DAFNE

A **D**ecision-**A**nalytic **F**ramework to explore the
water-energy-food **NE**xus in complex and transboundary
water resources systems of fast growing developing countries

EVALUATION OF INDICATORS, VALUE FUNCTIONS AND PATHWAYS

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Abbreviations

BAU	Business As Usual
DAF	Decision Analytic Framework
DMs	Decision Makers
EAPP	Eastern African Power Pool
FC	Factors of Change
GCM	General Circulation Model
NLS	Negotiation Simulation Lab
OTB	Omo-Turkana Basin
PIP	Participatory and Integrated Planning
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SAPP	Southern African Power Pool
SHs	Stakeholders
SSP	Shared Socio-economic Pathway
WEF	Water-Energy-Food
ZRB	Zambezi River Basin

1. INTRODUCTION

This document is the deliverable *D5.1 – Evaluation of Indicators, Value Functions and Pathways,* which is part of Work Package 5 activities undertaken in task *T5.1 Pathways and indicators*.

The goal of WP5 is the development of a robust Decision Analytic Framework (DAF) to explore alternative pathways (i.e., temporal sequence of actions) for advancing water management strategies under baseline (historical) and future scenarios, and identify efficient/robust pathways to be negotiated in the Negotiation Simulation Lab (NSL) in WP6.

The workflow of WP5 and its interconnections with the other WPs are illustrated in Figure 1: WP5 receives from WP2 and WP4 the full set of evaluation indicators and candidate actions identified through a participatory process involving all the relevant Stakeholders (SHs) with the support and integration of the DAFNE experts.

These sets are organized and analyzed in task T5.1 to identify:

1. a small set of **design indicators** capturing the main components of the Water-Energy-Food (WEF) Nexus to be used in the DAF for the optimization of the efficient pathways
2. a small set of **candidate pathways***,* i.e. temporal sequence of actions, to be evaluated via simulation in order to generate reference solutions for the analysis of the efficient pathways designed by the DAF.

The DAF employs a strategic *design model* coupled with an *optimization engine*: the design model is a parsimonious model conceptualizing the main natural processes and human decisions at the whole river basin scale. The optimization engine implements a simulation-based optimization via multi-objective evolutionary algorithms (Maier et al., 2014), which iteratively improves a set of candidate solutions by optimizing their performance estimated via simulation of the design model (see the dashed lines in Figure 1) with respect to the selected design indicators[1].

The resulting set of Pareto optimal (efficient) pathways (or a selection of them) is finally simulated by the integrated WEF developed in Task 3.2 for estimating the system performance according to the original full set of evaluation indicators organized in task T5.1. The NSL (WP6) will support the Stakeholders analysis of the resulting indicator values across sectors to facilitate a virtual negotiation over the designed pathways.

This deliverable focuses on the collection of *evaluation indicators and actions* for the different components of the WEF Nexus in the two DAFNE case studies, namely the Zambezi River Basin (ZRB) and the Omo-Turkana Basin (OTB), along with the selection of design indicators and definition of candidate pathways for Task T5.2.

The report is structured as follows: the next chapter introduces the methodological aspects related to the definition of indicators and pathways and the adopted participatory approach based on the NSL meetings. Chapter 3 reports a structured list of indicators organized by sectors (Energy, Food, Water and Ecosystems, Governance), discuss the definition of Value Functions, and formulate the design indicators for both the ZRB and the OTB, respectively. Chapter 4 instead illustrates the list of actions elicited during the NSL meetings organized by sectors (Energy, Food, Water and Ecosystems, Governance) and defines a small set of candidate pathways for both the ZRB and the OTB, respectively.

[1] More details about the DAF architecture are available in the report of Milestone *MS34 - Decision Analytic Framework architecture released*.

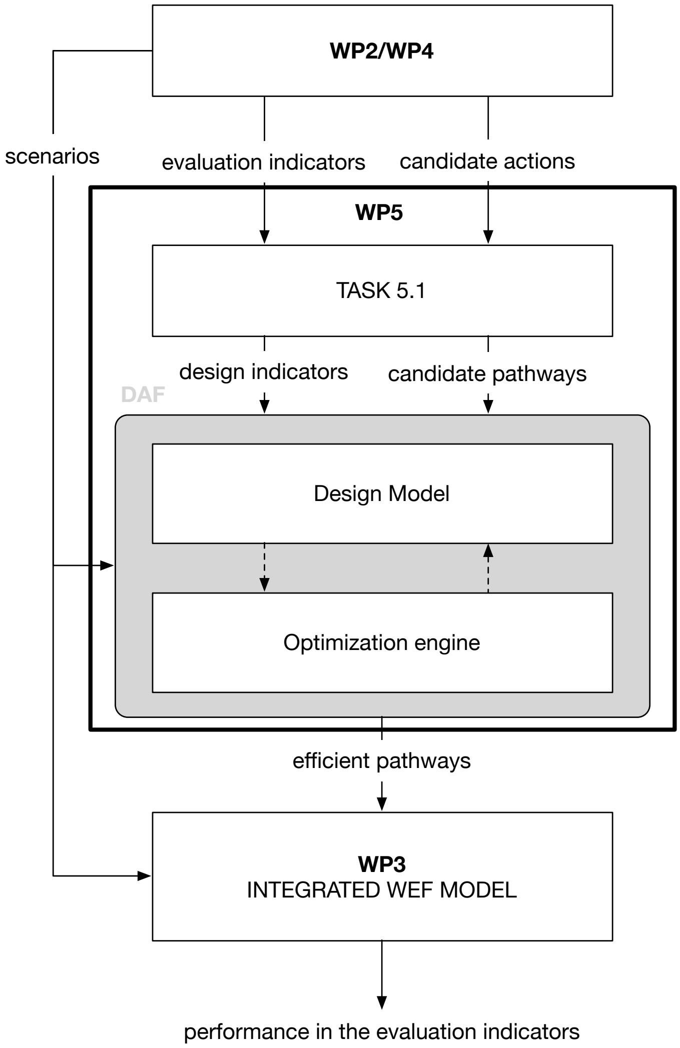

Figure 1 – WP5 workflow

2. METHODOLOGY

2.1 CRITERIA, INDICATORS AND VALUE FUNCTIONS

The goal of the DAF is to support the design of Pareto optimal pathways in addressing the tradeoff across the three components of the WEF Nexus. This requires defining *how to evaluate* the performance of a pathway in terms of the WEF Nexus and, more broadly, with respect to the interests of Decision Makers (DMs) and local SHs in the two DAFNE case studies.

DAFNE follows the Participatory and Integrated Planning procedure by Soncini-Sessa et al. (2007a) to infer and model DMs' and SHs' preferences. SHs with similar issues and priorities are grouped into **sectors** (e.g., water, energy, food, ecosystem). For each sector, an **evaluation criterion** is specified and associated to an **index** that DMs and/or SHs can use for the comparative assessment of the pathways with respect to the criterion. The index can be defined either on an ordinal scale (qualitative index) or on a cardinal scale (quantitative index), and must be a function of the pathway that describes the preferred direction of change embedded in the evaluation criterion.

The index supports the pairwise comparison of alternative pathways. For example, given two pathways P1 and P2, a DM should be able to select the "preferred pathway" with respect to a given criterion by contrasting the values that the index assumes under P1 and P2. The repetition of such pairwise comparison across a set of pathways allows the definition of the complete ranking of the pathways with respect to the criterion expressed by the index. In principle, the index value can be directly estimated by interviewing the SHs or, when this is not feasible, a representative Expert (Figure 2a). Yet, this direct approach frequently leads to subjective and hardly acceptable evaluations, and its implementation might become extremely difficult when the planning process involves a large number of alternative pathways. An automated procedure is therefore more appropriate to reproduce the SHs/Expert evaluations in order to compute the index (Figure 2b). The strong participation of both DMs and SHs is crucial in this step to ensure the results of the decision-making process will be perceived as trustable: *a direct involvement of the decision maker herself in the modelling process is the unique way to make credible models: these can in fact be built only by people who are familiar with both the problem and the institutional setting in which the problem is to be addressed* (Loucks et al., 1985).

In DAFNE, the impact of the pathways designed by the DAF is ultimately assessed via simulation of the WEF integrated model developed in Task T3.2 (see Figure 1). Technically, the index value can be therefore computed as a functional of the simulated trajectories of the relevant model variables (Figure 2c), such as water level in a specific river section, water flow in an irrigation canal, water flow through turbines in a hydropower plant. Such computation of the index is generally performed in two steps (Figure 2d): first, the effects of a pathway are measured in physical units by an **evaluation indicator**, and then the value of this indicator is mapped in to the actual satisfaction of the DMs' or SH' criterion by means of a **value function**.

It is worth noticing that the value of an indicator expressed in physical units could differ from the level of satisfaction of the associated criterion returned by the value function. For example, if the indicator quantifies the water level excess above a critical flood threshold and pathways P1, P2, and P3 produce different values of this indicator all above the threshold, the corresponding level of satisfaction can be null for all the three pathways.

In some cases, it might be difficult to formulate an indicator directly associated to the index used by DMs or SHs for the evaluation of their criteria. For example (for more details, see Soncini-Sessa et al., 2007b), an indicator related to flood protection could be the flood damage, which requires formalizing a relationship between the water level in a flood event and the economic damages produced by the flood. Defining such relationship, however, is very site specific and generally requires ad-hoc data collections that may prevent its use in practice. In these cases, the original flood damage indicator might be replaced by a **proxy indicator** measuring the flooded area rather than the economic damage (Figure 2e). The proxy indicator is a variable in a logical relationship with the evaluation criterion associated to the index and related to the effects of the pathways through a functional, objective, and potentially quantifiable link (Keeney and Raiffa, 1976). Then, DM/SHs can defined a value function for the proxy indicator to map this latter into a level of satisfaction. The proxy indicator hence assumes the role of an indirect ordinal estimator of the evaluation criterion and the degree of satisfaction of such criterion can be quantified through the value assumed by the proxy indicator, ultimately replacing the need for computing the original indicator.

2.2 ACTIONS AND PATHWAYS

Following the Participatory and Integrated Planning procedure by Soncini-Sessa et al. (2007), actions are **elementary options of intervention** on the system (e.g., the construction of a new dam or irrigation canal, the imposition of an environmental flow in a specific river stretch) that are expected to allow the achievement of a pre-defined goal (e.g., water, energy, food security). Each action can be completely and precisely identified through the specification of the values assumed by a set of attributes (parameters and/or functions), where each attribute is completed with the definition of a feasibility set (e.g., feasible capacities of the irrigation canal). Actions can assume values only within such feasibility set. These attributes are the decision variable of the planning problem (Soncini-Sessa et al., 2007).

Actions can be classified as **structural** actions and **non-structural** actions. The first class of actions concern the physical modifications of the system, such as siting and sizing of infrastructure for the collection, transportation, distribution, and use of water resources. Examples of structural actions are: the construction of a dam or a canal; the installation of an irrigation system; the construction of a waste water treatment plant. The actions of the second category either modify the system only functionally or they alter the effects that the system produces. Examples of non-structural actions are: a regulation setting water quality standards or environmental flows; setting tariffs for water services; an incentive program for farmers to encourage ‘virtuous’ behavior (e.g. adopting crops that need less water or planting woody buffer strips); the operating policy of a reservoir.

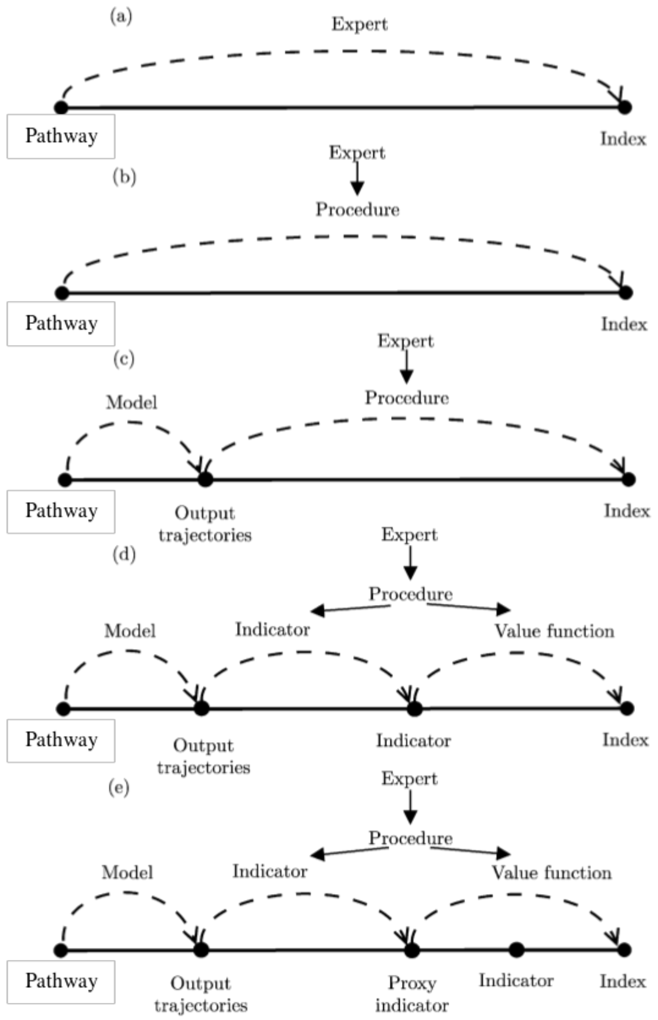

Figure 2 – Alternative approaches for the definition of an index evaluating the performance of a pathway with respect to the evaluation criterion of a specific sector (adapted from Soncini-Sessa et al., 2007a).

A second distinction is made between **planning actions** and **management actions**. Here, the discriminating factor is the time step with which the actions are decided. A planning action is decided over a very long time-horizon (e.g. years), sometime once and for all. A typical example of planning action is the construction of a new dam. Conversely, a management action is taken and revised periodically. A typical example of management action is the operation of a dam, which determines the volume of water to be released from the dam on an hourly/daily/weekly/monthly basis, with the action frequency that depends on the characteristics of the case study.

Generally, rather than selecting a single action to implement, SHs and DMs are interested in selecting an **alternative**, which is defined as a combination of actions. Alternatives are traditionally designed under the assumption of stationary boundary conditions. However, the ongoing nonstationary trends (Milly et al., 2008) suggest the need of more dynamic and adaptive solutions, i.e. pathways, able to better handle the uncertainty of future conditions by choosing near-term actions while keeping open the possibility to modify the selected plan in response to how the future unfolds (Haasnoot et al., 2013).

Pathways are defined as a *time-sequence* of structural and non-structural actions that enable policymakers to explore alternative adaptation options to climatic and socio-economic changes (Haasnoot et al., 2012). In order to design an adaptation pathway, it is necessary to first identify candidate structural and non-structural actions that can be taken over time together with their adaptation tipping points (Kwakkel et al., 2015). Adaptation tipping points (Kwadijk et al., 2010) are central to adaptation pathways and identify the conditions under which an action no longer meets required performance levels. The point in time at which this happens is called *sell-by-date* and is scenario dependent. After a tipping point is reached, additional actions are activated to compensate the failure of the previous action and their sequencing generates an adaptation pathway (Haasnoot et al., 2013). An optimization procedure is generally employed to determine both the timing and the type of actions to be taken over a certain time horizon to always meet performance criteria. Details about the optimization procedure adopted in DAFNE will be illustrated in Milestone *MS34 Decision Analytic Framework architecture released*.

The adaptation pathways approach generally generates **adaptation trees** (e.g., decision trees or roadmaps), which illustrate candidate sequences of actions that may be taken after reaching a tipping point, where any given route through the tree is an adaptation pathway that satisfy a minimum level of performance (i.e., a threshold that determines whether results are acceptable or not) across a large ensemble of future scenarios. A set of pathways can be graphically represented through an Adaptation Pathways map (Haasnoot et al., 2013, see Figure 3 for an example). This latter is similar to a Metro map and presents alternative routes (i.e., equivalent combination of actions in time) to get to the same desired point in the future, together with the moment of an adaptation tipping point and the available set of actions after that point. Due to unacceptable performance of some actions in a subset of scenarios, some routes are not always available (dashed lines).

In particular, the map represented in Figure 3 starts from the current situation (*current policy*), which fails to meet specific performance criteria after 4 years into the time horizon considered. Following the grey lines linked to the current policy, four alternative options can be taken: *Action A, B, C* and *D*. The first and the last action should be able to meet given requirements on system performance for the next 100 years in all the scenarios considered. If action B is selected after the first four years, another tipping point (black vertical line) is reached within about five years, leading to a shift to one of the other three actions in order to meet performance targets (follow the yellow lines). On the other hand, if action C is chosen after the first four years, a shift to the either one of the other three actions will be needed in case a specific future scenario (scenario X) will realize in the future as in under these conditions action C is no longer acceptable (it does not satisfy the minimum level of performance). It is worth mentioning that in all other scenarios except scenario X, action C is able to fully satisfy performance requirements throughout the entire 100-year horizon (dashed green line).

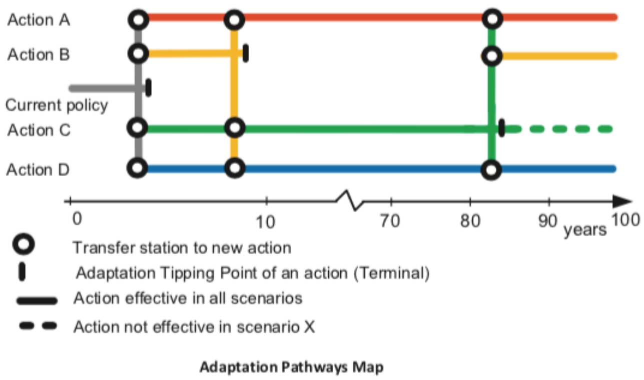

Figure 3 – Example of Adaptation Pathway map (Haasnoot et al. 2013).

2.3 PARTICIPATORY IDENTIFICATION OF INDICATORS AND PATHWAYS

The participatory approach adopted in DAFNE entails that both evaluation indicators and candidate actions (which represents the building blocks of the candidate pathways) are identified through a joint effort by project partners, who are responsible for the modelling exercise and express specific expertise on the different component of the WEF Nexus, and by local SHs, who have better knowledge and understanding of the Nexus in the specific context of each case study.

The central role of the SHs and the process adopted for their identification was illustrated in the deliverable *D6.1 Negotiation Simulation Laboratory Technical Implementation Plan* (Chapter 2 – Stakeholder participation in DAFNE), where the NSL is introduced as a safe environment to simulate negotiations and a way to facilitate interaction between stakeholders involved in the WEF Nexus.

DAFNE SHs actively participated to the first two NSL meetings held in Lusaka and Addis Ababa, respectively. During these meetings, a number of interactive sessions were organized where participants brought their knowledge and expertise to inform and orient project activities (see Figure 4 and Figure 5). Feedbacks and contributions collected during these two meetings represent the starting point for the process of identification of the evaluation indicators and candidate actions. This participatory process is structured in 6 steps, which are detailed hereafter.

