Reservoir operation simulation for existing and planned hydropower projects on the Niger and Benue catchments in Nigeria

Simulation de gestion de réservoirs hydroélectriques pour des projets existants et potentiels sur le Niger et la Bénoué, au Nigéria

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Abstract. In 2015/16, a hydropower site screening study was undertaken in Nigeria on the main stem of the Niger River and in the Benue River basin. The study assessed small (5-20 MW installed capacity), medium (20-100 MW) and large projects (> 100 MW) focusing on hydropower sites with potential multipurpose benefits. In the final stage of the study, three sites (two medium and one large project) were recommended for future development by the Government of Nigeria in liaison with the Niger Basin Authority (NBA). The study covered: Simulations of energy production and water demand satisfaction using the MIKE HYDRO Basin software. The modelling approach was based on maximizing energy production and maintaining a target mean load factor. (1) Impacts of reservoir development on hydropower production benefits, downstream flow variability, navigation downstream for three time horizons: current, mid development and maximum potential development. (2) Sensitivity analyses of water availability risks for hydropower generation for the three selected sites considering possible future abstractions and projected climate change. (3) Optimization of the use of the River Niger's White flood in Nigeria and study of the augmentation of the Kainji HPP in order to mitigate the potential future production losses due to upstream developments/abstractions outside Nigeria.

Résumé. En 2015-2016, un inventaire des sites hydroélectriques potentiels sur la branche principale du fleuve Niger et dans le bassin de son affluent la rivière Bénoué a été réalisé. L'objectif était d'identifier les sites potentiels pour développer de petits, moyens et grands projets hydroélectriques (puissances installées respectives de 5 à 20 MW, 20 à 100 MW >100MW), notamment pour les sites permettant le développement du multi-usages de

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l'eau. L'étude comprenait des : (1) Simulations du productible hydroélectrique et de satisfaction des demandes en eau avec le logiciel MIKE HYDRO. L'approche de modélisation était basée sur la maximisation de la production énergétique et le maintien d'un facteur de charge cible. (2) Impacts du développement des réservoirs sur la production hydroélectrique, la variabilité du débit et la navigation en aval, pour trois horizons : situation actuelle, horizons moyen et maximal de développement. (3) Analyses de sensibilité de la production hydroélectrique sur trois sites choisis par rapport aux prélèvements futures et projections climatiques. (4) Optimisation de l'utilisation de la crue dite « blanche » du fleuve Niger au Nigéria et étude de l'augmentation de la puissance de l'usine de Kainji pour réduire l'impact de la perte potentielle de production future due aux développements amont et externes du Nigéria.

1 Background

Nigeria is one of Africa's largest economies, however limitations in the power sector are a major constraint to its economic growth. Hydropower generation currently accounts for about 19% of total electricity generation in Nigeria [1]. The country currently has three large major hydropower plants: Kainji HPP (760 MW) and Jebba HPP (578 MW) on the Niger River and Shiroro HPP (600 MW) on the Kaduna River, a tributary of the Niger. A fourth large hydropower plant, Zungeru HPP (700 MW), is currently under construction on the Kaduna River downstream of Shiroro HPP.

New multipurpose projects (i.e. hydropower plus irrigation) or MPP are planned on the Niger River upstream of Nigeria. These include Kandadji MPP (Niger) which is in the construction phase, Taoussa MPP (Mali) and Fomi MPP (Guinea) which are currently in the planning phase. These developments are expected to reduce inflows to Nigeria and hence reduce the annual hydropower generation from the Kainji and Jebba HPPs. There remains significant hydropower potential in Nigeria, particularly in the Benue River basin and along the Niger River between Jebba and Onitsha. The Benue River is the largest tributary of the Niger River in Nigeria and its basin is largely unregulated. Natural flood events and uncontrolled releases from Lagdo MPP on the Benue River in Cameroon have resulted in a number of recent major flood events along the Benue and lower Niger rivers in Nigeria.

The country's renewable energy policy [1] includes objectives to "fully harness the hydropower potential in the country electricity generation" and "pay particular attention to the development of small, mini, micro and pico hydropower schemes for the growth of the rural economy". As part of efforts to harness the hydropower potential and prepare for future modifications of the Niger river's inflows, the Transmission Company of Nigeria – Project Management Unit (TCN-PMU) contracted Tractebel to undertake a hydropower site screening study in Nigeria. The study area included the Benue River basin within Nigeria and the main stem of the Niger River between Jebba and Onitsha, with the Benue River given priority for development in the short term.

