Effectiveness of Improved Watershed Activities in Mbé River, Gabon

Final report

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FutureWater Report 168

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Preface

Under the “Emerging Gabon” vision, Gabon’s future economic development is based in large part on harnessing its hydropower potential. With this in mind, The Nature Conservancy (TNC) is proposing the application of a pragmatic approach called Hydropower by Design, which plans for appropriate location and design of future dams in order to secure desired energy output with the least environmental impact possible. This approach is complemented by an ecosystem services valuation framework to ensure that future development accounts for the benefits provided to people and economic activities by healthy, functional ecosystems.

UNDP is supporting, in partnership with the Wildlife Conservation Society (WCS), the project called “Sustainable Management of the Mbé River Forested Watershed through the Development of a Payments for Ecosystem Services (PES) Mechanism”. The Nature Conservancy was involved recently to carry out the biophysical and economic impact assessment to support the development of new economic instruments in the basin. The Nature Conservancy partners with FutureWater to carry out part of this work.

This report describes the first component of the study where hydrological modelling is used to analyze how under different future scenarios, water quantity and quality is affected and can potentially be improved and conserved to preserve the watershed services the Mbé basin provides. This report is the first part of the study: in the second part a hydro-economic tool will be used to analyze the economic consequences of the different scenarios.

An addendum was added to this report that provides additional scenario analysis that was recommended by local stakeholders based on the outcomes of this study that were presented during a meeting in February 2017.

The authors would like to thank Erik Martin, Allison Aldous, Colin Apse, Steve Schill, Josh Goldstein, Tracy Baker, Matthew McGrath, Emmanuel Mambela and especially Marie-Claire Paiz from TNC for providing data, ideas and support to the study. Also, we would like to acknowledge the crucial inputs and data received from the various stakeholders in the watershed.

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1 Introduction

1.1 Background

The Mbé is Gabon's most economically important watershed, providing electricity for around 60% of the country's population inhabiting the capital city, Libreville. The watershed is also one of the most biologically diverse sites in Central Africa providing other ecosystem services such as regulating water flows, carbon sequestration, and biodiversity.

Despite the contribution of ecosystem services of the Mbé watershed to rural livelihoods and the national economy, the resulting benefits are not accounted for; or at best their value is underestimated. In Gabon, setting aside protected areas is still seen as being un-economical or as an opportunity cost by the general public and decision makers, rather than an investment in natural capital.

Figure 1. The Mbé River embedded in a dense forest cover

It is thus essential for Gabon to identify sustainable financing mechanisms for the long-term conservation of its protected areas. The development of economic instruments that consider the non-market value of services provided by the watershed is considered one promising response to the challenges of linking conservation and development in Gabon.

Within Gabon, the Mbé watershed is an excellent pilot area: downstream in the watershed the hydroelectric power utility depends 100% on reliable water flows and therefore has economic interest in the ecosystem services provided by the watershed. In other words, the watershed services of the Mbé are tangible and there is a clear local beneficiary.

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1.2 Objectives

The objective of this study is to evaluate the potential for improved watershed activities in the Mbé basin to reduce erosion and analyse biophysical and economic impacts. Hydrological and hydro-economic modelling will be used to: (i) Assess the biophysical impacts of these activities relative to the current situation, (ii) Quantify the economic benefits with specific focus on hydropower, (iii) Assess where improved land management activities are most cost-effective in reducing erosion.

This report shows the outcomes of the analyses. It provides results on how different future upstream management scenarios affect water quantity and quality and hydropower generation Upstream management can potentially be improved to preserve the watershed services the Mbé basin provides. The future scenarios studied were based on stakeholder consultations and future outlooks given current developments and policies. These scenarios are mainly related to forestry operations and agricultural developments and practices.

Figure 2. The principal storage dam in the Mbé watershed (Tchimbele) and surrounding forests

2 Data and methods

2.1 Analytic approach to assessment

To assess the expected impact of future changes, developments, and interventions in the watershed, a scenario analysis was carried out. Scenario analysis is a planning and modeling technique used to yield various projections for some outcome based on selectively changing inputs.

Scenario analysis allows alternative situations to be examined effectively and consistently. A scenario, in this context, is a potential circumstance or combination of circumstances that could have a significant impact -- whether good or ill -- on the watershed services.

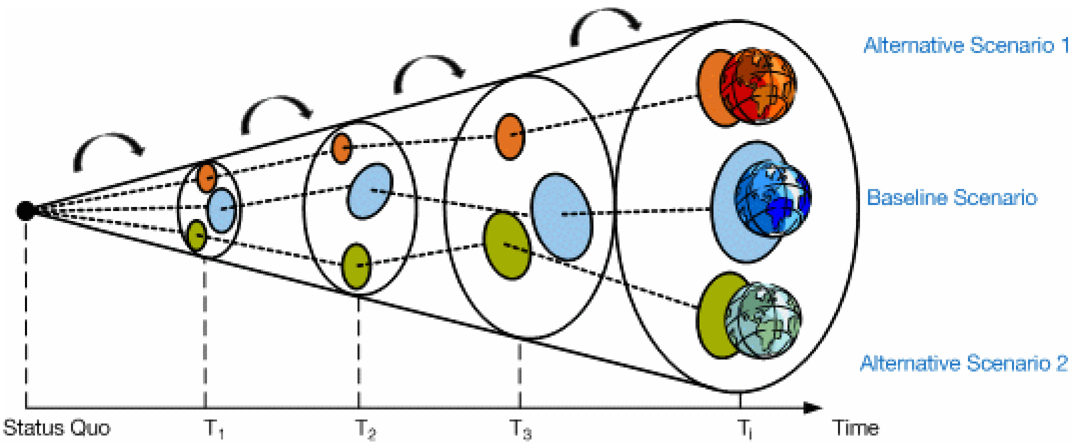

Figure 3. Scenario analysis as a tool to assess the expected impact of future changes, developments and interventions in the watershed

The stakeholders in the basin can use "what-if" scenario analysis to see how a given outcome, such as project costs, might be affected by changes in particular variables, such as intensification of land use.

For this approach, well-tested and scientifically proven dynamic simulation models were used. The effectiveness of the identified scenarios was assessed for the entire area. This provides quantitative outcomes that can be used directly to support decision making process.

The following sections describe input data, the model specifications, and the scenario definition.

2.2 Data

2.2.1 Land use and forest cover

Several sources of land use data were available for the area based on previous work for the Gabon Atlas done by TNC.

- The most complete source was the Ecosystem Services Landcover map built for the whole of Gabon by TNC supplemented by urban, agricultural, road and wetlands features from Google Earth and Bing imagery.

- A layer was available for the Mbé watershed of unpaved roads, digitized by TNC based on Google Earth imagery. The georeferencing of this layer was slightly corrected based on the Hansen dataset (Hansen et al., 2013).
- Globcover dataset - global land cover classification map produced by the European Space Agency based on satellite imagery.

The above three datasets were merged into one. Moreover, the following adjustments were included (the resulting map is shown in Figure 4):

- We assumed agricultural activities occurred within a 200 meter buffer zone around villages . In general agricultural activities occur within a radius between 0 and 1000 meters around the villages.
- A small buffer zone (100 m) was applied around wetlands, assuming that wetlands have normally a certain area of influence and transient zones where the type of forest and soil do not allow forest operations
- For roads an area of influence of 100m (50m each side) was assumed – accounting for landing sites and other alterations due to forestry operations.

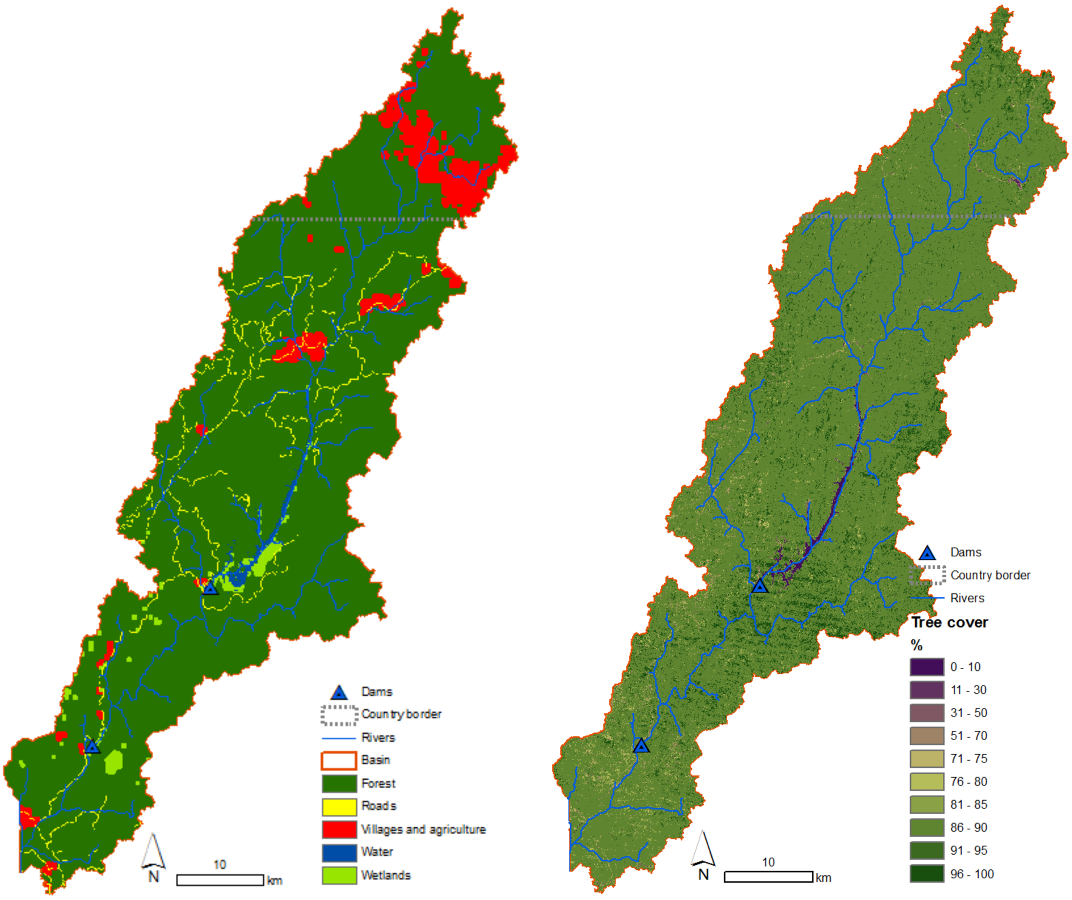

Figure 4. Left: land use map based on various sources (Globcover and TNC). Right: forest density derived from satellite data (source: (Hansen et al., 2013))

Recently, researchers released a global high-resolution map of forest density and forest cover loss (Hansen et al., 2013). This dataset can be considered as a scientific breakthrough as it is the first global dataset of its kind generated by a uniform and scientifically-based methodology. The dataset allows the comparison of land use changes among different regions. The dataset is annually updated at high-resolution of 30 by 30 meters, based on Landsat imagery. The latest update of gross forest cover loss includes the 2014 loss layer.

The available layers used for the current study are:

- Tree canopy cover for year 2000 (treecover2000) - Percentage canopy closure for all vegetation taller than 5m.
- Global forest cover loss 2000–2014 (loss) - Forest loss during the period 2000–2014, defined as a stand-replacement disturbance, or a change from a forest to non-forest state.

For the current study, this high-resolution satellite-based dataset was used as proxy for level of forest degradation. To estimate current forest cover density, the above two layers were combined. Figure 4 (right) shows this map. Dense forest covers almost the whole catchment. In fact, analysis showed that more than 90% of the watershed has a forest cover (i.e. canopy closure) of more than 85%.

2.2.2 Soil

The soil data used for this study originates from

- The digitized Soil Map of the World (v3.6) for bulk density, texture, and soil erodibility factor
- The global HiHydroSoil dataset (Boer, 2015) at 1km resolution that provides hydrological soil properties for modeling, based on the SoilGrids1km dataset

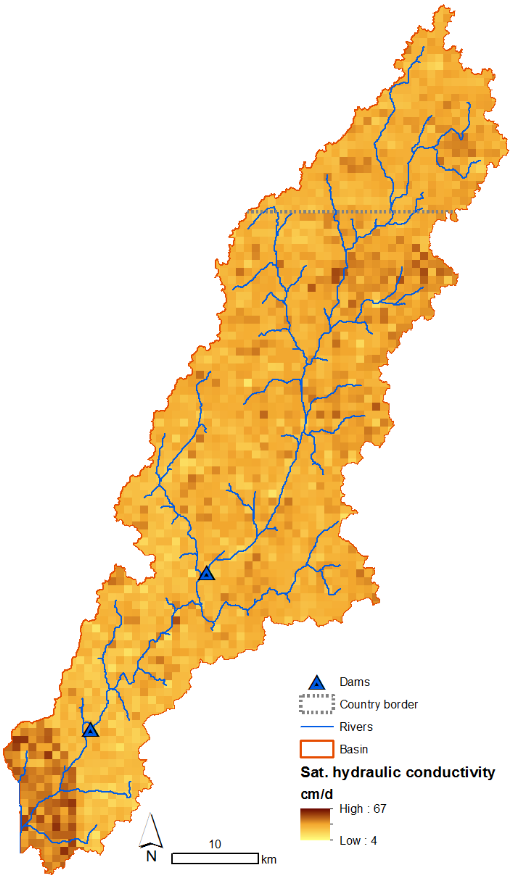

Figure 5. High-resolution saturated hydraulic conductivity based on HiHydroSoil dataset

2.2.3 *Elevation, watershed delineation and calculation units*

The Mbé (sometimes also referred to as “M'bei”) watershed covers an area of 2,000 km^2 (see Figure 6). The upstream part of the watershed (334 km^2) is located in Equatorial Guinea (above the dotted line in Figure 6).

A 30m resolution Digital Elevation Model was used to delineate the watershed and the sub-basins. A total of 121 sub-basins were delineated.

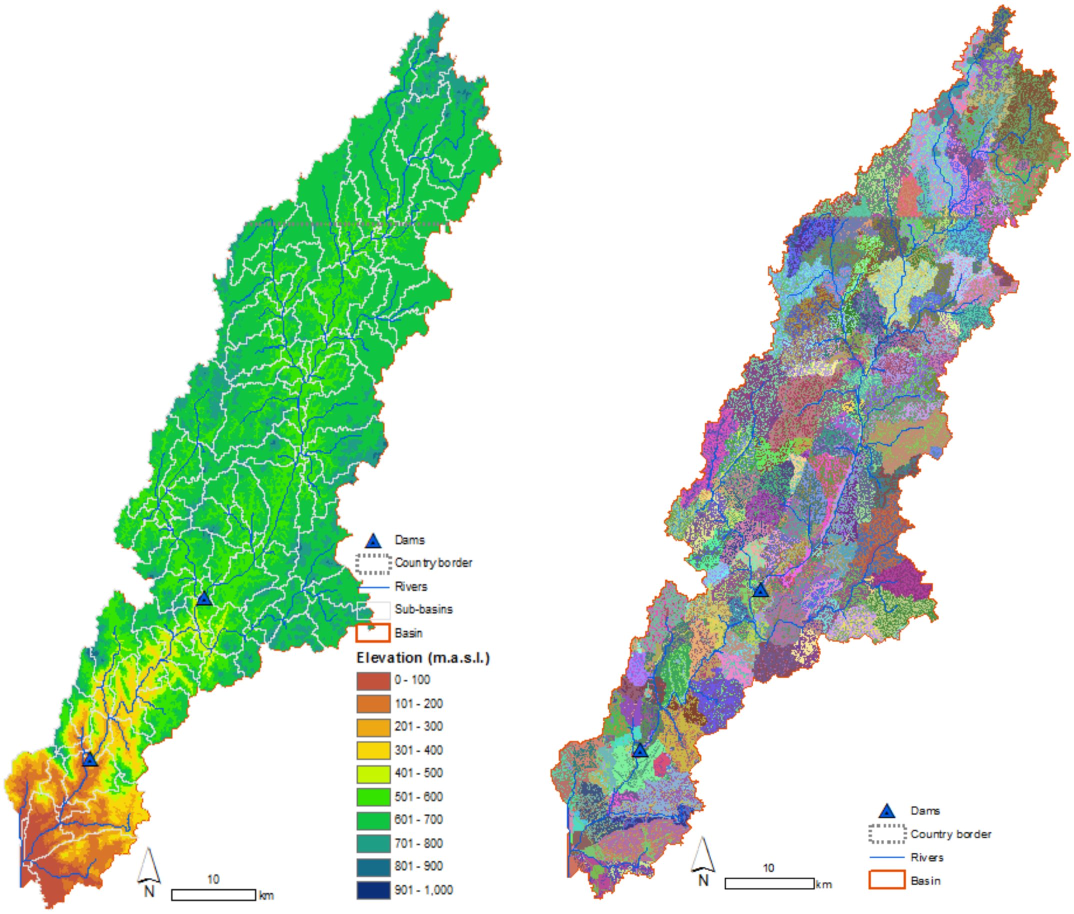

Figure 6. Digital elevation map with sub-basin delineation (left) and Hydrological Response Units (right).

The hydrological model used for this study (Soil Water Assessment Tool – SWAT, see section 2.4) partitions the basin into a number of sub-basins. Within each sub-basin, each unique combination of soil, land use and slope is a calculation unit (referred to as Hydrological Response Units, HRUs). In total for this basin, 1081 HRUs were identified.

2.2.4 *Climate data*

Daily rain gauge data were available for this study, measured in the vicinity of the two hydropower reservoirs, Kinguele and Tchimbele. Data were available for the full study period and with few data gaps.

A comparison was carried out with satellite-based rainfall data from the Tropical Rainfall Measuring Mission (TRMM), a collaboration between NASA and the Japanese Space Agency.

This comparison showed that within the watershed there is relatively low spatial variability in annual rainfall amounts. For this reason it was decided to use the rain gauge data as being representative for the rainfall over the entire watershed. Data are available over a period of 16 years (2000 – 2015).

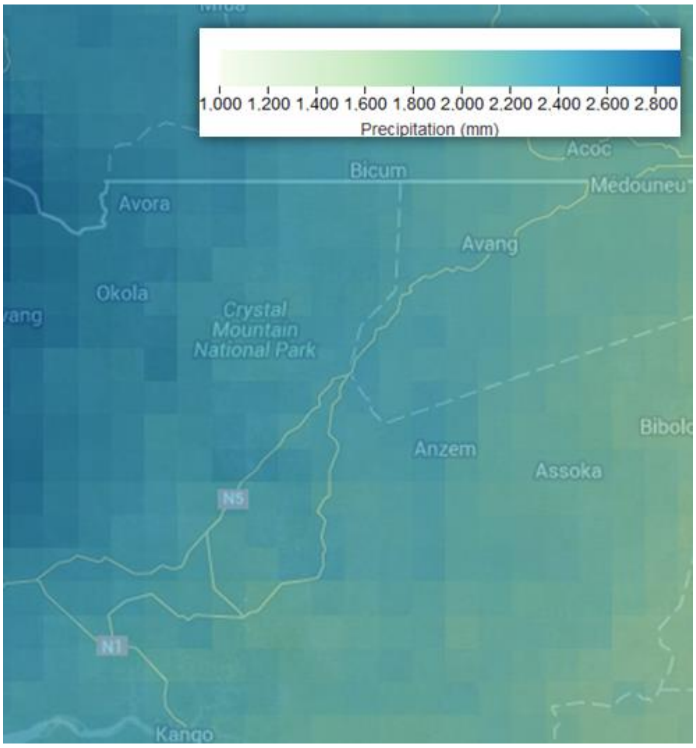

Figure 7. Mean annual rainfall amounts in the watershed area according to TRMM satellite

Figure 5 shows the annual exceedance probability and the mean monthly rainfall for the two stations available for a 16-year period (2000-2015). Tchimbele receives slightly less rainfall than Kinguele. The annual variability is relatively low due to the tropical climate conditions. There is a strong seasonal bimodal pattern though. The first rainy season peaks in March and April, while the second and most important rain season occurs in October and November. Maximum rainfall amounts over the year are received in October, and minimum amounts in July.

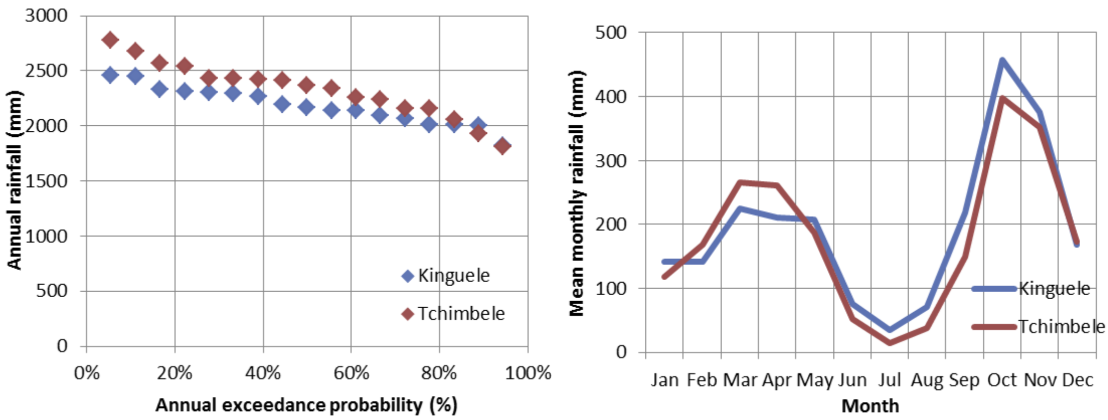

Figure 8. Annual exceedance probability and mean monthly rainfall for the available stations

2.2.5 Streamflow

Currently there are no streamflow gauges operational in the watershed, in spite of its economic importance. Historic data are available for a number of years (source: Office de la Recherche Scientifique et Technique Outre-Mer – ORSTOM) in the beginning of the 1970ies (see Table 1).

Table 1. Historic station data available

Code	*Name*	*Latitude*	*Longitude*	*Years available*	*Mean flow (m^3/s)*
1144001507	KINGUELE	0.4475	10.2778	1973-1977	63
1144001510	TCHIMBELE	0.6253	10.4083	1969-1973	41

Currently, SEEG estimates reservoir inflow from data on the daily reservoir water balance (reservoir level, evaporation, and outflow, where outflow is derived from a relationship between turbined flows and energy efficiency of the turbines). The number of active turbines during the day is not constant, so an approximate daily efficiency value is taken.

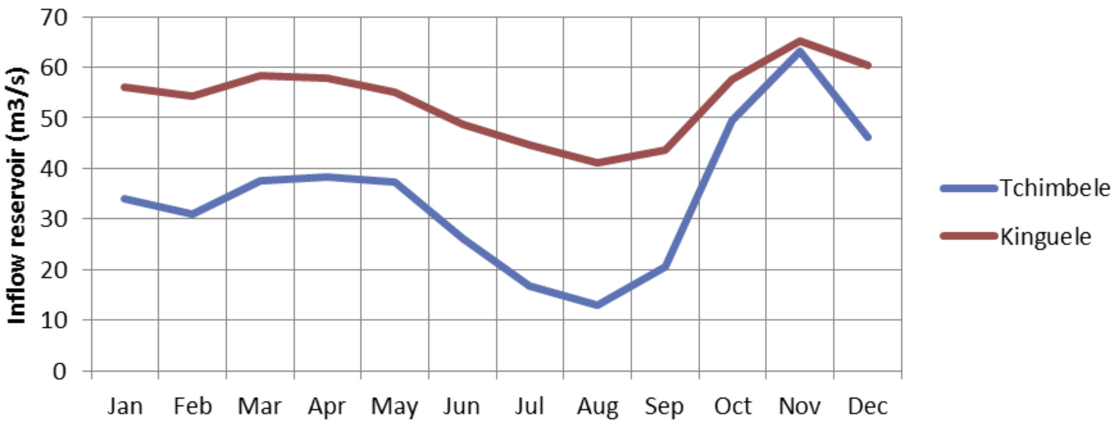

Figure 9. Average monthly inflow of the two reservoirs (source: SEEG)

This indirect method to estimate reservoir inflow is common in many basins in the world, but it is important to be aware of the different possible sources of error. Energy efficiency relationship normally change over time (maintenance, etc.), require calibration over the full range of flows, and of course changes in reservoir levels and the estimation of reservoir evaporation can also lead to errors.