Figure 4 – Interactive mapping session during the NSL Meeting for the Zambezi River Basin, Lusaka September 2017.

Figure 5 – Interactive mapping session during the NSL Meeting for the Omo-Turkana Basins, Addis Ababa, February 2018.

Step 1: During the NSL meeting, two interactive mapping exercise were performed:

- to identify **issues** related to the WEF Nexus;
- to single out **actions**, planned or proposed, able to solve or influence the identified issues;
- to collect proposal of relevant **indicators** able to measure effects of the identified actions.

Step 2: The outcomes of the NSL meetings were structured into a table reporting all the issues identified and four action tables, each one related to a specific sector: Energy, Food, Water and Ecosystems, Socio-Economic aspects. The indicators table is composed by the following fields:

- *Id:* unique identifier
- *Short Description:* Brief description of the indicator
- *Spatial extent:* Spatial domain for indicator computation (e.g. River basin, country, district, power plant/wetland/irrigation district)
- *Temporal aggregation:* Temporal domain and statistics used in the indicator formulation (e.g.: sum/max/min/average over the time horizon/yearly/monthly)
- *Unit of measurement*
- *Strategic or Detailed model:* To be computed with the DAF (strategic), WEF integrated model (detailed) or both
- *DAFNE:* To be considered in the project or not?
- *Location/Spatial reference:* position on the map
- *Formula:* Mathematical formulation
- *Definition:* Formal definition of the indicator
- *Data required:* Data/parameters needed for computing the indicator that are not provided directly by a model

- *Model required:* Models required to compute the indicator
- *Notes*

while the actions table are composed by the following fields:

- *Id:* unique identifier
- *Title:* name of the action
- *Description:* Brief description of action type and features
- *Country:* nation where the action takes place
- *Status:* implementation stage (e.g. proposal, planned, under construction, ...)
- *Expected timing:* Year or period of expected completion of the action
- *DAFNE:* Action considered in the DAFNE project or not
- *Location/Spatial reference:* position on the map
- *Attachment:* technical documents with information needed to implement models representing the action.
- *Type:* action type (e.g. new hydropower plant, enlargement of irrigation scheme, …)
- *Features:* Key features defining the action, suitable to be used for (geo)graphical representation (e.g. power capacity for hydropower plant, irrigated hectares for irrigation schemes, …). Features can be different for each action Type.
- *Notes*

Step 3: The DAFNE partners involved in the modelling exercise filled in the indicators and actions tables related to their specific expertise domain and role in the project with information deriving from their knowledge of the system, from academic publications or from grey literature. A first selection of indicators and actions was also proposed both with respect to their relevance with respect to the main issues identified in the NSL meetings and the possibility of actually modelling them with the DAFNE integrated model developed in Task T3.2. For example, during the NSL meeting the SHs of the OTB proposed, among others, the following two indicators in the Food Sector: "*Fish Biomass*" and "*Fish Biodiversity*". While the first indicator was selected (see Table 3) and better specified as "*i_F_13 - Total fish catch and production*", the second one could not be considered due to the insufficient information available for modelling fish species and simulating the impacts on fish biodiversity under of future pathways and scenarios. Similarly, they raised issues related to "*Pressure upon biodiversity in and around the national park area*", "*Sugar plantation is pushing the protected areas*", "*Biodiversity loss/migration and loss of animals*" associated to the proposals of the following actions: "*Forest/UNESCO biosphere reserve creation*" and "*Strengthening management of National Parks*". Since the integrated WEF model will allow simulating land use changes due to new protected area and ecosystem water requirements, but will not provide a dynamic representation of how these ecosystems respond to water availability changes, a single action generically described as "*Protected area management*" was considered at this stage.

Step 4: Indicators and actions tables were then shared with DAFNE SHs for a second round of feedback and for the validation of the proposed selection. For this step two different approaches were adopted in the two case studies:

- for the Zambezi River Basin, the tables were published in the *Online Stakeholder Interaction Area*[2], within the DAFNE website and SHs were invited to provide feedbacks and comments directly on the online version of the table. DAFNE local were also involved to facilitate this process and in directly collecting feedbacks from some SHs.
- for the Omo-Turkana Basins, two local facilitators (one for the Omo SHs and another for the Turkana SHs) were recruited through the DAFNE local partners and the indicators tables were filled in by these facilitators on the basis of their direct interaction with a number of relevant SHs.

Step 5: Indicators and actions tables were sent back to DAFNE partners, who eventually generated a consolidated list of indicators and one of candidate actions and pathways for the two case

[2] The "Online Stakeholder Interaction Area" can be accessed directly by the project homepage (http://dafne-project.eu/). For more details, see Report MS41, Section 1.1.

studies (see Sections 3 and 4) according to the feedbacks received in the previous step. For example, the generic action "*Protected area management*" defined in Step 3 received positive feedbacks from all SHs, which suggested examining in depth this aspect by breaking down this action into multiple site-specific actions, one for each existing or candidate protected area (see actions a_W_Ec1 to a_W_Ec4 in Table 14).

Step 6: The updated version of the two tables were finally uploaded in the *Online Stakeholder Interaction Area* in order to be continuously available to all stakeholders. A communication was sent to inform the SHs about this publication, including the credentials to get access the reserved area of the project website.

3. EVALUATION INDICATORS

3.1 FULL SET OF EVALUATION INDICATORS

3.1.1 Zambezi River Basin

The NSL meeting took place in Lusaka, Zambia on September 11 and 12, 2017 for the ZRB, which involved the following SHs[3]:

- Water and Ecosystem
  - Água de Chiúta (Waters of Chiúta)
  - World Wide Fund for Nature – Zambia (WWF)
  - Lukanga Water and Sewerage Organization (LWS)
- Energy
  - DIPREME – Tete Provisional Directorates of Mineral Resources and Energy
  - HCB - Cabora Bassa Hydropower
  - Lunsemfwa Hydropower
  - Zambia Electricity Supply Corporation (ZESCO)
  - Zambezi River Authority (ZRA)
- Food
  - Mulungushi Water Users association
  - Mafundzalo Farms
- Socio-economic aspects and governance (cross-sectorial)
  - Zambezi Watercourse Commission (ZAMCOM)
  - Southern African Development Community - SADC Water
  - Administracao Regional de Aguas do Zambeze
  - Zambia Department of Water Resources Development - Zambia
  - Water Resources Management Authority (WARMA)

All the SHs were involved in the participatory process described in Section 2.3 and provided important feedbacks and contributions. The issues suggested by the SHs related to the WEF Nexus in the ZRB, subsequently elaborated by project partners into evaluation indicators, are reported in the following tables.

[3] For details on Actor Analysis, invited Stakeholders, and list of participants, please refer to Deliverable *D6.1 Negotiation Simulation Laboratory Technical Implementation Plan.*

Table 1 – Evaluation indicators for the Water and Ecosystem sector (ZRB).

Id	Short Description	Spatial extent
i_W_Ec_1	Magnitude of flooding	River cross-section, representing sub-basin,
i_W_Ec_2	Duration of flooding	River cross-section, representing sub-basin,
i_W_Ec_3	Water requirements for Habitat and fish migration	Wetland
i_W_Ec_4	Sediment transport	River cross-section, representing sub-basin,
i_W_Ec_6	Land cover change	River basin
i_W_Ec_7	River discharge: Amount of flow at different river cross-sections in the basin	River cross-section, representing sub-basin,
i_W_Ec_8	Index of Hydrological alteration	River basin
i_W_Ec_9	Evaporation rate from water bodies	Reservoirs
i_W_Ec_10	Water table (surface and groundwater level)	River basin
i_W_Ec_11	Water temperature alterations	downstream Kariba dam
i_W_Ec_12	Dissolved oxygen	downstream Kariba dam

Table 2 – Evaluation Indicators for the Energy sector (ZRB)[4].

Id	Short Description	Spatial extent
i_E_1	Electricity production from hydro-power in river basin	Zambezi River basin
i_E_2	Electricity production from hydro-power at national level	Zambia, Zimbabwe, Mozambique
i_E_3	Electricity production from each hydro-power plant	Single power plant
i_E_4	Deficit with respect to electricity demand in the river basin	Zambezi River basin
i_E_5	Deficit with respect to electricity demand at national level	Zambia, Zimbabwe, Mozambique
i_E_6	Deficit with respect to electricity demand for each power plant	Single power plant

Table 3 – Evaluation Indicators for the Food sector (ZRB).

Id	Short Description	Spatial extent
i_F_1	Agricultural Area	All spatial levels
i_F_2	Yield of rainfed crops in terms of tons/ ha	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_3	Yield of irrigated crops in terms of tons/ha	Subbasins level 5 (9) and higher basin levels; administrative units; IA
i_F_4	Yield of rainfed and irrigated crops in terms of proteins/ ha	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_5	Yield of rainfed and irrigated crops in terms of calories/ ha	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_6	Water productivity of rainfed crops	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_7	Water productivity of irrigated crops	Subbasins level 5 (9) and higher basin levels; administrative units; IA

[4] These indicators refer to the major existing hydropower plants with a particular focus on Zambia, Zimbabwe and Mozambique given the presence of local partners as well as the nationality of the SHs involved in the NSL.

(Table 3 continued)

i_F_8	Irrigation water required for optimal production of irrigated crops	Subbasins level 5 (9) and higher basin levels; administrative units; IA
i_F_9	Total livestock count	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_10	Water required for optimal livestock production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_11	Calories yield from livestock	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_12	Protein yield from livestock	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_13	Total fish catch and production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_14	Calorie yield from fish catch and production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_15	Protein yield from fish catch and production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_16	Dietary supply adequacy - calories from crops, livestock and fisheries	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_17	Dietary supply adequacy - proteins from crop, livestock and fisheries	Subbasins level 5 (9) and higher basin levels; administrative units

Table 4 – Evaluation indicator list for Socio-Economic sector (ZRB).

Id	Short Description	Spatial extent
i_SE_1	Population	National, District
i_SE_2	Population Density	National, District
i_SE_3	Population by gender	National, District
i_SE_4	Population by age	National, District
i_SE_5	Population growth rate	National
i_SE_6	Population growth rate - urban	National
i_SE_7	Population growth rate - rural	National
i_SE_8	Life Expectancy	National
i_SE_9	Life Expectancy by gender	National
i_SE_10	Infant mortality	National
i_SE_11	HDI Ranking	National
i_SE_12	Employment rate	National, District
i_SE_13	Employment Per Sector	National
i_SE_14	Average household income	National, District
i_SE_15	Average household spend - Water	National, District
i_SE_16	Average household spend - Electricity	National, District
i_SE_17	Access to Electricity	National, District
i_SE_18	Access to drinking water	National, District
i_SE_19	Access to sanitation	National, District
i_SE_20	Population living in slums	National
i_SE_21	GDP	National
i_SE_22	GDP per Capita	National
i_SE_23	GDP per Sector	National
i_SE_24	GVA per Sector	National
i_SE_25	Goss Fixed Capital per Sector	National
i_SE_26	Water Price	National, District

(Table 4 continued)

i_SE_27	Electricity Price	National, District
i_SE_28	Displacement	National
i_SE_29	Poverty	National
i_SE_30	Accessibility of school education	National
i_SE_31	Accessibility of medical facilities	National

3.1.2 Omo-Turkana Basin

The NSL meeting took place in Addis Ababa, Ethiopia on February 15 and 16, 2018 for the OTB, which involved the following SHs[5]:

- Water and Ecosystems
  - Jimma University Jimma - Research and Community Services Office (Ethiopia)
  - Oromia Water, Mineral and Energy Bureau (Ethiopia)
  - Ethiopian Wildlife Conservation Authority (Ethiopia)
  - SNNPRS Water Resources Bureau (Ethiopia)
  - Ministry of Environment, Forest & Climate Change - Environmental and Social Impact Assessment and Environmental Licensing Directorate (Ethiopia)
  - National Environment Management Authority (Kenya)
  - Water Resources Authority (Kenya)
- Energy
  - Ethiopian Electric Power - Portfolio Projects Management Office (Ethiopia)
  - Oromia Water, Mineral and Energy Bureau (Ethiopia)
- Food
  - Fri-El Ethiopia Farming And Processing PLC (Ethiopia)
  - Ethiopian Pastoralist Research & Development Association (Ethiopia)
  - Ethiopia Sugar Corporation - Investment and Development DCEO (Ethiopia)
  - Ministry of Agriculture & Natural Resource - Sustainable Land Management Program (Ethiopia)
  - Water Resources Authority (Kenya)
  - Ministry of Water and Sanitation (Kenya)
  - Kenya Marine and Fisheries Institute Lake Turkana (Kenya)
  - Pastoralist Development Network of Kenya (Kenya)
- Socio-economic and governance (cross-sectorial)
  - Ministry of Foreign Affairs - Transboundary Resource Affairs Directorate (Ethiopia)
  - Ministry of Water, Irrigation & Electricity - Boundary and Transboundary Rivers Affairs Directorate (Ethiopia)
  - Ministry of Culture and Tourism - Sector Development Research and Study Directorate (Ethiopia)
  - Population, Health, and Environment (PHE) Consortium (Ethiopia)

All the SHs were involved in the participatory process described in Section 2.3 and provided important feedbacks and contributions. The issues suggested by the SHs related to the WEF Nexus in the OTB, subsequently elaborated by project partners into evaluation indicators, are reported in the following tables.

[5] For details on Actor Analysis, invited Stakeholders, and list of participants, please refer to Deliverable *D6.1 Negotiation Simulation Laboratory Technical Implementation Plan.*

Table 5 – Evaluation indicators for the Water and Ecosystem sector (OTB).

Id	Short Description	Spatial extent
i_W_Ec_1	Magnitude of flooding	River cross-section, representing sub-basin,
i_W_Ec_2	Duration of flooding	River cross-section, representing sub-basin,
i_W_Ec_3	Water requirements for Habitat and fish migration	Wetland
i_W_Ec_4	Sediment transport	River cross-section, representing sub-basin,
i_W_Ec_6	Land cover change	River basin
i_W_Ec_7	River discharge: Amount of flow at different river cross-sections in the basin	River cross-section, representing sub-basin,
i_W_Ec_8	Index of Hydrological alteration	River basin
i_W_Ec_9	Evaporation rate from water bodies	Reservoirs
i_W_Ec_10	Water table (surface and groundwater level)	River basin

Table 6 – Evaluation Indicators for the Energy sector (OTB).

Id	Short Description	Spatial extent
i_E_1	Electricity production from hydro-power in river basin	Omo-Turkana River basin
i_E_3	Electricity production from each hydro-power plant	Single power plant
i_E_5	Deficit with respect to electricity demand at national level	Ethiopia
i_E_7	Lifespan of the dam	Single Reservoir

Table 7 – Evaluation Indicators for the Food sector (OTB).

Id	Short Description	Spatial extent
i_F_1	Agricultural Area	All spatial levels
i_F_2	Yield of rainfed crops in terms of tons/ ha	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_3	Yield of irrigated crops in terms of tons/ha	Subbasins level 5 (9) and higher basin levels; administrative units; IA
i_F_4	Yield of rainfed and irrigated crops in terms of proteins/ ha	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_5	Yield of rainfed and irrigated crops in terms of calories/ ha	Subbasins level 5 (9)and higher basin levels; administrative units
i_F_6	Water productivity of rainfed crops	Subbasins level 5 (9)and higher basin levels; administrative units
i_F_7	Water productivity of irrigated crops	Subbasins level 5 (9) and higher basin levels; administrative units; IA
i_F_8	Irrigation water required for optimal production of irrigated crops	Subbasins level 5 (9) and higher basin levels; administrative units; IA
i_F_9	Total livestock count	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_10	Water required for optimal livestock production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_11	Calories yield from livestock	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_12	Protein yield from livestock	Subbasins level 5 (9) and higher basin levels; administrative units

(Table 7 continued)

i_F_13	Total fish catch and production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_14	Calorie yield from fish catch and production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_15	Protein yield from fish catch and production	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_16	Dietary supply adequacy - calories from crops, livestock and fisheries	Subbasins level 5 (9) and higher basin levels; administrative units
i_F_17	Dietary supply adequacy - proteins from crop, livestock and fisheries	Subbasins level 5 (9) and higher basin levels; administrative units

Table 8 – Evaluation indicator list for Socio-Economic sector (OTB).

Id	Short Description	Spatial extent
i_SE_1	Population	National, District
i_SE_2	Population Density	National, District
i_SE_3	Population by gender	National, District
i_SE_4	Population by age	National, District
i_SE_5	Population growth rate	National
i_SE_6	Population growth rate - urban	National
i_SE_7	population growth rate - rural	National
i_SE_8	Life Expectancy	National
i_SE_9	Life Expectancy by gender	National
i_SE_10	Infant mortality	National
i_SE_11	HDI Ranking	National
i_SE_12	Employment rate	National, District
i_SE_13	Employment Per Sector	National
i_SE_14	Average household income	National, District
i_SE_15	Average household spend - Water	National, District
i_SE_16	Average household spend - Electricity	National, District
i_SE_17	Access to Electricity	National, District
i_SE_18	Access to drinking water	National, District
i_SE_19	Access to sanitation	National, District
i_SE_20	Population living in slums	National
i_SE_21	GDP	National
i_SE_22	GDP per Capita	National
i_SE_23	GDP per Sector	National
i_SE_24	GVA per Sector	National
i_SE_25	Goss Fixed Capital per Sector	National
i_SE_26	Water Price	National, District
i_SE_27	Electricity Price	National, District
i_SE_28	Displacement	National
i_SE_29	Poverty	National
i_SE_30	Accessibility of school education	National
i_SE_31	Accessibility of medical facilities	National

3.1.3 Governance indicators

In addition to the evaluation indicators listed in the previous two sections focused on the WEF nexus components and the socio-economic conditions, a list of indicators related to governance were developed by identifying key legal principles that illustrate the level of legal expectation within the transboundary states of both DAFNE case studies. This governance framework should be seen as an overarching framework which crosses multiple sectors of the DAFNE project and applies to both ZRB and OTB. As described in Deliverable D4.4, in the governance model a doctrinal analysis was used to review legislation at national, basin, and regional level and attribute scores based on the inclusion of these key legal principles. It is worth mentioning that the use of these indicators cannot illustrate whether a particular project, such as the building of a dam or an agricultural project are legal *per se;* however, they can be used to illustrate the level of legal expectation which may arise in relation to the principles of international water law.

While a list of legal principles cannot be exhaustive due to the wide scope and constantly evolving nature of the law, 13 broad categories of principles relevant to both basins have been identified to underpin the governance model. In order to limit the infinite scope of the analysis, these principles relate directly to the use and management of water resources only. The legal principles are also split into substantive and procedural principles. Substantive principles can be considered as broad standards which should be met or upheld, and procedural norms set out the specific processes and procedures which must be followed in order to attain the substantive goals. However, it should be noted that these are loose categorisations, as they both necessarily contain elements of the other. It should also be noted that while some of the key principles used within the Governance Model are recognised as customary international law, meaning that they are binding upon all states, others are not and will only be binding upon states which have consented by ratifying relevant agreements.[6] The key legal principles utilised are also supplemented by soft law frameworks such as the Sustainable Development Goals, National Development Plans, and strategic policies and often work through operational frameworks such as models of benefit sharing[7].