2 Introduction

The purpose of the larger study was to identify the best potential hydropower sites in the study area. The study assessed small (5-20 MW installed capacity), medium (20-100 MW) and large hydropower projects (> 100 MW), with consideration given to sites with potential multipurpose uses such as irrigation and flood mitigation.

Table 1. Screening criteria.

Criterion	Contributing factors	Weighting (%)
Technical constraints	Hydrological risks Geological & geotechnical risks Connection point to existing power system Contribution to regional power system stability & diversity Construction works constraints	15
Financial feasibility	Role of scheme within the power system of Nigeria Financial characteristics	30
Social impacts	Involuntary resettlement Local & regional social impacts	20
Environmental impacts	Natural habitats Local & regional environmental impacts	10
Governance constraints	Local, regional and national water & energy policies Transboundary water and energy policies	10
Multipurpose benefits	Potential for multipurpose developments	15
TOTAL		**100**

3 Objectives of the study

The reservoir operation and energy studies were carried out to achieve two sets of objectives namely the evaluation of the impacts of new hydropower developments in the Benue River basin and on the main stem of the Niger River, and the optimization of the use of water resources for hydropower production on the Niger main stem.

The first objective involved the evaluation of the hydropower generation capacity at the 12 shortlisted sites based on the long-term river discharge dataset established for a period of 62 years (1951-2012), in accordance with the Client's requirement that stipulated that the hydropower generation simulations should be based upon a long-term period of at least 50 years. The aim of the simulations was to determine the individual and cumulative impacts of these potential schemes in the short-term, medium-term and long-term in terms of energy production and downstream water availability for other uses and navigation downstream of Lokoja. The second set of objectives was to (1) explore ways in which the Sokoto-Rima River System, a tributary of the Niger River, can be managed to optimize the use of the White flood of the Niger River main stem for hydropower production at Kainji and Jebba HPPs, and (2) study the possible augmentation of the Kainji HPP in order to mitigate the potential future production losses due to upstream developments/abstractions outside Nigeria.

4 Study area

The study area is defined as the Benue River basin within Nigeria and the Niger River main stem between Jebba and Onitsha. The Benue River basin falls within hydrological areas HA-III (Upper Benue) and HA-IV (Lower Benue) and was divided into 15 sub-basins for the purposes of this study. The Niger River main stem between Jebba and Onitsha falls within hydrological areas HA-II (Niger Central) and HA-V (Niger South).

The Benue River basin (HA-III and HA-IV) has the following characteristics:

- The largest right bank tributary of the Benue River is the Gongola River (53 000 km2) and the largest left bank tributaries are the Donga (20 000 km2), Katsina-Ala (23 000 km2) and Taraba (23 000 km2) rivers. Mean annual precipitation varies from > 2000 mm in the Eastern and North-Eastern Highlands and reduces in a northwards direction across the basin to < 600 mm in the northern-most areas of the Gongola River catchment. The North-Central Niger Plateau has mean annual precipitation of 1200-1400 mm.
- The basin is largely unregulated, with the only significant storages being Lagdo MPP (Cameroon), Dadin Kowa MPP (Gongola River, Nigeria) and Kiri MPP (Gongola River, Nigeria).

A map of the study area showing the hydrological areas is provided in Figure 1. The two stated study objectives were focussed in the areas illustrated in Fig. 2 and Fig. 3 respectively.

Fig. 1. The study area and the hydrological areas of Nigeria.

