Reply Letter

Title: Transboundary water sharing policies conditioned on hydrologic variability to inform reservoir operations

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MS No.: hess-2021-72 **MS type:** Research article

General comments

The article is well-written, scientifically sound and within the scope of the journal.

Reply: Thank you very much for your positive feedback. We specifically address your comments below, particularly focusing on providing more details about constraints and experiment settings for GERD reservoir operations.

Detailed comments

1. Following are the aspects that could be incorporated into the article.

The actual values of the constraints defined in equation 4 to 7 need to be specified. This is especially pertinent because the range of optimal power generation obtained in the study range from 1707 to 1788 MW while the estimated power generation of 15130GWH per year which implies an average power generation of 4202 MW. The reservoir storage trajectories on Figure 6d reveal an assumed maximum storage of 74 billion cubic metres which is the intended capacity of GERD. The article does not indicate whether the upper power generation limit (PU_t in equation 7) equals the intended installation capacity of 5000 MW. On Figure 6d, the reservoir trajectory for a power output of 1788MW is very high and close to full storage for most of the period suggesting that achieving 15130GWH (4202 MW) would require more of what has been simulated as spillage to run through the turbines to generate more electricity. A discussion of how the analysis here relates to the intended installed capacity and power generation would enhance the relevance of the article to the practical transboundary issues regarding the operation of the GERD.

Reply: Thank you for your suggestions. We have specified actual values of the constraints defined in equation 4 to 7 in the revised manuscript as below.

The reservoir structural and operational constraints can be expressed as:

$$S^{\min} \le S_t \le S^{\max} \qquad (1)$$

where $S^{\min}$ and $S^{\max}$ are the minimum (14.8 billion m^3) and maximum (74 billion m^3) allowable reservoir storage.

Additionally, S^{begin} and S^{end} represent the initial and final reservoir storage (m^3) for simulations (both of them are set as 65.1 billion m^3), respectively, and are prescribed as:

$$S_t = \begin{cases} S^{begin} & t = 1 \\ S^{end} & t = T \end{cases} \quad (2)$$

(c) Reservoir release limits:

The reservoir release constraints are expressed as:

$$QL_t \le Q_t^{out} \le QU_t \quad (3)$$

where QL_t and QU_t are the minimum and maximum release (m^3/s) in period t, respectively. The expected guidelines for GERD reservoir water release are not explicitly available, thus releases are set higher than zero and lower than the maximum reservoir inflow (21.9 billion m^3/month) during the high-flow season to reduce or eliminate downstream floods.

(d) Power generation limits (Tesfa, 2013):

$$PL_t \le P_t \le PU_t \quad (4)$$

where PL_t and PU_t are the minimum (0 MW) and maximum (6000 MW) power limits in period t, respectively.

Regarding the upper power generation limit or installed capacity, it needs to be noted that there is uncertainty in media reports around the number for GERD which ranges from 5,150 MW (Ezega News, 2019a) to 6,000 MW (Ezega News, 2019b;Zelalem, 2020). The number (6,000 MW) which was used both in the annual electricity production estimation (aforementioned 15130GWh = 15130*1000/(24*365) = 1727 MW) and previous publicly available scientific studies (Tesfa, 2013;Yang et al., 2021) is opted in this study. It is worth noting that re-running the simulations with an installed capacity of 5,150 MW instead of 6,000 MW does not change principal conclusions. We have further clarified it in the revised manuscript as below.

When completed, the GERD will become the largest hydroelectric dam (installed capacity more than 5,000 MW) in Africa (Government of Ethiopia, 2020) and will have a total reservoir capacity of 74 billion cubic meters. The GERD is expected to produce an average of 15,130 GWh of electricity annually (with mean output of 1727 MW) (Tan et al., 2017;Tesfa, 2013), which will contribute to Ethiopia's national energy grid and feed the East African power pool (Nile Basin Initiative, 2012). There is uncertainty in media reports regarding the total installed capacity for GERD which ranges from 5,150 MW (Ezega News, 2019a) to 6,000 MW (Ezega News, 2019b;Zelalem, 2020). A value of 6,000 MW, which was applied both in the annual electricity production estimation and previous *publicly available scientific studies (Tesfa, 2013; Yang et al., 2021), is opted for this study. It is worth noting that re-running the simulations with an installed capacity of 5,150 MW instead of 6,000 MW does not change principal conclusions.*

Ezega News: Power generation capacity of GERD slashed to 5150 MW—Ethiopian Minister, https://www.ezega.com/News/NewsDetails/7331/Power-Generation-Capacity-of-GERD-Slashed-to-5150MW-Ethiopian-Minister, 2019a.

