Reviewer 2

Review of "Disentangling Sources of Future Uncertainties for Water Management in Sub-Saharan River Basins", Amaranto et al. This paper presents a study that applies a decision framework for developing optimal operating policies for the Barragem de Pequeños Libombos (BPL) Reservoir in Mozambique. This reservoir has been constructed to serve the water supply to the greater Maputo area. It also serves irrigation up and downstream of the reservoir, and a hydropower station to generate energy. A multi-objective evolutionary optimisation approach is applied to find optimal operating policies. The robustness of these policies to changes in irrigation demand, urban demand, and climatic conditions is then explored. Finally, the sensitivity of both robust and non-robust policies to these changes is explored, concluding that robust policies are sensitive primarily to changes in climatic conditions and consequent changes in reservoir inflows, while non-robust policies are also sensitive to population growth and structural interventions. This last points is perhaps one of the more interesting aspect of the contribution to the readership of HESS. Besides that the paper seems to focus primarily on the application of the optimisation approach and exploration of robustness and sensitivity. In this sense the scope of the paper appear to hinge on two thoughts, one being the optimisation approach that is proposed and in particular the exploring the sensitivity of optimal polices, and the second the application to the case of the BPL reservoir. Though the application of the methodology is of interest, and to some extent of an interest to the readership of HESS, the manuscript does not reflect on the findings in the broader context than the particular case study in which the method is applied. As a result it is also not entirely clear to what extent the conclusions established are case study specific, or if these can be made more generically. This would require a much improved discussion interpretation of the results. This would also be more appealing to the scope of HESS if that discussion is presented within the hydro-sociological context and how the specific choices and assumptions that are made reflect on the generality of the conclusions. In the general comments below this is elaborated on. Overall the paper is well written and well structured. However, the authors have not really paid much attention to the correct use of grammar. While a possible copy-editing phase would easily solve several issues, a more careful preparation would have been expected. There are many sentences with multiple grammatical errors. Some examples are included in the detailed comments, though these are not considered to be exhaustive but rather as illustrative.

AR: We thank the reviewer for this outstanding review. Her/his constructive comments helped us improve the manuscript and strengthen our analysis.

General Comments

RC: It would be very helpful if more details are provided on the hydrological characteristics of water availability and demand, and also reflecting on the size of the reservoir in relation to that demand. First, it would be useful to be explicit as to the average availability of water. A rough estimate made from figure 2 would suggest that the mean annual inflow is about 7.5 m3 /s, with 10-90 percentile variability as indicated. This constitutes about 236 Mm3 per year. The volume of the reservoir is reported to be 382 Mm3 per year. This would then be 50% more than the average annual inflow, which means that for this reservoir the inter-annual variability is of importance. The paper does mention that a part of the storage is inactive, which also influences the sensitivity of the policies, but it is not clear how much this inactive storage is. Reviewing the numbers pertaining to demand, the irrigation demand (upstream and downstream) is mentioned to be some 33 Mm3 per year on average. The water supply demand is stated to be 80 Mm3 so it is clearly the dominant demand, which is in line with the purpose of the reservoir (it would be useful to understand the date for which this demand has been established). Demand to meet environmental needs is set at 15%, with a simple estimate being about 35 Mm3 . In any case, these numbers suggest that total demand (irrigation + urban + environmental) used as a benchmark is about 62% of the average annual inflow. It is also some 38% of the storage of the reservoir. Though these percentages have been estimated somewhat roughly based on the data, they are useful to interpret the results, to understand the degree of water stress, and also how well the reservoir can buffer the variability of the inflow to meet demands. I believe the authors should develop a more extensive reflection on how the results they find depend on these ratios of availability and demand, as a more stressed situation where availability and demand could well yield quite different results. It would also be important to understand the inter and intra annual variability of the inflow, related to these ratios, and a more elaborate discussion of how these ratios influence the conclusions on robustness and sensitivity. What would happen if, for example the available storage of the reservoir was much smaller than the average annual inflow, or the average annual demand? The numbers presented as a baseline do not suggest a situation that is under extreme stress. Also, the changes to irrigation demand (25%) and Urban demand (2%) constitute in absolute values only some 8 Mm3 and 1.6 Mm3 annually. This appears to be somewhat modest in relation the average annual inflow and the size of the storage, which would suggest variability and uncertainty can be easily buffered. I would be very curious if the authors could reflect on how these values influence their conclusions on the importance of the variability of the hydrological inflows which suggest a reduction of between 5% and 40% of the inflow, constituting some 12 to 95 Mm3 , so already much more dominant from the outset. The manuscript would increase in scientific interest if a more elaborate discussion is provided that reflects on the ratios between the available water and the demands, as well as the relative magnitude of variability and changes.