The governance indicators are reported in Table 9 (for more details, see Deliverable D4.4).

Table 9 – Governance indicators.

Id	Legal principle	Type of Indicator	Sectoral relationship to other DAFNE Indicators
i_G_1	Equitable and Reasonable Use	Substantive	Water and Ecosystem, Energy, Food, Socio-Economic
i_G_2	No Significant Harm Rule	Substantive	Water and Ecosystem, Energy, Food, Socio-Economic
i_G_3	Ecosystem Protection	Substantive	Water and Ecosystem
i_G_4	Pollution Prevention	Substantive	Water and Ecosystem
i_G_5	Intergenerational Equity	Substantive	Water and Ecosystem, Socio-Economic
i_G_6	Precautionary Principle	Substantive	Water and Ecosystem, Socio-Economic
i_G_7	Environmental Impact Assessment	Procedural	Water and Ecosystem
i_G_8	Transboundary Impact Assessment	Procedural	Water and Ecosystem

[6] Further details regarding which countries are bound by particular legal agreements can be found in Deliverable 4.4, as well as Milestones 4 and 57.

[7] Further details regarding the linkages between the Governance Model and the Sustainable Development Goals can be found in Deliverable 4.4. The Governance Model also considers the existing and potential future uses of benefit sharing as a method of operationalising a number of the key principles.

(Table 9 continued)

i_G_9	Provision for Establishment of Joint Body/Mechanism	Procedural	Water and Ecosystem, Energy, Food, Socio-Economic
i_G_10	Information/Data Exchange	Procedural	Water and Ecosystem, Energy, Food, Socio-Economic
i_G_11	Notification	Procedural	Water and Ecosystem, Energy, Food, Socio-Economic
i_G_12	Consultation	Procedural	Water and Ecosystem, Energy, Food, Socio-Economic
i_G_13	Dispute Settlement	Procedural	Water and Ecosystem, Energy, Food, Socio-Economic

3.2 VALUE FUNCTIONS

Value functions are a mean to map the evaluation indicators expressed in physical units into an index representing the level of satisfaction of DMs and SHs (see section 2.1).

Considering satisfaction indexes rather than the original evaluation indicators provides a number of advantages: it allows direct comparisons among indicators expressed in different unit of measure; it applies the same direction of preference to all the indicators (i.e., higher values corresponds to higher levels of satisfaction); it may support the aggregation of the indicators (e.g., through a weighted sum), in order to get sectorial or national indexes.

Taking advantage of the DAFNE participatory approach, which includes both face-to-face meetings with SHs and remote online interactions, we set up an iterative process for the definition of value functions which is composed of the following steps:

1. Each indicator was associated to a direction of preference and with a satisfaction index equal to 0 associated to the minimum (maximum) assumed by indicators representing benefits (costs).
2. Definition of preliminary piecewise linear value functions as the one illustrated in Figure 6.
3. Upload of the value functions in the indicators description pages of DAFNE Geoportal[8].
4. Validation and refinement of the value functions defined at the point 2 during the next NSL meeting (planned for July 2019), which will be focused on presenting the results of the efficient pathway design (which will be reported in Deliverable D5.2). Particular attention will be paid to potentially critical threshold values in the indicator value or the need of introducing nonlinear mapping of indicators into satisfaction.
5. Update of the value functions based on the NSL discussion outcome to generate more representative results in the next phases of the project.

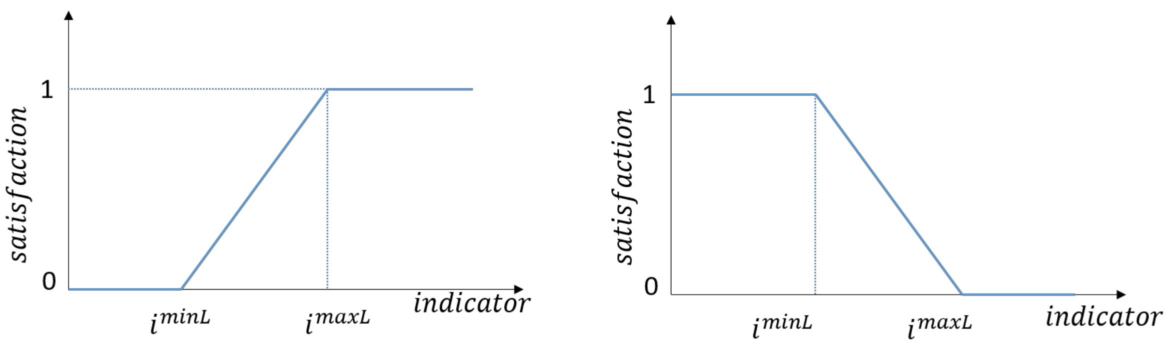

Figure 6 – Examples of piecewise linear value function, where i^{minL} and i^{maxL} are the minimum and maximum value of the considered evaluation indicator, respectively, which represents a benefit to be maximized (left) and a cost to be minimized (right).

[8] More details are reported in Deliverable D6.2.

3.3 SELECTED DESIGN INDICATORS

In this section, for each of the two case studies we define a specific subset of design indicators capturing the main components of the WEF Nexus to be used for the design of efficient pathways. Each of these design indicators reflects the interests of real SHs and is formulated in mathematical terms in order to quantify their expectation and satisfaction.

3.3.1 Zambezi River Basin

Within the ZRB, we decided to consider three design indicators representative of the water-energy-food components of nexus.

In particular, we selected the environmental flow deficit with respect to a specified environmental target flow in the Delta as representative of the water/ecosystem sector. This design indicator is widely adopted in the literature (e.g., Tilmant et al. 2010; Tilmant et al. 2012; Giuliani and Castelletti 2013) as a proxy for hydrological alteration and allows to group several SHs' interests within a single indicator, such as water requirements for natural habitats and the magnitude of flow at an ecologically-relevant cross-section of the Zambezi river. In addition, it only refers to the ecosystem in the ZRB Delta, as minimum environmental flow requirements at other specific protected areas (e.g., Kafue Flats, Victoria Falls) must be always satisfied, thus are considered as constraints on the releases from the water reservoirs within the DAF.

As for the energy sector, we selected the hydropower production deficit as design indicator. This latter reflects the operational objective expressed during the NSL meeting by the reservoir operators of different hydropower companies within the ZRB. In particular, they stated that their operational objective consists in tracking a target level of hydropower production in order to minimize deficit with respect to an energy demand.

Lastly, given the focus of DAF model on irrigated agriculture for the design of efficient pathways, we selected the irrigation deficit as design indicator for the food sector in order to generate optimal pathways that try to guarantee an adequate level of irrigation supply across all the irrigation districts in the ZRB.

Since the DAF considers development pathways at the basin scale, and all Socio-economic indicators emerged from the NSL are formulated at either the district or national scale, this latter cannot be used during the efficient pathways design phase but will be subsequently evaluated by aggregating the outputs generated by the WEF model simulations.

The three design indicators selected are mathematically formulated as follows:

- Squared environmental flow deficit (water):

  $$J^W = \frac{1}{H}\left[\sum_{t=0}^{h-1}(\max\,(wenv_t - r_{t+1}, 0))^2\right] \quad (1)$$

  where $wenv_t$ is the specified environmental target flow in the Delta, and r_{t+1} is the amount of water flowing in the area. As can be observed, the squared environmental deficit is averaged across all the months of the evaluation horizon. In addition, its quadratic formulation aims at penalizing severe deficits within a single time step, while allowing for more frequent, small shortages (Hashimoto 1982).

- Hydropower production deficit (energy):

  $$J^E = \frac{1}{Nyears}\left[\sum_{t=0}^{h-1}\sum_{r=1}^{rmax}|wen_t^r - prod_{t+1}^r|\right] \quad (2)$$

  where

  $$prod_{t+1}^r = \eta^r g\gamma \overline{h_t^r} q_{t+1}^{turb,r} \quad (3)$$

  and wen_t^r and $prod_{t+1}^r$ are the allocated energy demand (i.e., target level of hydropower production) and the actual hydropower production of the power plant r, respectively, and $Nyears$ is the number of years within the evaluation horizon *H*. As for the hydropower production $prod_{t+1}^r$ at each power plant r, $\eta^r [-]$ is the turbines efficiency, $g = 9.81\ [m/s^2]$ is the gravitational acceleration, $\gamma = 1000\ [kg/m^3]$ is the water density, $\overline{h_t^r}\ [m]$ is the net hydraulic head, and $q_{t+1}^{turb,r}\ [m^3/s]$ is the turbinated flow. As can be observed, the annual hydropower production deficit is computed at the Zambezi basin scale by summing the energy deficit occurring at all the $rmax$ operating power plants in each month and averaged across all the years of the evaluation horizon.

- Squared irrigation deficit normalized with respect to squared irrigation demand (food):

$$J^F = \frac{1}{H}\left[\sum_{t=0}^{h-1}\sum_{id=1}^{idmax}\left(\frac{\max\,(wirr_t^{id} - rirr_{t+1}^{id}, 0)}{wirr_t^{id}}\right)^2\right] \tag{4}$$

where $wirr_t^{id}$ and $rirr_{t+1}^{id}$ are the irrigation water demand and abstraction of the irrigation district id. As can be observed, the normalized irrigation deficit is computed at the Zambezi river basin scale by summing the normalized deficit occurring at all the $idmax$ irrigation districts in each month and averaged across all the months of the evaluation horizon. The normalized formulation allows to weigh all the irrigation districts deficits equally regardless of the magnitude of their demands, and thus split the overall irrigation deficit almost uniformly among all the districts. Therefore, districts characterized by very different demands in terms of their magnitude can be grouped within the same indicator. As in the formulation of the environmental flow deficit, the quadratic formulation aims at penalizing severe deficits within a single time step, while allowing for more frequent, small shortages (Hashimoto 1982).

3.3.2 Omo-Turkana Basin

In this section, we present the design indicators selected to assess the WEF nexus in the OTB, in particular, for each sector we justify the indicator choice based on issues and remarks raised during the NSL, and, secondly, we present and discuss in more details the mathematical formulation of each indicator.

Regarding the water/ecosystem sector, during the NSL SHs expressed concerns regarding the alteration of the basin ecosystem hotspots, namely the Omo wetland and lake Turkana. These issues are represented by two design indicators, measuring the alteration of the water circulating in these hotspots with respect to the ecosystems pristine conditions. The design indicators relative to the Water/ecosystem sector are named *Environment in the Omo delta*, and *Fish in lake Turkana*. Currently, no agreement has been reached between SH on whether the issue of flooding is still relevant for the basin after the construction of Gibe III, therefore, the addition of a flooding indicator to the design indicator set is still pending at the moment of writing this report. Other additional indicators listed in the NSL report (e.g., sediment transport, land cover change) require variables that are not modelled in the DAF, and their evaluation will be performed in the detailed WEF model.

The energy sector is represented by the *Hydropower production* indicator, aimed at the maximization of the hydropower production at basin level. This objective formulation was preferred to other alternatives (e.g., satisfaction of internal demand) given that the aim of the Ethiopian government is not only to reach internal energy security, but also to become a regional electricity exporter within the Eastern Africa Power Pool (see section **Error! Reference source not found.** for further details). As a consequence, any production exceeding the internal demand is assumed to be exported.

The food component of the nexus is here considered at two different scales, a *large-scale food* production of the irrigated agricultural districts, aimed at country level distribution and global export, and a *local scale food* production practiced by local population for sustenance. The large-scale food is represented in the design indicators set with the *Large-scale irrigation districts* indicator, which assesses the irrigation deficit of the two largest agricultural districts planned in the Omo valley (Kuraz Sugar Development Project) and delta (private investments). The assessment of the local scale food is instead more complex, as the local populations have developed a diversified set of food production strategies for their sustenance. Among them, recession agriculture, livestock production, and fishing are the main sources of nutrients and calories. For this sector, we developed the indicators *Recession flood,* which ensures that the peculiar hydrological conditions for the practice of recession agriculture are verified, and *Fish in lake Turkana.* This last indicator was already listed for the water/ecosystem sector, as it represents the abundance of fish population in lake Turkana, both representative of a local food source, and of the well-being of the lake ecosystem. Finally, the livestock abundance is not considered in the DAF, but will be assessed with the detailed model.

Lastly, the DAF considers development pathways at the basin scale, and all Socio-economic indicators emerged from the NSL are formulated at the district, or national scale and not suitable for this analysis. However, as in the case of ZRB, they will be subsequently evaluated by aggregating the outputs generated by the WEF model simulations.

Below, the mathematical formulation of the design indicators is presented and discussed in details.

- Environment in the Omo delta (water/ecosystem):

$$J^{Env} = \frac{1}{H}\left[\sum_{t=0}^{H-1}(wenv_t - r_{t+1}^{env})^2\right] \quad (5)$$

where $wenv_t$ is the cyclostationary trajectory of natural inflow regime in the Omo Delta, (Figure 7, left panel), and r_{t+1}^{env} is the streamflow reaching the delta in the pathway under evaluation. The indicator is formulated as the average squared distance between these two values across the simulation horizon [1, H]. This indicator is aimed at preserving natural flow conditions in the ecosystem of the Omo delta, penalizing both positive and negative deviation from the natural regime. As in previous objectives formulations, we more-than-proportionally penalize large deviations with a squared formulation.

- Hydropower production (energy):

$$J^{HP} = \frac{1}{Nyears}\left[\sum_{t=0}^{H-1}\sum_{r=1}^{rmax} prod_{t+1}^{r}\right] \quad (6)$$

where $prod_{t+1}^{r}$ is the hydropower production of the power plant r, computed as in (3). and $Nyears$ is the number of years within the evaluation horizon *H.* This indicator aims at maximizing the annual hydropower production at the basin level.

- Large scale irrigation districts (large scale food):

$$\mathrm{J}^{\mathrm{Irr}} = \frac{1}{\mathrm{H}}\left[\sum_{\mathrm{t=0}}^{\mathrm{h-1}}\sum_{\mathrm{id=1}}^{\mathrm{idmax}}\left(\frac{\max\left(\mathrm{wirr}_{\mathrm{t}}^{\mathrm{id}} - \mathrm{rirr}_{\mathrm{t+1}}^{\mathrm{id}}, 0\right)}{\mathrm{wirr}_{\mathrm{t}}^{\mathrm{id}}}\right)^2\right] \quad (7)$$

where $wirr_t^{id}$ and $rirr_{t+1}^{id}$ are the irrigation water demand and abstraction of the irrigation district id. The normalized irrigation deficit is computed at the basin scale by summing the normalized deficit occurring in the irrigation districts each time step, and averaged across the evaluation horizon. Analogously to the Zambezi food indicator, the normalization of deficit with respect to the water demand is motivated by the necessity of considering two districts characterized by very different water demands.

- Recession flood (local scale food):

$$J^{Rec} = \frac{1}{H}\left[\sum_{t=0}^{h-1}(\max\left(wrec_t - r_{t+1}^{rec}, 0\right))^2\right] \quad (8)$$

where $wrec_t$ is a target flood requirement in the lower Omo valley needed for the recession agriculture practice (Figure 7, right panel) (Avery, 2012), and r_{t+1}^{rec}, is the streamflow transiting the same river reach in the pathway under evaluation. This indicator thus computes the average streamflow deficit in the simulation horizon [1, H] with respect to recession requirements and it is aimed at guaranteeing the hydrological conditions required to perform recession agriculture.

- Fish in lake Turkana (water-local scale food):

$$J^{fish} = \max_{y=0,\dots,Ny-1}\left(\left|F^{nat} - F_{y+1}\right|\right) \quad (9)$$

$$F_y = \alpha \overline{h_{y-1}} + \beta ampl_y + \gamma$$

$$ampl_y = \max_{t\,\in[Sept-Dec]_y} h_{t,y} - \min_{t\,\in[Jan-Aug]_y} h_{t,y}$$

where F^{nat} is the average natural fish biomass present in lake Turkana, and F_{y+1} is the estimated fish biomass in year $t+1$ of the pathway under evaluation. J^{fish} assumes the value of the maximum distance between natural and simulated fish abundance: such *worst case* formulation guarantees a minimum acceptable performance in critical years. This choice is motivated by the fact the several tribes resort to fishing exclusively in exceptionally dry years, when other survival strategies fail to provide sustenance.

Fish biomass is estimated from hydrological variables: the average lake Turkana water level in the previous year $\overline{h_{y-1}}$, and the amplitude of lake level oscillation in the current year between dry season (January to August) and wet season (September to December). F^{nat} is estimated in an analogous way, from historical levels of Turkana from 1985 to 2001, when the system is considered in pristine conditions. The coefficients of this regression are $\alpha = 0.3252$, $\beta = 1.006$ and $\gamma = -110.91$. The relation between fish biomass and lake Turkana levels is retrieved from (1).

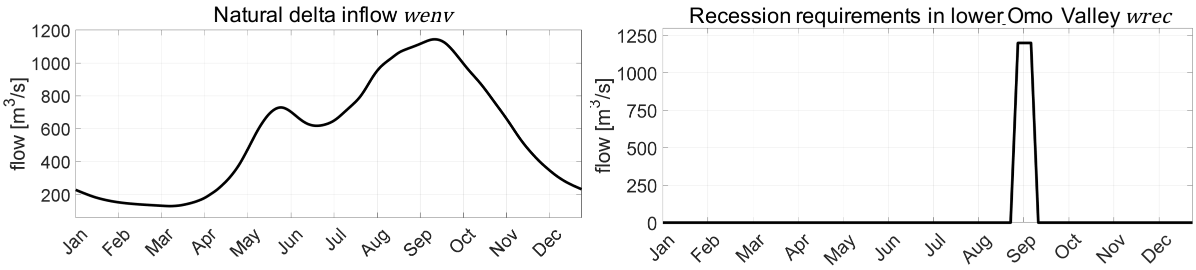

Figure 7 – Left panel – cyclostationary trajectory of natural inflow regime in the Omo Delta, computed averaging 15 years of inflow to the delta in a simulation of the pristine system (no dams). Right panel: target flood requirement in the lower Omo valley needed for the practice of recession agriculture.

4. ACTIONS AND PATHWAYS

4.1 ACTIONS FOR THE ZAMBEZI RIVER BASIN

The NSL meeting took place in Lusaka, Zambia on September 11 and 12, 2017 for the ZRB (see Section 3.1.1 for the list of SHs involved). All the SHs were involved in the participatory process described in section 2.3 and provided important feedbacks and contributions. The actions suggested by the SHs related to the WEF Nexus in the ZRB, subsequently elaborated by project partners, are reported in the following tables.

Table 10 – Selected actions for the Water and Ecosystem sector (ZRB).

