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Alterations of the Blue Nile hydrological regime, and ability to meet ecosystem requirements expressed through environmental flow

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:
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Countries of the Blue Nile basin depend on the river in many aspects of life. Transportation needs, agriculture, drinking water provision, livestock support—the river has many functions, nurturing human wellbeing for centuries. However, due to rapid post-industrial development, the water regime has undergone major changes. Extensive infrastructure development and climate change have already led to significant changes in the hydrological regime. Modified flow regimes pose risks for both water management and the ecosystems. Besides meeting human needs, there must be enough water left in the river to support healthy ecosystem functioning and the provisioning of ecosystem services. This is expressed through the concept of environmental flow. The purpose of this study is to identify current and anticipated changes in the Blue Nile flow regime due to infrastructure development and climate change, compare anticipated flow with environmental flow, and assess the impact on ecosystem functioning. In order to calculate flow projections at five selected sites, the PyWR model was used. This study has found that environmental flow requirements would not be met under most scenarios, both during the wet and dry seasons. In some scenarios, flow fluctuations would be minimized because of commissioning dams. Seasonality patterns of flow are also expected to be significantly shifted. Overall changes in volume and flow pattern shifts would inevitably lead to ecological problems, such as habitat disturbance, loss of biodiversity, and failure to provide ecosystem services. Consequently, socio-economic activities would be at risk, affecting major sectors such as agriculture and human wellbeing.

Keywords: environmental flow, ecosystem services, ecosystem requirements, river flow alteration, Blue Nile.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

BBM Building Block Methodology

DRIFT Downstream Response to Imposed Flow Transformations

DRM Desktop Reserve Model

EF environmental flow

ELOHA Ecological Limits of Hydrologic Alteration

EMCs environmental management classes

FDC flow duration curve

FLOWRESM Flow Restoration Methodology

GEFC Global Environmental Flow Calculator

GERD Grand Ethiopian Renaissance Dam

IFIM Instream Flow Incremental Methodology

IHA Indicators of Hydrologic Alteration

IWRM Integrated Water Resources Management framework

NBI Nile Basin Initiative

PHABSIM Physical Habitat Simulation Model

PyWR generic water resource simulation system written in Python

RCPs Representative Concentration Pathways

RVA Range of Variability Approach

SSPs Shared socio-economic pathways

1 Introduction

According to the United Nations World Water Development Report, 1.8 billion people will be living in absolute water poverty by the year 2025. Some parts of the planet experience extreme water scarcity more than others (WRI Aqueduct Water Risk Atlas 2019). By 2030, high water stress would become a concern for half of the global population, with sub-Saharan Africa being the area heavenly impacted (WWAP 2012). While the region is already under threat, the situation is expected to be even more serious when climate change consequences are considered. The cradle of Ethiopian and Sudanese cultures, the greatest source of water that sustains people, animals and ecosystems that breed on its banks, and the largest transportation corridor— the Blue Nile has been irreplaceable in the region for the time immemorial. The water of the Blue Nile has been not just historically important for people inhabiting Ethiopian and Sudanese lands but also for supporting the needs of people living in the Nile downstream (Juuti *et al.* 2007). The ancient mystery of the Nile delta — annual oscillations between high and low flows, without local demand change — has been answered only after investigating the connections between the Nile and the Blue Nile. The Blue Nile is as a main Nile tributary (see Figure 1 for the map of the Nile basin), and fluctuations in the Nile delta are caused mainly by the rainfall during the summer months and low precipitation for a good half of a year between January and May. Thus, the Blue Nile has been acknowledged as not only a key water source for the countries of a basin but also as an element supporting human activities, flora and fauna far beyond the basin.

Figure 1. The Nile River basin and its sub-basins. The Blue Nile basin is in the red circle. Source: Nile Basin Water Resources Atlas.

However, starting from the industrial revolution, the river has taken a key role in achieving development plans while as well meeting the food and water needs of a rapidly growing population. Even more ambitious plans continue to emerge, while water demand has increased significantly over the past decades, impacting something that previously was not acknowledged—requirements of the river basin ecosystems and the river itself. Even though the problem is understood, it hasn't been resolved, and there hasn't even been an attempt to calculate how much water the river must keep in order to meet ecosystem needs and provide services for humans. In addition to the question of how the water flow regime would be altered over the next decades, there is also a need to estimate how expected flow might affect the ability of the river to meet its own needs.

Figure 2. The Blue Nile waterfalls. Source: AdobeStock.

1.1 Problem statement — Blue Nile water scarcity

Given the particular dependence of human wellbeing on water resources, the evaluation of ecosystem services provided by rivers is increasingly important (Martin-Ortega *et al.* 2015). River ecosystems play many functions and provide essential resources such as drinking and residual water, water for irrigation, electricity generation, water for meeting industrial needs, habitat for stock and so on. Water, as one of the main abiotic ecosystem elements, has a huge variety of functions, given that in the river ecosystems the processes are dependent on not just the presence or availability of water but on its daily fluctuations and seasonal variability (Hayes *et al.* 2018). Besides, water is the primary habitat for many organisms at different trophic levels, hence, there is a need to maintain adequate quality of water in rivers and reservoirs (Silliman and Angelini 2012).

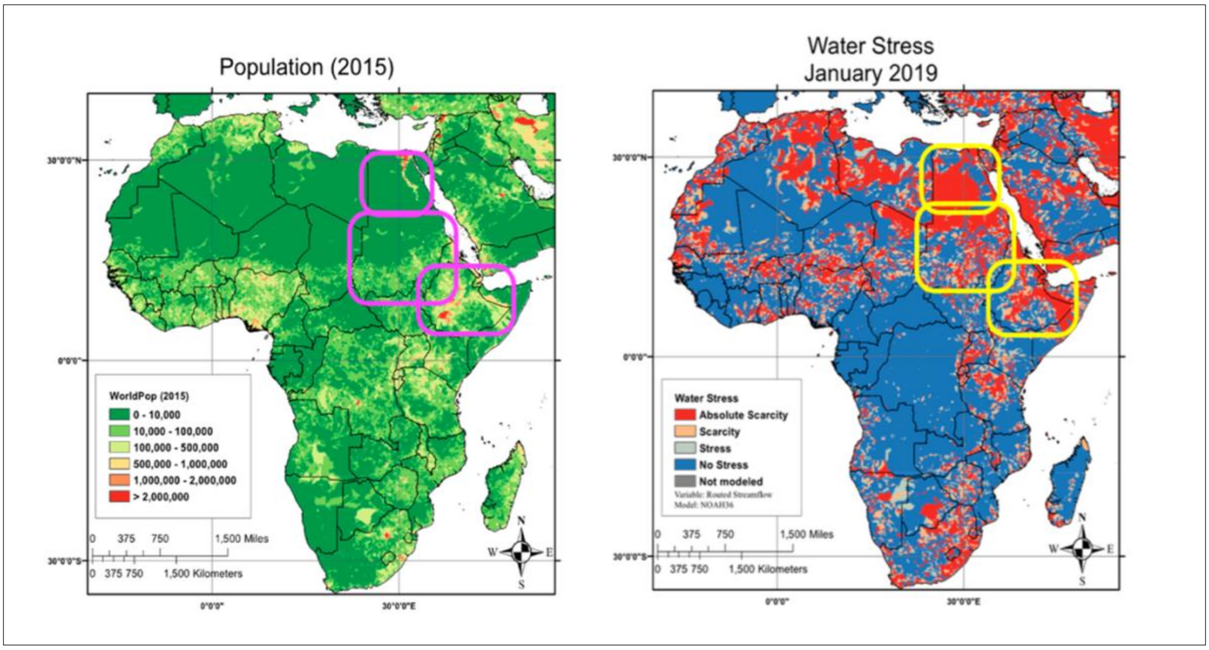


Figure 3. African countries population density and water stress index. Squares highlight countries of the Blue Nile and Egypt. Source: McNally *et al.* 2019.

Water scarcity happens when water demand is not met due to one or more reasons—physical unavailability or *physical water scarcity*, or due to inadequacy of the infrastructure to ensure supply which results in *economic water scarcity* (IPCC 2022). Climate change related uncertainties, growing population, and unprecedented development have interrupted water supply and escalated water demand (see Figure 3). The likely continuation of these patterns over the next decades is imposing very high risks on all ecosystems, particularly those that are already affected by water scarcity, while also jeopardizing human wellbeing (USENCO 2021). As a vital resource for the Eastern Nile, fresh water is essential for not only existential and economic purposes but also for maintaining ecosystems and biodiversity. Thus, safeguarding ecosystems and their functions are key to the mitigation of climate change risks and the development of climate resilience at both local and global levels (IPCC, 2022). Acknowledging the complex relationship between water resources, ecosystem services, human activities and future threats, there is a need to examine how the water regime might be altered in the nearest future in a vulnerable area of the Eastern Nile.

Some river ecosystems are more vulnerable than others to losing natural flow characteristics, hence, not meeting basic ecosystem maintenance needs. The Nile basin is one of the most heavily affected by the problem of both physical and economic water scarcity (Zeidan 2004). The river provides essential resources for a population spread over ten countries, including Burundi, Tanzania, Rwanda, the Democratic Republic of the Congo, Kenya, Uganda, Sudan, Ethiopia, South Sudan and Egypt (El-Kammash 2022). Approximately 257 million people, or 53 % of the Nile Basin population, are directly dependent on the river (NBI 2021). Providing 85% of its annual discharge, the Blue Nile is a main source of the Nile River, thus, its importance extends to all downstream countries as well (Elsanabary 2012). It flows through the Ethiopian highlands and merges with the White Nile waters as it enters Sudan (El-Kammash 2022). The seasonality of precipitation creates unique climatic and environmental conditions (Taye and Willems 2012).

Home to rich wildlife species, the Blue Nile is also essential for stimulating agriculture as one of the prevailing activities of the region (El-Kammash 2022). In recent decades, continuously expanding agriculture increased the problem of illegal water pumping. Water and food are inseparable from economic activities and physical processes, thus, securing water resources also secures food security. In addition, water executes as a source of energy in the region, hydropower reaches 80% of the total energy produced (Tan *et al.* 2017). Water security is inherently linked to energy stability— a key element for expected economic development in both Sudan and Ethiopia.

1.2 River flow alteration and ecosystem needs —environmental flow

Nowadays, more attention is paid to the trade-offs and connections that are represented by water resources and existing risks of water scarcity. It came after the realization of many interconnected functions water resources have, along with the transboundary nature of the water scarcity issue. The new approach to water resources management is reflected in the water-food-energy nexus concept (UNECE 2018). The nexus approach investigates the trade-offs emerging due to multi-dimensional water demands and water provision. The aim of the nexus framework is to use an integrated water management approach to allocate water resources in a way it does not compromise other sectors and needs. Following the nexus approach, the Blue Nile basin water resources have already been reviewed on their availability, energy production and food production potential. However, an analysis of ecosystem needs and services provided by the Blue Nile water is still missing. Ecosystem balance is crucial for securing ecosystem functions, therefore, ecosystem needs must be acknowledged in the water-food-energy nexus approach.

Healthy river ecosystems deliver not only the end products consumed by humans or animals (e.g., food, fibre, or water) but support the ecosystem processes, and thus initiate provision of essential ecosystem services (Millennium Ecosystem Assessment 2005). According to the 2nd Part of the IPCC's Sixth Assessment Report, protecting biodiversity and ecosystems integrity is crucial for securing resilient development of both ecosystems and human society, thus, ecosystem services are key to secure human well-being (IPCC 2022). The Millennium Ecosystem Assessment recognizes four categories of ecosystem services, namely *provisioning services* (food, fibre, water fuel, natural medicine etc.), *supporting services* (cycles of nutrients and water, soil formation, photosynthesis), *regulating services* (climate, water and air quality, natural hazards and diseases control, pollination) and *cultural services* (customs, ethical and spiritual values, recreation, and tourism) (Millennium Ecosystem Assessment 2005). However, measuring ecosystems services raises many conceptual and methodological challenges (Norton 2012). Apart from moral and ethical considerations, there is no common and straightforward approach to assessing the services of riverine ecosystems (DellaSala 2018).

Figure 4. The Blue Nile River in Ethiopia. Source: Wikipedia.

In order to ensure the healthy functioning of ecosystems, ecosystems' needs for water shall be met. Among the many approaches that estimate ecosystem needs, most are based on overly complex calculations and ecosystem modelling approaches. (Pascual *et al*. 2010). This can become a challenge for making use of the results, especially when these assessments are intended for use in practice (Ignatyeva *et al*. 2022). However, since modern society is obsessed with the numbers, the water needs of the river ecosystem must be quantified in order to be of use in policymaking and regulatory mechanisms (Pascual *et al*., 2010). When some measures use proxy indicators or aim at indirect evaluation of ecosystem needs, one of the methods directly assessing ecosystem requirements is the method of environmental flow (EF) evaluation.

Initially introduced by King and Brown (1999), the environmental flow (EF) approach is a hydrology-based method that *"describes the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and wellbeing that depend on these ecosystems"* (Arthington *et al.* 2018). There are different ways to quantify environmental flow, but they all share the same aim: to work out a compromise between the socio-economic needs of humans and the ecosystem water needs in order to get to the allocation regime that works for both (Acreman *et al.* 2022). Since the Blue Nile is experiencing intensive development that can result in severe ecosystem crises in general and major disruptions in water supply in particular, especially when one factors in the effect of climate change. Therefore, estimation of environmental flow is essential for sustainable ecosystem management. Studying environmental flow is a valuable approach to linking river regime alterations and the ability of ecosystems to function.

1.3 Research questions, aim and objectives

Water scarcity, meeting ecosystem needs, and provisioning of ecosystem services in support of human wellbeing are exclusively interconnected. Hydraulic infrastructure development, growing water demand and climate change have placed the Blue Nile ecosystem under stress. Combined with the already present and likely intensifying effects of climate change, the level of stress is likely to increase. As this issue has not been thoroughly investigated before, the main research question has been formulated as follows:

—How might the alteration of the Blue Nile flow regime affect meeting the water needs of the river?

To assist with answering the main research question, a set of sub-questions have been set will be addressed:

1. What is the present water flow regime, and how does it compare with the unaltered natural baseline?

2. What are the environmental flow requirements of the Blue Nile?

3. How does the alteration of the water regime impact meeting of ecosystem water requirements?

4. How would future infrastructure and climate change affect the river flow regime and meeting of environmental flow? To what extent do the chosen development option and climate change related pressure affect the river regime?

As mentioned previously, environmental flow illustrates the connection between the actual water flow regime and ecosystem requirements. Based on that, the aim of this research is formulated as follows:

To analyse the alteration of the Blue Nile water regime and implications for the satisfaction of ecosystem requirements based on the estimation of environmental flow.

In order to answer the research questions and achieve the research aim, specific research objectives have been identified, as detailed inTable 1.

Table 1. Research objectives.

Research objective	**Means to achieve the objective**
a. Review the literature on ecosystem services provided by the Blue Nile.	Literature review
b. Review the environmental flow estimation methods and practices.	Literature review
c. Collect the data for assessing river water flow alteration and calculation of environmental flow.	Formal data requests, construction, and entry into database
d. Assess the unmodified water flow based on the historical trends data	Unaltered flow modelling using the PyWR modelling tools
e. Estimate environmental flow requirements for selected study sites.	Flow requirements calculation using the Global Environmental Flow Calculator

f. Compare environmental flow requirements with current and projected river flow, taking into account infrastructure development and climate change-related effects.	Expected flow modelling using the PyWR modelling tools comparative analysis
g. Estimate how the impact of flow alteration would affect ecosystem water needs and the provision of ecosystem services.	Descriptive analysis, taking into account quantitative projections, as applicable

a. Review the literature on ecosystem services provided by the Blue Nile. This objective is identifying the relationship between environmental flow requirements, flow regime and ecosystem services provided in the Blue Nile basin. This objective helps to clarify the importance of meeting river ecosystem requirements. This objective would be fulfilled by conducting a literature review.

b. Review the environmental flow estimation methods and practices. Same for the previous objective, this would also be achieved through literature analysis. Special emphasis will be placed on environmental flow estimation techniques and methods. Beyond the main focus on the Blue Nile, the review would also touch on case studies from other countries of the region, as well as relevant theoretical approaches.

c. *Collect the data for assessing river water flow alteration and calculation of environmental flow*.

In order to continue with the analysis, related data would be collected from the relevant source, quality checked and entered into a database.

d. *Assess the unmodified water flow based on the historical trends data.*

The unmodified or unaltered flow would be simulated using the PyWR tool. For this simulation, historical data would be taken into account and infrastructure objects would be excluded from the model.

e. Estimate environmental flow requirements for selected study sites. Environmental flow estimation using a generalized network allocation model PyWR and the Global Environmental Flow Calculator.

f. Compare environmental flow requirements with current and projected river flow, considering infrastructure development and climate change-related effects. Environmental flow requirements would be divided into environmental management classes and compared with model outputs for both current and expected flow under the assumptions of new hydraulic infrastructure plans and climate change.

g. Estimate how the impact of flow alteration would affect ecosystem water needs and the provision of ecosystem services.

Based on the model results, discuss the ability of the Blue Nile to meet its ecosystem needs and likely impacts on the provision of ecosystem services.

1.4 Thesis layout

The research is divided into six chapters. The first chapter is an introduction to the context of the problem. Here, concepts of ecosystem needs, services provision and water scarcity risks are explained, and then the problem is stated for the Blue Nile river as one of the most vulnerable river basins due to the water shortages. Then, the environmental flow concept is presented as a link between the flow regime and meeting ecosystem needs. Next in the chapter, the research questions, aim and objectives are presented to narrow down the scope of this research.

The second chapter is divided into two main parts. The first part narrates about ecosystem services provided by the Blue Nile to the ecosystems dependent on its water. As a literature review chapter, it is primarily devoted to the previously published papers exploring the topic from the conceptual, methodological and, to some extent even policy point of view. The second part of the literature review is focused on the methods of calculating environmental flow requirements. While the primary emphasis is on the Blue Nile, other cases from the region are also presented for a broader view.

The third chapter introduces the overarching conceptual framework that is used for approaching the main research question and objectives. Methods are discussed in the fourth chapter, which also provides deeper background information about the Blue Nile basin geography, climate conditions, and hydrology. Data sources, types, and software are presented in this chapter as well.

The fifth chapter provides the results of the analytical analysis. Yet mainly showing the analysis results description without digging into the causal relationships, the chapter provides a detailed description of observed flow patterns.

The chapter presents the discussion based on the analysis results, thus, answering the main research question. The main research objectives are addressed after this chapter. Both causes of water change alteration, as well as the consequences of altered flow regime, are discussed in this chapter. In addition, the chapter also points out the limitations and suggestions for further research extensions.

The conclusion provides a summary of the results and discussion chapters, as well as elaborates on the practical applicability of the results.

2 Literature Review

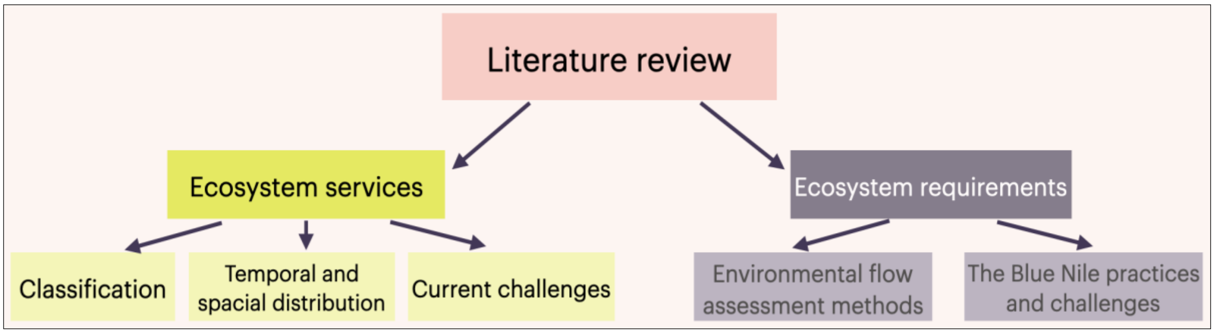


Figure 5. Literature review structure.

The literature review focuses on two main aspects. The first part is focused on the studies that assess water-related ecosystem services allocated to meeting ecosystem requirements. The second part of the literature review deals with environmental flow assessment methods. Figure 5 illustrates the structure of this chapter.

2.1 Ecosystem services provided by river ecosystems

2.1.1 Classification of ecosystem services

Millennium Ecosystem Assessment classification

Services provided by the river ecosystems encompass a wide range of values that can be divided to *provisioning, regulating, cultural and supporting services* according to the Millennium Ecosystem Assessment (2005). *Provisioning* services are those that can be literally extracted from nature; thus, river ecosystem provides drinking water, timber that grows in riparian ecosystems, crops and fibre sources growing on the riverbanks and floodplains, medical herbs, energy and so on. *Regulating* services regulate all natural phenomena, support ecosystem functioning, cleaning ecosystem and building ecosystem resilience. Speaking of a river ecosystem, these services include water purification, control of floods and erosions, climate regulation. *Cultural* services encompass non-material benefits that contribute to ancient cultures heritage, modern cultural rituals, and recreation (Hagan 2020). As has been already mentioned, freshwater and estuarial ecosystems are historically important areas where many civilisations have started to strive. Rivers have been providing navigations, food and water protection, thus, have become intrinsic centres of development and then have grown into urbanised areas. The least tangible, but not the least of importance are *supporting* services that support basic life forms safeguard ecosystem elements functioning and interconnections. Examples of such services are existence of water and nutrition cycle, soil formation processes, photosynthesis etc. These processes are irreplaceable and support primary production, energy exchange, fertility of the floodplain (Böck *et al*. 2018).

Classification based on ecosystem services evaluation

Apart from classification based on characteristics of river ecosystem services, ecosystem services can also be divided into three groups based on measurability of benefits they provided, and how these services are evaluated. Three categories of services include: *directly evaluable, indirectly evaluable non-evaluable existence services* (National Research Council 2007). *Directly evaluable* services are ones that can be understood and measured in finite monetary terms. They do generate market-priced goods, for example, commercial fish production, transportation, recreation, or water supply. *Indirectly evaluable* services are evaluated indirectly involving social surveys methods when participants are asked to put a value on a certain service. Nutrient recycling, flood protection, genetic material protection, wetlands etc. are services provided by the river ecosystem, people do use these services are aware of their existence, but it is very challenging to tangle them. Hence, these services are placed under the category if indirectly *evaluable* services. The third group, *existence services* related to use or consumption, but they secure the biological cycles and support the biological needs of wild species, e.g., related to breeding and nesting. To some extent, these services correlate with supporting services in the classification suggested by the Millennium Ecosystem Assessment (2005), although some of the mismatching might be observed. Table 2 represents two classifications of the river ecosystem services, alongside with separation do different biomes.

Table 2. Types and spatial distribution of ecosystem services provided by the Blue Nile River. Background color of the ecosystem services refers to the ecosystem services evaluation categories: directly evaluable, indirectly evaluable and existence services.

Types of service	**Ecosystem services**	**Biomes**							
		Rivers	**Coastal biomes**	**Riparian areas**	**Flood-plains**	**Wet-lands**	**Soil**	**Ground-water**	**Lakes**
Provisioning services	Provision of water for drinking and other use	√						√	√
	Food provision (fish and aquacultures)	√	√						√
	Timber provision		√			√			
	Cereals and fibre production				√	√			
	Energy production	√							√
	Transport	√							√
	Medical herbs	√	√	√		√			
Regulation services	Water purification and treatment	√	√	√	√	√	√	√	√
	Floods control	√	√	√	√	√			

	Erosion prevention		✓	✓		✓	✓		
	Coastal line protection	✓	✓						
	Climatic processes regulation	✓	✓	✓	✓	✓	✓		✓
	Biodiversity habitat	✓	✓	✓	✓	✓	✓		✓
	Safeguarding of trophic cascade	✓	✓	✓	✓	✓	✓		✓
Cultural services	Historical heritage	✓			✓				✓
	Customs and rituals	✓			✓				✓
	Recreation	✓	✓	✓		✓			✓
	Existence values (pleasure from enjoying the river views)	✓	✓	✓		✓			✓
	Tourism	✓	✓	✓	✓	✓			✓
Supporting services	Water cycle (including evapotranspirat ion)	✓	✓	✓	✓	✓	✓	✓	✓
	Nutrients cycles	✓	✓	✓	✓	✓	✓		✓
	Soil formation		✓	✓	✓	✓	✓		✓
	Photosynthesis	✓	✓	✓	✓	✓			✓

	Pollination processes		✓	✓	✓	✓			

2.1.2 Temporal and spatial distribution of the Blue Nile ecosystem services

River ecosystem services over time

A river provides so many types of ecosystem services that they are almost impossible to be fully assessed neither form the economic nor from non-monetary perspectives. However, bedsides the measurability of river ecosystem services, there is a concept of time or issue of intergenerational equity that can be acknowledged as well. To create a sustainable environment that is suitable as a habitat for next generations, protection of ecosystem services shall be provided (Martin *et al*. 2016). First, ecosystem services overuse would immediately create an ecosystem imbalance in an already vulnerable Blue Nile basin. At the same time, it might have an irreversible impact on ecosystem services provision right up to its complete disappearance. For instance, fresh water used for drinking and irrigation is essential for safeguarding food and water security, however, the more water is uncontrollably consumed now, the less water will remain for producing food for the next generations. It would happen not because less precipitation (since climate projections often say differently), but because if at some point in the nearest future the watershed would have less available water. Consequently, dependednt ecosystems would not have enough water for flora and fauna. Freshwater regulates chemical and biological processes, thus, even short time insufficiency of water would disturb ecosystem processes. Due to this reason, soil moisture level might decline, which might lead to the dehydration of the root systems and consequently to soil erosion, growing droughts frequency etc. Figure 6 provides a vivid example of seasonal flow differences for the Blue Nile Waterfalls.

Figure 6. The Blue Nile waterfalls in various seasons. Source: AdobeStock.

Spatial distribution of river ecosystem services

Services provided by river ecosystems do not only have a direct impact on the freshwater and riparian ecosystem but cover bigger areas. All river ecosystems vary greatly in scale, each basin ecosystem includes tributaries ecosystems that may have different water flow and biomes properties (Yeakley *et al*. 2016). From very fast and unpredicted headwater streams with high seasonal precipitation fluctuation, to vast river deltas defined by slower flow that creates floodplains and wetlands. Therefore, the range of services river provides to dependent ecosystems varies as well, based on the spatial properties of each biome (Ma *et al*. 2021). The Blue Nile provides services to the range of biomes, including coastal and riparian ecosystems, floodplains, groundwater systems, dependent lake ecosystems and so on (Böck *et al*. 2018; Yeakley *et al*. 2016). Table 2 provides an overview of biomes benefiting from the Blue Nile ecosystem, alongside with services classification and valuation categories of services received by the biomes.

2.1.3 Current challenges and threats

Until now, there is little research on the monetary estimation of services provided by the Blue Nile. Hence, it is not easy to estimate the losses experienced due to the ecosystem disturbance. Tesfaye estimated that the Blue Nile's annual contribution to the national economy of Ethiopia could reach 883 million Ethiopian Birr (ETB) or 52 million USD, varying between 794-968 million ETB (45-55 million USD) in 2011 (Tesfaye *et al.* 2016). Although these numbers contribute only to 1% of GDP, numbers cover only provisioning and regulating services. In addition, this estimation has been done more than ten years ago, before building and commissioning of the Grand Ethiopian Renaissance Dam (GERD), the region's biggest hydropower station, i.e., prior to currently experienced water use intensity.

