Effectiveness of Improved Watershed and Forestry Activities to secure Hydropower, Komo river, Gabon

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1 Relevance

Gabon is a rapidly developing country that contains many intact natural areas and biodiversity hotspots, and a substantial amount of untapped natural resource stocks, placing the country at the forefront of green economic development opportunities. Development plans and studies typically focus on biodiversity and carbon emissions across large geographies (e.g., countries, provinces), overlooking opportunities that arise from ecosystem services around water security in particular river basins. These Hydrologic Ecosystem Services (HES) are essential to include into development projects taking place in the country[1].

In 2016 and 2017 such a HES analysis was carried out for the Mbé basin in Northern Gabon. The study presented a set of scenarios demonstrating that improved land management activities in the watershed and controlled forestry activities in the Mbé basin can contribute to improved and more reliable water availability and therefore more sustainable hydropower opportunities.

The Komo basin (located east of Mbé basin) faces similar challenges identical to the ones identified in the Mbé basin. In the Komo basin, the Ngoulmendjim hydropower facility is going to be constructed over the coming years. This facility will have a capacity of 83 MW and a reservoir volume of 327 million m^3. According to the Social and Environmental Impact Assessment (SEIA) an area of 248 km^2 will be impacted. Moreover, a large diversion of the river section of the Komo will be channeled through the small creek Petite Tsibilé. The flow through the original Komo will be reduced by 83 to 100% over a length of 52 km, while flows in the Petite Tsibilé will increase by 2.5 up to 30 times the natural flow, depending on the location and season, over a section of 34 km.

The current study will evaluate, based on the HES approach, to what extent water resource management can improve and sustain hydrological flow conditions and hydropower options. The analysis will provide results on inter-sectoral linkages in the river basin and support the government in implementing an integrated water resources management (IWRM) approach.

In summary, the objective of this project is to provide an analysis of how hydrological ecosystem services provision in the Komo basin can be improved by a series of potential alternative scenarios based on hydrological modeling.

The authors would like to acknowledge the financial support from TNC and the fruitful discussions with staff from TNC and the Ministry of Water and Forest. Especially Mrs. Marie-Claire Paiz, Mr. Jean Churley Manfoumbi, and Mr. Jean-Hervé Mve Beh has helped with their stimulating interactions.

[1] Spatial planning for a green economy: National-level hydrologic ecosystem services priority areas for Gabon. PloS-ONE 2017.

2 Komo River Basin[1]

The Komo River Basin is located in Northern Gabon and Southern Equatorial Guinea. Gabon is located in equatorial Central Africa and covers a land surface of about 268,000 km^2. The country is 85% forested. For decades, Gabon's economy has been driven by oil exports, yet revenue from this primary source is declining. Manganese and timber are the other major exports in the natural resource-rich country. The relatively low population and the economically valuable natural resource exports, the country's gross domestic product per capita has is relatively high at US$ 14,747. This wealth, however, is not evenly distributed as an estimated one-third of the population is affected by poverty.

A recent study[2] looking at Hydrologic Ecosystem Services (HES) across the country identified the Komo basin as one of the highest priority areas (Figure *1*). The study concluded that in these priority areas, effective policy frameworks and planning processes will be key to proactively protect HES, reduce actual conflicts with development, and mitigate impacts that do occur. The study recommended that such a mitigation hierarchy should focus on avoiding, mitigating, and offsetting or compensating for impacts.

The study also emphasized that HES priority areas can add to an understanding of where development should be avoided to minimize impacts, and where mitigation offsets can be directed to maximize benefits and reduce offset costs. The study concluded that the HES priority areas that were identified for the country are at a spatial resolution that should be interpreted as a general indication of areas of importance, and could be used to inform broad-scale national development plans. They should not, however, be considered as strict avoidance areas for specific development projects. Finally, the study emphasized that within the identified priority areas, finer-scale analyses are necessary to identify site-specific avoidance areas that have the most critical watershed features warranting strict protection, as well as where development activities are most compatible. The current study on the Komo basin contributes to the needs of such a detailed analysis.

The larger Komo Basin includes various streams including the Mbé and the Komo. The larger Komo Basin is the third largest Gabonese river. It is born in Equatorial Guinea, but the largest part of its watershed is in Gabonese territory. Its main course covers an area of approximately 3,200 km^2. The river eventually drains into the Gabon Esturay close the capital Libreville. Only the lower reaches of the Komo are navigable all year round: from Kango to Libreville.

This particular study will focus on the Komo Basin and River down to the confluence of the Mbé and Upper Komo Rivers.

The western part of the Komo Basin The Monts de Cristal National Park, which is a state-owned estate, covers a total area of 120,000 ha, divided into two sectors known as Séni (in the north-west) and Mbé (in the south-east, concerned by the project). It is home to some of

[1] This section summarizes various sources. Detailed information can be found in the Environmental Assessment Study for the Ngoulmendjim hydropower project.
[2] Goldstein, J.H., Tallis, H., Cole, A., Schill, S., Martin, E., Heiner, M., Paiz, M.C., Aldous, A., Apse, C., Nickel, B., 2017. Spatial planning for a green economy: National-level hydrologic ecosystem services priority areas for Gabon. PLoS One 12, 1–21. https://doi.org/10.1371/journal.pone.0179008

the richest dense rainforests in Africa with a large number of plant and animal species, and endemic fauna of the mountainous regions of Lower Guinea. The park also contains a very great diversity of arthropods (spiders and related species, insects: butterflies, beetles, etc.), including also a significant proportion of endemic or very rare species.

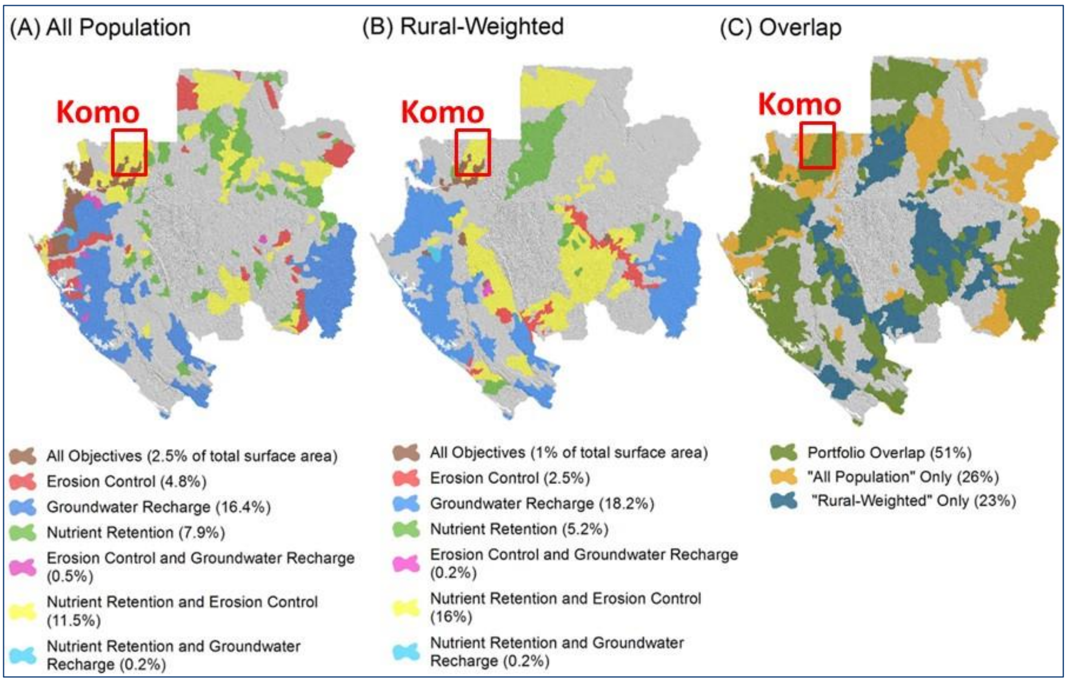

Figure 1. Hydrologic ecosystem services priority areas. Source: ***Spatial planning for a green economy: National-level hydrologic ecosystem services priority areas for Gabon. Goldstein, Heiner, Tallis, Cole, Schill, Martin, Paiz, Aldous, Apse, and Nickel. PloS-ONE 2017*****.**

Figure 2. Location of the Komo Catchment in Central Africa on the border of Gabon and Equatorial Guinea.

Figure 3. Main rivers in Gabon with the Komo River in the north-western part of the country.
Source: https://en.wikipedia.org/wiki/Ogoou%C3%A9_River

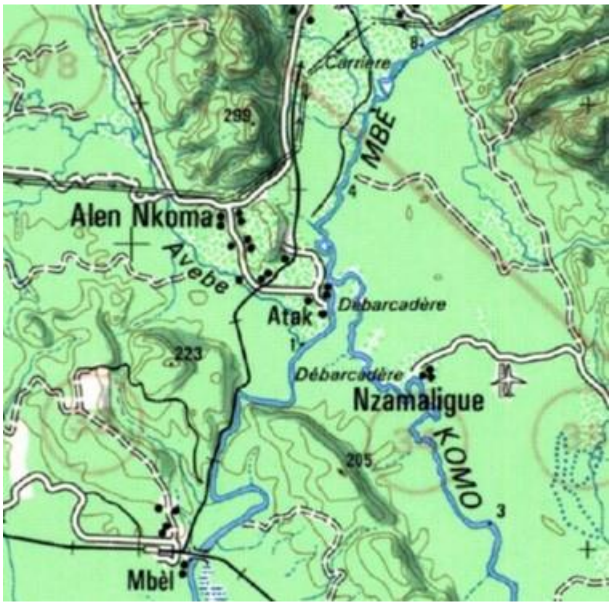

Figure 4. Confluence of the Mbé and Komo Rivers.
Source: https://afdb.org/sites/default/files/documents/environmental-and-social-assessments/eies_pges_kinguele_aval_rev2v6.pdf

Figure 5. Detail of the confluence of the Mbé and Komo Rivers.
Source: https://www.bing.com/maps

3 Methodology and Data

3.1 Analytical approach

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.

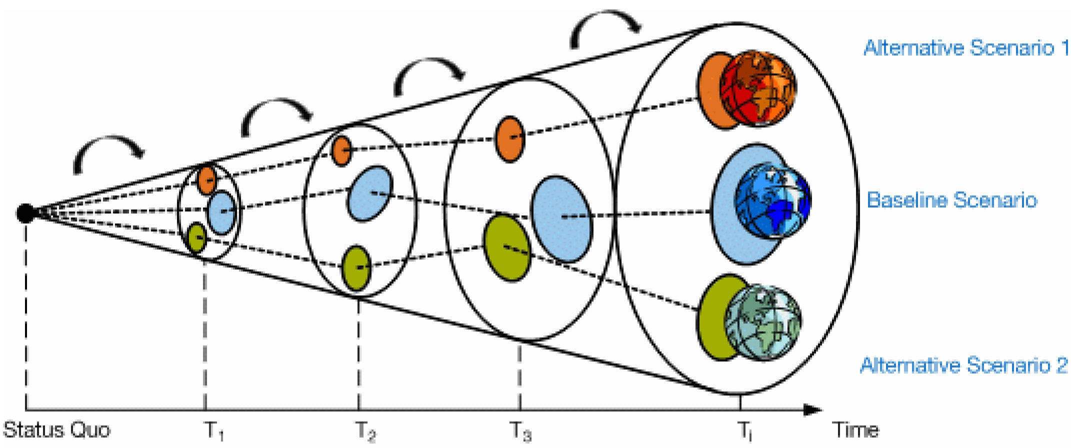

Figure 6. Scenario analysis as a tool to assess the expected impact of future changes, developments and interventions in the watershed

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.

3.2 Modeling Approaches

To evaluate the potential for sustainable watershed activities to support Hydrologic Ecosystem Services (HES) in the Komo Basin and its services downstream, the following modeling approach is applied:

- Watershed simulation under current conditions and management;
- Watershed simulation including the Ngoulmendjim hydropower facility;
- Watershed simulation with a range of alternative scenarios ("future options").

An appropriate model commonly used to analyze options for HES is the WEAP model (Water Evaluation And Planning System). 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 various hydrological modules for calculating the rainfall-runoff processes, including studying the impact of land use and management changes. Recently the WEAP model has included a module to evaluate erosion and sediment transport in streams.

A detailed discussion on WEAP can be found in the WEAP manual, available for from 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.
- 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.

[1] www.weap21.org

- 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.

3.3 Future scenarios

The overall aim of the study is to explore a set of scenarios that might happen in the future. Based on various discussions with stakeholders and lessons learnt from the previous Mbé Basins study the following scenarios were defined:

- **Business as Usual**: Ngoulmendjim will be developed including all associated activities (roads, power lines, migration to the area leading to human activities), but no mitigation actions will be taken
- **Classical mitigation actions**: actions are implemented to comply with environmental protection regulations, as described in the ESIA for Ngoulmendjim
- **Hydrological Ecosystem Services (HES)**: a holistic approach that covers a portfolio of improved catchment activities, leading to a sustainable catchment management strategy
- **Smaller reservoir**: Ngoulmendjim reservoir capacity will be 50% (163 MCM) compared to the original design.

3.4 Overview and Data

3.4.1 Land use and land cover

Land cover maps represent spatial information on different types (classes) of physical coverage of the Earth's surface, e.g. forests, grasslands, croplands, lakes, wetlands. Development in landcover data products has accelerated over the last years. For the previous Mbé study (2017) the so called Globcover data were used. GlobCover was a European Space Agency (ESA) initiative which aimed to develop a service capable of delivering global composites and land cover maps using as input observations from the 300m MERIS sensor on board the ENVISAT satellite mission. Images from December 2004 to June 2006 were used. Resolution is 300 meters and a total of 22 land cover classes were distinguished. GlobCover has been one of the most widely used land cover data over the last decade.

Recently, the ESA has started the Copernicus program. Copernicus is the European Union's Earth observation program, “looking at our planet and its environment to benefit all European citizens”. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data.

The latest and most up-to-date data is the Copernicus Global Land Service (CGLS)[1,2]. Originally the land cover map was based on the vegetation instrument on board of PROBA satellite (PROBA-V). Recently the Sentinel-2 satellite data has been used to derive the latest maps. CGLS has a resolution of 100 meters and is updated on an annual base and distinguishes 23 landcover classes [3].

It is known that in dense vegetated areas classification of roads and urban areas is difficult and prone to mis objects. Therefore, maps of roads and settlements from open street map (OSM) has been added to this satellite derived landcover map. Those OSM maps are point and line maps and an influence area has been added, using a buffer around roads and settlements of 50 meter and 1000 meter. The final land cover map for the Komo basin is shown in Figure 7[4].

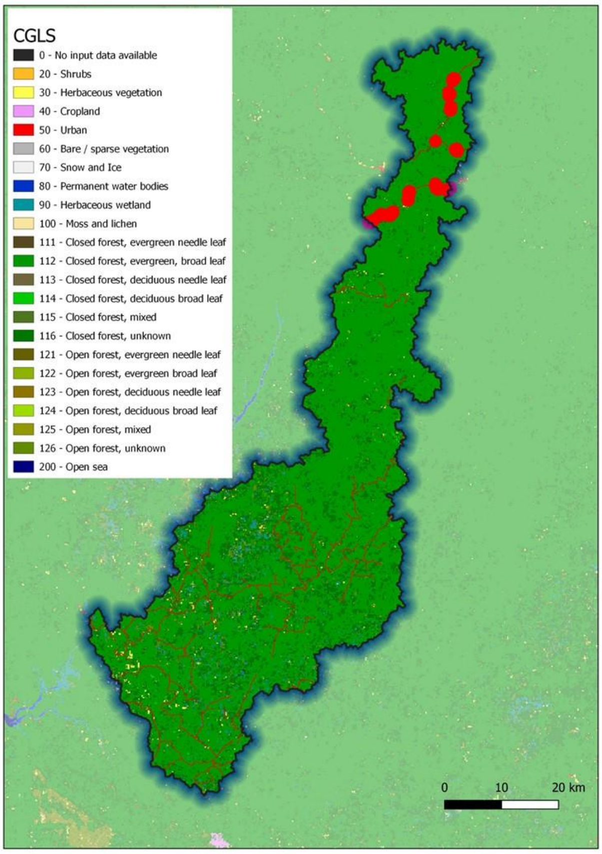

Figure 7. Landcover map for Komo basin based on the Copernicus Global Land Service dataset. Roads and settlement were added from open street map (OSM).

Based on this reclassification and aggregation the land classes used in the analysis are presented in Table 1 and Figure 8. Closed forest is the dominant land cover with nearly 75%

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[1] https://land.copernicus.eu/global/products/lc

[2] Buchhorn, M.; Smets, B.; Bertels, L.; De Roo, B.; Lesiv, M.; Tsendbazar, N.E., Linlin, L., Tarko, A.(2020): Copernicus Global Land Service: Land Cover 100m: Version 3 Globe 2015-2019: ProductUser Manual; Zenodo, Geneve, Switzerland, September 2020; doi: 10.5281/zenodo.3938963.

[3] Note that Copernicus has a comparable data set called the C3S global Land Cover (CCI-LC). This has a resolution of 300 meters.

[4] Note that maps are shown at full size in the Appendix

of the area, followed by a class referred to as "closed forest, unknown" with 17%. Urban area and roads including their influence area cover 4,5% of the catchment. Those classes were aggregated. For the modeling analysis using WEAP classes with small areas were added to the nearest ones with a more extended area. Also, the land use class "Closed forest, unknown" was assumed to be same as "Closed forest, evergreen, broad leaf". Similar, the class "Closed forest, deciduous broad leaf" is most likely not correct classified and was added to "Closed forest, evergreen, broad leaf". Finally five classes were defined to include in the WEAP model Table 2.

Table 1. Landcover for Komo basin as percentage based on the Copernicus Global Land Service dataset. Roads and settlement were added from open street map (OSM).

Land Use	%
Shrubs	0.0%
Herbaceous vegetation	0.5%
Cropland	0.0%
Urban/roads	4.3%
Herbaceous wetland	1.3%
Closed forest, evergreen, broad leaf	74.0%
Closed forest, deciduous broad leaf	0.5%
Closed forest, unknown	17.4%
Open forest, evergreen broad leaf	0.0%
Open forest, unknown	1.9%

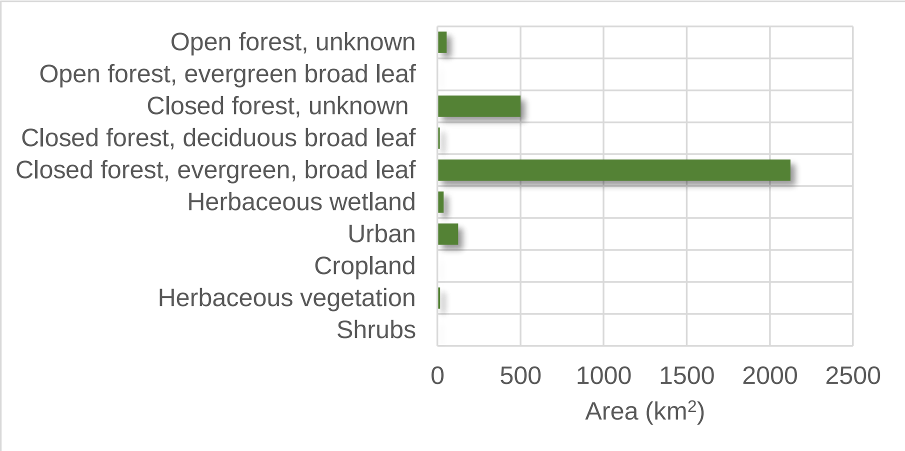


Figure 8. Landcover for Komo basin based on the Copernicus Global Land Service dataset. Roads and settlement were added from open street map (OSM).

Table 2. Landcover classes used in the WEAP analysis.

Land Use	Area(km^2)	%
Herbaceous	15	0.5%
Urban	124	4.3%
Wetland	37	1.3%
Forest Closed	2637	91.9%
Forest Open	57	2.0%

3.4.2 Elevation and slopes

Elevations in Komo Basin ranges from about 1000 MASL in the northern and western regions down to less than 100 MASL at the confluence of Komo and Mbé. Obviously, slopes are associated to elevation gradients and especially in the southern part (with the exception of the most southern part) quite steep slopes can be found. Those slopes are key in management and finding options to protect the watershed in order to preserve or improve the HES the catchment provides.

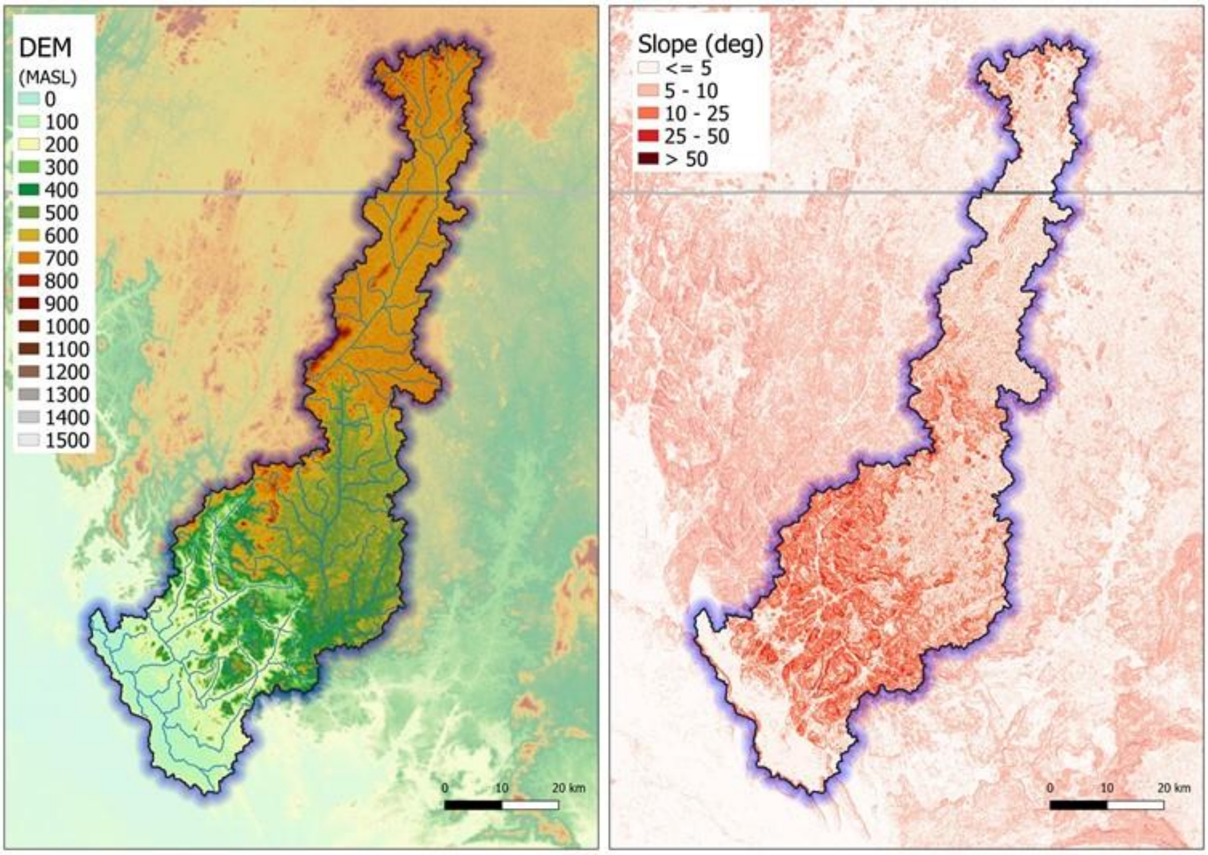


Figure 9. Elevation data (left) and slopes (right) derived from the SRTM data set.

