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Would Africa's largest hydropower dam have profound environmental impacts?

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Abstract

In the face of rapid growth in the global demands for water, energy, and food, the boom in building large dams is expected to continue. Due to its expected opportunities and risks for the 260 million people of the Eastern Nile Basin, the Grand Ethiopian Renaissance Dam (GERD) on the Nile River – currently under construction – has commanded regional and international attention. Once completed, it will rank the largest hydropower dam in Africa and among the largest worldwide. Discourse among scientists and negotiators from the three directly affected countries, namely Ethiopia, Sudan, and Egypt, on the design, initial filling, and long-term operation of the GERD is ongoing since the construction started in 2011, but no agreement has yet been reached. The discourse has hitherto focused on the impacts on hydropower production, water availability, and irrigated agriculture but overlooked possible environmental and climate impacts of the GERD. Here, we communicate our viewpoint on this gap. The hydro-ecological flow alterations associate with the GERD could negatively impact fish, aquatic plants, and biodiversity due to changes in the river flow pattern, water temperature, and water evaporation. The GERD expected flooded area, location at a low latitude in the tropics and the deep turbine intakes could signify greenhouse gas emissions, especially methane, to the atmosphere. With a maximum reservoir area of 1904 km^2, surface evaporation and consequently regional extreme precipitation and humidity could increase. These likely environmental and climate impacts would have transboundary ecological, agricultural, and health implications and, therefore, should not be ignored.

Keywords: Grand Ethiopian Renaissance Dam; Eastern Nile Basin; hydro-ecological alteration, regional climate; greenhouse gases; tropics

Introduction

Globally, the number of dams and the total hydropower capacity have been increasing in recent decades (Mulligan et al. 2020) and will continue to rise, with over 3,700 large hydropower dams either planned or under construction (Zarfl et al. 2015). The growing demands for water, food, energy, industry, and recreation are catalysts for an anticipated future boom in dam construction (St. Louis et al. 2000; Chen et al. 2016). The water sector is thought to be responsible for the lack of systematic documentation of impact analyses of large dams even after decades of operation (Biswas and Tortajada 2001).

The ongoing construction of the Grand Ethiopian Renaissance Dam (GERD) on the Nile River near the Ethiopian-Sudanese border is increasingly becoming of significant interest, not only to the 260 million people of the countries of the Eastern Nile Basin (Fig. 1) but also internationally. Upon completion, the GERD will become the largest hydropower dam in Africa and among the largest globally (Mulligan et al. 2020) with an installed capacity of 5,150 MW. The dam is anticipated to double the annual electricity generation of Ethiopia. Debates and negotiations between the three directly affected countries, namely Ethiopia, Sudan, and Egypt, on the design, initial filling, and long-term operation of the GERD are ongoing since 2011 when the construction started. From November 2019 to February 2020, the mediation embarked on the White House in the United States of America (USA), with the World Bank also joining the negotiations, but no agreement has been reached (United States Department of the Treasury 2020). Since July 2020, the African Union hosted further negotiations between the three riparians without reaching a consensus on the GERD management.

In the literature, the opportunities and risks surrounding the GERD are explored. On the one hand, the GERD could potentially ease the hydro-political tension between Ethiopia, Sudan, and Egypt by enhancing cooperation and coordination (Yihdego et al. 2016). On the other hand, the initial filling of the GERD reservoir, if not managed cooperatively, could result in water supply shortages and reductions in hydropower generation downstream (Zhang et al. 2015; Wheeler et al. 2016). In the long-term, the regulation effect of the GERD on the highly inter- and intra-annually variable flow of the Blue Nile (Siam and Eltahir 2017; Basheer and Elagib 2019) would induce positive externalities on Sudan in terms of higher hydropower generation, lower irrigation shortages, and lower flood occurrence (Digna et al. 2018; Wheeler et al. 2018; Basheer et al. 2018), but will negatively impact recession agriculture along the Blue Nile and the Main Nile (Mohammed 2015). In favor of Ethiopia's benefits from hydropower production and the impacts on water availability and irrigated agriculture in Sudan and Egypt, some possible environmental and climate-related impacts of the GERD do not seem to entice scientists and negotiators. Tropical hydroelectric dams require particular attention by carefully selecting their location, design, and operation (Barros et al. 2011). The present article arises on account of this gap in the discussion about the GERD.

