TPM802A Final Assignment

Balancing Development Goals and Water Security in the Omo-Gibe River Basin: A Proposal for a Multi-Objective Optimization Model.

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Picture Source: NS Energy

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1 Problem identification

Background[1]

The Omo-Gibe Basin is one of the 12 basins in Ethiopia. The basin spans over 79,000 km2 and encompasses parts of all 4 regional states. It is characterized by diverse landscapes ranging from wet highland areas with an annual average rainfall of 1200mm to relatively dry lowlands averaging 500mm. The basin is home to 7 million inhabitants, of which lowland pastoralists account for a significant portion.

The basin accounts for 45% of the current hydropower supply of Ethiopia with the Gibe hydropower plants and over 100,000 ha of large-scale irrigation. To accommodate its growth potential, Ethiopia is designing more hydropower dams (Gibe IV and V) and 150,000 ha for large-scale irrigation development.

Such developments dealing with large-scale irrigators and reservoir operations pose numerous implications for water security within the country and downstream countries. A non-exhaustive list of historical challenges and conflicts is as follows:

<u>National conflicts (Within Ethiopia)</u>

- Previously with the operations of the Gibe III dam, flood retreat agriculture was affected due to the decrease in ***seasonal flooding*** that is required for irrigation (Pertaub, 2019).
- The decreased water flow causes a ***demand deficit*** also negatively impacts the economic activities of pastoralists associated with the Omo River such as farming, and fishing (Avery, 2014).
- The decrease in water levels also reduces the ***recharging of groundwater*** and this could lead to a myriad of long-term negative impacts on both local communities and ecosystems such as subsidence, and drying up of aquatic ecosystems (African Resources Working Group, 2009).

<u>Cross-border conflicts (Upstream-Downstream)</u>

- Ethiopia lies on the upstream of the Omo River. The building of dams has greatly affected the ***water levels of Lake Turkana*** which is located downstream in Kenya. This resultant increase in salinity of the water disturbs the drinking water supply and habitats of fish which the livelihoods of indigenous communities depend greatly on (Avery & Eng, 2012)

Aims and Objectives

Learning from past challenges, this research works towards fostering sustainable development of the basin. Its primary goal is to proactively mitigate water-related conflicts and facilitate a developmental framework that balances both growth with peace and security.

To achieve this aim, the model is developed to arrive at jointly acceptable solutions – crafting a plan (reservoir operations and irrigation extractions) that takes into consideration the interests of various stakeholders. Here are some of the tentative research questions:

1) What are the trade-offs in objectives between the stakeholders?
2) What could be the potential national and cross-border conflicts from the operations of hydropower dams in Ethiopia?
3) What possible robust management policies in consideration of all stakeholder objectives?

Table 1 provides a high-level summary of the problem framing.

[1] Some of the contextual information is borrowed from Dr Saleshi's brief

***Table 1**. Summary of the Problem*

Spatial Boundaries	Omo River from the Omo-Gibe Basin up to Lake Turkana
Temporal Boundaries	The main time horizon of 2015 - 2035; ● 20 years to account for slow-onset changes in climate and development. ● Starting in 2015, the operational start of Gibe III Dam ● Through 2026, the expected operational date of the Gibe IV Dam
Goal	Manage the interests of stakeholders
Main Stakeholders and Main Interests	**Local Actors** ● <u>Pastoralists</u>: Availability of Land and Water Resources ● <u>Local Communities</u>: Livelihood security through fishing and farming ● <u>Government</u>: Manage natural resources, balance conservation and economic development ● <u>All</u>: Energy security for economic development **Downstream Countries** ● <u>Government of Kenya</u>: Conservation of Lake Turkana
Possible Actions	● <u>Water resource management</u> i.e. quantity of irrigation extraction ● <u>Reservoir control strategies</u> i.e reservoir release patterns

2 Conceptual model

Modelling Approach

This methodology is largely inspired by Sari's MSc (2022) thesis where he applied this to the context of the Nile River. Similarly, the methodology used for this simulation model would be Evolutionary Multi-Objective Direct Policy Search (EMODPS), visualized in Figure 1. This is apt because of the need to – 1) solve many-objective problems, i.e., manage multiple stakeholder interests and 2) simulate adaptive policies, since robust and practical reservoir controls are always based on the state of the system.