AR: We thank the reviewer for the very useful comment and the detailed explanation. Even though hydropower does not represent a consumptive water use, the turbine capacity exceeds downstream irrigation and urban demand combined. Once water is released from the reservoir and turbined to produce electricity, part is diverted to the irrigation district, part is used for urban supply, and the reminder flows in the estuary of the river, exiting therefore from the system under investigation. Consequently, the total water consumption might exceed the 62% of the average annual inflow. This, in turns, might cause water shortages during the winter season, when the inflow reaches its annual minima.

This is confirmed by the severe water scarcity issues affecting the Pequenos Libombos reservoir, which stood at about 18% capacity in January 2021, and 26% in January 2020 (similar issues were also recorded regularly, through the past decade). It is therefore reasonable to assume that the system under the baseline conditions is indeed under extreme stress.

However, we agree with the reviewer suggestion: it would be useful for the reader to provide more details on the hydrological characteristics of water availability and demand, contextualizing such trajectories on the size of the reservoir and the dynamics of storage though the year. Therefore, in the revised manuscript we will better clarify the water quantity involved and their relationship. Specifically, we will add a table including the average annual water volume entering the reservoir, pointing out how such volume is partitioned through seasons. The aggregated water demands for each sector, in relationship with the reservoir volume will be enclosed in an additional table. Information on the inactive storage will be explicitly mentioned as well in the revised manuscript. This will also provide insights for a better framing of the results regarding the sensitivity of the operating policies to uncertain exogenous factors.

RC: I have some doubts on the formulation of the optimisation problem, and how representative this is for the case being studied. It appears that the water supply to Greater Maputo is considered a lower priority to meeting irrigation demand. There is a hedging rule applied in Eqn 3, but ultimately the water supply of Maputo is established as the remainder of the actual downstream release, after actual delivery to irrigation and meeting the environmental flow demand (eqn.5). In the introduction, however, it is noted that the reservoir is currently operated in a different way. The supply to Maputo gains priority over irrigation, with the latter being stopped if there is insufficient water. This suggests a fundamentally different policy is followed than that which is suggested here. This raises the question how realistic the proposed approach in modelling the operating policy is, and what the impact of this limitation is on the findings and conclusions.

AR: The reviewer is correct. Meeting demand for the city of Maputo is pillar in the operation of the Pequenos Libombos reservoir. However, in the definition of the optimization problem, equation 3 does not prioritizes irrigation over urban supply. In fact, equation 3 defines the fraction of releases to be diverted for irrigation purposes as inversely proportional to α, and exponentially growing with respect to β.

The feasibility set of such parameters allows the evolutionary algorithm to also explore α and β values (and combinations thereof) which places urban supply in foreground with respect to irrigation. It is (as an example) the case of α values much higher than the reservoir releases (the $\frac{r_{t+1}^d}{\alpha}$ term would assume near zero values) or the case of large β values for $\frac{r_{t+1}^d}{\alpha} < 1$ (the amount of water diverted to irrigation drops to about 15% of the demand for $\frac{r_{t+1}^d}{\alpha} = 0.9$ and $\beta = 20$, and to 1% of the demand for $\beta = 45$). The opposite would be true for α values considerably smaller than the release decision.

In other words, the optimization problem formulation generates α and β combinations which could allow the exploration of the whole irrigation-urban supply tradeoff. We are aware that, in the actual operation of the Pequenos Libombos reservoir, the supply to Maputo gains priority over irrigation, with the latter being stopped if there is insufficient water. However, to analyze any possible behavior of the regulator, we decided to include also operating policies which prioritize irrigation over urban demand.

Considering the importance of a clear understanding of the operating rules which characterize the diversion dam, we will provide a more detailed explanation of equation 3 in the revised manuscript.