3.4.3 Soils

Soil characteristics are important parameters to define and assess the potential HES. Soil data is scarce in the region and therefore a global data set were used. The global HiHydroSoil dataset (Boer, 2015) at 1km resolution that provides hydrological soil properties for modeling, and is based on the SoilGrids1km dataset.

From Figure 10 it is clear that soils in the basin have in general a high soil water holding capacity, although at the southern part of the basin it is somewhat modest. The saturated hydraulic conductivity of the soil, that determines the infiltration capacity, is very high and in general values between 5 and 10 cm per day can be found. In the northern part and some patches across the basin values below 5 cm per day can be found.

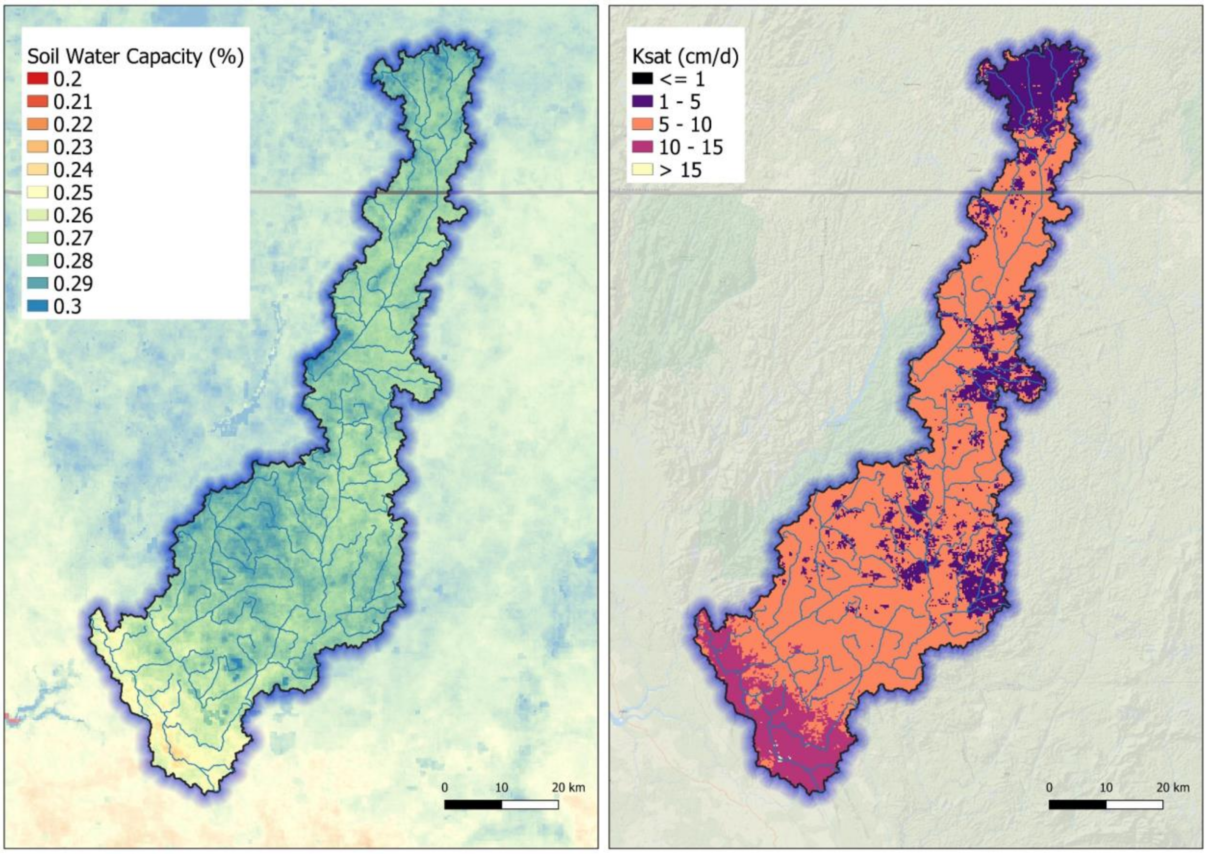


Figure 10. High-resolution soil data. Left soil water storage capacity; left the saturated hydraulic conductivity.

3.4.4 Climate data

Rain gages are missing in the Komo Basin and therefore global datasets are used to obtain precipitation and temperatures. The amount of global climate data sets is growing substantially; a nice overview is provided by [*Gleixner, S., Demissie, T., Diro, G.T., 2020. Did ERA5 improve temperature and precipitation reanalysis over East Africa? Atmosphere (Basel). 11, 1–19. https://doi.org/10.3390/atmos11090996*]. Many of those products are based on so-called reanalysis methods. Reanalysis data are produced by combining climate model estimates with observations via data assimilation, therefore providing optimized global estimates of climate data without spatial or temporal gaps.

The ERA5 reanalysis product is considered as state-of-the art and is often seen as reference to be used. It is known that the ERA5 data is consistent with all other climate variables (temperature, wind, dewpoint, etc). Recently it was found that for some regions the ERA5 precipitation amount over tropical areas has a slight positive bias and therefore a correction factor was adjusted to compensate for this[1]. Figure 11 presents as a typical example the annual precipitation for the 2019. It is clear that the Komo Basin is located in a kind of converging zone between the very wet coastal regions and the dryer inland. Variation within the basin is quite high and it is clear that by just using point data from rain gauges and applying those to bigger regions might lead to incorrect estimates. Obviously rain gauges can be very useful in bias correcting the spatial data from ERA5. It should also be emphasized here that ERA5 in its reanalysis approach local rain gauging station data are included, although it is not clear which stations and which periods are actually included in the algorithms.

Figure 12 provides an overview of the variation in precipitation between years, months and catchments.

Box: ERA5 and ERA5-Land Reanalysis Data

ERA5 is the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate and weather for the past 4 to 7 decades. Currently data is available from 1979. Reanalysis combines observations into globally complete fields using the laws of physics with the method of data assimilation (4D-Var n the case of ERA5). ERA5 provides hourly estimates for a large number of atmospheric, ocean-wave and land-surface quantities.

ERA5-Land is a reanalysis dataset at an enhanced resolution compared to ERA5. ERA5-Land has been produced by replaying the land component of the ECMWF ERA5 climate reanalysis. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. Reanalysis produces data that goes several decades back in time, providing an accurate description of the climate of the past.

Source: ECMWF

[1] A correction factor of -20% was applied based on: [*Gleixner, S., Demissie, T., Diro, G.T., 2020. Did ERA5 improve temperature and precipitation reanalysis over East Africa? Atmosphere (Basel). 11, 1–19. https://doi.org/10.3390/atmos11090996*] and [*Harrigan, S., Zsoter, E., Alfieri, L., Prudhomme, C., Salamon, P., Wetterhall, F., Barnard, C., Cloke, H., Pappenberger, F., 2020. GloFAS-ERA5 operational global river discharge reanalysis 1979-present. Earth Syst. Sci. Data 12, 2043–2060. https://doi.org/10.5194/essd-12-2043-2020*] and [*Cucchi, M., P. Weedon, G., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., Hersbach, H., Buontempo, C., 2020. WFDE5: Bias-adjusted ERA5 reanalysis data for impact studies. Earth Syst. Sci. Data 12, 2097–2120. https://doi.org/10.5194/essd-12-2097-2020*]

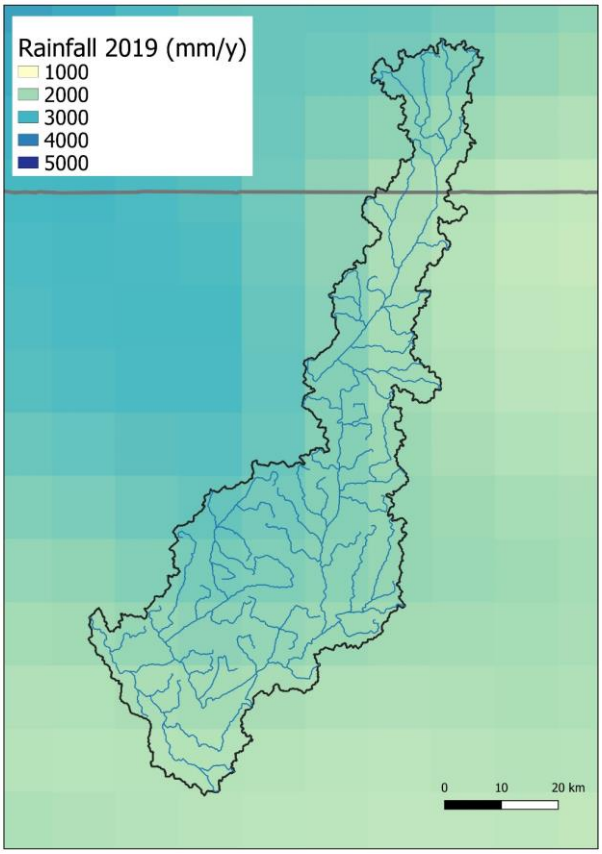


Figure 11. Example of annual precipitation for the years 2019 based on the ERA5-Land data set.

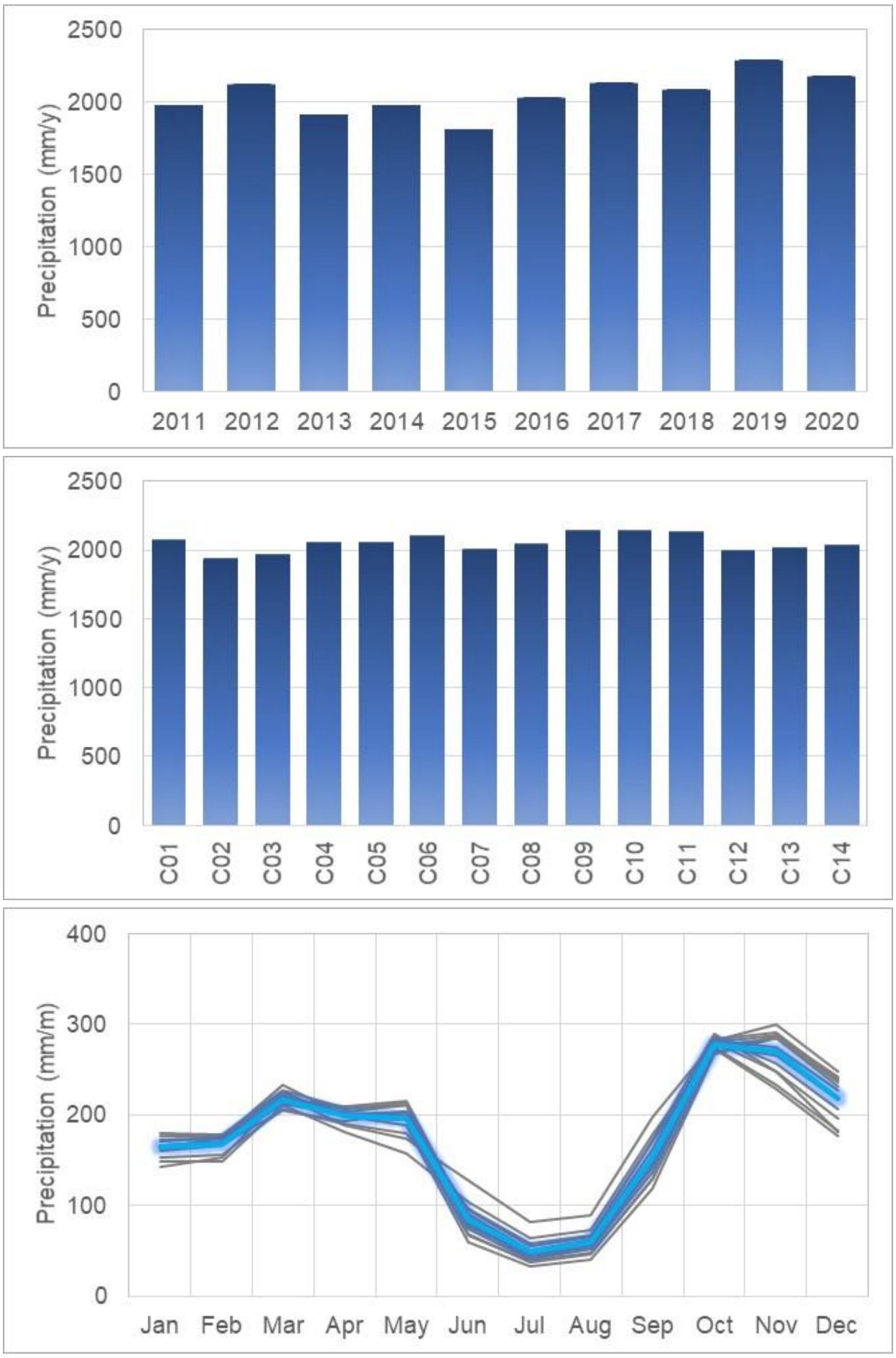


Figure 12. Summarized precipitation based on ERA5-Land for the years 2011-2020. Top: annual total averages over the entire basin; middle: 10 years average for each catchment; bottom: monthly total averaged over the ten years (grey lines the 14 catchments, blue line average over the basin).

3.4.5 Streamflow

Streamflow records are not available for the Komo Basin. This is somewhat striking as especially the analysis in the context of the Ngoulmendjim hydropower facility could benefit of such observation. However, the feasibility study includes some streamflow graphs and analysis, but those are based on some simplified rainfall-runoff "reconstructions" Figure 13. According to the Ngoulmendjim Environmental and Social Impact Assessment (ESIA) the overall runoff factor (defined as fraction of precipitation that enters into streams) is about 50% (flow is 1050 mm per year, precipitation is 2000 mm per year). Such a runoff factor of 50% seems very high for such a densely vegetated basin where much of the rainfall is converted to evapotranspiration by the vegetation. From the ESIA it is not clear where this runoff factor of 50% is derived from.

Another useful source of information regarding typical runoff conditions in the area is the Mbé basin study. For that analysis, flow data was derived from hydropower generation data. That study estimated that about 40% of the rainfall the catchment receives is converted to streamflow; the other 60% is used within the watershed by evaporation and canopy transpiration. The Mbé basin is located west of the Komo and receives slightly more rainfall. Since rainfall-runoff processes are non-linear one could expect that the runoff-fraction for the Komo is somewhat higher compared to the Mbé one given its somewhat lower rainfall.

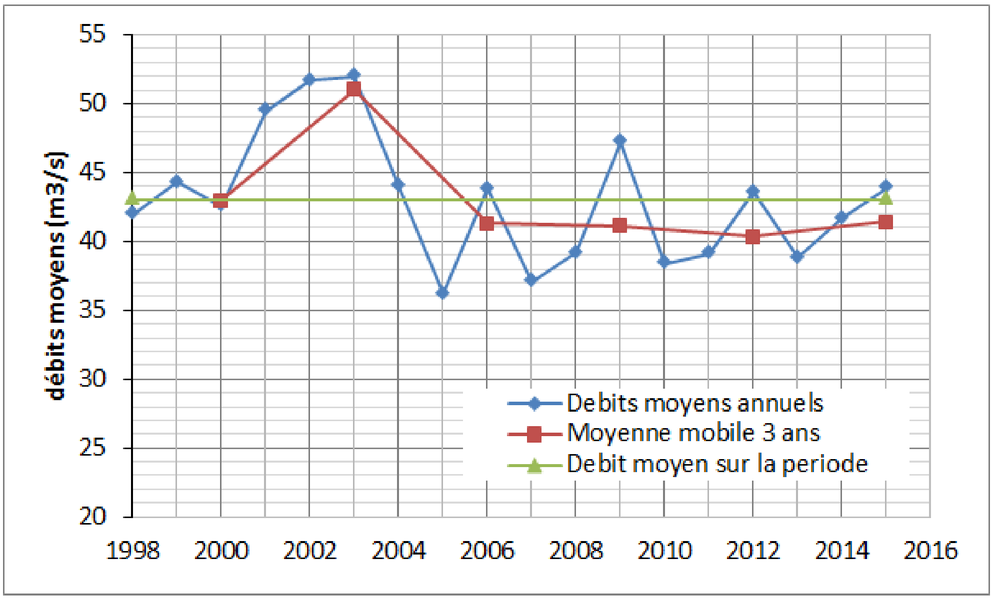


Figure 13. Annual flows at the Ngoulmendjim location. Data are based on "reconstruction". Source: Environmental Impact Assessment analysis Ngoulmendjim hydropower (2019).

3.4.6 Reservoirs and hydropower

Currently no reservoirs exist in the Komo Basin, but detailed planning, technical as well as financial, for a hydropower facility (Ngoulmendjim) are nearly completed. Below a summary of the project (mainly based on the ESIA); details can be found in the Annex. Note that the ESIA is in France and the translated text below might include some grammar issues.

General Setting

The Ngoulmendjim hydroelectric development project is being developed by a consortium composed of FGIS (Fonds Gabonais d'Investissements Stratégiques), created in 2012 to help the country to develop new projects to generate sufficient revenues to replace those from the oil sector, and of the ERANOVE group, a major player in the *management of public services and the power generation in West Africa. The ERANOVE Group provides the technical development of the project on behalf of the FGIS consortium - technical development of the project on behalf of the FGIS consortium - technical development of the project on behalf of the FGIS-ERANOVE.*

The consortium organised the creation of a project company called ASOKH ENERGIE "Master (MO), which will be responsible for the design, financing, construction and operation of the project operation and maintenance-maintenance of the Ngoulmendjim hydroelectric power plant. The ESIA is in the process of being finalized and is created by a consortium composed of ARTELIA (representative of the grouping), GEO-GUIDE, its Gabonese partner, and BIOTOPE, subcontractor in charge of aspects biodiversity.

The Ngoulmendjim project is located about 125 km east of Libreville in the Komo department of the Estuary province near the Parc national des monts de cristal secteur Mbé (PNMC), one of Gabon's 13 national parks

The Project is located in a "registered productive State forest" belonging to the permanent State forest estate currently exploited by the Société Equatoriale d'Exploitation Forestière (SEEF), through a Sustainable Development Forest Concession (CFAD).

The process of defining the study area started very early in the project and was carried out jointly for the physical, biological and human environments by the thematic experts involved. For the physical environment: the study zone's rights-of-way extend downstream including the TCC and is limited to the confluence with the Mbé (a module close to that of the Komo). The study zone also includes the Tensié river and its immediate surroundings as well as its tributaries.

For the biological environment: the project's area of influence, in addition to the project's direct rights-of-way and in particular the reservoir, is considered in a watershed logic. For the human environment: the study area includes (i) the area of the project's physical rights-of-way, (ii) the zone of direct influence in which people may be directly affected and (iii) the zone of indirect influence in which the population may feel the effects induced by the Project, such as economic and health impacts, but to a much lesser extent by being exposed to other sources of impact outside the project. The field surveys focused mainly on the zone of direct influence, where people may be directly affected by the project.

Project Justification

Gabon's electricity demand is estimated to reach 1,039 MW in 2020. To meet this demand, the Gabonese government aims to develop a sustainable, diversified and accessible electricity supply for all. This action aims to increase the current energy production capacity from 660 MW to 1,200 MW by 2020.

With this in mind, the state is determined to fully exploit Gabon's hydroelectric potential with the aim of increasing the share of hydroelectricity in the energy mix to 80% in order to meet demand at a competitive cost.

Thus, on 21 October 2016, the State of Gabon and the consortium, comprising the Gabonese Strategic Investment Fund (FGIS) and the ERANOVE group, signed two concession agreements for the design, financing, construction and operation of two hydroelectric schemes, in the form of a "Build Own Operate and Transfer" - "BOOT" type contract. These developments will be located on the sites of Ngoulmendjim, with an estimated capacity of 83 MW, and Dibwangui, with an estimated capacity of 15 MW.

The implementation of the Ngoulmendjim project, with an installed capacity of 83 MW and a seasonal regulation operation, will contribute to meet the existing demand while continuing the development of the electrification of the Estuary province. According to the Société d'Energie et d'Eau du Gabon (SEEG), the cost of a hydroelectric kWh is much lower than for the other components of the Gabonese energy mix.

The project is also an alternative renewable energy production alternative to thermal equipment (e.g. fuel oil) on the Libreville sector or interconnected network.

Ngoulmendjim is located close to tracks used by the Société Equatoriale d'Exploitation Forestière (SEEF) for logging, and will benefit from the presence of power lines from the region's hydroelectric schemes (Kinguélé, Bisségué, the future downstream Kinguélé). This makes it possible to reduce the extent of the infrastructure to be built. The additional lines can be used for possible future hydroelectric projects, and will help secure electrification in the region.

In summary, the Ngoulmendjim project will make it possible to :

- *Increase Gabon's generation capacity at the base in the region of the capital Libreville;*
- *Develop the electricity network of the Estuary province;*
- *Control the price per kWh and promote economic development;*
- *Continue Gabon's energy transition towards a renewable energy sector and thus contribute to meeting the voluntary commitments made at COP21 by Gabon with a target of reducing GHG emissions by 50% in 2025 compared to 2010 emissions.*

Storage Capacity:	*327 MCM*
Volume elevation:	*83.16 MCM →453m*
	83.16 MCM →453m
	282.83 MCM →463m
	327.35 MCM →464.5m
Net evaporation:	*2 mm/d*
Max outflow:	*45 cms*
Capacity	*83 MW*
Annual production	*~500 GWh*

Bid text

https://www.hydropower-dams.com/news/epc-contractor-sought-for-ngoulmendjim-storage-project-gabon/
EPC contractor sought for Ngoulmendjim storage project, Gabon
Hydropower & Dams October 8, 2018
France's Eranove Group, in partnership with Gabon's state investment fund, Le Fonds Gabonais d'Investissements Stratégiques (FGIS), has invited expressions of interest from qualified contractors or consortia to construct the Ngoulmendjim storage plant in the southwestern African state of Gabon.

Pre-qualification bids are sought by 31 October 2018 for the design and construction of the project to be located on the river Komo, about 125 km east of the capital Libreville in the northwestern province of Estuaire, under an engineering, procurement and construction (EPC) contract. The entire work consists of three lots and will be the subject of a single contract grouping all three lots.