SEEG estimates with the above daily water balance calculations the contribution of the tributaries that contribute streamflow between the two dams Tchimbele and Kinguele. The approach gives a rough estimate of what these catchments contribute on average. For the seasonal pattern this estimate cannot be taken as sufficiently reliable to be used for model calibration: it is based on too many indirect steps. In fact, an unlikely decreasing trend was found in this estimate. This trend was not observed in Tchimbele inflow while climate and land use conditions are similar. This is likely due to changes in energy efficiency and operations in the two plants that affect the indirect estimation method.

The above can also explain the significant difference between historic observed (ORSTOM) and current calculated (SEEG) flows: mean flow into Tchimbele according to the SEEG calculations is 34 m3/s, while the historic observed data by ORSTOM is 41 m3/s. For Kinguele, current estimates by SEEG indicate an average inflow of 54 m3/s, while the historic observations showed 63 m3/s (see Table 1), a difference of 15% and 17% respectively. Considerable differences can also be seen in the flow duration curve (percentage of time flow exceeds a certain value) between the SEEG calculations and the ORSTOM observations, especially for the low flows.

There are several factors that can explain these differences, beside of course estimation and measurement errors (which can be significant in this case due to the indirect method). Reservoir evaporation can explain part of the difference (today reservoirs are a net consumer of water due to evaporation, while historically reservoirs were not present), but also climate change and land use changes can have had a significant impact on the flow regime. A more in-depth analysis and additional monitoring can help to understand the role of each of these factors.

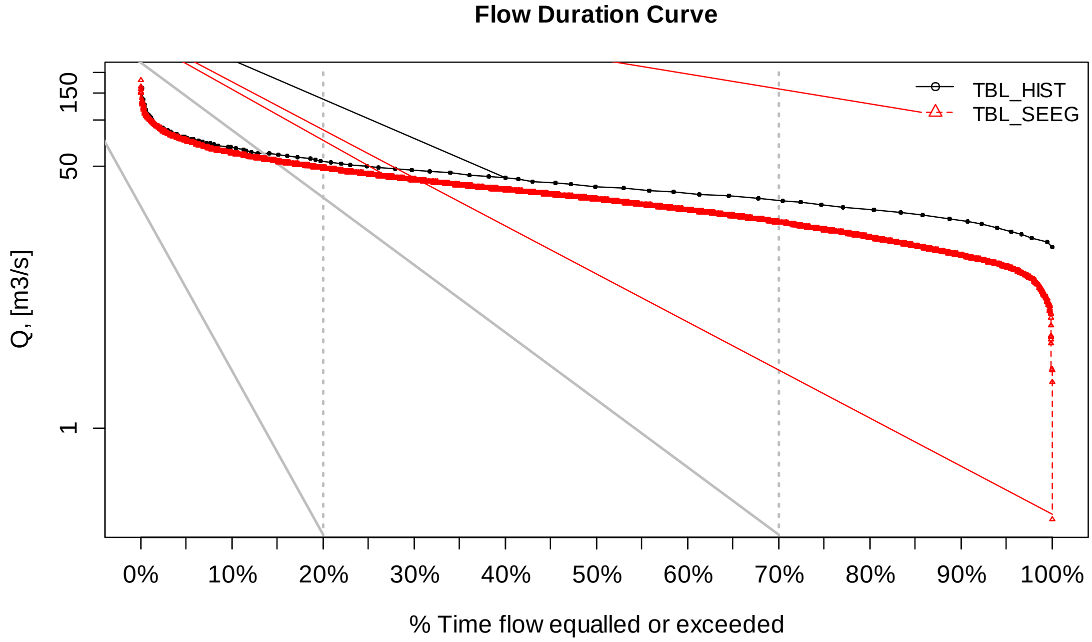

Figure 10. Flow duration curve of Tchimbele (TBL) historical flows observations by ORSTOM versus current flow estimates by SEEG

The available data indicate that about 40% of the rainfall that the catchment receives is converted to streamflow; the other 60% leaves the watershed by evaporation and canopy transpiration.

2.2.6 Reservoirs and hydropower

The two hydropower plants Tchimbele and Kinguele along the Mbei River supply the electricity grid in Libreville. Their installed capacity is respectively 68.4 and 57.6 MW, for a total average generated power of 680 GWh per year according to reports from the SEEG.

- Tchimbele has a large storage reservoir, with an original design volume of 247 hm3. It is not known how much storage capacity has been lost by sedimentation since its construction in 1980.
- Kinguele has a much smaller reservoir (0.45 hm3) without over-year storage, but flows are regulated by the upstream Tchimbele reservoir (travel time between both reservoirs is about 6 hours).

Table 2. Reservoir characteristics

Name	***Start of operations***	***Total capacity***	***Surface at full capacity***	***Max level***	***Min level***	***Turbine level***	***Capacity***	***Mean annual production***
Unit	*year*	*hm3*	*ha*	*masl*	*masl*	*masl*	*MW*	*GWh*
Tchimbele	1980	247	2300	531	515	410	68.4	270
Kinguele	1980	0.45	5	220	200	85	57.6	410

Figure 11. The Tchimbele dam

There are plans for new hydropower developments in the watershed. AECOM has carried out a study in 2010, on potential hydropower expansion in Gabon. Three potential locations were identified. Currently the most likely to be built over the next decades is the dam called “Kinguele Aval”. Potential installed capacity was analyzed to be 40 MW, producing 220 GWh per year. Two other potential sites for hydropower are also identified in this study. In total, there is a possibility for an addition capacity in the basin of 136 MW, and 880 GWh/year production.

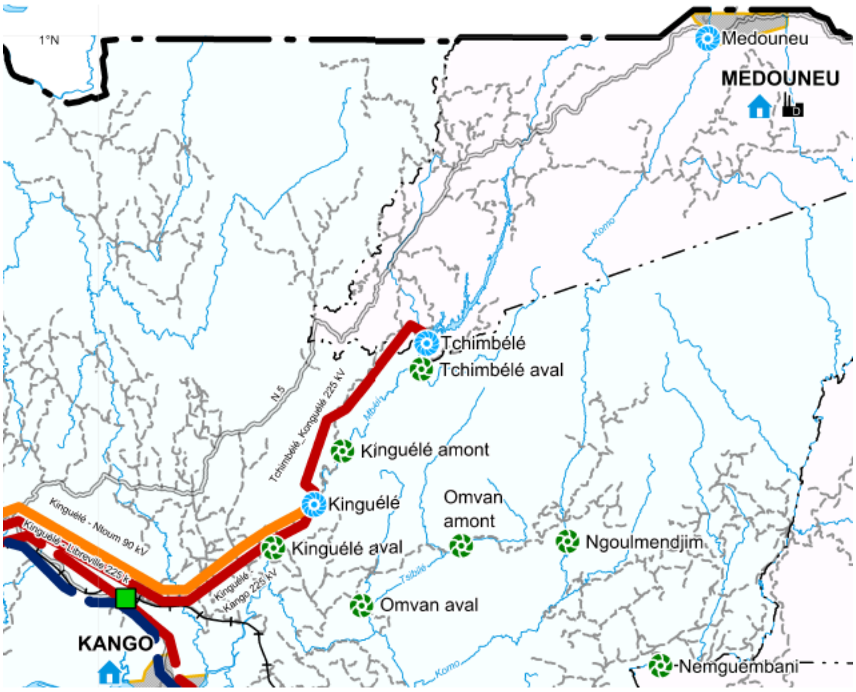

Figure 12. New potential hydropower developments according to AECOM report, 2010

2.3 Major water and land users

2.3.1 Villages and agriculture

The watershed has a very low population density. The villages follow the main unpaved road between Kougouleu and Medouneu. Today, there are about 13 villages within the Gabonese part of the watershed (c. 1100 inhabitants). A significant part of the inhabitants most likely do not permanently reside in the villages, but only stay in the villages during a short period of the year. Less is knows about the Equatorial Guinean part of the basin, but the land use map (see data section, Figure 4) shows that there is a relatively higher occupation of agricultural areas than in Gabon (in total around 80 km^2, compared to 43 km2 in Gabon).

Currently, the local population’s economic activity is subsistence farming primarily for manioc, bananas, pineapple, peanuts, peppers and eggplant, and marginally yams and sweet potato. Currently, agricultural activities are on a very low level in the basin but the possibility for commercial agriculture remains given given close proximity to urban markets. In other areas of Gabon, abandonment of forestry concessions has in some cases led to agricultural occupation.

Figure 13. Small village in the Mbé watershed

As part of a large national program (GRAINE - *Gabonaise des Realisations Agricoles et des Initiatives des Nationaux*) to stimulate the agricultural economy and address food security, some recent conversion from forest to agriculture has occurred in the area around Medouneu, which is located outside the Mbe watershed. The GRAINE program transfers parcels of land to co-operatives of Gabonese citizens, and provides training to farmers. The program is executed by the government of Gabon and Olam International Limited.

Three GRAINE projects around Medouneu were visited in May 2016 by the project team. These three projects are not within the Mbé watershed. The local representatives received us and showed us around the implemented sites (total of approximately 150 ha). For two out of the three projects it was evident that the execution was not in agreement with regulations on best management practices. The distance to the water course was less than 100 m – in some areas even directly bordering the river. In addition, steep slopes (> 10%) were converted to agriculture. The executing organization (OLAM) has been informed and assured us that they would take action.

Nowadays there are no GRAINE projects within the Mbé basin. It is not yet sure whether, where or when a GRAINE project will be implemented within the basin. However, it is likely that some agricultural conversion under the GRAINE project will take place in the future. This will influence the hydrological response of the Mbé basin and might have an impact on the services the basin provides to downstream water users (hydropower). Therefore, this was included in this study as a possible future scenario.

Figure 14. Cleared forest next to a water coarse, at one of the GRAINE projects close to Medouneu, east of the Mbé watershed

2.3.2 Forestry

There are currently around ten logging concessions in the watershed, for so-called “selective logging” (only a few species are allowed). This practice leaves the rest of the forest intact, but requires clearing, landing sites and roads for the operations. The area covered by forestry concessions has been increasing considerably over the last 10 years, and corresponds to roughly 90% of the non-protected area (see Figure 16).


Figure 15. Forestry operations in the watershed (June 2016)

The national policy goal is to reduce the area with forestry concessions from 15 Mha to 11 Mha in the country over the following years. On the other hand, it is very likely that the government will allow logging of other species than currently permitted. This might increase logging intensity of the existing concessions.

Currently, none of the forestry concessions are certified and labeled eco-friendly according to the Forest Stewardship Council (FSC) certification, nor do they use reduced impact logging (RIL) techniques. The concessions do have a management plan which in principle requires to use “best management practices”, such as maintaining distance to water courses, and avoiding steep slopes. However, field evidence shows that these are generally not adhered to.

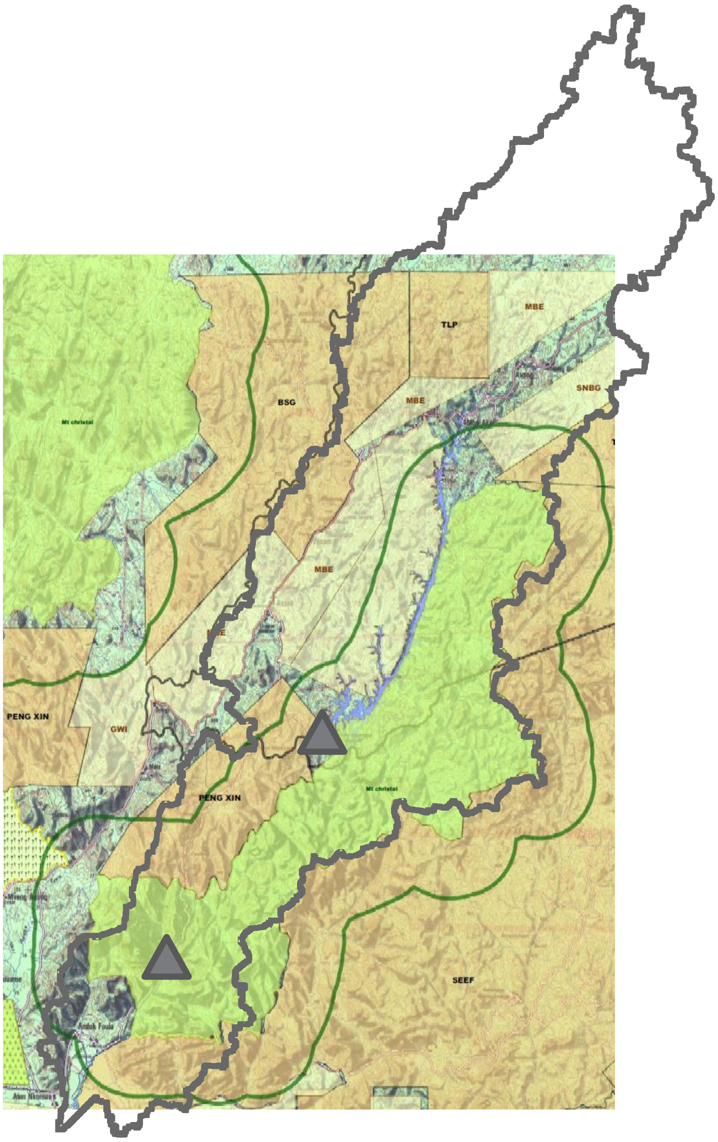

Figure 16. Map of forestry concessions in the watershed area, year 2016 (source: Ministry of Environment). The grey line indicates the Mbé basin, the grey triangles the two reservoirs

2.3.3 Mining

The Mountains of Monts de Cristal are rich in minerals and there are potentially large deposits of gold, diamonds, iron and platinum. Gold is currently being exploited by artisanal gold miners in the basin but at very low intensity and are not likely to have an impact at the watershed level.

Sand mining is occurring downstream in the watershed for road construction elsewhere. The mines are downstream of the current dams so do not have any impact on the services the watershed provides to water regulation and hydropower. Therefore, their impacts were not assessed in this study.

Figure 17. Gravel mine for road construction downstream in the watershed

2.3.4 Hydropower

The principle economic actor in the basin that relies on the Mbé watershed services is the hydropower company Société d'Energie et d'Eau du Gabon (SEEG, a Veolia Water subsidiary). There are two hydropower facilities operational since the 1980s. They provide about half of the electricity demand in Libreville and are therefore of strategic importance to the country.

Low water flows and reservoir levels, particularly in the fall dry season, are a concern for these hydropower facilities. Maintenance issues with the turbines are common (the facilities spend around 100 million CFA for part replacement each year), which causes the plants to operate generally below full capacity. Suspended sediments may be responsible for part of these issues, but this has never been studied. The operator recognizes however that they face issues sometimes with clearing the water for cooling the facilities due to high sediment concentrations.

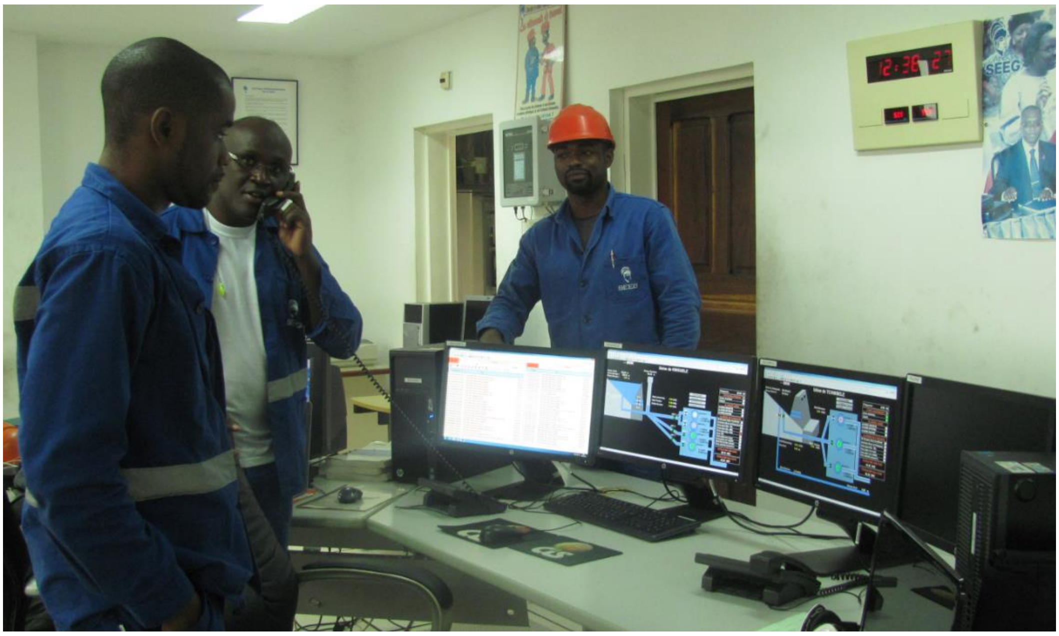

Figure 18. Dam operators in the Kinguele facility

Since the construction of the reservoirs, no data has been collected on reservoir sedimentation – no bathymetrical studies have been carried out. Under the current conditions the storage reservoir Tchimbele seems to have enough capacity to buffer the available water during the wet season: spills (flows not passing the turbines) do occur but not because of lack of capacity. This may change under climate change or changes in land use and management upstream when baseflows reduce and runoff increases, but this has not been studied.

For the much smaller Kinguele dam an estimate was carried out on sedimentation, which indicated that it lost 200,000 m^3 in capacity between 2002 and 2010. This is likely only a portion of total sediment inflow into the dam: firstly only a minor part has enough time to settle, and secondly, the accumulated sediments obstructing the facilities and inlets are currently flushed through a system in place.

Figure 19. Sedimentation in the Kinguele reservoir

The above confirms that flows, sediment concentrations and loads are an issue of concern to the hydropower operator in the basin, putting at risk hydropower generation for the future. Improved watershed activities can lead to direct benefits for hydropower and the country.

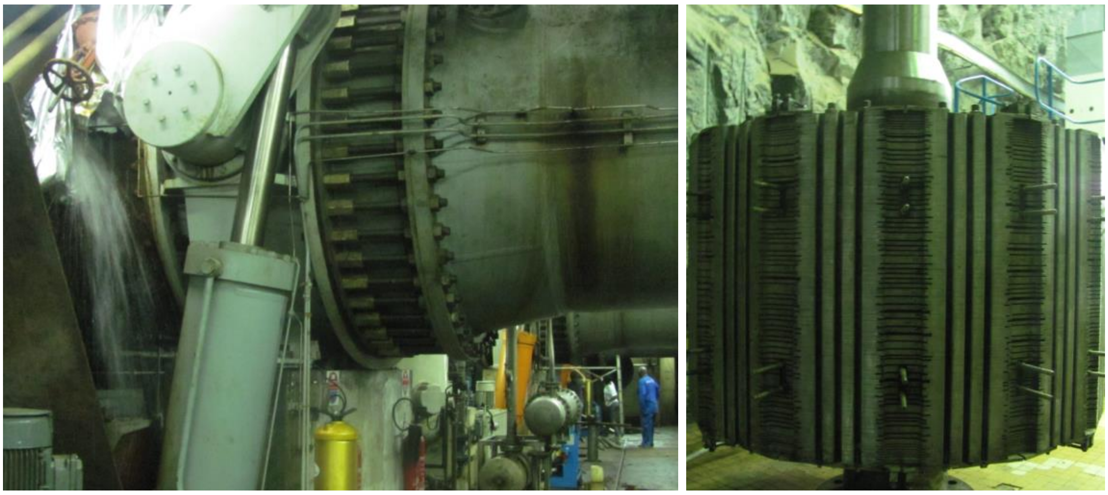

Figure 20. Maintenance issues with turbines and leaks in conducts of Tchimbele facility

2.4 Model simulation

2.4.1 Model selection

To evaluate the potential for sustainable watershed activities in order to reduce erosion impacting the Mbé River and its services downstream, the following modeling approach was used:

- Watershed simulation under current conditions and management
- Watershed simulation with a range of land management options (“future options”)
- Benefit-cost analysis of these land management options, comparing current with future scenarios

The following activities and ecosystem services in the Mbé watershed are of relevance for the hydrological simulation:

- Upstream land management (forestry and agriculture)
- Downstream services relying on reservoir storage, mainly hydropower

For the simulation of the hydrological and erosion processes upstream under current and future conditions, a model is required that:

- Simulates erosion processes for all combinations of soil type, land use, and management in the watershed
- Simulates hydrological processes and routing in streams and water bodies
- Is physically-based to ensure that model results are accurate for scenarios, beyond the range of calibration and validation
- Includes sufficient spatial detail to simulate processes at locations of interest for the stakeholders

One of the models meeting all these requirements is the Soil-Water-Assessment-Tool (SWAT) and therefore we selected it for this project. This model has been used before in the assessments for Water Funds in South-America and Nairobi (Hunink and Droogers, 2015), but also in many other similar studies on payment for ecosystems services around the world.

Moreover, a downstream hydro-economic model is required to:

- Have a focus on reservoirs and water allocation
- Be sufficiently flexible to include operational rules of reservoirs
- Allow simulation of hydropower generation and demand
- Simulate reservoir sedimentation impacts

An appropriate model commonly used for water allocation and hydropower studies is the Water Evaluation And Planning System (WEAP).

In summary, to study impacts of land management interventions on hydropower, two models are used that are linked to each other (Figure 21):

- SWAT: erosion and upstream impact of interventions,
- WEAP: hydro-economic model for reservoir dynamics and hydropower

Strong aspects of the SWAT-WEAP modeling approach as applied for this study are:

- Two-tier modeling approach proven and applied in many similar studies
- Linking two state-of-the-art models for land management and reservoir management.