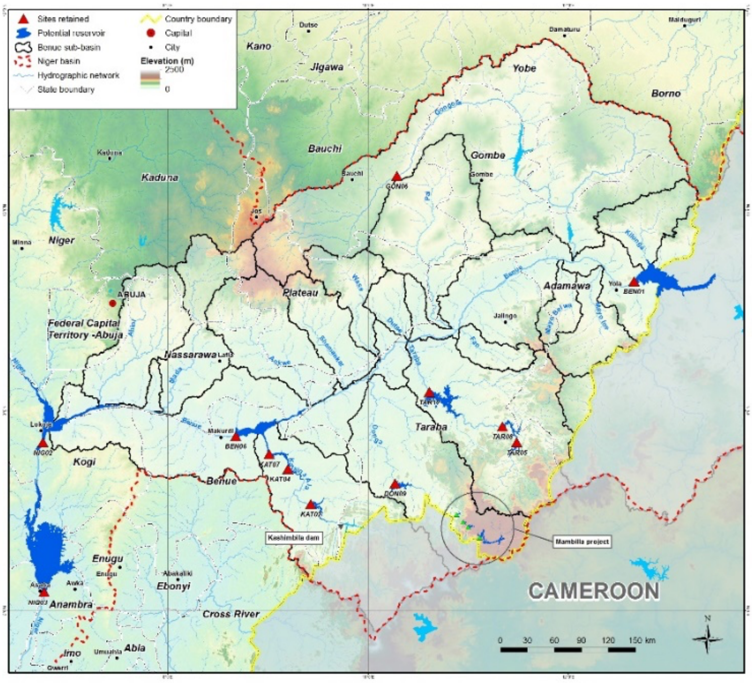

Fig. 2. Shortlisted sites (12) in the Niger and Benue basins.

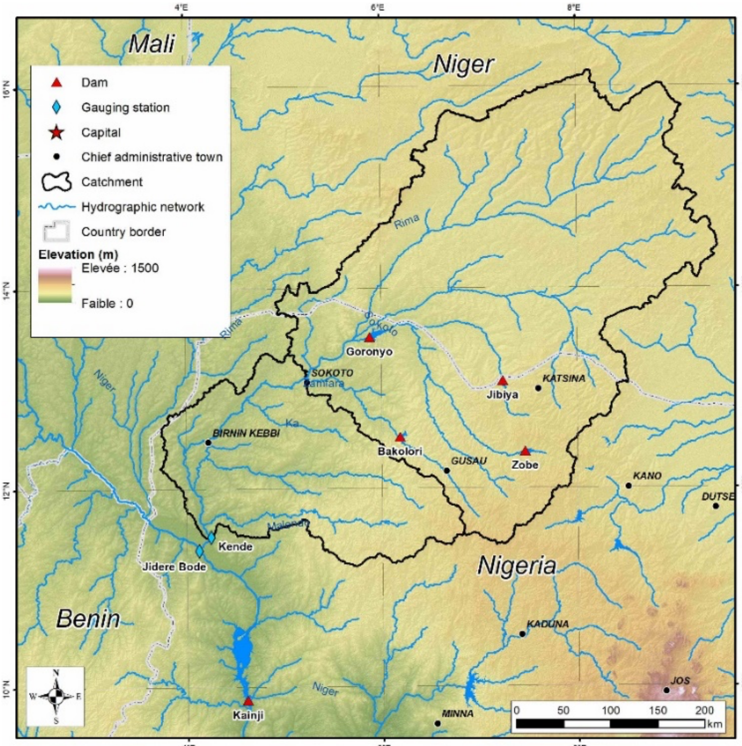

Fig. 3. Catchment area of Sokoto-Rima River System which produces the Nigerian White flood upstream of Kainji.

5 Data and modelling software

The required hydro-meteorological data were obtained from Nigerian Hydrological Services Agency (NIHSA), the Nigerian Meteorological Agency (NIMET) and Upper Benue River Basin Development Authority (UBRBDA) while reservoir operation data for existing dams were collected from the operators (Kainji, Jebba and Shiroro).

Relevant data on current and future water abstractions were collected from the Water Resources Masterplan [2]. Other relevant data related to dam developments outside Nigeria on the Niger River (particularly of Kandadji, Fomi and Taoussa dams) as well as irrigation development (enlargement of existing irrigation perimeters and the development of new perimeters associated with the dam projects) were taken from the Niger Basin Authority's Abstractions database report [3]. The reservoir and energy simulations were performed using the MIKE HYDRO Basin software, by the Danish Hydraulics Institute (DHI), which is a multipurpose, map-based decision support tool for integrated water resources analysis, planning and management of river basins.