Ezega News: Ethiopia dismisses reports of capacity reduction of GERD, https://www.ezega.com/News/NewsDetails/7321/Ethiopia-Dismisses-Reports-of-Capacity-Reduction-of-GERD, 2019b.

Tesfa, B.: Benefit of grand Ethiopian renaissance dam project (GERDP) for Sudan and Egypt, 2013.

Yang, G., Zaitchik, B., Badr, H., and Block, P.: A Bayesian adaptive reservoir operation framework incorporating streamflow non-stationarity, J Hydrol., 594, 125959, 2021.

Zelalem, Z.: Ethiopia and Egypt are pushing each other to the brink in a battle for control on the river Nile, Quartz Africa, https://qz.com/africa/1862962/ethiopia-egypt-battle-for-river-nile-grand-dam-without-trump/, 2020.

2. Following are the aspects that could be incorporated as recommendations for further work.

The study applies the historic sequence (from 1965 to 2017) just downstream of the GERD dam and reliability considerations are incorporated by the statistical treatment of the residuals of the linear function relating annual releases to annual inflows (equation 10) during low flow years. The resulting range of variability for the different exceedance levels as illustrated in Figure 4 is low and probably underestimates the impact of hydrologic variability. Since the historic sequence is not very long and seems to include only two severe drought periods (from 1978-1988 and 1991 - 1997 as seen on Figures 7 and also reflected on Figure 6d), the extension of the historic inflow records using (its correlation with) the longer-term records available in the Nile basin could enable a more realistic assessment of the effects of droughts on the system and how the GERD could be best operated during such severe droughts. It is during such periods of severe water shortage that tensions are likely to rise among the riparian countries. A more comprehensive probabilistic approach based on stochastically generated ensembles of the extended inflows could also be considered.

Reply: Thank you for your suggestions. We appreciate that you point out the impact of hydrological uncertainty on GERD operation simulations and optimizations. Yes, it is true that there are limited drought periods in the historical streamflow time series (during 1965-2017), which may lead to uncertainty in water sharing during severe droughts and may underestimate the impact of hydrologic variability on GERD operation. That said, we did test our model by bootstrapping observations to create many sequences, including those having longer drought periods that historically observed, however the overall hydropower and release outcomes were virtually indistinguishable. Thus we opted to continue with the historical time-series.

However, we full agree with the reviewer, and for future work we will extend the streamflow record at the El Diem gauging station (which is located just downstream of GERD site) by relating it to other gauging stations in Nile basin. We agree that this synthetic GERD inflow records could further our understanding of the impacts of hydrological uncertainty on the trade-off between upstream benefits and downstream drought risks and the corresponding drought policy design.

In addition to the hydrological uncertainty, the uncertainty in drought policy design (e.g., choosing slope parameter α and exceedance parameter z in equation 10) should also be considered to better understand its influence on GERD power generation and downstream drought risk. Finally, the trade-off in objectives may be affected by land use or climate changes, and if significant, the drought policy may need to be adjusted accordingly.

We have included these future work opportunities in the conclusion of the revised manuscript as below.

It is worth noting that there are limited drought periods in the historical streamflow time series, which may lead to greater uncertainty in water sharing during severe droughts and may result in underestimating the impact of hydrologic variability on GERD operations. To address this, the GERD inflow record could be extended by relating it to other long-term gauging stations in the Nile basin to capture more historical droughts and better characterize hydrologic conditions for enhanced policy design. In addition, the trade-off in objectives may be affected by land use or climate changes, and if significant, the drought policy may need to be adjusted accordingly in the future.