used as a tool to indicate to dam owners and operators, as well as local government officials, that deforestation has to be controlled and reforestation activities in targeted areas should be implemented.

Future studies should try to explore impacts of deforestation in the whole watershed, including the Brazilian section of the Parana River basin. However, I recommend for this to be a more spatially detailed study at a resolution of at least 1 ha, as I reported earlier for the Calima dam in Colombia (Saenz et al., 2014). Using this higher spatial scale would allow for more realistic estimates of soil loss and sediment transport to the reservoir, as well as fog and wind driven rain processes in headwaters.

What's more, an assessment at the complete watershed scales, including Brazil's sections, would enable for runoff accumulation and sediment transport, which could be verified against Itaipu's operational data, in order to interrogate results for impacts at the multiple inlets of the larger dam reservoir. However, this would be a comprehensive study that should take the form of a feasibility assessment of the benefits of reforestation in the watershed of Itaipu Binational. Such a study should be carried out full time over a period of at least between 8 to 12 months. Such an assessment should have the support from local consultants in Paraguay and Brazil to collect data and interface with Itaipu Binational, as well as a modelling assistant to process time series of meteorological and operational data required to implement such a more comprehensive study

Finally, rainfall estimates to reflect a more deforested watershed over the 2000 – 2010 period, or later, should be assessed by using statistical correlation analysis between time series of annual rainfall and deforestation at least over a period where deforestation has occurred and when the rainfall signal can be distinguished from inter annual variability and ENSO phenomena. Moreover, I recommend this analysis to be performed particularly at locations in the Atlantic forests of Brazil, since the effect of deforestation on rainfall peaks, some distance upwind from mountain crests, could be better filtered as reported by Barros (2014). Such a signal would be much more difficult to identify in the lowlands of the watershed, where rainfall changes, if any, are likely to have been contaminated by impacts of deforestation on cloud formation and rainfall occurred outside the watershed.

Some of the data that can be used to perform such an analysis may include radar rainfall products like TRMM (2006) or the Global Precipitation Project, as well as Landsat based forest loss products such as Hansen, et al., (2013).

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9. Appendix 1

- Description of WaterWorld

The WaterWorld model was designed to understand spatial and seasonal (monthly) changes in water inputs and evaporative losses associated with the conversion of tropical forest (including cloud forests) to pasture in data-sparse and tropical environments (including tropical mountainous environments). The model is an important tool allowing better estimations of precipitation inputs to remote head water areas, identification of hydrological hot and cold spots in the landscape and evaluation of the hydrological impacts of deforestation or climate change at operational and policy making scales (Mulligan and Burke 2005; Bruijnzeel *et al*. 2005; Bruijnzeel *et al*. 2010; Mulligan *et al*. 2010). The model is recommended for land-cover and climate-change hydrological impact scenario analysis and can be coupled with economic models by environmental economics to predict the socio-economic consequences of specific land cover interventions (Bruijnzeel *et al.* 2005; Bruijnzeel *et al*. 2010). More recently, the model has been made available to run online as a policy support tool and as a hydrological hotspotting tool (Mulligan, 2013).

- How it operates

Modelling of water yield and flow

WaterWorld is a process based spatially distributed model, which simulates the hydrological balance including inputs of wind driven precipitation and fog minus evapo-transpiration losses (Mulligan and Burke 2005; Mulligan *et al.* 2010; Saenz 2011). The model runs in a monthly time step and includes a diurnal time step that characterizes the average daily dynamics of fog incidence and interception for each month. The water balance is accumulated downstream as an indication of runoff. Model outputs can be generally validated against observed flow estimates. The model is grid based and can be parameterized at any spatial scale depending upon data availability. See model documentation at Mulligan, (2013) and www.policysupport .org for an enhanced description of water balance calculations.

Modelling Soil Erosion, deposition and transportation

WaterWorld implements a physically based modelling approach of wash – runoff based erosion and sediment transport/deposition along river streams based upon the empirical work of Thornes (1990), Kirkby (1976) and Morgan (2001). Applications of the model equations produced by these authors have been reported for hillslope-tropical and mountainous applications. The Thornes (1990) model, in particular, has been widely used (Mulligan, 1998; Diodato, 2006).

Equations are used to characterise patterns of change in soil erosion and potential changes in sediment inputs to rivers following conversion of forests to pasture or bare soil. WaterWorld's approach is tailored for poor data availability (Mulligan, 2013), as was the case of this study.