Range of services that originally could be provided by the Blue Nile can not do so in the modern days due to the unprecedented pace of population growth and human development. Hydro-ecological state of the Blue Nile basin defines the ability to provide services, when hydro-ecological conditions are defined not only by climatic and hydrological patterns but infrastructure development as well (Tesfaye *et al*. 2016). As an example, Gebreselassie found that the erosion process affects ecosystem health, consequently, human well-being by reducing water supply, biological diversity, and land productivity (Gebreselassie *et al*. 2016). However, erosion is often a result of newly integrated man-made infrastructure. As a result, ecosystem requirements can not be satisfied, thus, ecosystem survives would not be provided.

Out of many challenges the Blue Nile exposed to is land use patterns change. In early 2000s, Nyssen found that the Ethiopian Highlands ecosystems have been experiencing natural resources losses due to land degradation and soil erosion (Nyssen *et al*. 2005). According to Hong, countries of the sub-Saharan Africa are affected more by land use change than other regions, and that it causes serious deterioration of ecosystem balance, thus, provision of ecosystem services (Hong *et al*. 2021). Land erosion is often an indicator of unbalanced interactions between natural and anthropogenic factors (Moges *et al.* 2020), thus, severe land degradation processes indicate serious hydrological problems. However, there are few studies document the relationship between land use change and ecosystems functionality in the Blue

Nile basin. These studies usually focus on smaller watersheds or areas, although the findings still can be used to identify the severity of ecosystem degradation induced by human intervention. For instance, after studying the Guder watershed in Ethiopia, Muleta and Biru make a statement that grasslands, shrub land and forest lands have been reduced by 83.5%, 48.5%, and 37.5% when settlement and cultivated land areas have been grown by 572.2% and 7.1% between 1973 and 2015. Same studies indicated significant correlation between land use change and decline of ecosystems services (Muleta and Biru 2019). Hamere has had similar findings, stating that farmlands and plantations have higher negative influence on the hydrological ecosystem services provision compared to other land use types (Hamere *et al.* 2021).

Despite the absence of such research for the basin as a whole, estimation of ecosystem functions for smaller can be scaled up to understand the basin's trends. Assefa and colleagues have estimated change in landcover for the city of Bahir Dar (Upper Blue Nile) and found that when built-up areas increased by 216.24% (+2599 ha), wetlands and water bodies decreased by 75.71% (−1618 ha) between 1984-2019. Such pattern change had resulted in overall reduction of ecosystem functions values from 29.73 × 10^6 USD to 20.84 × 10^6 USD (Assefa *et al.* 2021). The same research found that amongst the declined ecosystem services, the biggest damage was recorded for water regulation, waste treatment and habitat provision for freshwater organisms and wetlands species (Assefa *et al*. 2021). In the case study of the Andassa watershed (Upper Blue Nile) conducted by Gashaw, expansion of cultivated lands and built-up areas, as well as reduction of forests, scrubland and grassland areas have been identified as a main cause of ecosystem services reduction (Gashaw *et al.* 2018). Change in land use patterns have induced ecosystem services losses of 1.58 × 10^6 USD between 2000 and 2015 (from 22.58 × 10^6 USD to 21.00 × 10^6 USD) and 4.25 × 10^6 USD between 1985 and 2015 (from 26.83 × 10^6 to

21.00 × 10^6 USD). In addition, ecosystem values are estimated to fall under 17.94 × 10^6 USD by 2030 and 15.25 × 10^6 USD by 2045 for the same study area (Gashaw *et al.* 2018).

If appropriate measures for river ecosystems were not implemented in time, associated ecosystems services might be lost forever. One of the research projects conducted in the Omo Gibe Basin (the Blue Nile tributary, Ethiopia) exhibits large scale deforestation and biodiversity loss due to escalating demographic pressure, agricultural development and removal of natural vegetation (Aneseyee *et al.* 2022). Very similar phenomena have been observed downstream, and the pattern might be repeated in future due to the expanding infrastructure.

2.2 Water requirements of ecosystems

2.2.1 Main environmental flow assessment methods

In comparison with direct evaluation of ecosystem services provided by river ecosystems, environmental flow assessment allows to estimate the minimum requirements of the river ecosystem. In recent years, a rapid development of methods estimating environmental flow has been observed, from lower resolution desktop-based approaches to resource- and time-consuming applications that return more accurate results. Assessment conducted by Tharme attempted to categorize environmental flow evaluation methods. The author reviewed 207 methodologies used worldwide, and then divided them into four categories: *hydrological*, *hydraulic rating*, *habitat simulation* and *holistic* methods, and the *combination-type methods* (Tharme 2003).

Hydrological methods use hydrological data, i.e., daily and monthly flow recordings to measure environmental flow requirements. Out of all common hydrological methods, the Tennant (or

Montana method) is the most well-known. It uses a certain percentage of annual flow to establish minimum flow requirements, requirements are divided into seven classes according to the ecological conditions of a river– from A to F (best to worst) (Tennant 1976). The Tessmann method divides annual flow to three seasons and allocates different percentage of flow to each of them (Tessmann 1980). Indicators of Hydrologic Alteration (IHA) method explores current flow regime properties and relates them to the ecological processes (Richter *et al*. 1997). Range of Variability Approach (RVA) is based on five groups of IHA indicators and characterises flow's properties using these categories (Armstrong *et al*. 1999).

Theoretical background of the ***hydraulic methods*** is tied to the hydraulic variables. They are used as proxy indicators to estimate habitat area of a specific river's cross-section. For example, Wetted Perimeter Method uses hydraulic data to estimate the cross section's water saturated area (Knighton 1998). It is helpful for assessing fish habitat during the sprawling season.

Habitat simulation techniques use hydrological, hydraulic, and biological responses to assess how suitable the habitat is for the target species under the chosen flow regime. For instance, in-stream flow incremental methodology (IFIM) observes correlation between river discharge, temperature, and fish species richness (Bovee 1986; Navarro *et al.* 1994). Another widely used method is the physical habitat simulation model or PHABSIM (Bovee 1982). This method assumes that the environmental needs of each river ecosystem differ from one stage of ecosystem lifecycle to another (Palau and Akzar 2010).

Holistic methods are the most comprehensive and complex. They are based on the assessment of relationship between river flow, ecological functions, geomorphological conditions and even social responses. Holistic methods combine all previously described approaches and place an emphasis on interdisciplinarity and experts knowledge (Pastor *et al.* 2014). Holistic methods require significant resources, take more time to perform, but still do not always provide accurate results. There are different methods that can be considered as a holistic method.

The Building Block Methodology (BBM) is a commonly implemented holistic approach for assessing environmental flow. BBM divides riverine ecosystem relationships to blocks and addresses each of them separately (Tharme and King 1998). According to this method, certain components of the ecosystems have fundamental importance, thus, define functionality of the ecosystems. These components act as so-called 'building blocks' (King *et al*. 2008). The BBM approach pays particular attention to the minimum and maximum flows during the driest and average years. The Desktop Reserve Model (DRM) calculates the building blocks for each month of the year (Hughes 2001). ELOHA method (Ecological Limits of Hydrologic Alteration) involves establishment of the hydro-ecological relationships based on river hydrological conditions and ecological conditions (Poff *et al.* 2010). FLOWRESM (Flow Restoration Methodology) developed by Arthington combines the literature review, hydrological modelling, original field trip and desktop research (Arthington *et al*. 1999). The DRIFT (downstream response to imposed flow transformations) methodology introduced by Arthington is a scenario-based approach that also combines multi-disciplinary and local knowledge about the ecosystems and river flow (Arthington *et al*. 2003).

There is no best methodology for environmental flow assessment, each approach has its strengths and weaknesses, and applies accordingly to each case (Sood *et al*. 2017). Short descriptions of environmental flow methods are provided in Table 3 below.

Table 3. Overview of environmental flow estimation methods.

Methodology	Description	Examples
Hydrological approach	Uses daily and monthly flow recordings to create minimum flow recommendations, do not account seasonality of flow. A rapid and simple method that is used when ecological data are missing, or when the results are urgently needed, mostly for a preliminary assessment.	Tennant (Montana method); Tessmann method; RVA
Hydraulic Rating	Based on hydraulic variables (e.g., depth and velocity) as proxy indicators. Hydraulic methods are applied to each cross-section.	Wetted Perimeter Method
Habitat Simulation	Based on hydrological, hydraulic, and biological responses, provide understanding between discharge and habitat conditions. Key species are used to predict how habitat will react to water flow regime alteration.	IFIM; PHABSIM
Holistic approach	Complex and resources-consuming approach based on identification of relationship between flow, ecosystem, geomorphology and socio-economic systems.	BBM; DRM; FLOWRESM; DRIFT; ELOHA

2.2.2 Blue Nile flow estimation practices and challenges

Even though the Blue Nile is a major tributary of the Nile River and that its flow regime has been significantly altered, the relationship between environmental flow, ecosystem needs and services are still understudied. This is mostly due to the economic status of Blue Nile countries. Apart from physical water scarcity, both Ethiopia and Sudan experience water and energy allocation problems due to economic instabilities. When the possibilities to develop river infrastructure have appeared, the priority was placed on power generation, whilst environmental aspects have been largely ignored.

There is a limited number of studiers assessing environmental flow for this area, and more of them are not up-to-date due to the presence of new river objects. For instance, the construction of the largest river dam in Africa —Grand Ethiopian Renaissance Dam (GERD) has just been finished. GERD has negative impact on water resource allocation, increasing tensions between Ethiopia, Sudan and Egypt (De Falco and Fiorentino 2022). Construction works of GERD have been initiated only in 2011, and the first stage of reservoir filling has started only in July 2020. GERD's catchment area is unprecedented and reaches 172 250 square kilometres, with planned annual energy generation of 16 153 GWh (ENA 2017). GERD impact is not yet assessed, but it creates a problem for meeting environmental flow requirements. Nevertheless, the literature investigating the Blue Nile environmental flow prior to the construction of GERD might be used for observation of environmental flow methods.

One of the first attempts to assess the connections between flow alterations and environmental flow has been made for the Chara-Chara weir upstream (McCartney *et al.* 2009). Chara-Chara weir regulates the Lake Tana outflow and controls water resources supplying in the Tis Abay-I and II energy plants. This paper has become the first of its kind, assessing ecosystem needs rather than water requirements for the Tis Issat Falls aesthetic purposes. To do this, the South African Desktop Reserve Model (DRM) (Hughes and Hannart 2003) was used to estimate environmental flow requirements between the diversion to the Tis Abay power stations and the point where the water is returned to the river. The study estimated environmental flow annual requirements of 862 million cubic meters, which is equivalent to 22% of natural flow. This water volume is needed to meet minimum ecosystem needs. The same paper estimated that currently observed flow reaches only 70% of environmental flow requirements. In addition, flow alteration resulted in extended dry seasons and shortened wet seasons (McCartney *et al.* 2009).

ELOHA approach (Poff *et al.* 2010) was used for the Nile Basin Initiative environmental flow management practices establishment (NBI 2016). The assessment methodology described in the NBI requires significant data describing both current flow, and the factors affecting expected impact. After realising that the region does not have enough of the necessary data to perform ELOHA calculation, this approach ran into serious limitations.

Alrajoula and colleagues used the Range of Variability Approach (RVA) to assess the Er Roseires dam influence on the hydrological regime. The Er Roseires hydropower dam is located in Sudan, approximately 110 km downstream from the border with Ethiopia and 700 km upstream from Khartoum and has been operating since 1965. Although focusing more on the dam heightening project, affected reservoir capacity and energy production, the research found that flow alteration resulted in minimizing the seasonal flow fluctuations. The reservoir area increase is expected alongside with increasing evaporation rate, which would lead to the human health issues and sewer system problems (Alrajoula *et al.* 2016).

In 2020, Abebe approached the flow-ecology relationships based on hydrological characteristics of the Gumara River (Lake Tana tributary). The study used the IHA software to study alterations of natural flow regime, determine current flow regime and connect it to the ecosystem processes. Results show that flow was declined significantly due to the uncontrolled abstractions, catchment management interventions and agricultural areas development. Moreover, flow reduction resulted in the decrease of floods, thus, developed disconnections between floodplain wetlands and the river. As a result, it affected aquatic organisms' breeding and migration (Abebe *et al.* 2020).

In a followed study, Abebe examined the altered flow regime and previously ignored environmental flow requirements for the same study area (Abebe *et al.* 2021). In this research, they sought to establish a holistic method for estimating environmental flow. In order to do so, different types of data have been used: flow characteristics, macro-invertebrates samplings, Shannon Index, water physicochemical variables (dissolved oxygen, temperature, total phosphorus etc.), land use data, fish catch, as well as surveys. They found a correlation between non-compliance with environmental flow requirements and deterioration of water quality (increased phosphorus and nitrogen concentrations). In addition, decreased riparian vegetation cover and fish diversity, as well as associated health problems among local communities have been recorded (Abebe *et al.* 2021).

To the author's knowledge, none of the scientific papers examined the connections between ecosystem requirements and alteration of flow regime due to the development of infrastructure for the broader area of Blue Nile. Usually, the literature focuses either on smaller watersheds or even gaiging stations, or on the narrower topics. For instance, Gashaw studied the relationship between the Andassa watershed land use change and water flow regime alterations (Gashaw *et al.* 2017). Woldesenbet paid his attention to Upper Blue Nile catchment response to land use and climate change (Woldesenbet *et al.* 2018). Gelete produced a holistic overview of climate change impact on the hydrological properties of Ethiopian Blue Nile (Gelete *et al.* (2020). The general tendency observed in these studies as follows: flow regime is already significantly altered by infrastructure, and as a result, ecosystem requirements for water can not be met. Moreover, escalating climate change and growing water demand for agriculture would inevitably lead to the further changes in land use by imposing water scarcity risks. It would result in the replacement of natural ecosystems by mono-cultural plantations, severe water shortage, evapotranspiration rate acceleration and disruptions of species reproductive behaviour. This would lead to further negative economic and environmental consequences.

2.3 Literature review results

The literature review provided not only a more detailed understanding of the research topic, but also identified gaps in the environmental flow assessments. Key findings of the literature review are as followings:

- The literature shows that the Blue Nile water regime is impacted by infrastructure and growing water demand. However, there is a lack of studies presenting trends of the flow regime across multiple river sections.

- There is no study examining how altered flows are related to the Blue Nile ecosystem's ability to meet its water needs. Typically, ecosystem services are related to land use change rather than water flow change and environmental flow.

- Although environmental flow assessment method is a suitable approach to investigating the research question, studies focused on environmental flow assessment for the Blue Nile are limited. The cases usually focus on the specific river section or on smaller watersheds, when the larger picture is missing.

- Even with an abundance of methods assessing environmental flow, the papers reviewed Either use hydrological or complex holistic approaches. They represent rather quantitative outcomes, and the relationships between environmental flow requirements, ecosystem needs, and provision of ecosystem services are often neglected.

- There are no studies that explore the likely consequences of expanding development and climate change impact on the water regime. However, water demand is expected to grow due to the expansion of agricultural sites and hydropower production.

The literature review findings highlight the connections between water flow alterations and ecosystem requirements for water. In addition, it addresses the gaps found in the methodology of environmental flow assessments for the Blue Nile. The next chapter provides an overview on the conceptual framework that is a basis of my research.

3 Conceptual framework

In order to build a cohesive research structure and connect flow alteration to its drivers, a conceptual framework has been created. Figure 7 illustrates how framework elements interact with each other, presenting an overview of the research approach.

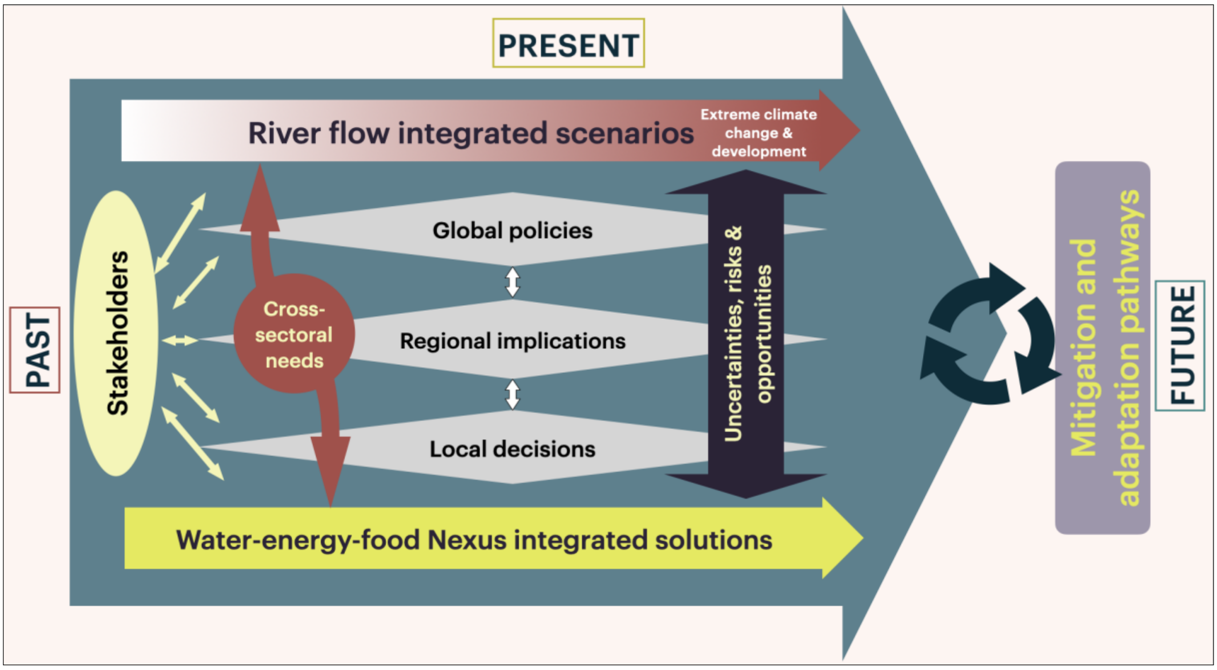


Figure 7. Research framework. Adapted from: Harrison *et al.* 2019.

regime. *Past*, *present* and *future* are equally important in order to track historical tendencies, causes of ongoing water regime alterations, as well as to come up with management recommendations. Actions in the past, such as industrial development, related policies, and river infrastructure projects, define the conditions that determine the current conditions of the river. Present is a connecting element between past and future. Current flow is observed in present, water management problems exist now, but the actions and decisions impacting the future state can be taken now as well. Future is inherently uncertain and can be predicted only to a certain extent. The complexities imposed by the future uncertainties are assessed by many researchers studying integrated management issues, such as by van Asselt and Rotmans (2002), Funtowicz and Ravetz (2003). Whether the river would be meeting its ecosystem requirements that would also safeguard human well-being, is determined by both past and present. This approach is standard practice in integrated assessment, with such examples as the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) of the IPCC assessments (2022) or IMPRESSIONS project (Harrison *et al.* 2019). Past, present and future are intertwined, and these connections are reflected in the methods. Hence, Blue Nile flow patterns are observed in the past and in the present, but they are also simulated in future, reflecting how the regime can change on the basic of future assumptions. Stakeholders' decisions are impacted by the past experience, these decisions determine how river resources would be used. However, a strategical course for the future can be adjusted by the stakeholders, which is leading to a course correction for the future.

In order to assess how both infrastructure and climate change would affect the Blue Nile water availability, a simulation approach is needed. Modelling tools have been used to run projections under different sets of assumptions that gradate from unmodified water flow to various combinations of climate change and new infrastructure development. *Integrated scenarios simulating flow* tendencies reflect the possible global developments pathways that consider both the socio-economic development tendencies and global temperature increase. These are represented as alternative integrated scenarios. Scenarios used for analysis are explained further in the methods chapter.

Water demand and supply are manifested on multiple scales, with strong cross-scale relationships. There are three main scales relevant of this research: *global*, *regional*, and *local.* Global scale refers to the global climate change problem and related international policies. Although the impact of global scale processes is significant, regional scale processes are equally important. Climate change and its impact on water resources availability differ from one geographical location to another. Thus, the regional situation would always be reflecting both global trends and regional socio-economical aspects. Local scale is referring to a specific study area—the Blue Nile watershed itself and selected study sites. Due to the limited research scope, study sites could represent the river basin only to a certain extent, and with primary attention to hydrological and geographical characteristics.

Hydrological patterns are defined by existing strategies or i*ntegrated solutions* that take many human activities into account. However, flow alteration would lead to water management challenges. Since water resources are key for ecosystem functioning and human activities, water resources should be viewed through an integrated approach. *Integrated solutions* take a range of factors into account, aiming to reach a balance between human and environmental needs. The Water-Food-Energy Nexus approach is one of the integrated approaches assessing the problem. It aims to realise gains across water, energy, food, and ecosystems in transboundary river basins such as the Blue Nile is, simultaneously focusing on ecosystem health and human well. In order to address the risks identified via the simulation and analysis, new policies and management practices needed be introduced.

Cross-sectoral needs are the essential element of this framework. Water resource demands are coming from different sectors, include but are not limited to environmental flow requirements, agricultural requirements, social sector requirements (residual water use, cooking, drinking, energy production) and industrial requirements. Cross-sectoral needs connect flow scenarios with integrated solutions, stakeholders and mitigation pathways.

Stakeholders refer to actors who determine the policies implementations at three scales (global, regional, local) and define cross-sectoral needs (particularly the socio-economic sector).

Stakeholders participation is necessary for finding solutions aligned with the integrated approach management.

There are *uncertainties, risks, and opportunities* due to water management challenges. For this particular case, *risks* are connected with a gap between expected river water flow and environmental flow. The bigger the gap, the higher are the risks. Moreover, there is a risk of not meeting the socio-economic water demands. Although this study focused on the environmental flow, there are residual, agricultural and industrial demands that would only increase in future. However, it is unclear how these demands would affect the water balance, representing the *uncertainties*. In addition, there are further uncertainties represented by population growth and climate change, each with their own uncertainties. Consequences of emerging risks range from direct (such as droughts and lack of energy due to reduced water flow), to biodiversity losses and even the ecosystem malfunctioning. However, there are also *opportunities* related to the risks and uncertainties, they are leading to potential solutions. The simulations assist in identifying the risks and uncertainties. When risks are recognized in time, there is still room for mitigating them, then risks become opportunities.

All components of a conceptual framework are leading to the *mitigation and adaptation* measures. Mitigation and adaptation pathways connect scenarios results with strategic decision-making and integrated solutions, as well as with stakeholders. Mitigating and adaptations pathways at the same time are determined by global, regional, and local policies and context. However, before defining mitigation and adaptation measures, risks and uncertainties assessment is done. Climate change and modified water flow may require new measures—both mitigative and adaptive nature. For example, if the river infrastructure project were to endanger water resources availability and ecosystem functioning, project cancellation or decommissioning need to be considered. In other cases, strategies adaptation might be enough to mitigate risks. For instance, water demand could be reduced across multiple sectors through technological improvements. Mitigation and adaptation pathways are not the final result, and although they are indicated as part of the 'future' dimension, the element is connected to the 'present'. Thus, mitigation and adaptation strategies would be part of scenario assumptions, as well as of integrated management approaches.

The framework connects many initially interlinked elements. Following analysis is based on the framework elements relationships, although placing emphasis on scenarios and cross-sectoral demands. While some elements of the framework are not studied in detail considering the scope of this research, but they can be addressed through research in the future.

4 Study area and research methods

An understanding of the methodological logic is necessary before proceeding to the study area or data detailed description. Figure 8 presents a flowchart of the methodological approach, i.e., the main steps of the study in their logical and chronological order.

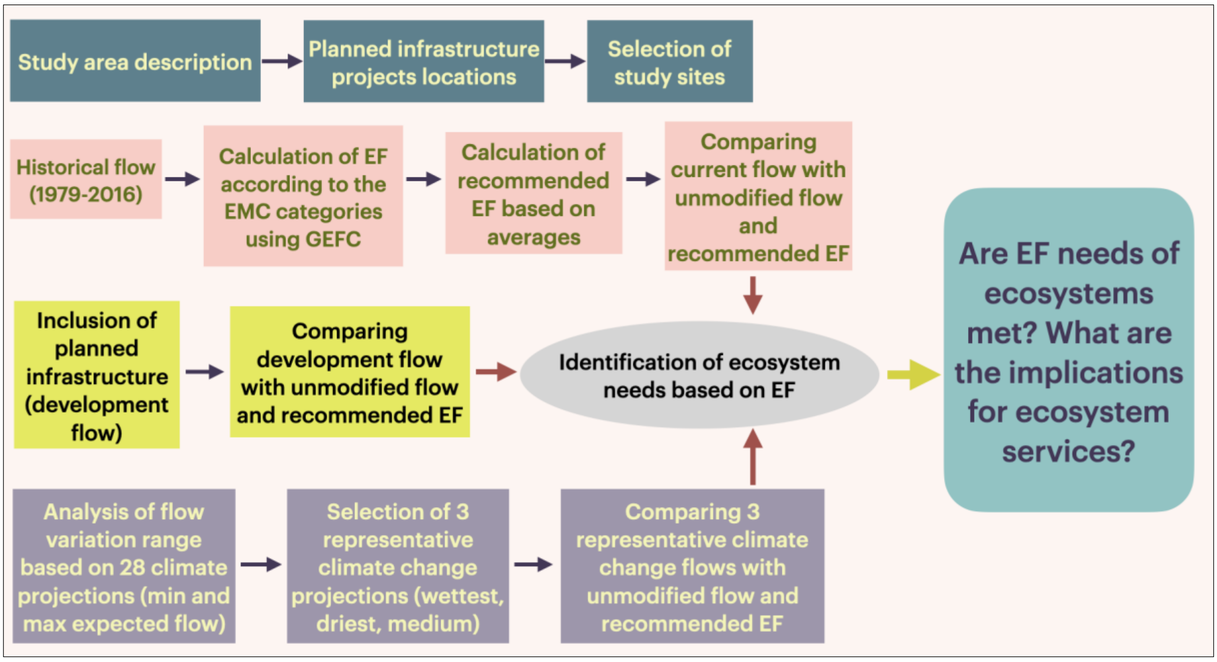


Figure 8. Research methodology flowchart.

4.1 Study area description

Geographic location and geomorphology

The Blue Nile originates in Ethiopia, where it flows 800 km of its full length of 1,450 km. After crossing the border with Sudan, river travels for 650 more km before merging with the White Nile water closer to Khartoum (Britannica 2014). Part of the Eastern Nile hydrological system, the Blue Nile sub-basin covers an area of 325,000 square km with 63% located in Ethiopia and 37% in Sudan (Ascegdew *et al.* 2018). The Blue Nile has several tributaries, but the Gilgel-Abai River located in Central Ethiopia, is considered as its main source (Vijverberg *et al.* 2009). The Gilgel Abay flows into Lake Tana, from which the river officially acquires the Blue Nile status. Heading Southwards, the river passes through a series of rapids, looping through North-

Western gorges of Ethiopia. The river then circles around the Choke Mountains, flowing through the deep canyons of the South-Eastern Ethiopia, before turning North-West. After crossing the border, the river takes a North-Westerly course (Yibeltal *et al.* 2019). Elevation varies widely in the basin, exceeding 4,000 m upstream in the rainfall-rich region and decreasing to 700 m downstream in Sudan, where less steep geomorphological conditions provide more opportunities for infrastructure development (Yibeltal *et al.* 2019). The Blue Nile has an average flow gradient of 1.5 m/km, providing the river with unique potential for hydropower development (Ascegdew *et al.* 2018). Figure 9 gives a better overview of the Blue Nile basin geography, as well as shows the countries dependent on it.