Id	Title	Description	Country	Status	Expected timing
a_W_Ec_1	Cameia National Park	Game reserve since 1938 and national park since 1957	Angola	Existing	Present
a_W_Ec_2	Kafue National Park	Largest National Park in Zambia with important openland but also forest and wetland areas	Zambia	Existing	Present

(Table 10 continued)

a_W_Ec_3	Lukanga Swamp	Major wetland in the upper catchment of the Kafue river	Zambia	Partial	Present
a_W_Ec_4	Kafue Flats	Vast seasonally inundated swamp with importance for fisheries and wildlife	Zambia	Existing	Present
a_W_Ec_5	North Swaka	Protected forests in the upper catchment of the Lunsemfwa river	Zambia	Existing	Present
a_W_Ec_6	Wonder Gorge	Gorge in the lower part of the Lunsemfwa river	Zambia	Partial	Present
a_W_Ec_7	Lower Zambezi National Park	National park founded in 1983 between Kariba and Cahora Bassa reservoirs	Zambia	Existing	Present
a_W_Ec_8	Lake Malawi catchment (Malawi)	One of the largest and most biodiverse lakes in Africa	Malawi	Partial	Present
a_W_Ec_9	Lake Malawi catchment (Mozambique)	One of the lagest and most biodiverse lakes in Africa	Mozambique	Partial	Present
a_W_Ec_10	Lower Shire	Wetlands and floodplains along the Shire river with high importance ofr agriculture	Malawi/Mozambique	Partial	Present
a_W_Ec_11	Zambezi Delta RAMSAR	Part of the Zambezi delta that contains the RAMSAR site	Mozambique	Unknown	NA
a_W_Ec_12	Zambezi Delta	Other part of the Zambezi delta, largely drained and used for agriculture.	Mozambique	Partial	Present
a_W_Ec_13	E-flow downstream of all the dams and irrigation diversions	Artificial flood releases from dams to ensure "environmental flows" by mimicking natural floods	all Zambezi	implementation phase	Present
a_W_Ec_14	Coordinate transboundary e-flows	Monitoring of discharge and water quality across borders	all Zambezi and Omo	Existing for lake Kariba	NA
a_W_Ec_15	West Lunga NP and Lukwakwa GMA	One of the densest forest areas in the ZRB. Areas combines the West lunga National Park and the Lukwakwa Game Management Area	Zambia	Existing	Present
a_W_Ec_16	Deforestation and forest degradation	Permanent conversion of forest to agriculture, logging for timber and charcoal	Zambia, Malawi, Mozambique	Existing	NA

(Table 10 continued)

a_W_Ec_17	Kavango-Zambezi TFCA	The Kavango Zambezi is a transfrontier conservation area, roughly the size of France, established to secure large-scale habitat connectivity for wildlife. It is now on the way to become Southern Africa's premier tourist destination. It was established in 2006 through a memorandum of understanding between ministers of all concerned countries and finalized in 2011 with the presidents of all countries signing a treaty (http://www.kavangozambezi.org)	Angola, Zambia, Namibia, Botswana, Zimbabwe	Treaty signed	Present
a_W_Ec_18	Malawi-Zambia TFCA	This TFCA is based on a an MoU from 2004 and a treaty signed in 2015 (http://www.malawizambiatfca.org)	Malawi Zambia	Treaty signed	Present
a_W_Ec_19	Zimbabwe-Mozambique-Zambia (ZIMOZA) TFCRA	Potential extension to the Kavango Zambezi TFCA, scheduled for 2018 (https://www.giz.de/en/downloads/giz2015-en-tfca-zimoza.pdf)	Zimbabwe, Mozambique, Zambia	Conceptual	2018
a_W_Ec_20	Lower Zambezi-Mana Pools TFCA	Potential extension to the Kavango Zambezi TFCA, scheduled for 2018. MoU in preparation (http://www.peaceparks.org/tfca.php?pid=19&mid=1019)	Zambia, Zimbabwe	Conceptual	2018
a_W_Ec_21	Liuwa Plains-Mussuma TFCA	Crucial for the second largest wildebeest migration in the world, first agreements to protect this corridor were made in 2003, but the formal MoU for this TFCA is currently in preparation. (http://www.peaceparks.org/tfca.php?pid=19&mid=1020)	Zambia, Angola	Conceptual	2018

(Table 10 continued)

a_W_Ec_22	Barotse Floodplains	Vast floodplains with high importance for recession agriculture and wetland habitats. RAMSAR site.	Zambia	Partial	Present
a_W_Ec_23	Mosi-Oa-Tunya National Park (Victoria Falls)	National park around the famous Victoria falls. Most important tourist attraction in the ZRB	Zambia	Partial	Present
a_W_Ec_24	Batoka Gorge	Gorge between Victoria falls and lake Kariba, world renowned location for whitewater rafting	Zimbabwe	Partial	Present

Table 11 – Selected actions for the Energy sector (ZRB).

Id	**Title**	**Description**	**Country**	**Status**	**Expected timing**
a_E_1	Victoria Falls	Run of the river hydropower plant.	Zambia	Existing	Completed
a_E_2	Kariba	Dam and power plant	Zambia/ Zimbabwe	Existing	Completed
a_E_3	Ithezi Thezi	Dam and power plant	Zambia	Existing	Completed
a_E_4	Kafue Gorge Upper	Dam and power plant	Zambia	Existing	Completed
a_E_5	Cahora Bassa	Dam and power plant	Mozambique	Existing	Completed
a_E_6	Kafue Gorge Lower	New dam and power plant	Zambia	Under construction	2019
a_E_7	Batoka	New dam and power plant	Zambia/ Zimbabwe	under environmental evaluation	2026
a_E_8	Devil's Gorge	New dam and power plant	Zambia/ Zimbabwe	proposal	2029
a_E_9	Cahora Bassa northern expansion	New power plant with 3 Francis Turbines and	Mozambique	feasibility study	2026
a_E_10	Mphanda Nkuwa	New dam and power plant	Mozambique	Approved	2026
a_E_11	Boroma	New dam and power plant	Mozambique	proposal	Not Available (NA)
a_E_12	Lupata	New dam and power plant	Mozambique	proposal	NA
a_E_13	Mupata Gorge	New dam and power plant	Zambia/ Zimbabwe	proposal	NA
a_E_14	Redesign the operation considering more coordination/synchronization	Redesign the operation considering more coordination/synchronization	All Zambezi	proposal	NA

Table 12 – Selected actions for the Food sector (ZRB).

Id	Title and Description	Country	Status	Expected timing
a_F_1	Land currently equipped for irrigation in subbasin 12100	Malawi	Present	Present
a_F_2	Land currently equipped for irrigation in subbasin 12221	Malawi	Present	Present
a_F_3	Land currently equipped for irrigation in subbasin 12223	Malawi	Present	Present
a_F_4	Land currently equipped for irrigation in subbasin 12224	Malawi	Present	Present
a_F_5	Land currently equipped for irrigation in subbasin 12226	Malawi	Present	Present
a_F_6	Land currently equipped for irrigation in subbasin 12227	Malawi/Tanzania	Present	Present
a_F_7	Land currently equipped for irrigation in subbasin 12228	Malawi/Tanzania	Present	Present
a_F_8	Land currently equipped for irrigation in subbasin 12231	Mozambique	Present	Present
a_F_9	Land currently equipped for irrigation in subbasin 12232	Mozambique/Zim-babwe	Present	Present
a_F_10	Land currently equipped for irrigation in subbasin 12234	Mozambiqe	Present	Present
a_F_11	Land currently equipped for irrigation in subbasin 12235	Mozambiqe	Present	Present
a_F_12	Land currently equipped for irrigation in subbasin 12237	Mozambiqe	Present	Present
a_F_13	Land currently equipped for irrigation in subbasin 12238	Zimbabwe	Present	Present
a_F_14	Land currently equipped for irrigation in subbasin 12242	Zambia	Present	Present
a_F_15	Land currently equipped for irrigation in subbasin 12246	Zambia	Present	Present
a_F_16	Land currently equipped for irrigation in subbasin 12250	Zambia	Present	Present
a_F_17	Land currently equipped for irrigation in subbasin 12261	Zambia	Present	Present
a_F_18	Land currently equipped for irrigation in subbasin 12269	Zambia	Present	Present
a_F_19	Land currently equipped for irrigation in subbasin 12272	Zimbabwe	Present	Present
a_F_20	Land currently equipped for irrigation in subbasin 12277	Zambia	Present	Present
a_F_21	Land currently equipped for irrigation in subbasin 12278	Zambia	Present	Present
a_F_22	Land currently equipped for irrigation in subbasin 12279	Zambia/Zimbabwe	Present	Present
a_F_23	Land currently equipped for irrigation in subbasin 12281	Namibia	Present	Present
a_F_24	Land currently equipped for irrigation in subbasin 12291	Namibia/Zambia	Present	Present
a_F_25	Land currently equipped for irrigation in subbasin 12292	Angola	Present	Present

(Table 12 continued)

a_F_26	Land currently equipped for irrigation in subbasin 12293	Angola	Present	Present
a_F_27	Land currently equipped for irrigation in subbasin 12296	Zambia	Present	Present
a_F_28	Land currently equipped for irrigation in subbasin 12297	Angola	Present	Present
a_F_29	Land planned to be equipped for irrigation in subbasin 12210	Mozambique	Planned	NA
a_F_30	Land planned to be equipped for irrigation in subbasin 12221	Malawi/Mozambiqe	Planned	2031
a_F_31	Land planned to be equipped for irrigation in subbasin 12223	Malawi	Planned	NA
a_F_32	Land planned to be equipped for irrigation in subbasin 12224	Malawi	Planned	NA
a_F_33	Land planned to be equipped for irrigatio in subbasin 12227	Malawi	Planned	2022
a_F_34	Land planned to be equipped for irrigation in subbasin 12228	Malawi/Tanzania	Planned	2022
a_F_35	Land planned to be equipped for irrigation in subbasin 12229	Malawi	Planned	2022
a_F_36	Land planned to be equipped for irrigation in subbasin 12232	Mozambique/Zimbabwe	Planned	2018
a_F_37	Land planned to be equipped for irrigation in subbasin 12234	Mozambique	Planned	NA
a_F_38	Land planned to be equipped for irrigation in subbasin 12235	Mozambique	Planned	NA
a_F_39	Land planned to be equipped for irrigation in subbasin 12237	Mozambique/Zimbabwe	Planned	NA
a_F_40	Land planned to be equipped for irrigation in subbasin 12238	Zimbabwe	Planned	NA
a_F_41	Land planned to be equipped for irrigation in subbasin 12242	Zambia	Planned	2018
a_F_42	Land planned to be equipped for irrigation in subbasin 12248	Zambia	Planned	NA
a_F_43	Land planned to be equipped for irrigation in subbasin 12249	Zambia	Planned	2019
a_F_44	Land planned to be equipped for irrigation in subbasin 12250	Zambia/Zimbabwe	Planned	2019
a_F_45	Land planned to be equipped for irrigation in subbasin 12261	Zambia	Planned	NA
a_F_46	Land planned to be equipped for irrigation in subbasin 12271	Zambia	Planned	2019
a_F_47	Land planned to be equipped for irrigation in subbasin 12274	Zimbabwe	Planned	NA
a_F_48	Land planned to be equipped for irrigation in subbasin 12275	Zambia	Planned	2019
a_F_49	Land planned to be equipped for irrigation in subbasin 12277	Zambia/Zimbabwe	Planned	2019
a_F_50	Land planned to be equipped for irrigation in subbasin 12278	Zimbabwe	Planned	NA
a_F_51	Land planned to be equipped for irrigation in subbasin 12279	Zambia/Zimbabwe	Planned	NA

(Table 12 continued)

a_F_52	Land planned to be equipped for irrigation in subbasin 12281	Namibia	Planned	NA
a_F_53	Land planned to be equipped for irrigation in subbasin 12291	Zambia	Planned	NA
a_F_54	Land planned to be equipped for irrigation in subbasin 12292	Angola	Planned	NA
a_F_55	Land planned to be equipped for irrigation in subbasin 12293	Angola	Planned	NA
a_F_56	Land planned to be equipped for irrigation in subbasin 12296	Zambia	Planned	NA
a_F_57	Land planned to be equipped for irrigation in subbasin 12297	Angola	Planned	NA

Table 13 – Selected actions for the Socio-economic sector (ZRB).

Id	Title	Description	Country	Status	Expected timing
a_SE_1	Dangote Plant I	Cement Manufacturing Plant	Zambia	Operational	Present
a_SE_2	Dangote Plant II	Cement Manufacturing Plant	Zambia	Planned	NA
a_SE_3	Zambia Brewries	Beverage manufacturing plant	Zambia	Operational	Present
a_SE_4	Zambia Sugar	Sugar plantation	Zambia	Operational	Present
a_SE_5	Chambishi	Copper Mine	Zambia	Closed	
a_SE_6	Chambishi 2	Copper-cobalt mine	Zambia	Operational	2008
a_SE_7	Mopani- Mufulira	Copper Mine	Zambia	Operational	Present
a_SE_8	Mopani- Nkana	Copper-cobalt mine	Zambia	Operational	Present
a_SE_9	Konkola (KCM)	Copper Mine	Zambia	Operational	2010
a_SE_10	Nchanga Copper Mines	Copper-cobalt Mine	Zambia	Closed	
a_SE_11	The Nampundwe Mine	Pyrites Mine	Zambia	Operational	2007
a_SE_12	Kansanshi Mine	Copper Mine	Zambia	NA	2005
a_SE_13	Lumwana Mine	Copper Mine	Zambia	NA	NA
a_SE_14	Synclinorium	Copper Project	Zambia	Planned	2018
a_SE_15	Mwambashi	Copper Project	Zambia	Planned	2014
a_SE_16	Enterprise (Kawako)	Run-off Nickel Mine	Zambia	Planned	2016
a_SE_17	Chirundu	Uranium Project	Zambia	Planned	NA
a_SE_19	Mkushi	Copper-Gold Project	Zambia	Planned - feasibility	NA
a_SE_20	Mulungwa	Coal Project	Zambia	Planned - feasibility	NA
a_SE_21	Chipirinyuma	Zinc Project	Zambia	Planned - feasibility	NA
a_SE_22	Kafue JV	Copper Project	Zambia	Planned - prefeasibility	NA
a_SE_23	Benga	Run-off Coal Mine	Mozambique	Operational	2011
a_SE_24	Mavuzi	Unranium, Copper, Nickel Mine	Mozambique	Operational	Present

(Table 13 continued)

a_SE_25	Chirodzi	Coal Mine	Mozambique	Operational	Present
a_SE_26	Minas Moatize	Coal Project	Mozambique	Operational	Present
a_SE_27	Zambeze	Coal Mine	Mozambique	Planned - feasibility	NA
a_SE_28	Revuboe	Metallurigal Coal Mine	Mozambique	Operational	Present
a_SE_29	Ncondezi	Coal Mine	Mozambique	Operational	Present

4.2 ACTIONS FOR THE OMO-TURKANA BASIN

The NSL meeting took place in Addis Ababa, Ethiopia on February 15 and 16, 2018 for the OTB (see Section 3.1.2 for the list of SHs involved). All the SHs were involved in the participatory process described in section 2.3 and provided important feedbacks and contributions. The actions suggested by the SHs related to the WEF Nexus in the OTB, subsequently elaborated by project partners, are reported in the following tables.

Table 14 – Selected actions for the Water and Ecosystem Sector (OTB).

Id	Title	Description	Country	Status	Expected timing
a_W_Ec_1	Omo National Park	Openland and flooded grassland depending on water from the Omo	Ethiopia	Existing	Since 1959
a_W_Ec_2	Lower Omo Trans Frontier Conservation Area	Floodplains depending on flow variation from the Omo	Ethiopia	Proposed	NA
a_W_Ec_3	Lake Turkana and Omo delta Trans Frontier Conservation Area	Wetland depending on sediment input and flow variation from the Omo	Ethiopia	Proposed	NA
a_W_Ec_4	Lake Turkana Trans Frontier Conservation Area	Desert lake depending on flow variation from the Omo	Kenya	Proposed	NA
a_W_Ec_5	Sediment management	Sediment transport across dams by diversion of turbid waters or flushing of sediment		Proposal	NA
a_W_Ec_6	Avoided deforestation and forest restoration	Incentives and enforcement of sustainable forest uses		Proposal	NA
a_W_Ec_7	Degazetting of protected areas for Kuraz sugar development	Parts of Omo National Park, Tama Wildlife Reserve and Mago National Park will lose their protection status due to plantation of sugar cane with channel irrigation	Ethiopia	in process	ongoing

Table 15 – Selected actions for the Energy sector (OTB).

Id	Title	Description	Country	Status	Expected timing
a_E_1	Gibe I	Dam and power plant	Ethiopia	existing	Completed
a_E_2	Gibe II	Power plant	Ethiopia	existing	Completed
a_E_3	Gibe III	Dam and power plant	Ethiopia	existing	Completed
a_E_4	Koysha	Dam and power plant	Ethiopia	under construction	2021
a_E_5	Re-operation of dam management	Redesign the operation considering more coordination/synchronization	Ethiopia	proposal	NA
a_E_6	Forced releases	Forced releases to reproduce the natural pattern of flood pulses	Ethiopia	proposal	NA

Table 16 – Selected actions for the Food sector (OTB).

Id	Title and Description	Country	Status	Expected timing
a_F_1	Land currently equipped for irrigation in subbasin 11542	Kenya	Present	Present
a_F_2	Land currently equipped for irrigation in subbasin 11543	Kenya	Present	Present
a_F_3	Land currently equipped for irrigation in subbasin 11544	Ethiopia	Present	Present
a_F_4	Land currently equipped for irrigation in subbasin 11545	Ethiopia	Present	Present
a_F_5	Land currently equipped for irrigation in subbasin 11547	Ethiopia	Present	Present
a_F_6	Land currently equipped for irrigation in subbasin 11548	Ethiopia	Present	Present
a_F_7	Land planned to be equipped for irrigation in subbasin 11542	Kenya	Under construction	NA
a_F_8	Land planned to be equipped for irrigation in subbasin 11544	Kenya	Under construction	NA
a_F_9	Land with potential for irrigation in subbasin 11545	Ethiopia	Potential	NA
a_F_10	Land with potential for irrigation in subbasin 11546	Ethiopia	Potential	NA
a_F_11	Land with potential for irrigation in subbasin 11547	Ethiopia	Potential	NA
a_F_12	Land with potential for irrigation in subbasin 11548	Ethiopia	Potential	NA
a_F_13	Land with potential for irrigation in subbasin 11549	Ethiopia	Potential	NA

Table 17 – Selected actions for the Socio-Economic sector (OTB).

Id	Title	Description	Country
a_SE_1	Improve road networks		Kenya
a_SE_2	Market development for livestock		Ethiopia
a_SE_3	Two new bridges over River Omo	Where: Omorate (region in south Omo basin)	Ethiopia
a_SE_4	Rural electrification program		Ethiopia
a_SE_5	Roads infrastructure development Railway line development project	Side effects on tourism (+) and local communities (+/-)	Ethiopia
a_SE_6	Employment development: Organise Communities to get benefit from Eco-tourism	Cooperative creation to provide touristic services	Ethiopia
a_SE_7	Mining activity		Kenya, Ethiopia
a_SE_8	Existing and planned manufacturing projects		Kenya, Ethiopia
a_SE_9	Highways		Kenya, Ethiopia
a_SE_10	Major housing development		Kenya, Ethiopia
a_SE_11	Railway		Kenya, Ethiopia

4.3 FUTURE SCENARIO

The future scenario we consider is conceptually driven by a combination of Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs). Specifically, we focus on a most likely "middle of the road" future (SSP 2 with RCP 4.5). This will be expanded in task T5.3 to include additional SSP/RCP combinations to explore future uncertainties and assess the robustness of the designed pathways (task T5.4).