- User-friendly interfaces of both models
- Large user-group worldwide
- Excellent documentation, including training materials
- Consortium extensive experiences in application as well as providing training

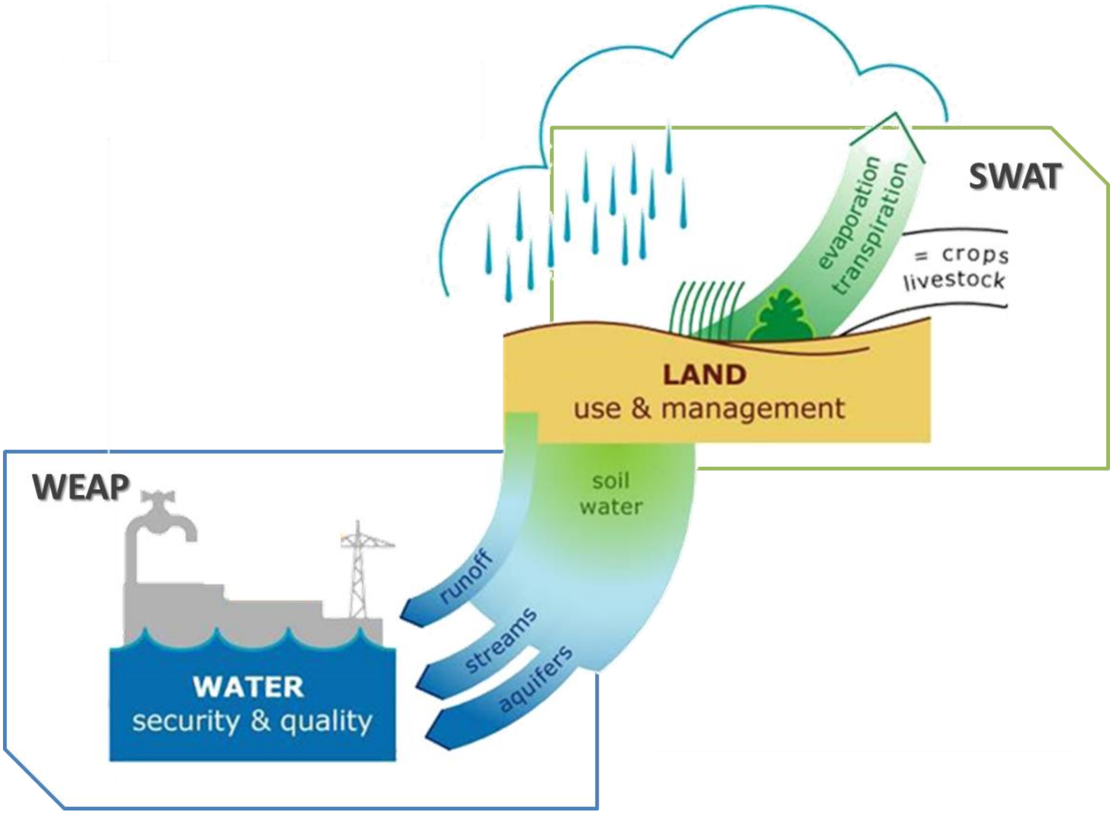

Figure 21. Conceptual modeling approach, linking upstream hydrological land-management model with downstream hydro-economic model

2.4.2 SWAT model specifications

SWAT[1] was developed primarily by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in complex watersheds with varying soils, land use and management conditions over long periods of time. The SWAT model has been extensively used, is in the public domain and can be considered the de-facto standard in hydrological decision support systems.

SWAT represents all the components of the hydrological cycle including: rainfall, snow, snow-cover and snow-melt, interception storage, surface runoff, up to 10 soil layers, infiltration, evaporation, evapotranspiration, lateral flow, percolation, pond and reservoir water balances, shallow and deep aquifers, and channel routing. It also includes irrigation from rivers, shallow and deep groundwater stores, ponds/reservoirs and rivers, transmission losses and irrigation onto the soil surface. It includes sediment production based on a modified version of the Universal Loss Equation and routing of sediments in river channels.

[1] http://swat.tamu.edu/

Simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water and sediment loadings to the main channel in each sub-basin.

The second division is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet. Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure.

The SWAT model estimates erosion and sediment yield with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). While the original USLE (Universal Soil Loss Equation) uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. This modification is reported to increase the prediction accuracy of the model, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated

The sediment yields of each HRU are routed to the channel of the corresponding sub-basin. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. SWAT has various state-of-the-art modeling options for determining channel degradation as a function of channel slope and velocity.

2.4.3 SWAT calibration and validation

The SWAT model is calibrated and validated using monthly reservoir inflow data of the Tchimbele reservoir. The calibration period was 2000-2010, and the validation period 2011-2015. Table 3 shows the performance indicators (see Annex 2 for their explanation).

Table 3. Performance indicators (see Annex 2) of the calibration and validation

Variable	***p-factor***	***r-factor***	***R2***	***NS***	***PBIAS***	***RSR***
Calibration	0.77	1.17	0.72	0.63	-8.4	0.61
Validation	0.72	0.78	0.72	0.62	-12.4	0.62

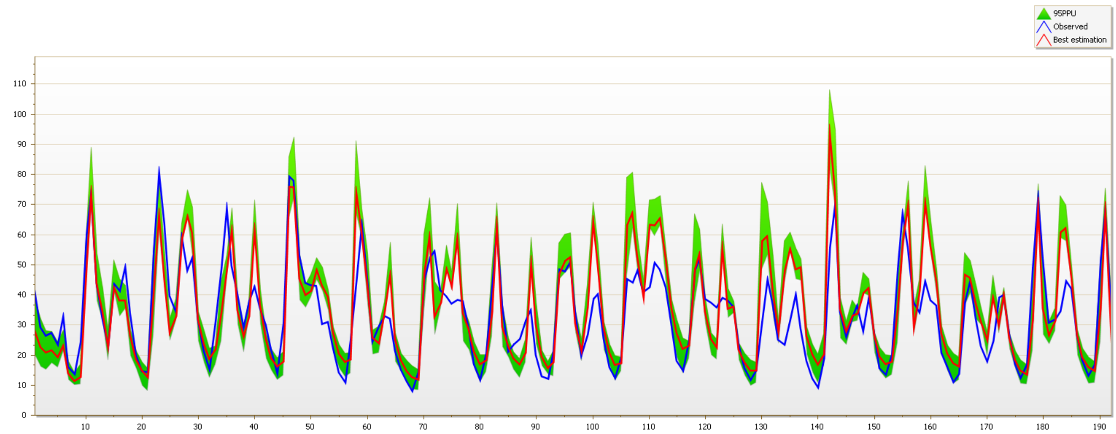

Figure 22. Observed (blue) versus simulated (red) flow of the Tchimbele reservoir for the 16-year simulation period, and including the 95% prediction uncertainty (green)

As can be seen from the above, the simulations compare well with the observations. As usual, there are differences, due to errors in input data, observations and model simplifications. However, it is important to note that for scenario analysis, fully accurate predictions of absolute flows are not necessary; however, the model should respond correctly to changes in input parameters. For this reason it is necessary to use physically-based model like SWAT to make sure that the processes are well represented and the model responds correctly to changes from the current condition. Several authors have highlighted this difference between what can be called “absolute accuracy” versus “relative accuracy” for scenario analysis in hydrological modeling (Droogers et al., 2008).

2.4.4 WEAP model specifications

The WEAP model was developed by the Stockholm Environmental Institute (SEI) with the main aim to assist in policy evaluation and water resources planning. WEAP is an easy-to-use tool that can be used to give insight in water supplies and competing demands, and to assess the upstream–downstream links for different management options in terms of their resulting water sufficiency or unmet demands, costs, and benefits. It uses the basic principle of water balance accounting: total inflows equal total outflows, taking into account any change in storage (in reservoirs, aquifers and soil). WEAP represents a particular water system, with its main supply and demand nodes and the links between them, both numerically and graphically. The concept-based representation of WEAP means that different scenarios can be quickly set up and compared, and it can be operated after a brief training period. WEAP is being developed as a standard tool in strategic planning and scenario assessment and has been applied in many regions around the world.

WEAP has a user-friendly GIS-based interface with flexible model output as maps, charts and tables. WEAP is available in the French language. The WEAP license is provided free of charge to non-profit, governmental or academic organizations based in a country receiving development bank support.[1]

The WEAP model is used for studies on water allocation and water supply-demand analysis, and used often for studying reservoir management and hydropower. It includes a few hydrological modules for calculating the rainfall-runoff processes, but these approaches have their limitations for studying land use and management changes. Therefore, for this study the streamflows and sediment concentrations that are calculated with SWAT are used as input for the WEAP model, instead of using its own hydrologic modules. WEAP then simulates reservoir management, hydropower generation and economic outputs. Energy demand can be specified in WEAP to inform the reservoir operations.

A detailed discussion on WEAP can be found in the WEAP manual, available for freefrom the WEAP website (http://www.weap21.org/). In summary WEAP has the following features:

- Integrated Approach: Unique approach for conducting integrated water resources planning assessments.
- Stakeholder Process: Transparent structure facilitates engagement of diverse stakeholders in an open process.
- Water Balance: A database maintains water demand and supply information to drive mass balance model on a link-node architecture.

[1] www.weap21.org

- Simulation Based: Calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage; pollution generation, treatment, and discharge; and in-stream water quality under varying hydrologic and policy scenarios.
- Policy Scenarios: Evaluates a full range of water development and management options, and takes into account multiple and competing uses of water systems.
- User-friendly Interface: Graphical drag-and-drop GIS-based interface with flexible model output as maps, charts and tables.
- Model Integration: Dynamic links to other models and software, such as QUAL2K, MODFLOW, MODPATH, PEST, Excel and GAMS. Links to all other models can be developed quite easily since WEAP can read and write plain text files similar to SWAT, SPHY, SWAP, Mike11, HEC-HMS, HEC-RAS and Geo-SFM.

2.4.5 WEAP model setup

For five locations, the SWAT output was extracted and converted to the input format required by WEAP. This was done for all scenarios included in this study (see following section on scenarios). The model includes the Tchimbélé reservoir and the Kinguélé reservoir. The characteristics as listed in Table 2 were used to parameterize the reservoirs (see a screenshot of the input fields in Figure 23).

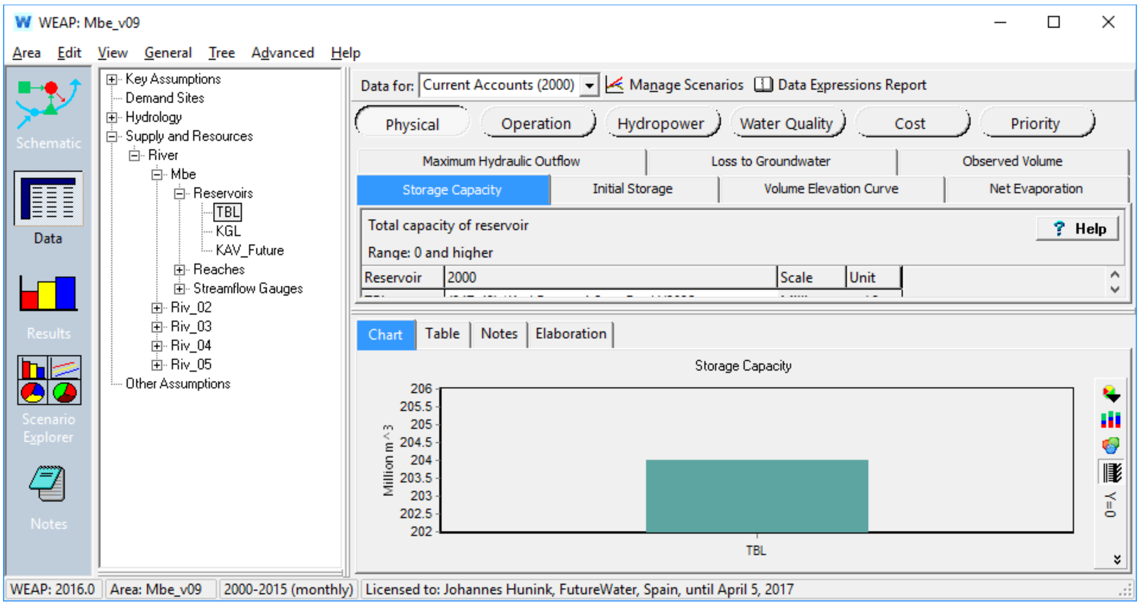

Figure 23. Input fields for the physical parameters of the reservoir nodes in the WEAP model

As previously explained, there are plans to build several new dams within the watershed (three sites). Therefore, another node was added to the model, representing these potential new reservoirs. Studying these possible future dams was not required by the ToR for this study but we decided to add this to the model assessment after consultations with the stakeholders, as future changes in the basin may impact the economic effectiveness of this potential investment.

Figure 24 shows the schematic setup of the Mbé watershed in WEAP. It must be stressed that WEAP allows for easy modifications and updates by the stakeholders of the model. The model will be available to the stakeholders and a training will be given to make sure that they are acquainted with the tool and setup for this watershed.

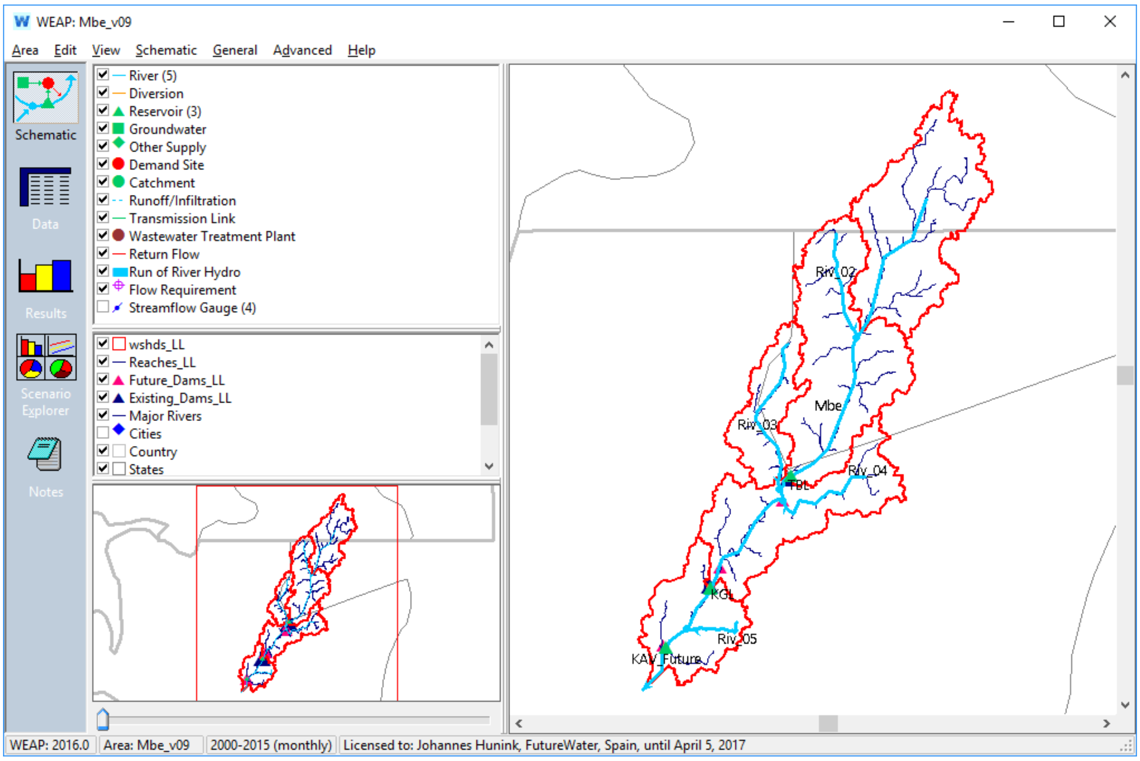

Figure 24. WEAP schematic setup of the Mbé watershed

Figure 25 shows the observed variability by means of a box-whisker plot in the turbined flows as derived by SEEG (estimated from generated hydropower) and the monthly mean turbined flows as simulated by WEAP. Table 4 shows the mean turbined flows (observed versus simulated), the percentual bias (i.e. the relative difference) and the Pearson correlation coefficient. As can be seen, the model gives reasonable agreement with the SEEG-derived flows. It has to be noted that for the purpose of this assessment, it is important to have a model that mimics the water balance of the reservoirs on a monthly timestep. A complete match with actual operations that take place on an hourly basis and depend on a wide variety of factors is not feasible nor practical for a strategic scenario assessment.

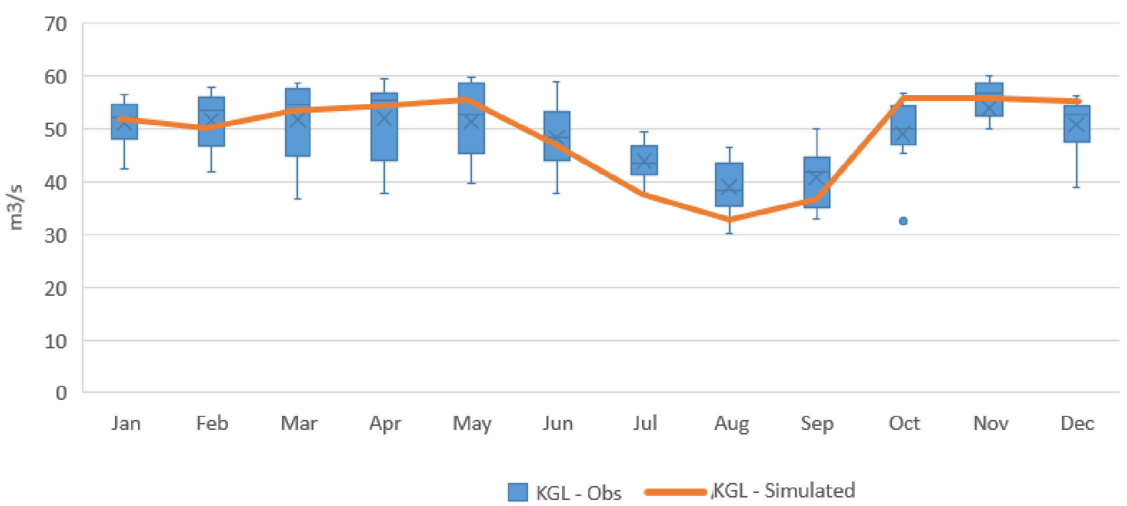

Figure 25. Boxplot of the turbined flows according to SEEG, and mean simulated turbined flows.

Table 4. Turbined flow Kinguele (2006-2015)

	Average Turbined Flow (m^3/s)	*Percent bias*	*Pearson*
Average Monthly			
Observed	48.6		
Simulated	49.6	2%	0.64

2.5 Future scenarios

A set of future scenarios was specified based on current policies and developments in Gabon, and on inputs received during the stakeholder meetings 26-May-2016 and 27-May-2016 with representatives of the following organizations:

- Agence Nationale des Parcs Nationaux (ANPN)
- Ministry of Town Planning, Environment and Sustainable Development – Water
- Ministry of Town Planning, Environment and Sustainable Development – Forestry
- Société d'Energie et d'Eau du Gabon (SEEG)
- Olam International Limited

The proposed scenarios apply to a certain area (non-protected versus protected, agricultural areas, Gabon versus Equatorial Guinea). Table 5 shows the defined scenarios, their description, and the land classes (see Figure 4) that are influenced by each specific scenario. All scenarios apply to the Gabon-part of the watershed except scenario 6. This distinction is because improved management comes at the behest of the government, and both governments don't necessarily work together in this direction.

Table 5. Future management scenarios, description, and areas affected

No	*Scenario name / description*	*Short name*	*Area affected**
1	**Forestry intensification poorly managed** Intensification of forestry operations with new additional allowed species, not complying with management plans and requirements	**1_Frs_Int_NO** 	Non-protected forest, including park buffer zone

2	**Forestry intensification well managed**	**2_Frs_Int_RI**	Non-protected forest, including park buffer zone
	Intensification of forestry operations but implementing Reduced Impacts measures (stream buffer zones, reduce damage to soil, prevent steep slopes, etc.)		
3	**Protection park buffer zone**	**3_Frs_Prt_Buf**	Park buffer zone
	Conservation of the buffer zone of Monts Cristal park, forbidding forestry concessions in the 5km border zone around the park		
4	**Road mitigation activities**	**4_Road_Mit**	Unpaved roads
	Road mitigation activities including stabilization of disturbed areas by seeding, mulching, erosion control blankets, reduce ditch slopes, reduced drainage runs, prevent reshape during rainy periods, etc.		
5	**Improved practices current small-scale scale agriculture**	**5_Ag_Gab_Imp**	Current agricultural areas
	Current small scale agriculture in Gabon, but with improved agricultural practices, as terraces, mixed cropping, mulching, etc.		

6	**Improved agricultural practices in Equatorial Guinea**	**6_Ag_EqG_Imp**	Current agricultural areas in Equatorial Guinea
	Current small scale agriculture in Equatorial Guinea but with improved agricultural practices, as terraces, mixed cropping, mulching, etc.		
7	**Large scale agricultural intensification - poorly managed**	**7_Ag_Int_NO**	Non-protected forest, excluding park buffer zone
	Large scale agricultural development, converting forest plots to agricultural lands, without implementing sustainable land management practices, as respecting riverine areas, avoid steep slopes, contour farming, etc.		
8	**Large scale agricultural intensification - well managed**	**8_Ag_Int_SLM**	Non-protected forest, excluding park buffer zone
	Large scale agricultural development, converting forest plots to agricultural lands, but with implementation of sustainable land management practices, as respecting riverine areas, avoid steep slopes, contour farming, etc.		
	** except for scenario 6, the scenario applies only to the Gabonese part of the basin*		

3 Results

The results section gives an overview of the analysis using the SWAT model:

3.1. For the current situation:
   a. Spatial
   b. Temporal
   c. Sediments per land use
   d. Discharge versus sediment relationships

3.2. Impacts on flows and sediments:
   a. A comparison of the scenarios using key indicators
   b. Then for each scenario separately:
      i. Spatial difference with reference scenario
      ii. Changes in flow and sediment response of the watershed

3.3. Impact on hydropower generation of the different scenarios, including the extension of hydropower facilities in the basin

3.4. Net benefits of the scenarios for hydropower

3.5. Cost-effectiveness of the scenarios, with maps that help to identify priority areas

3.1 Current situation

The SWAT model mimics hydrological processes as they occur in reality. This means that rainfall falling on an area is converted either to evaporation, direct runoff, sub-surface flow or groundwater percolation. The advantage of using models likes SWAT is that it provides insights into hydrological and erosion/sedimentation processes that can never be obtained by observations in terms of spatial detail and temporal resolution. The first step in the study was therefore to use SWAT in order to better understand the hydrological conditions in the Mbe basin over the last 15 years.