General features of the Blue Nile Basin

The Blue Nile originates from Ethiopia and contributes around 57% of the Nile flow as measured near the Sudanese-Egyptian border (Nile Basin Initiative 2012). The Natural flow of the Blue Nile is highly seasonal, with nearly 80% of the flow occurring from July to October. The river partly supplies large-scale irrigation schemes, comprising a total irrigated area of over 4.5 million ha, in Sudan and Egypt with water. Irrigated agriculture on the Blue Nile in Sudan has been for decades supplied with irrigation water from two seasonal dams, namely the

Roseires and the Sennar dams (MoIHES 1977). The two dams are also used for hydropower production, though as a secondary purpose. On the one hand, the soil erosion process in the Upper Blue Nile Basin threatens the lifetime of the downstream reservoirs and irrigation canals in Sudan by inducing excessive sediment deposition and eutrophication (Ahmed 2009; Betrie et al. 2009; Alrajoula et al. 2016; Al Zayed and Elagib 2017). On the other hand, soil erosion in the upstream constitutes an important natural fertility source to cultivated lands downstream in Sudan (Alrajoula et al. 2016). Apart from irrigated agriculture, mechanized, and traditional rainfed farming is widely practiced in the Lower Blue Nile Basin (Bussmann et al. 2016; Elagib et al. 2019). Next to climate extremes, such as droughts and floods (Elagib and Mansell 2000; Elagib et al. 2019), disorganized human activities are also considered responsible for environmental degradation in the Sudanese part of the basin (Akhtar and Mensching 1993; Glover and Elsiddig 2012; Sulieman and Elagib 2012; Biro et al. 2013; Bussmann et al. 2016; Sulieman 2018). The Upper Blue Nile Basin is no exception from such human activities. High risks of soil erosion by water – strongly linked to population density and land use/land cover (LULC) changes – lead to severe degradation in the Upper Blue Nile Basin (Gebremicael et al. 2013; Haregeweyn et al. 2017; Woldesenbet et al. 2017).

GERD hydrological alterations

Quantifying the potential hydrological alterations of the GERD, as a result of flow storage and regulation, is essential for understanding and addressing the dam's likely environmental impacts (Brismar 2004). To this end, we used a daily river system model of the Blue Nile Basin, developed by Basheer et al. (2018), to simulate hydrological alteration parameters of the dam’s steady-state operation across 27 stochastic river flow sequences (each is 27-year long) developed using the index-sequential method (Ouarda et al. 1997). It was assumed that the GERD's steady-state operation would aim to maximize the firm annual energy generation while maintaining the reservoir water level between the minimum operating level and the full supply level. Fig. 2 shows seven simulated indicators of hydrological alterations due to the GERD presented as probability curves.

Fig 2a shows that the GERD's steady-state operation would reduce the day-to-day variation in the Blue Nile flow and alter the timing and duration of flow peaks. The GERD is expected to regulate the river flow, i.e., increase the minimum and decrease the maximum daily river flows downstream (Figs. 2b and 2c).

Fig. 2d depicts the GERD reservoir area during the steady-state operation. The reservoir area is expected to range from 703 to 1904 km^2. Dam reservoirs increase the contact surface of river water with the atmosphere due to increased water surface and residence time, hence resulting in modifications to thermal (temperature) regimes, i.e., increase of downstream maximum and minimum daily temperatures of running waters, the effect of which can extend for tens of kilometers (Chandesris et al. 2019). Dam reservoirs were also found to shift the flowing water temperature causing a time lag of several days (Kędra and Wiejaczka 2016).