It is worth mentioning that the scenario described here is composed of a subset of the future scenarios and drivers illustrated in Deliverable D2.2, which are selected as informative for the DAF model design of the efficient pathways (Task 5.2) with respect to the selected design indicators discussed in section 3.3. This motivates, for example, the focus on projected irrigation demands according to the food design indicators formulated in eqs. (4)-(7) rather than on projected food demand, or the need of transforming in the case of the ZRB the projected energy demands at the national scale into projected target production for each hydropower plant according to the energy design indicator formulated in eq. (2).

4.3.1 Demographic projections

The demographic projections of this chapter are based on the assumptions surrounding the reference future scenario of this model, the SSP2 scenario. The main feature of SSP2, i.e. the second shared socioeconomic pathway, is that it is following a pattern of action that is consistent with the experience of the last century. Moreover, four aspects of the demographic trends are explored: the population growth and the future water, energy and food consumption of the eight riparian countries. In particular, population growth has been forecasted in different levels including projections per country, per major and non-major city and per subbasin with and without urbanization. Also, population growth affects significantly the projections of the other three variables in this path. Lastly, the time horizon of the projections is the period 2015-2060 for ZRB and 2018-2100 for OTB.

Zambezi River Basin

In terms of population growth forecasting, the annual population growth rates of each country are collected by UN (2017) calculations, the main advantage of which is the 5-year period time-slice of the estimations, making, so, the projections more accurate than an average growth rate. Also, these growth rates are in alignment with the SSP2 assuming moderate values for the factors related to population growth, such as international migration, mortality and fertility rates. The results show that the population of Tanzania is expected to more than double until 2060 reaching 150 million inhabitants, while the population of small countries such as Botswana and Namibia will remain low. In alignment with Deliverable 2.1, it is projected the population of the major urban centers, i.e. centers with at least 100,000 inhabitants, located within the ZRB area assuming homogeneous distribution within the countries and hence, using the population growth rates of each country. After, we also considered non-major cities, which are becoming major until the end of the period. The majority of major and potentially major urban centers characterized by rapid growth is lying in Zambia and Zimbabwe.

However, what this study is interested into is the forecasting at a subbasin level. Hence, using the map of ZRB per subbasin presented in Deliverable 2.1, we categorized the subbasins according to the country they belong to. However, some subbasins are lying into two or even three countries, creating so, an extra burden in choosing the appropriate growth rate. In this case, it was selected the rate of the country having the greatest share in the controversial subbasin. A potential harm of this approach is to weight unequally the impact of one country over the other. However, the benefits outweigh the costs of this approach, since in total unequal weights occur for the advantage of all the countries due to the big amount of subbasins located in more than one country. Moreover, the fact that the growth rates are changing every 5 years means that any other approach would be even more complicated without a significant benefit.

Lastly, we considered internal migration represented by urbanization using estimations provided by UN (2018). In order to incorporate the urbanization rates into the projections, we divided the 67 subbasins into rural and urban areas using urban mapping projections by SEDAC (2018). However, one challenge of this stage was the fact that some subbasins were located in two to three countries with one rural and one urban side. In this case, no change is attributed, since the change in population, which migrated from the rural area equalizes the change in population in the urban area, as the urbanization rates of most of the African countries of interest are lying in a range between 3% and 4%. Lastly, since the urbanization rates estimated by the UN (2018) are projected until 2050, it is assumed that the urbanisation rates in the period 2050 to 2060 are as high as their corresponding values in the period 2045 to 2050. The final results showed that the total population living within ZRB under internal migration assumptions is 3 million greater than without those assumptions reaching 99 million people by 2060.

Water consumption in the domestic sector is the second variable projected in this section per country and subbasin within the ZRB for the period from 2016 to 2060. Using the data from Deliverable 2.1. for the annual water use per capita for each country within the ZRB and the demographic projections per country's share in ZRB and per subbasin with urbanization assumptions, we computed the projected water consumption by private households. In the event of a subbasin being shared by two or three countries with different water consumption rate, we computed the average consumption of those countries, and then, we multiplied it with the population of the subbasin. Also, it is assumed that the annual water needs per capita remain stable across time. The outcomes of this forecasting show that considering only the demographic growth of the riparian countries the total water consumption within ZRB will increase dramatically reaching 1,8 billion m^3 by 2060, while now it is approximately 0.8 billion m^3. Moreover, households in Zambia and Zimbabwe consume more water than Malawi and Mozambique, although they are not dominating demographically within the basin.

Energy consumption is the third projected variable. As in the previous section, data from Deliverable 2.1. regarding the energy consumption per capita of each country of the ZRB are used to estimate the annual energy consumption per country's share within the ZRB and per subbasin (under urbanization assumptions). It is assumed that the annual energy needs per capita remain stable across time in each country. Energy consumption refers to energy usage from petroleum and biomass and waste electricity (the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source). In case of a subbasin being shared by two or three countries with different energy consumption rate, we computed the average consumption of those countries, and then, we multiplied it with the population of the subbasin. By 2060 the total energy consumption within ZRB is expected to reach 207 TWh, which is more than twice as much as it is today. Zambians living within the ZRB are expected to consume in total more energy than inhabitants of Zimbabwe and Mozambique, not because of their demographic advantage, but because of their high energy use per capita.

In alignment with the previous two sections in order to estimate the food consumption in the long-run, data for the daily calorie, protein and fat intake needs of an individual for each country are used from FAO (2018). After, we computed the annual food consumption per person, which we multiplied with the population projections per subbasin and per country estimated in the previous chapter including urbanization. At this point, it is assumed that the average food consumption of each person of each country remains stable. The results show that Malawi, Zambia and Mozambique have the greatest consumptions, with Malawi being the leader. In terms of total calorie intakes, the total expected consumption in ZRB in 2060 will reach 66,4 trillion calories, with Malawi consuming 35% of them. In terms of protein and fat intakes, the total consumption will reach 1,7 Gigatonnes and 1,3 Gigatonnes respectively, with Malawi consuming 32% and 26% in each case.

Omo-Turkana Basin

In terms of population growth projections, the annual population growth rates of each country are determined by UN (2017) calculations, the main advantage of which is the 5-year period time-slice of the estimations, making, so, the projections more accurate than an average growth rate. Also, these growth rates are in alignment with the SSP2 assuming moderate values for the factors related to population growth, such as international migration, mortality and fertility rates. The results show that the population of Ethiopia is expected to increase dramatically reaching 210 million people by the end of century, while the other three countries are increasing up to the range of 89 and 147 million people. In alignment with Deliverable 2.1, it is projected the population of the major urban centers, i.e. centers with at least 100,000 inhabitants, located within the OTB area assuming homogeneous distribution within the countries and hence, using the population growth rates of each country. After, we also considered non-major cities, which are becoming major until the end of the period. Both major (Jimma) and potentially major (Sodo) cities are lying in Ethiopia.

Nonetheless, this study is interested into forecasting at a subbasin level. Hence, using the map of OTB per subbasin presented in Deliverable 2.1, we categorized the subbasins according to the country they belong to. However, some subbasins are lying into two or even three countries, creating so, an extra burden in choosing the appropriate growth rate. In this case, it was selected the rate of the country having the greatest share in the controversial subbasin. A potential harm of this approach is to weight unequally the impact of one country over the other. However, the benefits outweigh the costs of this approach, since the rates do not diverse significantly between them. Moreover, the fact that the growth rates are changing every 5 years means that any other approach would be even more complicated without a significant benefit.

Lastly, we considered internal migration represented by urbanization using estimations provided by UN (2018). In order to incorporate the urbanization rates into the projections, we divided the 9 subbasins into rural and urban areas using urban mapping projections by SEDAC (2018). According to SEDAC (2018), only Ethiopia seems to have urban areas in this case with Kenya, Sudan and Uganda being mainly rural in the areas of interest. Hence, in order to get more accurate results, the expected population trends for the former countries will decrease by 3% to 4,2%, i.e. as much as the urbanization rate in their countries, while the expected population in areas located in Ethiopia, will increase from 3% to 4,6% annually. Lastly, since the urbanization rates estimated by the United Nations (2018) are projected until 2050, it is assumed that the urbanisation rates in the period 2050 to 2100 are as high as their corresponding values in the period 2045 to 2050. The final results showed 500 thousand more people will inhabit within OTB by the end of the century due to internal migration reaching a total of 21.9 million.

Water consumption in the domestic sector is the second variable projected in this section per country and subbasin within the OTB for the period from 2018 to 2100. Using the data from Deliverable 2.1. for the annual water use per capita for each country within the OTB and the demographic projections per country's share in OTB and per subbasin with urbanization assumptions, we computed the projected water consumption by private households. It is assumed that the annual water needs per capita remain stable across time in each country. In case of a subbasin being shared by two or three countries with different water consumption rate, we selected the rate of the country having the greatest share in the controversial subbasin. The outcomes of this forecasting show that considering only the demographic growth of the riparian countries the total water consumption within OTB will increase dramatically reaching 238 million m^3 by the end of the century, while now it is approximately 120 million m^3. As expected, Ethiopian households consume more water than Kenyan, due to their demographic dominance within the basin, constituting 88 percent of the population within the basin.

Energy consumption is the third projected variable. As in the previous section, the energy consumption per capita in the domestic sector for each country of the OTB computed in Deliverable 2.1. is used to estimate the annual energy consumption per country's share within the OTB and per subbasin for the domestic sector under urbanization assumptions. It is assumed that the annual energy needs per capita remain stable across time in each country. Energy consumption refers to energy usage from petroleum and biomass and waste electricity (the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source). In case of a subbasin being shared by two or three countries with different energy consumption rate, we selected the rate of the country having the greatest share in the controversial subbasin. By 2100 the total energy consumption within OTB is expected to reach 73,845 GWh, which is twice as much as it is today. As expected, Ethiopians living within the OTB are expected to consume in total more energy than Kenyans, due to their demographic advantage.

In alignment with the previous two sections in order to estimate the food consumption in the long-run, data for the daily calorie, protein and fat intake needs of an individual for each country are used from FAO (2018). After, we computed the annual food consumption per person, which we multiplied with the population projections per subbasin and per country estimated in the previous chapter including urbanization. At this point, it is assumed that the average food consumption of each person of each country remains stable. In terms of total calorie intakes, the total expected consumption in OTB in 2100 will reach 15,6 trillion calories, with Ethiopia consuming 88% of them. In terms of protein and fat intakes, the total consumption will reach 450 Megatonnes and 192 Megatonnes respectively, with Ethiopia consuming 87% and 77% in each case.

4.3.2 Climate projections

The climate scenarios developed to date are based on a three phase approach (outlined in more detail in Deliverable D2.2):

1. we analyse an ensemble of 22 Regional Climate Model (RCM) and General Circulation Model (GCM) pairs. Using the ensemble, we develop a time series of Factors of Change (FC) by comparing the changes in climate variables (e.g. precipitation, temperature) for the historical control period (1976-2005) and projections of 30 years intervals of future climate under the RCP 4.5 forcing.
2. we fit a stochastic gridded weather generator (Peleg et al., 2017) using the present observed climate for each of the study basins, and generate an ensemble of plausible gridded present climate sequences at high spatial and temporal resolution. Simulations are generated for the following meteorological variables – precipitation, near surface air temperature, solar radiation, wind speed, and relative humidity.
3. we apply the FCs to the weather generator simulations to produce a set of future climate forcing grids for the DAFNE modelling chain using the methodology described in Peleg et al. (2019).

For the ZRB we have produced a gridded time series at 8 km horizontal spatial resolution and hourly temporal resolution, for the period 2020-2099 using different FCs for each of the 7 decades based on the RCP 4.5 ensemble (see Figure 8 and Figure 9).

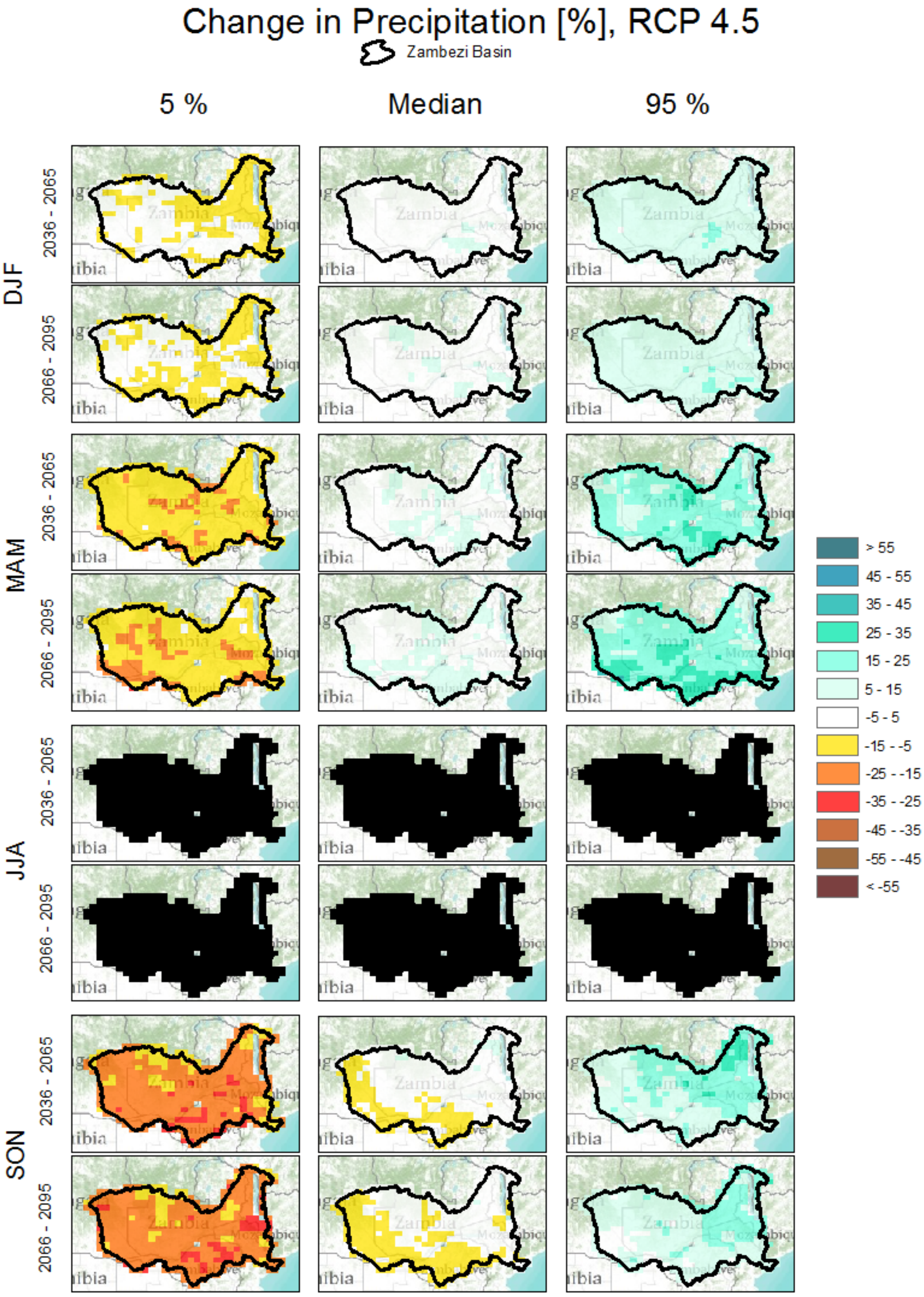

Figure 8 – Expected percentage change in seasonal precipitation amount in the ZRB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

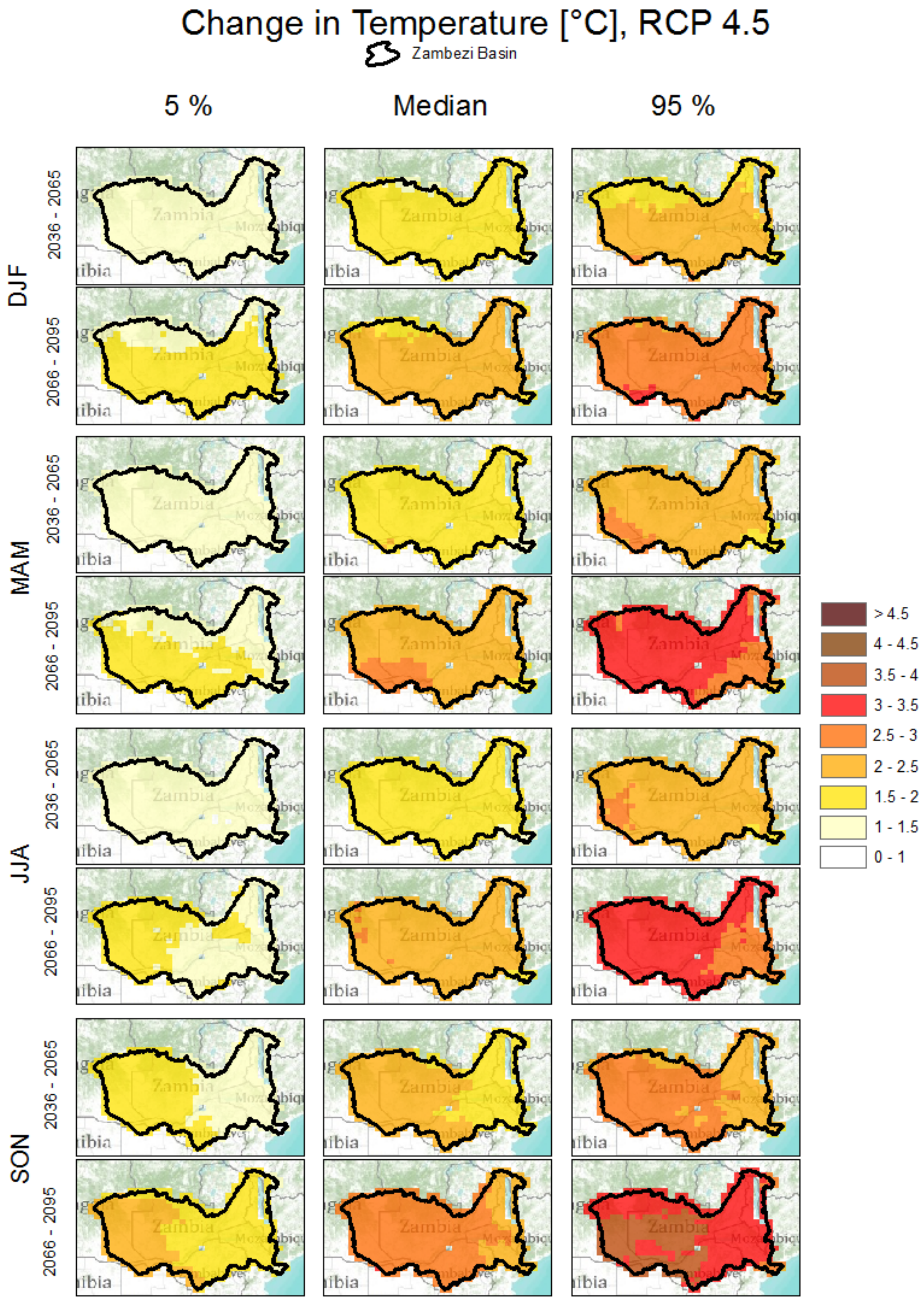

Figure 9 – Expected percentage change in seasonal average temperature in the ZRB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

For the OTB we have produced a climate scenario which consists of precipitation at 269 locations within the OTB (virtual stations used by the Topkapi simulations already produced in the past months) and temperature at 69 locations within the OTB (again virtual stations), both at daily resolution for the period 2020-2099 using different FCs for each of the 7 decades based on the RCP 4.5 ensemble (see Figure 10 and Figure 11). As detailed in Deliverable D2.2, we are now completing the generation of an equivalent dataset of climate projections as in the ZRB (gridded time series at hourly resolution).