Figure 26 and Figure 27 show maps of the principal hydrological flows for the study area (all annual totals or averages):

- Evapotranspiration
- Baseflow
- Direct runoff

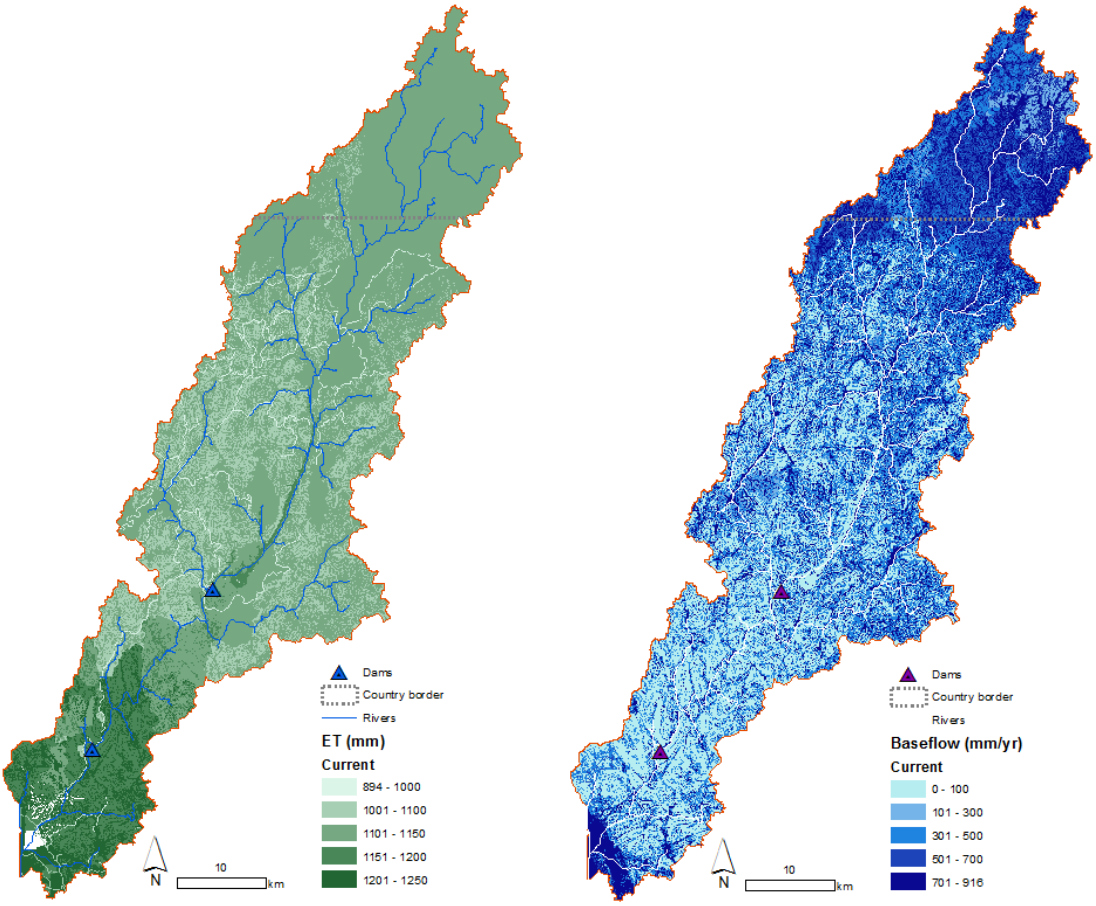

Figure 26. Annual evapotranspiration and baseflow generation for the current scenario (mm/year)

From these maps it can be observed that evapotranspiration rates are generally higher downstream in the basin, due to slightly higher temperatures. The spatial variability in baseflow is mainly a function of slope: low slopes favor percolation to groundwater. The opposite for direct runoff (Figure 27): steeper slopes generate more direct runoff. The erosion pattern is dominated by land cover and use. Agricultural areas and roads generate the highest erosion rates. Steepness primarily dictates erosion in forested areas, although the forest cover also plays a small role.

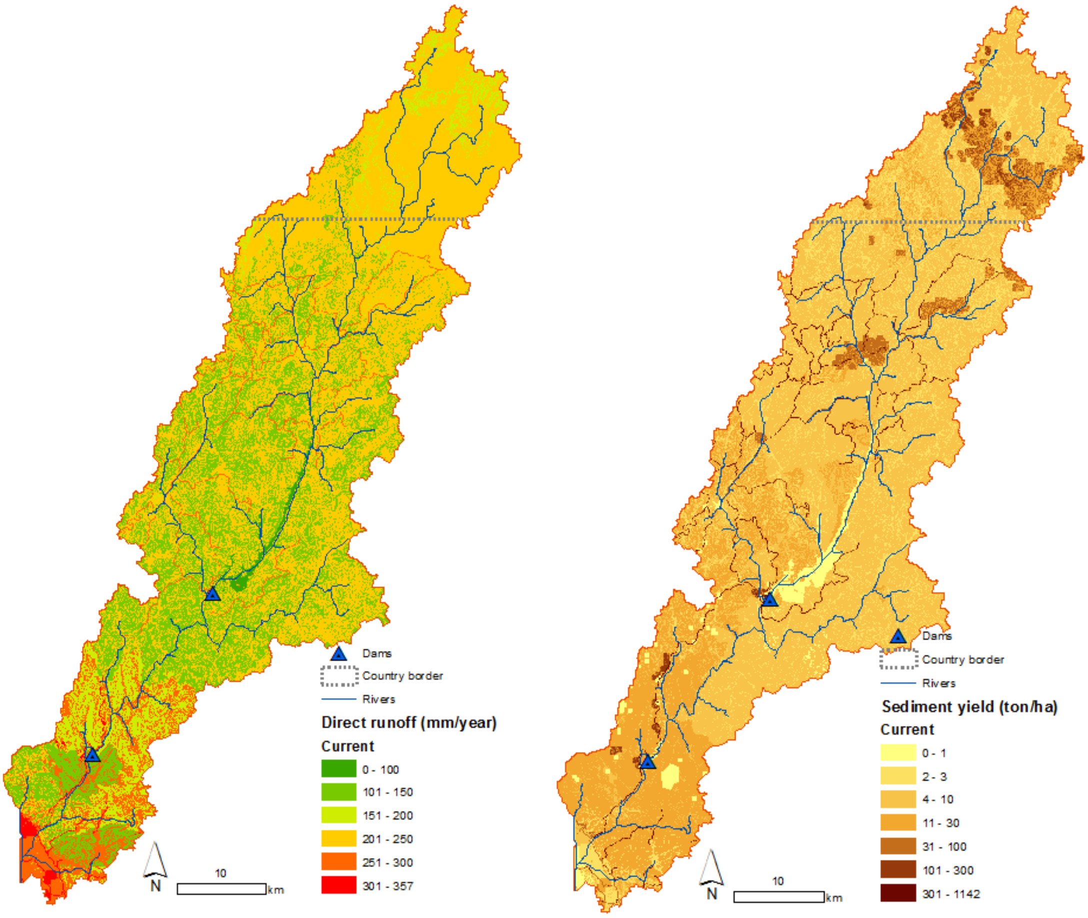

Figure 27. Annual runoff generation (mm/year) and sediment yield (ton/ha) for the current scenario

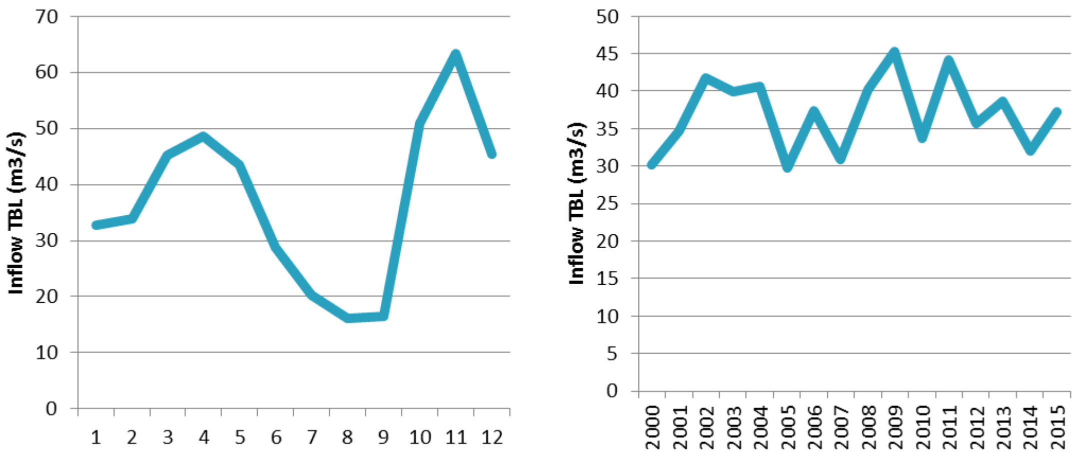

Figure 28. Monthly and annual average streamflow (m3/s) flowing into Tchimbele reservoir for the current scenario

Figure 28 shows the monthly flow regime entering the Tchimbele reservoir (left) and the annual variability in mean annual flow. A bimodal rainfall pattern is observed: a low peak in the first rain season, and a higher peak in October-December season. Annual variability is relatively low. For sediment yield (Figure 29) the annual variability is somewhat more pronounced, with annual amounts that can differ by a factor of two.

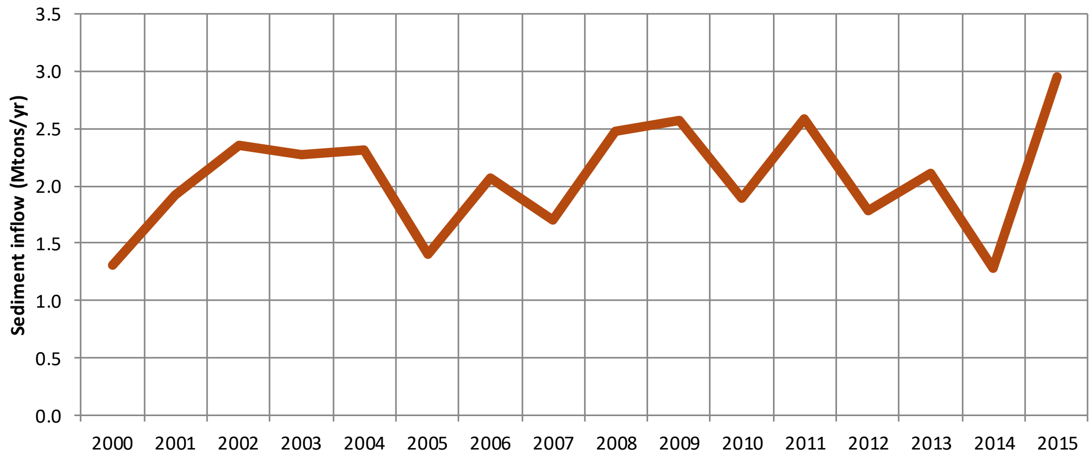

Figure 29. Annual sediments entering the main reservoir Tchimbele (Megatons/year)

The estimated annual sediment inflow entering the Tchimbele reservoir is 2.1 Mtons. Given the large length of the reservoir and its size, we can assume that most of these sediments have time to settle down and deposit. Converting this sedimentation rate into a volumetric unit gives a mean annual capacity loss of the reservoir of 1.3 MCM/year.

The reservoir has been operational for 35 years. Most likely the pressure and intensity of logging has increased over time. So the calculated rate cannot be taken as representative for the whole period. If we assume that during the first 15 years the sedimentation rate was half what it is now (i.e, 0.7 MCM/year), the reservoir could have lost about 40 MCM, which is around 16% of its original design capacity (247 MCM). In 2050, the capacity may be reduced to 160 MCM if current rates continue (Figure 30). This may be an underestimate though if forestry operations intensify further over the following decades.

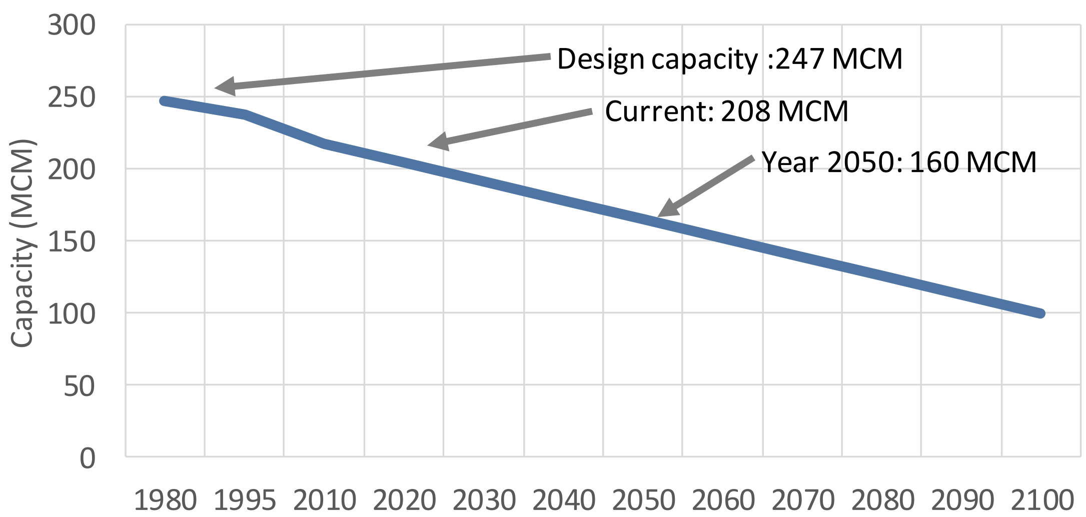

Figure 30. Reservoir capacity from original design to 2100, assuming the current sedimentation rates.

These results are based on the best available data on land use, soils and climate, and relationships with erosion and sediment transport. However, no data are available for calibration of the sediment outcomes, so the absolute outcomes of this analysis have to be taken with caution. However, as the principal focus of the study is to undertake scenario analysis, results are considered to be of sufficient reliable as focus is on relative differences.

An in-depth analysis of the sources of the sediments (see Figure 31) shows that most of the sediments originate from forests in non-protected areas (including the forest roads, linked landing sites and other land use modifications due to forestry operations). The forest buffer zone and the forest in protected area also contribute to the total sediment load, but obviously much less (specific sediment yield from these areas is about half that of the non-protected areas). In addition, significant amounts of sediments originate from the agricultural areas in both countries. The amount of sediment coming from Equatorial Guinea is somewhat higher than the total amount from agriculture in Gabon.

Land use	Mean annual specific sediment yield (ton/ha)	Mean annual sediment yield (Mtons)
Villages and agriculture Gabon	74	0.3
Villages and agriculture in Eq. Guinea	60	0.5
Forest in buffer zone	14	0.5
Forest in non-protected area	27	1.8
Forest in protected area	12	0.6
Forest in Eq. Guinea	7	0.2
Roads	360	0.3
Water bodies	0	0.0
Wetlands	1	0.0

Figure 31. Total sediment yield per land cover, country and zone

The main concern of the reservoir operator today is sediment concentration as this is already affecting the hydropower facilities and turbines, incurring maintenance and replacements costs (see section 2.3.4 on Hydropower). Figure 32 shows the monthly sediment concentration and its relationship with flows entering the Tchimbele reservoir. Model simulations indicate that the sediment concentration peaks are similar for both rain seasons. As can be expected, there is a strong relationship between sediment concentation and flows, although the relationship is not lineardue to the nonlinear behavior of erosion processes (thresholds, hysteresis, etc.).

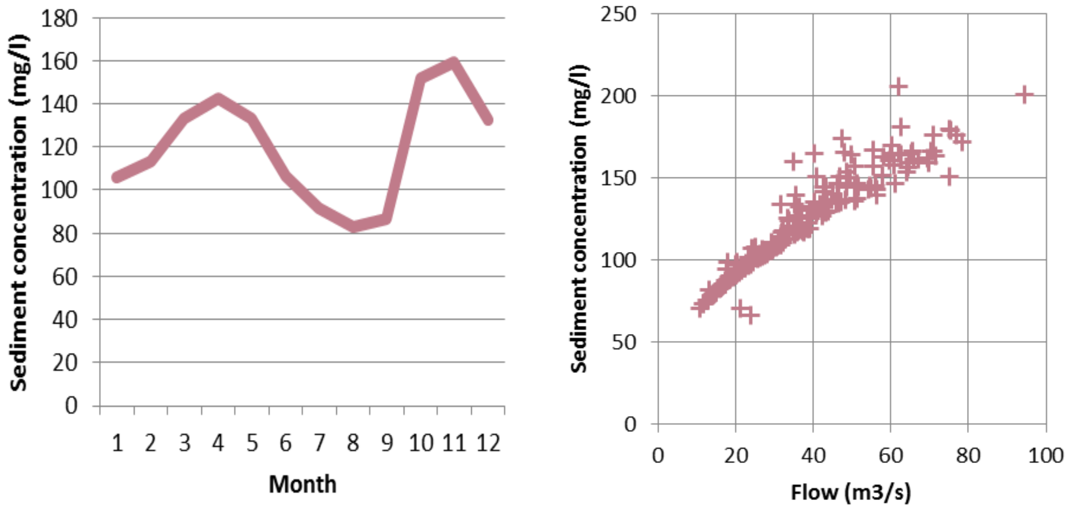

Figure 32. Monthly sediment concentration for Tchimbele reservoir (left) and its relation with flow (scatterplot right)

3.2 Impacts on flows and sediments

3.2.1 Impact overview

The SWAT model, calibrated and validated for the Mbé watershed, was used to analyze the impact of the scenarios defined above (Table 5) on flows and erosion/sedimentation. For this it was assumed that climate conditions are same as used for the base line (2000-2015).

To understand better the relative impacts of the different scenarios, an additional run was done, representative of "pristine" conditions, in which the watershed is covered entirely with mature forest. Each of the future scenarios is discussed separately in the following sections, while an overview of the impacts is given in Table 6. Impacts are summarized using the following indicators for each of the scenarios:

- Dry season flow (September)
- Mean annual sediment yield
- Sediment concentration in October
- Annual hydropower generation

The first three indicators correspond to the entry point of the Tchimbele reservoir. Hydropower generation corresponds to the total generation (Tchimbélé and Kinguélé). The absolute values are given in Table 6 and the relative changes in Table 7.

Table 6. Four key indicators in absolute values.

Scenario name	Pristine	Current	Frs_Int_NO	Frs_Int_RI	Frs_Prt_Buf	Road_Mit	Ag_Gab_Imp	Ag_EqG_Imp	Ag_Int_NO	Ag_Int_SLM
Scenario number	0	0	1	2	3	4	5	6	7	8
Dry season flow (m3/s)	23.2	22.4	21.0	22.1	22.5	22.3	22.5	22.7	21.3	22.0
Mean annual sediment yield (Mton/yr)	0.0	2.1	3.1	2.2	1.9	1.5	2.1	2.1	2.6	2.4
Sediment concentration in October (mg/l)	24	1095	1705	1175	1023	751	1056	1015	1412	1280
Hydropower generation (GWh)	0	696	629	724	750	783	738	736	688	710

Table 7. The relative changes of the key indicators compared to the current scenario

Scenario name	Current	Frs_Int_NO	Frs_Int_RI	Frs_Prt_Buf	Road_Mit	Ag_Gab_Imp	Ag_EqG_Imp	Ag_Int_NO	Ag_Int_SLM
Scenario number	0	1	2	3	4	5	6	7	8
Dry season flow (m3/s)	0%	-6%	-1%	1%	0%	1%	2%	-5%	-2%
Mean annual sediment yield (Mton/yr)	0%	52%	6%	-7%	-25%	0%	3%	25%	14%
Sediment concentration in October (mg/l)	0%	56%	7%	-7%	-31%	-4%	-7%	29%	17%
Hydropower generation (GWh)	0%	-10%	4%	8%	12%	6%	6%	-1%	2%

The most negative impacts in terms of dry season flow are observed for scenario 1 (forestry intensification without best management practices) and 7 (agricultural intensification without best management practices). Low flows are on average around 8% lower compared to current. Small increases of flows in the dry season can be expected for the sustainable land management scenarios with current agricultural practices (scenarios 5 and 6).

The relative changes may appear low, but they can be significant for hydropower production. Especially during the dry season, small changes of a few percent can already affect hydropower production significantly. This sensitivity can even be higher when reservoir capacity becomes lower due to reservoir sedimentation.

Compared to pristine conditions, these indicators become much more extreme. Figure 33 shows the relative changes compared to current and compared to pristine conditions of the dry season flow. The model simulations indicate that currently, flows at the end of the dry season are about 7% lower than a watershed in pristine conditions (fully covered by forest and no forestry operations, nor agriculture). The indicated percentages give an idea of the existing scope in the watershed to improve the hydrological flows for hydropower.

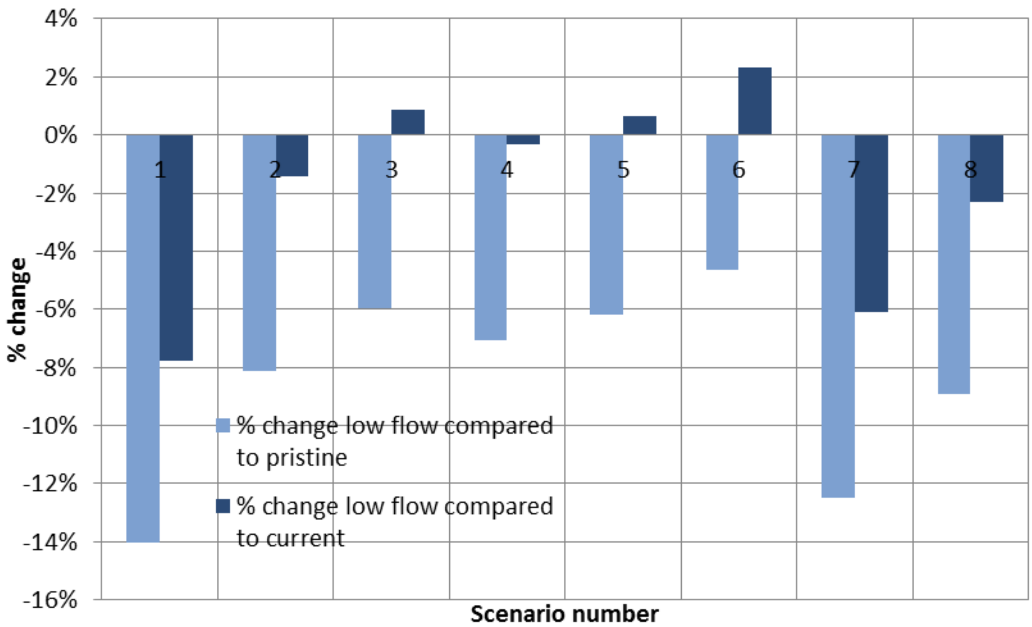

Figure 33. Relative change of dry season flow indicators for each of the scenarios, compared to current and pristine conditions (%)

In terms of sediments (Figure 34), scenario 4 (road mitigation activities) has the highest impact on the watershed. The protection of the buffer zone also has a significant impact (around 5% less sediment yield). Scenario 1 has the most adverse impact and will increase sediment yield significantly (around 10%). Scenario 7 (agricultural intensification without sustainable land management practices) will also increase sediment yields considerable.

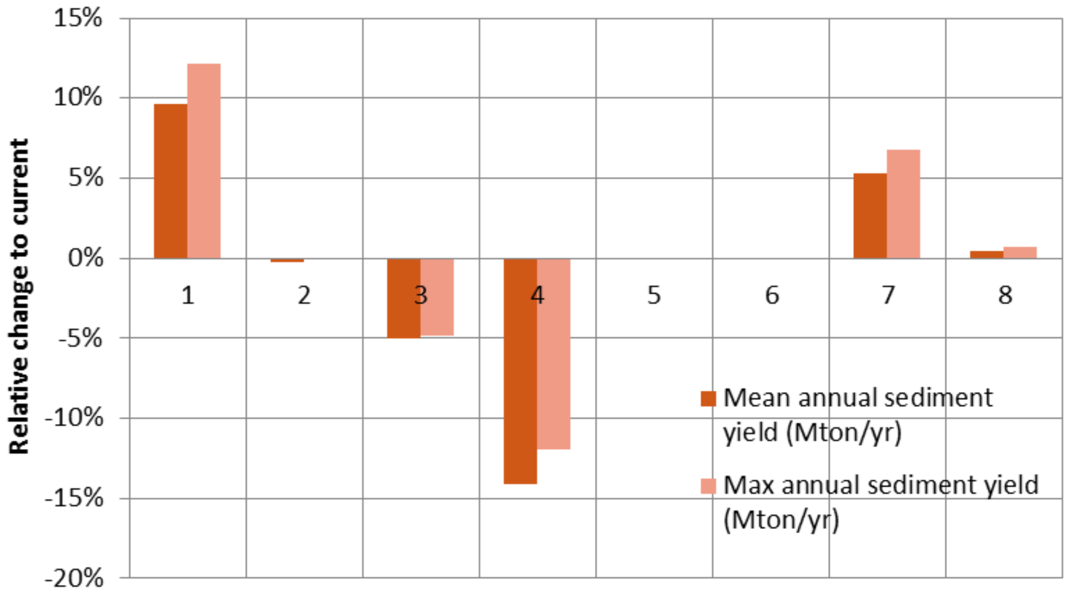

Figure 34. Relative change of sediment indicators for each of the scenarios, compared to current (%)

More details on each of the scenarios are found in the following sections.