- *Lot 1 covers the construction of a mixed RCC and rockfill dam with a maximum height of about 45 m with an uncontrolled spillway,*
- *Lot 2 covers the plant and hydraulic system including an external intake in one of the arms of the reservoir, an underground hydraulic system that will be approximately 3 km long and nearly 5 m in diameter, and a hydroelectric plant of nearly 80 MW comprising three units with Pelton type turbines and,*
- *Lot 3 will entail the construction of a 225 kV evacuation line approximately 100 km long, and associated substation.*

A call for tenders defining the draft contract, the terms of reference and the bid evaluation criteria, as well as instructions for applicants to submit technical and financial proposals will be launched at a later stage for shortlisted companies or groups of companies following this call for expressions of interest. Pre-qualified candidates must submit a global offer including all three lots.

3.5 Model simulation

The WEAP model has been setup using data and information as described above. The model has the following components and characteristics:

- Period: 2011-2020
- Timestep: daily
- Number of catchments: 14

- Number of Hydrological Response Units (HRUs): 150

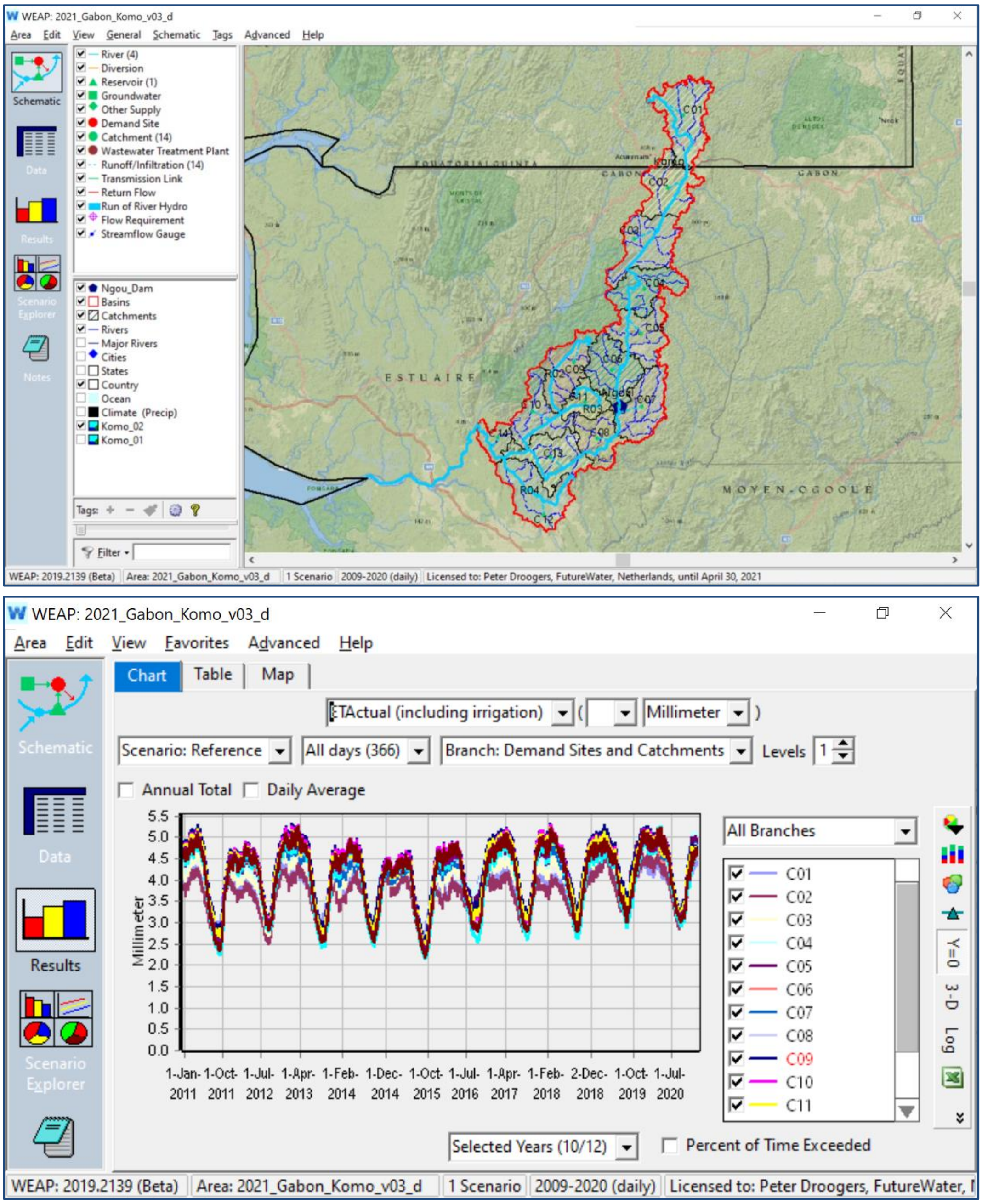


Figure 14. Screenshots of the WEAP model as setup for Komo Basin. Top: schematic view; bottom: example of output screen.

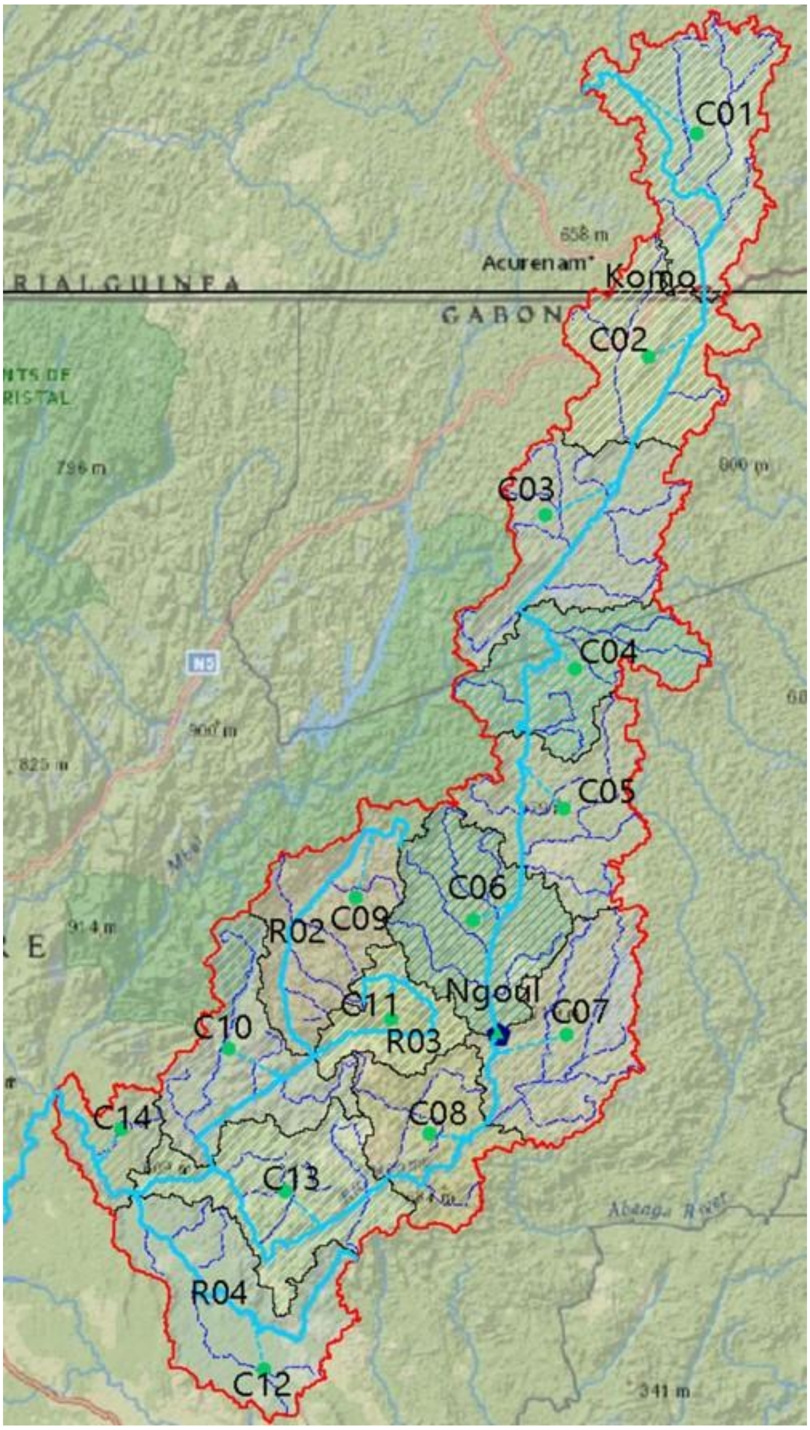


Figure 15. Schematic of the WEAP model of Komo Basin showing catchments and river network.

4 Results

4.1 Current situation (no reservoir)

Highlights:

- Forest transpiration is the largest water consumer
- Natural buffer capacity to retain water is high
- Streamflow at Ngoulmendjim is lower compared to the feasibility study
- Surface runoff, as proxy for erosion risk, is high

4.1.1 Water resources overview

The data and model as described in the previous sections provide insight in the current conditions in the Komo Basin. As a first step it is relevant to access the dynamics of the conversion of precipitation into the different hydrological components. Figure 16 and Table 3 show the annual water balance indicating that rainfall on average is about 2050 mm per year and that the majority of rainfall is used for evapotranspiration. As percentages 72% of the rainfall is converted into evapotranspiration, and the remainder (28%) ends in the streams and flows out of the Komo Basin. Of this total of 28% water yield about 4% flows as surface (fast) runoff to the streams. This erosive (surface) runoff is a trigger for erosion with resulting loss of fertile topsoil and potentially high sedimentation in the streams.

Variation between the different years is relatively low. Rainfall ranges from about 1990 mm per year up to 2180 mm per year. Variation in evapotranspiration and runoff follow more or less the same trend as the amount of rainfall.

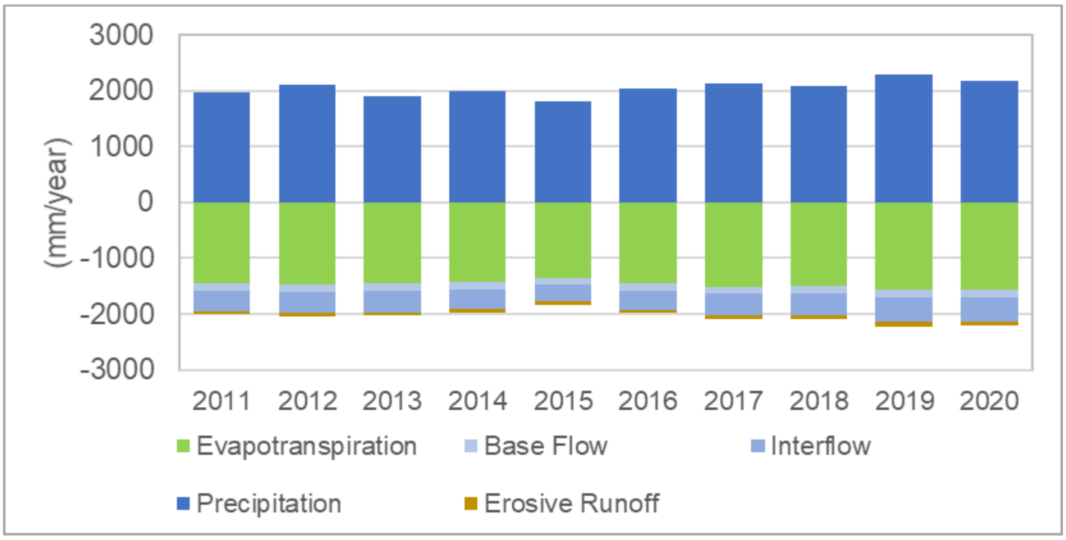


Figure 16. Annual water balance of Komo Basin.

Table 3. Ten years (2011-2020) average annual water balance of Komo Basin.

	mm/y	MCM/y	%
Precipitation	2050	5698	100%
Evapotranspiration	1475	4098	72%
Erosive runoff	64	179	3%
Slow runoff	509	1414	25%

Seasonal variation is quite substantial in the basin. Figure 17 shows the daily components of the water balance. The general picture of wet and dry periods can be clearly observed with low precipitation starting somewhere in June and lasting till September. Evapotranspiration is only partly reduced during the dry season as water stored in the soil is used during the dry months to support water demand of the vegetation. Runoff shows a more seasonal response to the rainfall and during dry years, runoff is reduced quite substantially.

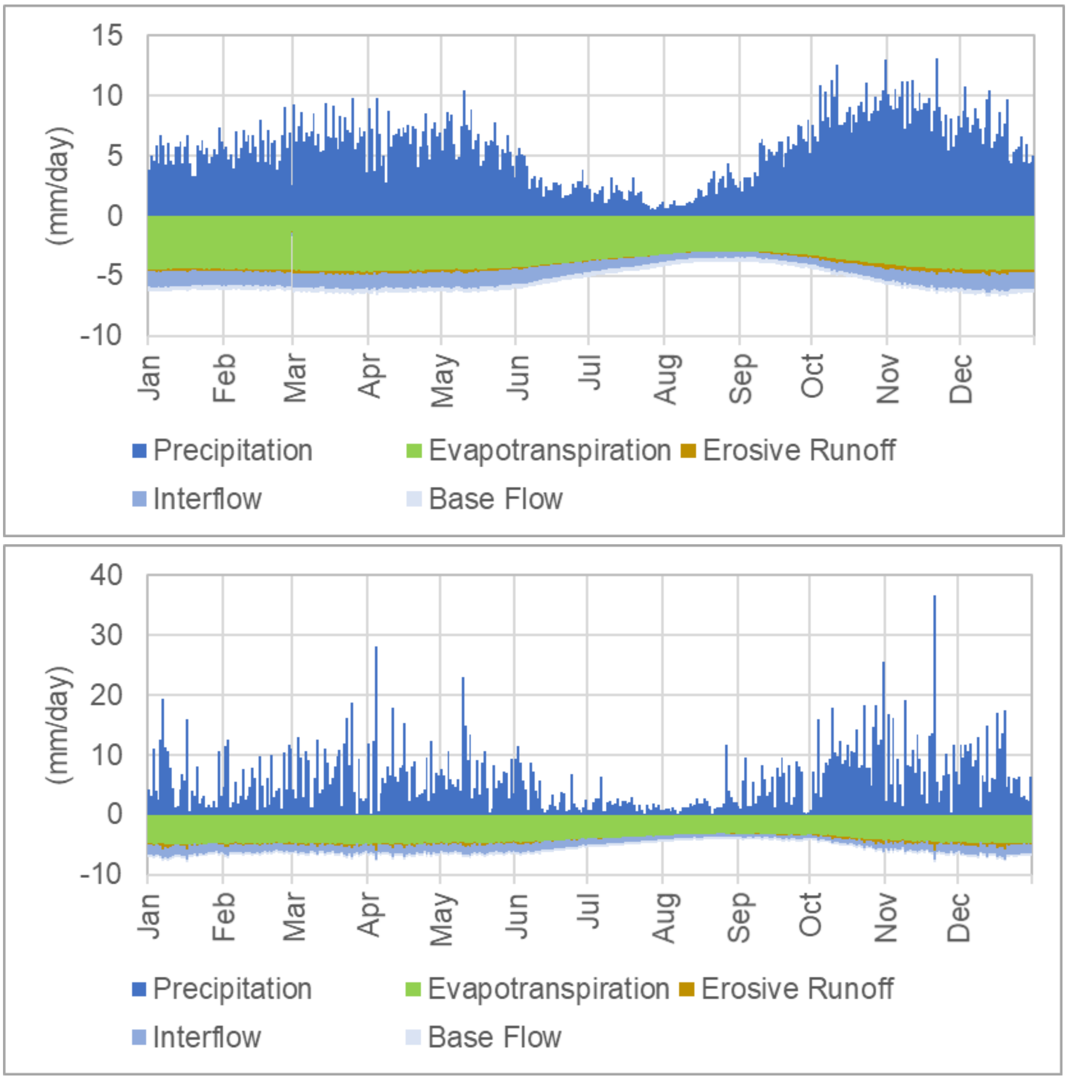


Figure 17. Daily water balances for the Komo Basin for an average year (top) and the year 2020 (bottom).

4.1.2 Streamflow

Streamflow can be obtained for each point in all the rivers and streams using the WEAP model. Here focus is put on the potential Ngoulmendjim site and outflow of the Komo River at the confluence with the Mbé River. Figure 18 and Figure 19 show the daily streamflow and the time aggregated ones respectively. Daily flow series clearly show that quite some extremes occur in the river with flows going up to over 100 $m^3 s^{-1}$ at the downstream and up to 60 $m^3 s^{-1}$ at the Ngoulmendjim site. The flow duration curve (Figure 18, bottom) indicates a flow of 22 $m^3 s^{-1}$ is exceeded 50% or time, and 20 $m^3 s^{-1}$ is exceeded 80% of time. The relatively flat flow duration curve is typical for a basin with high internal water storage and buffer capacity.

Mean annual and mean monthly flows are shown in Figure 19. It is clear that some year-to-year variation occurs. Especially during the last few years (2019-2020) flows have been somewhat higher compared to the other years. The monthly flows reflect the seasonal rainfall patterns but more buffered, e.g. difference in low-high rainfall are less visible in streamflow.

Comparing streamflow with the ones presented in the Ngoulmendjim Environmental and Social Impact Assessment (ESIA) shows some interesting differences. In general, flows reported in the ESIA are substantially higher compared to what is found in the current study. It is unclear what method has been used in the ESIA as it was reported that flows were "reconstituées" (reconstructed). The ESIA indicates that data from the Tchimbelé location on the River Mbé were used (see Box). As stated before, although the two basins are adjacent, Komo receives somewhat less rainfall compared to Mbé. Since runoff factors are non-linear applying those runoff factors from a wetter basin directly to a somewhat dryer basin will result in an over-estimation of the runoff. Moreover, landcovers of the two basins are showing some differences, with Komo a larger percentage of dense forest that transpires high amount of water compared to Mbé basin.

The current study focusses on comparing different alternatives (scenarios) and on an evaluation of the Hydrologic Ecosystem Services (HES) rather than repeating or verifying the flow estimates in the ESIA. For scenario analysis, a physically-based model like the one used in this study is needed to make sure that that relative flow differences are well presented even if there are absolute differences with measurements or flow estimates from other studies.

Box. Ngoulmendjim Feasibility Study (p. 212):

Les données exploitées sont des séries de débits moyens journaliers et mensuels, reconstituées à partir des débits naturels au droit de Tchimbelé sur la rivière Mbé, et transposées au site de Ngoulmendjim (EDF – ISL, 2018). Les débits ont ainsi été reconstitués sur la période 1998-2015. Ces séries de données ont été exploitées pour la détermination des différentes valeurs caractéristiques hydrologiques (identification des variabilités annuelles et saisonnières, détermination des apports intermédiaires par bassin versant, valeurs des débits d'étiage…).

<u>Translated (with DeepL):</u>

The data used are series of average daily and monthly flows, reconstructed from natural flows at the Tchimbelé station on the River Mbé, and transposed to the Ngoulmendjim site (EDF - ISL, 2018). The flows have thus been reconstructed over the period 1998-2015. These data series were used to determine the various hydrological characteristic values (identification of annual and seasonal variability, determination of intermediate inputs per catchment area, low water flow values, etc.).

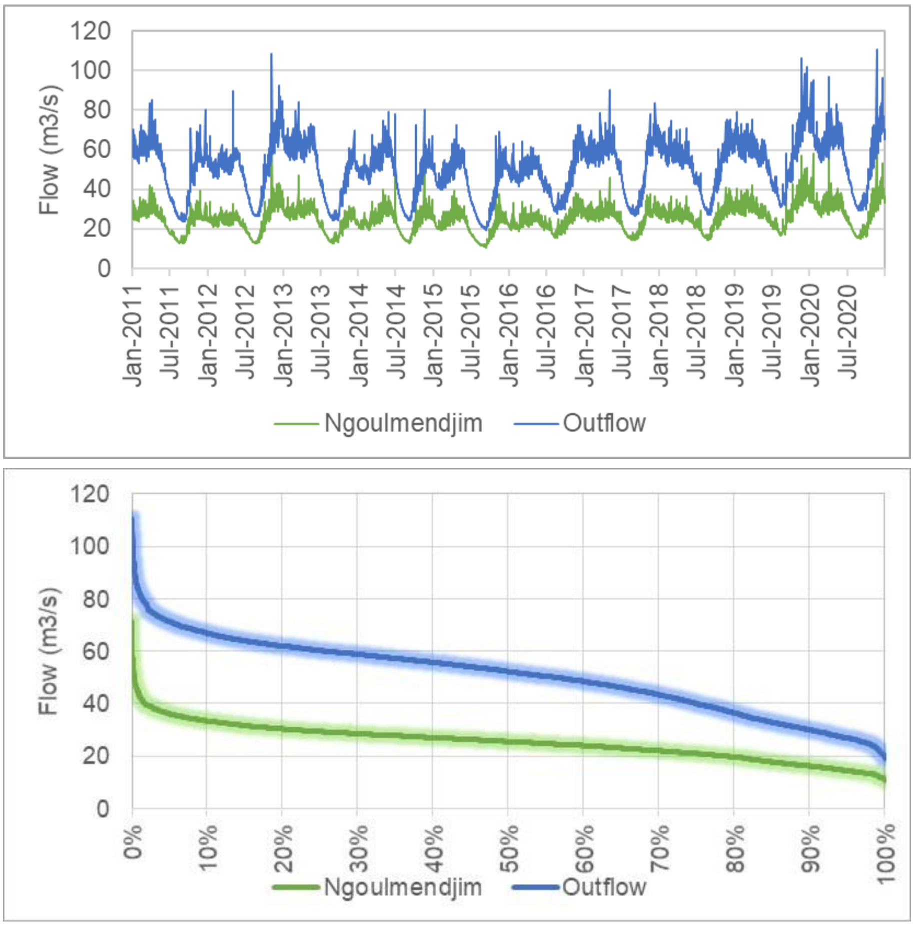


Figure 18. Streamflow at two locations in the Komo river: Ngoulmendjim site and outflow of the basin (=confluence with the Mbé River). Top: daily flows; bottom: exceedance levels (flow duration curve).