As a result of the GERD reservoir surface area, water evaporation is expected to range from 826 to 1960 Mm^3 (Fig. 2e). Furthermore, due to the GERD's expected flow regulation effect, the Roseires Dam (located directly downstream of the GERD; see Fig. 1) will need to be operated at higher water levels (Wheeler et al. 2016). This modification to the operation of the Roseires Dam would increase its water evaporation (Fig. 2f). Higher water evaporation increases water salinity (Brismar 2004). GERD's reservoir water level is expected to fluctuate in a 50 m range (see Figs. 2g and 2h).

GERD contribution to greenhouse gases emissions

Dams contribute to emissions of greenhouse gases (GHGs) to the atmosphere (St. Louis et al. 2000; Deemer et al. 2016), especially in the tropics where forests and high-biomass landscapes exist (Fearnside 1995; Fearnside and Pueyo 2012). Post flooding of reservoirs, loss of carbon dioxide (CO_2) and methane (CH_4) from reservoirs to the atmosphere is caused by the death and decomposition of the flooded vegetation and organic carbon in soils (Fig. 3a), as the photosynthetic CO_2 sink is eliminated in favor of stimulated microbial production of the GHGs (Kelly et al. 1997; St. Louis et al. 2000). The effectiveness of the latter GHG is seven times higher than the former (Fearnside 1995). In a warming world, increased soil organic carbon (SOC) decomposition is expected to increase CO_2 emissions from soils (Knorr et al. 2005). Sedimentation of SOC behind dams increases because of the river flow retention by the reservoir (St. Louis et al. 2000). Large dams are known to cause riverbed scouring and morphological changes in the lower reaches due to sediment retention in the reservoir and release of clear water downstream (Al-Taiee 1990; Zheng et al. 2018), as shown in Fig. 3a.

The main drivers of CH_4 emissions from reservoirs are water temperature and reservoir mean depth, with the emission rate having a positive linear relationship with the former factor but decreases exponentially as a function of the latter determinant (León-Palmero et al. 2020). Downstream emissions of methane through the turbines of hydroelectric dams in the tropics are proportional to streamflow (Fearnside and Pueyo 2012). For example, of the total methane emission, the emission downstream of the Balbina Dam (located in Brazil) is around 53% but reaches approximately 88-93% downstream of the Tucuruí Dam (also located in Brazil), which has a 17 times higher streamflow (Fearnside 2002; Kemenes et al. 2007; Fearnside and Pueyo 2012). Rates of GHGs emissions are highest at both young age and low latitudes of the reservoir (Fearnside, 1995; Rosenberg et al. 1997; Barros et al. 2011; Demarty and Bastien 2011). Because annual water temperatures in tropical reservoirs are high, decomposition rates are also high (St. Louis et al. 2000).

The multi-decade cumulative GHG emissions from tropical dams often surpass those from fossil-fuel generation, especially when large areas are flooded per unit of electricity generated (Fearnside, 1995; Fearnside and Pueyo 2012). Methane emissions released through the spillways and turbines of some tropical hydroelectric dams (e.g., Brazil’s Teles Pires Dam)

– driven by the change in temperature and hydrostatic pressure (Fearnside 2004; Demarty and Bastien 2011) – could be significant compared to those generated from fossil-fuel electricity (Fearnside 2013). Dam construction material also implies emissions even before producing electricity (Fearnside 2004).

Given the GERD location at a latitude of 11.21 °N (Fig. 1a) and the expected maximum reservoir area (1904 km^2), the resulting GHGs could be significant (Rosenberg et al. 1997). The emissions also depend on the location and morphometry of the reservoir as well as the design of the dam outlets, i.e., the deeper the outlets, the higher the emissions (Fearnside and Pueyo 2012; Zarfl et al. 2015). The purpose of the GERD is hydropower generation; thus, water will be mostly released through turbines (Basheer et al. 2020). The GERD turbine intakes are as deep as 45 to 80 meters from the full supply level (Fig. 3b) and could imply considerable emissions with water releases directly downstream of the dam.