Climatic and biological conditions

The basin straddles several climatic zones. The upstream parts of the Ethiopian Highlands are located in subtropical areas and experience heavy rains — more than 1,520 mm annually during the summer months. On the contrary, the Sudanese parts are located in semiarid climate with almost zero precipitation during the winter months, annual precipitation does not go above 100-500 mm (Khir-Eldien and Zahran 2016). Figure 10 represents precipitation patterns within the basin.

Average temperature along the upstream sections varies between 17 and 26 degrees Celsius, while the downstream sections have 26-30,5 degrees Celsius on average (Khir-Eldien and Zahran 2016). Figure 11 illustrates temperature patterns for the entire Nile basin, highlighting the Blue Nile in green. Maximum temperature is recorded during the dry season, from December to February. Temperature rises to a daily average of 41 °C in Khartoum, while minimum temperatures usually occur between July and August (Smith *et al.* 2022). As a result, upstream areas experience rainfall induced floods, while Sudan areas are frequently impacted by strong winds that carry dust and sand (Smith *et al.* 2022).

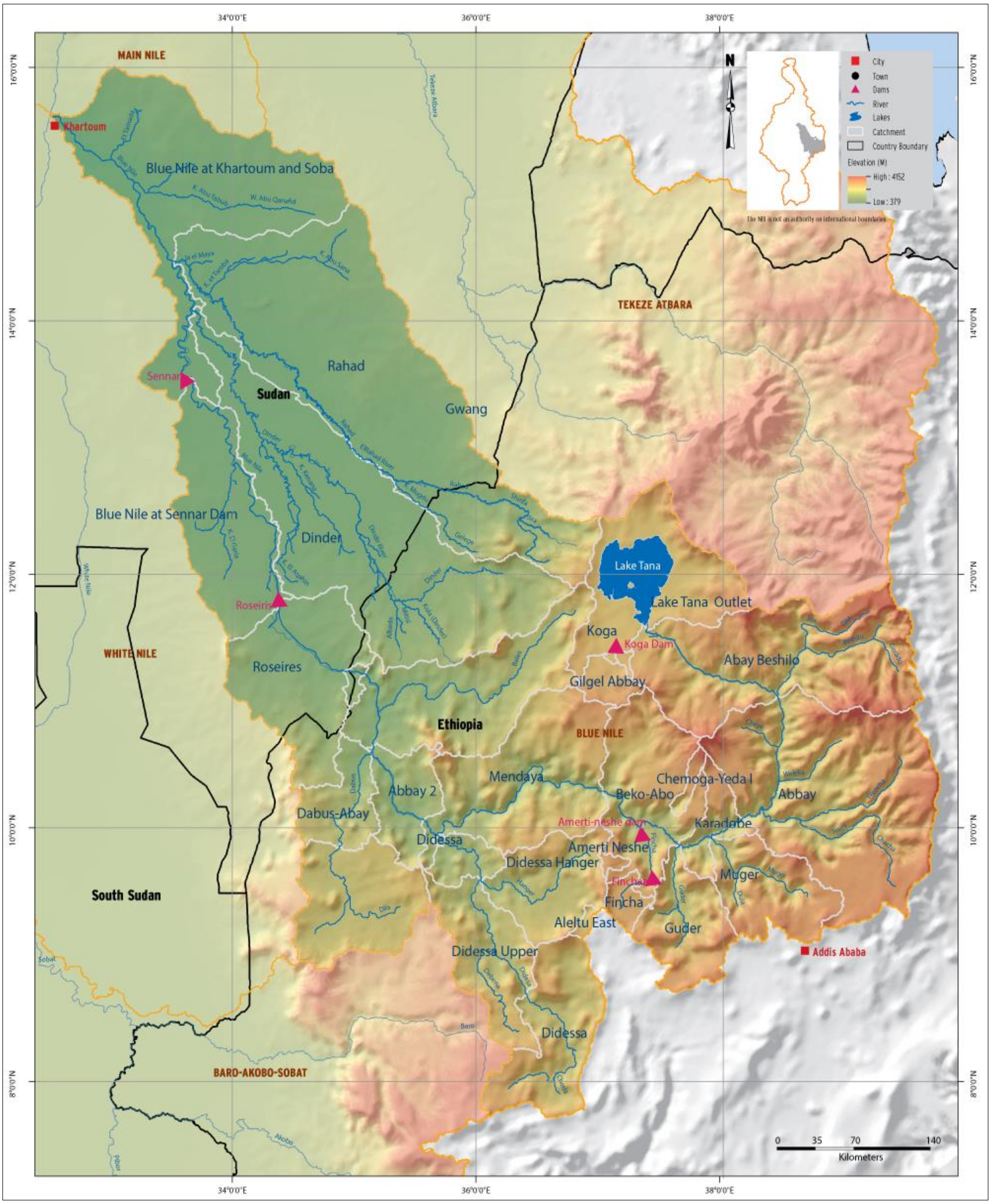


Figure 9. The Blue Nile sub-basin and its geomorphological conditions. Source: Nile Basin Water Resources Atlas.

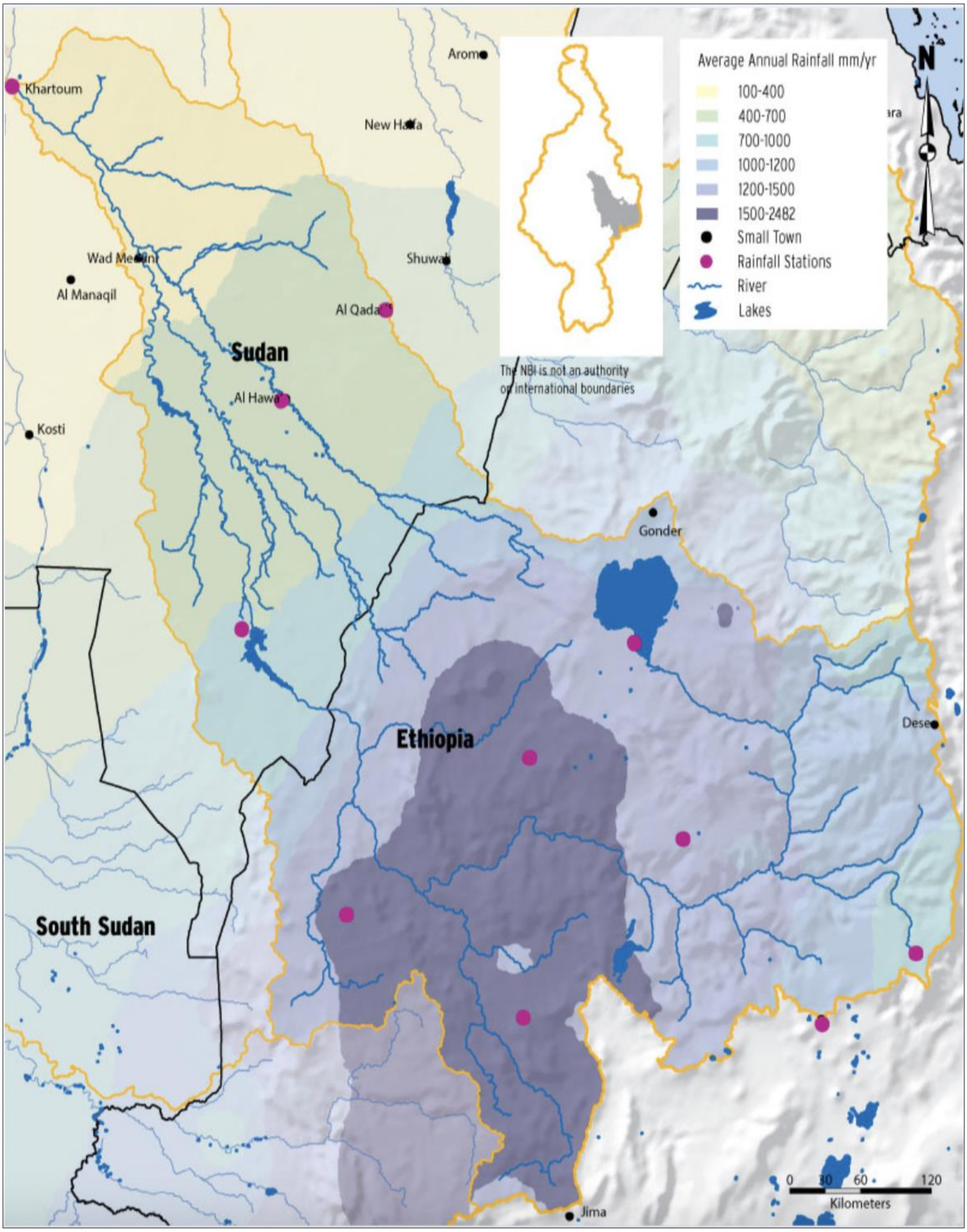


Figure 10. Average Annual rainfall, the Blue Nile basin. Source: Nile Basin Water Resources Atlas.

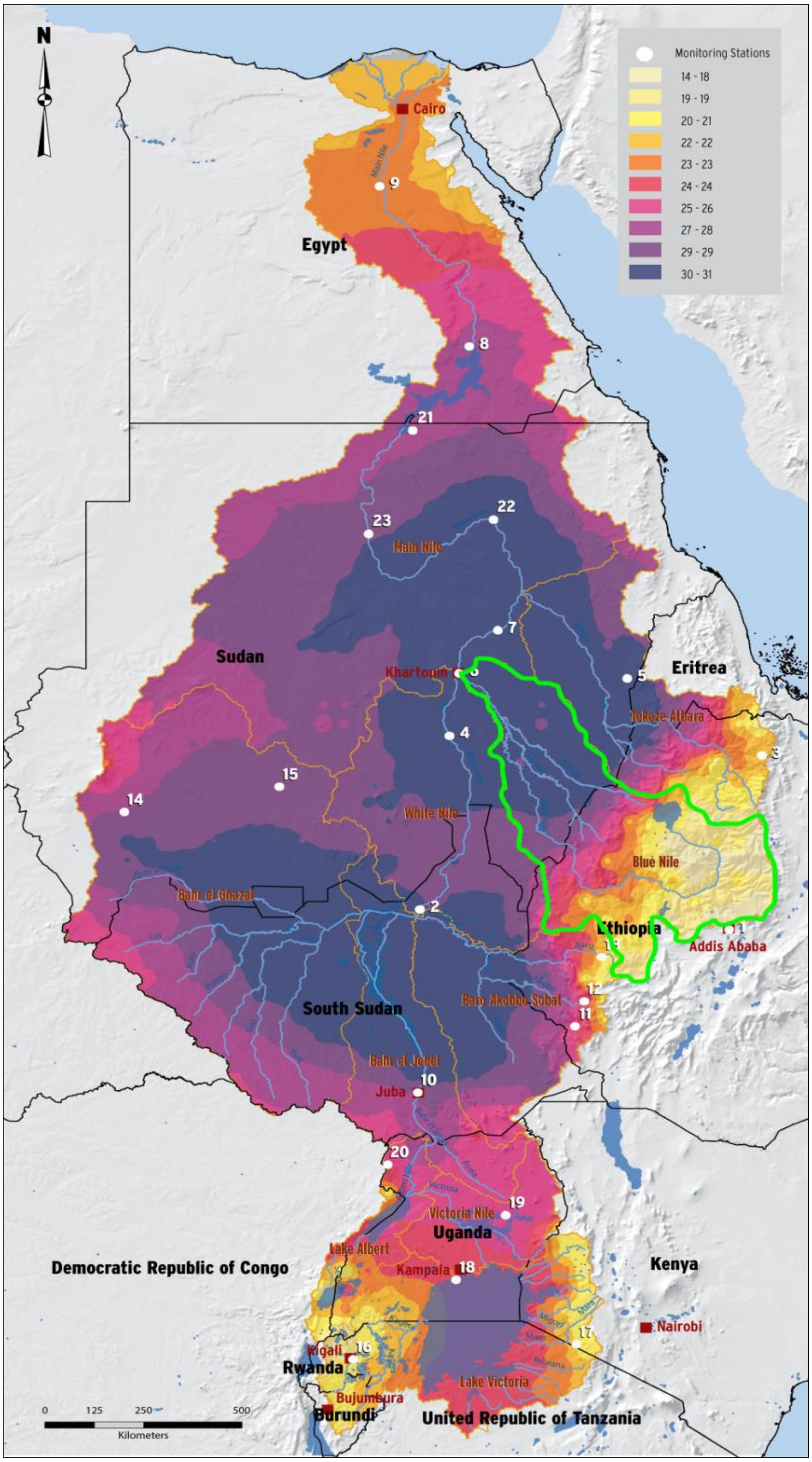


Figure 11. Average Annual temperature, Nile basin and its sub-basins. Source: Nile Basin Water Resources Atlas
The Blue Nile basin shape is highlighted in neon green.

The basin's flora and fauna changes along the river according to climatic conditions, geographic and geological characteristics. Mixed woodland and savanna with medium height trees and grasses dominate upstream areas (Smith *et al.* 2022). Vegetation changes to a mix of bush, thorny trees and open grassland in the dryer midstream sections. The desert starts from Khartoum, and vegetation declines further downstream (Gebrehiwot *et al.* 2010). With diverse climatic conditions, the Blue Nile is one of the highest biodiversity areas, however, with many endangered species due to climate change and human pressure (Pimm *et al*. 2014; IUCN 2021). As a result, the Blue Nile basin has one of the lowest Biodiversity Intactness Index scores (De Palma *et al.* 2021).

Major infrastructure

As already mentioned, water is a scarce resource for the Blue Nile downstream areas due to very low precipitation and semiarid climateic properties (McCartney and Girma 2012). However, even Ethiopian upstream areas face water scarcity, albeit due to a different reason. Hydraulic infrastructure is lacking for Ethiopian areas of the river, thus, non-interrupted water supply can not be ensured (Behailu *et al*. 2016).

There are many infrastructure objects controlling river flow and allocating water to meet human needs. The paper differentiates and considers the effects of existing and planned hydraulic infrastructure but cataloguing all existing and planned infrastructure is beyond its scope. Figure 12 shows the main infrastructure over the entire Nile, with the Blue Nile infrastructure highlighted in neon pink.

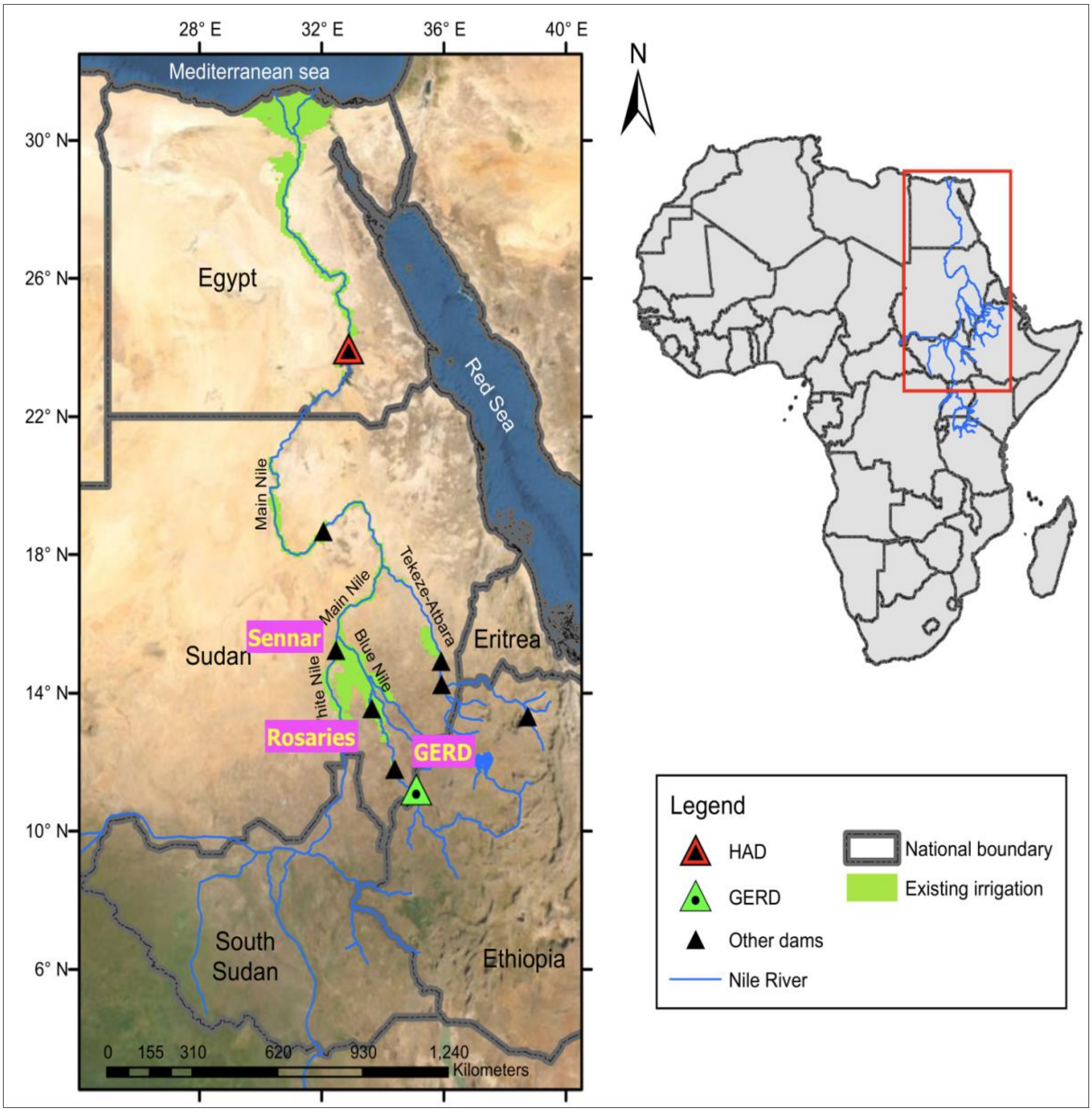


Figure 12. Map of the Nile Basin with major infrastructure. Source: Basheer *et al.* 2021. The Blue Nile key infrastructure includes GERD, Sennar and Rosaries dams.

The major dams are represented by the Grand Ethiopian Renaissance Dam (GERD) located in Ethiopia right before Ethiopian-Sudanese border, and two dams in Sudan— Rosaries and Sennar. Sudanese water resources have been exploited since 1930s-1940s, two Sudanese dams provide 80% of all energy generated in the country, with production reaching 280MW for Rosaries and 15MW for Sennar dams (UFZ 2020). In contrast, GERD is a very recent project with twenty times higher power production capacity compared to two largest Sudanese dams together. GERD's installed capacity is expected to reach 6.35 GW (Roussi 2019). The hydropower dam would supply power to energy-poor Ethiopian population that often experiences power cuts. While this goal is commendable, GERD faces a lot of controversy regarding its impact on water resources availability in countries downstream (Salman, 2018). However, GERD is not the only project that causes concerns. According to a master plan of the Abbay river basin, the hydrological potential of the Blue Nile would be further exploited through already adapted infrastructure projects in water resources abundant Ethiopia (Ministry of Water Resources 1999).

4.2 Study sites

Flow alterations and environmental flow assessment can not be performed for the entire Blue Nile basin due to the limited research scope imposed by time and resources constraints. To keep within the scope, a limited number of study sites that they represent the basin's characteristics have been selected. Five study sites have been chosen for this purpose; each site representing the hydrologic conditions of a given river section. While the logic of site selection somewhat varied, for example, based on the ecological vulnerability or on the water stress indicators of the section, the dominant criterion was infrastructure presence — either in present days or expected in future. The selected sites represent areas where the infrastructure might significantly modify flow pattens due to the disturbance risks it imposes.

Due to the complexity of transboundary issues between the Blue Nile countries, and rapidly developing infrastructure, only five study sites have been selected in Ethiopian part of the Blue Nile basin: downstream of Tana-Beles hydropower project, Lake Tana outflow in downstream of Chara-Chara weir, downstream of Karadobi Dam, downstream of Finchaa Irrigation site and downstream of GERD (see Figure 13). Table 4 provides details on the selected study sites and expected impact on flow regime infrastructure creates for these locations.

Table 4. Selected study sites, their coordinates and artificial intervention of flow regime experienced.

Selected sections	ID #	Coordinates	Artificial intervention
Downstream of Tana-Beles hydropower	1	11°99'80" N 36°53' E	Tana-Beles basin transfers water from lake Tana through a tunnel to generate hydropower.
Lake Tana outflow downstream of Chara Chara weir	2	11°52' N 37°49' E	Reduction of natural outflow from Lake Tana due to the diversion of water from Lake Tana to Beles basin through Tana-Beles basin transfer.
Downstream of Karadobi Dam	3	10°13'70" N 38° 32'30" E	Future hydropower reservoir upstream of GERD, expected to start operation within the next 15 years.
Downstream of Finchaa Irrigation	4	9°55' N 37°39' E	Construction of Finchaa Dam to abstract water for Finchaa irrigation site.
Downstream of GERD (Grand Ethiopian Renaissance Dam)	5	11°21' N 35°06'70" E	Construction and launching of GERD hydropower reservoir (the biggest hydropower dam in Africa)

4.3 Data collection

The research is based and builds on outputs of the Eastern Nile model developed by the Water Resources research group of the University of Manchester Basheer *et al.* (2021). Figure 14 shows the structure of the model, with explanation of some of its characteristics. Original data to build and calibrate the model was provided by the authorities of Blue Nile countries, thus, have a high degree of confidentiality but can not be shared openly. However, the credibility of data can be confirmed by the corresponding author upon reasonable request at Zenodo: https://doi.org/10.5281/zenodo.4314574 (Basheer *et al.* 2021).

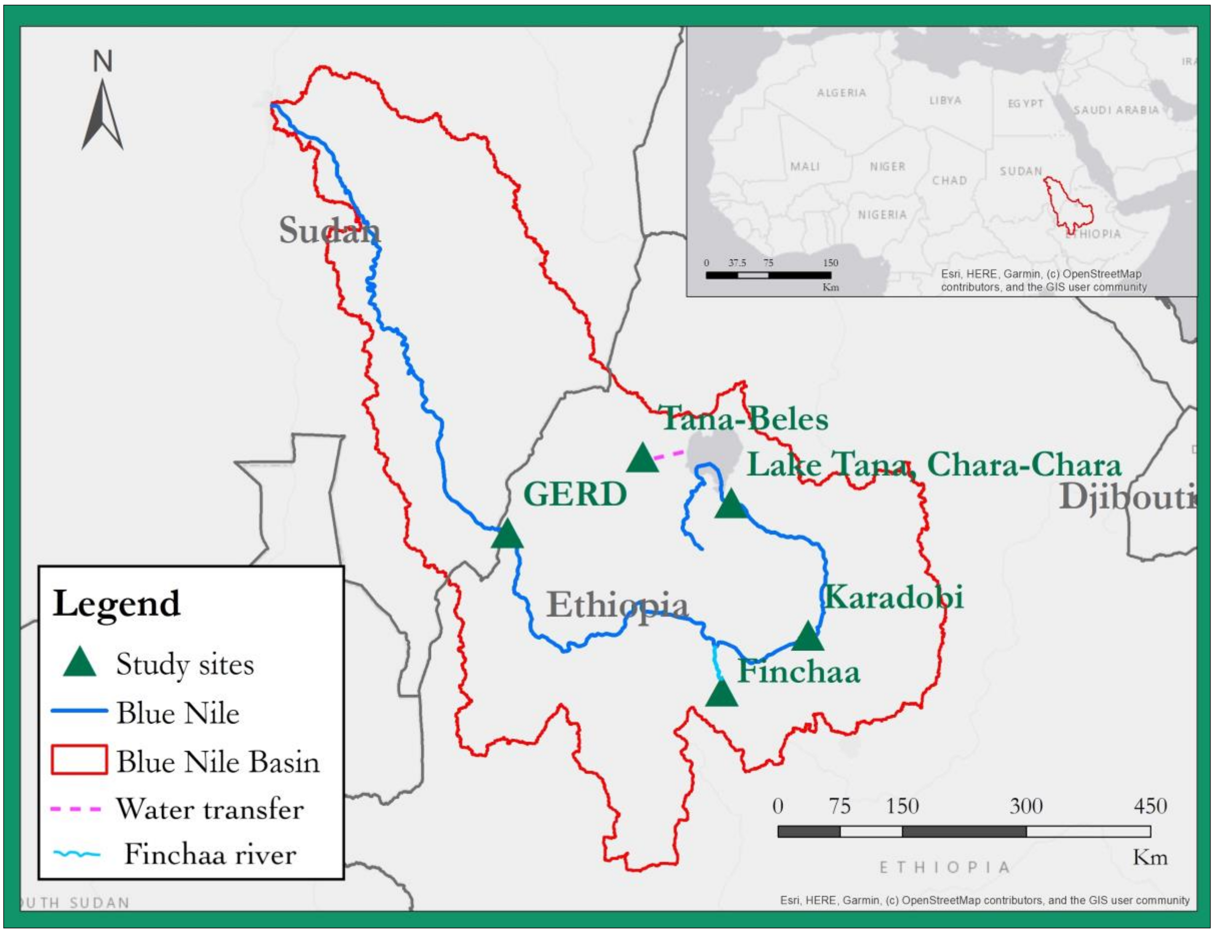


Figure 13. Study area: Blue Nile River basin and five study sites, Tana-Beles interbasin water transfer and Finchaa river.

Data used for analysis are provided in .CSV and .XLSX formats, that were transferred to either .XLSX or .TXT for further data processing. Original data have been presented in time series with a monthly time step and expressed accumulative daily flow in millions of cubic meters (MCM). Hence, model simulation results and calculated environmental flow requirements are also represented using MCM units in time series representation. For the next steps of analysis, outputs have been transformed to the average monthly data (for environmental flow) or were presented through flow duration curve analysis (FDC) approach.

4.4 Methodological tools

4.4.1 Water resource simulation library

For simulating water resource allocation system for the Blue Nile, PyWR or a generic open-source Python library has been used. PyWR is a powerful online modelling platform for solving hydrological network resource allocation problems using a time-stepping linear programming approach in time steps (Tomlinson *et al*. 2020). PyWR represents relationships between network nodes of inflow and outflow points, demand, reservoirs, hydropower dams and their spillways. The tool reflects flow direction, as well as simulate water allocation rules. Not only is each node assigned flow attributes (e.g., minimum flow/maximum flows), but also water allocation priorities. PyWR advantages include free use under the GNU General Public Licence, fast model run, user defined time steps (hourly, daily, weekly, and monthly), as well as the option to use it online or offline. A user-friendly interface allows novice users to create their own system and define the rules, which is often an asset when involving stakeholders. As an additional strength, PyWR allows the simulation of multiple scenarios to explore risks and uncertainties related to resource use. Besides, the same Python library can be used to study implications for interrelated sectors that require water, such as for energy and food security issues (Tomlinson *et al*. 2020).