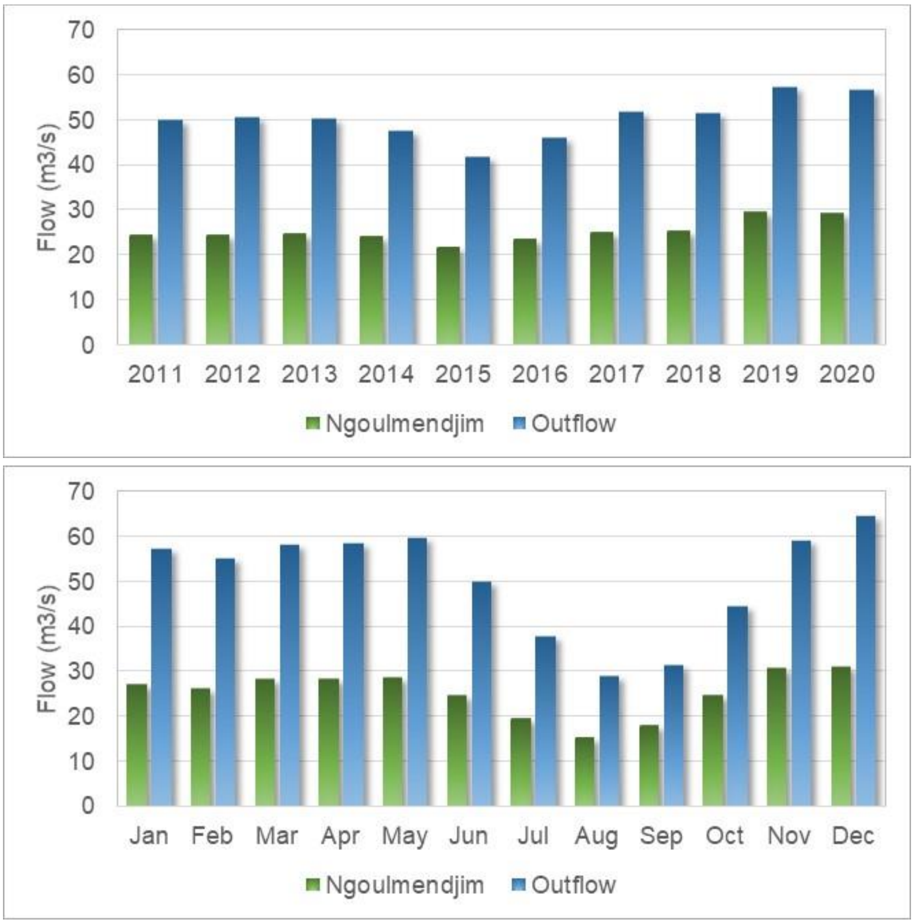


Figure 19. Streamflow at two locations in the Komo river: Ngoulmendjim and outflow of the basin (=confluence with the Mbé River). Top: mean annual; bottom: mean monthly over those 10 years.

4.1.3 Erosion and Sedimentation

Erosion and sedimentation have been evaluated by looking at the so-called "erosive runoff". This erosive runoff is synonym to surface runoff or overland flow and is the flow of water occurring on the ground surface which transports soil particles to streams and rivers. It has been reported that erosion and sedimentation is an issue in Komo Basin. Also Figure 20 and Figure 21 show clear proofs of high turbidity, so high sediment levels originating from erosion. This erosive runoff is an important factor to consider as this is precipitation that will not enter the soil and is therefore not available for vegetation and is also an important trigger for erosion. As shown above, on average about 3% of the rainfall is direct erosive runoff. However, as well reported in other studies, this erosive runoff is very much land cover-dependent. For the four dominant land covers in Komo Basin this erosive runoff is shown in Table 4 indicating that erosive runoff is on average 9 mm per year for the main land cover "closed forest". Also, erosive runoff is relatively low for the so-called "open forest" surface (51 mm per year) compared to the average annual rainfall of 2050 mm per year. For the herbaceous vegetation (including some small stretches of cropland) the analysis indicated that erosive runoff is 236 mm per year (~ 12% of the rainfall).

Erosive runoff of urban areas is large with on average 1851 mm per year. Note that those urban areas include settlements, roads and surroundings. Converting those mm per year to cubic meters provides interesting insights in this component of the water balance. Since 94% of the basin is covered with "closed forest" the total contribution of erosive runoff from this specific land cover is 25 MCM per year. The urban areas cover only 4% of the basin but their contribution to the erosive runoff is 84%. Important to note is that erosive runoff can show significant spatial variability due to characteristics, besides land cover, such as slopes and soil types.

This potential high erosion risk has various consequences. First of all, fertile soil will be lost and the risk of the well-known viscous circle might happen: erosion will lead to degraded land that will have less vegetation leading to even more erosion and degraded land. Second, river morphology can be altered with potential negative consequence for human beings and nature. Third, domestic drinking water and industrial water needs require additional sediment removal at high costs. Finally, turbines of hydropower plants will be exposed to accelerated wear and tear.

Table 4. Ten years (2011-2020) average erosive runoff for the dominant land covers.

	mm/y	MCM/y	%
Forest Closed	9	25	14%
Forest Open	51	2	1%
Herbaceous	236	1	1%
Urban	1395	147	84%

Figure 20. Sedimentation of Komo River close to Omvan Moutain. Source: Bing Maps

Figure 21. Sedimentation of Komo River. Source: Feasibility Study

4.2 Impact of Ngoulmendjim Dam

Highlights:

- Construction of Ngoulmendjim Hydropower Facility is expected to go beyond only the facility itself. Migration, settlements, economic development, forest and land degradation is quite likely.
- The impact of the dam only (unrealistic) might be manageable (see ESIA)
- The impact of the expected associated catchment degradation is substantial
- Generated hydropower is likely to be lower than the designed one

4.2.1 Relevance

The expected impact of the Ngoulmendjim Dam can be manifold. The Ngoulmendjim Environmental and Social Impact Assessment (ESIA) provides a very detailed description of all kinds of possible impacts and potential mitigation actions. The ESIA is very detailed in many small, yet important, components. However, a clear and broader overview is somewhat less developed in the ESIA. The ESIA is also very much focusing on impact on humans and nature; the changes in the overall Hydrologic Ecosystem Services (HES) are lacking.

It is important to assess the impact of the Ngoulmendjim project to a full extent including the potential impacts of the project on HES by migration, economic activities, land use exploitation, settlements, etc . In other words, one cannot assume that flows, sediment rates, erosion, etc., before and after the project will be similar. However, such an approach of ignoring the impact on HES is quite standard in project evaluations and is therefore analyzed in this study as well (further referred as scenario **[01_Ngoul_unrealistic]**)

This [01_Ngoul_unrealistic] scenario can be considered as a traditional approach: the performance and impact of a reservoir are evaluated without considering potential changes in the Hydrologic Ecosystem Services (HES) the basin delivers. Such an approach is non-realistic as such a big intervention as the Ngoulmendjim project will be accompanied by other developments in the basin, also upstream of the reservoir and definitely alter the HES. Some typical examples are: lower water availability by higher evaporation from the reservoir, more sediments in the stream by reduced vegetation cover, increased sediment load by changing land covers, higher peak flow by lower vegetated areas, increased domestic water consumption by higher population, reservoir storage loss by increased sedimentation, amongst others.

The impact of Ngoulmendjim project will be therefore also evaluated including those changes in HES. Results of this scenario should therefore be considered as more realistic compared to scenario where HES was assumed to be unaltered. The scenario including those potential HES changes is referred to as **[01_BaU]**.

The extent to what exactly those changes in HES will be in the future are difficult to assess. Those depend on policies to be put in place and control mechanisms to enforce those. In general, large scale activities in an unspoiled region will have substantial impact on the overall biophysical conditions. The following assumptions were made in this scenario [01_BaU]:

- Changes in land cover (according to the ESIA 24,812 ha will be impacted directly):
    - C[1]1-C4: no changes
    - C6: 2820 ha forest converted to open water
    - C5, C6 (around reservoir)
        - 1133 ha urban → 5 times higher
        - other landcovers reduces with this area
    - C7-C14
        - 3588 ha urban→ 5 times higher
        - other landcovers reduces with this area
- Changes in forest soils by human interventions and explorations
    - RRF -10%;
    - SWC 1000mm → 700mm;
    - Root conductivity: 5 mm/d → 4 mm/d
- Evaporation from the Ngoulmendjim reservoir
    - 2 mm/d
- Hydropower facility impacted by sedimentation
    - Plant Factor 90% → 80%
    - Max Turb Flow: 45 → 40 cms
    - Reservoir capacity -10%

The impact of the Ngoulmendjim project will be evaluated using the following indicators:

- Expected hydropower production
- Streamflow in Komo River downstream of dam (TCC[2])
- Streamflow in Petite Tsibilé
- Impact on erosion and sedimentation

[1] C refers to the catchments defined in the WEAP model.
[2] TCC Tronçon court-circuité = Short-circuited section. 56.2 km

4.2.2 Expected hydropower production

According to the ESIA the aim is to achieve a hydropower production of 500 GWh per year on average. The WEAP model has an advanced hydropower module and according to those results the expected hydropower production is closer to 350 GWh per year. This is due to a multiple number of factors including the lower expected flows compared to the ESIA and high erosion rates.

As described above, the **[01_Ngoul_unrealistic]** assumes that everything remains the same and no single development activities besides the dam construction will take place. Under this scenario the expected hydropower generation falls quite below the expected one of 500 GWh per year. The realistic projection **[01_BaU]** where the dam will lead to the expected additional impact in the region, indicates that the projected hydropower generation will be even lower and will be on average 280 GWh per year.

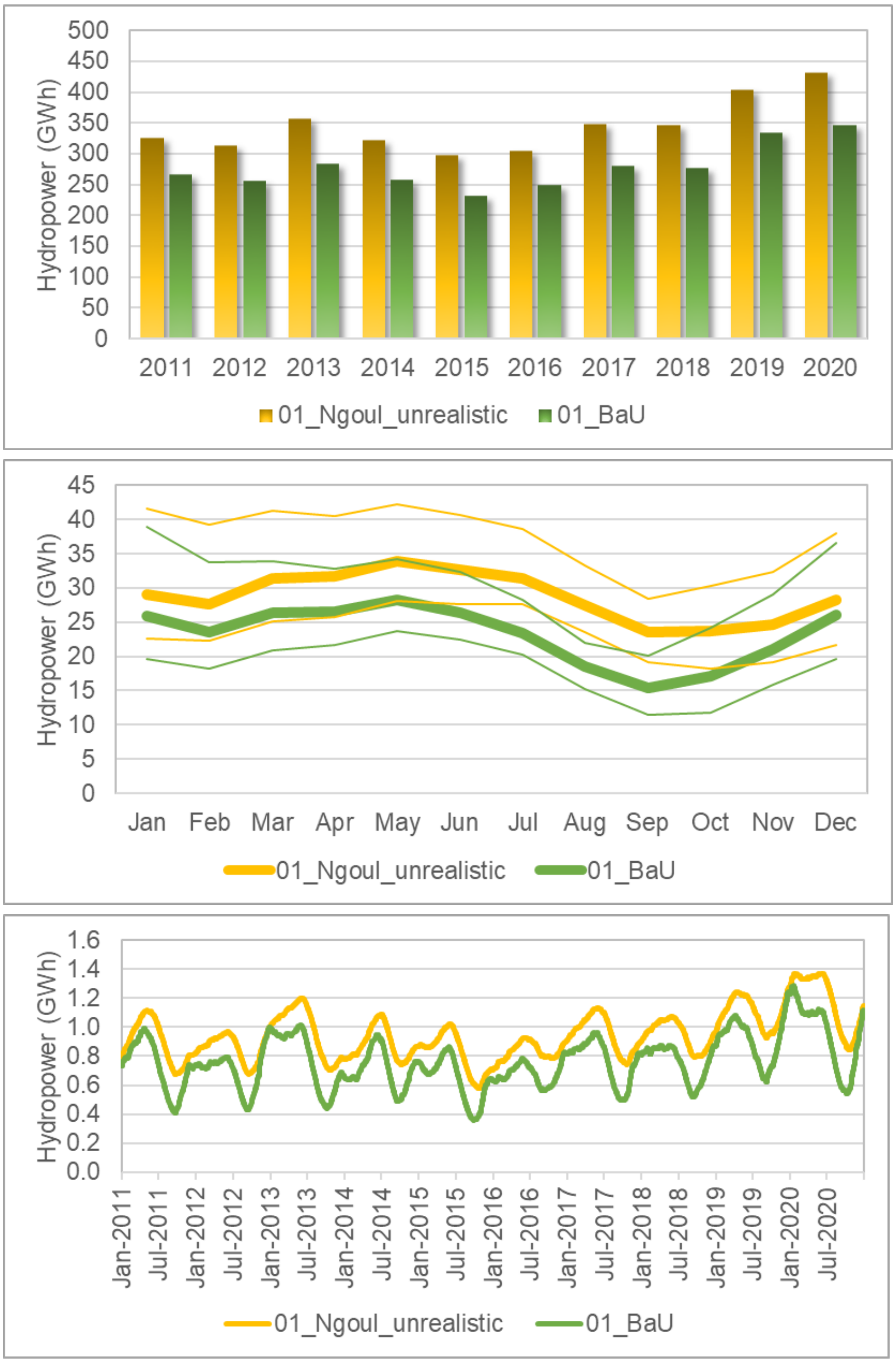


Figure 22. Projected annual (top), average monthly (middle) and annual (bottom) hydropower production. [01_Ngoul_unrealistic] is the unrealistic scenario that no changes in the catchment will happen. [01_BaU] is the realistic scenario that include those changes.

NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.2.3 Streamflow in Komo River (TCC[1])

To achieve a high elevation drop of water in order to maximize hydropower generation, water from the Komo will be channeled, through the hydropower plant to the 200 meter lower located Petite Tsibilé stream (located just west of the main Komo). Eventually water will flow from the Petite Tsibilé back into the Komo. A section of the Komo River with a length of 56.2 km will therefore see a sharp reduction in flow. The ESIA forecast is that after the project flows will be between 0% and 27% compared to the natural ones. However, it is foreseen that a minimum flow requirement will be imposed after the project. This environmental flow requirement will be 2 or 4 m^3/s (respectively 4 or 6 m^3/s in October, November and December) according to the ESIA. In the model the highest mitigation option was considered.

In Figure 23 the expected flows are shown. Since the environmental flow was included in the water allocation rules, and was assumed to have the highest priority, downstream flows at the TCC are reduced by a factor of about 10.

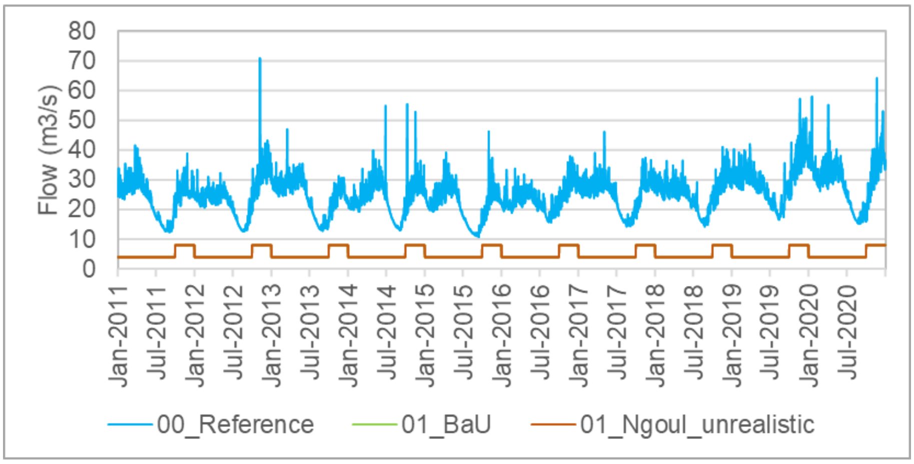


Figure 23. Flow just downstream of Ngoulmendjim for three scenarios, current situation and under the scenario of the Ngoulmendjim Hydropower Facility for a period of 10 years. Note that the two Ngoul scenarios ([01_Ngoul_unrealistic] and [01_BaU]) are exactly overlapping as the environmental flow requirements were same for both scenarios.

[00_Reference] is current without Ngoulmendjim; [01_Ngoul_unrealistic] is Ngoulmendjim without development and degradation in the catchment. [01_BaU] is Ngoulmendjim including expected development and degradation in the catchment.

NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.2.4 Streamflow in Petite Tsibilé

The small creek Petite Tsibilé has in the natural conditions flows of between 1 and 4 $m^3 s^{-1}$. Since water from the Komo will be channeled through the hydropower plant into the Petite Tsibilé. A section of 34.2 km will be exposed to unprecedented flows varying between 15 and 40 $m^3 s^{-1}$. The impact of this amount of water on the creek and its surrounding will be enormous. Currently flows are around 3 to 4 $m^3 s^{-1}$ and by the transfer from Komo to Petite Tsibilé thourgh the tunnel flows will increase about 10 folds.

[1] TCC Tronçon court-circuité = Short-circuited section. 56.2 km

The **[01_Ngoul_unrealistic]** assumes no single development in the catchment, while the realistic projection **[01_BaU]** includes degradation by developments. This expected degradation is clearly visible in the more erratic flows under this [01_BaU] projection.

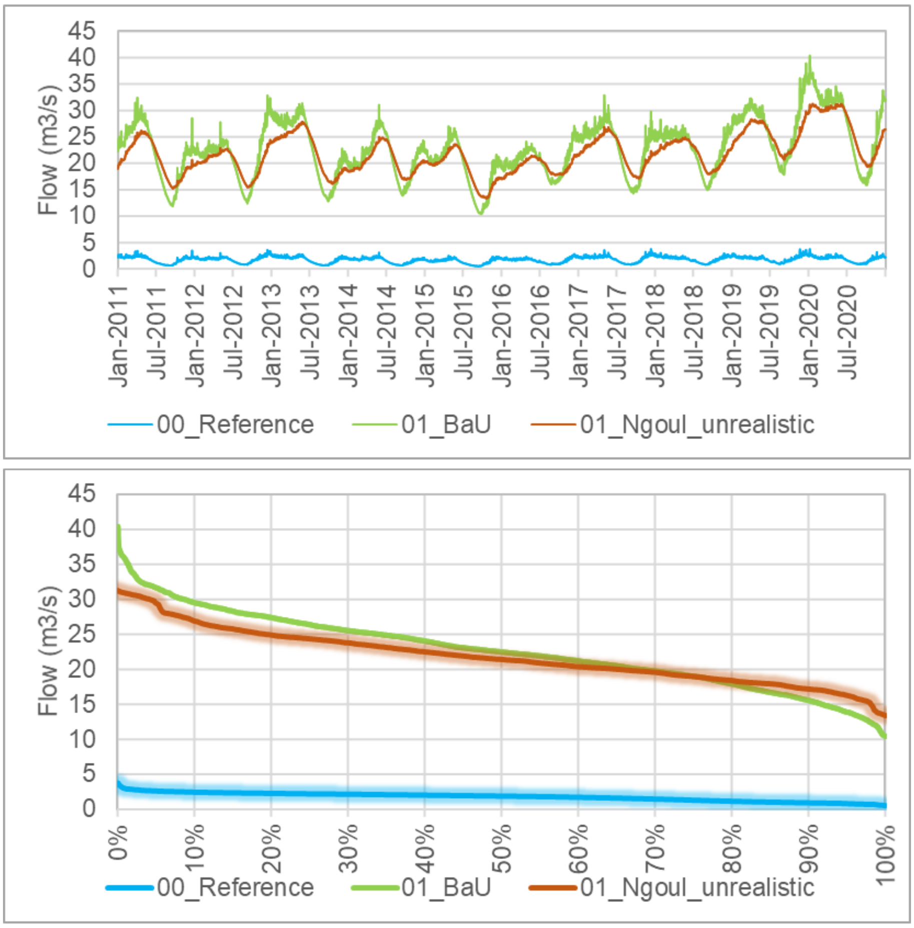


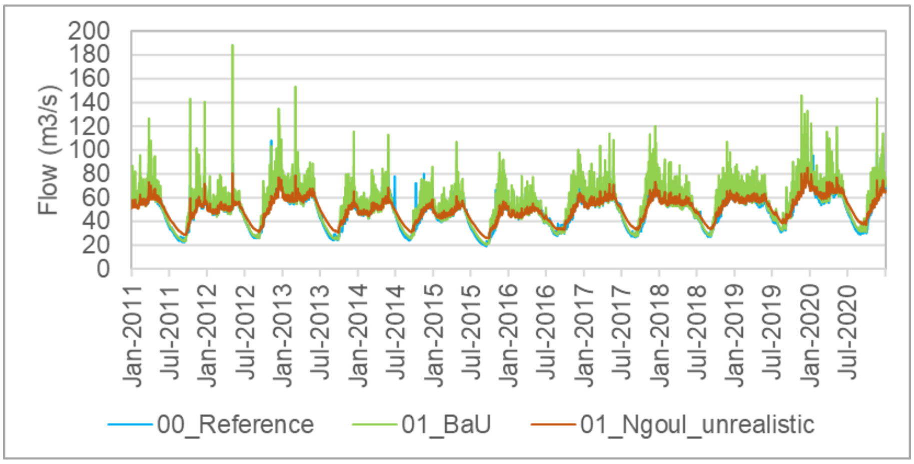
Figure 24. Flow in the Petite Tsibilé for three scenarios, current situation and under the scenario of the Ngoulmendjim Hydropower Facility for a period of 10 years. Top: daily flows, bottom: exceedance levels.

[00_Reference] is current without Ngoulmendjim; [01_Ngoul_unrealistic] is Ngoulmendjim without development and degradation in the catchment. [01_BaU] is Ngoulmendjim including expected development and degradation in the catchment.

NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.2.5 Streamflow at outlet

Total outflow of the basin (=confluence with the Mbé River) will change slightly by the development of the Ngoulmendjim facilities. Interesting is that developing Ngoulmendjim will increase total annual outflow as soils are more degraded, forest will be cut, and more roads and settlements will be developed. However more extremes in flows will happen with quite some high flows that might lead to flooding and lower flows during the dry season. Probably managing the reservoir for better flood control might overcome those extremes.



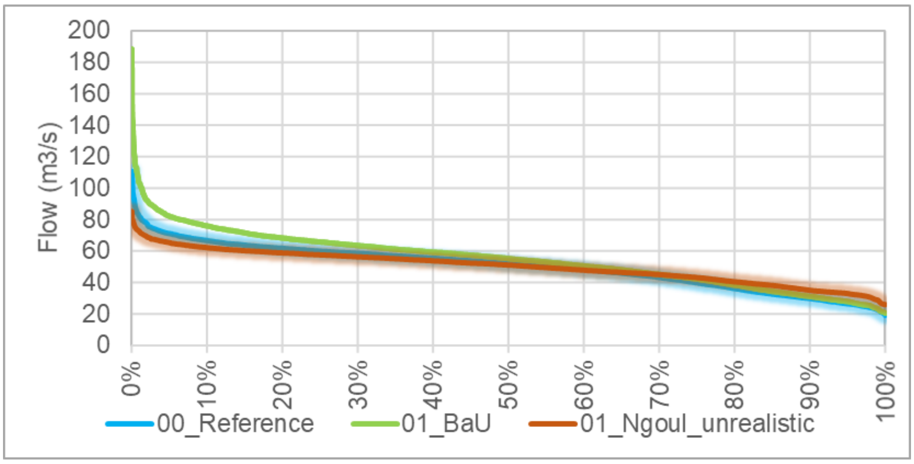


Figure 25. Streamflow at outflow point of Komo Basin (=confluence with the Mbé River) for the reference situation and the scenario with Ngoulmendjim. Top: daily average; bottom: exceedance levels. [01_Ngoul_traditional] is the unrealistic scenario that no changes in the catchment will happen. [02_Ngoul_HES] is the realistic scenario that include those changes.