RC: I would expect that a much higher sensitivity to population growth would then be found, and that the competition between urban supply and irrigation would be exacerbated, as in more extreme growth population growth scenarios this prioritisation would mean irrigations may become unfeasible. I would again think the manuscript would gain in interest if a discussion is provided as to the extent to which the formulation of the optimisation problem reflects the actual operation of the reservoir, as well as how that formulation influences the conclusions found.

AR: We thank the reviewer for the precious comment. The sensitivity to population growth strictly depends on the operating policy upon which the sensitivity index is calculated. For example, Figure 8 shows a negligible impact of population growth on the urban deficit for RUD (blue dots and boxes), while the opposite is true for NR (red dots and boxes).

In addition, Figures 5 and 6 evidence how the competition between urban supply and irrigation is indeed exacerbated in the most extreme scenarios, with RID and RUD providing similar objective function values in the baseline but penalizing in turns one stakeholder over the other under deep uncertainty conditions (i.e.: in water scarcity conditions).

The low sensitivity values of irrigation supply with respect to population growth, (as well as the high sensitivity of irrigation to agricultural area expansion) are depending upon the formulation of the operating rules for the diversion dam expressed in equation 3 (i.e., release from the dam and agricultural demand). However, figure 7 clearly show that the hypothesis of 'feasible irrigation no matter the population growth' holds only for expansion in irrigated area up to about 2%, while for any further expansion the operating rules of the diversion dam prioritize urban supply causing a strong deficit increase. This is also confirmed by figure 8a, which shows how RUD, by diverting water to the city of Maputo, can fulfill urban demand no matter the population growth rate, penalizing irrigation as a consequence (if the streamflow depletion is lower than about 35% and the construction of the pipeline is completed soon enough).

Once again, the reviewer is correct in pointing out that the supply to Maput would always gain priority over irrigation in a real-world situation, especially in the most extreme conditions. For the sake of providing the full spectrum of tradeoff, we have included all the possible operating options in our analysis. To ensure that the reader has the complete set of information, we will emphasize the actual operating rules of the reservoir in the revised manuscript.

RC: Related to this comment is also the question on how realistic the scenarios chosen are. The growth rate of Maputo has been set at some 2%, which seems modest. Those familiar with the area would know that Matola is growing much faster than Maputo, at some 4% per year, and is already larger than Maputo itself.

AR: The reviewer is correct: Matola is growing much faster than Maputo. The growth rate of 2% per year which is used in this study is representative of an average over the whole area: the metropolitan area of Greater Maputo which includes the Municipalities of Maputo, Matola, and Boane, and it is provided in the literature by:

"Droogers, P., de Boer, F., and Terink, W.: Water Allocation Models for the Umbeluzi River Basin, Mozambique, 2014, Report Future Water 132, Fryslân".

RC: Also, can the growth in demand be considered as linear with population? Several studies show that increasing development also result in an increase in water demand disproportional to population growth. Given the dominance of the urban demand, and the very modest increase such factors could well be discussed. It may be that the conclusions found on the sensitivity of robust strategies are indeed valid within the very modest growth scenarios explored. There may well be a limit to the change in which the conclusion on sensitivity holds, after which this sensitivity may increases dramatically. This would help generalise the findings of the paper.

AR: we thank the reviewer for the suggestion. It is true, we assumed an irrigation demand which grows linearly with population. However as in *Droogers* et al., (2014), the demand grows overall exponentially, considering an exponential population growth of 2% every year.

The reviewer is right: the sensitivity of robust strategies holds within the perturbation set we assumed for this study. This is true for population, as well as for irrigation expansion and streamflow depletion. We will clarify this aspect in the revised version of the manuscript.

RC: Continuing on from this comment, it would also be useful to understand the rationale of the objective functions themselves. Hydropower is clearly a by-product in the operation of the dam as there is no demand to meet (or a penalty if such demand is not met) and simply maximises the profit from generation. Given the primary purpose of the dam that would appear reasonable. The other objective functions, however, apply a squared residual to irrigation deficits and a linear residual to urban water supply deficit. This seems somewhat incongruous to already noted priority of urban water supply to irrigation, as it would tend to minimise irrigation deficits with respect to deficits in urban supply. I agree that the factors in eqn.3 influence this preference, but it would be good to understand the rationale behind this choice. A more detailed description of the water allocation policy to irrigation would be useful. If there is insufficient water, and given that the crops are predominantly cash-crops, it would make sense that farmers simply scale the cropped area - which would suggest a linear loss if demands are not met.