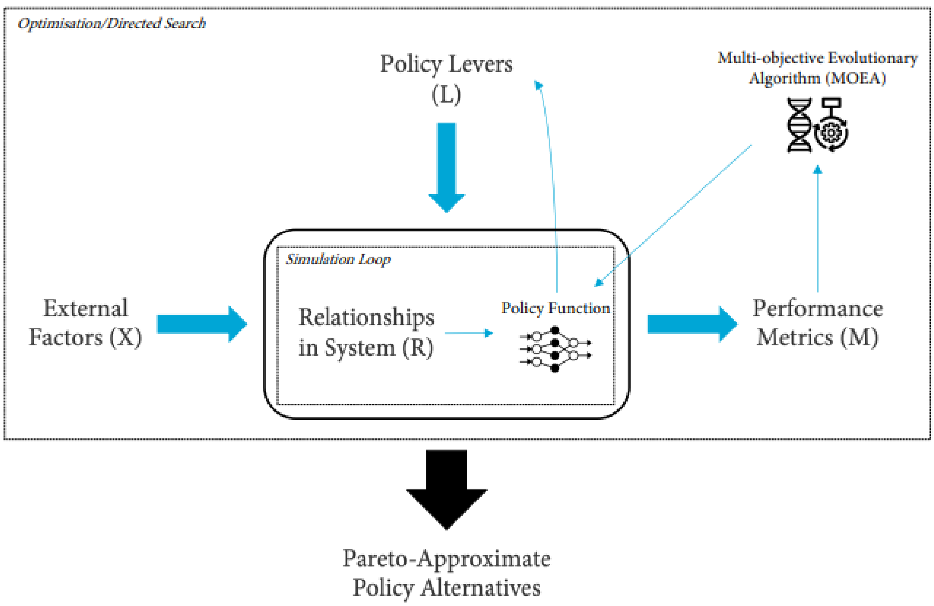

***Figure 1**: Visual summary of the EMODPS methodology (Sari, 2022)*

Model Scope
Spatial Boundaries:
Of all the tributaries of the Omo River, only the Gilgel Gibe river will be modelled in depth while the other tributaries (Gojeb and Wyobo) will be included exogenously using historical river flow data. This is because Gilgel Gibe river contributes one of the most flow and also directly influences the hydropower generated at Gibe I Dam.

As the overarching goal of the model is to understand and intervene in water security conflicts, the model would place a greater emphasis on capturing the complexities in the Lower Omo Valley as the majority of the existing conflict in water security occurs there. Lake Turkana, even though, is geographically outside the basin, will also be included for its similar historical significance too.

Temporal Boundaries:
The model should be simulated with a monthly timestep for 20 years. As expressed in the problem framing, the problem focuses on sustainable development in the long term hence the 20-year time horizon, and also needs to capture the season dynamics of agriculture hence the monthly time step.

Assumptions:
Other main assumptions include how we mostly take the activities upstream of the Omo-Gibe Basin and the Omo River to be constant and hence modelled exogenously. Also, Gibe V is not included in the model even though is in the construction process as its influence on the model is thought to be similar to Gibe IV.

Components
The main components of the model are described in Table 2 and Figure 2 provides the geographical and topological structure of these components.

Table 2: *Components of the Conceptual Model*

Components	**Objects**	**Description**
Irrigation Districts	Flood Retreat Agriculture, Sugar Plantation, Commercial Agriculture, Villages	They represent locations of water demand. Water is diverted from the main channel of the Omo River or pumped from aquifers and is consumed.
Reservoirs	Lake Turkana, Gibe I to IV	Reservoirs are essentially water storages and water can be released (i.e. Gibe I to IV) or extracted from (e.g. Lake) and consumed.
Hydroelectric Plants	Gibe I to IV	These dams are also reservoirs but are able to generate hydroelectric energy through the release of water.
Aquifers	(Modelled at a basin level)	This represents the underground storage of groundwater that is used for consumption. Recharge times are affected by water levels in the Omo River.
Catchments	(Modelled at a basin level)	This represents the area where precipitation accumulates and becomes an inflow into the main river channel