[00_Reference] is current without Ngoulmendjim; [01_Ngoul_unrealistic] is Ngoulmendjim without development and degradation in the catchment. [01_BaU] is Ngoulmendjim including expected development and degradation in the catchment.

NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.2.6 Impact on erosion and sedimentation

The analysis presented here did not include a full erosion and sedimentation evaluation. As discussed before erosive (surface) runoff can be used as a proxy for this erosion and will be presented here. The impact of developing Ngoulmendjim [01_BaU] will increase erosive runoff substantially by a factor 3 to 4 on an annual base. Daily erosive runoff can be even more extreme having big impact on erosion and sedimentation of the reservoir.

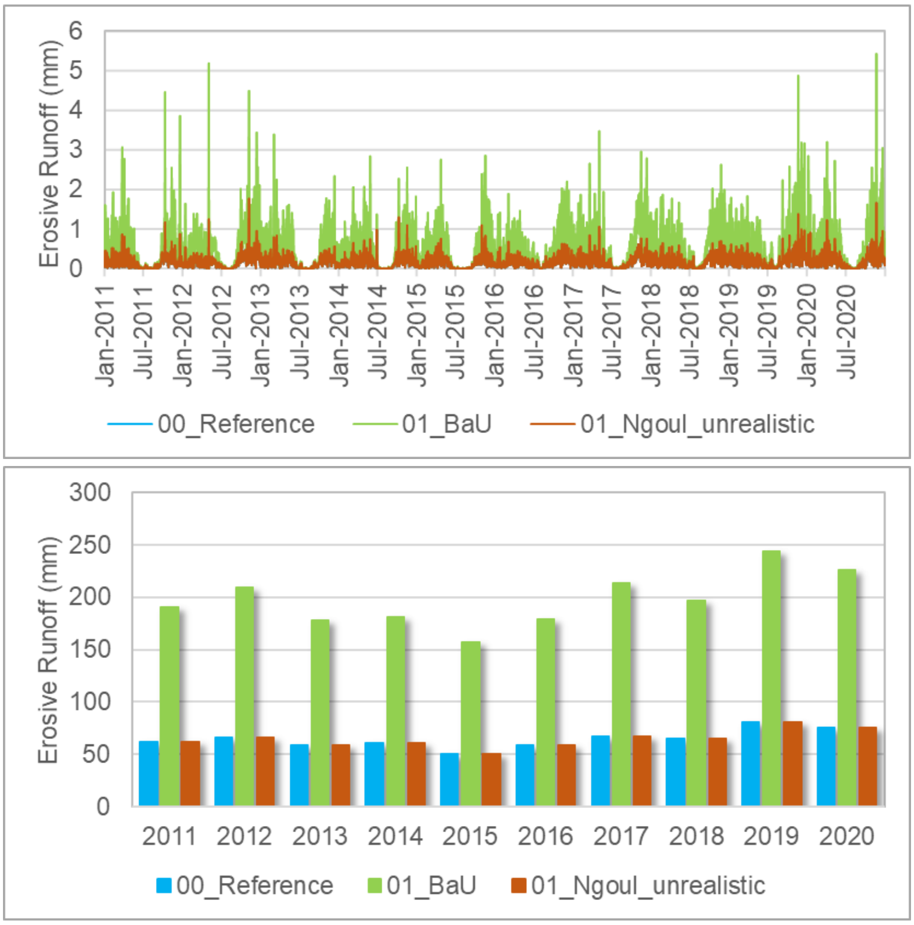


Figure 26. Erosive runoff presented as mm over the entire basin. Top: daily runoff; bottom: annual.

[00_Reference] is current without Ngoulmendjim; [01_Ngoul_unrealistic] is Ngoulmendjim without development and degradation in the catchment. [01_BaU] is Ngoulmendjim including expected development and degradation in the catchment.

NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.3 Alternative Scenarios

Highlights:

- Four alternative scenarios have been evaluated to mitigate the impact of Ngoulmendjim Hydropower Facility
- The classical mitigation actions as defined in the ESIA will not be sufficient to overcome all the negative impacts caused by the Ngoulmendjim project and associated developments
- The full Hydrological Ecosystem Services scenario will lead to a hydropower production close to the design values and erosion and sedimentation will be reduced substantially.

4.3.1 Relevance

As discussed in section 3.3 a set of scenarios have been defined to explore what can be done to mitigate the negative impacts of the Ngoulmendjim Hydropower facilities and the associated development and degradation of the basin. The following scenarios were evaluated:

- **[01_BaU]** *Business as Usual*: Ngoulmendjim will be developed including all associated activities (roads, power lines, migration to the area leading to human activities), but no mitigation actions will be taken
- **[02_EIA]** *Classical mitigation actions*: based on the ESIA appropriate responses will be taken.
- **[03_HES]** *Hydrological Ecosystem Services (HES)*: the holistic approach leading to a full improved catchment management strategy.
- **[04_Sma]** *Smaller reservoir*: Ngoulmendjim reservoir capacity will be 50% (163 MCM[1]) compared to the original design.

The impact of those scenarios is evaluated by using the following key performance indicators:

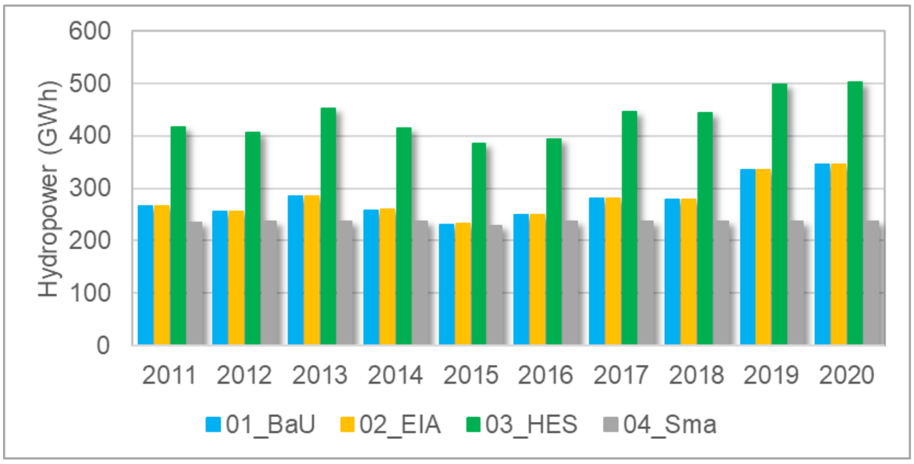
- Expected hydropower production
- Expected daily reservoir levels
- Streamflow in Komo River downstream of dam (TCC[2])
- Streamflow in Petite Tsibilé
- Streamflow at outlet
- Relative impact on erosion and sedimentation

4.3.2 Expected hydropower production

According to the ESIA the aim is to achieve a hydropower production of 500 GWh per year on average. As shown previously, according to the hydropower module of WEAP and based on the hydrological simulations, the expected hydropower production is closer to 350 GWh per year (see Figure 22 and accompanying text). This is due to a multiple number of factors including the lower expected flows compared to the ESIA.

Figure 27 shows the [01_BaU] scenario in comparison with the other three alternative scenarios. As can be seen, the [02_EIA] scenario will allow for very similar hydropower outputs. The [04_Sma] scenario which aims at a smaller reservoir, reduces hydropower generation slightly. The most notable positive impact can be seen for the [03_HES] scenario that includes the holistic approach of a fully improved catchment management. Here, hydropower production can be increased by around 25%, to up to values that come close to the targeted design values of 500 MWh.

[1] Note that the sedimentation rate of 20% also applies so that the effective storage capacity is 130 MCM.
[2] TCC Tronçon court-circuité = Short-circuited section. 56.2 km



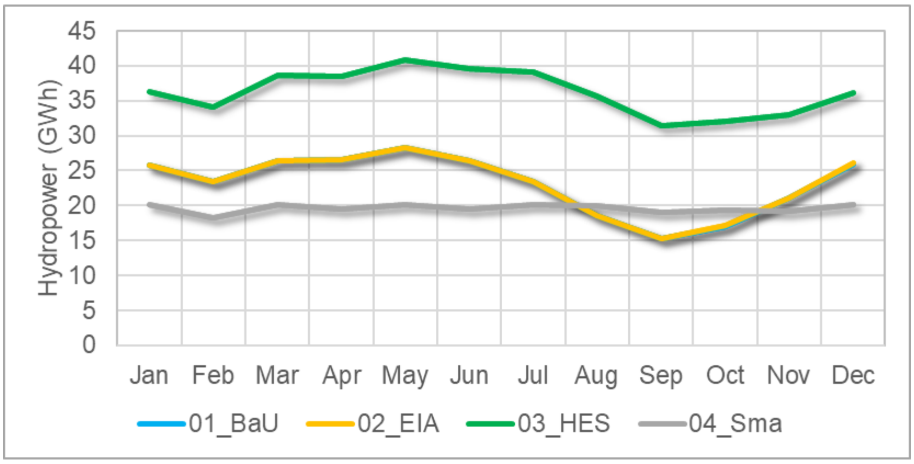


Figure 27. Projected annual (top), average monthly (bottom) hydropower production.
[01_BaU] Business as Usual: no mitigation; [02_EIA] Classical mitigation based on the ESIA; [03_HES] Hydrological Ecosystem Services (HES) full improved catchment management; [04_Sma] Smaller reservoir capacity of 50%.
NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.3.3 Reservoir levels

The projected daily reservoir levels under the various scenarios are presented in Figure 28. The reduction in reservoir scenario [04_Sma] has hardly any impact as for most years inflows are not sufficient to fill the reservoir. The full HES scenario [03_HES] is quite effective in filling the reservoir. Especially in years where rainfall is somewhat higher (2019-2020) the reservoir can be filled completely, and will generate hydropower at the design capacity of the turbines. Obviously, reservoir dynamics can be influenced substantially by operational rules, which were not further investigated in the current study.

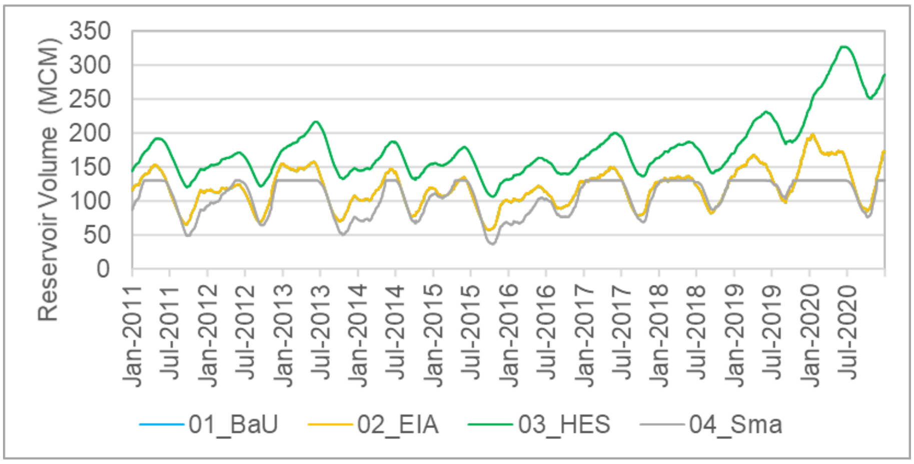


Figure 28. Projected reservoir volumes. [01_BaU] and [02_EIA] are nearly overlapping.
[01_BaU] Business as Usual: no mitigation; [02_EIA] Classical mitigation based on the ESIA; [03_HES] Hydrological Ecosystem Services (HES) full improved catchment management; [04_Sma] Smaller reservoir capacity of 50%. NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.3.4 Streamflow in Komo River (TCC[1])

To achieve a high elevation drop of water in order to maximize hydropower generation, water from the Komo will be channeled, through the hydropower plant to the 200 meter lower located Petite Tsibilé stream (located just west of the main Komo). Eventually water will flow from the Petite Tsibilé back into the Komo. A section of the Komo River with a length of 56.2 km will therefore see a sharp reduction in flow. The ESIA forecast is that after the project flows will be between 0% and 27% compared to the natural ones. However, it is foreseen that a minimum flow requirement will be imposed after the project. This environmental flow requirement will be 4 m^3/s and 6 m^3/s in October, November and December according to the ESIA.

In Figure 23 the expected flows are shown for the four scenarios. Since the environmental flow was included in the water allocation, and was assumed to have the highest priority, all scenarios provide the same pattern. Only exception is [04_Sma] where the reservoir capacity is sometimes not sufficient to store all water and emergency spillways releases are made.

[1] TCC Tronçon court-circuité = Short-circuited section. 56.2 km

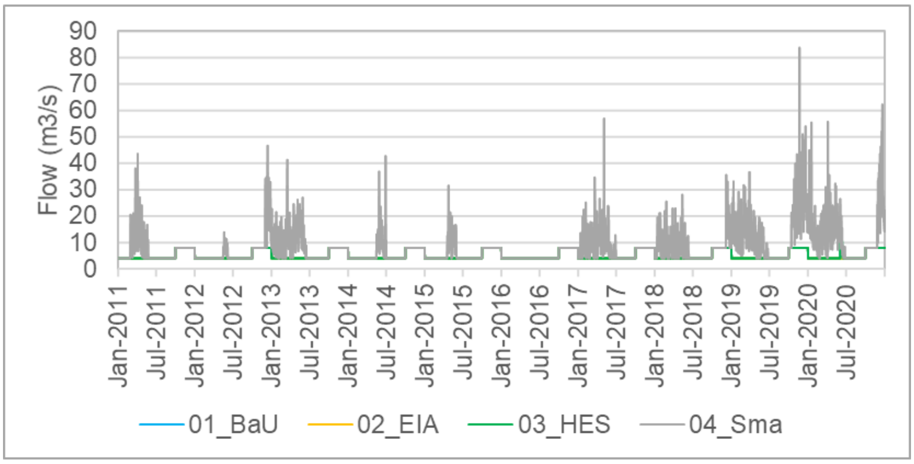


Figure 29. Flow just downstream of Ngoulmendjim in Komo River. All scenarios are overlapping with the exception of the [04_Sma] one.

[01_BaU] Business as Usual: no mitigation; [02_EIA] Classical mitigation based on the ESIA; [03_HES] Hydrological Ecosystem Services (HES) full improved catchment management; [04_Sma] Smaller reservoir capacity of 50%. NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.3.5 Streamflow in Petite Tsibilé

The small creek Petite Tsibilé has in the natural conditions flows of between 1 and 4 $m^3 s^{-1}$. Since water from the Komo will be channeled through the hydropower plant into the Petite Tsibilé flows will be much higher when Ngoulmendjim will be completed. A section of 34.2 km will be exposed to unprecedented flows varying between 15 and 40 $m^3 s^{-1}$. Flows under the smaller reservoir scenario will be somewhat lower as more water will remain flowing to the Komo River. During wetter years (2019-2020) the positive impact of HES is clearly observable: much more regulated flows.

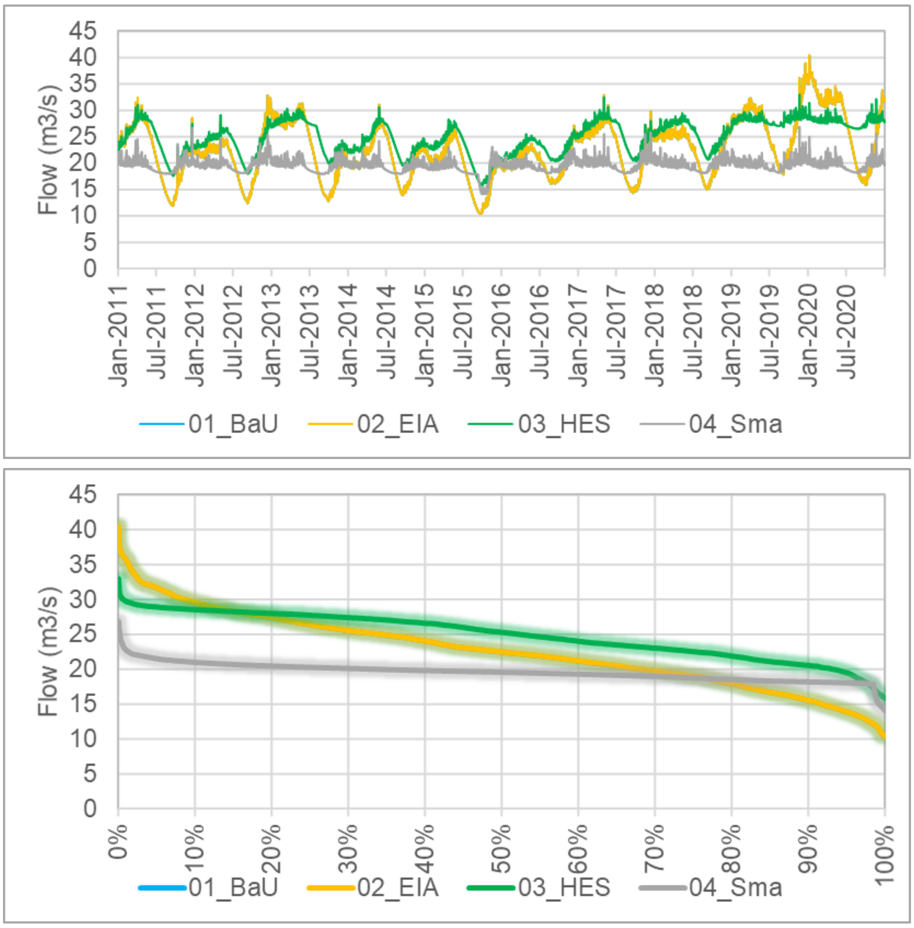


Figure 30. Projected flows in the Petite Tsibilé for the four scenarios. Top: daily flows; bottom: exceedance levels.

[01_BaU] Business as Usual: no mitigation; [02_EIA] Classical mitigation based on the ESIA; [03_HES] Hydrological Ecosystem Services (HES) full improved catchment management; [04_Sma] Smaller reservoir capacity of 50%. NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.3.6 Streamflow at outlet

Total outflow of the Komo Basin (=confluence with the Mbé River) under the four scenarios is presented in Figure 31. Difference between those four scenarios are not big, although the full hydrological ecological services scenario [03_HES] will provide the highest outflow by a combination of various factors as improved soil infiltration, lower evaporation, higher baseflow, lower erosive runoff, etc . More important, under this scenario the lower flows occurring from July to September will be substantially higher compared to the other scenarios.

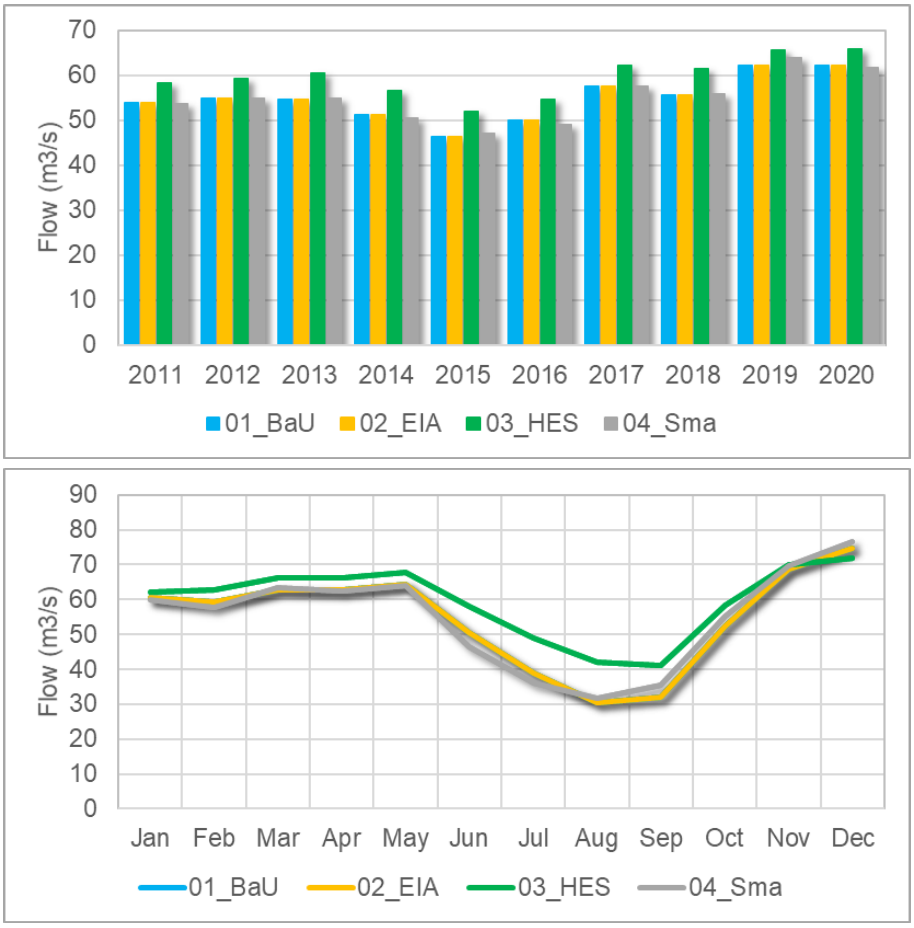


Figure 31. Projected streamflow at outflow point of Komo Basin (=confluence with the Mbé River) for the four scenarios.

[01_BaU] Business as Usual: no mitigation; [02_EIA] Classical mitigation based on the ESIA; [03_HES] Hydrological Ecosystem Services (HES) full improved catchment management; [04_Sma] Smaller reservoir capacity of 50%. NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

4.3.7 Impact on erosion and sedimentation

The analysis undertaken did not include dynamic simulation of erosion and sediment routing through the basin. Instead, for the scenario analysis, the assumptions on sediment concentration and sedimentation of the reservoir were based on the relative differences in erosive runoff. As discussed before erosive runoff can be used as a proxy for erosion rates. For this region, as was shown in the Mbé study which included dynamic modeling of erosion and sediment yield, a reduction in erosive runoff leads to a reduction in the same order of magnitude in sediment yield.

Figure 26 shows that the only scenario that clearly reduces this erosive runoff, and therefore erosion and sedimentation, is the hydrological ecological services one [03_HES]. Reductions by nearly 50% can be expected. This can have a major positive impact on sediment concentrations leading to degradation of infrastructure (e.g. turbines), loss of reservoir storage capacity, and downstream sediment inflow into the estuary, affecting biodiversity.

A full erosion and sedimentation modeling will refine and quantify in a higher level of detail and accuracy of the results presented here. The WEAP Erosion Plugin (WEP)[1] might be used for this.