As mentioned previously, this research is based on an already existing model of the Eastern Nile created by Basheer *et al.*, where the Blue Nile is represented as an element of a larger model. Figure 14 shows the structure of the Blue Nile basin model with all present infrastructure and water allocation patterns. The original model was set up with monthly data for the period from1979 to 2016.

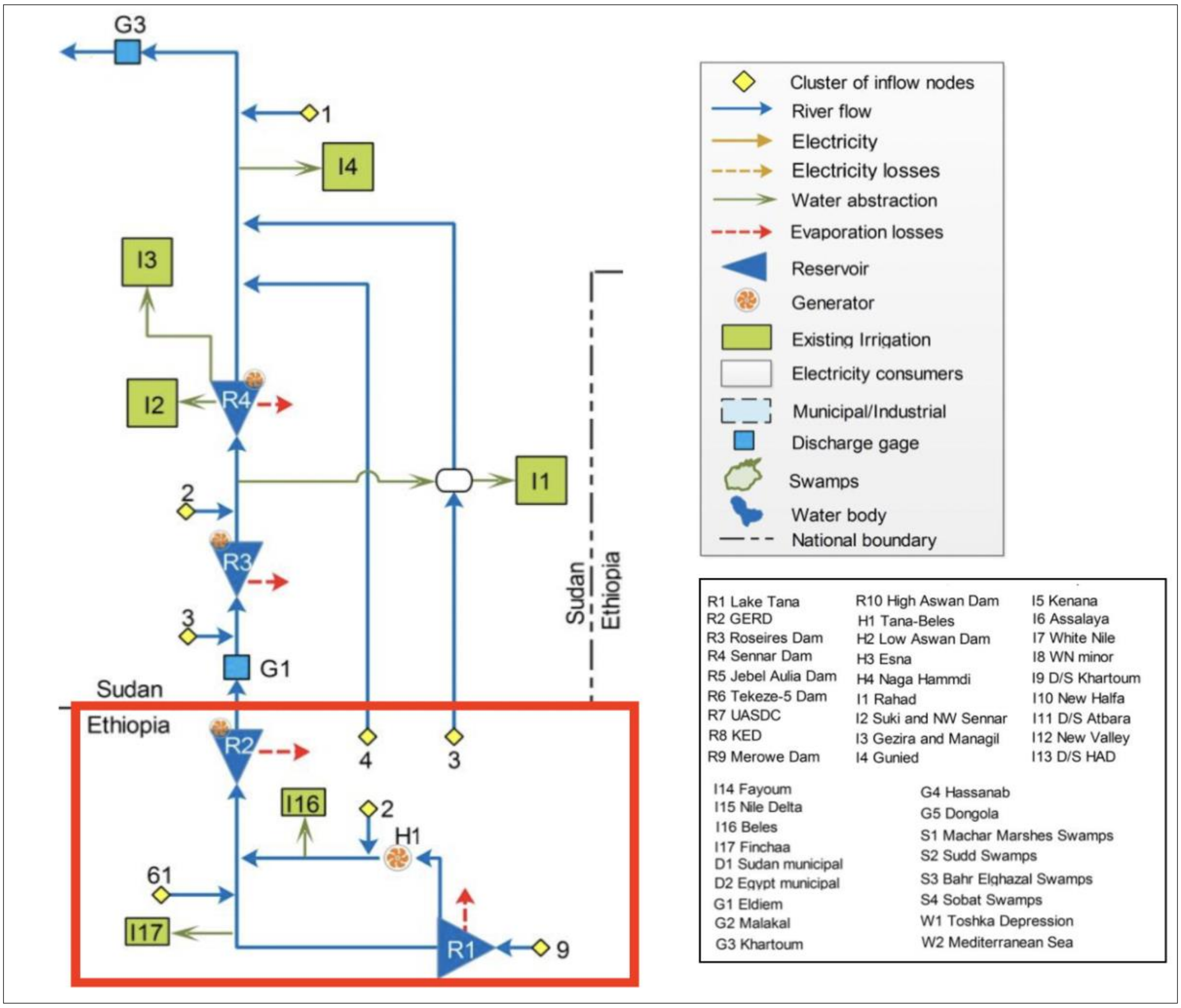


Figure 14. Schematic of the Blue Nile River Simulation Model. Source: Basheer *et al*. 2021. Study area is highlighted in red.

PyWR tool has been used to run a range of scenarios and provide data for further analysis. The online platform allows changing nodes properties according to research objectives. Specifically, PyWR provides data for the comparison of unmodified flow with observed and expected flow, under alternative assumptions about hydraulic infrastructure and climatic conditions. After setting flow at a desirable level (accordingly to scenario conditions), PyWR runs the simulation and returns time series with monthly data. Due to data security issues, each scenario was run remotely, and scenarios outputs were used as primary data for the analysis.

4.4.2 Global Environmental Flow Calculator and environmental flows

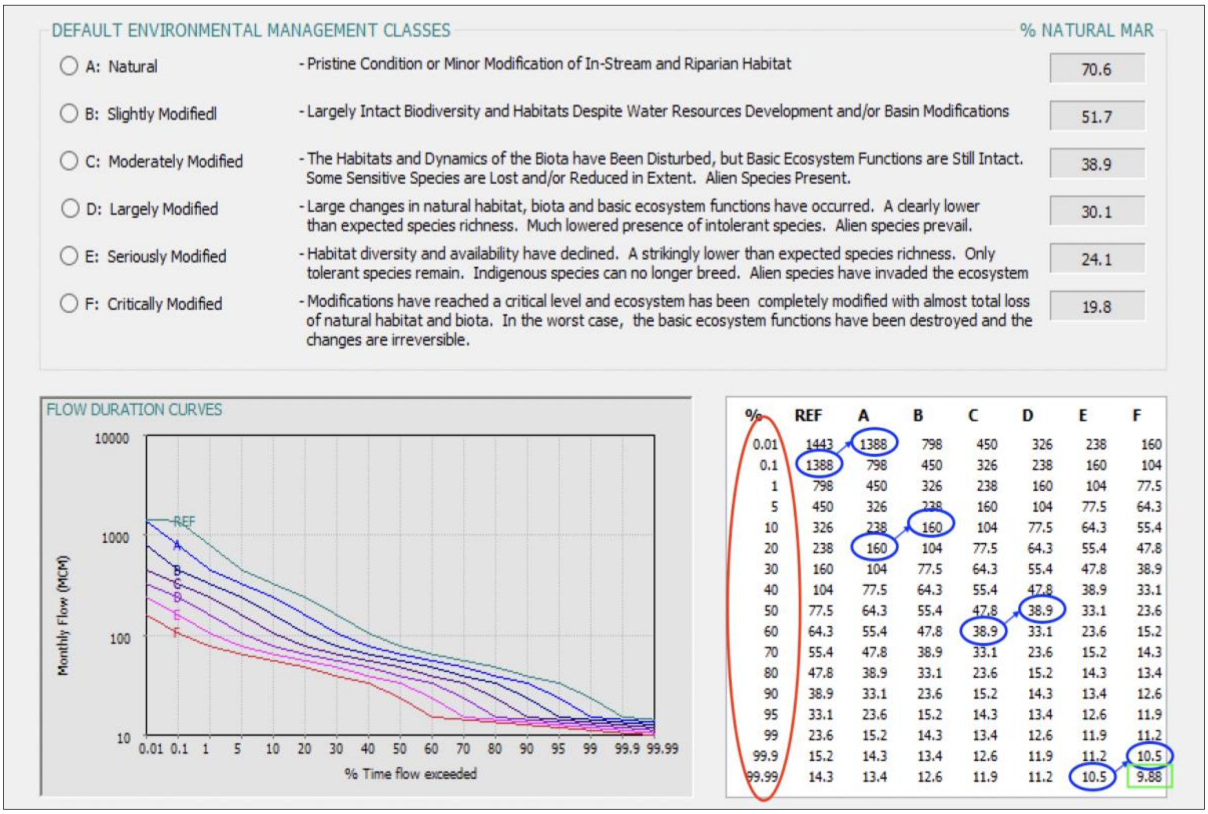
Calculation of environmental flow was conducted using the Global Environmental Flow Calculator or GEFC (Smakhtin and Eriyagama 2008). GEFC is a software used for rough approximation of environmental flow. The method is based on arithmetical assumptions rather than on comprehensive case-to-case analysis. The software establishes environmental flow requirements based on unmodified flow data that are originally produced by PyWR under the assumptions of no river infrastructure and covering the period between 1979 and 2016. Environmental flow requirements are presented in Table 5 according to specific environmental management classes (EMCs). Each EMC comes with environmental flow requirements necessary for meeting ecosystem needs.

Table 5. Environmental Management Classes (EMCs). Source: Smakhtin and Eriyagama 2008.

EMC	**Most likely ecological condition**	**Management perspective**
A	Natural rivers with minor modification of in-stream and riparian habitat	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions) allowed
B	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed
C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present	Multiple disturbances associated with the need for socio-economic development, e.g., dams, diversions, habitat modification and reduced water quality

D	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation
E	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem	High human population density and extensive water resources exploitation. Generally, this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to 'move' a river to a higher management category
F	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern and river habitats (if still possible/feasible) to 'move' a river to a higher management category

To identify the EMCs and corresponding environmental flows, GEFC requires flow duration curve (FDC) statistics. Properties of unmodified flow are presented by a cumulative probability distribution function of flow. In other words, flow duration curve analysis graphically illustrates how often flow of a given volume is observed — the horizontal axis represents flow discharge, and the vertical axis shows time percentage of flow of a given volume. Based on the FDC statistics, GEFC calculates a range of flows corresponding to 17 fixed flow percentage points: 0.01%, 0.1%, 1, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, 99.9% and 99.99%. This range is used to calculate environmental flow requirements for each EMC through a lateral shift procedure: unmodified flow FDC value for each percentage points is shifted to the left along the probability axis. Thus, flow originally observed in 99.99% of the time would now be observed in 99.9% of time, flow of 99.9% time would become flow at 99% of the time, and so on. For defining new values of flow, linear extrapolation method is used (Smakhtin and Eriyagama 2008). The process is presented on the Figure 15.



%	REF	A	B	C	D	E	F
0.01	1443	1388	798	450	326	238	160
0.1	1388	798	450	326	238	160	104
1	798	450	326	238	160	104	77.5
5	450	326	238	160	104	77.5	64.3
10	326	238	160	104	77.5	64.3	55.4
20	238	160	104	77.5	64.3	55.4	47.8
30	160	104	77.5	64.3	55.4	47.8	38.9
40	104	77.5	64.3	55.4	47.8	38.9	33.1
50	77.5	64.3	55.4	47.8	38.9	33.1	23.6
60	64.3	55.4	47.8	38.9	33.1	23.6	15.2
70	55.4	47.8	38.9	33.1	23.6	15.2	14.3
80	47.8	38.9	33.1	23.6	15.2	14.3	13.4
90	38.9	33.1	23.6	15.2	14.3	13.4	12.6
95	33.1	23.6	15.2	14.3	13.4	12.6	11.9
99	23.6	15.2	14.3	13.4	12.6	11.9	11.2
99.9	15.2	14.3	13.4	12.6	11.9	11.2	10.5
99.99	14.3	13.4	12.6	11.9	11.2	10.5	9.88

Figure 15. Estimation of environmental flow duration curves for six Environmental Management Classes.
Red circle highlights the percentage of time when flow of given volume is observed, blue circles illustrate the lateral shift procedure, the green rectangular shows one of the extrapolated values. Source: Smakhtin and Eriyagama 2008.

To present environmental flow recommendations in time series, GEFC uses the correlation between received FDC and flow properties (Smakhtin and Eriyagama 2008). After calculating environmental flow requirements presented in time series (1979-2016), the average values for each month have been taken for providing environmental flow recommendations. This study is focused only on EF requirements for classes A-D, excluding classes E and F as not desirable for environmental management goals. Environmental management class C aims at reaslistic management goals and present the average environmental flow requirement. Hence, class C environmental flow has been provided a particular attention in further analysis.

4.5 Scenarios assumptions

Table 6 illustrates the scenarios that have been run in PyWR and used in further analysis, together with the details of assumptions underlying each scenario reviewed.

Table 6. Overview of analysed scenarios.

Scenarios	**Assumptions**
Naturalized flow	The effects of all the artificial interventions such as diversions, irrigation abstractions and dams were removed for the model run.
Baseline scenario	- Assumes existing artificial infrastructure and water demand continue to be observed in a way as they are now. - Assumes GERD's filling is completed and start routine operation after the initial filling. - GERD is assumed to target 1600 MW (a power target that maximises 90% power generation reliability).
Expected future development scenario	- All the assumptions in the "Baseline scenario". - Plus future developments expected to be commissioned by 2035: Lake Tana and Beles basin irrigation expansion; Karadobi Dam commissioning.
Future climate changes scenarios	- All assumptions included the expected future development scenario. - Plus the impacts of climate change (range of 28 scenarios).

The unmodified water flow scenario simulates flow under the assumptions of no man-made infrastructure and human-induced water demand absence. These model settings have been derived from the original model by deleting representative nodes. The outputs present the so-called 'naturalised flow' and simulate how much water would have been kept in a river without human activities. Simulation outputs have been used not only to observe flow alteration, but as baseline data for calculating environmental flow in GEFC.

Current conditions scenario simulates Blue Nile flow under the baseline conditions, i.e., with already existing infrastructure, demand and supply. This is the original model simulating present water use patterns. Even though the filling GERD reservoir has already started, it is not accounted for this scenario.

Expected future development scenario illustrates how expected infrastructure development might affect flow with a 2035 time horizon. Scenario includes all existing infrastructure, current water demand, GERD's filling to its capacity, Lake Tana and Beles basin irrigation expansion and the commissioning of the Karadobi Dam.

Future climate change scenarios simulate how climate change would affect water flow regime patterns on top of the impact of expected infrastructure development by 2035. There are 28 climate change projections run by the model to investigate a range of future climate conditions. These climate change simulations are based on the assumptions in the Coupled Model Intercomparison Project 6 (CMIP6) and cover different *shared socio-economic pathways* (SSPs), alongside different *representative concentration pathways* (RCPs) expected by the end of this century (O'Neill *et al.* 2016). *SSPs* refer to the social, political and economic development pathways of human civilization, and are divided into four indicative categories:

sustainability (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequality (SSP4) and fossil-fuelled development (SSP5) pathways. *RCPs* are identified by the radiative forcing, i.e., the difference between the planet's incoming and outgoing energy. When the concentration of radiative forcing agents (mostly greenhouse gases) is higher in the atmosphere, it leads to the warming of the surface and air. The higher the radiative forcing the higher the expected future temperature. More information on the SSPs and RCPs can be found in Riahi (Riahi *et al.* 2017).

Only 4 SSP- RCP combinations have been used in the CMIP6 assessment, and assumptions of these 4 combinations have been derived for running 28 climate change projections. Figure 16 shows a matrix of SSPs-RCPs assumptions, highlighting combinations used in 28 projections, whilst

Table 7 explanains the assumptions.

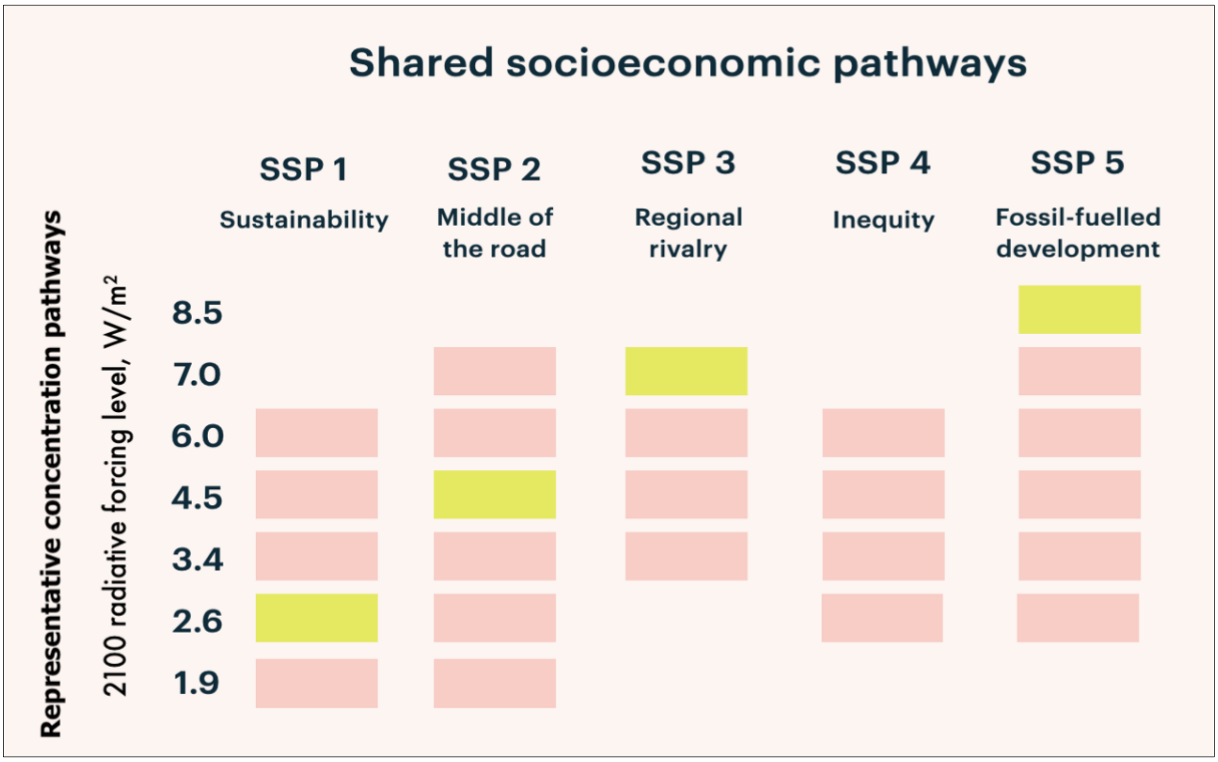


Figure 16. Matrix of climate change assumptions used in CMIP6 and four combinations reflected in 28 PyWR projections. Based on: O'Neill et al. 2016.

Table 7. Four combinations of climate change assumptions reflected in 28 climate change projections. Based on: Riahi *et al.* 2017.

SSP	RCP	Description
SSP 1	RCP 2.6	Gradual shift towards more sustainable development path with a respect to environmental boundaries. Investments in education and health, demographic transition, emphasis on human well-being, reduced inequality. Low growth of material consumption, lower resource intensity. High GDP and lowest population growth rate. Emissions peaks between 2040 and 2060, then decline. Results in 3-3.5C warming.
SSP 2	RCP 4.5	No change in social, economic, and technological trends. Uneven development, slow progress in achieving sustainable development goals. Degradation of environment is continuing, but intensity of resource use declines. Moderate population growth. “Middle of the road” scenario with slowly increasing pollutant emissions, resulting in 3.8-4.2C warming.
SSP 3	RCP 7	Competition for resources, focus on regional energy and food security. Low investments in education and technologies, slow economic development, material-intensive consumption. Unequal development and high population growth rate, lowest GDP. Strong environmental degradation in developing countries. High emission level, estimated warming of 3.9-4.6C.
SSP 5	RCP 8.5	Prevalence of competitive markets, rapid technological progress, switch to the sustainable development path. Integrated global markets. Economic and social development is coupled with the exploitation of fossil fuel resources and energy intensive lifestyle. High GDP and declining population. Successful management of local environmental problems, but not global. High-speed growth and energy-intensive scenario, overall emission level results in 4.7-5.1C warming.

Out of 28 climate change projections, 20 have been bias-corrected based on the Multi-Source Weighted-Ensemble Precipitation (MSWEP), the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5), and the Princeton Global Forcing (PGF). Eight other climate projections were generated based on 8 out of 20 initially selected projections by removing the wetting tendency. Wetting tendency is often observed in Eastern African climate projections but does not reflect the real state of matters (Wainwright *et al.* 2019). These 8 projections are more pessimistic about precipitation in comparison with the 20 other projections. The 28 scenarios simulating climate change impact can be found in Table 8.

Table 8. Scenarios used for projecting the impact of climate change on the Blue Nile regime. Colours represent the SSPs-RCPs as SSP5-RCP8.5 (red), SSP3-RCP7 (orange), SSP2-RCP4.5 (yellow), SSP1-RCP2.6 (green). Climate projections marked with ** are derived from other correlating projections but exclude the tendency for wetting usually observed in the climate projections of East Africa. Source: Basheer *et al.* 2021.

Scenario index	Shared Socio-economic pathway	Representative concentration pathway (W/m^2)	CMIP6 climate model name
0	SSP 5	RCP 8.5	ACCESS-CM2
1	SSP 2	RCP 4.5	ACCESS-ESM1-5
2	SSP 5	RCP 8.5	ACCESS-ESM1-5
3	SSP 1	RCP 2.6	BCC-CSM2-MR
4	SSP 2	RCP 4.5	CESM2
5	SSP 3	RCP 7	CESM2
6	SSP 5	RCP 8.5	CESM2-WACCM
7	SSP 1	RCP 2.6	GFDL-ESM4
8	SSP 2	RCP 4.5	GFDL-ESM4
9	SSP 2	RCP 4.5	GISS-E2-1-G
10	SSP 3	RCP 7	GISS-E2-1-G
11	SSP 3	RCP 7	GISS-E2-1-G
12	SSP 5	RCP 8.5	GISS-E2-1-G
13	SSP 3	RCP 7	IPSL-CM6A-LR
14	SSP 2	RCP 4.5	MIROC6
15	SSP 2	RCP 4.5	MPI-ESM1-2-HR
16	SSP 3	RCP 7	MRI-ESM2-0
17	SSP 5	RCP 8.5	MRI-ESM2-0
18	SSP 1	RCP 2.6	UKESM1-0-LL
19	SSP 5	RCP 8.5	UKESM1-0-LL
20	SSP 5	RCP 8.5	ACCESS-CM2**

21	SSP 2	RCP 4.5	ACCESS-ESM1-5**
22	SSP 5	RCP 8.5	ACCESS-ESM1-5**
23	SSP 2	RCP 4.5	CESM2**
24	SSP 3	RCP 7	CESM2**
25	SSP 5	RCP 8.5	CESM2-WACCM**
26	SSP 2	RCP 4.5	MIROC6**
27	SSP 1	RCP 2.6	UKESM1-0-LL**

Due to the difficulties related to the analysis of water flow regime alterations in all 28 scenarios, only three representative scenarios have been selected out of 28. These scenarios represent the wettest, the driest and middle-of-the-road futures for the Blue Nile flow regime. They have been selected for comparison with each other and with environmental flow recommendations.

would be compared to each other and to. In addition, one of the 28 scenarios has been selected as a representative of current climate conditions based on the comparison with historical and present regime trends.

4.6 Limitations

Although answering the research questions and addressing the research aim, this research had a number of limitations. The limitations are (1) technical or methodological, and (2) connected with the analysis and interpretation of results and the underlying framework. Both limitation categories define and are simultaneously limited by the research scope. In other words, theoretical framework always aims at scoping the problem well, when methodological tools are used to assess certain aspects of the problem, thus, they both define the depth and the width of analysis. However, scoping is essential to address the research questions. Figure 17 is a graphical representation of this research limitations and the relationship with scope.

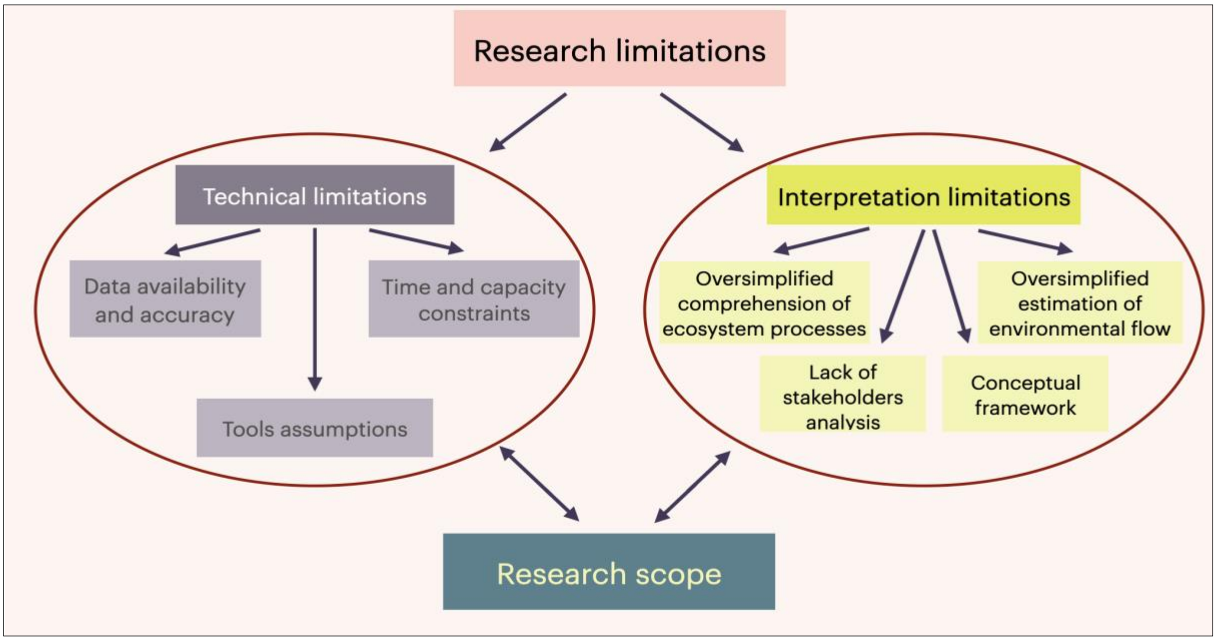


Figure 17. Overview on research limitations and their connection to the research scope.

To overcome data availability problems related to actually measured flow and other ecosystem parameters, proxies (e.g., for fish nesting, number of endangered species, water scarcity index etc.) and remote sensing techniques (vegetation index calculation etc.) could be used. The research covers a small number of study sites that limits the possibility for generalisation.

First, technical limitations relate to resource constraints and the choice of methodological tools. Due to limited capacity, resources, and time, not all relevant aspects of the problem could be studied. Working in a tight timeline, only with secondary data from the model, as well as no fieldwork have restricted both depth and width of the research. Historical data to build and calibrate the model was limited to the 1979-2016 period, and 2016 was the last year of recordings. Therefore, projections start from 2017, not taking recent years into account.

The model is set up for a general case, and out of necessity oversimplifies details. Expressed through model structure and coefficients, there are assumptions about key system elements and interactions related e.g., to water demand-supply, climate change projections, impact of deleting model nodes on flow estimates etc. with no precise information about their numerical accuracy. In addition, model sensitivity analysis couldn't be performed, thus, it is impossible to estimate how sensitive the model is to the changing any of its parameters.

As for the GEFC tool, environmental management classes do not consider hydrological or geomorphological conditions of the watershed. Hence, environmental flow calculations are only approximate, and their confidence interval is not known. Each ecosystem has a unique set of characteristics, and environmental flow requirements might need to be adjusted based on contextual parameters, rather than be based primarily on historical flow.