3.2.2 Intensification of forestry operations (Scen. 1 and 2)

The intensification of forestry operations is a likely scenario and might affect the entire non-protected forested area in the watershed. In fact, as has been explained before, today the majority of this area is under concession. Future policies may allow the extraction of new species and economic interests may increase timber extraction and pressure on the forest.

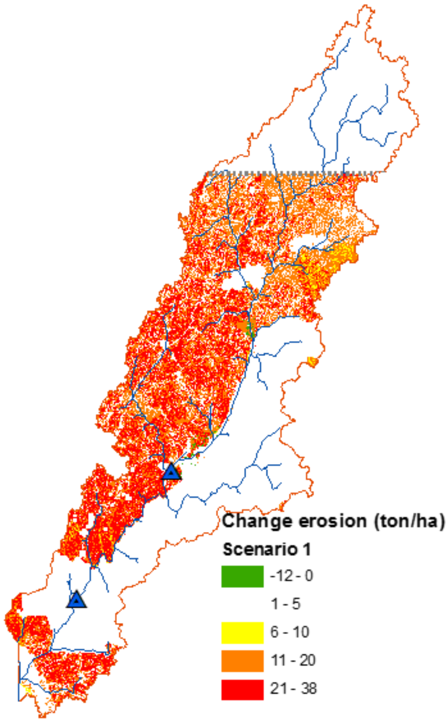

Figure 35. Changes in erosion (ton/ha) of the forestry intensification scenario (1) compared to current

Figure 35 show maps indicating where impacts on runoff and erosion occur. Runoff is expected to increase slightly, but most impact can be expected on the seasonal flow pattern, as shown by the red bars in Figure 36. Flows in the wet months, especially during the first rainy season (first half year) will increase by about 2-3%, while flows in the dry season (August, September) will decrease by about 5 to 7%.

For scenario 2, implementation of best management practices and reduced impact logging, impacts are projected to be insignificant (green in Figure 36)

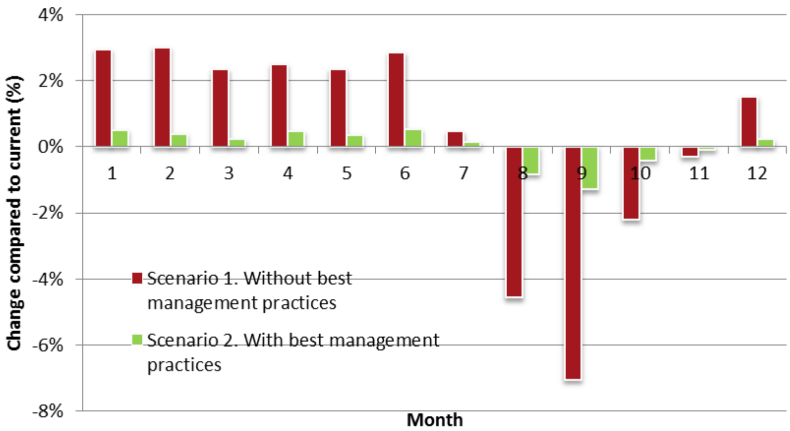

Figure 36. Changes (%) in monthly flows coming into Tchimbele reservoir, compared to current

The SWAT model predicts a considerable increase of erosion for forestry intensification: up to more than 20 tons/ha (Figure 35). This will lead to an increase in mean monthly sediment concentration as is shown in Figure 37. This figure shows the difference between scenario 1 and 2 (no reduced impact versus reduced impact measures). Similar to what can be seen in flows, scenario 2 shows hardly any difference with the current scenario (not shown here) but scenario 1 (without best management practices) will likely increase sediment loads significantly.

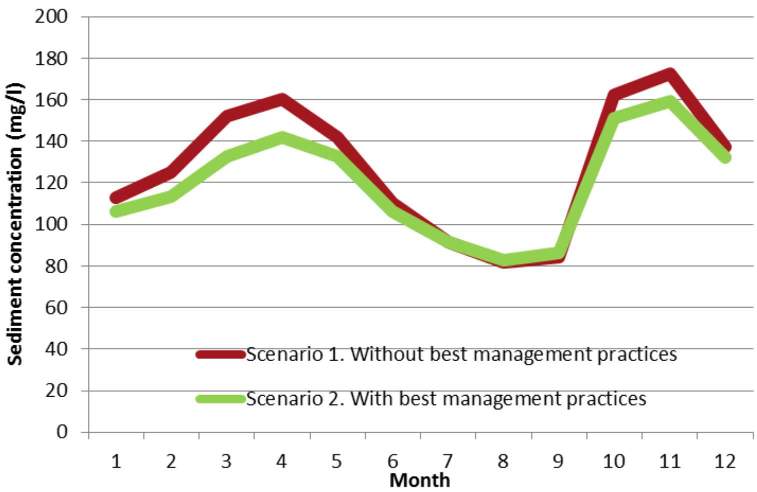

Figure 37. Monthly mean sediment concentration for Tchimbele inflow, for forestry intensification scenarios with and without best management practices

3.2.3 Park buffer zone (Scen. 3)

The park buffer zone is currently not effectively protected, but future policies may do so as the zone has already a special status. Excluding forestry concessions from this area will reduce runoff and erosion slightly as is shown in Figure 38. This will also lead to a slight decrease in sediment concentrations (Figure 37) and sediment yield entering the reservoir (see Figure 34 in overview section).

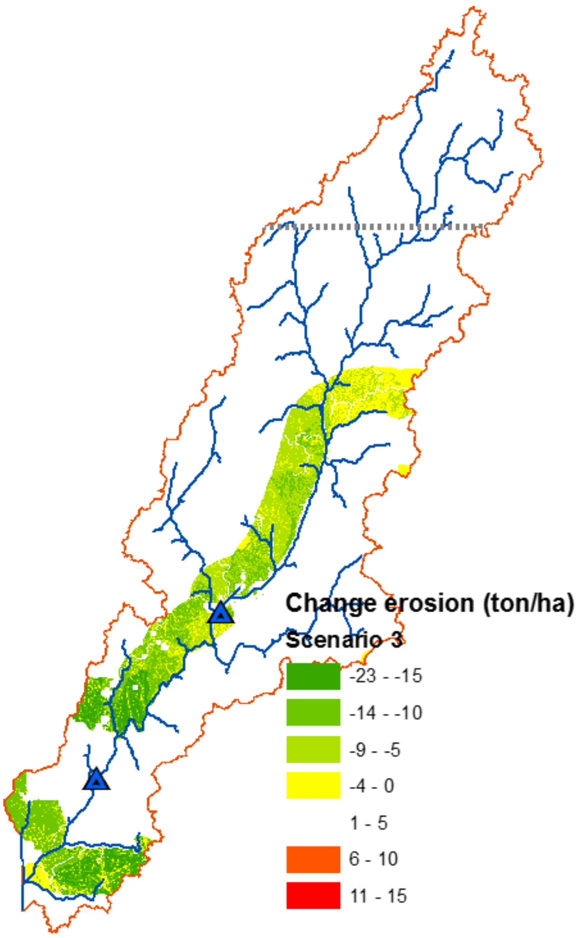

Figure 38. Changes in erosion (ton/ha) of the park buffer zone scenario (3) compared to current

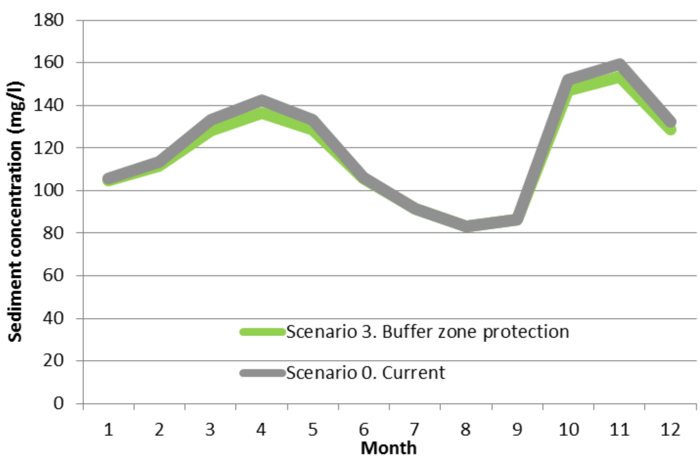

Figure 39. Monthly mean sediment concentration for Tchimbele inflow for buffer zone protection (scenario 3) compared to current (scenario 0)

3.2.4 Road mitigation (Scen. 4)

Unpaved roads and connected landing sites are the most important source of sediment in the area, as shown previously. Figure 40 shows a detail of the area upstream of Tchimbele reservoir, where the road network can be identified. Considerable reductions can be potentially obtained when roads are better protected by activities such as:

- stabilization of disturbed areas by seeding, mulching, erosion control blankets,
- reduction of ditch slopes,
- reduced drainage runs,
- prevent reshaping during rainy periods

The impact on sediment concentration of the water inflow into Tchimbele is also significant, especially in the rainy season. On average, a reduction of sediment concentration of about 10% can be achieved if this measure is implemented.

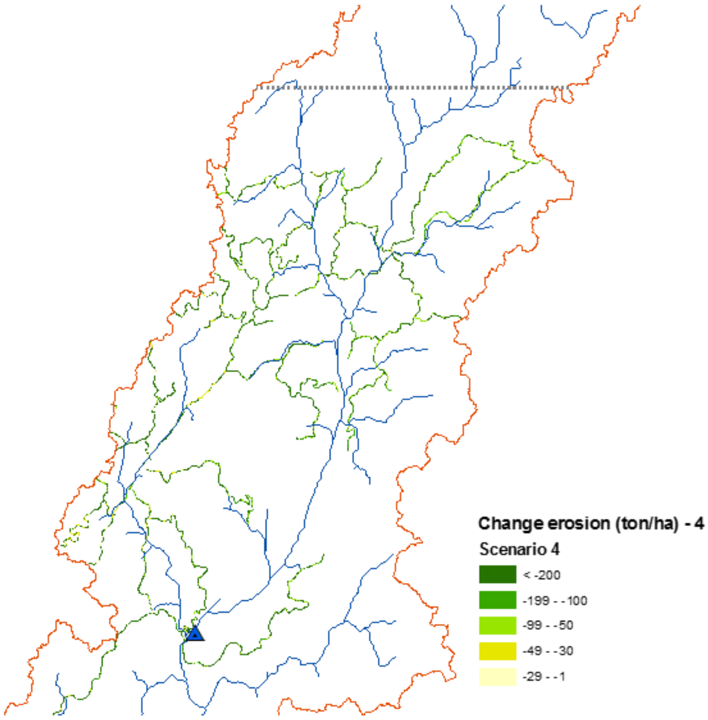

Figure 40. Changes in erosion (ton/ha) for the road erosion mitigation scenario (4) compared to current

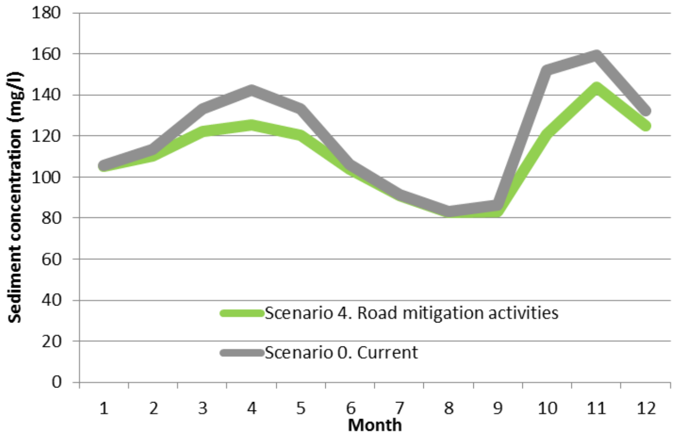

Figure 41. Monthly mean sediment concentration for Tchimbele inflow for road mitigation activities scenarios (scenario 4) compared to current (scenario 0)

3.2.5 Agricultural practices and intensification (Scen. 5 - 8)

There is likely some scope in the current agricultural areas for improved agricultural practices that reduce erosion and sediment yield. Figure 42 shows a detail of the current agricultural areas in both countries and the relative difference in erosion. Local impacts are significant, although very small on the basin scale and for Tchimbele inflows (see previous overview in Figure 33 and Figure 34)

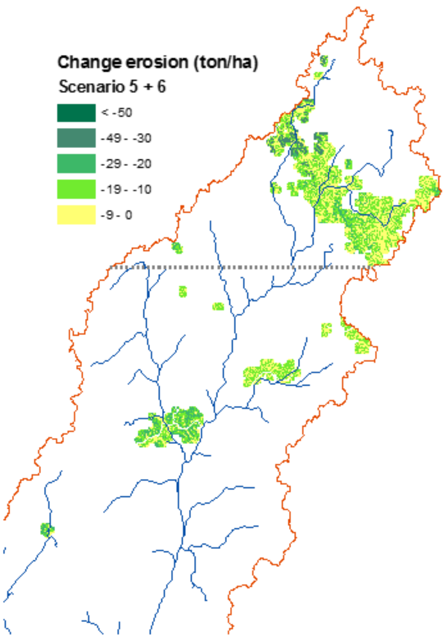

Figure 42. Changes in erosion (ton/ha) for the improved agricultural practices scenarios in Gabon (5) and in Equatorial Guinea (6)

The neighboring watershed to the Mbé basin has already undergone considerable changes over the last year, where plots of forested land were converted and prepared for agriculture. In some cases it was evident that this transformation was not carried out following the requirements to generate minimum impact on soil and water (riverine areas, avoid steep slopes, contour farming, etc.). For this scenario it was assumed that 10% of current non-protected area, excluding the buffer zone, is converted to agricultural land.

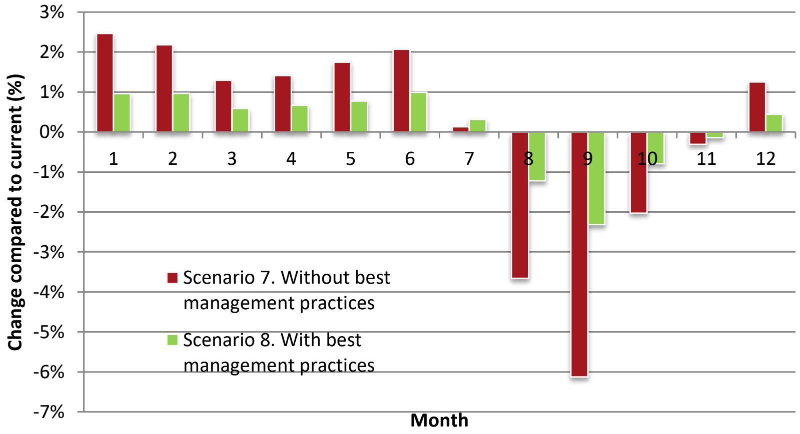

Figure 43. Changes (%) in monthly flows coming into Tchimbele reservoir, compared to current

Figure 43 shows the relative impact on flows compared to the current scenario: with and without best management practices. Similar to the scenarios with intensification of forestry operations, flows in dry season are reduced, while in wet season they increase. For sediment concentrations (Figure 44), a notable difference is also expected between the scenario with and without best management practices.

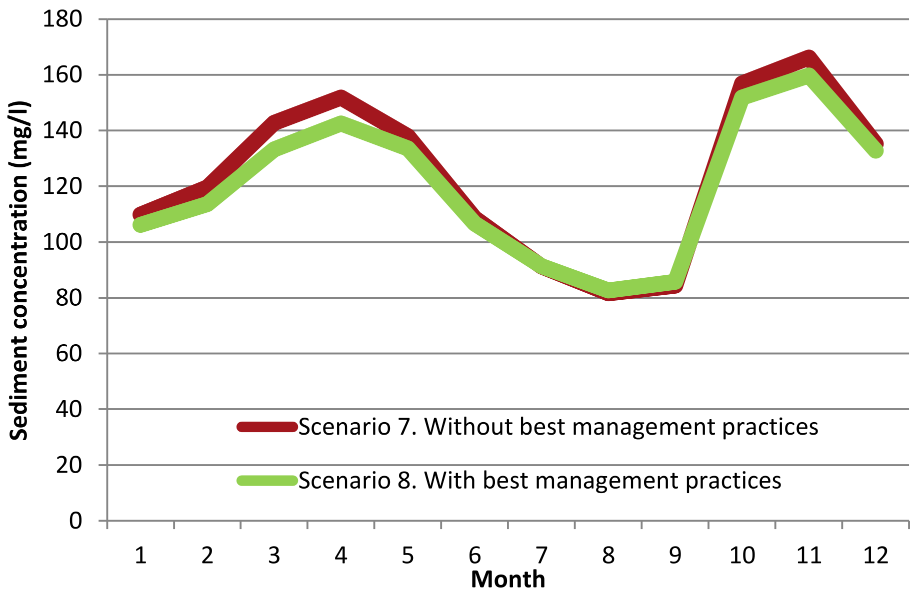

Figure 44. Monthly mean sediment concentration for Tchimbele inflow, for agricultural intensification scenarios with and without best management practices

3.3 Impact on hydropower generation

3.3.1 Overall approach

As described in the previous section (3.2) management scenarios can have a substantial impact on flows, erosion and sediment load. The amount of hydropower generated by TBL and KGL is obviously related to these expected changes in flows and sediments. We used the WEAP model to evaluate these effects by considering the impact of these management scenarios in 20 years, which corresponds to approximately the year 2035. These 20 years were selected since impacts of selected management scenarios on the short term might be low, despite that they may eventually become very significant if not addressed.

The impact of these management scenarios on hydropower generation has multiple dimensions. First of all, total flows into the reservoirs might change due to hydrological processes such as variations in evaporation and groundwater recharge. Second, flow patterns might be impacted resulting in changes in peak and low flows. Third, cooling water availability and quality might become a constraint forcing a reduction in power generation. Fourth, reservoir capacity might decrease due to the sedimentation. Finally, wear on turbines due to high silt concentration in the water can reduce the capacity and might also reduce lifespan of the turbines.

The interaction of these factors is complex and analyzed in an integrated way using WEAP. In WEAP these factors have to be quantified. Since limited actual data are available on these factors, expert knowledge has been primarily used. Obviously, if better data become available, those can be easily incorporated into the existing WEAP model. For the five following factors data have been input into the WEAP model (see Appendix for the technical details on how to implement in WEAP):

- **Total flows**. Results of the SWAT model are used for this and are included in WEAP by using the ReadFromFile command. As described in the previous sections the impacts of the management scenarios have a limited impact on the total flows.
- **Flow patterns**. Same as the total flows and implemented in WEAP using ReadFromFile. Since the WEAP analyses are based on monthly time steps an additional conversion factor is used to account for changes in daily high and low flows. This was implemented by adjusting the total flows by a factor correlated to the sediment load.
- **Cooling water**. The so-called plant factor was adjusted to represent the reduction in cooling water intake as function of actual reservoir levels.
- **Reservoir capacity.** This was implemented by summing the total sediment inflow over a period of 20 years.
- **Wear on turbines.** This factor was included in WEAP by adjusting the maximum turbine flow.

In order to take into account variation in weather conditions in the year 2035, WEAP was set up to run for a period of 10 years. It was assumed that past weather conditions (2006-2015) are representative for the years around 2035. Obviously, a detailed climate change impact study should be undertaken to test this hypothesis, but that fell outside of the current scope of work.

A typical result of these analyses using WEAP can be seen in Figure 45. Although years are indicated, the specific behavior of hydropower production in a given future year (high vs. low) cannot be known. It is therefore more logical to display results in so-called box-and-whisker plots. A typical example is shown in Figure 46 based on the same data as Figure 45. Box-and-whisker plots are very powerful in showing mean values and associated annual variation. The first and third quartiles are at the ends of the box, the median is indicated with a horizontal line in the interior of the box, and the maximum and minimum are at the ends of the whiskers. Box-and-whisker plots are helpful in interpreting the distribution of data, in this specific case the annual distribution in hydropower generation.

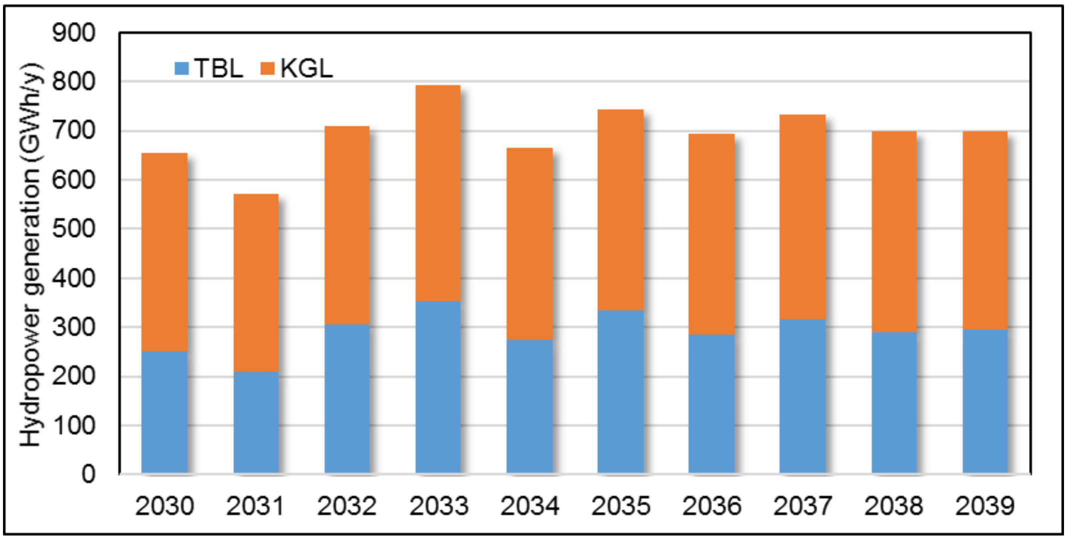

Figure 45. Projected future hydropower generation for Tchimbele and Kinguele reservoir.

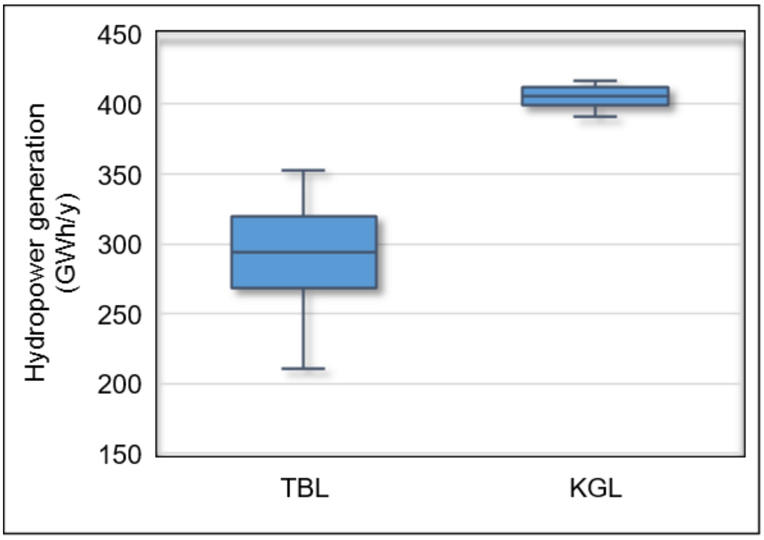

Figure 46. Future hydropower generation for Tchimbele and Kinguele reservoir around the year 2035. This box-whisker plot is based on same data as presented in Figure 45.