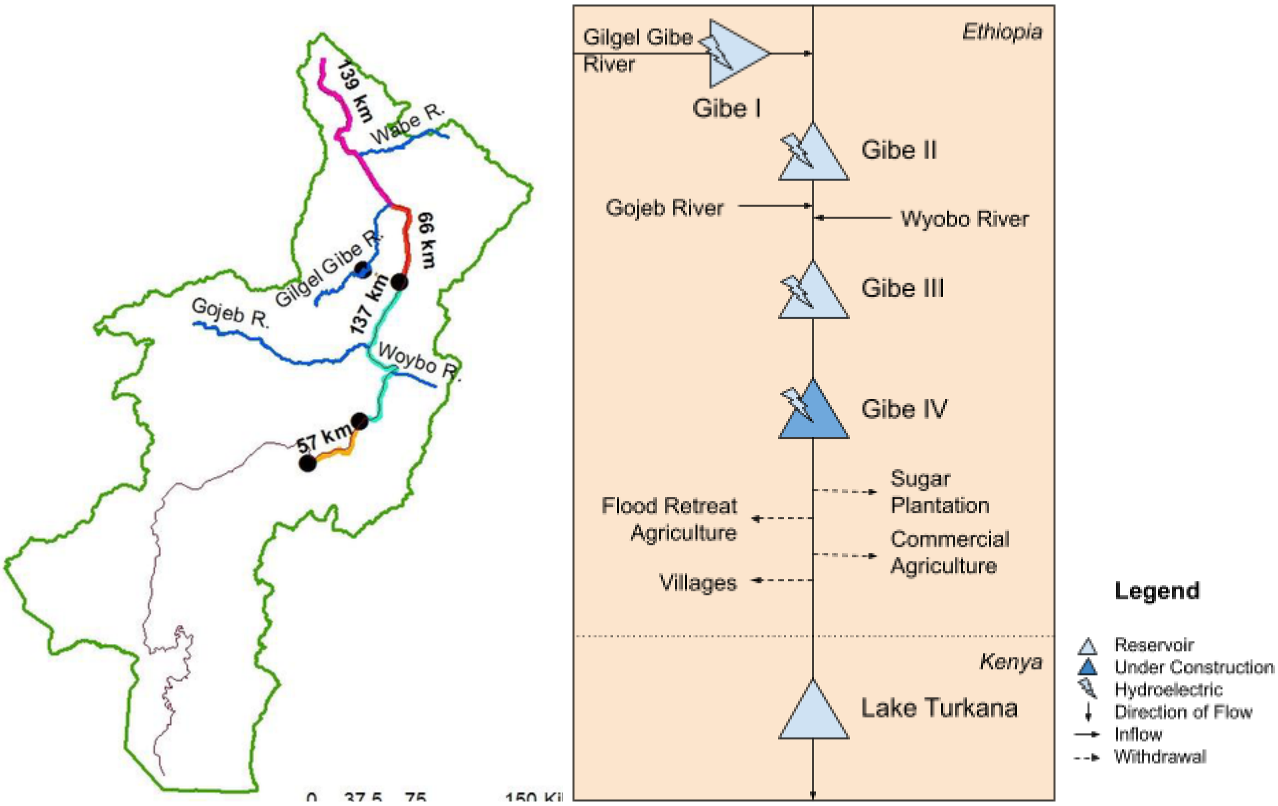

Figure 2*: Map of the Omo-Basin Areas (Gebre, 2023) alongside a topographical representation of it.*

Defining Objectives:
Based on the historical context of conflicts (in the *Introduction)*, these are the objectives from the perspectives of the different stakeholders:

- Maximize ***hydropower production*** in dams
- Minimize ***demand deficit*** in Lower Omo Valley
- Minimize ***groundwater depletion*** in Lower Omo Valley
- Maximize ***periods of seasonal flooding*** to enable flood retreat agriculture
- Minimise periods of ***water level deficits*** in Lake Turkana

These objectives are formulated specifically in Table 3 where the aggregation type, unit and direction of optimization are conceptualized. An objective can be formulated in multiple ways to account for the multi-facetedness of a specific problem, e.g., aggregated as an annual average or with a target percentile range.

Table 3: *Conceptual Objective Formulations*

	Stakeholder	**Objective**	**Aggregation**	**Unit**	**Direction**
1	All	Hydropower Production	Annual Average	TWh/year	Maximize
2	Villages and Pastoralists	Demand Deficit	Annual Average	BCM/month	Minimise
3	Villages and Pastoralists	Demand Deficit	90th Percentile Worst Months	BCM/month	Minimise
4	Villages and Pastoralists	Groundwater Depletion	Annual Average	m	Minimise
5	Flood Retreat Agriculturalist	Periods of Seasonal Flooding	Frequency over typical Flood Months	%	Maximize
6	Kenya	Water Level Sufficiency (Lake Turkana)	Frequency over Time Horizon	%	Maximize

3 Quantitative Model

This section describes the key mathematical formulation required for the model.