6 Methodology

6.1 Modelling with MIKE HYDRO Basin software

The MIKE HYDRO Basin simulation software allows a 'target' power demand to be set with the possibility of producing in excess of this target up to the given 'installed capacity' when the reservoir is at the full supply level. The target power demand as well as the installed capacity can be given in units of flow (m3/s) or power (MW). The flow rate used for energy production at each time step is calculated based on the formula below:

$$P = \Delta h(Q) * Q * \varepsilon(\Delta h) * g * \rho_{water} \tag{1}$$

where:

P is the generated power in MW; *Δh* is the available effective head, which is a function of the downstream discharge and is the difference in elevation between the water level in the reservoir and the tail water level; *Q* is the turbine flow rate at each time-step; *ε* is the energy efficiency which is a function of the effective head (assumed constant at 0.86 for the purpose of these calculations); *g* is the acceleration due to gravity (9.81 m^2/s).

6.2 Evaluation of the impacts of new hydropower developments

A long-term inflow series was constituted for a 62-year period (1951-2012) for each of the 12 sites. Where necessary the inflow series were corrected for irrigation or other water withdrawals or to account for the current influence of existing dams on the Benue and Niger River main stems. In addition to the long-term hydrologic dataset, the simulations considered variable constraints over the short- to long-term linked to multipurpose water use and projected climate change.

In addition to meeting the Client's requirements for the length of the inflow record, the record comprises wet periods and a particularly dry period between 1982 and 1990 and allowed the simulations to be carried out over a wide range of real inflow conditions. Furthermore, the results can be analysed statistically in the context of dry year/average year/wet year. The most recent period is also a wet period.

6.2.1 Modelling approach

The modelling approach applied in this study, based on the modelling possibilities available within the software*, was one that:

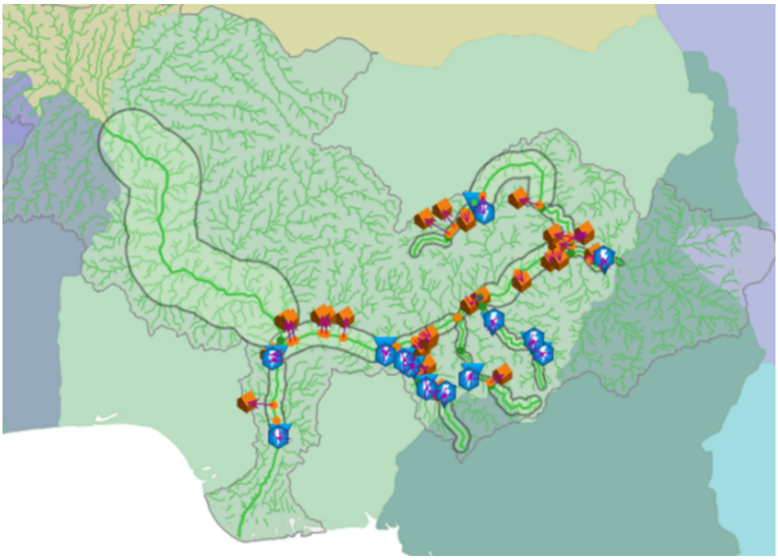

Fig. 4. Schematic representation of the MIKE HYDRO Basin Niger-Benue water resources allocation model (12 shortlisted sites).

- Sought to maximize the energy that can be produced in 95% of all months in the discharge record at each site.
- Targeted an agreed upon mean annual load factor of 0.5 (ratio of actual production for a given month to the installed capacity).

The required load factor served as a basis for selecting the installed capacity (together with the maximum obtainable guaranteed power) at each site. The maximum monthly energy that can be produced at each site was determined iteratively and was dependent on the flow duration characteristics of the inflow time series as well as on the storage (volume) of each reservoir. In other words, this corresponds to the maximum flow that can be supplied by the reservoir to the power plant 95% of the time considering the 744 months in the discharge record.

6.2.2 Dam development scenarios

Twenty development scenarios were developed in order to characterize the potential impacts of reservoir development on hydropower production as well as on the Niger-Benue system. The influence of the recently completed Kashimbilla reservoir on the Katsina-Ala River was considered, as was the influence of the planned Mambilla hydropower project on the Donga River's flows to DON09. The influence of the other existing dams upstream of the projects (such as Lagdo dam in Cameroun and Shiroro, Jebba and Kainji dams in Nigeria) were

* See screen shot (Fig. 4) of the developed model (reservoirs and hydropower plants – shown in blue) as well as the water abstraction points that affect each of the 12 sites (shown in light brown).

accounted for by correcting the long-term inflow record for the Benue and Niger rivers respectively as described in section 6.2.