AR: The reviewer provides an interesting insight: it is indeed true that it would make sense that farmers simply scale the cropped area - which would suggest a linear loss if demands were not met.

One the other hand, the quadratic water supply deficit is a traditional formulation in reservoir operations since the work by Hashimoto et al. (1982). The square of the irrigation deficit accounts in fact for crop vulnerability by penalizing higher shortages, which are more likely to compromise the crop growth, with respect to more frequent but smaller shortages, which are less dangerous to the crops. To better clarify, we have included this explanation in the revised manuscript.

Further references on the use of the squared deficit as an irrigation step-cost can be found at:

Denaro, S., Castelletti, A., Giuliani, M., & Characklis, G. W. (2018). Fostering cooperation in power asymmetrical water systems by the use of direct release rules and index-based insurance schemes. Advances in Water Resources, 115, 301-314.

Giuliani, M., Li, Y., Castelletti, A., & Gandolfi, C. (2016). A coupled human-natural systems analysis of irrigated agriculture under changing climate. Water Resources Research, 52(9), 6928-6947

Hashimoto, T., Stedinger, J., Loucks, D. (1982). Reliability, resilience, and vulnerability criteria for water resource system performance evaluation. Water Resources Research, 18(1), 14–20.

RC: Further discussion should also be provided on the scenarios developed to represent climate change. The method chosen is simple, which I agree is appropriate within the context of this study. However, if I understand correctly the change is a linear factor applied to the whole time series. This does not resolve any changes to the inter-annual variability of inflows. I am not fully familiar with climate outlooks for this particular basin, but presume the influence of climate change may be more multi- dimensional than a simple proportional reduction across the year. There could also be changes in the distribution of flow across the wet and dry season. Such shifts are of important to reservoir operation policies. This may be relevant to the ability of the reservoir to the meeting of irrigation demand, which is (logically) primarily in the mid and late dry season.

AR: in our study, we adopted an approach resembling the delta change for the states of the world generation (Brown et al., 2012). The sampling strategy decreases the historical streamflow (which includes both dry and wed hydrological conditions) by as much as 40%, following the results obtained by a conceptual hydrological model fed by nine downscaled general circulation models' results. The 5000 samples are drawn from a uniform distribution over the multiplier interval (0-0.6).

However, we agree with the reviewer. A change in the hydroclimatic patterns would most likely imply a shift in the hydrological regime of the river basin, with implications on the distribution of streamflow across seasons. Such variations in the streamflow distribution are not embedded in the so-generated states of the worlds.

On the other hand, the 55000 (5000 multiplier perturbations of the 11 years of historical data) hydrological years upon which the system is simulated provide, together with the samples from the other uncertainty source, a states of the world discretization grid which is dense enough to consider both the extremes and the intermediate scenarios over which the robustness of the various operating policies is computed, together with their sensitivity across uncertainty sources.

Following this line of thought, we modified the manuscript to provide the reader an understanding of the limitations of our approach in characterizing streamflow distribution through the year, and we enhanced the description on the scenarios developed to represent climate change.

"Brown, C., Ghile, Y., Laverty, M., & Li, K. (2012). Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. Water Resources Research, 48, W09537. https://doi.org/10.1029/2011WR011212"

Detailed Comments:

AC: Please revise the grammar in the whole manuscript. Here is an example of one or two sentences with multiple grammatical errors. All minor and easily resolved, but a careful grammatical review could improve the readability (green indicates and addition, red-strikethrough a deletion, while text in blue indicates where the text does not make sense, grammatically).