Modelling the Water System

Reservoirs: Control Volume Approach

A mass balance equation is useful to describe how the reservoir essentially works. This is used in various water systems, and its idea is to track the inputs and outputs of water in a closed system:

$$s_{t+1} = s_t + Q_{t+1} - E_{t+1} - R_{t+1} \quad (1)$$

where s is the volume of water in the system, Q is the inflow to the reservoir, E and R are outflows to the reservoir - they are net evaporation and water released respectively.

Reservoirs: Release Policy Function

A policy function is quite important to capture the most accurate relationship between inputs and release decisions. The idea of radial basis functions (RBFs) is used as it is tested to outperform other functions like artificial neural networks (ANNs) (Guilinani et al, 2015). Below is a short overview of how it works.

$$u_t^k = u_\theta^k(\overline{z}_t) = \sum_{i=1}^{n} (w_i^k \varphi_i(\overline{z}_t) + a_k) \quad (2)$$

Where u_t^k is the kth release decision at timestep t, and this is computed by the weighted (w_i) sum of a layer of RBFs (φ_i) that is fed by an input vector ($\overline{z}_t$) describing the system state. Additionally, a_k allows for a constant adjustment for the kth release decision,

Objective Functions

The conceptualized objectives (based on Table 3) are further mathematically formulated.

(1) Hydropower Generation (Annual Average)

This is calculated through equation 3, the power output of a dam per hour, and equation 4, the annual average of hydropower generation.

$$P_t^{dam} = \eta g \gamma_w h_t q_t^{Turb} \quad (3)$$

Where η is turbine efficiency, g is the gravitational constant, γ_w is water density, h_t is net hydraulic head, q_t^{Turb} is turbine flow

$$Hydropower\ Generation^{dam} = \frac{1}{20}\sum_{t=1}^{240} P_t^{dam} \cdot 24\ hours/month \quad (4)$$

(2a) Demand Deficit (Annual Average)

$$Demand\ Deficit^{district} = \frac{1}{20}\sum_{t=1}^{240} max\,(0, D_t^{district} - V_t^{district}) \quad (5)$$

Where t is the time step, D is water demand and V is water flow at the district

(2b) Demand Deficit (90th Percentile)

Calculated similar to 2a, but averages the 90 percentile of the deficit at every time step (equation 6).

$$Demand\ Deficit_t^{district} = max\,(0, D_t^{district} - V_t^{district}) \quad (6)$$

(3) Groundwater Depletion (Annual Average)

This is calculated through equation 7, an assumed linear relationship between water and recharge rate, and equation 8, the annual average of groundwater depletion.

$$R_t = a \cdot G + b \quad (7)$$

Where G is groundwater levels, a and b are coefficients to be calibrated empirically

$$Groundwater\ Depletion^{district} = \frac{1}{20}\sum_{t=1}^{240} R_t - E_t \quad (8)$$

Where R is the recharge rate and E is the extraction rate

(4) Periods of Seasonal Flooding (% Frequency)

$$SF^{distict} = \frac{1}{T_{sf}} \cdot \sum_{t=1}^{240} ifelse(WL_t^{district} > h, 1, 0) \quad (9)$$

where WL is the water level, h is channel height and T_{sf} is the typical/appropriate number of flooding months for flood retreat agriculture.

(5) Water Level Sufficiency (%)

$$Sufficiency^{Turkana} = \frac{1}{240} \sum_{t=1}^{240} ifelse(WL_t^{Turkana} > tr, 1, 0)$$

(10)

where $WL_t^{Turkana}$ is the water levels in Lake Turkana, and tr is the acceptable threshold.

4 Data Selection

Based on the conceptual and mathematical models, Table 4 shows a summary of the input data required for the simulation, including its data source as well as the granularity of data.

Table 4: *Summary of Data Available*

Data Source	Span (which variables)	Granularity (resolution)	Purpose
EEPCO (2004a) EEPCO (2004b) EEPCO (2008) UN Global Compact (2018)	Hydropower Dam Data - Hydropower Generation Water Demands (m3/week) - Various Turbine Data - Efficiency - Generation Capacity (MW) - Storage Capacity (MCM)	* Data for Each Dam ** Weekly data estimates	Hydroelectric plants
MoWE (2021)	River Inflows/streamflow (mm3/month)	* Measured at various stations including the main river channel ** Monthly data for at least 10 years (anywhere from 1990-2019)	Reservoirs
NAMA (2021) Gebre (2023)	Meteorological Data - Precipitation (mm/month) - Effective Precipitation (mm/month) - Max and Min Temperature (degC) & Evapotranspiration (mm/day)	* Farms at various weather stations ** Monthly data from years 1998-2017	Catchment
CSAG (N.D)	Climate Projections	* Modelled regionally in Africa ** Time frames are continuous (no set time frames)	Catchment
(unable to find at the moment)	Soil Data - Groundwater recharge rates	//	Aquifers
Avery (2013) Ethiopia Ministry of Water and Energy Strategy Report (2020)	Water Demand Data - Targeted Irrigated Area (ha) - Crops - Average Water Demands (m3/s)	*Data for each District	Irrigation Districts