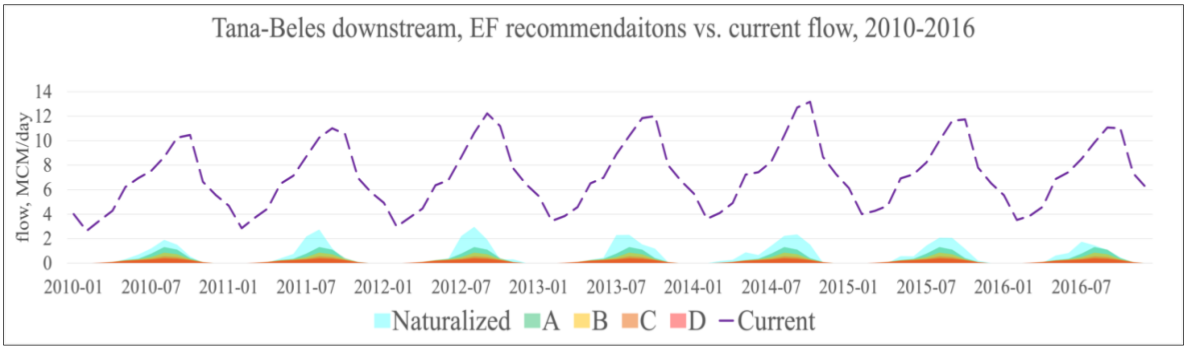
With respect to and beyond its conceptual framework, the research would have benefited from a field work component and local stakeholder input. Specifically, estimating the socio-economic and ecological impacts of changing Blue Nile flow at the various study sites would benefit from interaction with stakeholders to assess their preferences, sensitivities, and to take their understanding of local ecosystem processes into account. Field work part is often taken for similar studies, such as one for Okavango basin in Southwest Africa (CRIDF 2017). This element both adds to the research credibility and allows to track issues that are not accessible using the desktop-based approach.

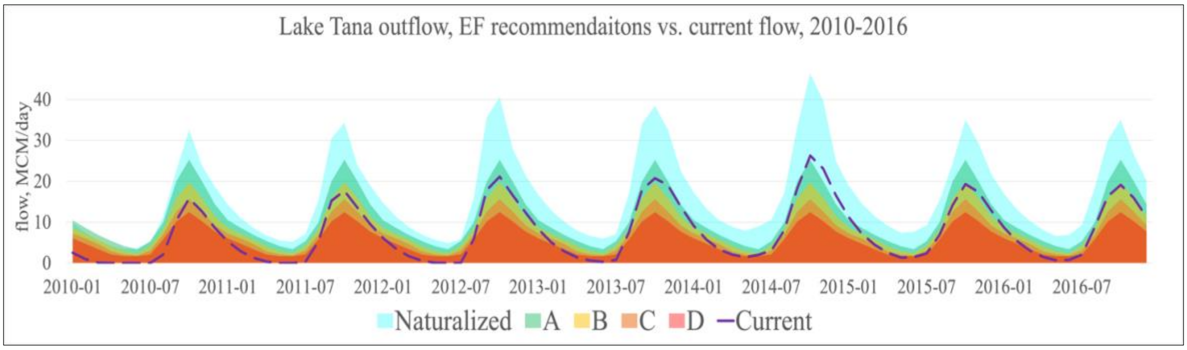
5 Results

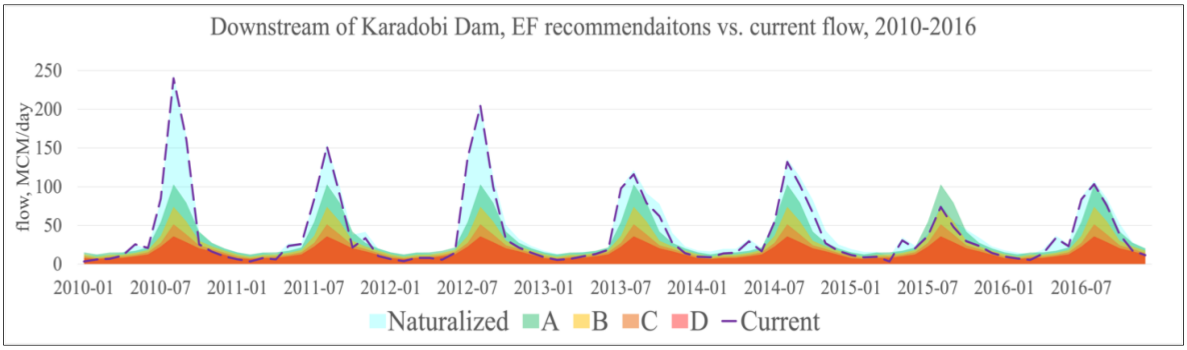
This chapter illustrates observed patterns of flow simulated under different assumptions, as well as presents a comparative analysis between flow and environmental flow requirements. The chapter begins with analysis of observed flow alterations, then goes through estimated environmental flow. Only after that, environmental flow requirements are compared with current flow tendencies, as well as with future tendencies imposed by both infrastructure development and climate change.

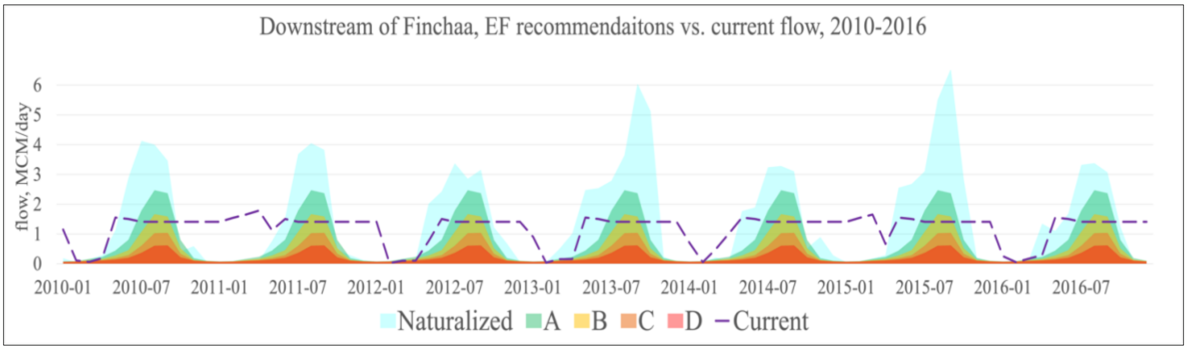
5.1 Observed water regime alteration

To proceed with the analysis of ecosystem requirements, one must compare currently observed flow with unmodified flow first. This comparison allows to see how already existing river infrastructure and anthropogenic demand have affected flow and water availability. As shown on the Figure 18, existing infrastructure already creates quite a difference in observed flow compared to unmodified. For the period between 2010 and 2016, observed flow significantly differs from unmodified flow in 3 out of 5 locations—Tana-Beles hydropower downstream, Lake Tana outflow and Finchaa irrigation downstream. Tana-Beles flow is several times higher than unmodified flow which is induced by water transfer from the Lake Tana to the hydropower station. As an advance observation, this is the main reason why not only currently observed flow, but all future projections would result in very high flow values, which would be always too high for recommended environmental flow. Consequently, Lake Tana's currently observed outflow is lower compared to unmodified—due to the water transfer project, as well as growing water demands. As for the Finchaa location, observed lower flow is a result of sugar cane agriculture that requires stable water level for irrigation. The reservoir helps to stabilise water availability throughout the year, minimising the difference between normally fluctuating monthly values from June to December. Since this study takes 2016 as the last year of the current water regime, there are now flow alteration due to Karadobi downstream or GERD yet.









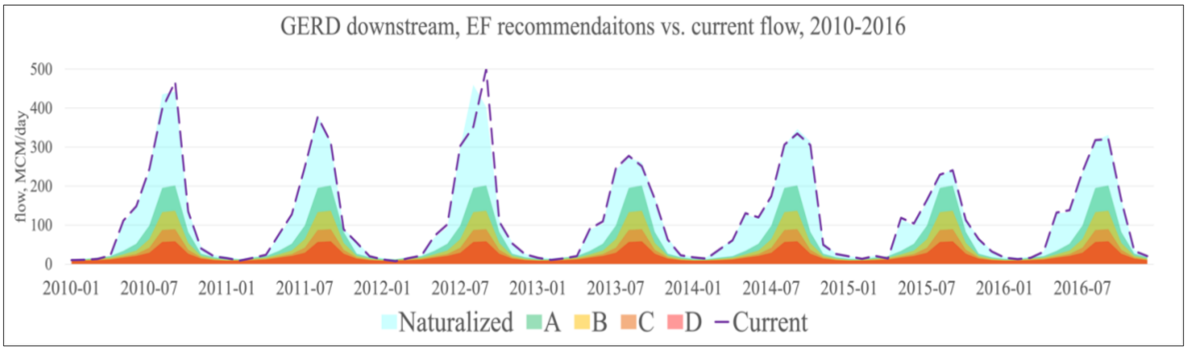


Figure 18. Currently observed flow in comparison with unmodified (or naturalised) flow and environmental flow for A-D classes requirements, years 2010-2016, for the 2010-2016 period. A-D classes refer to the state of ecosystem conditions, from the best to the worst.

5.2 Observed flow patterns and environmental flow requirements

To estimate environmental flow requirements, unmodified or naturalised flow data have been simulated for the 1979-2035 period. See Appendix A—Environmental flow requirements for calculated environmental flow recommendations. Flow estimation for the years 1979-2016 is based on the historical data, while unmodified flow projection for 2017-2035 is based on the climate change projection closest to historical flows. Projection #1 has been selected for this purpose, it represents one of the SSP2-RCP4.5 scenarios (ACCESS-ESM1-5 model), i.e., it is likely the closest to the baseline unaltered by human intervention. This simulation's outputs have been used to both calculate environmental flow recommendations and for showing flow under baseline climatic conditions. Projection #1 reflects future tendencies in social, economic, and technological development that are similar to historical patterns (Riahi *et al.* 2017).

As shown on the Figure 18, Tana-Beles flow is dangerously higher than EF recommendations. Lake Tana outflow mostly satisfies requirements for classes A-B during the wet seasons but not during the dry seasons. EF requirements are maintained within category A (pristine or slightly modified ecosystems) for Karadobi Dam, when flow dramatically falls to levels associated with lower class criteria from October till June. Same tendency as when compared with unmodified flow, the flow downstream form Finchaa shows its ability to meet EF requirements at a class B level for the periods of high-intensity, while water exceeds the recommended level later. GERD (which is not commissioned at this point) maintains natural flow patterns. Hence, no vulnerability is observed for this location before 2017. Table 9 provides an overview of environmental flow and observed flow characteristics.

Table 9. Environmental flow vs. observed flow characteristics. Colored cells are highlight seasonal alterations.

Characteristics of C class environmental flow			
	Number of peaks	*Flow max period*	*Flow min period*
Tana-Beles	1	August	December-April
Lake Tana outflow	1	October	May-June
Karadobi	2	October	February-March
Finchaa	1	August-September	November-April
GERD	1	August	January-March
Characteristics of observed flow			
	Number of peaks	*Flow max period*	*Flow min period*
Tana-Beles	1	September-October	February
Lake Tana outflow	1	October	May-June
Karadobi	1	October	February-March
Finchaa	1-2	June-December	January/May
GERD	1	October	January-March

Results of the flow duration curve (FDC) analysis shown the general tendency of current flow to be slightly lower than unmodified only for one location —Karadobi dam (Figure 19). In 99% of the time, the same water flow as unmodified is observed for GERD. This location has shown higher water flow only during periods of higher discharge (1% of the time). As described above, Lake Tana's flow can meet only high discharge periods requirements, when failing to meet water requirements of dry seasons, resulting in a total mean annual flow percent reduction of 26 precents. Finchaa site's flow can not meet class C requirements for environmental flow in the 10 % of time, resulting in a static flow. Static flow, or flow with a very small or no difference between high and low flow, can impose serous risks and may contribute to a failure of natural processes such as breeding and nesting, as well as to a failure to redistribute main nutrients through hydrodynamic turbulence.

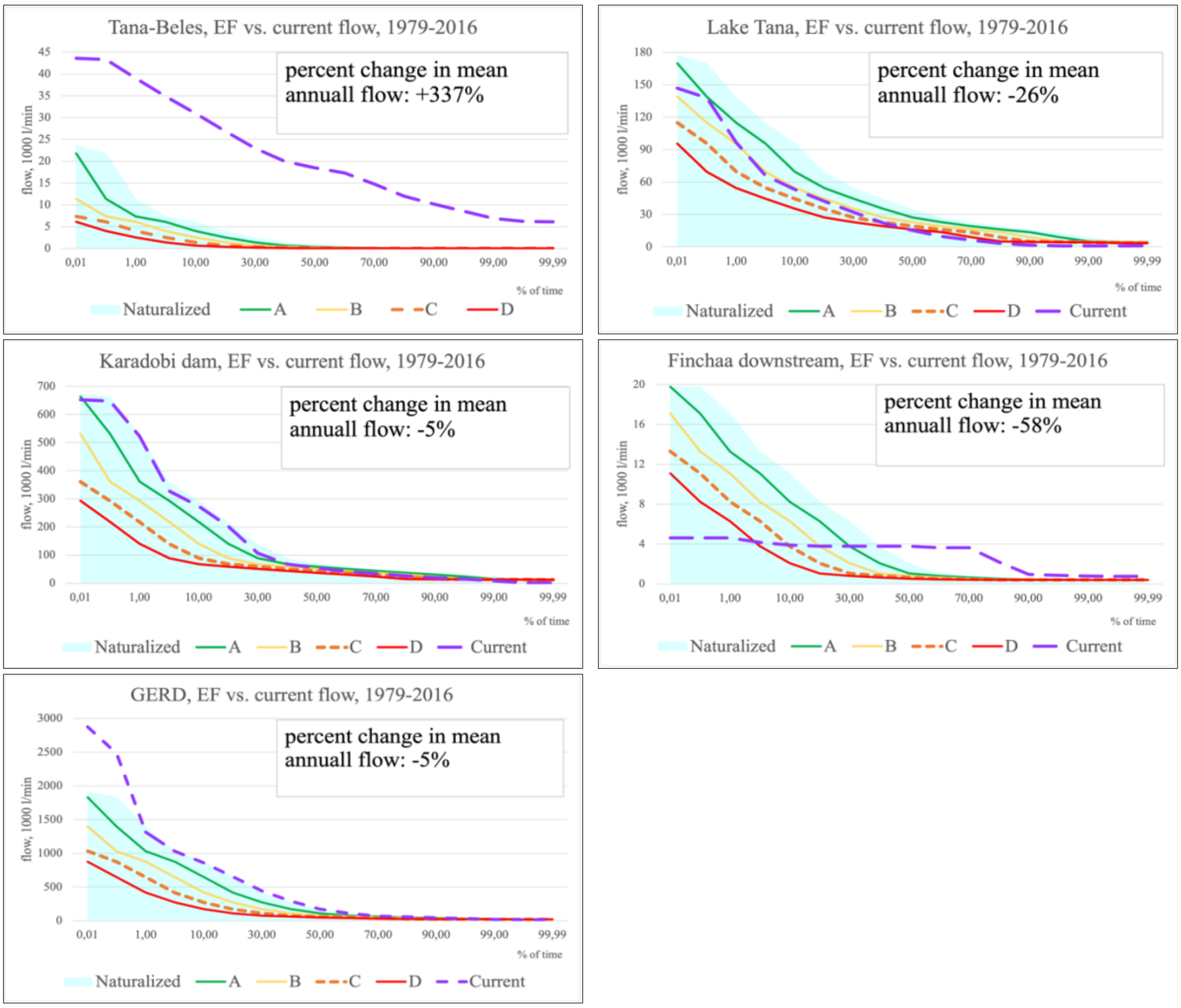
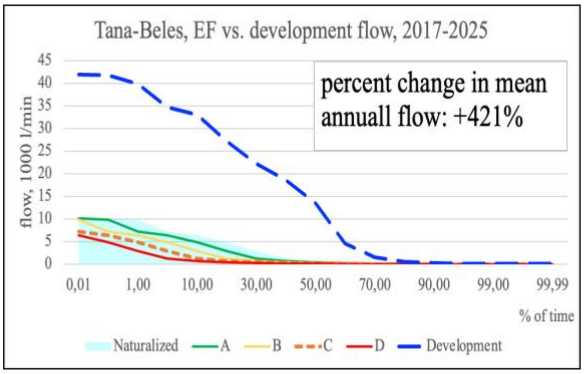
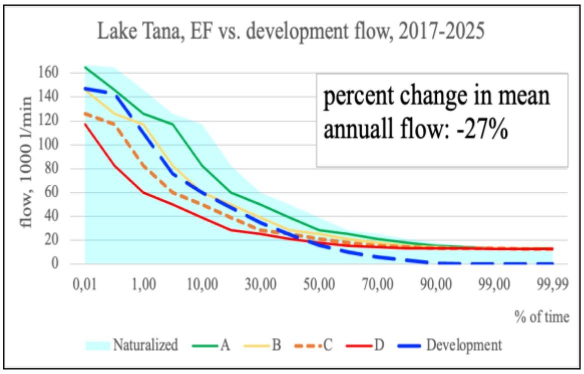


Figure 19. Flow duration curve (FDC) analysis for unmodified, current flow and EF recommendations, years 1979-2016.
Classes A-D are presented. Environmental flow class C requirements are highlighted in dashed orange line as the average environmental flow recommendation. Percent change in mean annual flow refers to percent change between area under unmodified flow curve and area under currently observed flow curve. Positive value speaks of water flow increase, negative value refers to water flow decline.

5.3 Impact of planned infrastructure: flow alteration and environmental flow requirements

Model run outputs have shown that introduction of development plans would inevitably alter availability of water resources. Significant reduction of accumulative flow volume and alteration of seasonality patterns have been observed for at all study sites (Figure 20 and Figure 21). To analyse patters of flow volume alteration, FDC analysis needs to be mentioned first. Flattening of flow appeared for downstream of Karadobi, Finchaa and GERD, as flow for these locations dropped to a value lower than originally observed during short but high-intensity events (Figure 20). This tendency leads to a total loss of 48, 66 and 22 precents of flow volume for Karadobi, Finchaa and GERD representatively. For Karadobi and Finchaa locations, high-intensity flow can not meet even D level requirements, while in 50 % of time it exceeds recommendations for the dry season. GERD downstream's flow barely satisfies C level requirements, but then maintains closer to A-B categories. Lake Tana location does not show significant anomalies, its flow meets C class requirements, apart from the low-intensity events that result in 27 presents decline in the area under FDC. Tana-Beles location exhibits very high flow well above all EF classes (Figure 20).





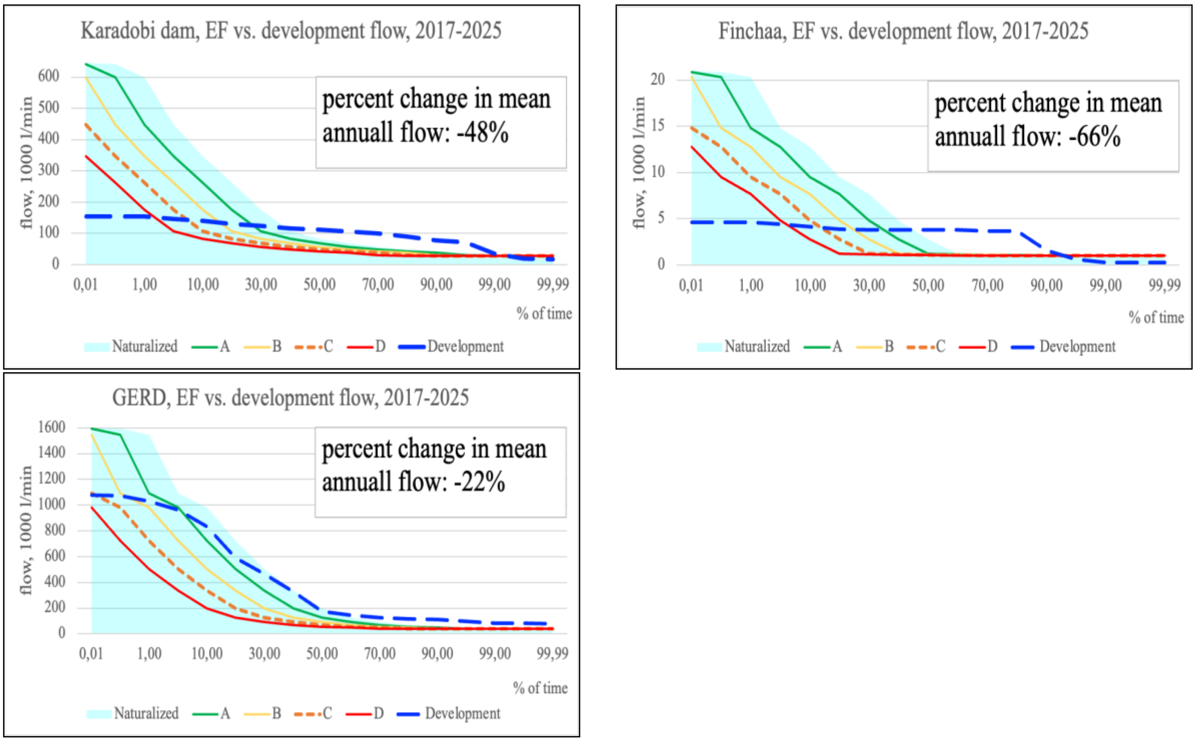
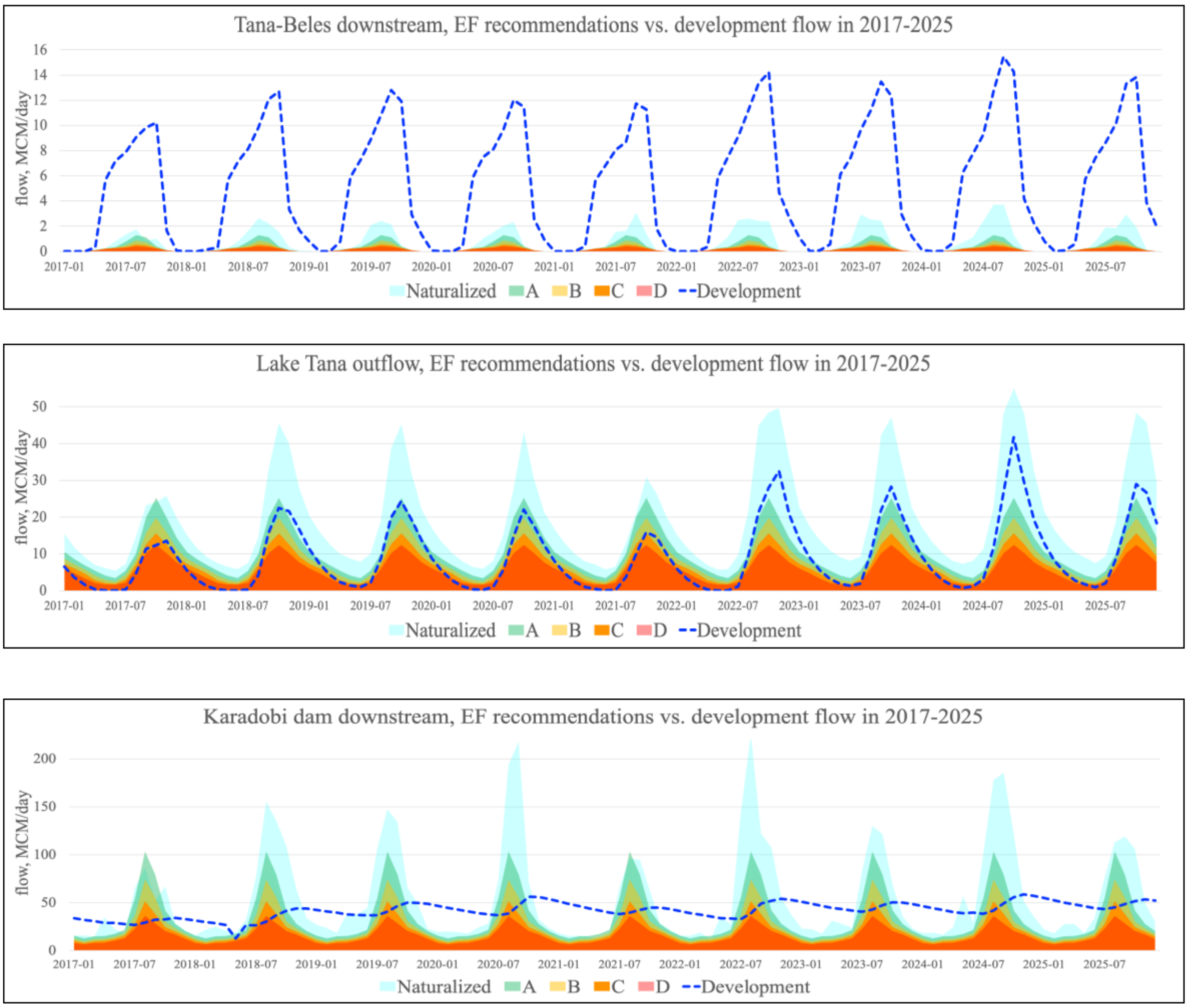
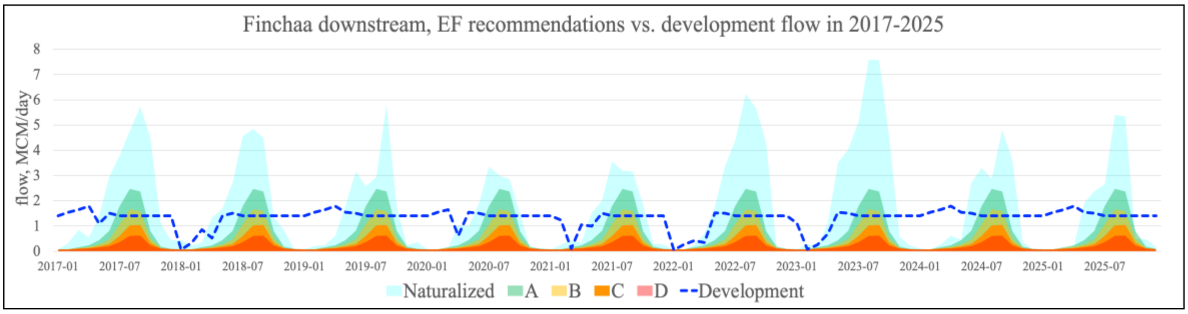


Figure 20. FDC analysis, unmodified flow, environmental flow recommendations and expected development flow, for 2017-2025 period.
Environmental flow class C requirements are highlighted with a dashed orange line as the average environmental flow recommendation. Percent change in mean annual flow refers to percent change between area under unmodified flow curve and area under currently observed flow curve. Positive value speaks of cumulative water flow increase, negative value refers to cumulative water flow decline.

Time series analysis presented on Figure 21, shows how new infrastructure would be altering water availability in the 2017-2025 period. As already mentioned, flow of Karadobi and Finchaa locations would be losing its strong seasonality, i.e., flow fluctuations between seasons would become less obvious. In addition, although general flow regime patterns remain closer to historically observed, both locations experience a slight shift of flow peaks and valleys. Ecosystem requirements are satisfied within B-C class recommendations only for a 1/4 of year for these locations. This places ecosystem processes that require high fluctuations in water level under threats and affects breeding and migration processes. Interesting behaviour is observed for locations downstream from GERD. While unmodified flow simulations shift to April-May. In addition, the secondary peaks are occasionally observed in June-July after flow reduction, and even the third peak can be found around October-November. GERDS's minimum flow has been historically observed during April-May, but shifting to August-September after the commissioning of the dam. This kind of serious flow alteration might cause a range ecosystem services disfunction. For instance, changes in the temporal patterns of peaks may also have ecological consequences, as they may fall out of sync with the rhythm of species sensitive to it. As in previous scenarios, Tana-Beles' expected flow exceeds all recommendations, whilst the Lake Tana's flow barely meets D class EF requirements during the low flow season in January-October (Figure 21). Table 10 highlights flow alterations observed at all five study sites, compared to EF class requirements.