GERD impacts on other meteorological elements

Human-made reservoirs lead to changes in LULC, which in turn displace precipitation cells and lead to changes in the amount and timing of local precipitation. Apart from the modification of precipitation occurring post-dam changes in LULC and reservoir size, Woldemichael et al. (2014) explain the effect on localized circulations, moisture advection, and convergences to result from several factors. These factors are the alteration in surface and dewpoint temperature, partitioning of latent and sensible heat fluxes, resulting in an increase or a decrease in atmospheric water vapor, and low-level wind flow variation. Large dams increase regional extreme precipitation due to increased surface evaporation, humidity, and fog, especially in arid and semi-arid regions (Brismar 2004; Hossain et al. 2009; Xu et al. 2013). The Czorsztyn and Sromowce Wyżne reservoirs on the Dunajec River were found to raise the air temperature (Kędra and Wiejaczka 2016).

Drawing on the GERD case, the aforementioned impacts might intensify, given the dam's reservoir area and the recently expanded reservoir of the Roseires Dam in Sudan – not far from the GERD (Fig. 1c). The current maximum area of the Roseires reservoir is 565 km^2, following the dam's heightening in 2012/2013. Expanding the reservoir of Sudan’s Roseires Dam has increased atmospheric humidity (Alrajoula et al. 2016). As shown in Fig. 2f, evaporation from the Roseires Dam reservoir is expected to increase following the GERD operation, implying increased perturbations in the local climate downstream.

Transboundary implications of the potential GERD-induced environmental impacts

The economies and livelihoods in Ethiopia, Sudan, and Egypt primarily rely on agricultural activities. Decisions on the construction of hydropower dams need to consider the food-water-energy security nexus, especially if the impacts traverse different countries or are experienced by multinationals (Moran et al. 2018). It is imperative not to undermine multiple implications for the regional climate in particular and the environment in general, notably in Ethiopia and Eastern Sudan in the vicinity of the GERD, where rainfed agriculture contributes considerably to food security (Bussmann et al. 2016; Elagib et al. 2019). For example, the construction of the largest dam in Sudan in northern Sudan (Merowe Dam) has caused a rise in atmospheric humidity and water salinity that negatively affected the production of date palms and citrus trees and fish biodiversity (Mohammed-Osman 2017). The increase in water salinity is explained by an increase in evaporation from the reservoir surface, thus affecting plant populations and the aquatic biodiversity (Brismar 2004). Changes to regional precipitation resulting from the GERD are likely to affect rainfed farming in the region close to the dam. These effects will heavily impact the indigenous households who have subsistence lifestyles. Changes to extreme precipitation would increase the likelihood of unpredictable and severe flash flood events during the wet season. Heavy rains often catch the usually unwary communities within the vulnerable zone and cause loss of lives, property, crops, and resources.

Hydrological alterations also have profound environmental impacts. Fluctuation in the reservoir level of the GERD would affect plant and animal populations in the reservoir (Brismar 2004). Negative impacts on the river aquatic biodiversity also occur due to changes in downstream water temperatures (Brismar 2004). The flow regulation effect of the GERD would result in a loss of natural floodplains on the Blue Nile and the Main Nile and would, consequently, negatively impact plants, animals, and agriculture that depend on these floodplains. Changes to river flow patterns cause detrimental damage to fish migration, health, survival, and production, fragmentation of aquatic plants, and affects aquatic biodiversity (Brismar 2004; Wyatt and Baird 2007; Reid et al. 2019; Barbarossa et al. 2020). Physical and chemical effects due to reduced sediments would pose a threat downstream where naturally fertile soil is key to irrigated and recession agriculture (Alrajoula et al. 2016).