* represents the spatial resolution

** represents the temporal resolution

5 Assessment of results

With respect to each research question, I will describe the main analysis techniques used and how results will aid in answering these questions. The techniques listed are also likely to be in chronological order of implementation where the results of the previous analysis are expected to inform the next analysis better.

RQ 1: What could be the potential national and cross-border conflicts from the operations of hydropower dams in Ethiopia?

A **Global Sensitivity Analysis** can be used to understand how variation in uncertainty variables and policy levers will influence outputs. Some techniques include feature scoring and sobol indices (Herman & Usher, 2017). In this context, it can give us a hint as to what could be the key drivers and uncertainties that cause significant impacts on the potential conflicts.

Scenario Discovery examines the output space and traces it to the policy and uncertainty space that produces such results. Some techniques include PRIM (Friedman & Fisher, 1999) and dimension stacking. This helps identify the critical scenarios (with its set of conditions) for us to be wary about that might cause conflicts to escalate.

In general, the above are exploratory methods that could give us a first hint at the unseen nature of the problem context, and give us a general direction to how to approach a joint management plan.

RQ 2: What are the trade-offs in objectives between the stakeholders?

A **Trade-off Analysis** can be a structured way to understand conflicting objectives. The first step would be establishing a Pareto-optimal set of policies from the multi-objective optimization process based on scenarios of interest (or the critical scenarios identified in scenario discovery). Then, by comparing these Pareto-optimal policies, some patterns can be found where certain objectives have to be compromised to achieve a better performance for other objectives. This is often visualized with a parallel plot because of its effectiveness in analyzing high-dimensional (multiple objectives) results.

Analyzing trade-offs can be particularly important for engagement as a means for various stakeholders to be aware of the different concerns that each other has. And by being aware of such contextual constraints, allows more room for compromises and cooperation.

RQ 3: What possible robust management policies in consideration of all stakeholder objectives?

Robustness analysis can be done to assess the performance of policies across a set of scenarios. The policies of interest are likely to be a subset of the Pareto optimal policies gathered from the optimization process. This technique is meant to test them under various conditions of uncertainties as this would be useful for the development of strategies and contingency plans to manage unexpected situations.

The **90th Percentile Maximum Regret Score** could be a metric for this analysis. Regret scores are essentially a comparison between the performance of this option versus the best possible option for the outcome (Kwakkel et al., 2016). By taking the 90th percentile, it emphasizes on worst case scenarios and helps identify policies that minimize the most adverse conditions.

These techniques help the operational plans to take a more forward-looking approach towards decision-making. It ensures that water management strategies are future-proof and resilient–which is rather apt, especially for a context revolving around sustainability and long-term water security.

6 Reflection

Limitations
At this point, the model proposal is largely a proof-of-concept – I have written about it based on my mental model of the problem context. However, if there is a commitment to the research aims of ensuring sustainability and water security, there is a need for participatory modelling, to directly engage with the stakeholders, especially vulnerable and marginalized communities through interviews or group model building. This is to understand various problem framings and find the best way to capture their concerns and interests in the model. It is critical to do it from the start since it consequently affects the way the boundaries will be conceptualized.

Also, the conceptualizing of the current objectives is still very limited as there is still a lack of scientific knowledge on the “ideal” state of things especially on ecological impacts. For instance, the objective of seasonal flooding will likely not be as simple as maximizing high flood levels or frequency - because there is a more complex social-ecological interaction to understand. As much of the model revolves around optimizing these objectives, there should be a greater focus on it. There might be a need to consult experts and the scientific community.