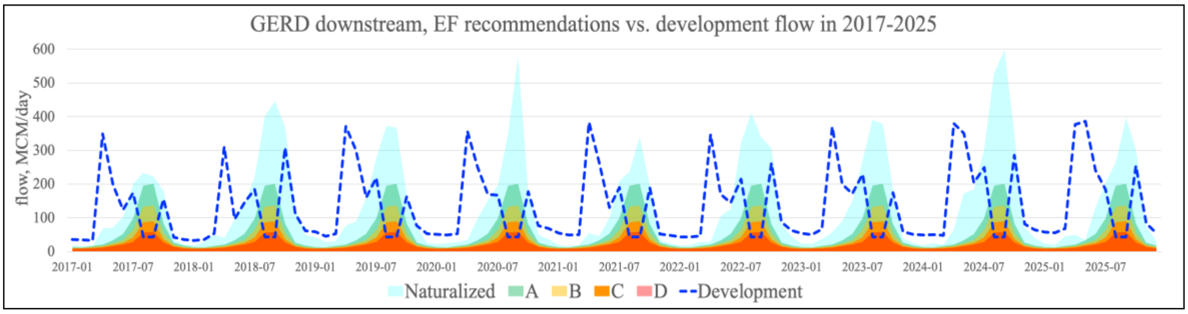


Figure 21. Simulated flow under the assumptions of expected river infrastructure development. Comparison to unmodified flow and environmental flow A-D classes requirements, years 2017-2025.

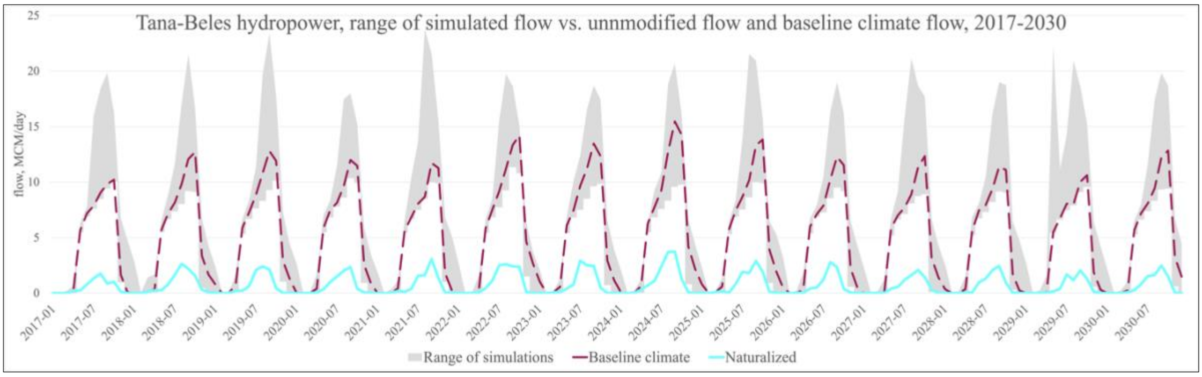
Table 10. Expected development flow characteristics, compared to class C environmental flow requirements.
Colored cells highlight significant seasonal flow alterations.

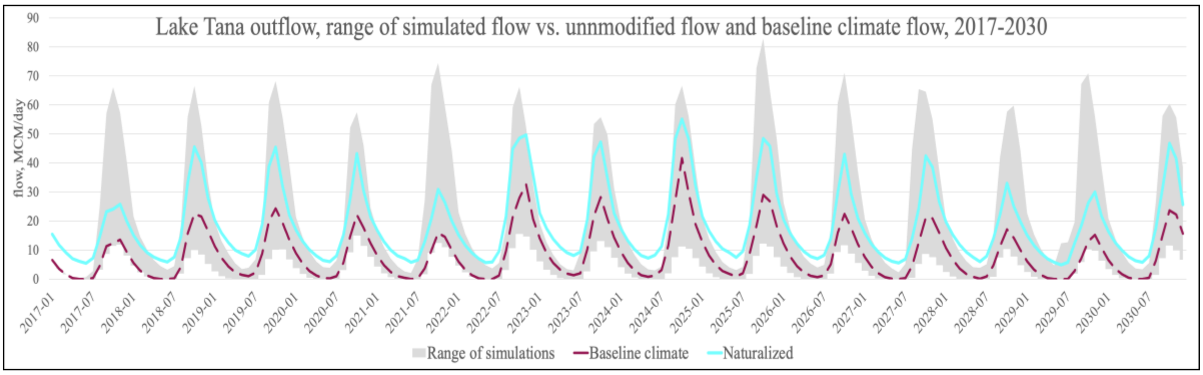
Characteristics of C class environmental flow			
	Number of peaks	*Flow max period*	*Flow min period*
Tana-Beles	1	August	December-April
Lake Tana outflow	1	October	May-June
Karadobi	2	October	February-March
Finchaa	1	August-September	November-April
GERD	1	August	January-March

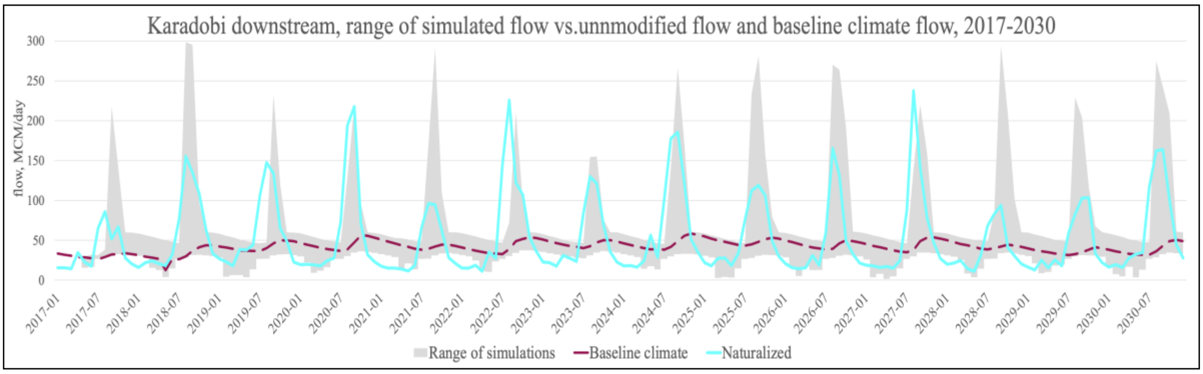
Characteristics of development induced flow			
	Number of peaks	*Flow max period*	*Flow min period*
Tana-Beles	1	September-October	February-March
Lake Tana outflow	1	October	May-June
Karadobi	1	November	June-July
Finchaa	1-2	May-November	February-March
GERD	3	April	October-February

5.4 Flow patterns alteration due to expected climate change

Although results of the previous sections already showed how development plans will alter water availability and seasonality patterns, climate change plays an additional vital role in defining future flow patterns. 28 climate change scenarios take the impact of ***both*** future infrastructure development ***and*** climate change on flow into account. The range of projected flow modifications is based on the difference between maximum and minimum expected flow for every time step and from all models. Figure 22 presents expected flow deviations from unmodified simulated flow and flow expected under current climatic conditions. Climate change induced impact is still uncertain, because it is mostly determined by the global level political decisions. Accordingly, the Blue Nile expected flow might vary significantly. The wide spread of between very high and very low flow values is striking, both for the rainy and dry seasons. Speaking about two radically different study sites, the Tana-Beles location illustrates how high-intensity flow can develop, while Finchaa downstream shows extreme low discharge. Lake Tana outflow and Karadobi dam downstream might experience both higher and lower flows, however, keeping their seasonal flow characteristics. Unfortunately, this is not the case downstream of GERD. There are no clear flow pattern shift tendencies for this site, but the irregular changes in flow patterns disrupt the tendencies of unmodified flow. As described previously, development plans, more precisely GERD's commissioning significantly alter this location's hydrological characteristics.







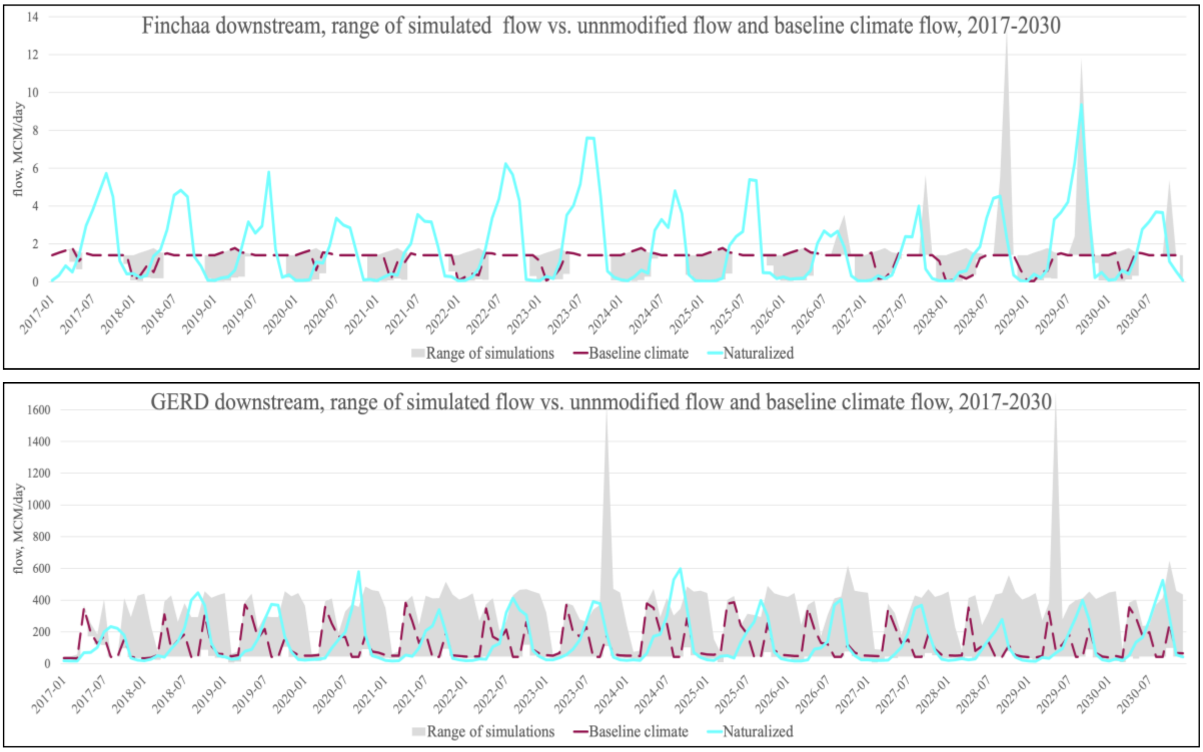
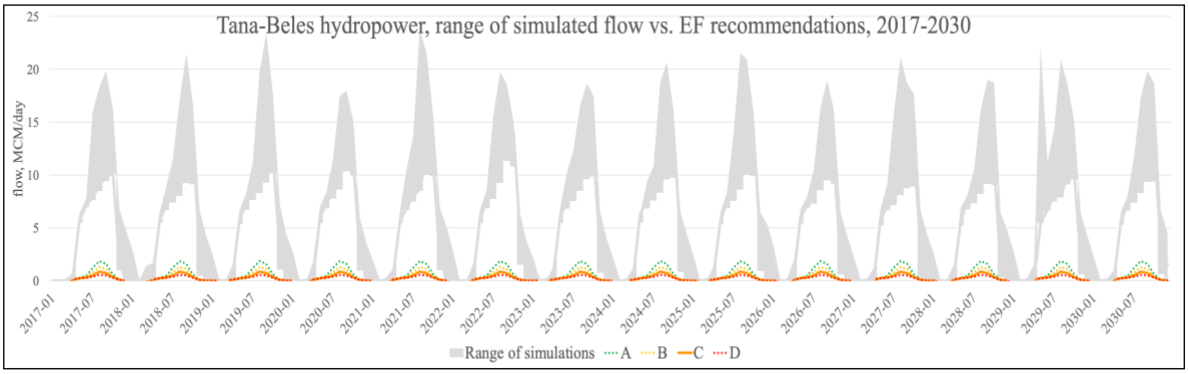
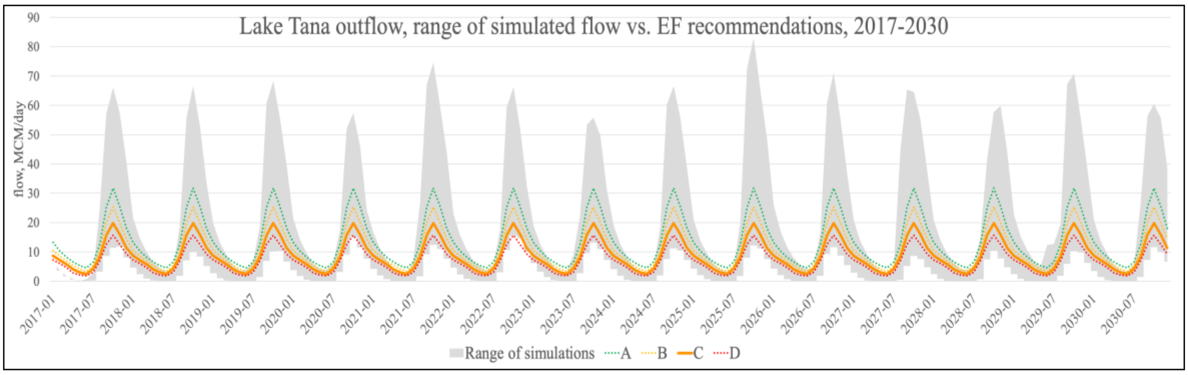


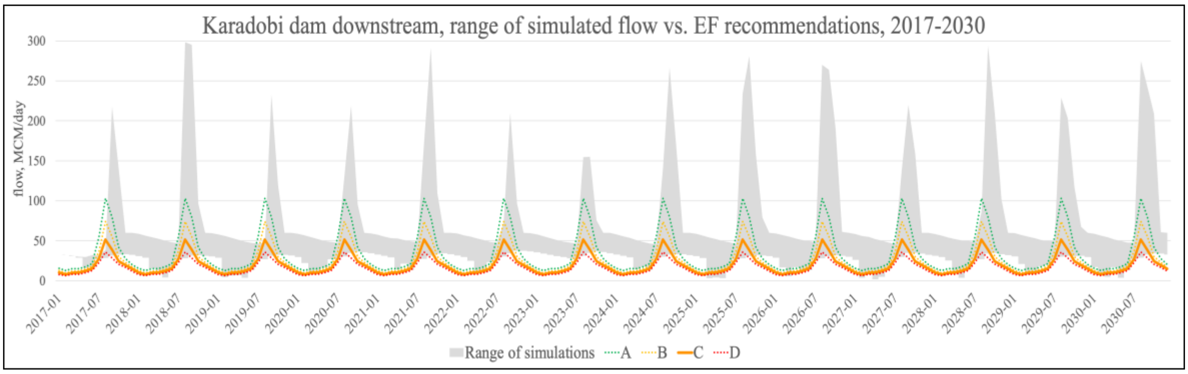
Figure 22. Range of expected flow under 28 different sets of climate change assumptions compared with unmodified flow and flow anticipated under climatic conditions closest to current.

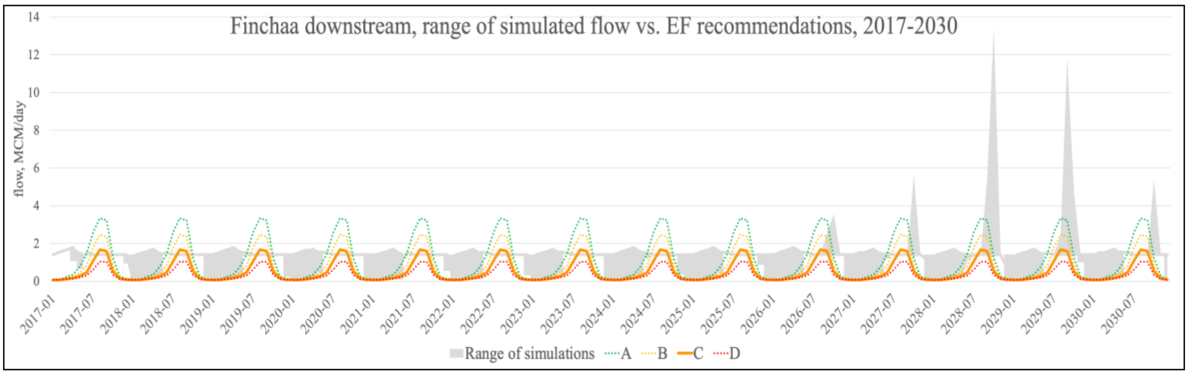
5.5 Climate change and challenges of meeting environmental flow requirements

Figure 23 shows to what extent the Blue Nile environmental flow requirements would be satisfied when the impact of climate change on flow regimes is added to the impact of infrastructure development. In order to keep the analysis robust, expected flow is compared only with class C environmental flow requirements that are highlighted by the orange solid line. See projections based on all 28 climate scenarios in Appendix B — . Results of this analysis resemble the comparison to unmodified flow for the 2017-2030 period. The summary of alterations and possible flow variability is presented in the Table 11.


Tana-Beles hydropower, range of simulated flow vs. EF recommendations, 2017-2030
flow, MCM/day
Range of simulations A B C D


Lake Tana outflow, range of simulated flow vs. EF recommendations, 2017-2030
flow, MCM/day
Range of simulations A B C D


Karadobi dam downstream, range of simulated flow vs. EF recommendations, 2017-2030
flow, MCM/day
Range of simulations A B C D


Finchaa downstream, range of simulated flow vs. EF recommendations, 2017-2030
flow, MCM/day
Range of simulations A B C D

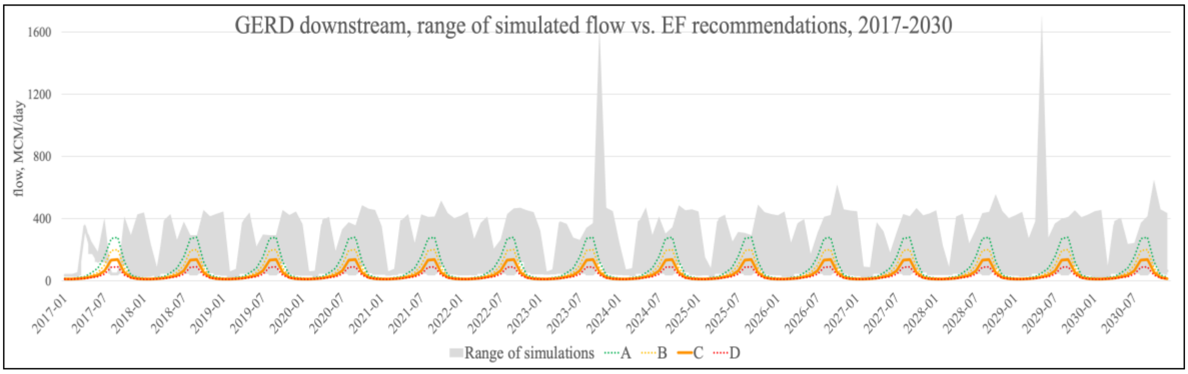


Figure 23. Range of expected flow under 28 different climate change scenarios, compared with environmental flow requirements. Class C requirements are highlighted by the bright orange solid line in order to show average environmental flow requirements.

Table 11. Range of expected flow under 28 different climate change scenarios, compared to class C environmental flow criteria.

Study site	**Ability to meet class C environmental flow criteria**
Tana-Beles	Expected range is many times higher than environmental flow recommendations for most of the time; class C requirements are met only during the dry season and for a short period of time
Lake Tana outflow	There are scenarios that return values way higher then unmodified flow (thus, class C requirements), as well as those that do not meet class C requirements even for the wet season. Thus, further study required
Karadobi	Class C requirements are rarely met, only for maximum and minimum water discharge events, which are limited to 2-3- months in a year
Finchaa	Class C requirements are met only for the dry season, water shortage during previously observed 'high flow' season
GERD	No consistent patterns due to diverse model results, climate change assumptions determine not only flow but also seasonality. Further study required.

5.6 Climate change projections, current development, and adapted infrastructure flows

For further analysis, three climate change projections have been selected to observe how different their underlying assumptions can affect flow alterations, as well as the ability of the Blue Nile to meet EF requirements. #19 has been selected as one of the highest flow scenarios, scenario #27 as the lowest, and scenario #11 as the middle-of-the-road one. The selected projections also integrate different SSPs: #19 for SSP5-8.5, #27 for SSP1-2.6 and #11 for SSP3-7, which represent a wide range of possible futures for a river basin. Table 12 explains each of the scenarios, with a brief recap of scenario #1 which has been used to calculate environmental flow recommendations and simulate the effects of current and expected development projections.

Table 12. Characteristics of representative climate change scenarios. Source: Riahi *et al.* 2017.

#	SSP	RCP	Model	Model recap
27	SSP 1	RCP 2.6	UKESM1-0-LL**	Gradual shift towards more sustainable development path with respect for environmental boundaries. Emission peaks between 2040 and 2060, then declines. 3-3.5C warming.
1	SSP 2	RCP 4.5	ACCESS-ESM1-5	No change in social, economic and technological trends. "Middle of the road" scenario with slowly increasing emission that result in 3.8-4.2C warming.
11	SSP 3	RCP 7	GISS-E2-1-G	Competition for resources, focus on regional energy and food security. High emission level, estimated warming of 3.9-4.6C.

19	SSP 5	RCP 8.5	UKESM1-0-LL	Prevalence of competitive markets, rapid technological progress, decoupling. High-speed growth energy-intensive scenario, overall emission level results in 4.7-5.1C warming.

Prior to comparing the three representative scenarios and environmental flow requirements, the differences between 5 scenarios shall be reviewed: 3 climate change projections, projection simulating flow under the assumptions of only current (up to 2016) infrastructure, and projection representing flow under the assumptions of new river development and current climatic conditions. Figure 24 illustrates the logic between each of the reviewed scenarios, next steps of analysis are concentrated on these scenarios comparison.

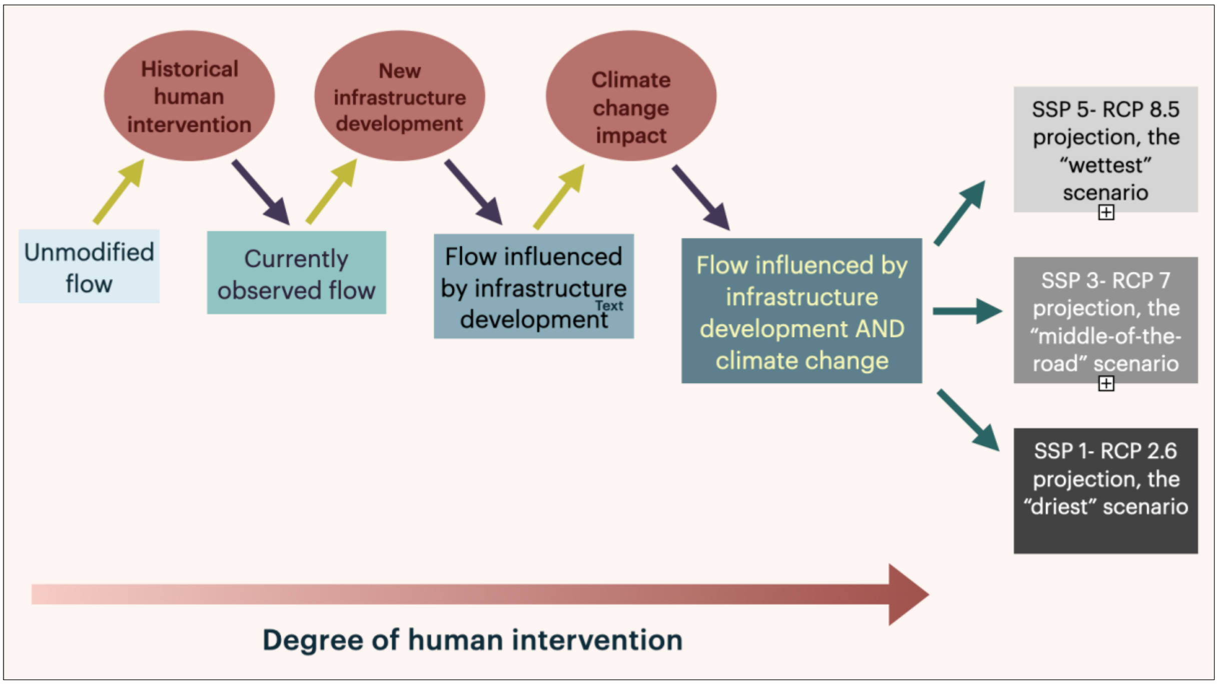
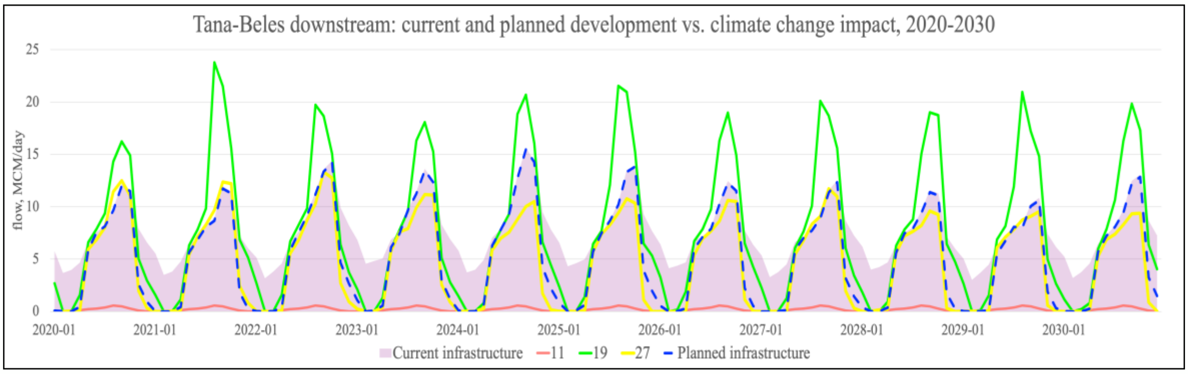
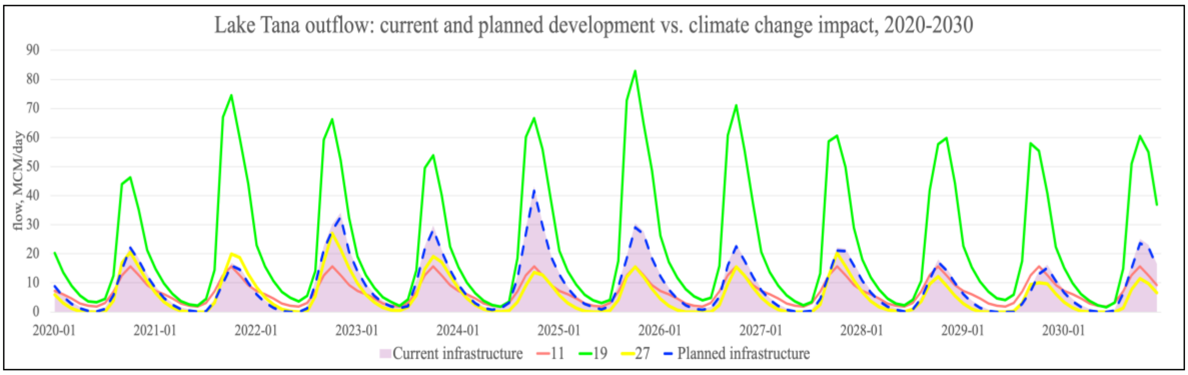


Figure 24. Schematic of the analysed scenarios.
The flow is showing the gradation from the unmodified flow scenario to the scenarios that include existing infrastructure, planned infrastructure and climatic change.