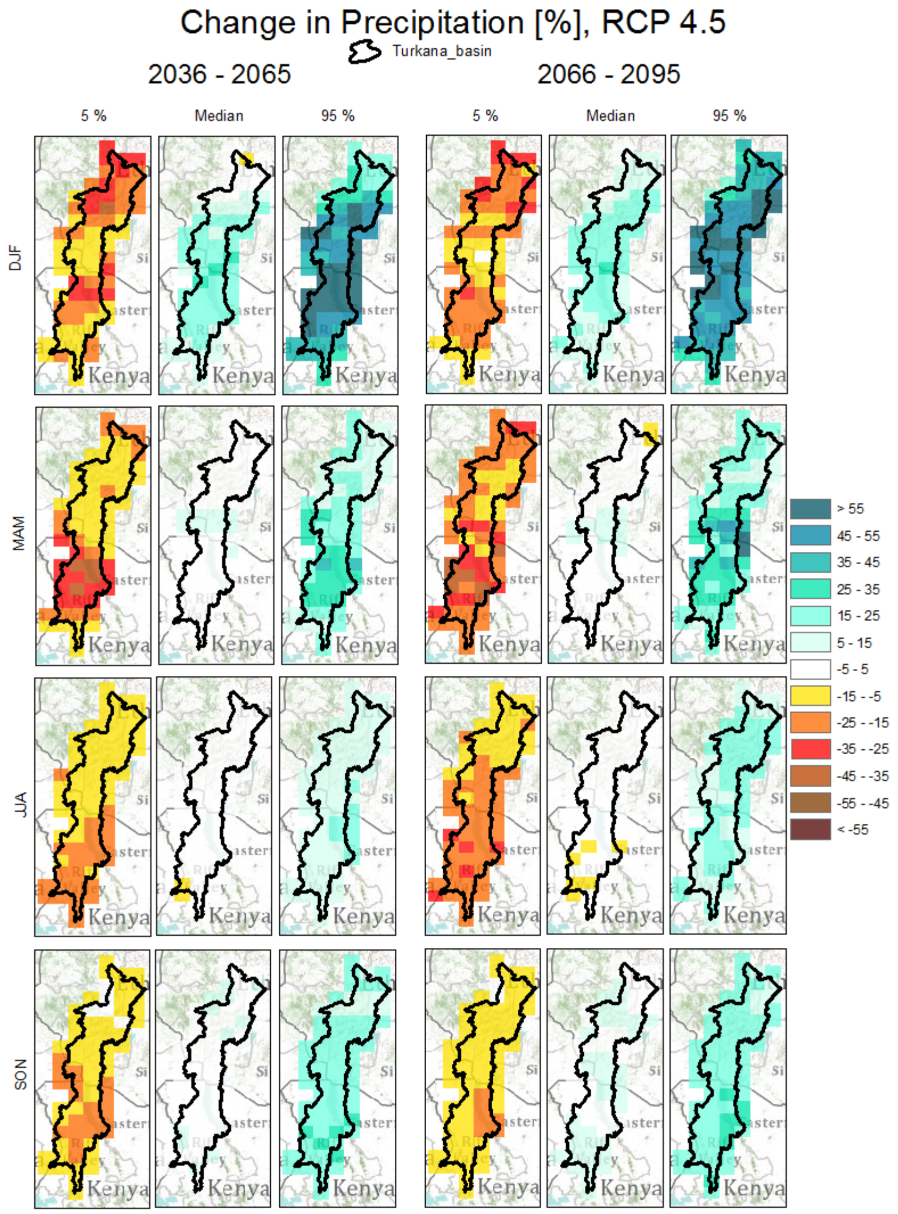

Figure 10 – Expected percentage change in seasonal precipitation amount in the OTB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

4.3.3 Energy demands projections

Zambezi River Basin

In the ZRB case study, the design indicator representing the energy sector is formulated as yearly average hydropower production deficit with respect to an energy demand (i.e., target level of hydropower production) disaggregated at the power plant level (refer to eq. 2 in section 3.3.1). The projections of future energy demand provided at the national scale and presented in the section 4.3.1 must be thus disaggregated at the single hydropower plant level to numerically quantify this energy indicator during the efficient pathways design phase under future scenario.

In order to do so, the national projections of future energy demand are given as input to the Osemosys energy model, a dynamic, bottom-up, multi-year energy system model applying linear optimization techniques to determine the optimal investment strategy and production mix of technologies (including hydropower) and fuels required to satisfy an exogenously defined energy demand at the power pool scale (Howells 2011).

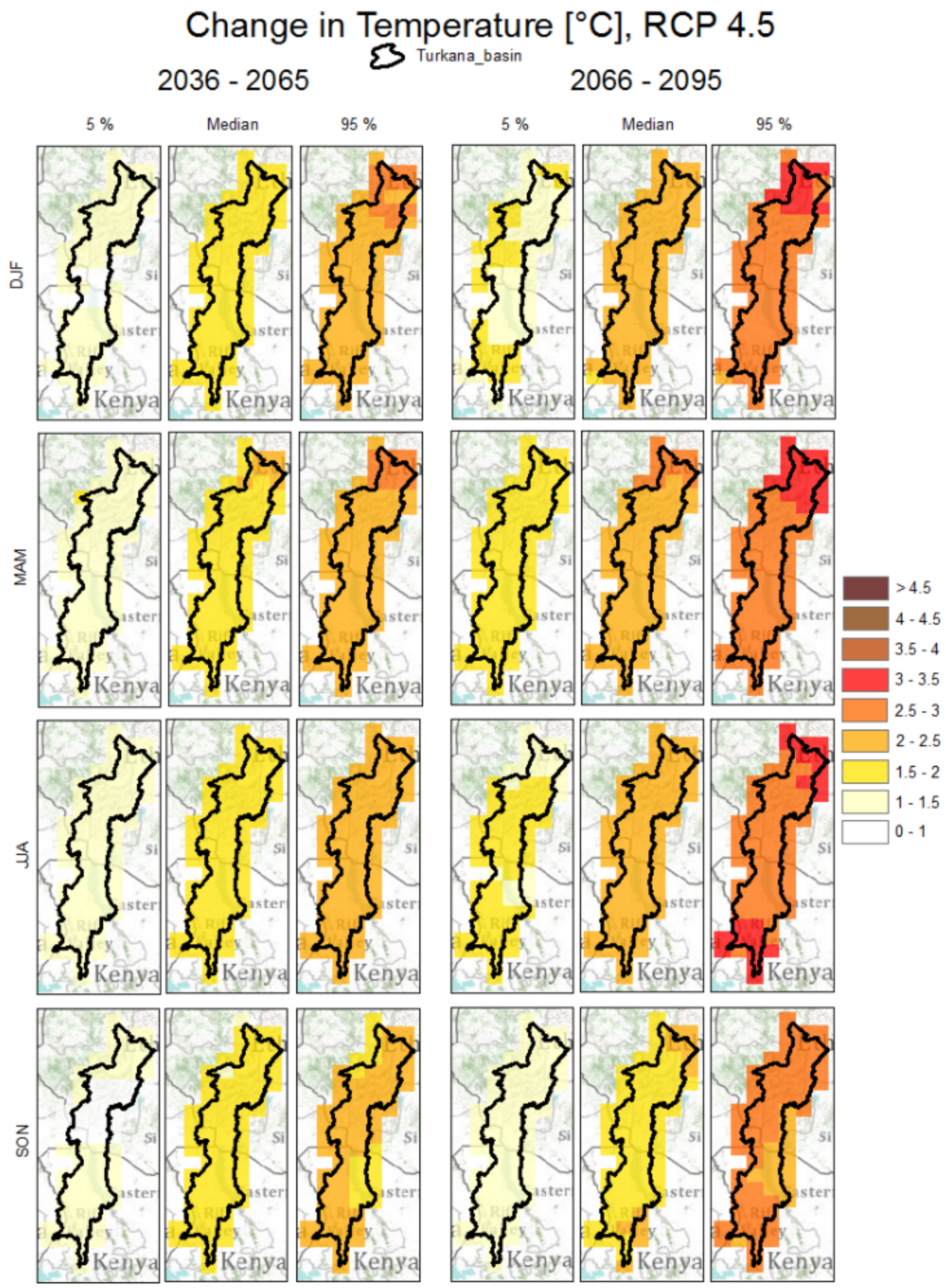

Figure 11 – Expected percentage change in seasonal average temperature in the OTB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

In order to do so, the national projections of future energy demand are given as input to the Osemosys energy model, a dynamic, bottom-up, multi-year energy system model applying linear optimization techniques to determine the optimal investment strategy and production mix of technologies (including hydropower) and fuels required to satisfy an exogenously defined energy demand at the power pool scale (Howells 2011).

Osemosys model was employed to develop an open-source model of the entire African electricity system, called TEMBA (Taliotis 2016). TEMBA includes both the Southern and Eastern African Power Pool (SAPP and EAPP respectively), to which the hydropower plants in the ZRB and OTB are connected. To estimate the future hydropower demands for each power plant in the ZRB, we run the SAPP power pool optimization over the 2015-2060 future scenario. The resulting optimal production mix is designed to always satisfy the energy demand at the power pool level. The simulated production at the power plant scale therefore represents a good estimate of the allocated demand of each power plant in the ZRB and can be thus employed during the efficient pathways design to calculate the corresponding energy indicator. It must be noted that, in order to run the Osemosys model over the entire SAPP, projections of energy demand for all the countries belonging to the power pool must be generated. To this end, the same methodological procedure for estimating future energy demands of the countries within the ZRB has been applied to all the other nations belonging to the SAPP (i.e., DRC, Lesotho, South Africa, Swatziland).

In this section we analyze the future energy demand trends at the national and power plant scale for the ZRB. Two illustrative examples are conducted in order to present and discuss hydropower demand projections at the power plant scale under two alternative system configurations: existing (4 major existing hydropower plants) and fully developed future (4 existing + 4 planned hydropower plants) system configurations.

Figure 12 shows the projections of future yearly energy consumption [GWh] at the national scale for all the countries belonging to the SAPP. As can be observed, all the nations but South Africa experience a slightly exponential increase in their energy demands in the future. On average, Angola (dark blue), Tanzania (pink) and Zambia (light blue) are characterized by the highest rise in their energy consumption rates, equal to a +2% increase per year. The only exception is made for South Africa (dark red), whose future energy consumption projection is characterized by a downward parabolic behavior. In particular, an increase in its energy demand is estimated up to 2050, driven by a large population growth. After this breakpoint, its population will start decreasing, causing energy consumption rates to diminish consequently. Yet, the South African future energy demand is expected to rise by +0.3% on average across the entire time horizon.

Figure 13 displays the energy demand projections at the SAPP scale, where it is highlighted the share of each nation to the total demand of the power pool on an yearly time-step. As can be observed, South Africa (dark red) is responsible for the largest energy consumption, covering about 70% of the SAPP future energy demand on average. Yet, its consumption share is likely to decrease from 77% in 2015 down to 62% in 2060 of the overall demand. Zambia (light blue) presents an opposite trend with respect to South Africa and is the second-largest energy consumer within the SAPP in the future. In particular, its energy demand share is likely to increase from 8% in 2015 to 16% in 2060 of the entire power pool consumption, covering about 12% of the SAPP future energy demand on average. As already discussed in Figure 12, the same increasing trend of energy consumption share forecasted in Zambia can be observed in all the other countries belonging to the SAPP, except for South Africa.

These future energy consumption data at the SAPP scale are then given as input to the Osemosys model in order to downscale them at the hydropower plant level and obtain the corresponding target production for each power plant in the ZRB. The first illustrative example that we conducted consists in running Osemosys under the existing system configuration of the ZRB, which comprises the four major existing water reservoirs and associated hydropower plants, namely Itezhi-Tezhi, Kafue Gorge Upper, Kariba and Cahora Bassa (Figure 14). Under this first specific system configuration, the electricity demand at the hydropower plant scale (i.e., target level of hydropower production) remains constant throughout the entire time horizon, regardless of the power plant considered. This is due to the fact that Osemosys does not take hydrological variability into account and calculates the target hydropower production at each power plant based on a time-invariant factor, which keeps constant throughout the 2015-2060 time period. We can observe that Cahora Bassa is associated to the highest target production, namely 14.5 TWh/yr, and is thus responsible for about 48% of the entire downscaled energy demand of all the hydropower plants within the ZRB. Kariba presents an energy demand of about 9.7 TWh/yr and covers 32% of the overall demand, whereas Kafue Gorge Upper must satisfy a target production of about 5.4 TWh/yr and is responsible for 18% of the total demand. In the end, Itezhi-Tezhi is associated to the lowest energy demand, namely 0.65 TWh/yr, and is thus responsible for the remaining 2% of the overall energy demand. Overall, the total target level of hydropower production the four existing hydropower plants within the ZRB are responsible for amounts to 30.2 TWh/yr. On average, this quantity corresponds to about 6% of the entire energy consumption projections at the SAPP scale and 22% of the total future energy demand of the eight countries belonging to the ZRB.

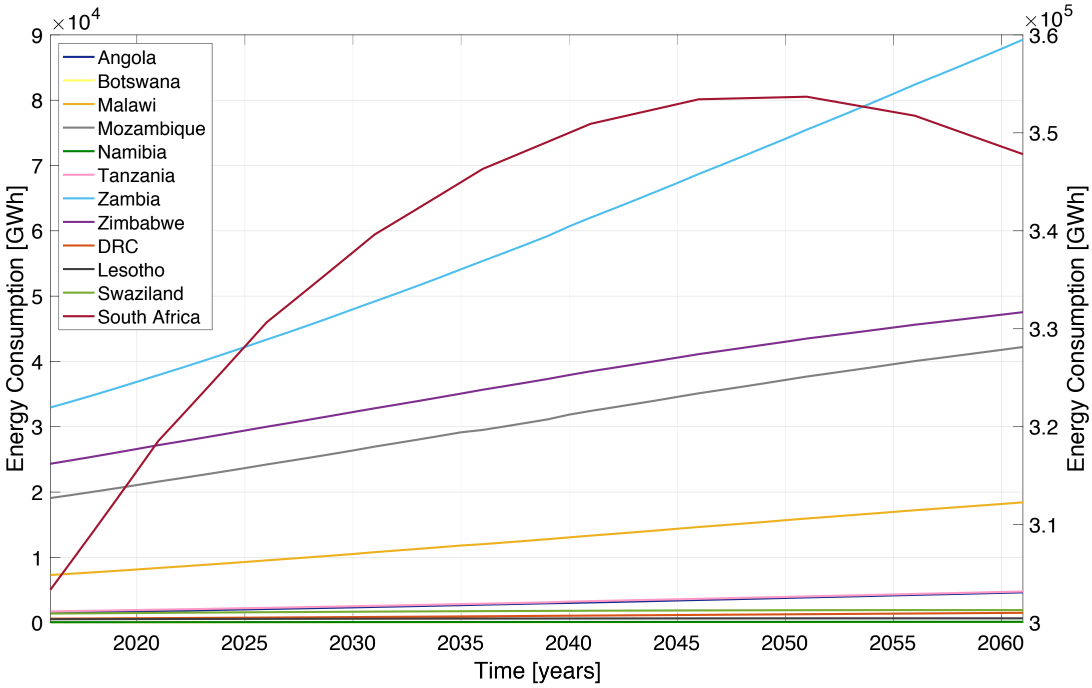

Figure 12 – Projections of future yearly energy consumption [GWh] at the national scale over the 2015-2060 time horizon for all the countries belonging to the Southern African Power Pool. Each color refers to a specific nation within the SAPP. Secondary y-axis refers to South Africa only, as its energy demand data are one order of magnitude bigger with respect to all the other countries.

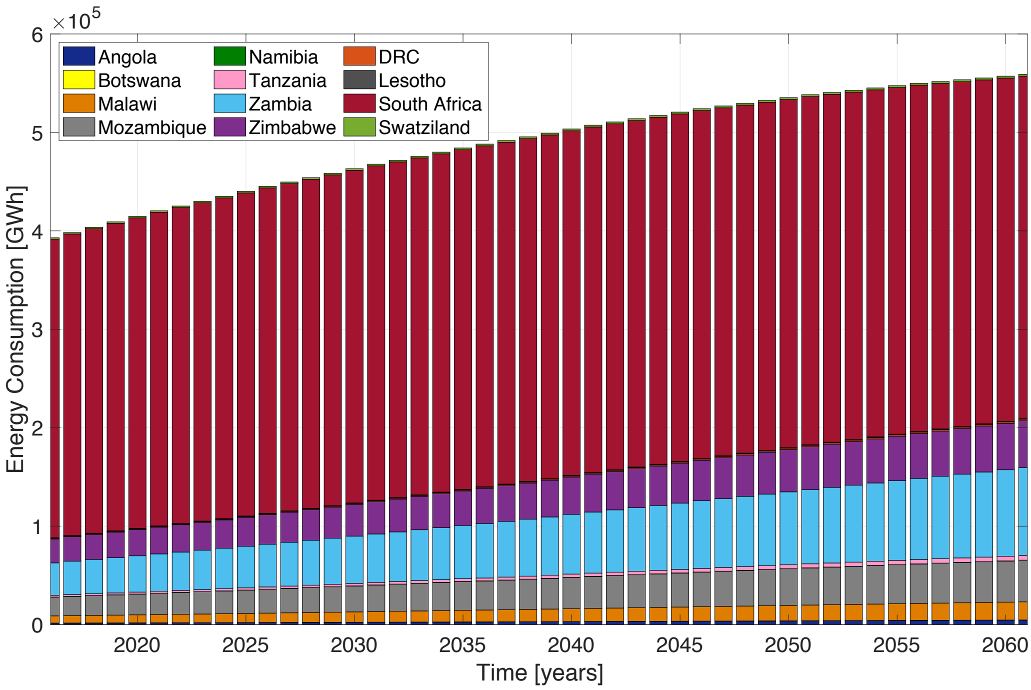

Figure 13 – Projections of future yearly energy consumption [GWh] over the 2015-2060 time horizon at the entire Southern African Power Pool scale. Each color refers to one specific nation’s contribution to the total energy consumption within the SAPP each year.