Lines 33-38 An archetypal example of a highly regulated, fast evolving South-Saharan hydrosystem is the Lower Umbeluzi river basin, Mozambique. About 45 km upstream of its delta in the Maputo bay, the river flows in the Barragem de Pequenos Libompos reservoir, which is operated to balance hydropower production, urban supply to the two million inhabitants of the Maputo province, and irrigation supply for to the 3600 ha of agricultural districts, mostly growing tropical fruits and sugarcane. A currently undergoing five year long drought have has boosted crop prices by about 50%, hindering food access to a population currently growing at rate of 0.6% per year and exacerbating conflicts among the urban, agricultural and energy sectors. currently undergoing: this is not grammatically correct as it is not clear what is currently undergoing a five year long drought.

Line 38: Fryslân et al. 2014 is a very peculiar reference. In fact Fryslan is the organisation that published the report and is not a person. Either the organisation should be used, or the actual authors – but not a mix. The details of the reference in the reference list are insufficient and need to be completed.

Line 42: The world bank is funding

Lines 44-47: This section describes that the policy makes have certain needs. How were these needs ascertained? Was this a discussion held with these stakeholders, or are the fact that these are needs based on an assumption made by the authors?

Line 51: I am not sure this paper can be said to be tackling the evolution of the system drivers. Perhaps identifying would be a better word.

Line 71: what does not seem the correct word – please rephrase.

Lines 80-88. Please provide more detail on the dam and its outlets. In particular the size of the inactive zone (see general comments) and the maximum capacity of the penstock, and if the penstock is the only controlled outlet structure. This is suggested to have a capacity of 2x the combined downstream irrigation and urban demand, which would be 2.9 m3/s. Back-calculating with an installed capacity of 1.8 MW this would suggest the turbine efficiency is 73%, which is quite low. Please provide the correct numbers to help interpret the various results. In several places in the text it is suggested these are known, but they do not appear to be explicitly mentioned. Additional discussion should also be included on the presence of upstream reservoirs in the basin in Eswatini. These do exist.

Line 80: upstream of the estuary

Line 81: goal of supplying

Line 82: in Line 36 it is mentioned that irrigation is used for tropical fruits and sugar-cane. Here bananas as mentioned (which are tropical fruits). What happened to sugar cane?

Figure 2a. I do not fully understand the red line in this figure, but assume this is the median daily inflow. However, there are several peaks where the red line is at the limits of what the caption suggests is the 10-90 percentile range. Also, during the dry season, there seems to be an almost constant maximum to the 10-90 percentile range. Please clarify these data as these are if I understand correctly simulated data from the HBV model.

Figure 1a. The upstream irrigation areas in the map are incorrectly coloured. Also, the figures show there are unregulated tributaries. To what extent do these have a role in meeting demand?

Line 106: I assume the water is pumped to the irrigation districts and not from.

Line 129: Check spelling

Line 177/179: Please clarify the units for hydropower. Also, please provide the value of the efficiency of HP production applied.

Line 199: the sentence "which are known for well-validating out of sample data" needs to be rephrased as it is not clear

Line 234-260: The description of the samples is not clear. It would be clearer to describe each set of samples as a vector that is made up of the four parameters that sampled from their respective (uniform) distributions. Then K-vectors are sampled.

Line 254: What is value of the project horizon H?

Line 286: Please be specific on the likelihood function used. Is this constructed based on the simple summation of the four constituent objective functions? Please clarify how these are weighted.

Line 289: What is the rationale of selecting the 5%? Is there any relationship to impacts? Also it is not completely clear if this is the 5th exceedance of 5th non-exceedance percentile. Please clarify.

Line 371-374: It is somewhat confusing to refer to hydropower having a demand in the context here. Hydropower is generated as a by-product of the release to downstream irrigation and to meet urban demand. I would rather rephrase it as hydropower production.

Line 378-379: The grammar of this sentence is very poor. Please improve.

Line 387-388: Could the ability to meet the RID to endure water supply no matter the expansion of the irrigation area be linked to the size of the area. The maximum change of the d/s irrigation is on the order of 2.7 Mm3 which is quite a limited amount (~3.4%) compared to the benchmark public water supply (see also general comments)

Line 394: Please check the units (also in other lines). What does 140 m3 /s/Year mean? This would suggest this is the mean annual flow? That does not appear to be correct. Please check this and other similar units.

AR: we would like to thank the reviewer for the thorough review of the manuscript, we appreciate how addressing all the detailed comments provided above will undoubtfully improve the overall quality and readability of the paper. Therefore, we took them in consideration while revising the document.