Figure 25 reflects how new development and climate change together can alter currently observed flow. For Lake Tana, the middle-of-the road scenario #11 shows the lowest flow, when flow seasonality is maintained for all three scenarios. Lake Tana's driest scenario shows the lowest flow level, whereas the wettest projection exceeds both current and development flows twofold, however, without changes in seasonal patterns. For the Karadobi site, the driest and the mid-range simulations show the same fluctuation patterns as the currently observed flow, while the driest scenario reflects the same patterns as a planned infrastructure flow i.e., shifting flow peaks and valleys. Interestingly, while Finchaa's scenarios #11 and #27 follow the same pattens as current and new development flows, scenario #18 returns almost constant flow with peaks till 2028, and only then returns unprecedentedly high flow for the rainy season. GERD's driest scenario #27 follows the adopted development trends, but with slightly decreased values. The same site's scenario #11 shows the lowest flow values that repeat the patterns of current observed flow. Projection #19 returns new flow pattens, thus, all three climatic projections illustrate how unpredictable the consequences of GERD commissioning, combined with additional infrastructure and climate change might be.





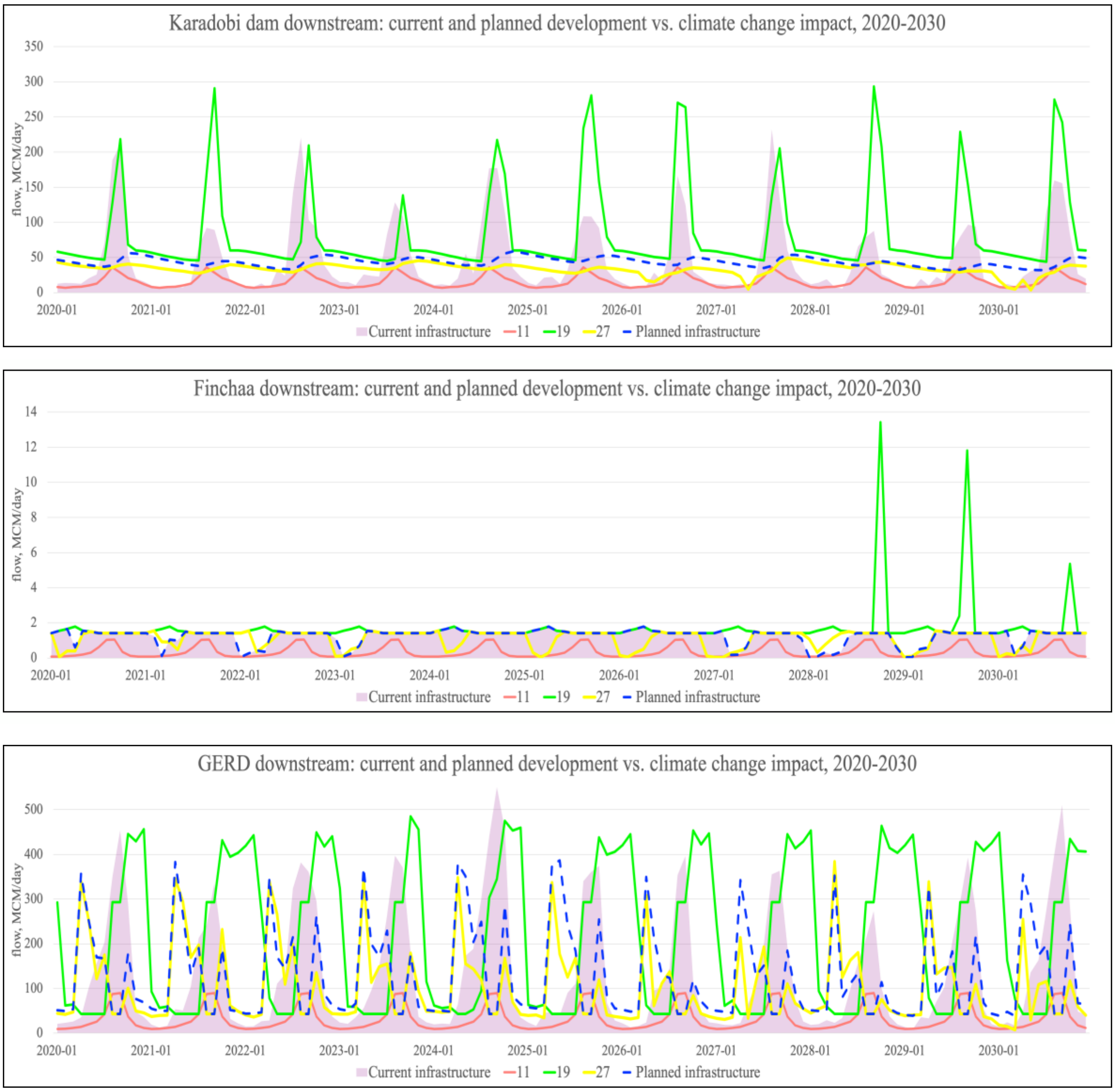
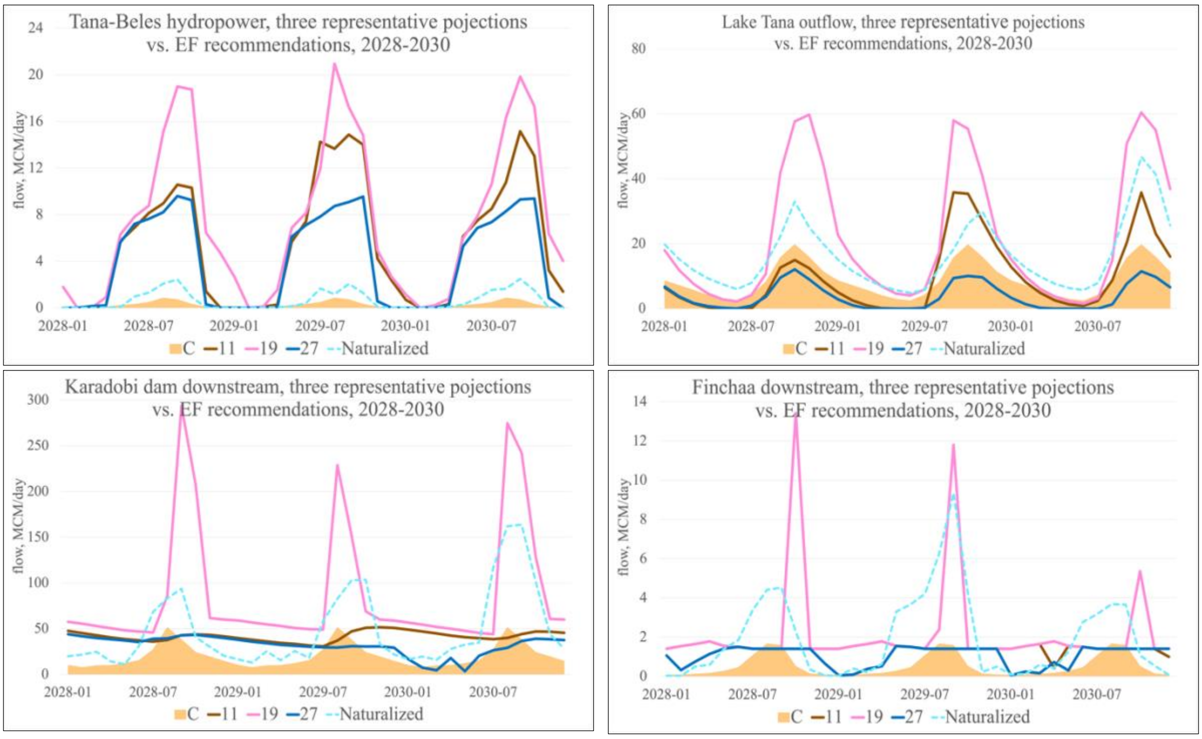


Figure 25. Three representative climate change projections, compared to flow under current infrastructure and new planned infrastructure projections (under current climatic conditions), 2017-2030 period.

5.7 Three representative climate scenarios and ability to meet environmental flow requirements

The same representative scenarios (highest, mid-range, lowest) have been used for comparison with naturalised flow and with class C environmental flow. All three scenarios return very high values for the Tana-Beles' EF recommendations. Lake Tana's scenario #11 fits better the EF requirements in comparison with the driest and wettest scenarios. Both Finchaa and Karadobi sites have too high flow under the wettest scenario #19, while two other scenarios illustrate a stable flow that exceeds historically observed peaks. As stated previously, all representative scenarios return very different patterns for the GERD due to the huge impact this dam would play for the region's water availability. None of the climate change projection returns values closer to the unmodified flow for the downstream of GERD. Only scenario #11 (middle-of-the-road) satisfies seasonality requirements of environmental flow. However, even this scenario goes far beyond dry season recommendations. Scenario #19 (the wettest) shows very high flow with altered seasonal patterns: originally observed in October, now flow peaks are observed in November and January. In contrast, the driest projection (#27) not only returns peak flow in March and creates secondary and tertiary peak, but displays minimum observed flow in August-September—historically the period of maximum flow. All these tendencies and flow alterations are shown on Figure 26 for three years. Appendix C — provides the graph for years the 2017-2030 period.



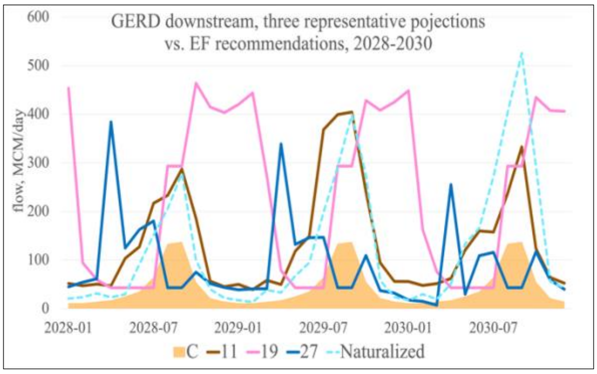


Figure 26. Flow rates under three representative climate change projections, compared to unmodified flow and class C environmental flow requirements, years 2028-2030.

The very last part, flow duration curve analysis includes the analysis of flow intensity patterns based on the percent change in flow over a given time period (Figure 27.). The largest flow alteration is observed for the Tana-Beles location, resulting in an almost 7-times higher FDC area. The Lake Tana location's scenario #19 scenario is returning significantly higher values for high-intensity events. Scenarios #11 and #27 satisfy environmental flow criteria for the wet season better, resulting in a small mean annual flow change compared to naturalised flow. A similar tendency is observed for the Karadobi study site for scenarios #11 and #19. Meanwhile, scenario #27 returns insufficient flow for high-discharge events and very high for low-discharge seasons, which might result in serious ecosystem degradation. However, the same phenomena are observed for Finchaa's location amongst all the reviewed scenarios. Speaking about the downstream of GERD, both scenarios 11 and 27 meet class C environmental flow requirements for high discharge periods, and both scenarios have FDC patterns similar to class A criteria.

For low discharge events, both projections return too high flow values. The wettest scenario #19, though, illustrates very intense, high-volume flow that results in overshooting not only EF criteria, but also naturalized flow patterns. See Figure 27. for a visual representation.

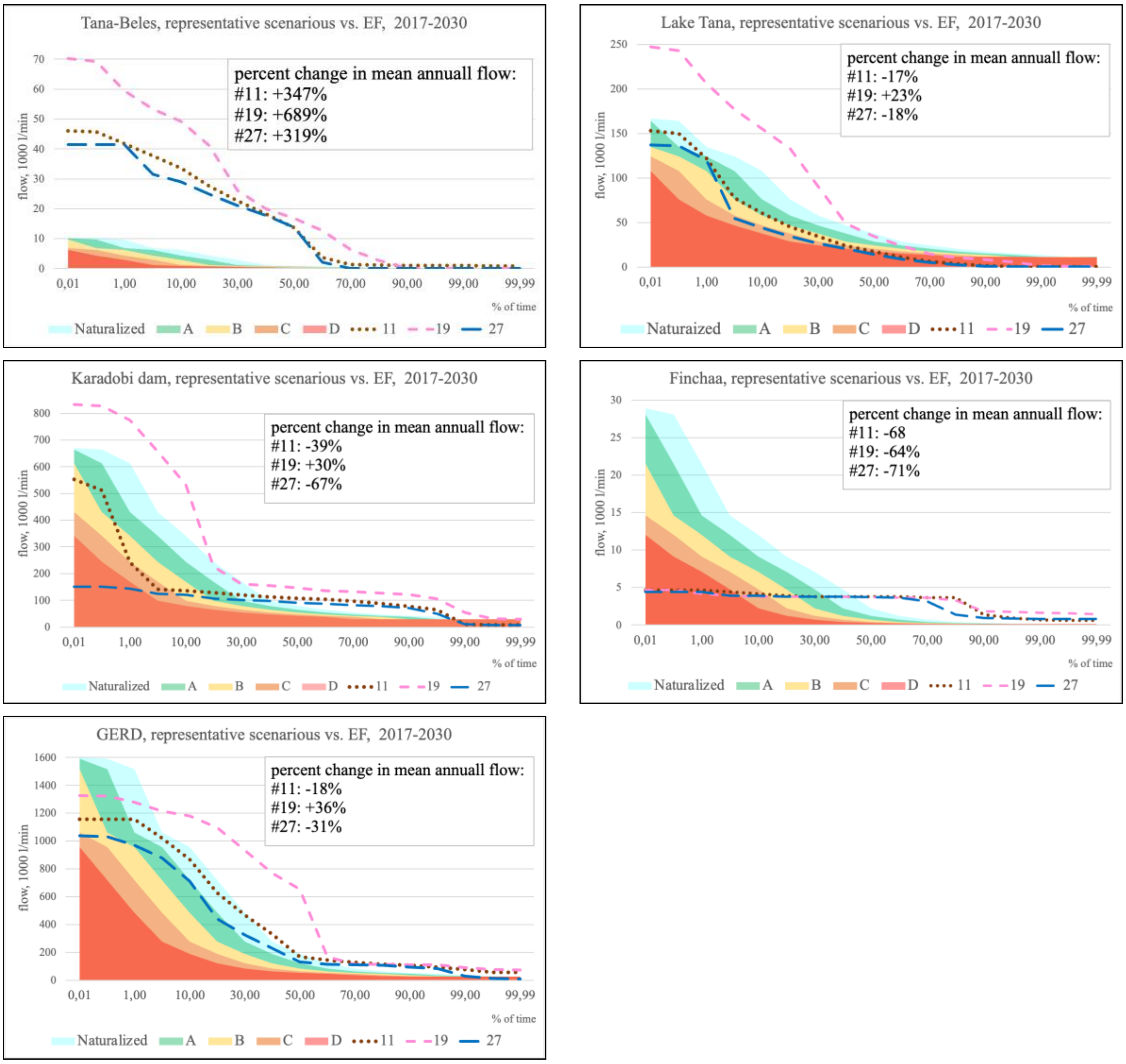


Figure 27. FDC analysis, comparing three representative scenarios to unmodified flow and environmental flow requirements of classes A-D, 2017-2030 period.
Percent change in mean annual flow refers to percent change between area under the unmodified flow curve and area under the climate change projections flow curves. Positive value indicates water flow increase, negative value refers to water flow decline.

5.8 Summary of results and risks associated with future flow uncertainties

Flow simulation reflects the extent to which flow affected by development and climate change might differ from unmodified flow and environmental flow requirements. The analysis starts with a comparison of flow under currently existing infrastructure, then extends to the flow projections that consider new infrastructure development. After that, risks associated with different climate change assumptions are also take into account and visually represented.

Apparently, three projections reflecting different climate change conditions, all return different flow patterns. Some of the projections show flow that might meet environmental flow requirements, but only for a certain period during the year. Other projections show expected flow being significant different from environmental flow recommendations, with even altered seasonality. However, neither of the study sites would express flow characteristics similar to the unmodified flow, which is proving the big impact anthropogenic factor has on the Blue Nile flow regime.

This analysis shows that the differences between environmental flow recommendations and flows simulated under different assumptions vary from minimal to very significant, and the size of this gap between them is determined by a set of climatic conditions. Table 13 represents characteristics of expected flow, as well as shows which climate change projection returns a smaller gap compared to estimated environmental flow requirements.

Table 13. Three representative scenarios and meeting of class C environmental flow requirements. Green cells highlight the scenario in which the gap between expected flow and environmental flow C class requirements is smaller.

Study site	**Ability to meet C class environmental flow requirements**		
	Driest, #27	Middle, #11	Wettest, #19
Tana-Beles	Very high flow	Very high flow	Very high flow
Lake Tana outflow	Does not meet class C requirements	Better fit to class C requirements	High simulated flow, especially for high-discharge events
Karadobi	Static flow, does not meet dry season's even D level requirements,	Static flow, can meet B-C classes EF requirements for high-intensity discharge events only	Very high flow all the time; slight seasonality shift

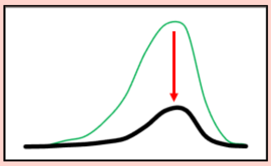
	but higher for low-discharge events		
Finchaa	Static flow, peak is flattened and spread to longer time	Static flow, peak is flattened and spread to longer time	High flow scenario exceeding environmental flow requirements; peaks are shifted to 2-3-months, does not satisfy any of EF requirements
GERD	3 water peaks; reserved flow seasonality that does not match any EF requirements—the worst scenario to happen, however not the worst fit according to the FDC analysis	Better meets the C classes requirements, but not for the dry season—returns too high values; the best fit from the FDC perspective—meets A-B classes EF requirements; higher flow for the low intensity events	Unacceptably high water flow; 3 flow peaks; flow exceeding ecosystem needs

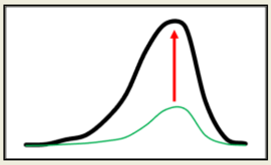
6 Discussion and recommendations

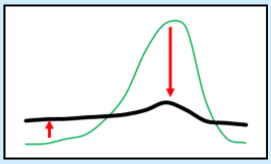
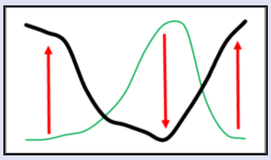
6.1 Expected flow tendencies and challenges of meeting environmental requirements

As expected, both the introduction of new infrastructure and climate change represent new challenges for meeting environmental flow and related ecosystem requirements of the Blue Nile. Current water balance would be altered due to new demands of hydropower stations, growing agricultural water demand, and by shifting baseline climatic characteristics. As the results have shown, not only would the water level be inevitably altered, but all water discharge patterns, such as seasonality of peaks and valleys, as well as flow fluctuations. The summary of expected flow tendencies and related consequences are shown in Table 14 .

Table 14. Table 14. Summary of expected flow alteration tendencies of the Blue Nile study area, through the lens of meeting environmental flow requirements.

Expected tendency	**Likely ecosystem response**	**Related socio-economic risks**
Simulated flow does not meet environmental flow volumes 	• General drying of river, riparian and wetland ecosystems • Disappearance of connecting water corridors between ecosystems and shallow marshes supplied by corridors • Loss of key ecosystem species in the affected areas	• Loss of tropic chains, disruption in food supply • Degradation of natural landscapes and gradual loss of soil productivity • Growing risk of food security due to impact on water-dependent agriculture sectors (e.g., fisheries)

	due to their inability to spawn and breed • Gradual colonization of drying habitat by drought-tolerant and invasive species • Loss of ecosystems, species, and genetic biodiversity • Degradation of wetlands • Deterioration of water quality • Loos of soil moisture and lower groundwater level	• Loss of access to valuable ecosystem goods as raw materials (e.g., reed) • Growing water pollution risk • Growing need and higher cost, but reduced opportunity for irrigation • Growing risk of water conflicts • Need for and cost of decommissioning of dams and hydropower stations • Long-term economic losses
Simulated flow exceeds environmental flow requirements 	• Growing flood frequency and severity • Disruption of physical habitat sensitive to flooding • Loss of ecosystems sensitive to flooding, species, and genetic biodiversity • Increasing riverbank erosion • Growing area with seasonal / permanent water cover and higher evaporation rate • Loss of key ecosystem species sensitive to flooding	• Loss of agricultural harvest on flooded areas and related economic losses, impact on food security • Dams and hydropower stations decommissioning or need to upgrade dams not designed for tolerance of increased water levels • Likely impacts on pests of agricultural crops, affecting food security • Loss of ecosystem assets such as timber and productive soil

	due to inability to feed, spawn and breed	• Growing moisture index and developing diseases (malaria) • Alien species prevalence, food scarcity
Constant stable flow without fluctuations 	• Disturbance of processes that require flow fluctuations • Reduced nutrients circulation • Loss of key ecosystem species dependent on fluctuating flow due to their inability to spawn and breed • Algae growth, increased risk of eutrophication • Emerging of new ecosystems favouring stable water levels	• Less water fluctuations, thus, less diversity within the ecosystem. Hence, economic losses • Economic costs due to invasive species favouring stable water levels • Food security impacts due to loss / reduced productivity of sensitive agricultural systems • Economic cost of water pollution and treatment;
Seasonality patten shifts 	• Mismatch between climatic conditions and water flow • Failure of original ecosystems, emerging of new ecosystems due to temporal mismatch of ecosystem cycles and water availability	• Unexpected timing of droughts and floods • Crop losses due to temporal mismatch between water need and water demand of crops / livestock, food insecurity

Lower expected flow

In most cases, expected flow either falls below the necessary level, particularly during the dry seasons, or goes far above environmental flow recommendations during the rainy seasons. These disruptive tendencies are getting more prominent under both new development and climate change assumptions, which might have a negative impact on the ecosystems. There are many key ecosystem processes that rely primarily on low flow, such as energy and material exchange or regulation of the extent of aquatic habitat, facilitation of migration processes of specific species and so on (Zeiringer *et al.* 2018). Moreover, low flow determines drinking water quality, which is particularly important for the survival of floodplain fauna and human well-being (Hayes *et al.* 2018). However, when flow is falling below environmental flow requirements during the dry season, it might seriously affect nesting and breeding capabilities of ecosystem organisms, therefore, result in a disruption of tropic chains and structure. Last but not least, when ecosystem water requirements are not met, it might damage ecological corridors and affect ecological connectivity (Rolls *et al*. 2012).

Higher expected flow

Many of the simulated climate change projections result in increased water flow during the rainy seasons, especially for SSP5-RCP8.5 scenarios, referring to the highest temperature increase. Although opposite from the drying tendency described previously, increased flow would not necessarily result in less negative consequences. First, increased flood frequency would represent a risk for affected agricultural plantations, up to the point of making them physically and economically unviable for future use. Wetlands riparian ecosystems of the Blue Nile are known to be sensitive, and they might also be destroyed and become ecologically unsuitable for their currently dominant species, some of which may also have direct economic uses and value (Rebelo 2008; Nilsson and Berggren 2000). Higher water discharge can also result in escalated erosion rate and growing sediment movement. In addition, higher water level in reservoirs and higher water volume in the river itself comes with increasing evaporation produce a higher moisture index. Under tropical and subtropical climate conditions, increased moisture index might catalyse the spread of tropical diseases such as malaria (Ahmed *et al.* 2019). Although these risks are present at all study sites, high flow is expected to affect particularly the areas downstream of the Tana-Beles hydropower station due the ongoing water transfer. As a result, the original ecosystems of this stretch of the river might experience a regime shift and collapse. A new stability domain, with new hydrological conditions might emerge as well. Such dynamics is known in the case of other river systems that have limited resilience to significant changes in flow rates (Botter *et al.* 2013). Although this research could not study in probabilistic terms the regime shift to new ecosystems at the various locations, this would be worth exploring in future research.

Flow seasonal patterns alteration

Although concerning, currently observed flow trends do not show any immediately dangerous flow regime patterns alterations. However, the situation become different when reviewing projections associated with infrastructure development and climate change assumptions. In some of the cases and at some of the locations, the patterns of projected flow would look radically different when compared with the original. For instance, flow line flattening has been observed at some of the locations even for the current development scenario: downstream from the Finchaa dam, experiences this tendency due to the dam's commissioning in support of irrigation. This trend might be observed not due to these dams commissioning, curve flattening it is often the very reason why the infrastructure projects are being proposed. However, steady flow might be observed due to infrastructure development as well, which poses risks of not meeting environmental flow. Finchaa flow would lose fluctuations at a more significant extent in the future, and a similar trend is observed for Karadobi for all development and climate change scenarios. The largest risk associated with this kind of change of the water regime is the reduced likelihood of balanced water allocation for human and ecosystem purposes. Ecosystem services provided by the river vary throughout the year due to the seasonal changes of climate, and the services provided are often interlinked. If some processes become absence in the dry season, many co-dependent processes would not take place during the wet season, and vice versa (Nilsson and Renöfält 2008).

A different and more dangerous phenomenon — reversed flow, is projected to occur at several locations in the future. Reverse flow means that initial flow seasonality patterns would be reversed, i.e., low flow would be observed during the initially high-flow periods, and vice versa. GERD downstream is the most prominent example of a reversed flow regime. It has been projected both in the case of development only and for all climate change projections. In some of the climate projections, GERD's water peaks and valley shift to 2-3- months, along with being higher than the base flow. This endangers all ecosystem functions, but one of the reviewed scenarios represents a regime shift that goes even beyond that and presents a new picture. According to this scenario (#27), GERD's periods of lowest and highest flow switch, and the original period of lowest water discharge would become a period of the highest flow, and vice versa. It goes without saying that the new regime would not be able to satisfy environmental flow requirements and may result in a failure to maintain ecosystem functions.

Disruption of flow seasonality would lead to inability to distribute essential ecosystem elements, such as nutrients, would prevent habitat's formation and maintenance, and would not allow original species to meet their reproductive requirements. On the long run, this would destroy currently existing ecological niches that would result in extensive biodiversity losses and disruptions of currently existing tropic cascades. This has been documented by Zeiringer *et al.* (2018), Weiskopf et al. (2020). However, in contrast with the Tana-Beles example, GERD's flow intensity redistribution would be unlikely leading to the development of a new ecosystem. First, the difference between the natural and expected water flow of this location is very large (thousands of MCM). Secondly and most importantly, it is unlikely due to a mismatch between climate conditions and hydrological conditions. All ecological processes require certain climatic conditions and flow requirements to be met simultaneously, which is not the case of some of the future GERD projections. In addition, abrupt changes in minimum and maximum river flow observed for GERD downstream might impact flow velocity, thus, increase sediment transport movements (Greimel *et al.* 2018).