A total of eight scenarios have been evaluated, which are grouped into Forest interventions and Agriculture interventions. These eight scenarios are compared to the current situation (Reference). A summary of these scenarios is provided in Table 8, while details have been discussed in the precious Chapters (see Table 5 for a summary).

Table 8. Summary of the scenarios analyzed.

	0_Reference	Current situation
FOREST	1_Frs_Int_NO	Forestry intensification poorly managed
	2_Frs_Int_RI	Forestry intensification well managed
	3_Frs_Prt_Buf	Protection park buffer zone
	4_Road_Mit	Road mitigation activities
AGRICULTURE	5_Ag_Gab_Imp	Improved practices current small-scale scale agriculture
	6_Ag_EqG_Imp	Improved agricultural practices in Equatorial Guinea
	7_Ag_Int_NO	Large scale agricultural intensification - poorly managed
	8_Ag_Int_SLM	Large scale agricultural intensification - well managed

3.3.2 Forestry scenarios (1 – 4)

Four different forest scenarios and their impact on hydropower generation have been explored using the WEAP model. Results are presented as box-and-whisker plots in Figure 47. The first scenario, referred to as 01_Frs_Int_NO, presents a future where forestry intensification will be poorly managed. It is no surprise that increases in erosion and changes in flow regime will have a negative impact on the hydropower generation. Interestingly, not only will the mean hydropower generation decrease, but at the same time year-to-year variation will increase significantly. This might have clear societal impact as the number and frequency of blackouts will increase.

In contrast, for the other three scenarios (forestry intensification well managed, protection park buffer zone, forest road protections) higher hydropower production can be expected compared to the reference situation. Equally important is that these scenarios all reduce year-to-year variation as can be observed from the smaller boxes in Figure 47. The introduction of protected buffer zones is even more beneficial than well managed forest intensification. It is well known that erosion from forest roads might play an important role in sediment load of the rivers and reservoirs. From Figure 47 it is clear that mitigating erosion from roads (scenario 04) is very effective in terms of [improving/maintaining] hydropower generation, compared to the other scenarios.

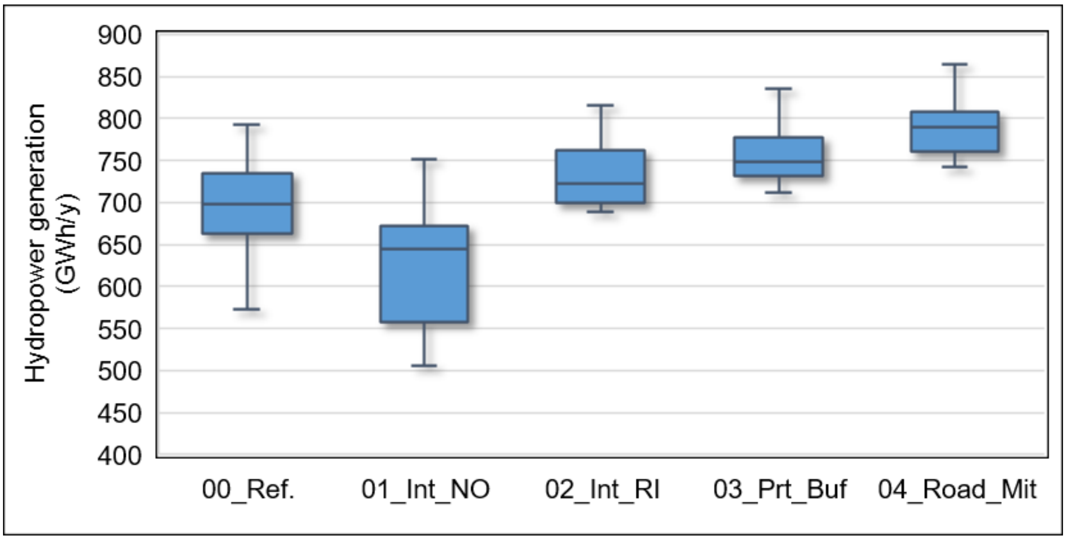

Figure 47. Projected hydropower generation for the reference and the four forest scenarios around year 2035.

3.3.3 Agricultural scenarios (5 – 8)

Four different agricultural scenarios have been proposed and analyzed using the WEAP model. The improved small-scale agricultural practices, 05 in Gabon and 06 in Equatorial Guinea, will result in an average annual increase in hydropower generation of about 5% (Figure 48). At the same time will these scenarios result in smaller year-to-year variation; in particular, years with below-average hydropower production will decrease.

In contract to these small-scale agriculture scenarios two large scale agricultural interventions were analyzed (07: poorly managed and 08: well managed). Compared to the reference situation, these two interventions have rather limited expected impacts. As shown before, erosion is expected to increase for the poorly managed large scale intervention, while a small decrease in erosion can be expected for the well managed one compared to the reference. However, since agriculture evapotranspirates less water than forests, total flows are expected to be somewhat higher compared to the reference situation.

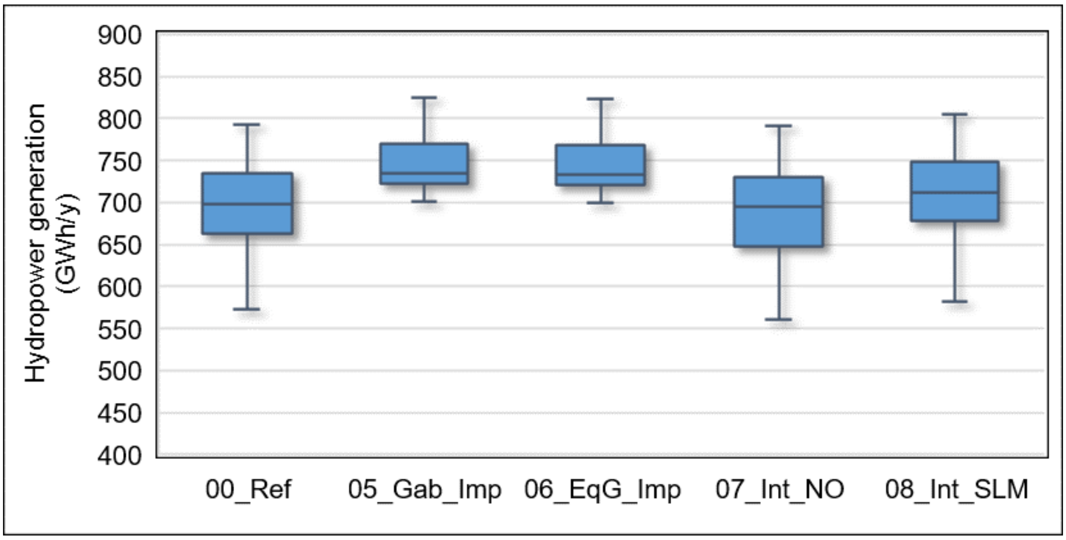

Figure 48. Projected hydropower generation for the reference and the four agricultural scenarios around year 2035.

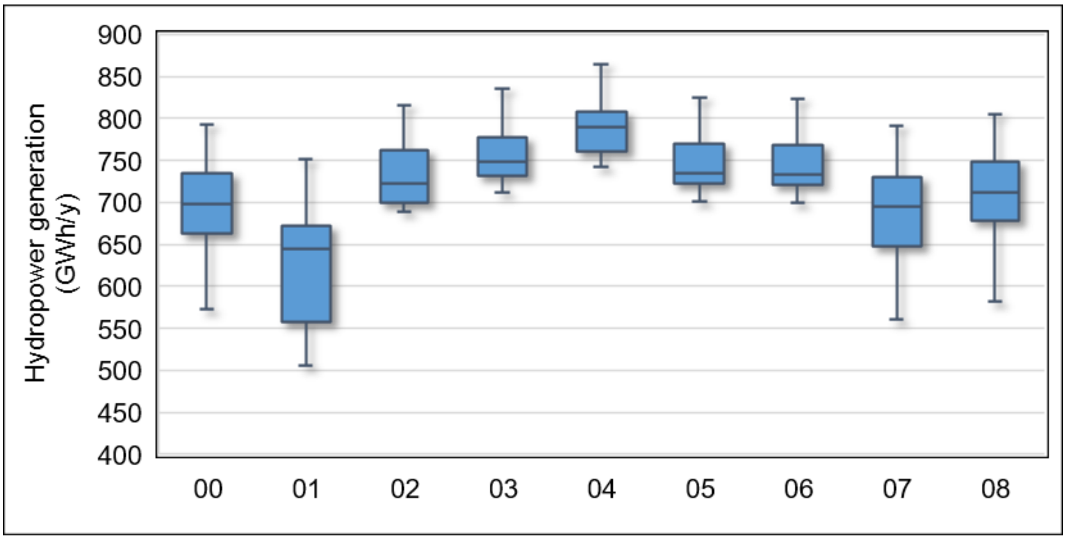

Figure 49. Projected hydropower generation for the reference and all scenarios around year 2035.

3.3.4 Future electricity demands (10 – 11)

Current electricity consumption per capita in Gabon is about 860 kWh/y[1]. Compared to other countries this is quite low, e.g. USA: 12,190; France: 6,990. It is expected that electricity demand will increase on average by 7% per year in Gabon, which means that in 20 years' time electricity demand will raise by a factor of 3.8 (1.07^{20}). Currently, the Mbé basin produces on average 680 GWh/y (TBL: 270, KGL: 410). Given this factor of 3.8 this must increase up to 2584 GWh/y by 2035. It is clear that even the most optimistic management scenario explored in this study cannot achieve such an increase by itself (Figure 49).

Therefore two additional scenarios were introduced:

- 010_New_Res_Ref

[1] http://www.indexmundi.com/g/r.aspx?v=81000

- A reservoir with a capacity of 100 MCM and a working water head of 100 meters (this represents planned investments in three new dams in the Mbe watershed – a more detailed analysis involving more details of the planned dams can be done by the stakeholders based on this existing model).
- 011_New_Res_FullMeasures
    - Same as above, but now with all proposed sustainable measures included (02_ForestIntegrated, 03_ForestBuffer, 04_RoadMitigation, 05_Agr, 06_Agr).

These scenarios were input into WEAP and analyzed. From Figure 50 it is clear that a new hydropower facilities are able to double the current hydropower generation. If this would be combined with the complete set of integrated mitigation measures (forest, road, agriculture) total hydropower generation can be even increased up to 1800 GWh/y, almost a factor of three higher than the current amount of 650 GWh/y.

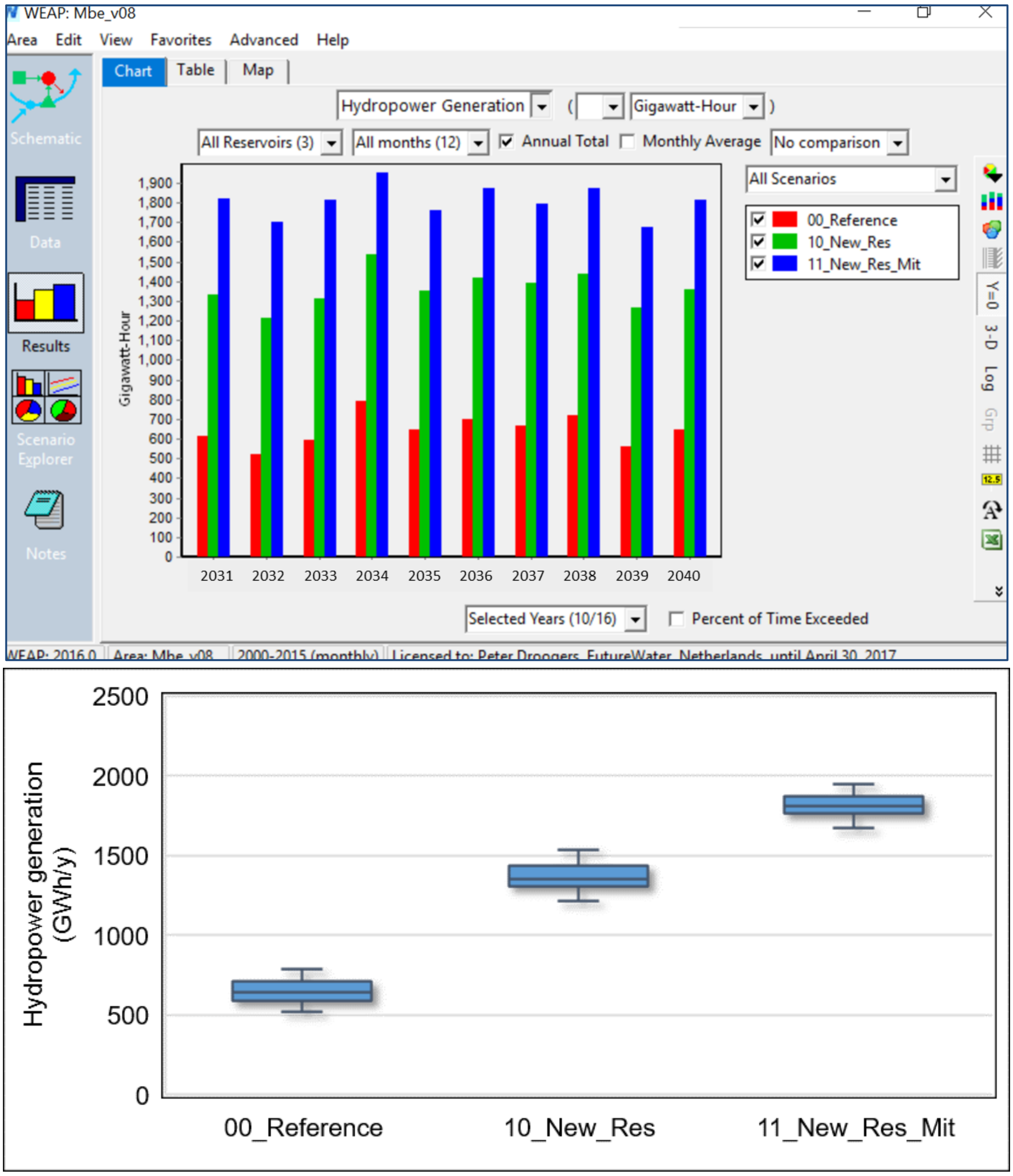

Figure 50. Projected hydropower generation for the reference and two new scenarios around year 2035. Shown as WEAP output (top) and as box-and-whisker plots.

3.4 Net benefits for hydropower

According to the previous sections it is clear that potential benefits can be obtained by improved management practices: reduced erosion and sediment loading in rivers and reservoirs, more regulated flows, and higher hydropower generation, amongst others. To assess the financial implications an analysis has been undertaken of net benefits for hydropower. A full analysis of benefits and costs requires a very detailed site specific analysis, which is beyond the scope of this study. However, based on literature and generic data we were able to carry out a first order analysis. Data from various sources were completed with expert judgement.

The following data have been used for this first order benefit-cost analysis:

- Investment costs of hydropower[1]: US$5,000 / kW
- Variable operating costs: US$ 0.01 / m^3 / yr
- Fixed operating costs: US$ 0.02 / MW / yr
- Electricity revenues: US$ 0.15 / kWh
- Interest rate: 5%

In 2010, the average effective electricity tariff in Africa was US $0.14 per kilowatt-hour (kWh) against an average of US $0.18 per kWh in production costs[2].

There are clear benefits to hydropower and other sectors from having reduced sediments in the water, ranging from reduced purification costs, reduced turbine wear, and improved health of aquatic life. A detailed analysis of the factors influencing damages to the turbines and more data on the current bathymetry could provide more accurate figures on the benefits. For the current study, it was assumed that the value of water decreases by US$ 0.005 per m^3 of water for each million m^3 of sediment per year. Therefore, lower sediment loading will increase benefits. The implementation costs of the various scenarios are considered to not have any net costs as the benefits to forests, people, nature etc will balance out as was shown in many similar studies and implementations; but this assumption has to be validated (Vogl et al., 2017).

In Figure 51 results of the benefit-costs analysis are presented as WEAP output. One of the most striking results is that for the reference situation an annual net loss of about US$ 5 million is estimated (or approximately -3,000 million FCFA/year, see Table 9). The average electricity revenues were estimated at US$ 72 million, but total operation costs were US$ 77 million per year. These operating costs consist of annualized investment costs of US$ 32 million and operational costs (variable and fixed) of US$ 45 million. It might be that the annualized investment costs are in reality lower as local conditions might be more favorable than used here.

The benefit-cost analysis of the eight scenarios show obviously a similar pattern as the hydropower generation, but somewhat more prolonged. This is because improved management practices result in more hydropower generation, but at the same time maintenance costs are

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[1] Hydropower : renewable energy technologies: cost analysis seriesThe International Renewable Energy Agency (IRENA). 2012

[2] http://www.afdb.org/en/blogs/afdb-championing-inclusive-growth-across-africa/post/the-high-cost-of-electricity-generation-in-africa-11496/

lower. The more sustainable management scenarios are able to generate a positive net return, while the unsustainable scenarios generate a negative benefit. Under non-sustainable forestry intensification, net annual loss will increase compared to current by 11 million US$. However, a combination of scenario 2 and scenario 4 (forestry roads) leads to a net annual benefit of 18 million US$/year, compared to the current reference.

As indicated before, results presented here are based on a first-order benefit-cost analysis. If more local specific data are available these can be included relatively easily in the WEAP model to update the analysis. The absolute values will change to a certain extent, but the relative difference will remain more or less the same, confirming that sustainable management of forests and agriculture is profitable to hydropower generation.

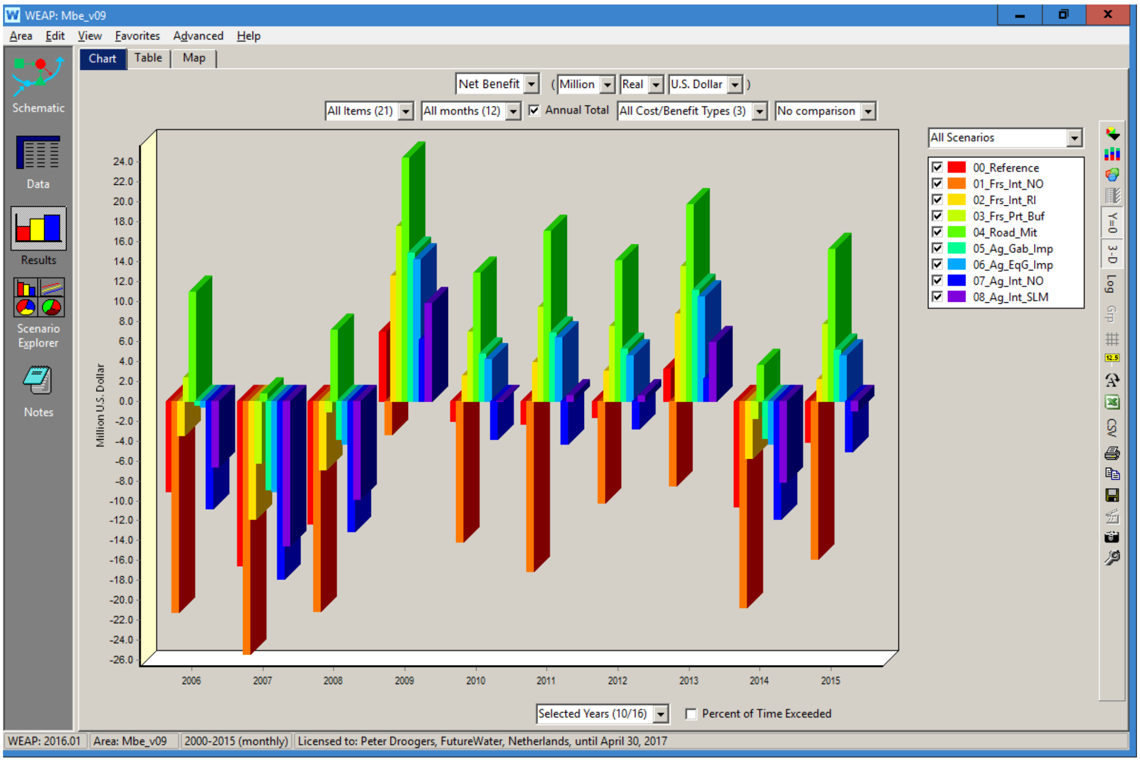

Figure 51. Net benefits in million US$ per year 2035, as simulated by WEAP. Negative values indicate costs are higher than profits.

Table 9. Annual net benefit for all scenarios

Scenario	**Net benefit (million US$/year)**	**Net benefit (billion FCFA/year)***
00_Reference	-5	-3
01_Frs_Int_NO	-16	-9
02_Frs_Int_RI	0	0
03_Frs_Prt_Buf	6	3
04_Road_Mit	13	8
05_Ag_Gab_Imp	3	2
06_Ag_EqG_Imp	3	2
07_Ag_Int_NO	-6	-4
08_Ag_Int_SLM	-2	-1

*1 US$ = 600 FCFA

3.5 Cost-effectiveness of scenarios

To assess where improved land management activities are most cost-effective in reducing erosion, the previously presented results were combined. The outcomes used for this analysis were:

- Erosion reductions for each spatial unit
- Benefits for hydropower
- First-order cost-estimates per unit area of the activities

For this analysis, a Benefit-Cost Ratio (BCR) was used to assess the effectiveness across the watershed. The equation is:

BCR = Benefits / Costs

Benefits refer in this case to the net benefits to hydropower (previous section), and do not include other benefits (agricultural, forestry, livelihoods, etc), expressed in US$ per area. Costs refer to the overall costs of implementation and its maintenance, also expressed per unit area, and over a certain reference period.

The BCR was calculated for all calculation units in the watershed, and for all scenarios with positive benefits for hydropower. The benefit per unit area was calculated by:

- Calculating for each spatial calculation unit, the difference in erosion compared to the baseline (ton/ha)
- From the above, the total difference of the entire watershed compared to the baseline (tons)
- Benefit for hydropower divided by the total tons of erosion reduction: US$/ton
- From the previous follows: US$/ha for each calculation unit.

If the BCR is below 1, the costs are higher than the benefits obtained. If BCR is above 1, the measure or investment in that location can be considered cost-effective. The maps show 4 classes of the BCR. It must be noted that the costs and benefits estimates used for the cost-effectiveness maps are first approximations and can be improved afterwards easily when more precise estimates are available. However, the spatial patterns in the B/C ratio will remain similar.

The following sources are used for the cost estimates:

- Enters, T. et al. (2002). Applying Reduced Impact Logging to Advance Sustainable Forest Management. FAO, Bangkok, Thailand
- Medjibe, V.P. (2014) Reducing logging impact in Gabon. ITTO Tropical Forest Update 23/2, Yokohama, Japan
- Barrow, Christopher J. Alternative irrigation: the promise of runoff agriculture. Routledge, 2014.

The costs for sustainable forestry management, Reduced Impact Logging and buffer zone protection were based on the following assumptions:

- Costs compared to conventional logging, assumed to be 10 US$/m3 (volume of logged trees)

- Assuming that in the Mbé area, the logging intensity is 10 m3/ha
- From this follows that the annual cost per unit area = 100 US$/ha

Costs for sustainable land management for agricultural areas:

- Estimates made for contour terracing
- Assumption: 300 person-days for implementation/maintenance for 10-year period
- Annual: 30 person-days/year
- Cost person-day farmer = 10 US$/day
- Thus, the annual cost per unit area: 300 US$/ha

The scenarios 2 (sustainable forestry intensification and reduced impact logging) and 4 (road mitigation activities) were combined for this analysis. In addition, scenario 3 (buffer protection) and scenario 5 and 6 (sustainable land management for current agricultural areas in Gabon and Equatorial Guinea, respectively) were analyzed. Figure 52 shows the maps with the cost-effectiveness for these four (combination of) scenarios.