From the health perspective, rheumatism cases attributable to increasing atmospheric humidity were reported by Alrajoula et al. (2016) post the heightening of the Roseires Dam, and the subsequent expansion of its reservoir, in Sudan. Besides, the increase in evaporation, humidity, and fog increases proliferation risk of insect disease vectors (Brismar 2004). Changes in water temperatures downstream of large dams enhance schistosomiasis (Bunn and Arthington 2002). Post flooding of reservoirs, Kelly et al. (1997) reported that toxic methyl mercury increases in water, peat, vegetation, and fish due to enhanced microbial (bacterial) activities.

Conclusions

The GERD construction is nearly completed, and the initial reservoir filling already started in the flood season of 2020. Credible environmental and social impact assessments can be useful only when two conditions are satisfied: (i) if the assessments are performed with sufficient lead time and (ii) if they can stop dam-building whose costs exceed the benefits (Moran et al. 2018). Added to the expected impacts of climate change on the Nile Basin, i.e., the rise in temperatures and enhanced hydrological uncertainty (Whittington et al. 2014; Siam and Eltahir 2017), the likely environmental impacts of the GERD should concern the basin decision-makers given its beyond-country implications. The current state of knowledge on large dams' environmental impacts in warm regions (tropics), especially GHGs emissions, remains limited and hardly generalizable (Demarty and Bastien 2011). However, we hope this contribution will draw more attention to some underexplored climate and environmental impacts of Africa's largest hydropower plant.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The hydrological modeling data used in this study are not publicly available due to state restrictions and contain information that could compromise research participant privacy/consent.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Nadir A. Elagib conceptualized and conceived the study, wrote the original draft of the manuscript, and designed Fig. 3a. Mohammed Basheer conducted the hydrological analysis and designed Figs. 1, 2 and 3b. Nadir A. Elagib and Mohammed Basheer contributed to the writing, reviewing and editing of the final manuscript.

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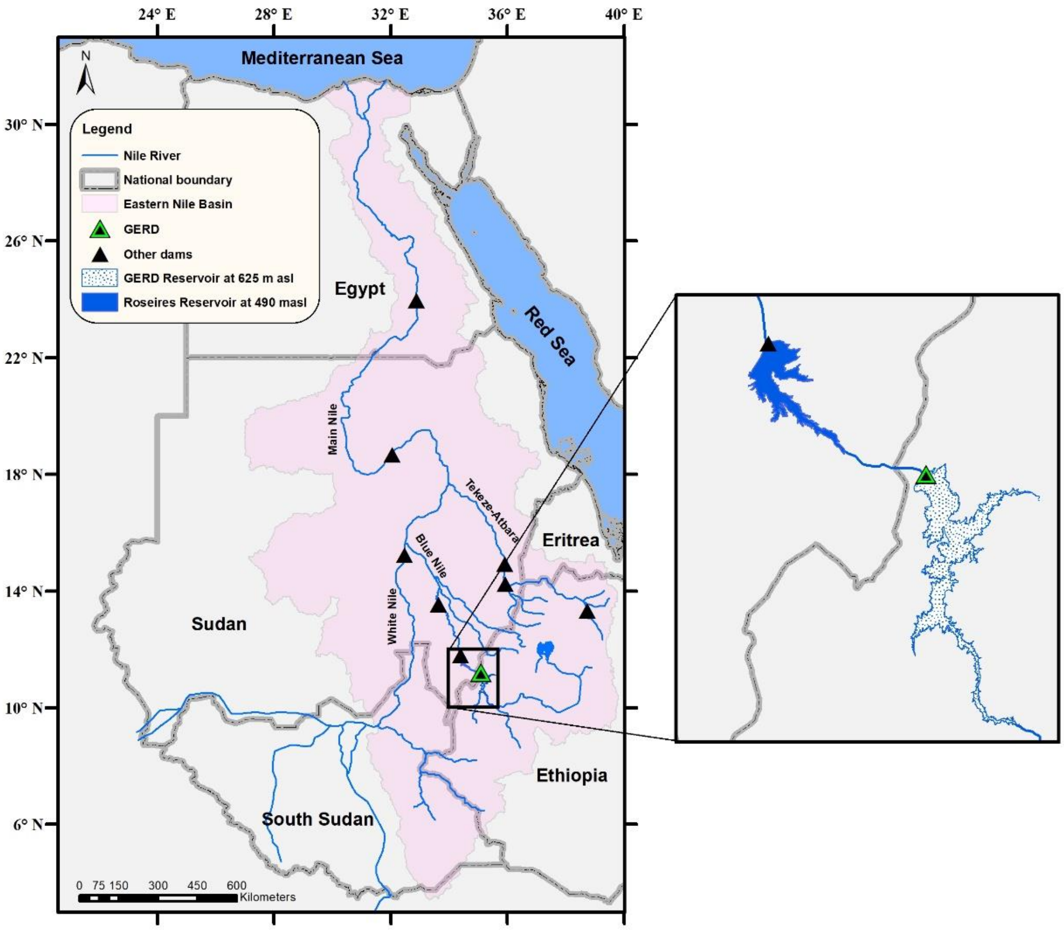