Based on the information provided in a World Bank publication [4], navigability thresholds were determined in the Niger Basin Authority's Sustainable Development Action Plan (SDAP) for the Niger basin [5]. These analyses were applied to the reference data 1951-2012 to develop the thresholds for navigability downstream of Lokoja based on the reservoir operation simulation results.

6.2.3 Definition of inflow scenarios

The irrigated surfaces for three time horizons (current, mid development and maximum potential development) were determined based on data in the National Water Resources Master Plan [2]. These horizons correspond to short-term, medium-term and long-term situations respectively.

The current values were taken as the actual cropped areas. The maximum development horizon was taken as the estimated future irrigation area by 2030 (potential area of irrigation estimated from surface water availability). The mid development horizon was considered as the mid-way point between the two horizons. The study also evaluated uncertainties due to projected climate change. Projected impacts [6] of climate change on inflows were based on the values for the 2050 horizon (2036-2065) and the 10th, 50th and 90th percentile values were adopted as the low, most probable and high flow future scenarios, respectively and applied to the calculated monthly inflows at the selected sites for the 1951-2012 period. On the annual scale, the low to high probability flow ranged from - 21% to +90% of the calculated inflows to the selected sites.

6.3 Optimization of the use of the White Flood and study of HP augmentation

6.3.1 Optimization of the use of the Niger River's White flood

The "White flood", which is usually heavily laden with silt and is derived from more local flows driven by the Niger River's tributaries downstream of the inner delta (including the tributaries in Nigeria), occurs between August and October at Kainji (see Fig. 5). The major tributary of the Niger River producing the White flood is the Sokoto-Rima River System (see Fig. 3).

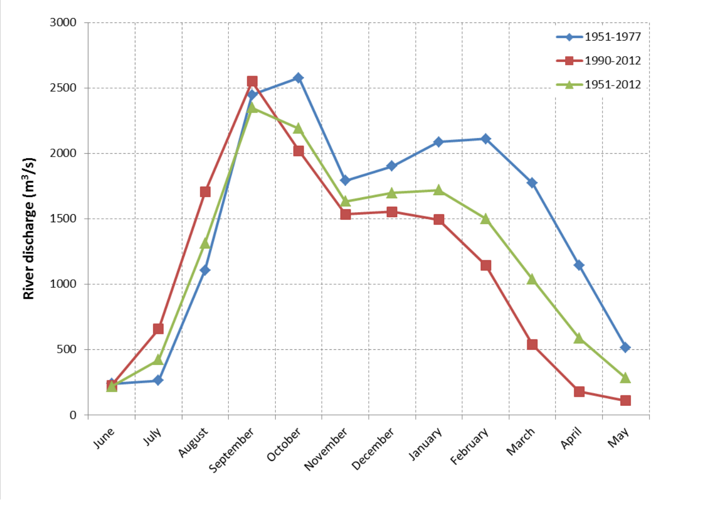

Fig. 5. Hydrographs of the Niger River at Kainji showing the two distinct floods.

In addition to the decreasing trend of inflows since the 1980's, the White flood has also been modified by the development of dams in the Sokoto-Rima basin (developed for irrigation and completed between 1978 and 1990). Therefore, the approach to the question of optimizing the use of the White flood for hydropower production of Kainji and Jebba HPP involved the following:

- An analysis of the reservoir characteristics and the operations of the four major dams upstream of Kainji (Bakolori, Zobe, Jibiya and Goronyo);
- An analysis of the relative contribution and timing of inflows of the Sokoto-Rima system to the White Flood at Kainji.

6.3.2 Feasibility of augmentation of Kainji HPP

The specific objectives of this analysis were to (1) Estimate the theoretical energy production possible at Kainji with the current installed capacity of 760 MW, and (2) Study the possibility of increasing the installed capacity of the Kainji power plant based on given inflows for the current situation (historical inflows) and future inflows due to upstream developments outside Nigeria.

The methodology to achieve the above objectives consisted of:

- Determining the monthly energy that can be produced 95% of the time (as described earlier) based on the simulation period 1951-2012 and current and future inflow scenarios.
- Simulating the theoretical energy production of the Kainji power plant for the current installed capacity of 760 MW and in 50 MW increments to test the sensitivity of the installed capacity/total energy relationship.