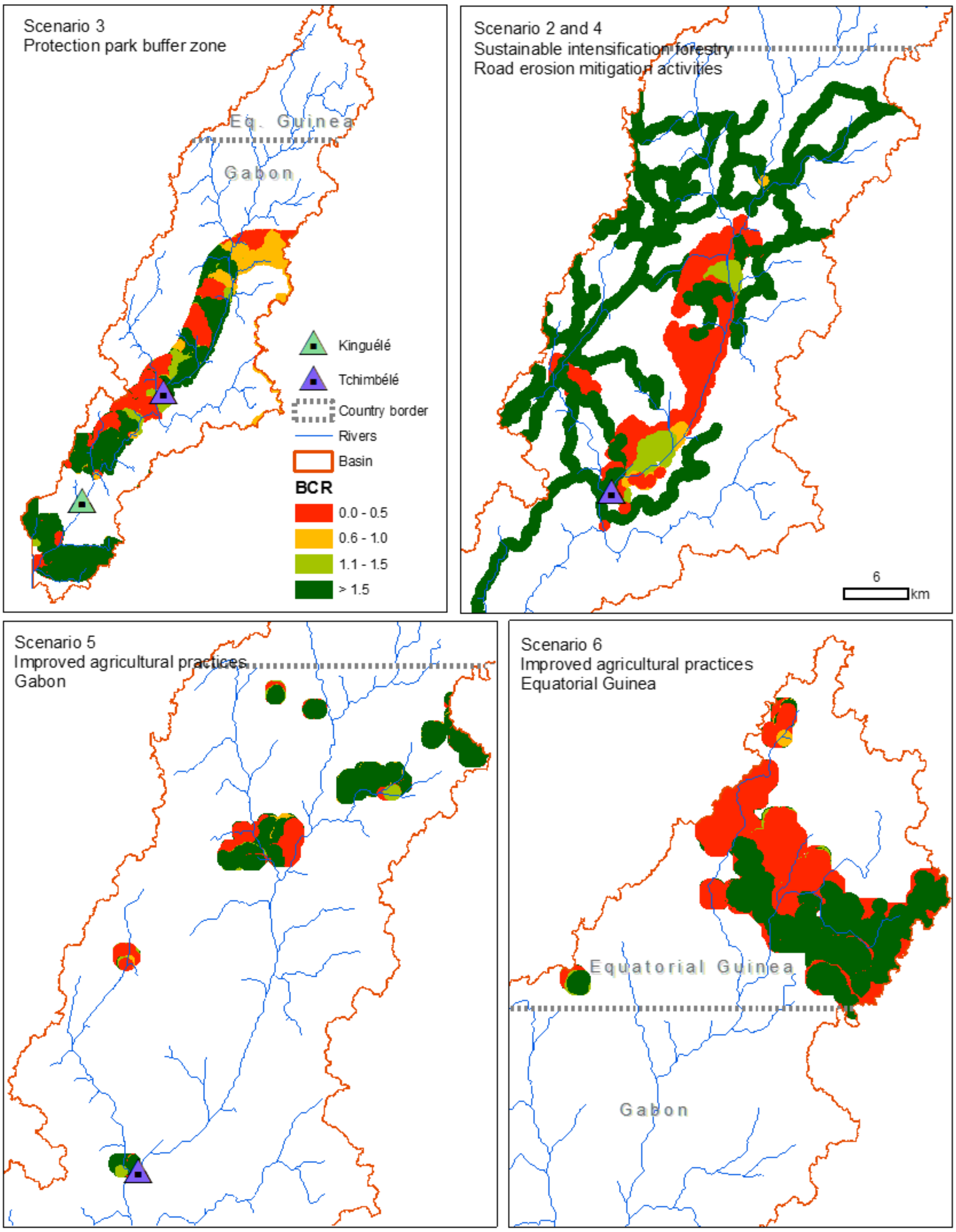

Figure 52. Maps showing the cost-effectiveness of the scenarios

Figure 52 shows that for scenario 3 (park buffer protection), the southern areas are more cost-efficient than the northern areas (due to steeper slopes in the south). Obviously, the areas downstream of Kinguélé are only of interest for new potential dams totally downstream in the watershed (e.g., Kinguélé Aval).

In the cost-effectiveness map of scenario 2 and 4 (sustainable forestry intensification and road mitigation activities) the road network (including a 1 km buffer zone) can be distinguished clearly: these are the most cost-efficient areas for implementing reduced impact logging practices and similar sustainable activities. Table 10 shows the average BCR for the different scenarios (last row). The average BCR is much higher for scenarios 2 and 4 than for scenario 3.

For scenarios 2 and 4, benefits per unit area are on average more than 20 times higher than costs per unit area, while for scenario 3 they are on average only 20% higher (average BCR = 1.2).

The two agriculture-scenarios studied show an average BCR of 2.7 for Gabon (scenario 5) and 1.4 for Equatorial Guinea (scenario 6). As the maps show, in Equatorial Guinea, most cost-efficient areas are in the southern agricultural areas. In Gabon, the pattern is mixed, but most villages where agricultural activities currently take place are cost-efficient.

Table 10. Overview of annual economic estimates for the cost-effectiveness calculation for the entire Mbé basin

Variable	No. Unit	3 Park buffer zone protection	2 + 4 Sustainable forestry and road mitigation	5 Improved agric. practices Gabon	6 Improved agric. practices Eq. Guinea
Benefits hydropower	million US$	6	13	3	3
Erosion difference with baseline	Mton/yr	-0.3	-1.1	-0.1	-0.1
Benefits per ton reduced erosion	$/ton	19	12	34	31
Costs implementation	$/ha	100	100	300	300
Average BCR	-	1.2	23.6	2.7	1.4

Overall, the analysis confirms that activities should be directed towards sustainable forestry intensification with reduced impact logging, including road erosion mitigation activities. Protection of the park buffer zone is also cost-effective in most areas. For agriculture, sustainable practices are cost-effective in most parts of the currently cultivated areas, both for Gabon as well as in Equatorial Guinea. These maps can be used to target the investments optimally and can be considered a first step towards planning interventions and activities in the watershed.

4 Conclusions

The following conclusions and recommendations can be made based on the current analysis of the Mbé watershed conditions, services and future potential:

- The Mbé watershed is currently already under pressure due to the large percentage of area that is covered by forestry concessions, including in the buffer zone around the protected area. Over the last decade, the area under concession has increased, and this will most like increase further in the future. In addition, new agricultural developments may occur in the near future within the watershed. The analysis showed that already today the dry season flows are considerably lower than under pristine conditions. It is likely that if current conditions continue, flows during the dry season will become even lower and erosion and sediment yields will increase, reducing reservoir capacity. There is a clear challenge in the watershed to turn towards more sustainable practices not only in forestry but also in agriculture in order to preserve the services the watershed currently provides, in particular for hydropower production
- To understand the current conditions and obtain insight in the different future scenarios, an analysis has been performed using a hydrological model that mimics current conditions and is able to predict how the response of the watershed (flows and sediments) will change when forestry and agriculture will be managed differently in the future. The state-of-the-art hydrological model SWAT was used for this purpose. The SWAT model has been used for many similar types of assessments and in similar areas around the world.
- The best available data was used for this analysis, in terms of land use, forestry cover, soil, flows and climate. The model was set up with data representing a period of 15 years (2000-2015).
- The model simulations indicate that under the current situation, sediment yields are considerable and may have reduced the reservoir storage capacity of the dam Tchimbele considerably since its construction. In particular, roads and the bare areas related to roads, sand mines and landing sites for forestry operations contribute most to sediment loads in the reservoir. Current agricultural practices do contribute a significant share of total sediment yield, but they are not as important as the road network principally related to forestry.
- Future scenarios of intensification of forestry operations indicate that the situation may worsen (scenario 1) but can be mitigated when recommendations for reduced impact practices are followed. Activities to reduce the sediments coming from forest roads (scenario 4) can significantly reduce reservoir sedimentation and sediment concentrations directly affecting the hydropower facilities, whereas improved agricultural management practices in Equatorial Guinea and protection of the park buffer zone are the most important for a more even generation of hydropower over the year.
- The same conclusions can be drawn based on the agricultural intensification scenarios: new agricultural development in the watershed will affect dry season flows, sediment yields and hydropower generation negatively, but these impacts can be reduced significantly if sustainable land management practices are pursued and implemented.
- Forestry intensification will have a negative impact on hydropower generation in the Mbe watershed. Year-to-year variation will increase significantly if best management practices are not followed, leading to less reliable power supply. Investments in more

sustainable forestry management can lead to higher hydropower production and reduce year-to-year variation.

- The analysis confirms that there are clear economic benefits for the horizon studied (2035) in investing in the watershed: promoting sustainable forestry practices and mitigating erosion from forestry roads. Compared to the current situation, the benefits-costs analysis (using first-order estimates that can be further improved by the stakeholders) shows that benefits can go up to 18 million US$/year. The developed hydro-economic tool WEAP will be shared with the stakeholders and a participative workshop will be organized to allow for further improvements of the economic analysis by the stakeholder.

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6 Addendum: additional scenarios

The outcomes detailed in this report were presented to local stakeholders in Libreville, Gabon, on February 8th 2017. The results were very well received by the stakeholders who are interested in using them to make the case for improved management in the basin and seeking for potential sustainable funding mechanism for conservation and hydropower production. Key stakeholders (ANPN; Gabon's national parks agency, and DGEPN, Environmental Unit within the Ministry) requested three additional scenarios to be analyzed to strengthen the case for conservation and improved basin management.

For this reason, the analysis was extended with three additional scenarios, that can be considered "worst case and best case" scenarios. These scenarios are:

- ***12_NoConsv***: No conservation activities in the basin: this scenario assumes Mont de Cristal National Park was not created in the past (2007), and the catchment continued degraded from 2007 onwards as in the previous years.
- ***13_GabonConsv***: Highest conservation status on the Gabonese side of the basin: For Gabon, all forestry concessions are declared "special interest zones for ecosystem services" and protected 100%. All agricultural areas implement best management practices. In Equatorial Guinea: business as usual.
- ***14_TransbConsv***: Highest conservation status in the whole basin, including Equatorial Guinea: Building on the previous scenario, in Equatorial Guinea (EG) a transboundary "peace park" is implemented, implying no forestry activities within the Mbé basin. Also all agricultural areas in EG implement best management practices.

For the three scenarios, a transitory phase of 20 years will be assumed, in which forest recovers (scenario 2 and 3) or degrades (1). Details of how these scenarios were implemented in the model can be found in Annex 3.

6.1 Key indicators

The three additional scenarios were analysed using the two modelling tools that were used for the previously analysed scenarios (SWAT for flows and sediments, WEAP for hydropower and economic impacts). As in the main report, a summary of the outcomes is given by means of the key indicators that were used in Table 6. The following Table 11 shows the outcomes of these three additional scenarios, in absolute values, and compares them with current conditions (first column). Table 7 provides the relative changes of these indicators compared to the current scenario.

As can be seen from the table: dry season flow is reduced by 7% on average (this can be even higher in dry years) when no conservation activities at all take place within the basin and the National Park would not exist (scenario 12). Full conservation of the basin (no forestry concessions) leads to an increase in dry season flow, by 3% and even 6% when also forestry is conserved in Equatorial Guinea (scenario 14).

Sediment yield increases substantially as is shown by this study when no conservation takes place: by around 70% in scenario 12. However, conserving the basin mean annual sediment yield by around 50%, thus improving life expectancy of the Tchimbele reservoir, and reducing dredging and maintenance costs for the Kinguele reservoir. For sediment concentration (an indicator for turbidity and damage to turbines) the relative changes are similar, which can lead to potential cost savings (see economic analysis).

Table 11. Four key indicators in absolute values and the relative changes compare to the current scenario

Scenario name	Current	NoConsv		GabonConsv		TransbConsv	
Scenario number	0	12		13		14	
Dry season flow (m3/s)	22.4	20.8	-7%	23.0	3%	23.6	6%
Mean annual sediment yield (Mton/yr)	2.1	3.4	66%	1.1	-47%	1.0	-52%
Sediment concentration in October (mg/l)	1095	1851	69%	482	-56%	324	-70%
Hydropower generation (GWh)	696	600	-14%	822	18%	832	20%

The fourth key indicator shows that on average hydropower generation is reduced by 14% in the “No Conservation” scenario 12: a considerable reduction that would lead to critical issues with power supply to Libreville. Full conservation of the basin however, could increase power supply by around 20% (scenario 13 and 14). More details of these outcomes are given in the next two sections.

6.2 Impacts on flows and sediments

A more detailed look at the biophysical (flows and sediment) impacts of the three additional scenarios is given in this section. Figure 53 shows the relative changes in average monthly flows that feed the Tchimbele reservoir, compared to current conditions.

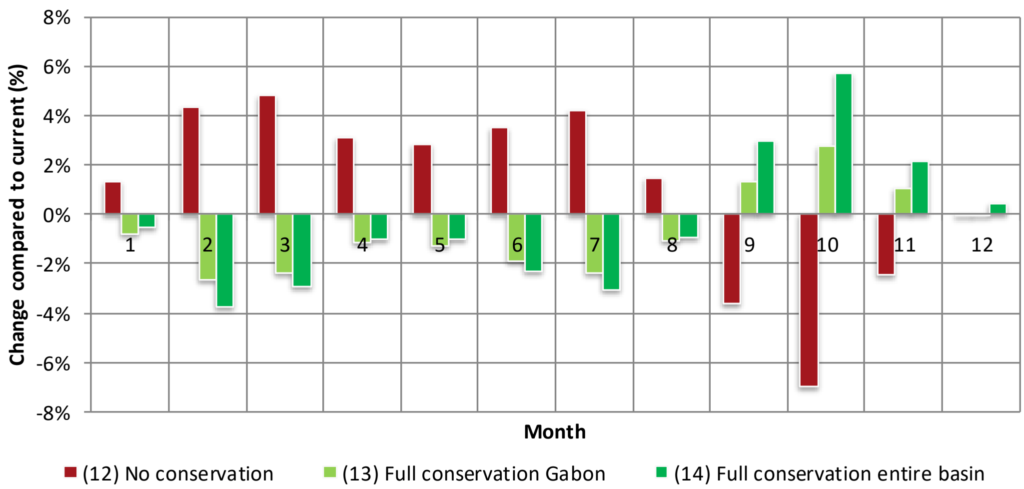

Figure 53. Changes (%) in monthly flows coming into Tchimbele reservoir, compared to the current scenario

What can be seen from Figure 53 is that with No Conservation in the basin (scenario 12), flows in the high-flow season generally increase, while for the driest month September (as was shown as key indicator in Table 11) and October and November flows decrease. Overall on the annual scale, a slight increase in flows is predicted of 1% due to reduced forest canopy and thus canopy transpiration. The opposite happens for the conservation scenarios: flows are slightly lower in most months, but a significant increase is predicted in September and October which are relevant months for hydropower generation and already reported to be critical under current conditions. Overall, annual average flow is predicted to decrease slightly by 0.5%.

Then, erosion and reservoir sedimentation was analysed for the three additional scenarios. Figure 54 shows the changes in erosion (ton/ha) compared to current conditions, showing considerable impacts (see Figure 27 for comparison with erosion in the current situation). Highest impacts can be found in the southern part of the basin where slopes are highest. But also, the areas draining to the Tchimbele reservoir can expect changes of more than 10 tons/ha/year. No conservation (scenario 12) will increase erosion rates, especially in the southern part of what is currently the Mont de Cristal National Park.

The full conservation (no forestry concessions) scenarios 13 and 14 show similar maps, with the difference of Equatorial Guinea (scenario 14). These scenarios show reductions in erosion rates of around 10 tons/ha.

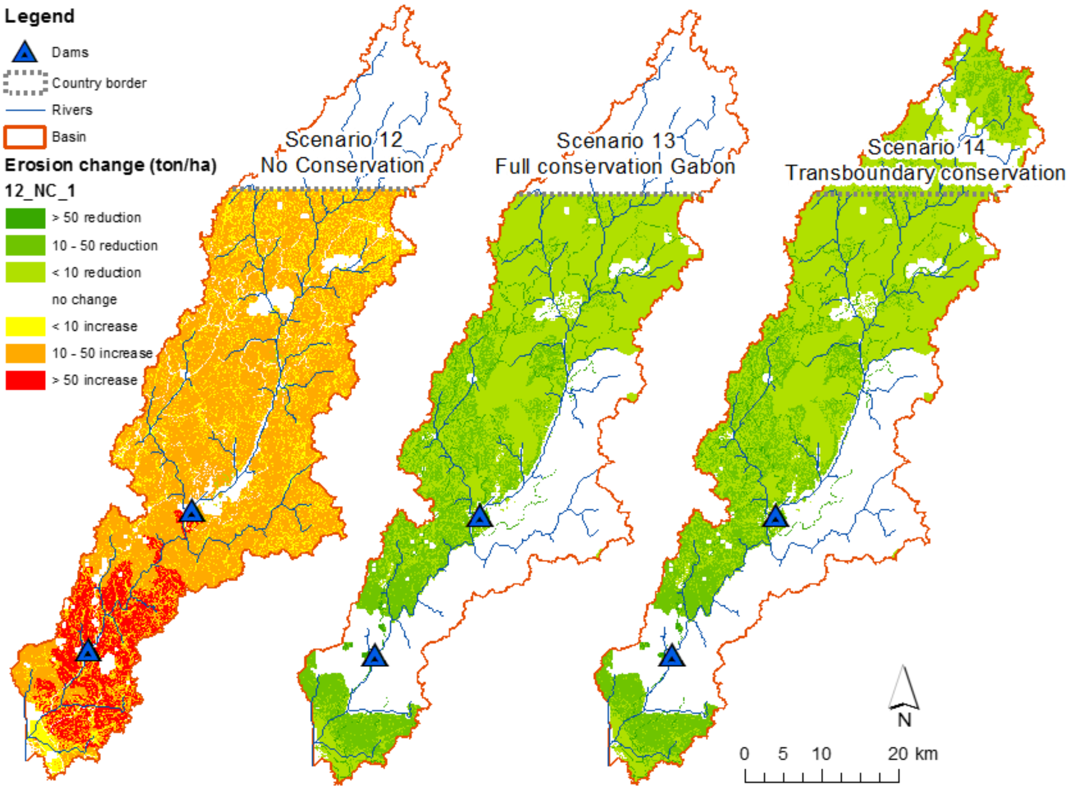

Figure 54. Changes in erosion (ton/ha) for three scenarios compared to current

The erosion reductions for the Full Conservation scenarios lead to less sediment entering the streams and thus a reduction in sediment concentrations reaching the reservoirs and hydropower facilities. This is what can be seen in Figure 55: the grey line indicates the average monthly sediment concentration of the water that flows into the Tchimbele reservoir nowadays – under current conditions. The greenish lines for these two scenarios show considerable reductions, especially for October and November when the wet-season starts and typically sediment concentrations are highest. These are also the months when the reservoir is filling up after the dry season, which means that typically water has less travel time to reach the turbines than during the wet season in March/April – thus sediment concentrations are likely to affect the turbines mostly in October/November. The reduction in sediment concentration (about half) shown in this analysis will certainly be beneficial to hydropower by reducing damage to turbines and maintenance costs.

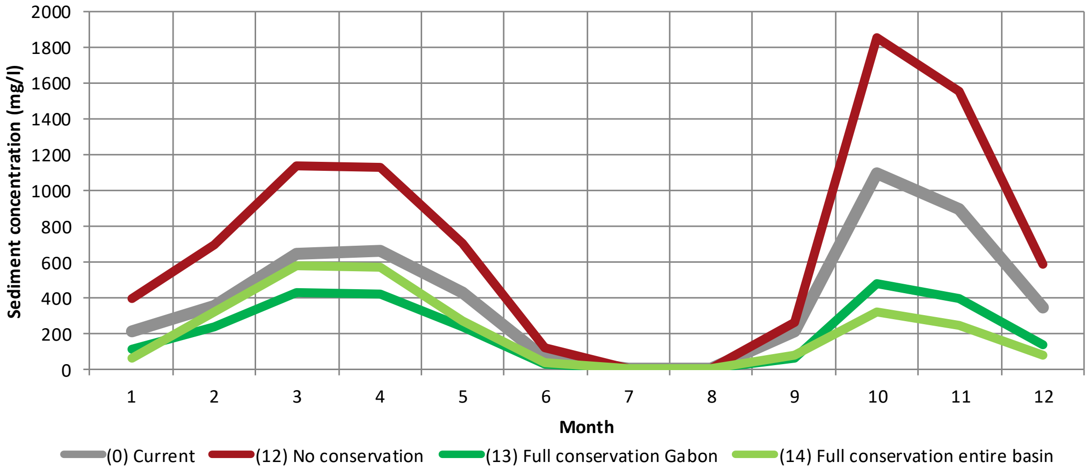

Figure 55. Monthly mean sediment concentration for Tchimbele inflow for the three scenarios compared to the current scenario

On the other hand, Figure 55 shows that No Conservation and without the presence of the Mont de Cristal National Park (scenario 12), sediment concentrations will almost double in the wet-season, potentially harming the facilities and increasing current maintenance considerably. The same effects are also seen for the water reaching the Kinguéle facility.

The reductions in erosion cause also a reduction in sediment being trapped in the reservoir, both for Tchimbéle as Kinguéle. Most relevant is the Tchimbéle reservoir, which has currently lost approximately 16% of its original design capacity (Figure 56). However, due to its large capacity this has not yet affected significantly hydropower generation but as the analysis has shown in the main body of this report this is likely to change over the next decades.

Figure 56 shows that on the medium-term (2050s) there is the potential to reduce reservoir sedimentation rates drastically if the basin is conserved 100% (scenario 13/14): the reservoir would lose around only 20 million cubic meters (MCM) for scenario 14 (around 10% of current capacity), compared to 43 MCM for business-as-usual sedimentation rates (21% of current capacity). In the worst-case scenario under no conservation (scenario 12), capacity loss would be 67 MCM – 32% of current capacity. By the end of this century impacts would be notable: under no conservation the Tchimbéle reservoir would have lost most of its original capacity due to sedimentation.

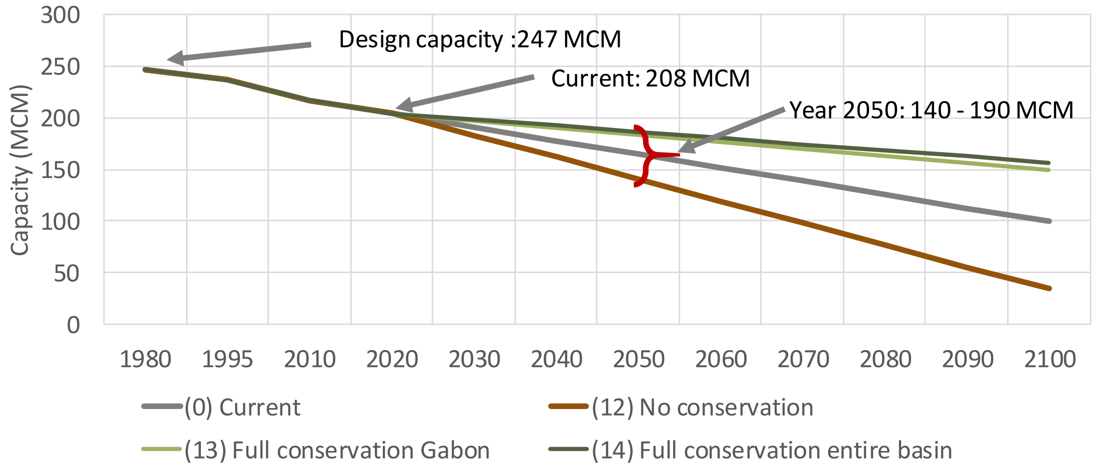

Figure 56. Reservoir capacity from original design to 2100, assuming the current sedimentation rates (grey) and the sedimentation rates of the three additional scenarios.