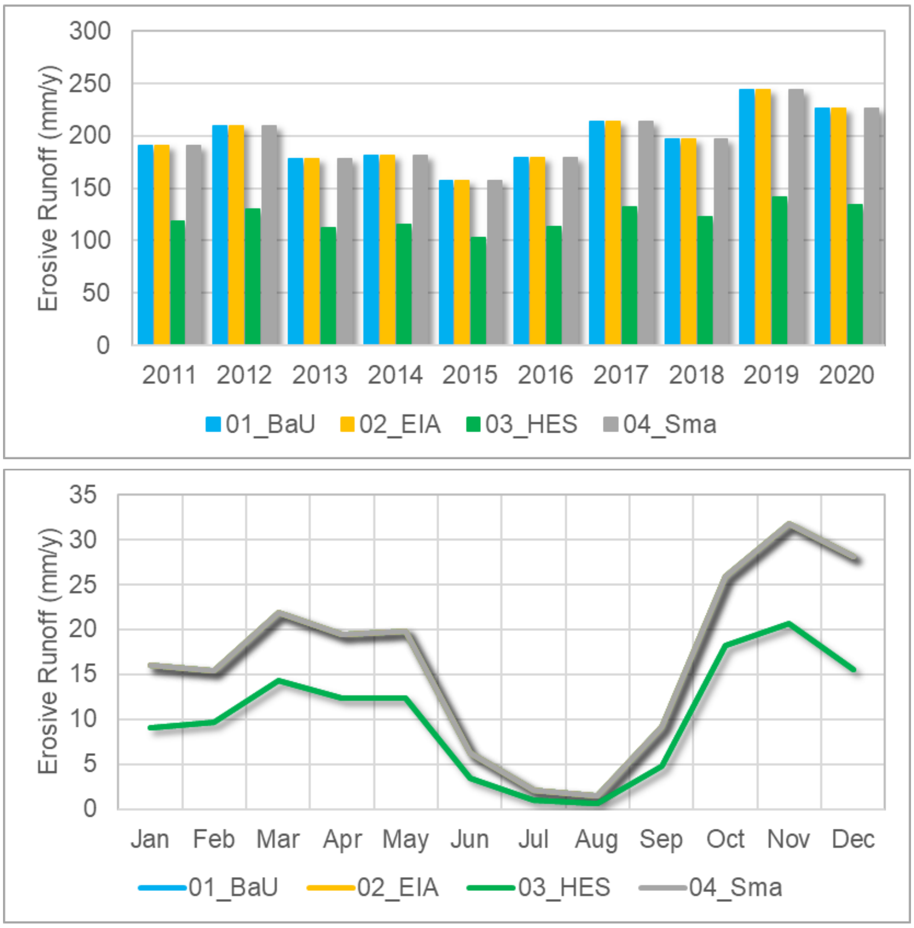


Figure 32. Erosive runoff presented as mm over the entire basin. Top: daily annual runoff; bottom: average monthly.

[01_BaU] Business as Usual: no mitigation; [02_EIA] Classical mitigation based on the ESIA; [03_HES] Hydrological Ecosystem Services (HES) full improved catchment management; [04_Sma] Smaller reservoir capacity of 50%. NOTE: the years at the x-axis reflect the current 10 years climate that was used to assess the future scenarios.

[1] Droogers, P., J.E. Hunink, J. Sieber. 2021. WEP: WEAP Erosion Plugin. FutureWater Report 223.

5 Conclusions

The Komo basin in Gabon is projected to undergo major changes when the **Ngoulmendjim** hydropower facility is going to be constructed. The current study is an expansion of the classical Environmental and Social Impact Assessment (ESIA) by including a full Hydrologic Ecosystem Services (HES) approach. the study is based on available data and previous analysis, and the HES approach was based on the WEAP model.

The expected **impact** of the Ngoulmendjim Dam is evaluated to its full extent. In other words, not only the impact of the facility in isolation is considered, but the full socio-economic developments and impacts on soils, land covers, new settlements, roads etc. are included. Results from other basins has shown that those supplemental impacts will occur within a few decades and have a huge impact. For the Ngoulmendjim investments this might even lead to lower than expected hydropower generation by higher erosion and sedimentation and reduced flow and more flow extremes.

Therefore, a set of **adaptation scenarios** is explored and by using a set of key performance indicators it could be assessed where potential gains are from including a full set of Hydrologic Ecosystem Services improvements. Results show that hydropower generation could be much higher, and erosion and sedimentation could be reduced, while impact on flow could be partly mitigated.

This study is based on the situation in the Komo basin and the projected Ngoulmendjim facility. However, the approach, conclusions, and lessons learnt are generic and can be applied to other situations as well.

Table 5. Summary table on the impact of the four scenarios on the six key performance indicators.

	01_BaU	02_EIA	03_HES	04_Sma
Hydropower production (GWh/y)	↘ 278	↘ 279	↑ 435	↓ 235
Reservoir levels (MCM)	↓ 119	↓ 119	↑ 177	↓ 106
Streamflow downstream of dam (TCC	↓ 5.0	↓ 5.0	↓ 5.0	↑ 8.1
Streamflow in Petite Tsibilé (m3/s)	→ 22.7	→ 22.7	↑ 24.9	↓ 19.6
Streamflow at outlet (m3/s)	↓ 54.8	↓ 54.8	↑ 59.6	↓ 54.8
Erosive runoff (mm/y)	↓ 198	↓ 198	↑ 122	↓ 198

Note that the arrows reflect worse or better rather than actual values. E.g. high hydropower production is positive (green upwards arrow) while high erosive runoff is negative (red downwards arrow).

6 Annex: Environmental Assessment Ngoulmendjim

This Annex is a copy/paste from sections important for the current study from the Environmental Social Impact Assessment Ngoulmendjim Report

p. 31:
The Ngoulmendjim hydroelectric scheme includes a dam on the Komo with a reservoir of about 30 km^2, a water intake and an underground gallery of 3,650 m leading an average flow of 45 m^3/s to a plant with an installed capacity of 83 MW. The water will be returned to the Petite Tsibilé, which joins the Komo after about 40 km, which makes it possible to reach a remarkable head of more than 200 m thanks to which the scheme can be economic feasible.

The hydroelectric plant is planned to operate "on base", i.e. 70% of the time, and the reservoir will have a seasonal regulation capacity. A daily lock operation is not envisaged.

The planned development includes :

- A closing structure on the Komo to create a seasonal regulation reservoir ;
- An intake structure;
- A hydroelectric plant;
- An evacuation channel to recalibrate the south arm of the Petite Tsibilé;
- A release device for the instream flow released downstream of the dam into the TCC downstream section;
- An energy evacuation station;
- A 225 kV overhead power discharge line to the Ndouaniang substation via downstream Kinguélé, the precise route of which remains to be defined.
- Ancillary facilities to ensure optimal operation, operation and maintenance;
- Temporary works required during the construction phase and which will either be deconstructed or rehabilitated for later reuse.

The project consists of building and operating an 83 MW hydroelectric power plant on the Komo River in the Estuary province. The development plan includes :

- a concrete dam on the Komo;
- an intermediate size reservoir for an inter-seasonal regulation of about 28.2km^2 (RN);
- a water intake device, an inlet gallery to the plant and a tailrace in the upstream of the Petite Tsibilé ;
- a short-circuited section (TCC) of about 56 km which allows to obtain a head of 208 m approximately.
- a plant with an installed capacity of 83 MW and an equipment flow rate of 45 m3/s ;
- an electrical departure station;
- a 225 kV energy evacuation line 95 km long, of which approximately 30 km passes through an existing line corridor between the future structure at Kinguélé aval and Ndouaniang;

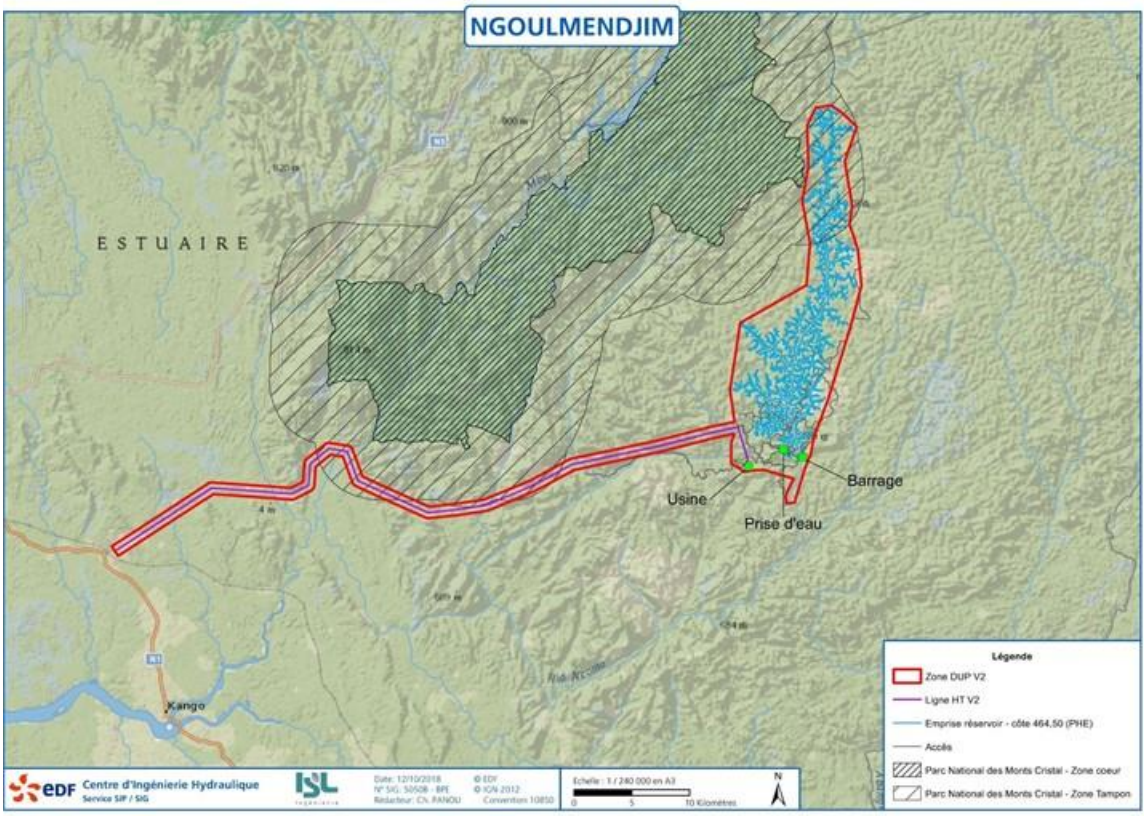
The site of Ngoulmendjim is characterised by the fact that it is not directly linked by road to the national network. Its access remains dependent on crossing the Komo by river. Access to the site is currently possible by road or by river, between Nzamaligue and Atak. Taking into account the difficulties of access to the site of Ngoulmendjim and the needs of the building site, the following works are also to be planned:

- Possible development work at the landing stage.
- The creation of a temporary bridge over the Mbé.
- Rehabilitation work on the SEEF road over approximately 60 km from the bridge over the Mbéi or from the SEEF's Nzamalingue landing stage.
- The construction of a permanent laterite road of about 10 km at the dam site.
- Construction site tracks for the circulation of machines between the quarry site, the earthworks areas and the depot areas, life bases, etc.
- The creation of accesses for the installation of the HT line towers.

p.34:

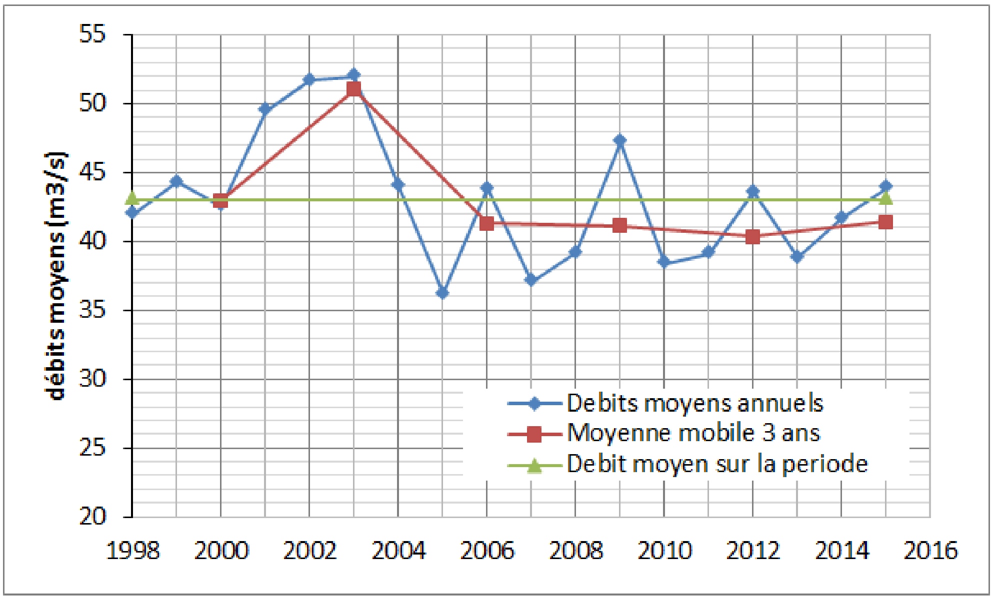
Configuration	Seasonal regulation arrangement with support from dry season low-water levels by storage in the rainy season
Average power of the installation	83 MW
Equipment throughput	45 m3/s
Tank surface at RN (normal)	28.20 km² (28.20 km²)
Tank volume at RN (normal)	282.83 hm3
Tank surface to NME (minimal)	12.75 km² (12.75 km²)
Tank volume at NME (minimal)	83.16 hm³
Drop height	208,65 m
Reserved debit	2 to 6 m3/s according to the configuration to be defined by the EPC.
Annual production	~500 GWh
Catchment area	1430 km².
Average annual precipitation	2000 mm/year
Flow deficit	1050 mm/year
Interannual average Low water (August)	16,9 m3/s
Inter-annual average High water (November)	79,3 m3/s
Average annual flow rate (module)	44 m3/s
Total Annual Volume	1388 hm3
Specific flow rate	31 L/km²/s
Average minimum monthly flow rate QMNA5	15,3 m3/s
Construction flood (100 years)	570 m3/s
Project flood (10,000 years)	1080 m3/s

p:32



p 46
Flows have been reconstituted over the period 1998-2015. These data series have been used to the determination of the different hydrological characteristic values (identification of variabilities, annual and seasonal, determination of intermediate inputs per catchment area, values of the low water flows,etc).

The hydrology of rivers has many dependent components with in particular: hydraulics (consequences on flows such as speeds and depths,...), transport,...aquatic and riparian ecosystems, as well as all uses of water by the population and waterborne diseases. The hydrological component is therefore particularly sensitive to the right to water of the project and downstream.



p. 46

Sedimentation

There are no data on the solid transport of the Komo, either in terms of fine materials transported in suspension (clay, silt) or coarser sediments (sand, gravel, pebbles). The profiles along the Komo River downstream of the dam and the Petite Tsibilé are blocked by the numerous points by the outcropping substratum which limits the erosive activity of these rivers. That said, the field observations indicate that alluvial materials are also transported on the Komo and on the Petite Tsibilé.

Solid transport can have multiple consequences such as bank erosion, modification the morphology of rivers and estuaries, the disturbance of aquatic habitats and the airworthiness. Solid transport is a sensitive component of the physical environment.

p. 52

The complete potential impact area covers an area of 24,812 ha. The potential impact area is 99% covered by natural habitats (forests, savannahs and watercourses) and 1% by habitats modified, linked to human activity. Plane and relief forests (mostly secondary forests) occupy almost all (97.5%) of the surface area of the potential impact zone.

p. 80

At the Petite Tsibilé (34.2 km section), important changes in the flow rate with a including multiplication of the average monthly debit between 2.5 and 30 times the natural flow, depending on the location and season. The gap is narrowing progressively downstream and in the wet season.

At the TCC (= downstream), the flow rate is decreasing. The values downstream from 0% to 27% the natural flow according to the contributions of the basins intermediate slopes. Decrease in water lines, solid transport, and water speeds, loss of hydraulic connections downstream and primary tributaries.

By considering the reduction of impacts on the natural environment and the economic viability of the project to provide one kWh at a price acceptable to the population, an instream flow must be returned to the dam in the TCC. Two scenarios of 2 or 4 m 3/s (respectively 4 or 6 m3/s in October, November and December) will be integrated into the project design.

p. 154

Surface-elevation-volume reservoir

Level	Surface Area (km^2)	Volume (MCM)
453	12.75	83.16
463	28.20	282.83
464.5	31.11	327.35

This structure, installed in the dam from the temporary breakwater, will be designed to deliver the instream flow from 2 to 4 m3/s in dry periods and up to 6 m3/s in wet periods (October to December). The waters will be taken immediately below the NME rating to avoid water loaded with sediments and to take better quality water (less deoxygenated and less rich in methane). The optimum would be to take the reserved flow from two different levels of the useful portion of the unit so that the oxygenated upper layer (estimated at 5 m high over a distance of 5 m) can always be sampled the work of Petit Saut, in French Guiana). A hollow jet valve is preconditioned to ensure the reoxygenation and degassing of water returned downstream.

p. 160

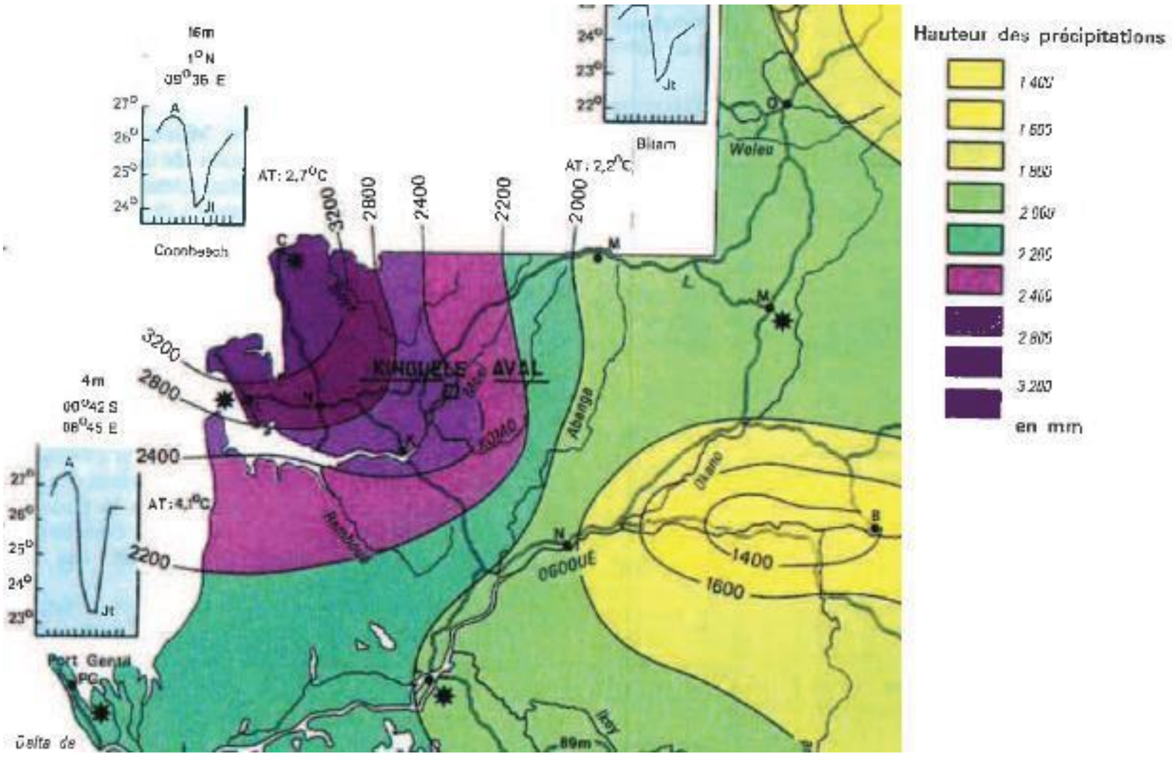
The factory is located in the south arm of the little Tsibilé. It is an outdoor factory (semi buried) housing 3 Pelton groups 9 vertical axis with a total power of approximately 83 MW for a flow rate of approximately of equipment of 45 m3/s :

Equipment throughput : 15 m3/s per group.

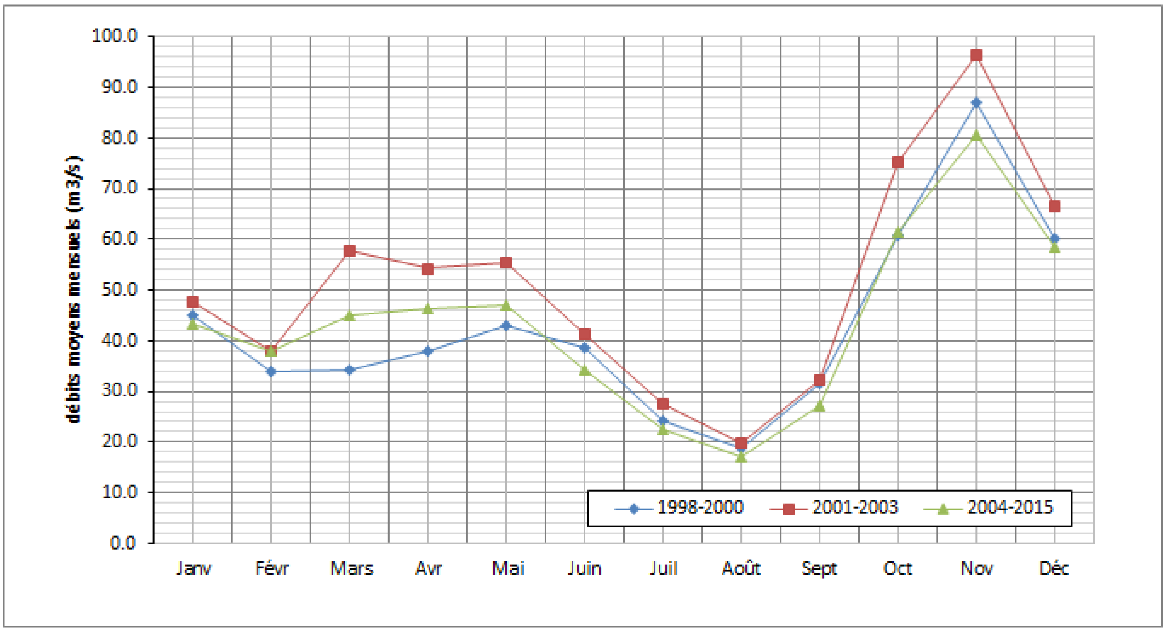
Nominal power: 28.5 MW per group.

Nominal net drop: 208.7 m.