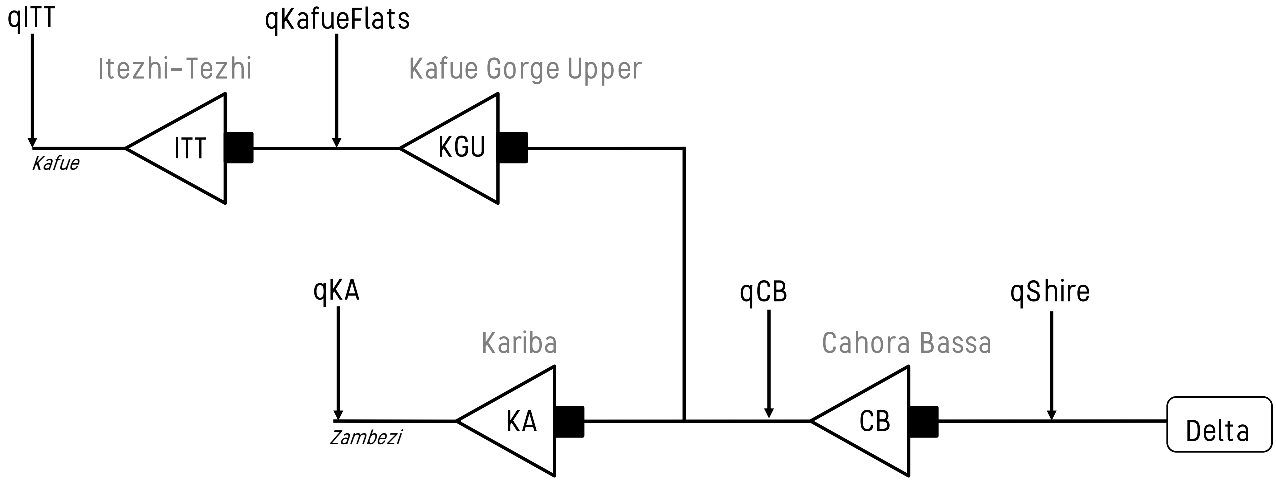

Figure 14 – Topologic scheme of the existing ZRB system configuration used in Osemosys, which comprises the four major existing water reservoirs (white triangles) and associated hydropower plants (black squares), namely Itezhi-Tezhi, Kafue Gorge Upper, Kariba and Cahora Bassa. Arrows indicate the five inflow points to the system, while the ZRB Delta is displayed as a white rectangle.

The second illustrative example that we conducted consists in running Osemosys under the fully developed future system configuration of the ZRB, which comprises the four major existing (i.e., Itezhi-Tezhi, Kafue Gorge Upper, Kariba, Cahora Bassa) and four planned (i.e., Kafue Gorge Lower, Batoka Gorge, Devil's Gorge, Mphanda Nkuwa) water reservoirs and associated hydro-power plants (Figure 15). Under this second specific system configuration, the electricity demand at the hydropower plant scale (i.e., target level of hydropower production) still remains constant throughout the entire time horizon, regardless of the power plant considered. As can be observed in Table 18, the four existing hydropower plants are characterized by the same target levels of hy-dropower production as in the previous example. Yet, their percentage contribution to the overall energy demand changes because, when adding four additional planned reservoirs in the system, the total target production increases consequently. In particular, the overall demand increases by +92%, going from 30.2 TWh/yr up to 58.1 TWh/yr, due to the almost +100% additional hydropower capacity installed. On average, a total energy demand of 58.1 TWh/yr at the power plant scale cor-responds to about 12% of the entire energy consumption projections at the SAPP scale and 42% of the total future energy demand of the eight countries belonging to the ZRB. When analysing the percentage contribution of each hydropower plant to the total target production, we can observe that Cahora Bassa and Kariba are still responsible for the largest share, with their 24.9 % and 16.7% respectively, as their nominal installed capacities are the highest within the ZRB. They are followed by Mphanda Nkuwa (15.6%) and Batoka Gorge (14.5%), which are characterized by the second largest installed capacities.

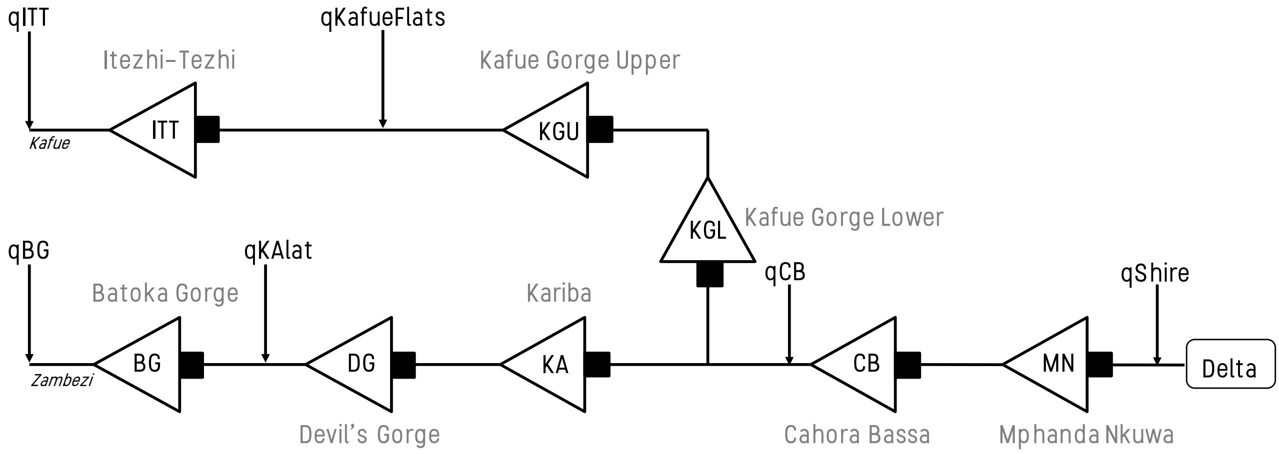

Figure 15 – Topologic scheme of the fully developed future ZRB system configuration used in Osemosys, which comprises the four existing (i.e., Itezhi-Tezhi, Kafue Gorge Upper, Kariba, Cahora Bassa) and four planned (i.e., Kafue Gorge Lower, Batoka Gorge, Devil's Gorge, Mphanda Nkuwa) water reservoirs (white triangles) and associated hydropower plants (black squares). Arrows indicate the five inflow points to the system, while the ZRB Delta is displayed as a white rectangle.

Table 18 – Target level of hydropower production [TWh/yr] calculated via Osemosys for each of the eight hydropower plants and their percentage contribution to the overall energy demand.

Hydropower plant	Target hydropower production [TWh/yr]	Share of total production within the ZRB [%]
Cahora Bassa	14.50	24.9 %
Kariba	9.70	16.7 %
Mphanda Nkuwa	9.10	15.6 %
Batoka Gorge	8.40	14.5 %
Devil's Gorge	6.30	10.9 %
Kafue Gorge Upper	5.40	9.3 %
Kafue Gorge Lower	4.10	7.0 %
Itezhi-Tezhi	0.65	1.1 %
TOTAL	**58.10**	**100.0%**

Omo-Turkana Basin

As envisioned by the 2010-2015, and the following 2015-2020 Ethiopian Growth and Transformation Plans, the Ethiopian Electric Power Company is financing dams and hydropower plants incrementing the hydropower generation capacity from 2.4 GW installed before 2010, to more than 20 GW with several hydropower projects in its main rivers and tributaries including the Omo and the Blue Nile.

The Ethiopian energy policy aims at achieving internal energy security by covering domestic demand, and becoming a regional power provider, exporting the excess production to neighboring countries (Asress et al., 2013).

The country-specific total energy demand within the OTB is reported in the top panel of Figure 16, highlighting the contribution of electricity from the remaining components of the energy demand (non-electrical energy). Electricity demand is here estimated multiplying the population projections illustrated in the section 4.3.1 with a country-specific coefficient of electricity consumption per capita retrieved from Eglitis (2014). In both countries, the share of electricity with respect to the total energy use and demand is very low, given the discontinuous and irregular access to modern energy services in rural areas (International Energy Agency, IEA 2017). Hydropower production contributes to the satisfaction of the electricity demand, isolated for clarity in the bottom panel of Figure 16.

Such demand is projected to peak in 2085 reaching a maximum of 2056 GWh/year (Figure 16), while the nominal installed capacity in the basin is currently slightly lower than 9000 GWh/year, and will surpass 15000 GWh/year with the construction of Koysha dam.

Despite the assumption of a constant electrification rate may not hold in the future, and the electricity demand of the region may grow faster than with this simple projections, it is clear that the hydropower production in the basin is well above regional requirements. In accordance to the Ethiopian energy policy, the hydropower production in OTB is not constrained to an internal demand, instead, it is maximized in order to target the export market. Coherently, the selected design indicator for the energy sector in OTB considers the maximization of the hydropower production, and not the satisfaction of an allocated demand as in the ZRB case.

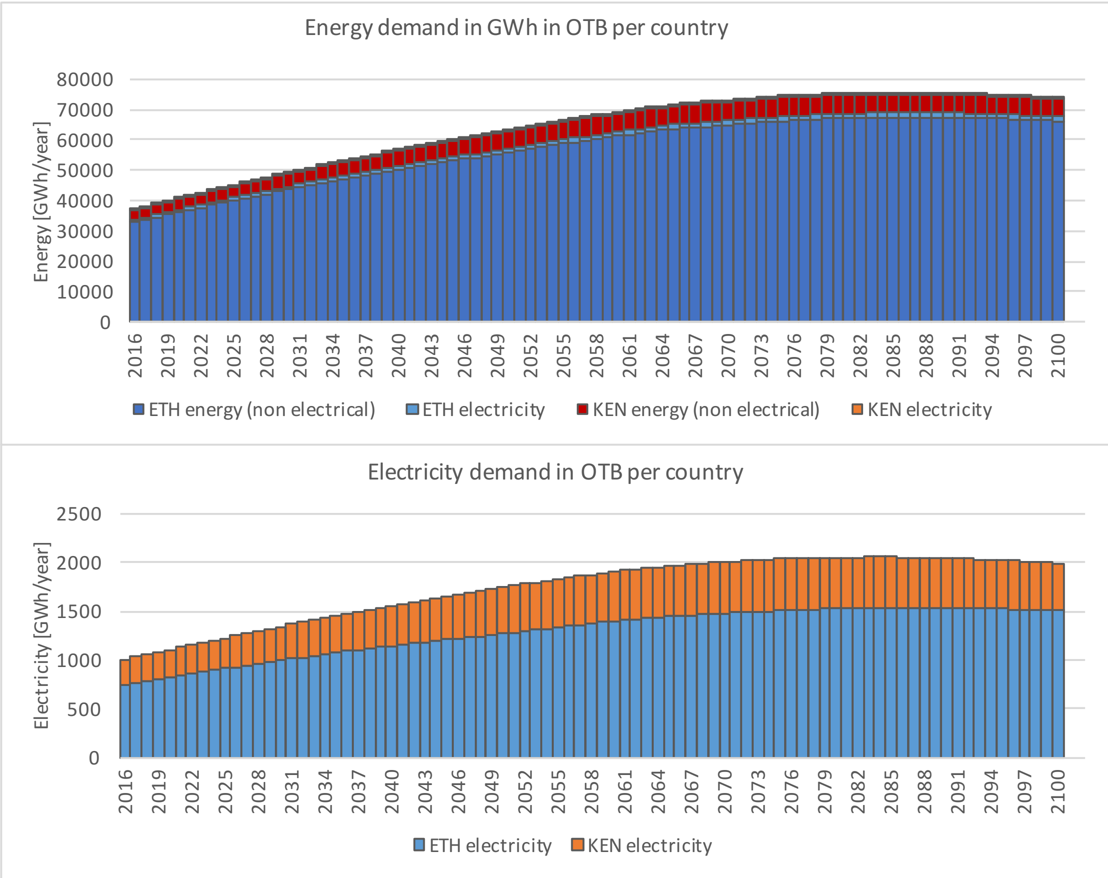

Figure 16 – Top panel: projected Energy demand for the countries in OTB, specifying the contribution of electricity, and non-electrical demand from 2016 to 2100. Bottom panel: zoom of the projected Energy demand for the countries in OTB from 2016 to 2100.

4.3.4 Irrigation demands projections

Although a proper assessment of crop water consumption will be provided through modelling results to be reported in Deliverable D3.5, in this section we present a first estimate of water requirements for irrigated agriculture between 2020 and 2099 under the projected climate scenario illustrated in section 4.3.2. This analysis includes both existing and short-term planned irrigation schemes.

Zambezi River Basin

The operational and planned irrigation schemes in the ZRB are mapped in Figure 17. The planned irrigation projects are mainly located near Lake Kariba and Lake Malawi, which both have the potential to serve as major water suppliers for irrigated agriculture. For existing and planned irrigation schemes, net irrigation water requirement was estimated by multiplying the reported areas under irrigation with the net irrigation requirement calculated by AquaCrop assuming an irrigation efficiency of 45% (for further details see Deliverable D2.2). Figure 18 shows the total water demand by irrigated sugarcane if all planned sugarcane developments were to be realized. These results illustrate an increasing trend in irrigation water requirements in all subbasins generated by the changes in climatic variables under the RCP 4.5 scenario, with the maximum demands expected in in subbasins 1226 and 1222 which contain the large Mazabuka sugar estate in Zambia and the sugar-producing areas in Malawi and Mozambique. Similar results for crops different from sugarcane are reported in detail in Deliverable D2.2.

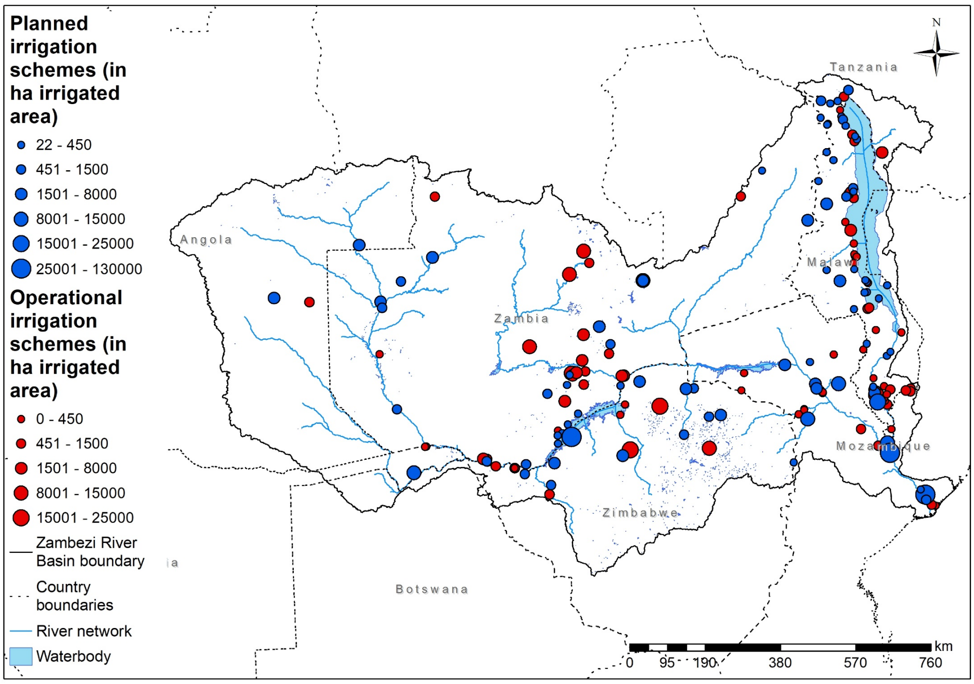

Figure 17 – Operational and planned irrigation schemes in the ZRB. Size of the dots reflects the size of the scheme.

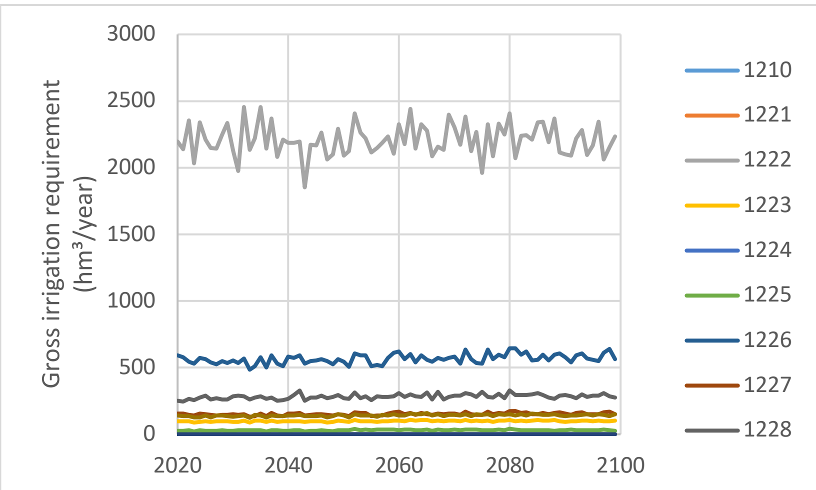

Figure 18 – Gross irrigation requirement for operational and planned sugarcane irrigation schemes in the ZRB in hm³/year. The different lines represent different subbasins.

Omo-Turkana Basin

The operational and the planned irrigation schemes in the OTB are mapped in Figure 19. Besides the planned irrigation projects along the Kerio and Turkwel river, the most notable planned irrigation project in the OTB is the Kuraz sugar estate expansion in Ethiopia. By 2026, the development of three sugar blocks is expected, with a total area of 100000 ha, sugarcane under furrow irrigation. The expected irrigated area of the left bank development area is 48000 ha, of the right bank block I it is 22000 ha, and of the right bank block II, which will be situated immediately downstream of the Omo National Park, it is 40000 ha [*FDRE Sugar Corporation*, 2018]. It is expected that these large-scale sugarcane developments will have a significant impact on the water availability locally and in the rest of the basin [*Avery*, 2012].

To estimate water consumption of irrigated sugarcane in the Kuraz sugar estate, we derived time series of temperature and precipitation data at the location of the estate based on the time series corresponding to the available virtual temperature and precipitation station using inverse distance weighting. The current and predicted agricultural areas of the estate were multiplied with the net irrigation requirement calculated by AquaCrop. The planting date was considered to be 1 January. Gross irrigation water requirement was estimated by assuming an irrigation efficiency of 45%. With the exception of the Kuraz sugar estate, maize was reported as one of or the only crop on the planned irrigation schemes for which the intended crop could be identified. Therefore, it is assumed maize will remain important as an irrigated crop in the OTB in the future. The projected irrigation water requirements are reported in Figure 20, which highlights the significance of the irrigation water requirement of the Kuraz scheme in subbasin 11545 after 2025, when the full 100000 ha of sugarcane irrigation is expected to be implemented.