According to Thornes (1990) soil erosion is expressed as:

$$E = K * Q^{m} * S^{n} * e^{-0.07 * v_c} \qquad \text{Eq. 1.}$$

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Where:

E = Soil erosion (mm month^{-1})
K = Erodibility
Q = Runoff (mm month^{-1}).
n = Manning's constant
S = Slope Tangent
sc = Slope constant (2). Empirical parameter obtained from field experimentation. It refers to the impact of slope angle on flow speed and thus erosivity (Thornes, 1990; Mulligan, 1998).
v_c = vegetation cover (%)

Here, erosion is a power function of surface runoff and slope, and is potentially reduced exponentially in relation to the fraction of vegetation effectively covering the soil. Although there are more temporally detailed approaches to model erosion where better data are available for wash erosion, as mentioned previously, a monthly time step is sufficient for application in this study. Both monthly and daily timesteps are significant aggregations for a process which is inherently event driven (erosional events occur at a subhourly level depending on bursts of high rainfall and runoff intensity) (Mulligan, 1998). No crop or plant cover factor to indicate any kind of crop management is assigned due to lack of realistic information on crop planning and management.

Model outputs can be validated if data on sediment concentrations in water are available. For cases where such information is not available the model can be used to provide an estimate of water pollution from sediments and to define priorities for mitigation as was the purpose of application here.

Lack of data from soils in Itaipu meant that we needed to run the model with global default parameters such as soil erodibility and FAO soils database recommended by WaterWorld developers. Thus, model outputs for sediment concentrations in rivers are presented in order to provide a potential indication of baseline values for scenario comparison and cannot be quoted as the actual sediment concentrations occurring until more detailed modelling using local data for soils and ground truthing is incorporated. For a more detailed description of model equations please see model documentation at Mulligan, (2013) and www.policysupport.org.

Description of variables and methods to parameterize WaterWorld

This section will examine the datasets that were used for the application of the model in Paraguay. FIESTA/WaterWorld requires around 125 variables to replicate the annual and seasonal hydrology anywhere on earth. These include data for cloud frequency, terrain, wind speed, temperature, precipitation, mean sea level pressure, solar radiation and vegetation cover. Cloud frequency is important to understand radiation, evaporation dynamics and the potential for ground level cloud (fog) presence (Mulligan and Burke 2005). WaterWorld requires maps that depict annual, seasonal and daily cloud frequencies as cloud cover varies spatially, seasonally and diurnally.

Terrain variables are fundamental to calculate fog inputs, correct solar radiation, estimate flow accumulations, correct rain from wind driven effects among others (Mulligan and Burke 2005). Terrain variables comprise a Digital Elevation Model *DEM* (masl) and derivatives including aspect (°), slope (°), local drain direction maps (*ldd*), real area ratios (an indication of the true area factoring in slope), and altitudinal bands (masl). Wind directions and speeds are important variables to calculate fog dynamics, correct rainfall from wind-driven effects and calculate exposure of land and vegetation to wind, rain and fog (Mulligan and Burke, 2005). Wind exposure determines to what extent areas are exposed or sheltered to winds from a given direction. WaterWorld requires eight maps of wind exposure in degrees each per wind direction (North, South, North East, South East, North West, South West, East and West).

Temperature variables are important for calculation of evapo-transpiration dynamics and fog formation (particularly for calculation of the Lifting Condensation Level, which is the elevation at which ground level cloud starts). Seasonal and diurnal variations of temperature are required to characterize these processes. Precipitation is essential for water balance calculations. WaterWorld can be parameterized using global datasets such as WorldClim (Hijmans *et al* 2004; Mulligan and Burke 2005), Tropical Rainfall Monitoring Mission (TRMM 2006) and interpolated local datasets.
The model includes sophisticated routines at a one hectare scale to account for the effects of wind and topography on the distribution of actual surface rainfall catches under prevailing conditions (Mulligan and Burke 2005; Bruijnzeel *et al.* 2006; Bruijnzeel *et al.* 2010). In that regard, Brunzell *et al.* (2006) and Bruijnzeel *et al.* 2010 illustrate how rain gauges can underestimate greatly the rainfall inputs in mountainous environments that are highly exposed and how this model can be a useful tool to illustrate the distribution of rainfall in such distant head waters.

Potential solar radiation is important to model evapo-transpiration. Solar radiation is a function of topography, location, time, shadowing by surrounding hills and cloud cover. Mean Sea Level Pressure is important to model the Lifting Condensation Level of the atmosphere and also wind directions. Mulligan and Burke (2005) indicate that there are no gridded or satellite based wind direction datasets over land, thus Mean Sea Level Pressure is used alongside topography to model them. Most of these datasets have been acquired or produced by the FIESTA/WaterWorld developers at King's College London and can be found online in the Waterworld system (Mulligan 2010; Mulligan *et al.* 2010). Finally, vegetation cover is essential to model evapo-transpiration and fog interception dynamics.