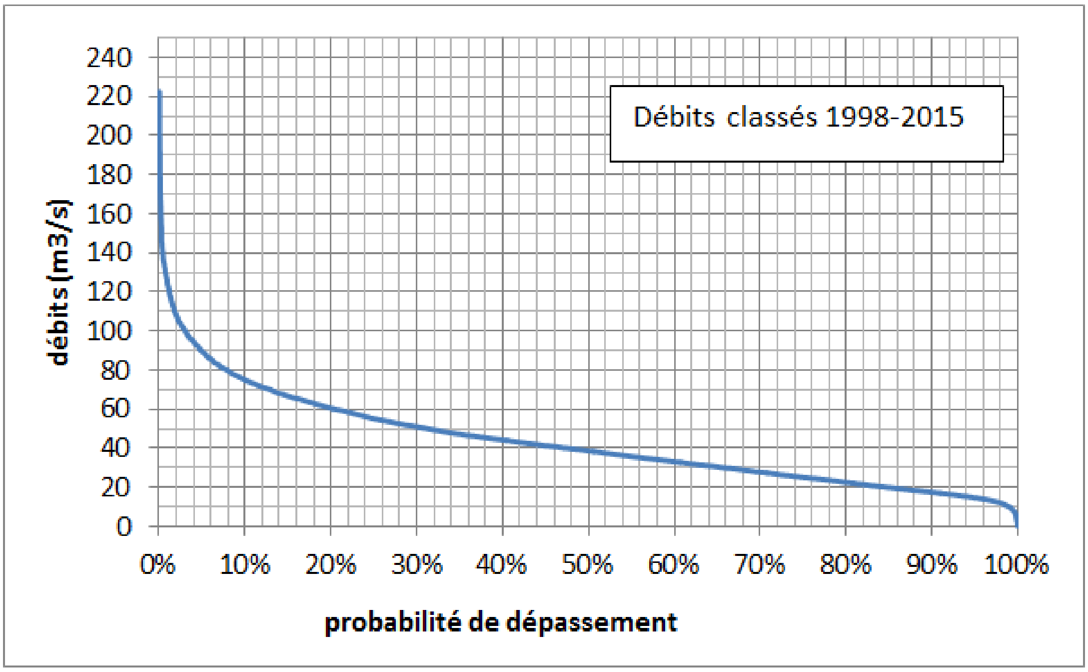
p. 188


Hauteur des précipitations
1 400
1 600
1 800
2 000
2 200
2 400
2 800
3 200
en mm
Cocobeach
Bitam
Woleu
KINGUELE AVAL
AT: 2,7°C
AT: 2,2°C
AT: 4,1°C
3200
2800
2400
2200
2000
1400
1600
OGOOUÉ
Abanga
Port Gentil
Delta de

p. 215


débits moyens mensuels (m3/s)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Janv
Févr
Mars
Avr
Mai
Juin
Juil
Août
Sept
Oct
Nov
Déc
1998-2000
2001-2003
2004-2015

p. 216



p. 221

There are no data on the solid transport of the Komo, either in terms of fine materials transported in suspension (clay, silt) or coarser sediments (sand, gravel, pebbles).

ISL (2018) considers a specific erosion rate in the catchment area of around 30 t/km²/year, i.e. 20 m³/km²/year, which makes it possible to estimate a contribution to the right of the dam of 30,000 m³ /year. This volume corresponds to an annual concentration of TCC in the water of 30-35 mg/l.

The specific input value of 30 t/km2/year has also been proposed for the Kinguélé downstream project on the Mbé, the main tributary of the Komo, which has been evaluated in the framework of the ESIA of this river. As the Mbé catchment area is neighbouring, and geographically very comparable to that of the Komo, similar specific erosion rates can be expected in the Komo and Mbé catchment areas. The arguments developed in the ESIA of the Kinguélé aval project (2018) are summarised below.

The value of 30 t/km²/year was first compared to specific erosion rates measured on rivers located in similar hydro-geographical contexts, available on the FAO website. Overall, the value of 30 t/km²/year is rather significant compared to other values in the literature, although it does not go beyond the range of values already measured. For example, on the Sanaga River in Cameroon, specific erosion rates of 20 to 28 t/km²/year have been measured.

The sedimentation data in the Tchimbélé and especially Kinguélé dams have made it possible to refine the evaluation of this value.

- The Tchimbélé reservoir, located at an altitude of about 550 m at the exit of the WoleuNtem plateau, has been in water for 37 years (catchment of 1120 km2). There is no quantitative element for this reservoir, however the sedimentation rate seems low in relation to its size.

- The upstream Kinguélé reservoir is located downstream of the previous one (intermediate catchment of 610 km²), at an altitude of 200 m. It has been in water since 1973. A bathymetric survey in 2009 (Neptune Service, 2009) revealed significant silting of around 300,000 m³, limited to the margins of the former minor bed, which is empty of sediment due to frequent emptying by the operator.
- By making the plausible hypothesis that the Tchimbélé reservoir retains 90% of the fine sediments produced upstream, and that the Kinguélé reservoir retains about 50% of the inputs, we obtain a specific erosion rate of about 20 m3/km²/year, i.e. 30 t/km²/year.

The erosion rate of 30 t/km²/year therefore seems plausible for the Mbé catchment area. In
In the absence of additional information, this value also seems to be relevant for the Komo River, although the uncertainty on this value is very large.

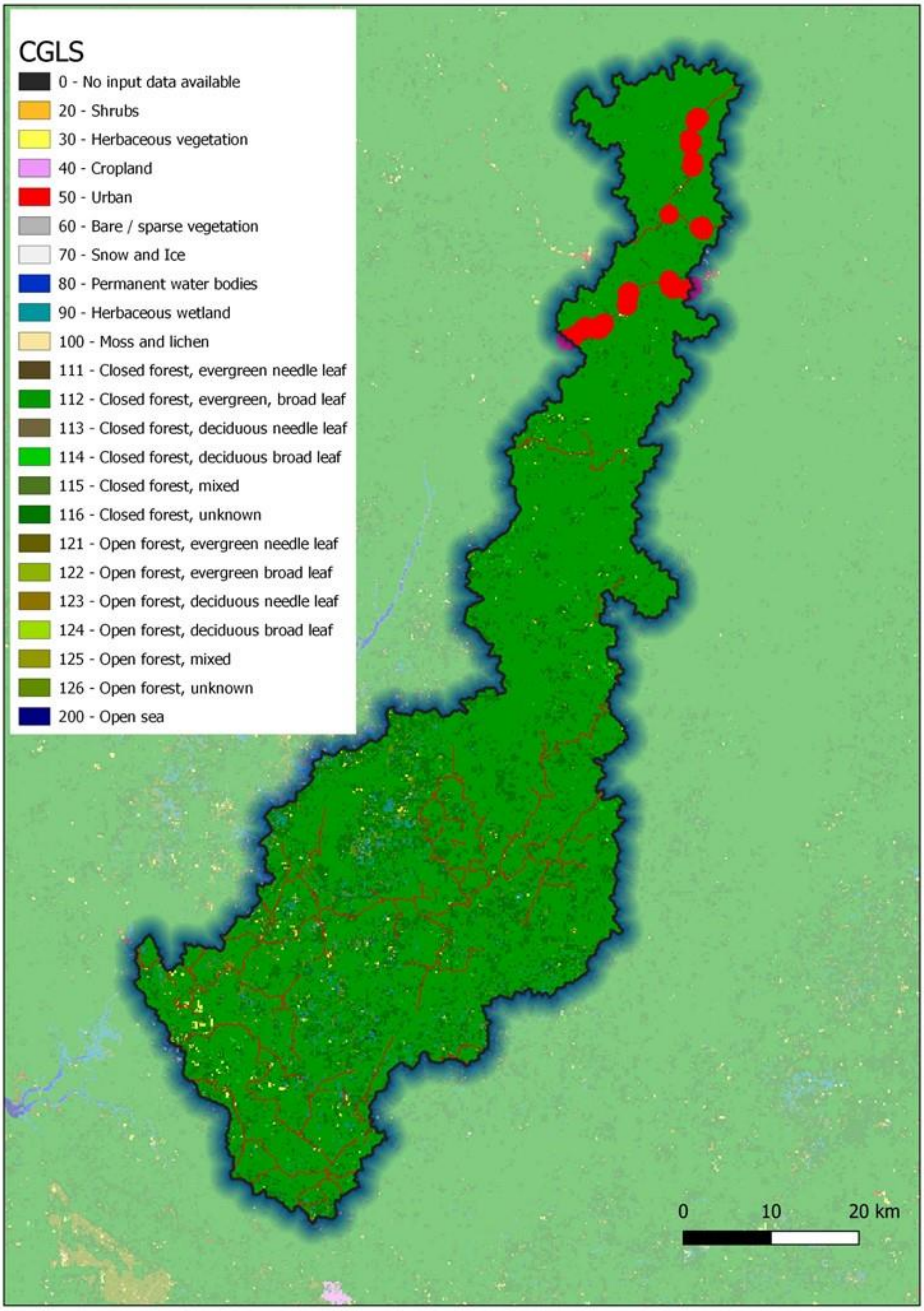
Since the Tchimbélé reservoir shows little sign of sedimentation after 35 years of activity, and taking into account the differences in relief, it is likely that specific erosion rates are less important on the Woleu-Ntem plateaus than in the Crystal Mountains. However, the previous calculation is largely based on the estimation of the inputs from the intermediate basin located between the Tchimbélé dam and the upstream Kinguélé dam, located in the Monts de Cristal. For this reason, it seems plausible that the value of contributions of 30,000 m3 per year to the Ngoulmendjim reservoir is a rather high estimate of the range of possible values.

On the Komo River, the water was turbid during the field visit of 19 July 2018, while on the Petite Tsibilé, the water was very clear during the field visit of 18 July 2018 (see Fig. 46 below). However, as the concentration of TCC is highly variable over time, this information does not allow us to conclude on a systematic difference in concentration between the Komo downstream of the dam and the Petite Tsibilé.

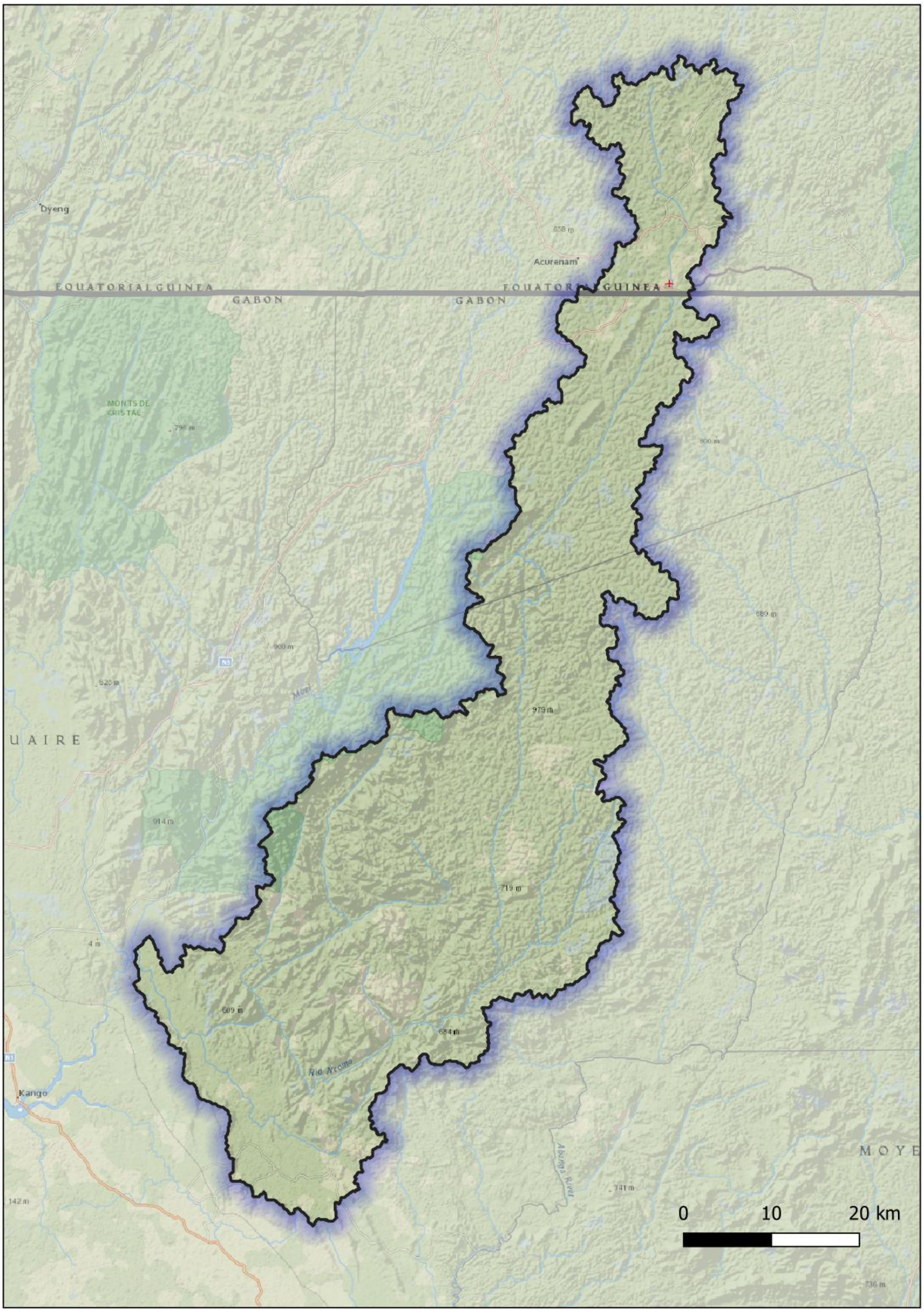
p. 223


Fleuve Komo
Petite Tsibile
1
Dépôt de sable, site barrage
4
Petite Tsibile amont route
(pente faible)
2
Komo, aval site barrage
5
Petite Tsibile Aval route
(pente faible)
3
Bac Komo (pente faible, marée)
6
Petite Tsibile inter route
(pente forte)
Elevation (NGF, m)
600
500
400
300
200
100
0
-96
-64
-32
0
32
64
96
128
Distance au barrage (103 m)
1 et 2
4
5
6
3
Amont retenue
Barrage
Confleunce Tsibile
Confleunce M'Bei
Komo, Lidar
Petite Tsibile, Lidar
Komo, SRTM
Petite Tsibile et aval Tsibile, SRTM

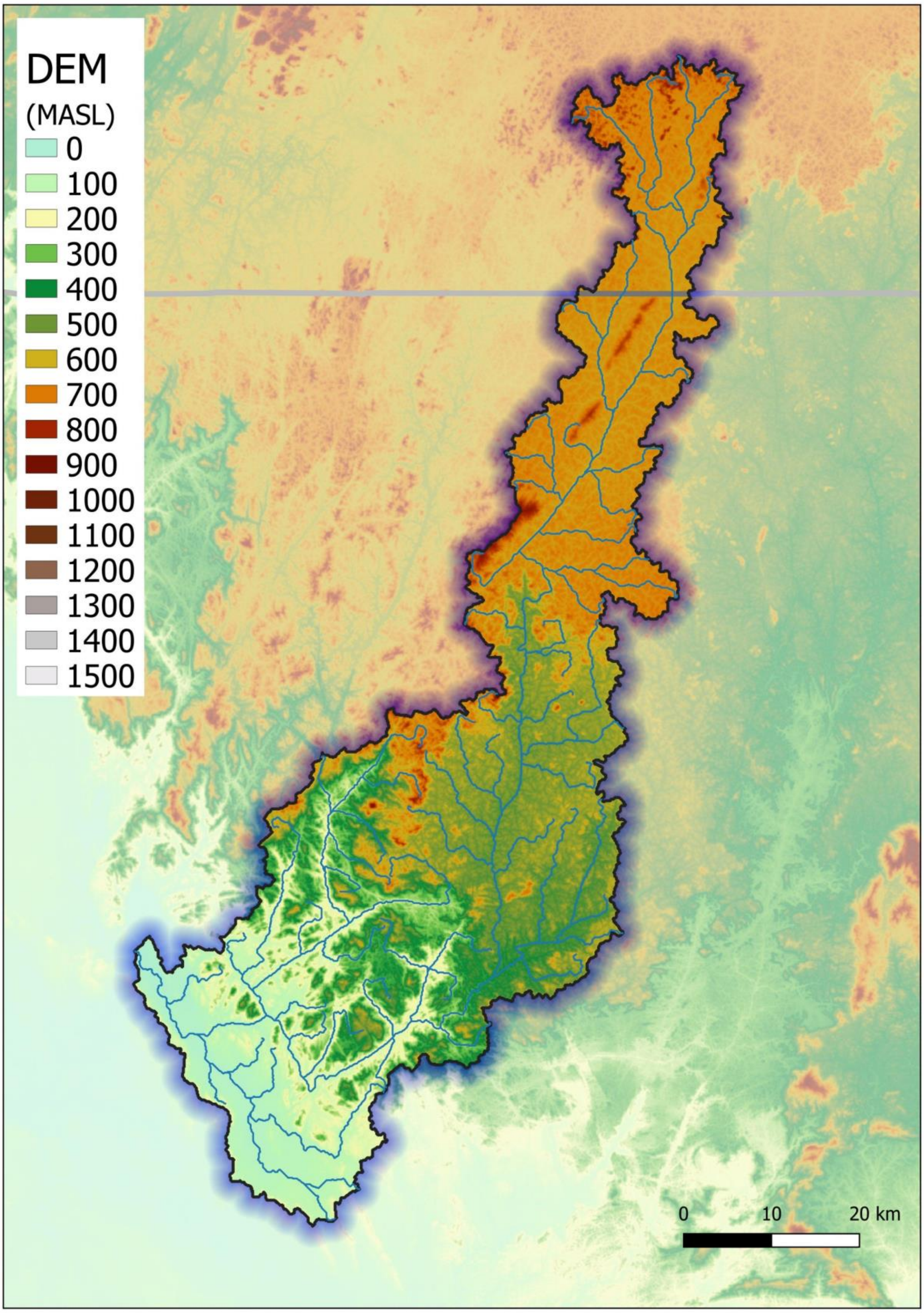
7 Annex: Enlarged Maps

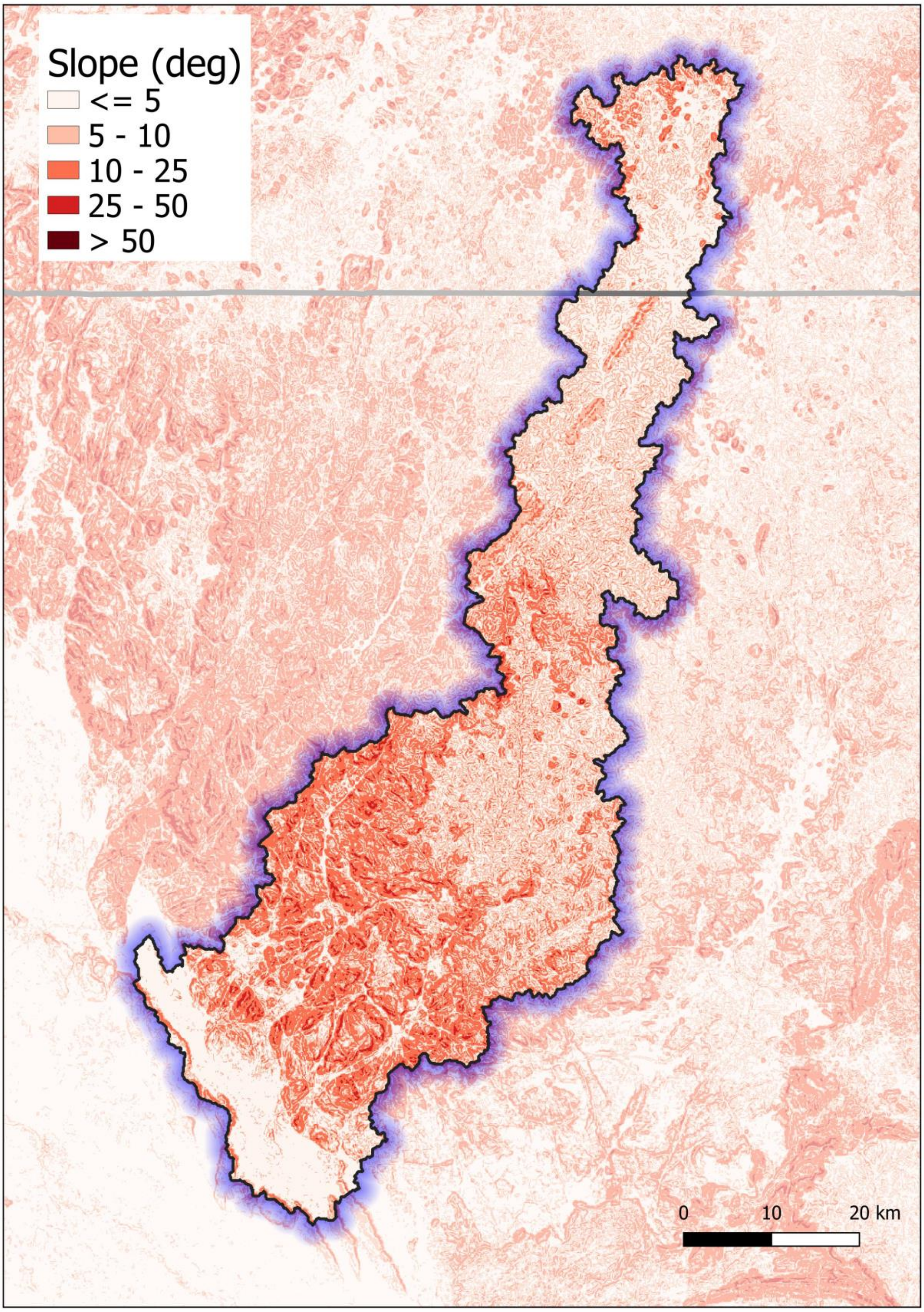


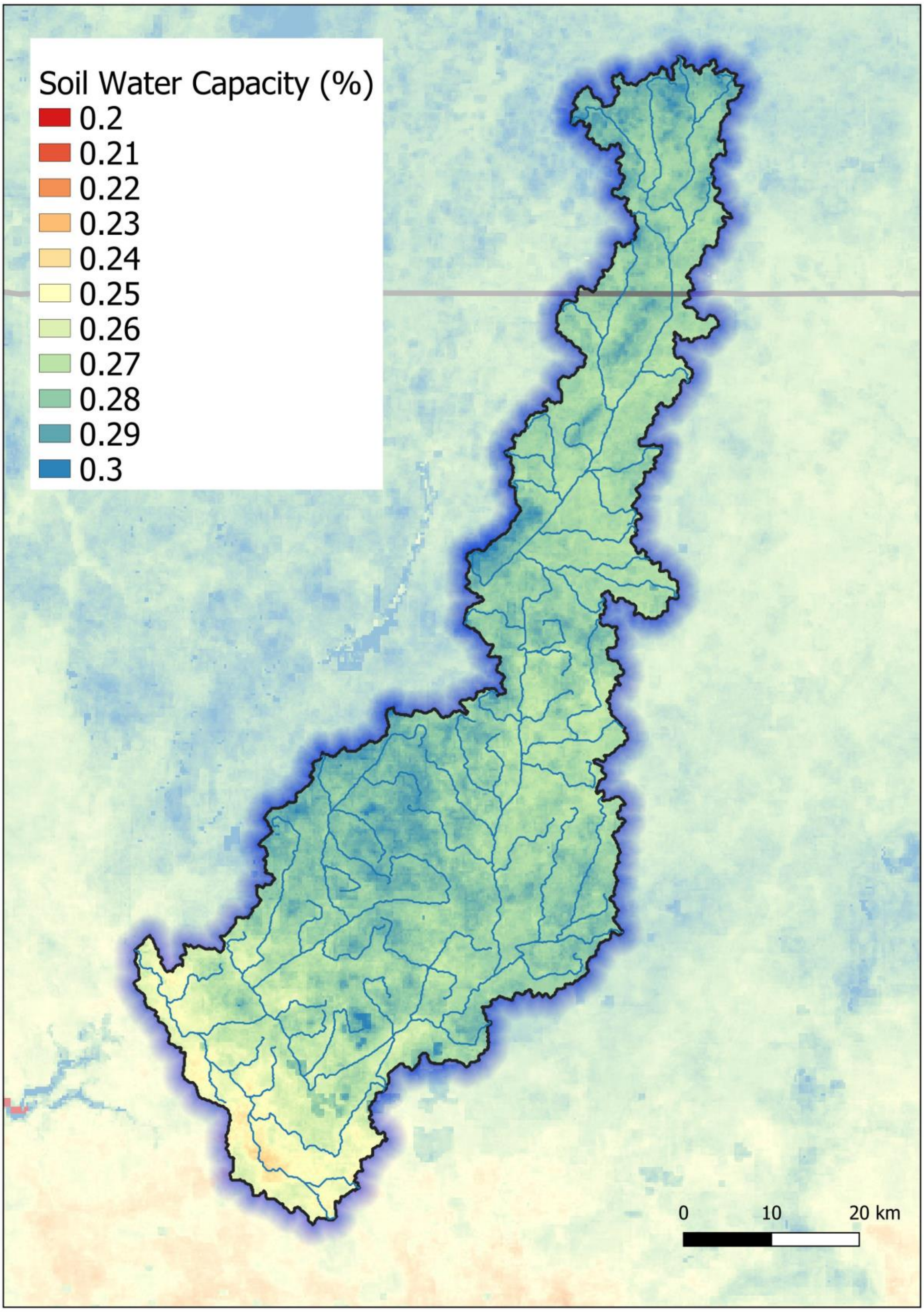

Oyem
Libreville
Makokou
Port Gentil
Lambarene
Kaulomoutou
Masuku
Mouila
Tchibanga
NIGERIA
CAMEROON
CONGO
EQUATORIAL GUINEA
SAO TOME AND PRINCIPE
Gulf of Guinea
Abuja
Yaoundé
Malabo
Douala
Brazzaville
Kinshasa
Luanda
0
300
600 km