The reservoir operation and energy simulations for studying the feasibility of the augmentation of Kainji HPP were carried out considering the current situation and the three future scenarios described below:

- Future scenario 1: The minimum impact case is the development of Kandadji dam in the Republic of Niger which is already underway. The developments represent an additional water volume demand of 5759 Mm^3 per year) for new irrigated surfaces.
- Future scenario 2: An intermediate development case with the full development of Kandadji but with the intermediate development (+10 years horizon) of all other irrigated surfaces including those associated with Fomi and Taoussa dams.
- Future scenario 3: A full development case (+20 years horizon) for irrigation perimeters associated with Fomi and Taoussa dams amongst others.

7 Key results

7.1 Twelve sites

The table below presents results of the reservoir operation and energy studies including the estimated installed capacity (MW), plant factor, firm energy[*] (GWh/year), annual guaranteed energy[**] and total energy (GWh/year).

[*] Calculated on a monthly basis;
[**] Calculated on an annual basis

Table 2. Summary of energy simulation studies.

No.	Site ID	Site name	Installed capacity (MW)	Plant factor	Firm energy (GWh/yr)	Annual guaranteed energy (GWh/yr)	Total energy (GWh/yr)
1a	BEN01(165)	Dasin	32	0.5	23	108	142
1b	BEN01(180)	Dasin	120	0.5	307	382	526
2	GON06	Kirfi	19	0.5	13	52	84
3	TAR05	Karamt	24	0.5	25	77	103
4	TAR08	Jamtari	60	0.5	82	201	265
5	**TAR12**	Garin	92	0.5	212	333	403
6	**DON09**	Manya	136	0.5	168	495	594
7	**KAT02**	Bawar	182	0.5	110	659	798
8	KAT04	Achin-Kondo	79	0.5	47	290	344
9	KAT07	Katsina-Ala	109	0.5	62	402	476
10	BEN06	Makur	290	0.5	258	992	1271
11	NIG02	Lokoja	467	0.6	1148	2062	2443
12	NIG03	Onitsh	441	0.65	1176	2150	2510

In terms of:

- Hydropower production benefits: While the development of any of the 12 shortlisted sites would increase hydropower generation and is therefore positive, if the reservoir capacities or the hydropower potential of their respective catchments are considered, much more hydropower can be produced either as storage schemes or as run-of-river schemes. The reservoir storages (harnessed potential) are typically small in relation to the total annual inflow volumes in the respective basins (mostly less than 10% except for BEN01 and TAR12).
- Downstream flow variability:
  - BEN01 and **TAR12** have a significant positive impact on dry season flows.
  - The proposed Mambilla project has a moderate positive impact on dry season flows; **DON09** has negligible impact.
  - BEN01 and **TAR12** have a mixed impact on wet season flows. The impact of the different dam development scenarios on annual flood ranged from negligible to moderate because of the relatively small reservoir capacities. The most impactful developments are the 3 dams on the Taraba River (3% to 20% reduction) and BEN01 dam (21% reduction). One of the objectives of the BEN 01 dam near the Cameroon – Nigeria border is to reduce the impacts of floods from the Lagdo dam in Cameroon.
  - None of the shortlisted dams is upstream of any of the Wetlands of international importance.
  - All other sites have a negligible to moderate impact on dry season flows.

- Navigation downstream of Lokoja:
    - The BEN01 reservoir, developed alone, is capable of improving the number of navigation days at Lokoja by 8 days per year.
    - The development of reservoirs on the Taraba River provides navigation benefits with an increase in the period of navigability of the Niger River at Lokoja: especially with the development of the **TAR12** reservoir and further improving if the three reservoirs on the Taraba River are developed.
    - The development of the BEN06 reservoir with all the other reservoirs also developed upstream will provide the most benefit to navigation below Lokoja (8 days per year).
    - All other developments have either a negligible impact or no impact on navigation downstream of Lokoja.