Fig. 1 The Eastern Nile Basin boundary, tributaries, and major dams. Note: GERD = Grand Ethiopian Renaissance Dam; the reservoir area of the GERD shown in the figure is not at the maximum level.

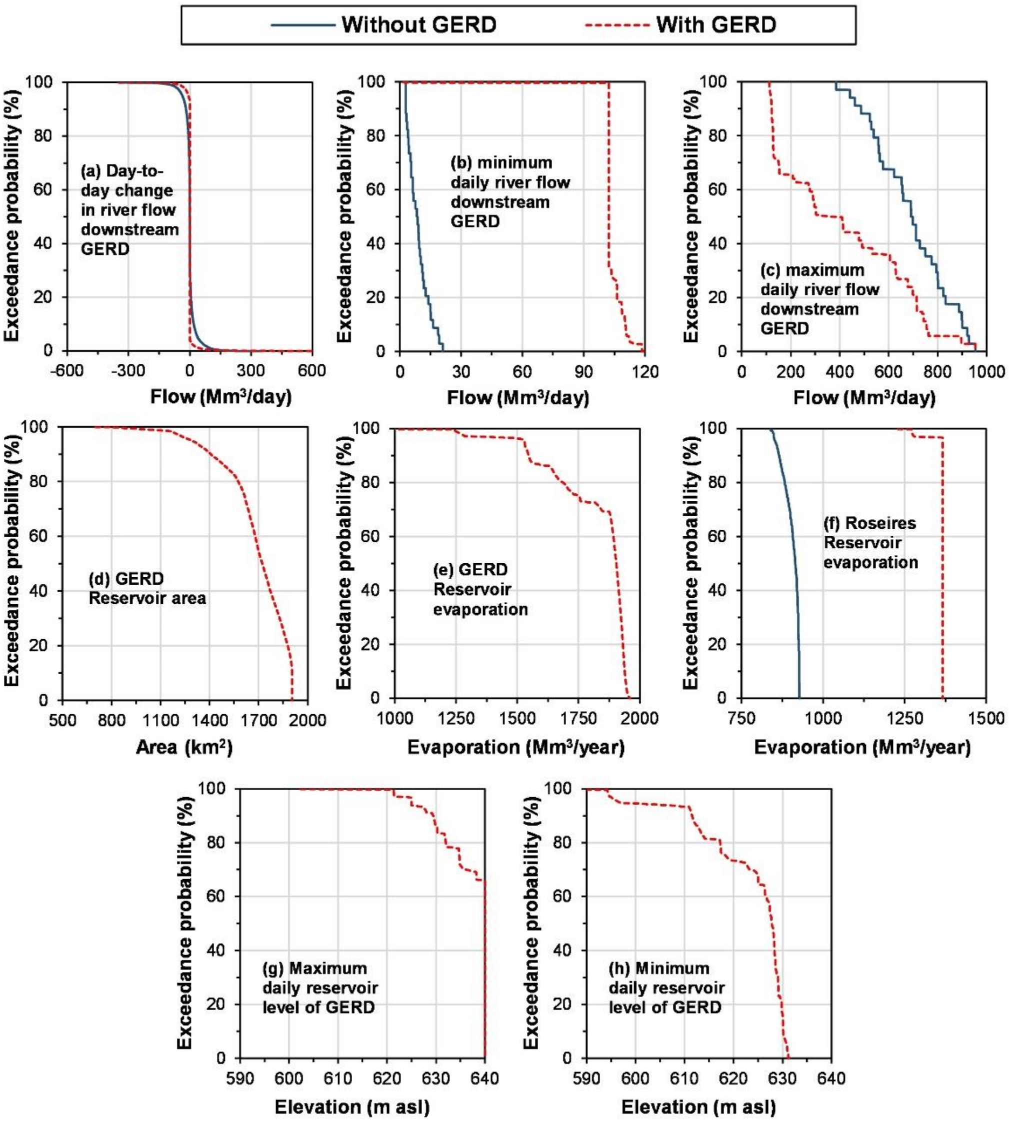
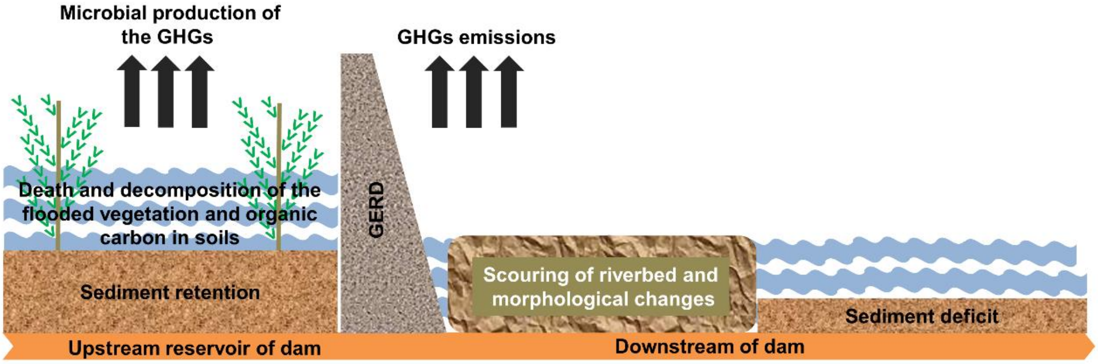