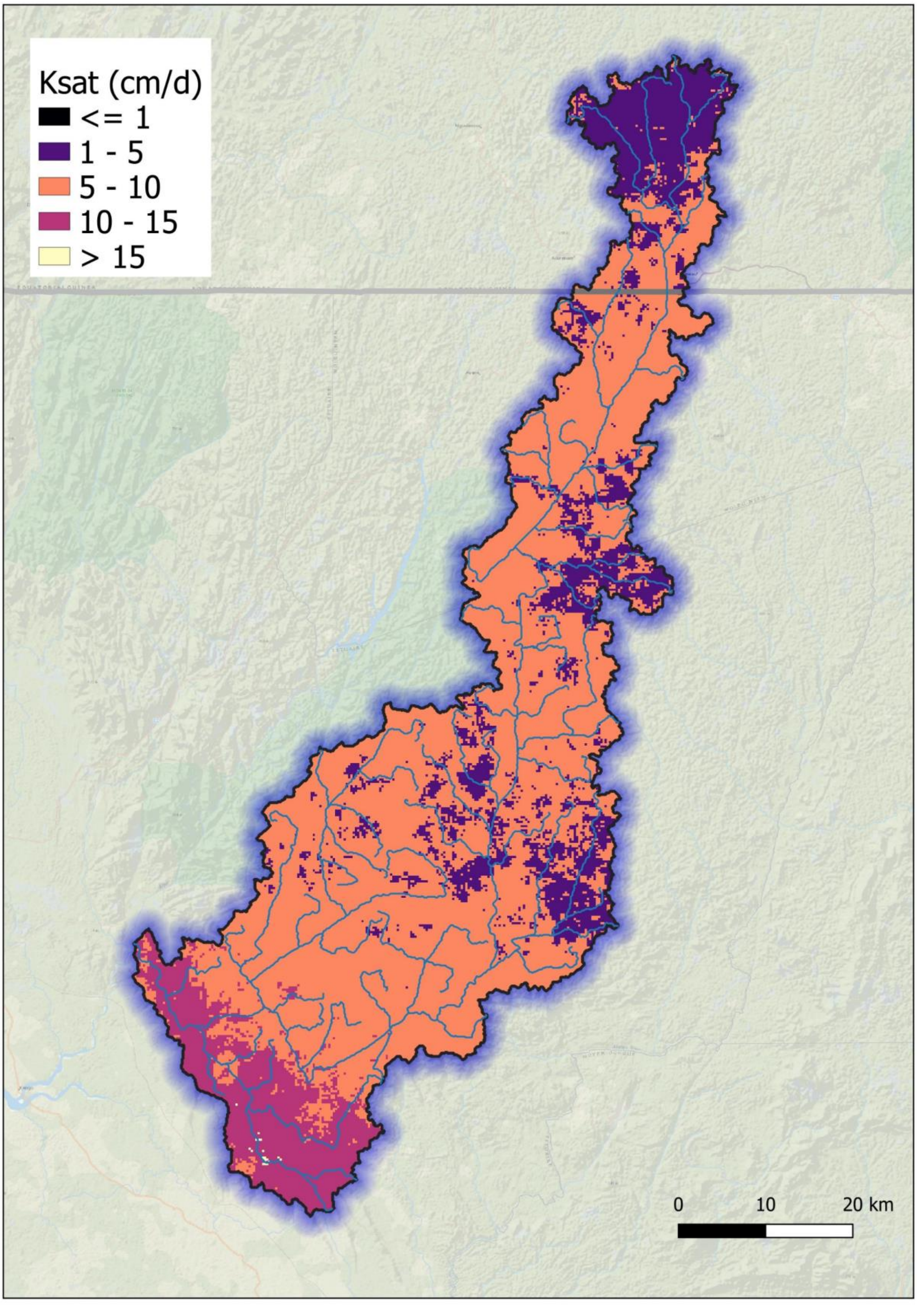


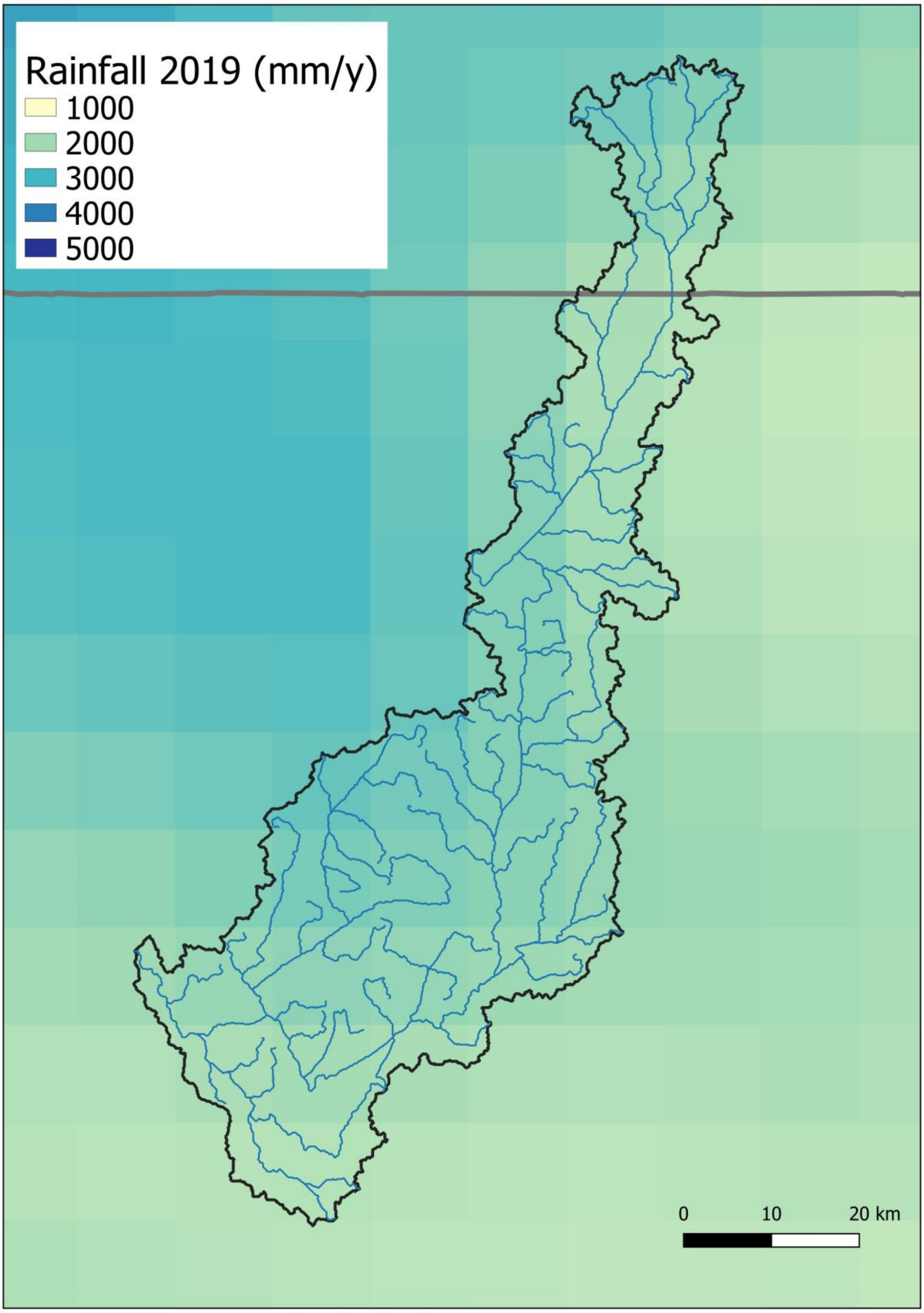
Dyeng
858 m
Acurenam
EQUATORIAL GUINEA
GABON
GABON
EQUATORIAL GUINEA
MONTS DE CRISTAL
900 m
889 m
N5
820 m
900 m
Mvei
979 m
U A I R E
914 m
719 m
609 m
684 m
Kango
Abanga River
341 m
M O Y E
142 m
736 m
0
10
20 km

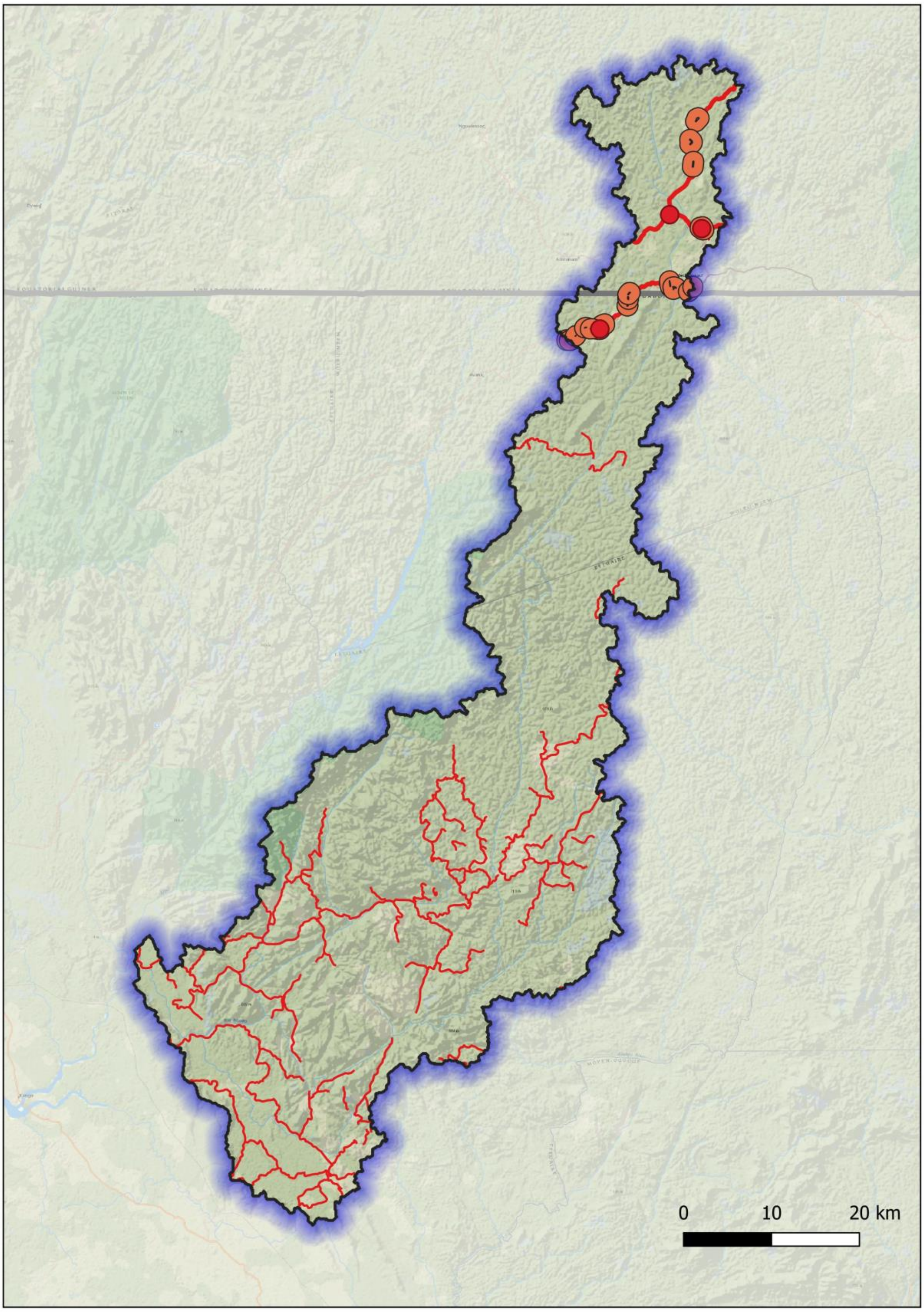

DEM
(MASL)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
0
10
20 km

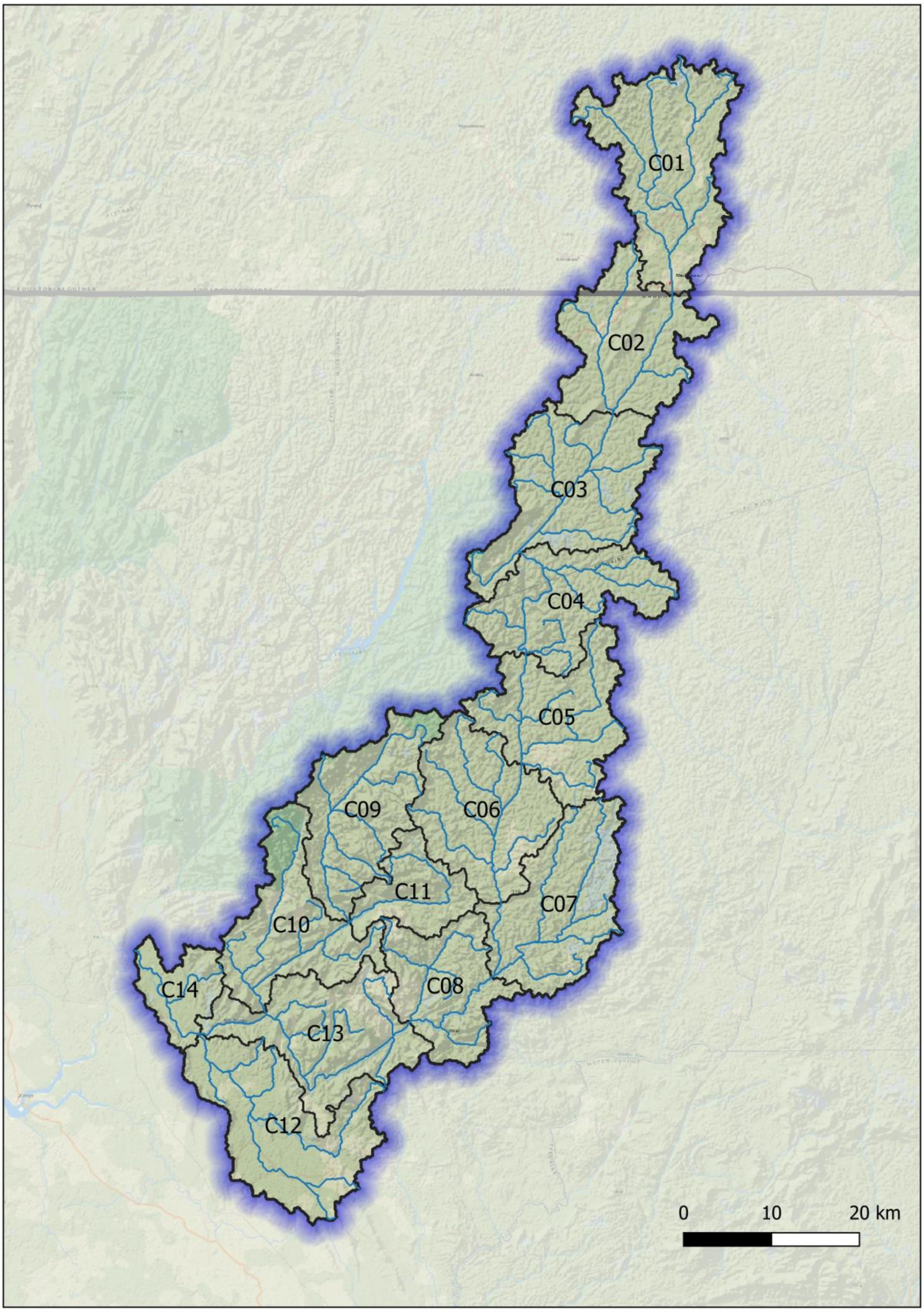

Slope (deg)
<= 5
5 - 10
10 - 25
25 - 50
> 50
0
10
20 km

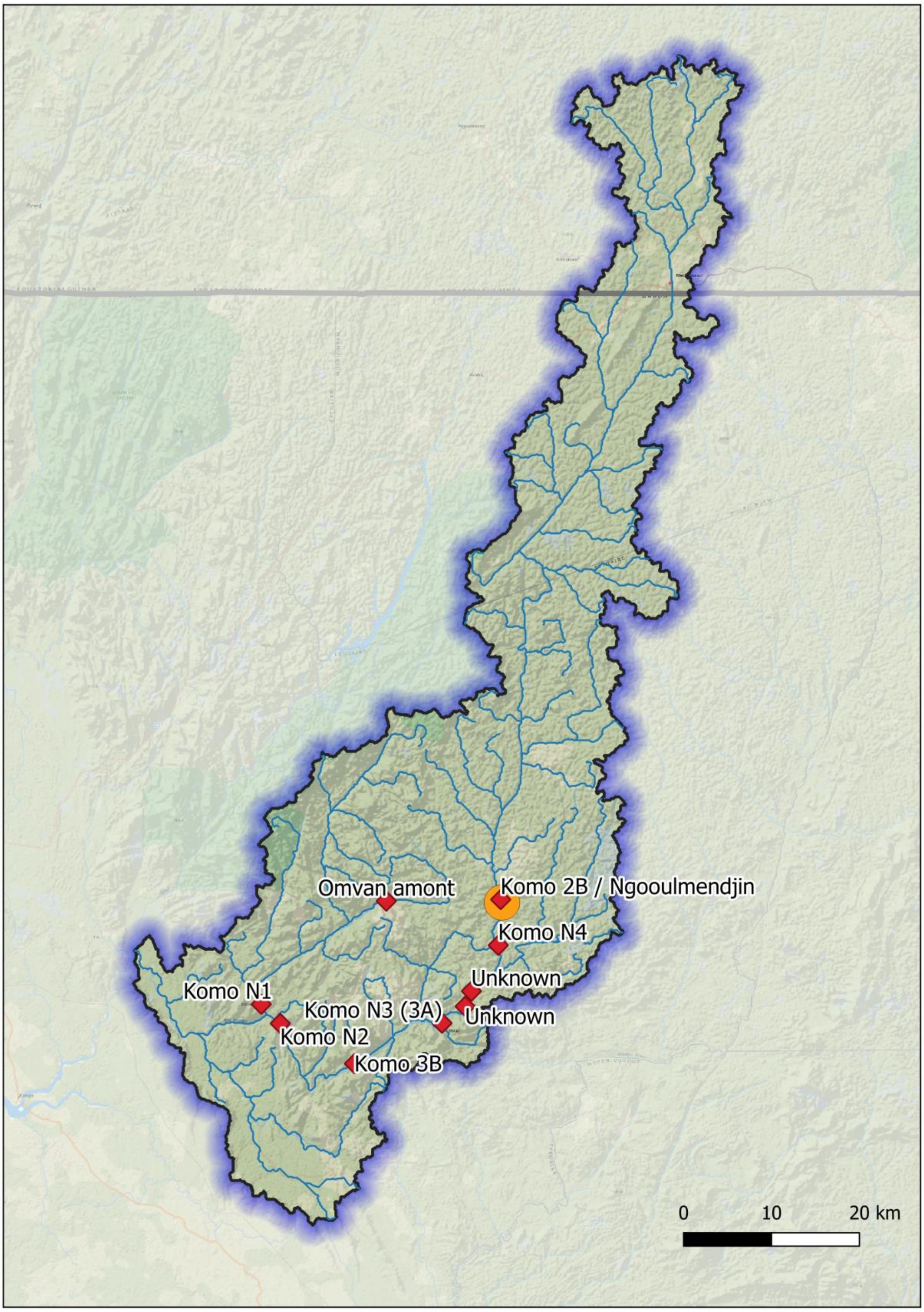

Soil Water Capacity (%)
0.2
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
0.29
0.3
0
10
20 km


Ksat (cm/d)
<= 1
1 - 5
5 - 10
10 - 15
> 15
0
10
20 km


Rainfall 2019 (mm/y)
1000
2000
3000
4000
5000
0
10
20 km


0
10
20 km


C01
C02
C03
C04
C05
C06
C07
C08
C09
C10
C11
C12
C13
C14
0
10
20 km


Omvan amont
Komo 2B / Ngooulmendjin
Komo N4
Unknown
Komo N1
Komo N3 (3A)
Unknown
Komo N2
Komo 3B
0
10
20 km