7.2 Final three sites recommended for development

The final phase screening was undertaken collaboratively with stakeholders in a workshop environment based on the characteristics and multi-criteria scores (see Table 1) of the 12 shortlisted hydropower sites. Two of the sites are newly identified sites (DON09 and KAT02), while the TAR12 site was already identified in previous studies. Water availability risks affecting hydropower generation and the satisfaction of downstream water demands were analysed for the final three sites: TAR 12 (medium) and DON09, KAT02 (large) multipurpose schemes. The risks relate to future irrigation water demands upstream and downstream of the sites and future climate change impact on inflows. The results are summarized below:

- Impact on hydropower production due to maximum future upstream irrigation water demands: Small impact for TAR12 (-1.3%; 5000 ha potential irrigation area), negligible impact for DON09 and KAT02.
- Impact on downstream irrigation water demands due to new reservoirs and maximum future upstream irrigation water demands: No negative impacts; TAR12 has a significant positive impact on dry season flows.
- Impact on hydropower production due to future climate change impact on inflows (current irrigation water demands):
    - DON09: -17% (low), -2% (average), +21% (high).
    - KAT02: -17% (low), -2% (average), +19% (high).
    - TAR12: -11% (low), +1% (average), +14% (high).
- The study also identified that some form of water regulation will be required upstream of TAR12 in order to satisfy the maximum future irrigation water demands under the climate change conditions (low flow scenario).

The analyses demonstrated that irrigation water demands – which are the only major water demands in the vicinity of the final three sites – have a negligible impact on hydropower production, even for the maximum future irrigation water demands. On the other hand, the climate change projections that can be considered as pessimistic would lead to reduction in hydropower generation of between 11% (TAR12) and 17% (DON09 and KAT02) when combined with the maximum future irrigation water demands.

For all the scenarios modelled, downstream irrigation water demands are satisfied 100% of the time on the Donga, Katsina-Ala and Taraba rivers.

7.3 Optimization of the use of the Niger River's White flood in Nigeria

While no dedicated reservoir simulation was carried out on this subject, the analysis of inflows and expected releases from the four irrigation dams indicated (Fig. 6) that although the White flood generated by the Rima River is at a maximum in September, the relative contribution to inflows at Kainji is not at the highest in September.

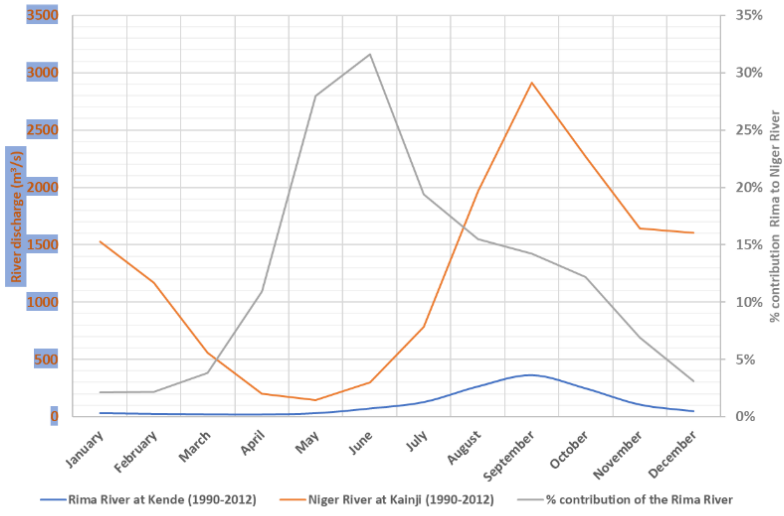

Fig. 6. Relative contribution of the Rima River to inflows at Kainji.

This is because the White flood is generated by all the tributaries downstream of the Niger River inner delta in Mali (the Gorouol, Dargol, Sirba Alibori, Mékrou rivers amongst others) before the White flood arrives in Nigeria. It can be assumed that the Rima River would contribute a higher percentage of Niger River inflows in August and September without the four irrigation dams. However, Fig. 6 shows that at the start of the White flood, the Sokoto-Rima River System sustains inflows to Kainji in May and June (28 to 32% of inflows due to the Rima River). The monthly variation of river discharge at Kende on the Rima River (catchment area: 169 461 km^2) for the post-irrigation reservoir development period (1990-2012) is shown and compared with discharge at Kainji in Fig. 6. It can be seen that on average, the White flood generated by the Rima River occurs between July and October, with a peak in September.

In order to maximise the use of the White flood, the operating regimes of the four irrigation dams located upstream of Kainji should be optimised to minimise evaporation (average evaporation losses amount to about 29% of the inflows, according to Oyebande [7]) and to promote the efficient use for irrigation and hydropower.