Bottlenecks
At this point, data was the most limiting constraint and it affected the extent of detail I could describe the model. This problem cascades; pragmatically speaking, the accessibility of data does influence how a model can be conceptualised (planned and scoped). However, even at this time of writing, I still do not have a comprehensive overview of the available data sources or have searched for unique means to approximate data. Hence, for the sake of continuity, much of the conceptual model was pursued with the optimism that data would not be a limiting factor –and that is also why the section on data selection has been moved to the back. However, this also means not all aspects of the mathematical formulation are described (e.g. accounting for meteorological dynamics) due to not knowing what input data I could be using.

Validation
A key missing aspect of the proposal at this point is model validation. At present, the models are at most numerically validated as many of the components and formulas are scientifically sound. However, structural validation for the model’s “fit-for-purpose” has not been planned extensively as of yet, since its “purpose” would have space to develop through stakeholder engagement. However, this would be very necessary when the model starts to get built up. Some tests such as extreme condition behaviour tests could be conducted, where extreme values are used as inputs and results are assessed if that is how the model was intended.

Final Remarks
I must admit that this assignment was quite a struggle for me – to put together a modelling proposal when I had just started reading about the problem context and the methods within a week. It was hard enough for me to completely understand the ideas that were going on in the Nile River model, the project I used as my main reference.

At present, much of the conceptual and mathematical models are based on the limited literature and models I have been exposed to and my design choices are of course heavily skewed towards what I have seen before. There is much room for iterative improvements in the future to read more about existing simulation and modelling literature so that I will have a more conscious choice towards the techniques, formulas and methods I will use.

References

African Resources Working Group (2009) A Commentary on the Environmental, Socioeconomic and Human Rights Impacts of the Proposed Gibe III Hydrodam in the Lower Omo River Basin of Southwest Ethiopia

Avery, S., & Eng, C. (2012). Lake Turkana & the Lower Omo: hydrological impacts of major dam and irrigation developments. *African Studies Centre, the University of Oxford*.

Avery, S. (2014). What future for Lake Turkana and its wildlife. *SWARA, Jan–Mar*.

CSAG (N.D) ESGF CORDEX Africa. https://www.csag.uct.ac.za/cordex-africa/

EEPCO. (2004a). Gibe II Hydroelectric Project. Weir General Report Level 1; EEPCO: Addis Ababa, Ethiopia, 2004.

EEPCO. (2004b). Gilgel Gibe Hydroelectric Project: Final Report on the Project Implementation; EEPCO: Addis Ababa, Ethiopia

EEPCO. (2008). Gibe III Hydroelectric Project. Reservoir Operation and Energy Production Studies Level 1 Design; EEPCO: Addis Ababa, Ethiopia

Ethiopia Ministry of Water and Energy Strategy Report (2020)

Friedman, J. H., & Fisher, N. I. (1999). Bump hunting in high-dimensional data. *Statistics and computing*, *9*(2), 123-143.

Gebre, S. L., Van Orshoven, J., & Cattrysse, D. (2023). Optimizing the Combined Allocation of Land and Water to Agriculture in the Omo-Gibe River Basin Considering the Water-Energy-Food-Nexus and Environmental Constraints. Land, 12(2), 412. MDPI AG. Retrieved from http://dx.doi.org/10.3390/land12020412

Herman, J., & Usher, W. (2017). SALib: An open-source Python library for sensitivity analysis. *Journal of Open Source Software*, *2*(9), 97.

Kwakkel, J. H., Eker, S., & Pruyt, E. (2016). How robust is a robust policy? Comparing alternative robustness metrics for robust decision-making. *Robustness analysis in decision aiding, optimization, and analytics*, 221-237.

MoWE. Hydrological Data Report; Ethiopian Ministry of Water and Energy: Addis Ababa, Ethiopia, 2021.

M. Giuliani, A. Castelletti, F. Pianosi, E. Mason, and P. M. Reed. Curses, Tradeoffs, and Scalable Management: Advancing Evolutionary Multiobjective Direct Policy Search to Improve Water Reservoir Operations. Journal of Water Resources Planning and Management, 142(2):04015050, Aug. 2015. doi: 10.1061/(ASCE)WR.1943-5452. 0000570

NAMA, (2021). Meteorological Data Report; Ethiopian National Meteorological Agency: Addis Ababa, Ethiopia,

Pertaub, D. P., Tekle, D., & Stevenson, E. G. (2019). Flood Retreat Agriculture in the Lower Omo Valley, Ethiopia. *East Lansing MI Omo-Turkana Res. Netw*.

Sari, Y (2022). Exploring Trade-offs in Reservoir Operations through Many Objective Optimization: Case of Nile River Basin

UN Global Compact (2018) Annual Report 2018.