Fig. 2 Likely hydrological alterations due to construction of the Grand Ethiopian Renaissance Dam (GERD).

a)



b)

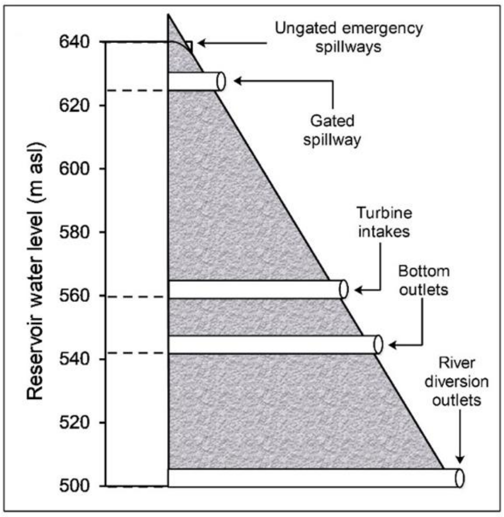


Fig. 3 A schematic illustration of potential impacts pathways of the GERD. a) Sediment deposition in the upstream (U/S) and deficit in the downstream (D/S) in addition to greenhouse gases (GHGs) emissions due to bacterial decomposition of the organic carbon stored in flooded plants and soils in the U/S and b) GHGs emissions due to outlet works, particularly deep tubines.