7.4 Augmentation of Kainji HPP

The analyses indicated that if operated optimally, the installed capacity at the Kainji hydropower plant can be greatly increased under the current conditions.

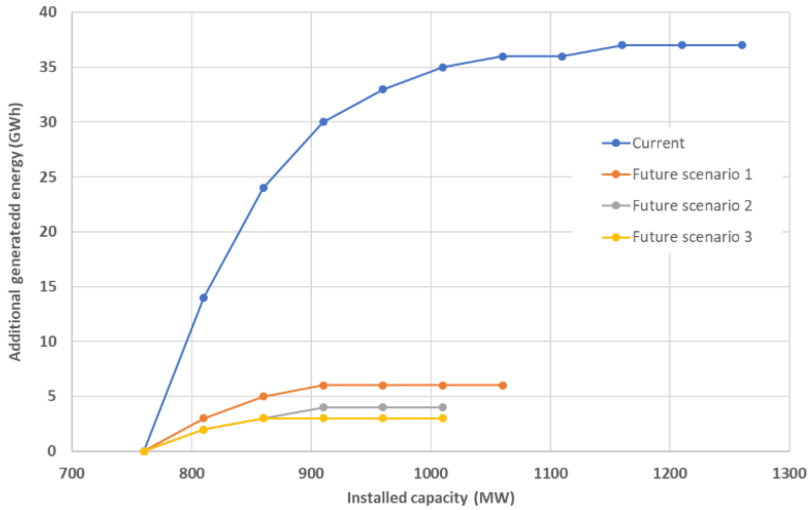

Fig. 7. Increase in mean annual energy vs increasing installed capacity at Kainji.

This possibility becomes limited with the upstream developments of reservoirs and planned increases of water abstractions for irrigation. The results illustrated in Fig. 7 indicate that for the worst-case scenario (Future scenario 3), a 50 MW increase in installed capacity would produce an additional 2 GWh/year compared to 14 GWh/year under current conditions. For the worst-case scenario (Future scenario 3), Fig. 7 shows that beyond an additional installed capacity of about 150 MW (910 MW installed capacity in Fig. 7), the added benefit in terms of annual energy is negligible.

7.5 Impact of upstream developments (outside Nigeria) on Kainji & Jebba

The Kainji and Jebba reservoirs and hydropower plant operations were simulated for the period between 1951 and 2012 with the aim of assessing the theoretical energy production of Kainji and Jebba plants for the current situation and for the three future scenarios described in section 6.3.2. The results of the present analysis are similar to a USACE evaluation [8] of the mean annual energy for "a hydro station the size and capacity of Kainji" if the power plant is operated at a plant factor of 45%. 3015 GWh/year in this study compared with the estimation in the Kainji technical assessment report (2996 GWh/year). Note that the observed average annual energy generation over the 26-year period between 1975 and 2000 in [8] is 1906 GWh with a 29% plant factor. The optimized plant factor in the present study for the Kainji simulations was found to be 45.2%.

The energy simulations for Jebba HPP resulted in an average annual energy of 2802 GWh/year. MacTavish & Matthews [9] estimated the average annual energy of the Jebba HPP in the design study phase to be 2646 GWh/year; therefore, the value from the energy simulation in the table below appears reasonable. Table 3 indicates that with full upstream development (for developments outside Nigeria), the combined mean annual energy generation at Kainji and Jebba could be reduced by up to 28%.

Table 3. Kainji and Jebba HPPs – impact of future upstream development scenarios.

Scenario	Kainji HPP (760 MW) Average energy (GWh/year)	Jebba HPP (578.4 MW) Average energy (GWh/year)	Combined Average (GWh/year)	% change from current case
Current case (theoretical)	3015	2802	5817	
Minimum development	2361	2355	4716	-18.9%
Intermediate development	2147	2201	4348	-25.3%
Full development	2051	2136	4187	-28.0%

8 Key learnings

This paper highlights water resources allocation modelling as a powerful tool for objective comparison between multiple development paths which enables the analysis of possible outcomes over the short-term, medium-term or long-term. The paper further demonstrates how future constraints such as climate change or new water demands that can affect the ability of multipurpose projects to fulfil set objectives can be integrated into the process of modelling and results analyses. Such reservoir operations simulations therefore provide a solid basis for focussing planning and decision-making.

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