Ecosystem disturbance

The described phenomena can disturb ecosystem services supply. This disturbance is often irreversible, and it might create a range of serious problems for not only sites reviewed in this study, but the entire basin, as it has also been documented in other cases, such as described for California by Zommers *et al.* (2016). Due to the interconnectivity of ecosystem functions and human well-being, new flow regime would alter water supply seasonality which determines socio-economic activities as residual demand, as well as agricultural and industrial demands. Due to poor agriculture management practices and over-prioritization of water for hydropower production, water level might drop below the lowest level of acceptable environmental flow (Ward *et al.* 2016). In addition to not meeting EF, there would also be a problem with newly developed agricultural sites water supply. If water requirements of agriculture are not met, it would lead to crop losses, and some of the affected farmland might even be abandoned, as it has been reported by FAO (2021). Abandoned farmland that was previously under monoculture would take a long time to regenerate original biomes, and may, for an extended period turn into degraded land or be even at risk of desertification.

Further to the consequences described above, alteration of the original flow might have effects on both existing and planned infrastructure. Every dam and hydropower station is designed with assumptions about certain hydrological conditions in mind, in other words, water should be at a defined level in order to run generators at their optimal potential. Due to their very high cost and long lifecycle, hydropower stations are usually financed through long-term loans, to be paid back from income from the sale of the generated electricity. If power production is below its expected level due to water shortage, this would entail enormous economic losses, on top of the damage caused by ecosystem degradation. At that point ecological and technical problems may easily lead to growing discontent among the local population and beyond, leading to the deterioration of transboundary conflicts.

However, high flow might result in exceeding the reservoirs' storage capacity and may pose a risk to the dams' physical structure, both in the case of those designed for flood protection or energy production. In both cases, commissioning and investment in further infrastructure might be necessary, with questions about their long-term socio-economic and ecological impacts. Benefits analysis would allow to make a right decision, because the avoidance of a dam collapse might bring more benefits, even if the measures designed to prevent it would lead to other (and perhaps even larger) disbenefits. This is why comprehensive environmental and even broader or cumulative impact assessments are necessary prior to the finalization and approval of infrastructure development plans, particularly large ones, such as GERD. Due to flow disruptions related to climate change and the resulting inability to meet environmental flow requirements, it might not even be feasible to construct projects at some locations or beyond a certain scale, such as documented in CRIDF report on the Okavango River basin (CRIDF 2017). Costs of reconstruction and refurbishment of these projects might go far beyond the economic capacity of individual Blue Nile basin countries, which raises the stakes further in terms of transboundary security.

Ability to meet environmental flow and influencing factors

Apart from a discussion of expected flow tendencies and related consequences, there is a need to reflect on a gap that has been observed between overall flows, as affected by development and climate change, and environmental flow requirements. Clearly, the smaller the gap between projected flow and environmental flow requirements, the more desirable are the climatic conditions of a given scenario. However, comparing the results of one scenario to another and drawing a conclusion is not that simple, because the results of each scenario vary in both time and space. Even more important is to analyse which climate scenario might induce a dangerous flow level. Thus, the simulation allows to think not only about the consequences that might arise from the unfolding of a given future development scenario, but also how to mitigate associated impacts through measures that are both anticipatory and robust i.e., work across a range of inherently uncertain scenario projections. In some cases, risks might be predicted and mitigated to some extent, when more extreme cases require a revision or even abandonment of projects and strategies. For a given study area, the biggest risks imposed on water availability arise from the operation of GERD, in association with the uncertainties related to climate change. Thus, course correction might be necessary at the level of strategical decision making, including at local, national, regional, and global scales.

The direction of future climate change is defined by the global policies: greenhouse gas emissions, transition to non-fossil energy systems, restricting of harmful subsidies, addressing waste management and so on. On another hand, local level of decision making is equally important for preventing unsustainable, or even catastrophic consequences. Better water resources management, agricultural development planning, population growth, material consumption, as well as a well-balanced approach to dam design, construction and operation are essential for meeting environmental flow requirements and avoiding the costs of not meeting them.

6.2 Recommendations

A list of recommendations can be provided based on the analysis results. Because flow alterations are likely to reduce ability of the river to meet environmental flow requirements, additional ecosystem management measures might be required. For already existing river infrastructure, such as dams and reservoirs, flow alteration and ecosystem damage are often irreversible due to the large scale of these projects and their long commissioning periods. However, adaptive measures related to negative consequences might be taken by state and municipal authorities, in cooperation with other stakeholders. They include biodiversity conservation measures of species most affected by changes of flow patterns (e.g., provision of ecological corridors and habitat conservation, invasive species control); additional water quality and sediment control; restrictions on irrigation and the expansion of agricultural areas, while supporting the switch to less water-intensive agroforestry practices instead of plantations. With respect to the selected study sites, operational rules connected with water transfer and water storage in reservoirs could be revised at the Tana-Beles hydropower location, Karadobi dam and Finchaa irrigation site. Water demand at these locations is primarily related to agriculture, but water-intensive agricultural practices are often non-sustainable. This should be considered in strategic planning.

For all major development projects in the future integrated impact assessments should always be conducted well in advance of final decisions, taking into account cross-sectoral analysis of benefits and costs (not only in economic terms), assessing environmental flow requirements and the impact expected flow might have on environmental flow and associated ecosystem services. Studies like this research, investigating both the separate and cumulative impacts on infrastructure development and climate change on the flow regime, should underpin environmental and social impact assessments. Given the significant differences between sites, as shown by this research, an assessment should also help identify serious site-specific vulnerabilities, which should influence site selection decisions for future infrastructure. This paper concluded that GERD's impact on water resources and ecosystems is so significant that it changes all seasonal patterns of the Blue Nile flow. Infrastructure projects of a similar scale might again place the entire river ecosystems at risk, especially if flow projections and implications for environmental flow and related ecosystem services are not included.

This research focuses on environmental flow requirements and related risks but expanding infrastructure and intensifying climate change would result in emerging issues connected with changes in underlying broader driving forces. Rapidly growing population and climate change would lead to a need to expand agricultural sites and produce more energy. Intensive crop production could for instance contribute to increasing water pollution through larger scale fertilizer and pesticide use and impacts on soil erosion and runoff. Changes in driving forces like these, combined with changes of the flow regime, would inevitably affect water quality and dependent ecosystems (Mateo-Sagasta *et al.* 2017)

Review of the limitations allows to consider the recommendations of methodological and theoretical nature as well. To begin with, data up to 2016 have been used to create and calibrate the model, which is the main methodological tool of this research. Thus, data for more recent years are unavoidable for getting more accurate results for both tracking flow alteration and calculating environmental flow requirements. Environmental flow estimation methods can also be improved by implementing more comprehensive approaches. As an alternative solution, several environmental flow estimation methods can be compared to each other, then the best estimation technique selected based on the specifics of Blue Nile basin specifics. Inclusion of environmental flow proxy indicators and remote sensing further help in this. In the interest of more representative, higher resolution, and statistically valid results the number of study sites could be increased to others of similar strategic importance.

Although with some limitations, PyWR was a useful tool for the purposes of this study. It would be possible to integrate environmental flow requirements into the original model, by formally representing and prioritizing environmental flows. This would help study new water allocation patterns as part of the planning process of new infrastructure, whether for energy or for water. PyWR outputs could serve as input data for other sector models related to e.g., food, energy, land use, transport, settlement planning etc., leading to a more integrated assessment.

Better understanding the relationship between altered flow and social impacts would require fieldwork and stakeholder consultations. This would not only help understand the connection between environmental flows and the potential disruption of ecosystem services but also help scope out options for simple technical or policy-level responses. In addition, this would also allow a more accurate assessment of the impacts of new infrastructure development and climate change on water availability. Stakeholders might also help pinpoint specific vulnerabilities, taking into account critical thresholds and adaptive capacity that require in-depth familiarity with local conditions. While this paper mainly focuses on ecosystem demands and associated risks, there are many other factors that would have a direct impact on water availability. These include population growth and associated increased water demand, growing illegal irrigation and other socio-economical phenomena that could all play an important role in shaping the Blue Nile future. Answering these and many other significant questions in a credible way without field research is not feasible.

7 Conclusions

The flow regime of the Blue Nile, a river that has been playing a crucial role in safeguarding the well-being of great civilizations and countries downstream, is experiencing growing challenges. Ethiopia, a major country that has been experiencing economic water scarcity for years, is rapidly expanding its water infrastructure, due to growing water demand by its increasing population. However, there is always competition for water, resulting in significant trade-offs and tensions. Should water be used for power generation, residential use, irrigation, or it stay in the river— questions like these present a challenge for water resources management and related strategic decisions. Water does not only provide for the needs of human society, but also plays a pivotal role in safeguarding the functioning of the Blue Nile ecosystem. Water is needed not only for providing ecosystem services, but also for meeting environmental flow requirements necessary for maintaining the basic functioning of the riverine ecosystem itself. Unfortunately, the flow regime of the Blue Nile is already significantly altered compared with its pre-human or at least pre-industrial natural condition, thus, environmental flow requirements are often not met. In addition, infrastructure development plans currently under consideration and climate change together introduce further risks and uncertainties for both the river and its ecosystems and societies depending on them. Estimation of future water flow, its comparison with environmental flow, and indicative assessment of ecosystem and socio-economic-impacts were the main aims of this research.

To prevent habitat disruption, biodiversity losses, increasing floods frequency, and select the most appropriate adaptation strategy, the effects of future water flow regime alterations can be assessed through modelling. Different scenarios, developed on the basis of assumptions related to relevant circumstances help project flow patterns, taking into account both future development and climate change impacts. These flow projections are compared with ecologically justified environmental flow and provide a picture of the Blue Nile's ability to meet its ecosystem requirements for water.

The main research questions have been answered via literature review, modelling, and the interpretation and discussion of model results. The analysis indicates that changes in the flow regime of the Blue Nile may have already caused serious disturbance in ecosystem functions. Flow regime changes have been assessed for five study sites along the Blue Nile. Results show a serious mismatch between the currently (up to 2016) observed flow and environmental flow requirements for at least half of the selected sites. However, taking into account the effects of expected infrastructure development, changes in water demand and the effects of climate change, it is clear that meeting environmental flow requirements in the future will be an even more serious challenge. At the sites analysed, expected flow can be either significantly higher than the recommended maximum EF rate, or significantly lower than the recommended minimum. Both high and low flow are important for ensuring uninterrupted breeding cycles of organisms inhabiting river ecosystems, for ensuring the circulation of nutrients, maintaining habitat structure, water purification and other ecosystem characteristics.

Besides overall effects of the volume of flow, there are locations that might experience significant changes in temporal flow patterns e.g., switch from non-static to static flow or changes in flow seasonality. Stable static flow is projected to happen at Karadobi and Finchaa downstream. Seasonal patterns might be switched around at GERD downstream, where the highest water discharge might be observed during the historical dry season, and vice versa. Such fundamental changes in the water regime patterns could contribute to the collapse of surrounding ecosystems, however, understanding the exact consequences would require more detailed study. Model results demonstrate that if the environmental flow is not considered e.g., in setting dam operation rules, policies and projects, there is a risk of potentially catastrophic outcomes.

However, there is not enough information in the literature on how exactly the ecological functions of the Blue Nile basin might be impaired if minimum flow requirements are not met. Nor is there information available on the Blue Nile specific impacts of flow exceedances. Therefore, one of the proposed recommendations is to carry out detailed field work with more recent and accurate data, including input and observations by residents and stakeholders. The methodological approach of this study can also be improved by updating original data and fine-tuning methods to assess environmental flow requirements.

Even if many open questions remain, the research aim, and objectives of this research have been largely fulfilled. This paper demonstrates the use of a model-based method for assessing water flow alterations due to the effects of infrastructure development and climate change and show that PyWR tool is accessible and user friendly even for relatively unexperienced users. The results of this study can be used not only for a preliminary assessment of water management policies and practices, but also stand as an example for replicating the method in other river basins. Furthermore, this study fills a knowledge gap in the sense that it analyses changes in the water regime and environmental flow and ecosystem service implications of the Blue Nile, as well as tries to capture the interdisciplinary nature of water use conflicts. Negligence of ecosystem needs shown in the results section can create serious problems, placing both aquatic and water-dependent ecosystems and human activities under threat. Thus, examining the relationship between ecosystem needs, water use, energy production and food production is key to protecting vulnerable ecosystems and safeguarding human well-being.

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Appendix A—Environmental flow requirements

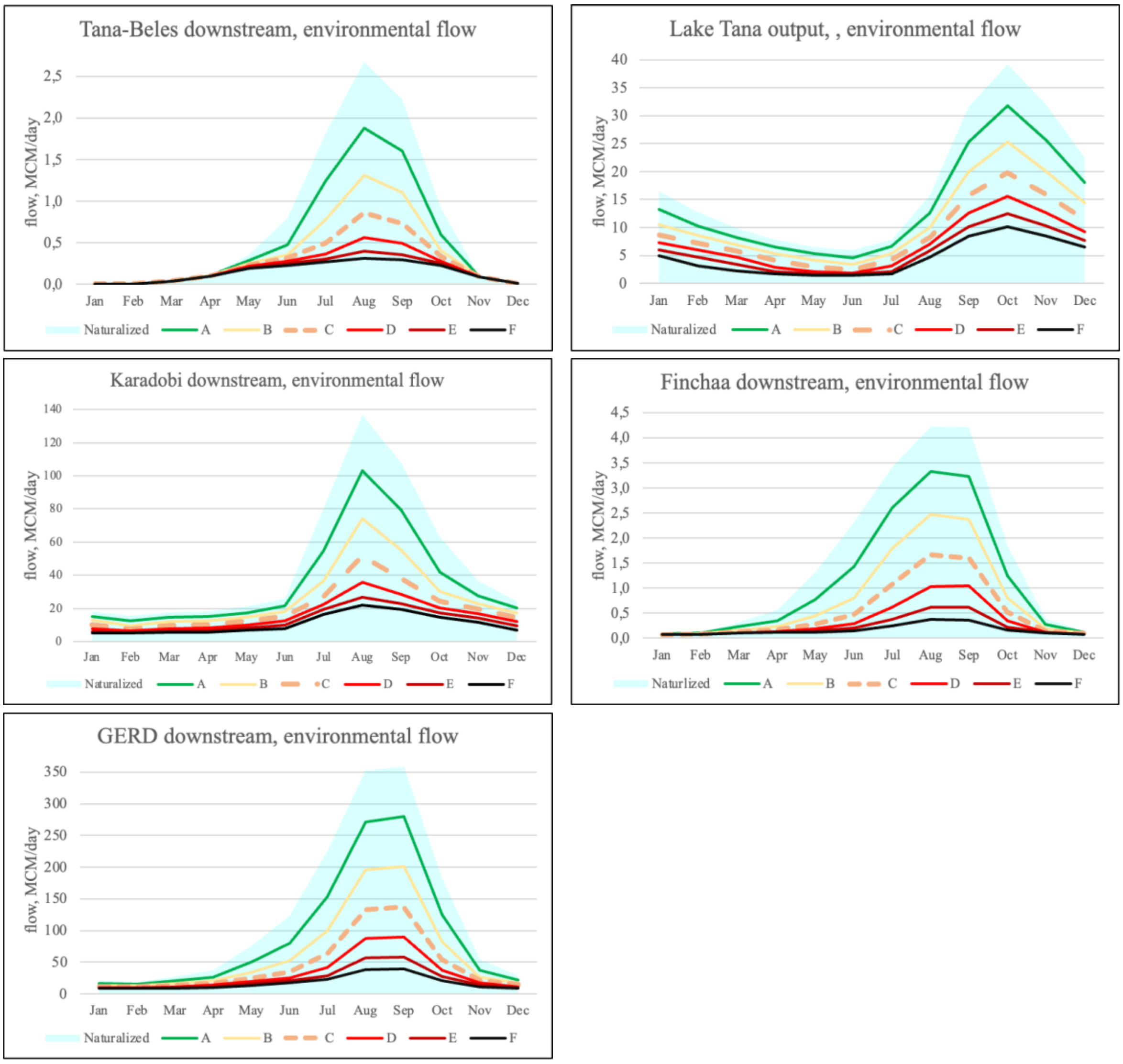


Figure A. Environmental flow classes: A (green), B (yellow), C (orange), D (red), E (dark red) and F (black). Based on the historical data average values (years 1979-2016).

Appendix B — Blue Nile flow under 28 climate change scenarios

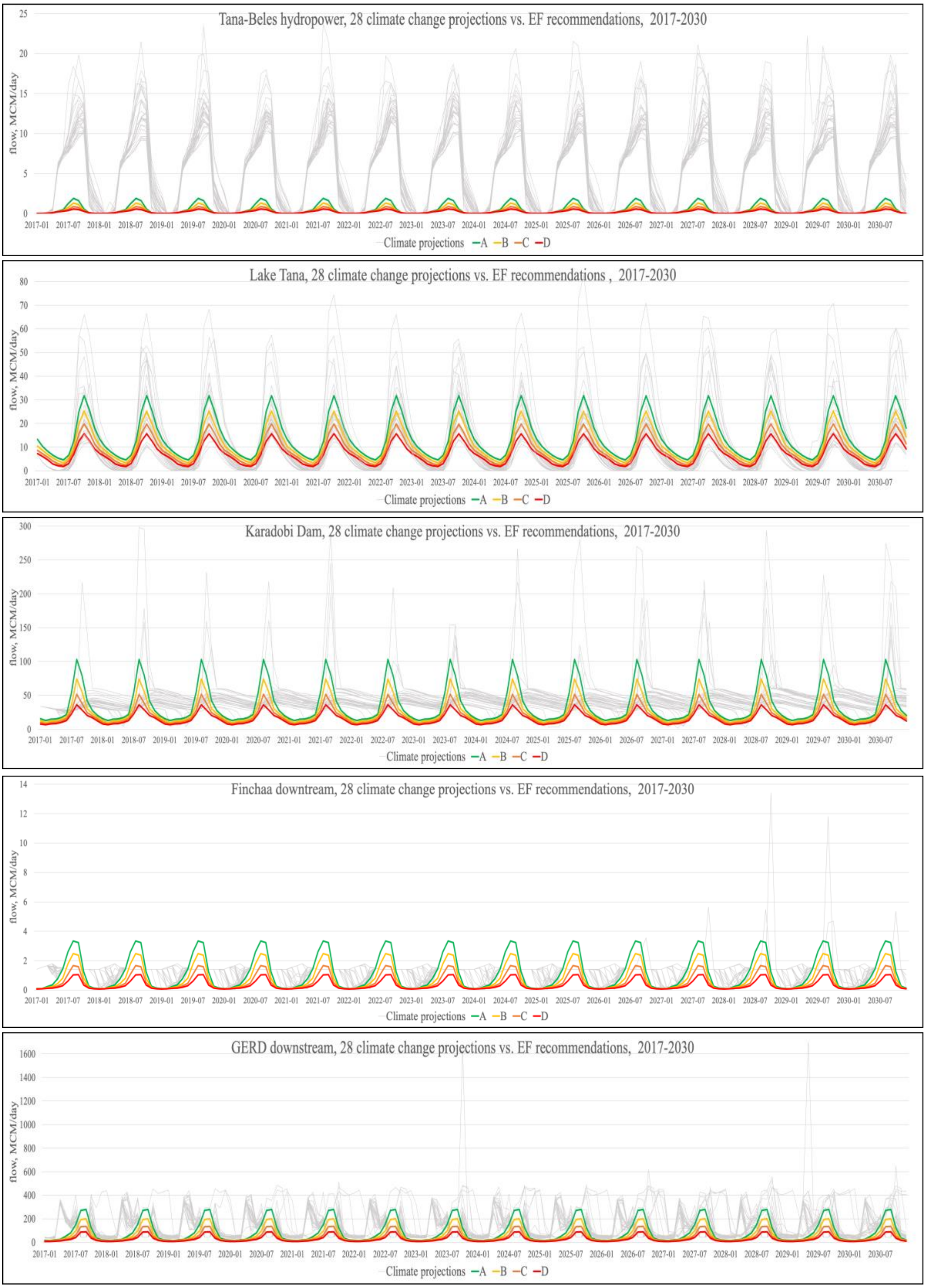
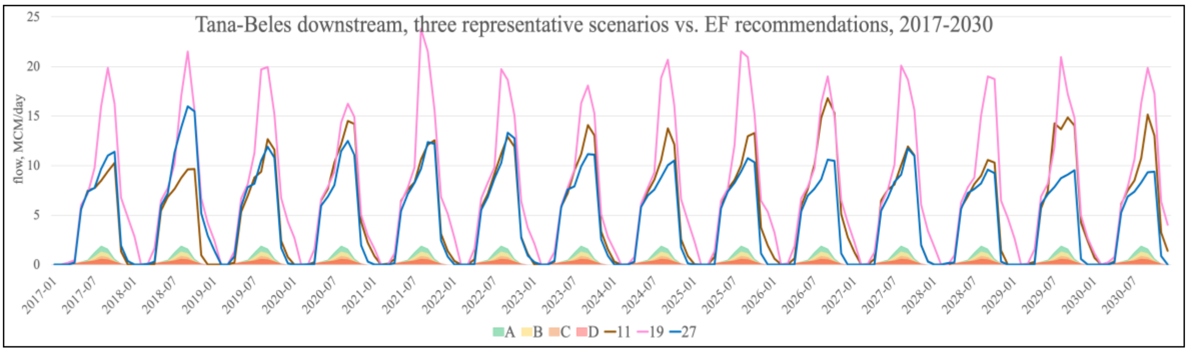
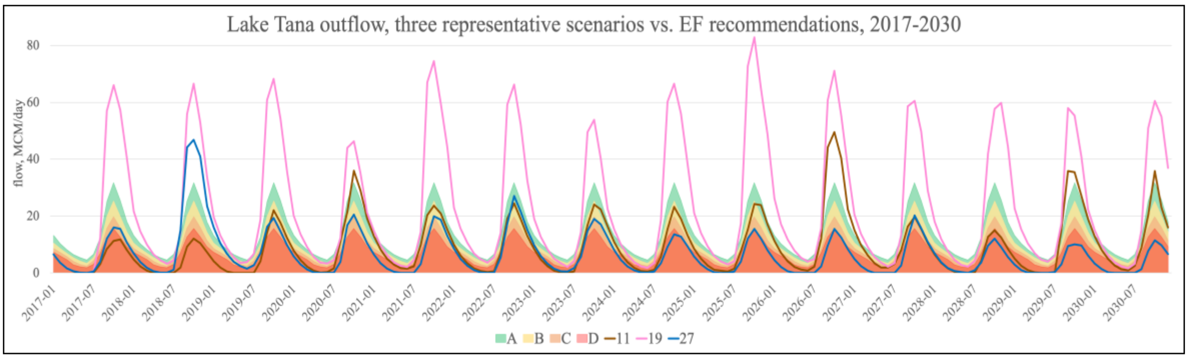
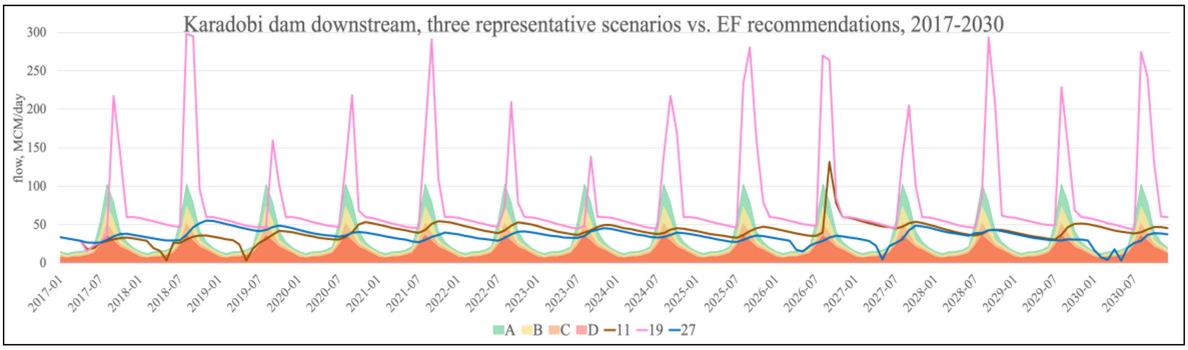


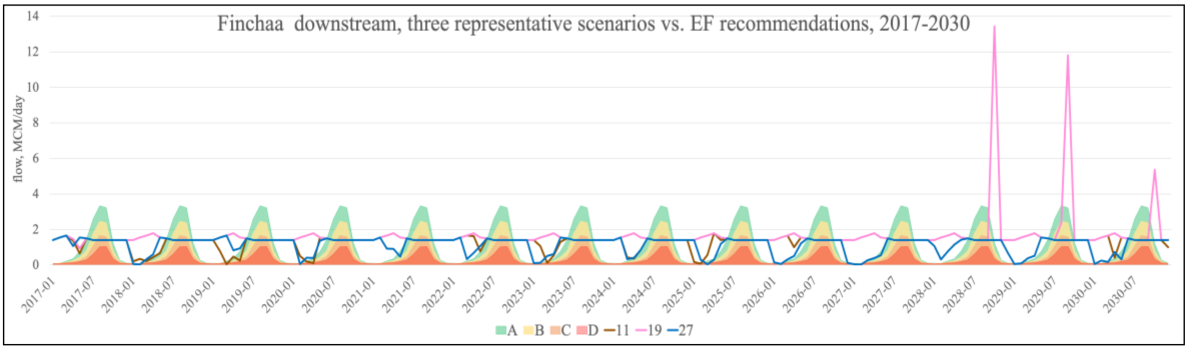
Figure B. 28 climate change scenarios in comparison with environmental flow recommendations of classes A-D, years 2017-2030.

Appendix C — Flow projections under climate change scenarios and environmental flows









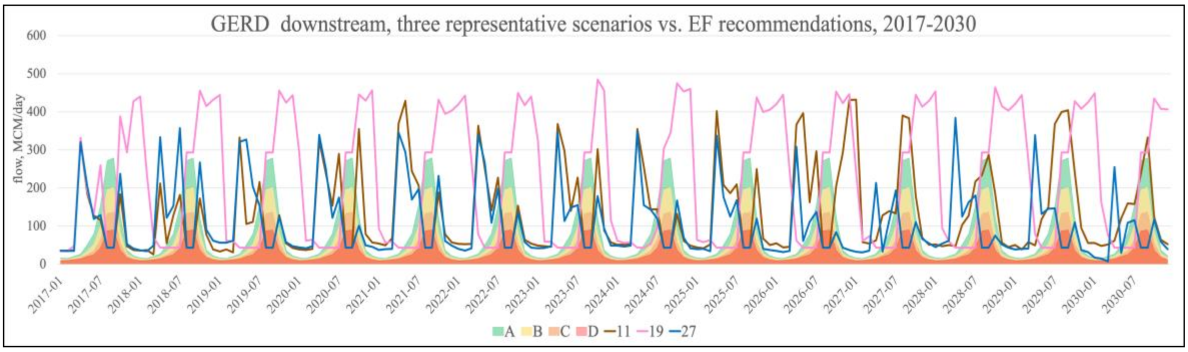


Figure C. Scenario #11 (brown solid line), scenario #19 (pink solid line), scenario #27 (dark blue solid line), and environmental flow recommendations: class A (green shade), class B (yellow shade), class C (orange shade), class D (red shade).