6.3 Impacts hydropower and economic benefits

The impacts on hydropower generation were analyzed for the three scenarios, taking into account impacts on flows and the different factors related to sediments (see section 3.3). The mean annual hydropower generation was shown previously in the key indicator table for the three scenarios (Table 11) and showed impacts of -14% for the No Conservation scenario 12 to up to +20% for the Full Conservation scenario 14. These were mean annual averages: Figure 57 shows by means of a boxplot the interannual variability in hydropower generation: the whiskers of the boxplot show the extremes (high-low) in annual production. As can be seen, from the figure, variability (distance between the whiskers) increases slightly between the Reference (current) scenario and the No Conservation scenario. But more importantly, generation capacity is reduced considerably which will be most critical in dry years: hydropower generation will be more than 100 GWh/year less than under current conditions.

For the Full Conservation scenarios (scenario 13 and 14), hydropower production will be more reliable (less variability) and as can be seen from Figure 57 hydropower generation in dry years (lower whisker) will be even slightly higher than average production in current conditions. This is even more the case for scenario 14 (conservation also on Equatorial Guinea part of basin). Comparing this figure with Figure 49 that shows the same for the other scenarios we can observe that the Full Conservation scenarios are clearly the most beneficial in terms of hydropower generation: the reductions in interannual variability and increase in capacity as in scenario 13/14 are not reached in any of the other scenarios.

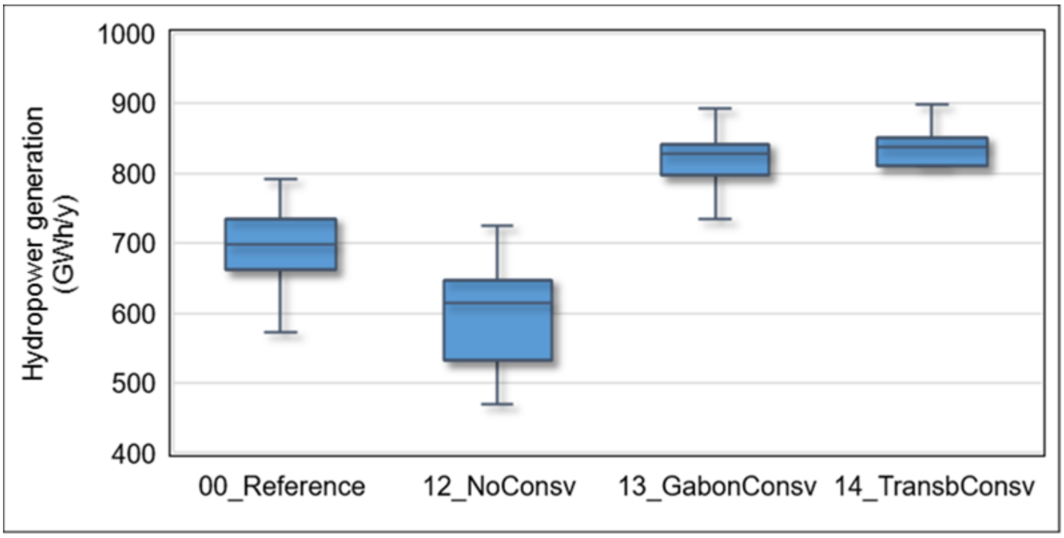

Figure 57. Projected hydropower generation for the reference and the three additional scenarios around year 2035.

Using the WEAP tool and the same procedures and assumptions as in section 3.4, the cost-benefit analysis for hydropower was carried for the three additional scenarios. The results of this are shown in Table 12. Most relevant in this table are the relative differences compared to the current (00_Reference) scenario (last column in the table). As can be seen, the No Conservation scenario would lead to a net negative benefit of -12 billion FCFA: 9 billion FCFA more than under current conditions (3 billion FCFA). However, Full Conservation of the basin could lead to a difference of 16 billion FCFA with current conditions (scenario 13) and even 18 billion FCFA if Equatorial Guinea is conserved (scenario 14).

Table 12. Annual net benefit for the reference and the three additional scenarios

Scenario	million US$/year	billion FCFA/year	Difference with 00_Reference
00_Reference	-5	-3	0
12_NoConsv	-21	-12	-9
13_GabonConsv	22	13	16
14_TransbConsv	26	15	18

*1 US$ = 600 FCFA

It can be expected that the net benefits for hydropower of full conservation in Gabon (scenario 13) or the entire basin (scenario 14) clearly outweigh costs related to the forestry concessions: tax payments received in 2007 from forestry in the entire country were reported to be 14 billion FCFA[1], and forestry sector generated a total income for the country estimated at around 50 million dollars (4% of GDP) for that year. This is generated from a total of around 10 million ha of concessions in the entire country. The total area with concessions in the Gabonese part of the Mbé basin is around 90,000 ha – a minor fraction (1%) of the total national area with concessions.

Assuming proportionality, and taking the economic income estimates of 2007 as representative for current conditions, this means that:

[1] Mvondo, S.A. "Gabon: current situation with verifcation and forest control activities. County Case Study." (2008). https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/4462.pdf

- Tax revenues from the Gabon forestry area in Mbe are around 140 million FCFA and income generated is 0.5 million US$ (300 FCFA)[1]
- For the 13_GabonConsv scenario net benefits are 13 billion FCFA which leads to a BCR (Benefit-Cost Ratio) of 43.

The above results and the high Benefit-Cost ratio is clear evidence that intensifying conservation efforts in the Mbé basin pays back: loss in income from forestry concessions is compensated fully by benefits to hydropower generation; in fact economic benefits are much higher than costs incurred by reducing forestry concessions. Please note that this analysis has not included other benefits that are difficult to quantify like environmental (biodiversity, carbon sequestration, etc) ones and socio-economic benefits.

6.4 Final remarks on the additional scenarios

The scenarios studied here give quantitative insight in the services the basin would provide in most optimal (Full Conservation) and worst (No Conservation) conditions. The difference compared to current conditions was assessed by means of the four key indicators, the different hydrological variables of interest were analyzed and an economic analysis was conducted.

Overall, this additional analysis has made even more evident that forestry management in the Mbé basin has considerable impacts on the main economic service the basin provides: hydropower generation. The complex inter-related factors influencing hydropower generation (flow regime, turbidity, sedimentation rates, reservoir capacity, etc) can on one hand lead to considerable loss in hydropower generation capacity if the Mont de Cristal National Park would not have been created, but on the other hand there is clearly a huge scope to enhance this ecosystem service by conserving the basin and increase the reliability and total hydropower generation, benefiting the many people in Gabon that rely on this renewable energy supply.

The analysis further shows that if a cross-border park was established with Equatorial Guinea, and forest is maintained or recovered, with no expansion of the current footprint of agricultural activities, and implementing best management practices, there is a potential benefit for the hydropower production in the basin – low flows in the dry season can be increased leading to about 20% higher production than the current scenario, and about 2% higher than if forest is conserved 100% only on the Gabonese side. Production reliability will increase which will be especially relevant during drought years.

The above outcomes may be of even more relevance in case climate change will reduce rainfall and increase evapotranspiration rates leading to less water availability for hydropower generation. Also, benefits of Full Conservation can be expected to be even higher if new hydropower facilities are to be built in the Mbé basin.

Based on this study, the following recommendations can be done for further study on the ecosystem services in the Mbé basin:
- Climate change impact analysis using the developed modeling tools
- Selection of monitoring indicators using outcomes of this study

[1] Mvondo, S.A. “Gabon: current situation with verifcation and forest control activities. County Case Study." (2008). https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/4462.pdf

- Using the developed tools, build an operational seasonal forecasting system of reservoir inflows (several months ahead) to be able optimize reservoir operations and generating efficiency.
- Bathymetric survey of the Tchimbéle reservoir
- Feasibility study for new hydropower facility locations in basin taking into account future scenario options.

Annex 1: Model comparison

A brief comparison of following models:

- RIOS (Resource Investment Optimization System) http://www.naturalcapitalproject.org/software/
- SWAT (Soil and Water Assessment Tool) http://swat.tamu.edu/
- INVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) http://www.naturalcapitalproject.org/software/
- WEAP (Water Evaluation and Planning) http://www.weap21.org/

Component	Model property	RIOS	SWAT	INVEST	WEAP
Model	Focus on land use and management	Yes	Yes	No	No
	Focus on downstream services and demands	No	No	Yes	Yes
	Free and public domain	Yes	Yes	Yes	Yes*
	Physically-based (high/low)	Low	High	Low	Low
	Spatial detail	High	High	Low	Low
	Timestep	None (static: only average conditions)	Daily	Annual	Monthly
Inputs	Key input datasets	Elevation, land use, soil, climate statistics, socio-economic	Elevation, climate data (>= 10 years), land use, soil, measured flows if available	Biophysical datasets (annual), Reservoir properties, hydropower valuation, annual demands	Reservoir operations and properties, hydropower valuation, demands (urban, industrial, agric.)
	Possibility for satellite-based data inputs (climate, land use, …)	Limited	High	Limited	Limited
	Possibility to compare with measurements (flows, sediments)	No	Yes	Yes (annual)	Yes
	Stakeholder input	Yes	Yes	Yes	Yes
Outputs	Effectiveness of measure portfolios	Qualitative (relative)	Quantitative (absolute)	Quantitative (annual)	Quantitative (absolute)
	Flows	No	Yes	Yes (annual)	Yes (monthly)
	Sediments	No	Yes	Yes (annual)	Limited
	Impacts of	No	Yes	Yes	Yes

	interventions				
	Reservoir storage dynamics	No	Limited	No	Yes
	Hydropower output	No	No	Yes (annual)	Yes (monthly)
Applications	Targeting interventions	Yes	Yes	Yes	Yes
	Impact assessments land use change	No	Yes	Yes	Yes
	Impact assessments climate change	No	Yes	No	Yes
	Water resources simulation	No	No	No	Yes
	Hydropower operation studies	No	No	No	Yes
Users	User-group	Small	Large	Medium	Medium
	Teaching modules	Limited	Many	Limited	Many
	Meeting needs water resources planners	Limited	High	Limited	High
	Languages	English only	English only	English only	French, Spanish, English, etc.

* for developing countries

Annex 2: Model calibration

Model calibration was carried out using the SWAT-CUP tool. This tool allows uncertain model parameters to be systematically changed, run model iteratively over the different parameter combinations, and extract the required outputs (corresponding to measured data) from the model output files.

The tool has an interface that provides a link between the input/output of a calibration program and the model. There are several calibration methods available (SUFI2, PSO, GLUE, ParaSol, and MCMC procedures). The most developed method in the tool is SUFI2 procedure, see for more details Abbaspour et al.,(2004, 2007). It has been applied to a wide range of applications world-wide (Abbaspour et al., 2015; Rouholahnejad et al., 2014).

In the SUFI2 calibration method, the goodness of fit and the degree to which the calibrated model accounts for the uncertainties are assessed by two measures. The P-factor is the percentage of observed data enveloped by the 95% prediction uncertainty. The R-factor is the thickness of the 95% prediction uncertainty envelop.

Theoretically, the value for P-factor ranges between 0 and 100%, while that of R-factor ranges between 0 and infinity. A P-factor of 1 and R-factor of zero is a simulation that exactly corresponds to measured data. The degree to which we are away from these numbers can be used to judge the strength of our calibration. It is important to note that a larger P-factor can be achieved at the expense of a larger R-factor. For P-factor, a value of >70% for discharge is suggested, while having R-factor of around 1.

Further goodness of fit can be quantified by the R2 and/or Nash-Sutcliff (NS) coefficient between the observations and the final “best” simulation. It should be noted that we do not seek the “best simulation” as in such a stochastic procedure the “best solution” is actually the final parameter ranges. For a description of SUFI-2 see the SWAT-CUP manual.

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \overline{Q}_m)(Q_{s,i} - \overline{Q}_s)\right]^2}{\sum_i (Q_{m,i} - \overline{Q}_m)^2 \sum_i (Q_{s,i} - \overline{Q}_s)^2}$$

Coefficient of determination R_2 where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, i is the i_{th} measured or simulated data

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \overline{Q}_m)^2}$$

Nash-Sutcliffe (1970), where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, respectively, and the bar stands for average.

$$PBIAS = 100 * \frac{\sum_{i=1}^{n} (Q_m - Q_s)_i}{\sum_{i=1}^{n} Q_{m,i}}$$

PBIAS, where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, respectively. Percent bias measures the average tendency of the simulated data to be larger or smaller than the observations. The optimum value is zero, where low magnitude values indicate better simulations. Positive values indicate model underestimation and negative values indicate model over estimation.

$$RSR = \frac{\sqrt{\sum_{i=1}^{n} (Q_m - Q_s)_i^2}}{\sqrt{\sum_{i=1}^{n} (Q_{m,i} - \overline{Q}_m)^2}}$$

Ratio of the root mean square error to the standard deviation of measured data where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, respectively. RSR standardizes the RMSE using the observation standard deviation. RSR is quite similar to Chi in 4. It varies from 0 to large positive values. The lower the RSR the better the model fit (Moriasi et al., 2007).

Annex 3: Scenario parameterization

Baseline parameterization using forest cover

The Hansen dataset (Hansen et al., 2013) allows extracting for each calculation unit (Hydrological Response Unit, HRU – in this model in total more than 1000) with forest cover, the current forest density (%). This was done by:

- Extract zonal mean of HRU from Tree canopy cover for year 2000 (treecover2000) - **A**
- Extract zonal mean of HRU from Global forest cover loss 2000–2014 (loss) - **B**
- Then current cover is derived by C = A * (1 – B)

Then each HRU is parameterized according to the current forest cover (%). This was done by adding new land covers to the SWAT database. This was done by scaling the crop parameters between:

- No (0%) cover. The existing BARR (Barren) class and corresponding parameters were taken as representative for 0% cover.
- Full (100%) cover. The existing FRST (Forest-mixed) class and parameters were taken as representative for 100% cover.

The following table shows a selection of the corresponding parameters:

Table 13. Most relevant crop parameters for Hansen-based newly added landcovers to SWAT crop database

ICNUM	*CPNM*	*CROPNAME*	*BIO_E*	*BLAI*	*CN2A*	*USLE_C*	*GW_DELAY*
201	HA00	Forest Density 00	0	0	77	0.20	10
202	HA10	Forest Density 10	2	1	73	0.18	30
203	HA30	Forest Density 30	5	2	64	0.14	70
204	HA50	Forest Density 50	8	3	55	0.10	110
205	HA70	Forest Density 70	11	4	47	0.05	150
206	HA75	Forest Density 75	12	4	45	0.04	160
207	HA80	Forest Density 80	13	4	42	0.03	170
208	HA85	Forest Density 85	13	4	40	0.02	180
209	HA90	Forest Density 90	14	5	38	0.01	190
210	HA95	Forest Density 95	15	5	36	0.00	200

Parameterization of future scenarios

Each of the scenarios applies to a certain area or zone. These areas were classified as different land-uses, as can be seen in the following figure and table. The crop parameters for these land use classes were taken from existing classes in the database, or based on Hansen as described above.

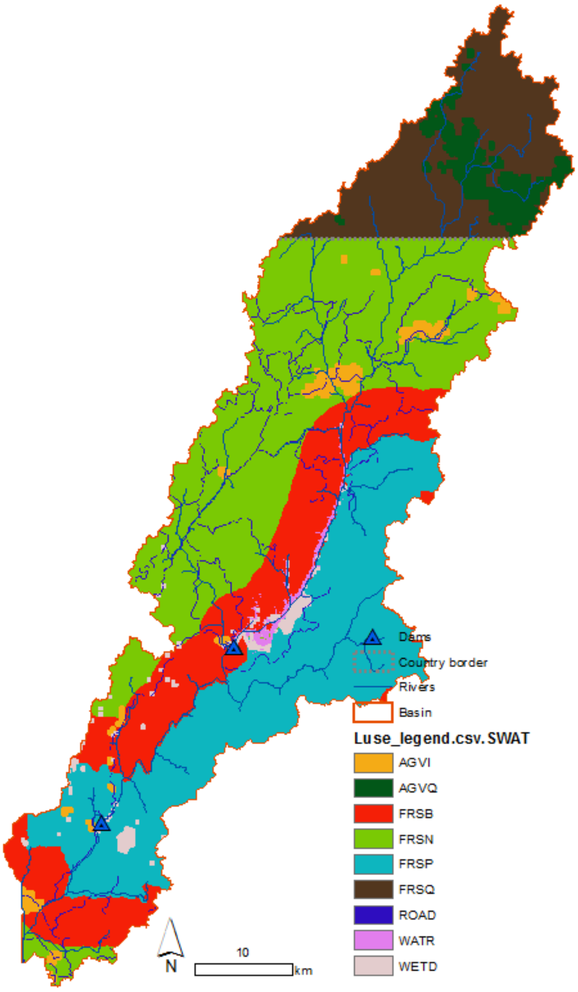

Figure 58. Map with landuses that were established in order to be able to assign each scenario to a certain landuse type.

Table 14. Land uses classes with the source of the corresponding crop parameters

Description	***Class name***	***Crop parameters***
Roads	**ROAD**	Barren (BARR)
Water bodies	**WATR**	Water (WATR)
Wetlands	**WETD**	Hansen, see above
Villages and agriculture	**AGVI**	Corn
Villages and agriculture in Eq. Guinea	**AGVQ**	Corn
Forest in protected area	**FRSP**	Hansen, see above
Forest in buffer zone	**FRSB**	Hansen, see above
Forest in non-protected area	**FRSN**	Hansen, see above
Forest in Eq. Guinea	**FRSQ**	Hansen, see above

The following table shows:

- _OP – what type of operation is carried out with the parameter: substitute/add/multiply
- _PERM – what is the permutation value used for the operation
- ID – the new plant_ID (ICNUM in Table 13)
- CN – the CN2 runoff curve number

- GWD – the GW_DELAY parameter (travel time to groundwater, assumed to be a function of landcover)

Table 15. Future scenario parameterization: land use classes and parameter permutations

SCENARIO	*LUSE*	*ID_OP*	*ID_PERM*	*CN_OP*	*CN_PERM*	*GWD_OP*	*GWD_PERM*
0_Hist (pristine)	ALL	substitute	210	add	-15	multiply	1.5
0_Current							
1_Frs_Int_NO	"FRSN", "FRSB"	substitute	205	add	11	multiply	0.6
2_Frs_Int_RI	"FRSN", "FRSB"	substitute	208	add	4	multiply	0.9
3_Frs_Prt_Buf	"FRSB"	substitute	210	add	-8	multiply	1.5
4_Road_Mit	"ROAD"	substitute	203	add	-15	multiply	1.5
5_Ag_Gab_Imp	"AGVI"	substitute	71	add	-10	multiply	1.5
6_Ag_EqG_Imp	"AGVQ"	substitute	71	add	-10	multiply	1.5
7_Ag_Int_NO	"FRSN"	substitute	206	add	12	multiply	0.6
8_Ag_Int_SLM	"FRSN"	substitute	207	add	-10	multiply	0.8
12_NoConsv	FRSP, FRSN, FRSB	substitute	205	add	11	multiply	0.6
13_GabonConsv	"AGVI", ROAD"	substitute	71	add	-10	multiply	1.5
	"FRSN", "FRSB"	substitute	210	add	-15	multiply	1.5
14_TransbCons	AGVI, AGVQ, ROAD	substitute	71	add	-10	multiply	1.5
	FRSN, FRSB, FRSQ	substitute	210	add	-15	multiply	1.5

Explanatory notes:

0 Current – current scenario, no changes
1 Forestry intensification poorly managed - assumes non-protected forest, including buffer zone, will have an effective canopy closure of 70%
2 Forestry intensification well managed - - assumes non-protected forest, including buffer zone, will have an effective canopy closure of 85%
3 Protection park buffer zone – buffer zone will have minimum 95% canopy closure
4 Road mitigation activities – unpaved roads and connected landing sites, etc., will see an increase in canopy cover, up to a total of 30%
5 Improved practices current small-scale scale agriculture – agricultural activities but with increased permanent soil cover leading to lower crop erodibility factor. Crop and hydrological parameters for a typical tropical crop with good soil cover (sweet potato).
6 Improved agricultural practices in Equatorial Guinea. Same as above
7 Large scale agricultural intensification - poorly managed. The assumption is that 10% of the non-protected area (excluding buffer zone) is converted to agriculture, leading to a decrease in forest cover (75%)

8 Large scale agricultural intensification - well managed. The assumption is that soil cover is maintained as current but with hydrological parameters leading to more runoff and less infiltration.

12 No Conservation: as scenario 1 but including the Park

13 Full conservation Gabon: parameterized as a combination of scenario 4, 5 and the pristine scenario for the forest within Gabon

14 Full conservation entire basin: parameterized as a combination of scenario 4, 5 and the pristine scenario for all forest covers

Scenario parameters in WEAP

Total flows:
Daily flows resulting from the SWAT model were used in WEAP using the ReadFromFile command. For each scenario and each sub catchment different files were used in combination with the HEADFLOW command.

Flow patterns:
Same as total flows. The account for the monthly timestep in WEAP a KeyAssumption was introduced called FlowFrac\Y2035. This factors was used to multiply all Headflows in WEAP. The FlowFrac was assumed to be linear with the mean annual sediment rate and varied between 0.9 and 1.1 (with corresponding 1.95 and 0.97 MCM/y). The derived linear relationship is: FlowFrac = 1.3 + -0.2*SedRate[MCM/y]. This was implemented WEAP using the equation:
Key Assumptions\FlowFrac\Y2035 = 1.3-0.2*Key\MeanSediment

Cooling water:
Access to cooling water has been related to the total water in the reservoir. It was assumed that if TBL reservoir level is below 50 MCM the Plant Factor would decrease linear to a factor of 0.5 if reservoir would be at zero level. Equation used is:
PlanFactor = 90 * Min(0.5 + 0.01*PrevTSValue(Storage Volume[m^3])/1e6, 1)

Reservoir capacity:
Reservoir capacity was multiplied by a factor derived from the 20 years of sedimentation. This factor was included in WEAP using the equation:
KeyAssumptions\ReservoirStoreFrac\Y2035 = 1- (Key\MeanSediment*3 / ((247-42)+0.45))

Wear on turbines:
This factor was included in WEAP by reducing the Maximum Turbine Flow as function of mean annual sediment load. The MaxTurbFlowFrac was assumed to be linear with the mean annual sediment rate and varied between 0.9 and 1 (with corresponding 1.95 and 0.97 MCM/y). The derived linear relationship is:
KeyAssumptions\MaxTurbFlowFrac\Y2035 = 1.1-0.1*Key\MeanSediment

Hydropower calculations and conversions

The theoretically power available from falling water can be expressed as (*http://www.engineeringtoolbox.com/hydropower-d_1359.html*)

$P_{th} = \rho\, q\, g\, h$
where
P_{th} = power theoretically available (W)
ρ = density (kg/m3) (~ 1000 kg/m3 for water)
q = water flow (m3/s)
g = acceleration of gravity (9.81 m/s2)

h = falling height, head (m)