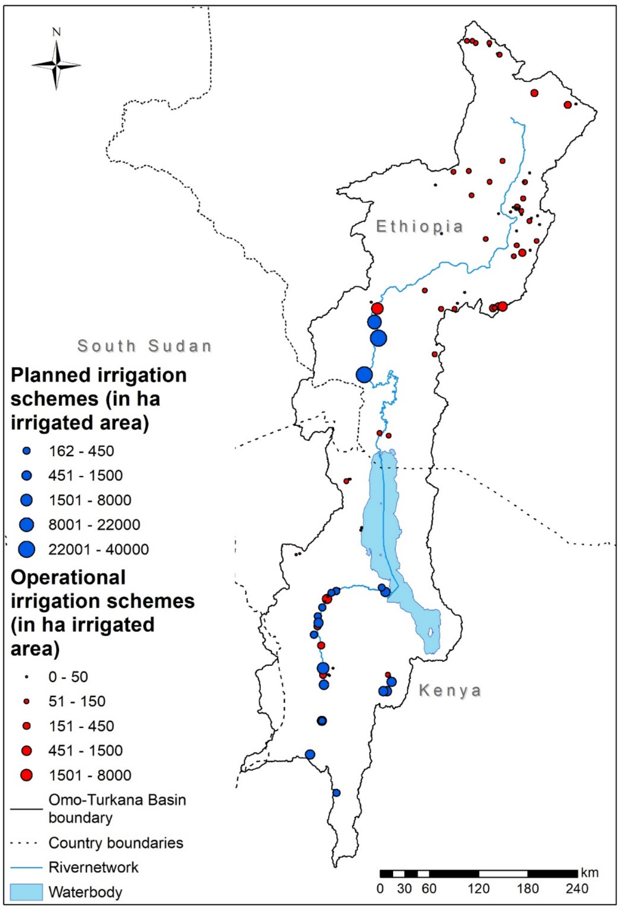

Figure 19 – Operational and planned irrigation schemes in the OTB. Size of the dots reflects the size of the scheme.

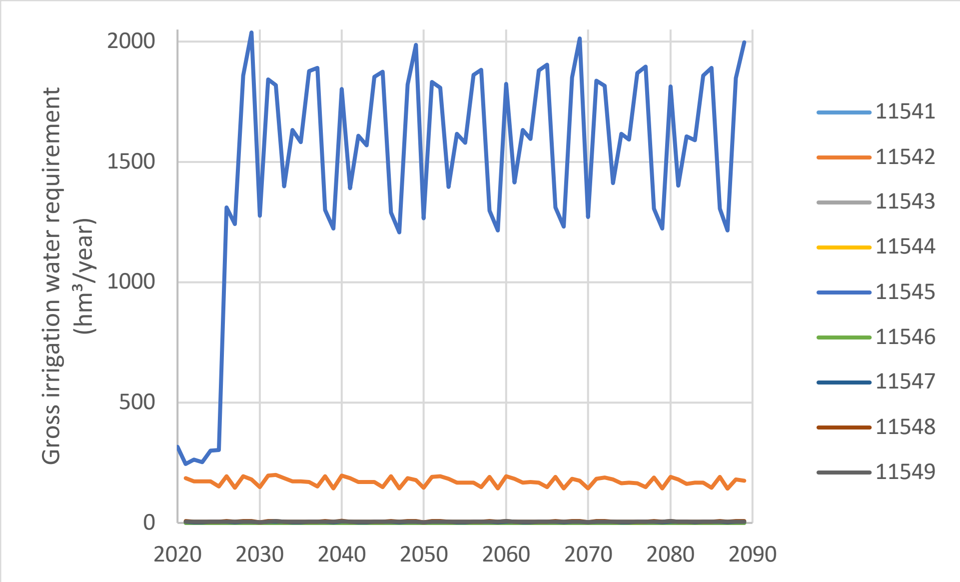

Figure 20 – Gross irrigation water requirement for current and planned irrigation schemes in the OTB in hm³/year. The different lines represent different subbasin.

4.4 DEFINITION OF CANDIDATE PATHWAYS

The aim of this section is to provide a brief description of few preliminary adaptation pathways for both the ZRB and the OTB, to be used as references in the analysis of the efficient pathways that will be generated in Task T5.2. These candidate pathways have been manually designed by selecting some combinations of actions from the tables reported in sections 4.1 and 4.2 with their sequencing determined by the expected timing of each action.

4.4.1 Zambezi River Basin

Figure 21 and Figure 22 shows the **Business As Usual (BAU) pathway** corresponding to the existing system configuration of the ZRB. As can be observed, the system is characterized by four main elements: 4 major existing water reservoirs (white triangles) and associated hydropower plants (black squares), 1 run-of-the-river hydropower plant (black diamond), 7 major irrigation districts (white rectangles) and 1 selected area in the Delta that is sensitive for ecosystem preservation. The current operation of the full system is driven by the hydropower interest.

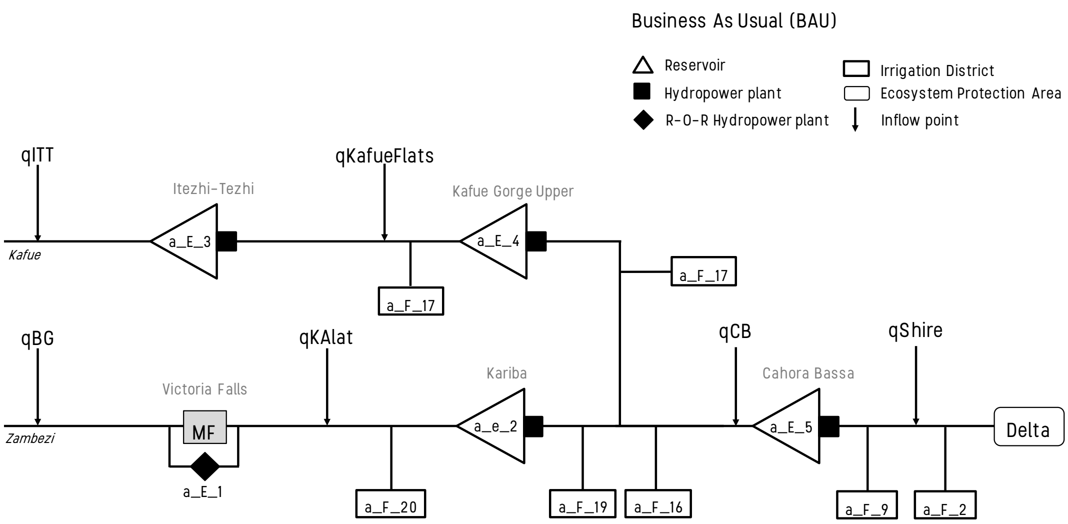

Figure 21 – Business As Usual (BAU) pathway corresponding to the existing system configuration of the ZRB.

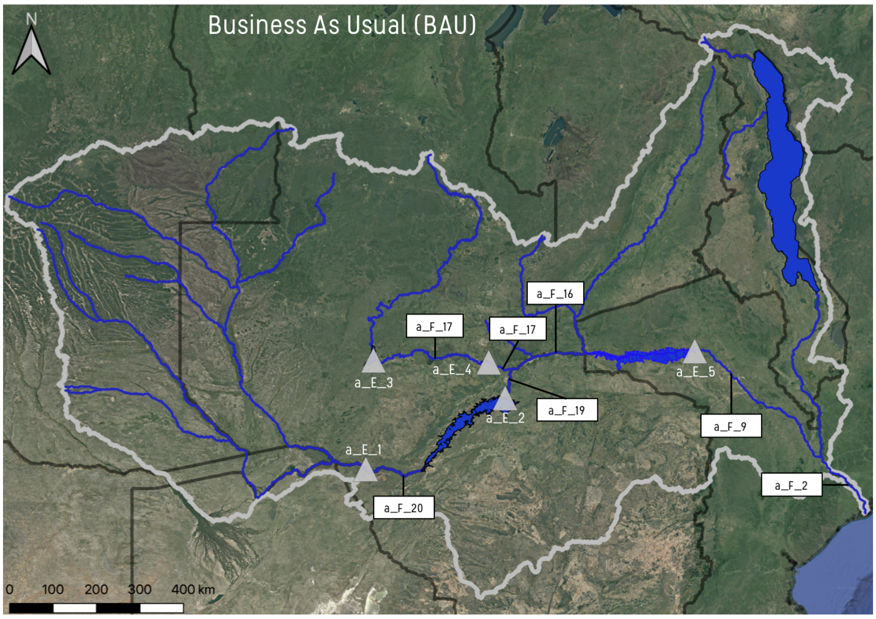

Figure 22 – Geo-referenced location of the planning actions comprising the Business As Usual (BAU) pathway, which corresponds to the existing system configuration of the ZRB.

Building on the BAU, we outlined the following four main adaptation pathways for the ZRB:

1. **ZRB energy pathway** (Figure 23 and Figure 24): Pathway focused on the full development of the energy sector only. Starting from the existing system configuration, this pathway includes the construction of three planned (i.e., Batoka Gorge, Devil's Gorge, Mphanda Nkuwa) and one under construction (i.e., Kafue Gorge Lower) hydropower reservoirs, together with the Synclinorium shaft copper mine project in the Upper Kafue. The timing of these planning actions is the year of expected completion reported in the corresponding project documents. In particular, the Synclinorium copper mine project (action a_SE_14) is the first action to be completed by 2018, followed by the construction of Kafue Gorge Lower (action a_E_6) in 2019, Batoka Gorge (a_E_7) and Mphanda Nkuwa (a_E_10) in 2026, and Devil's Gorge reservoirs (a_E_8) in 2029. Both the existing and the planned reservoirs will be operated with a hydropower prone policy, namely a trade-off operating strategy that tends to minimize energy deficit/surplus with respect to a given future projection of increasing energy demand.

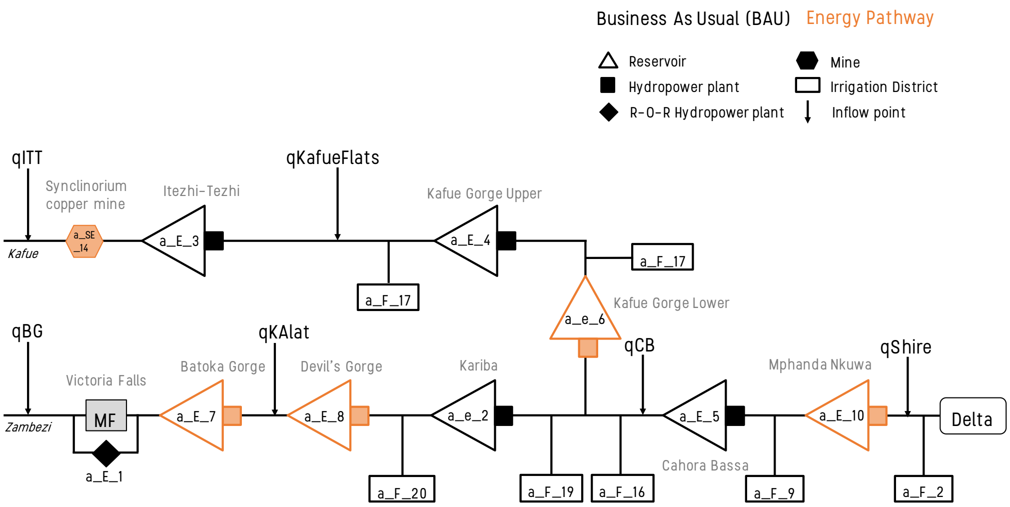

Figure 23 – ZRB energy pathway corresponding to the full development of the energy sector only.

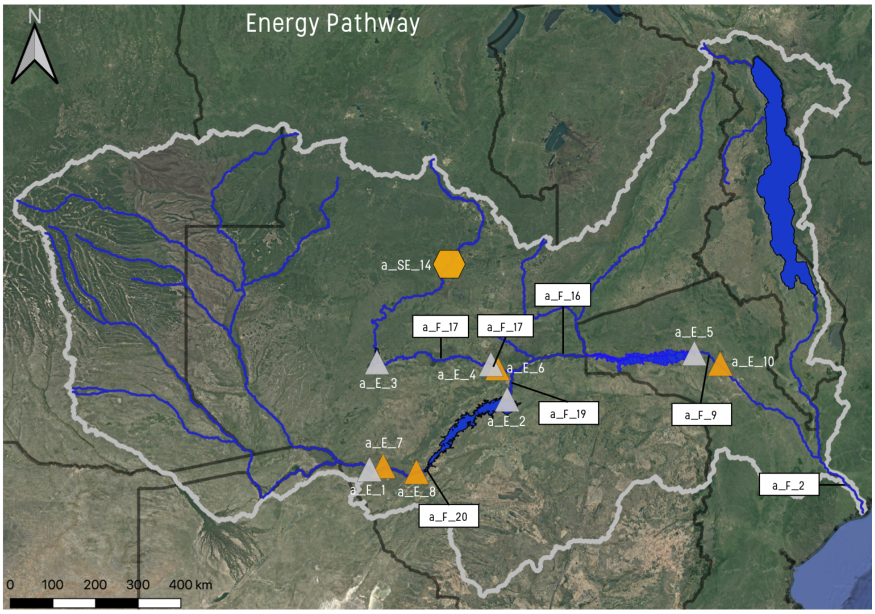

Figure 24 – Geo-referenced location of the planning actions included in the ZRB energy pathway, which corresponds to the full development of the energy sector only.

2. **ZRB food pathway** (Figure 25 and Figure 26): Pathway focused on the full development of the food sector only. Starting from the existing system configuration, this pathway includes the development of 7 new irrigation schemes across the entire Zambezi basin, whose timing corresponds to the year of expected completion reported in the project documents. At first, about 6,500 (action a_F_36) and 16,500 ha (action a_F_41) of irrigated land will be developed on the border between Mozambique and Zimbabwe and in Zambia respectively in 2018, followed by 142,000 ha in Zambia (actions a_F_46, a_F_48) and on the border between Zambia and Zimbabwe (actions a_F_44, a_F_49) in 2019. Finally, 75,000 ha will be irrigated on the border between Malawi and Mozambique (action a_F_30) in 2031. All these planned irrigation schemes will only concern areal expansions of a few existing irrigation districts. Both the existing and the planned irrigation water diversion schemes will be regulated with an irrigation prone policy, namely a trade-off operating strategy that tends to minimize irrigation water supply deficit with respect to a given future projection of increasing irrigation demand. This large agricultural expansion may conflict with the protected status of some transboundary conservation areas, such as the Zimbabwe-Mozambique-Zambia National Park (action a_W_Ec_19) and the Lower Zambezi-Mana Pools National Park (action a_W_Ec_20).

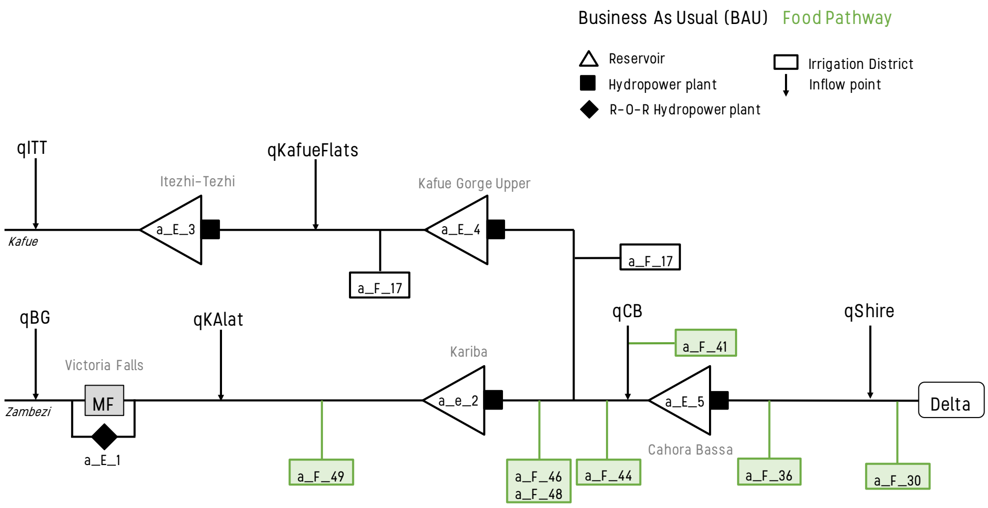

Figure 25 – ZRB food pathway corresponding to the full development of the food (i.e., irrigated agriculture) sector only.

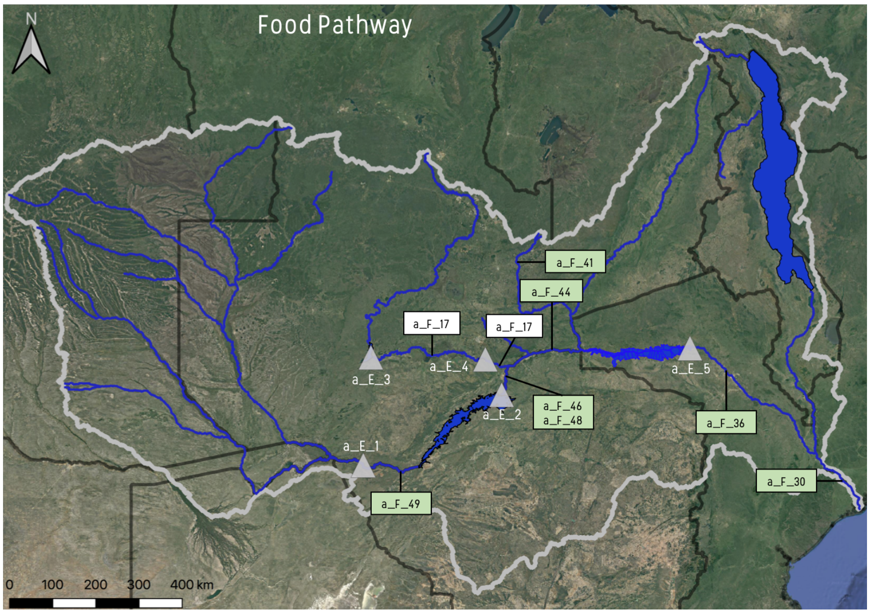

Figure 26 – Geo-referenced location of the planning actions included in the ZRB food pathway, which corresponds to the full development of the food (i.e., irrigated agriculture) sector only.

3. **ZRB water pathway** (Figure 27 and Figure 28): Pathway focused on the total preservation of natural ecosystems and hydrological regimes in the basin. Based on the existing system configuration, this pathway favors a regulation of the existing hydropower reservoirs and irrigation diversions aimed at preserving natural flood regimes in the Kafue Flats and the Zambezi Delta (action a_W_Ec_13). The existing infrastructures will thus be regulated with an environmental prone operating strategy, aimed at reducing the total normalized deficit with respect to the required environmental flows at the basin level. In addition, three transfrontier conservation areas will be fully completed by 2018, namely the Zimbabwe-Mozambique-Zambia, the Lower Zambezi-Mana Pools and the Liuwa Plains-Mussuma TFCAs (actions a_W_Ec_19, a_W_Ec_20, a_W_Ec_21).

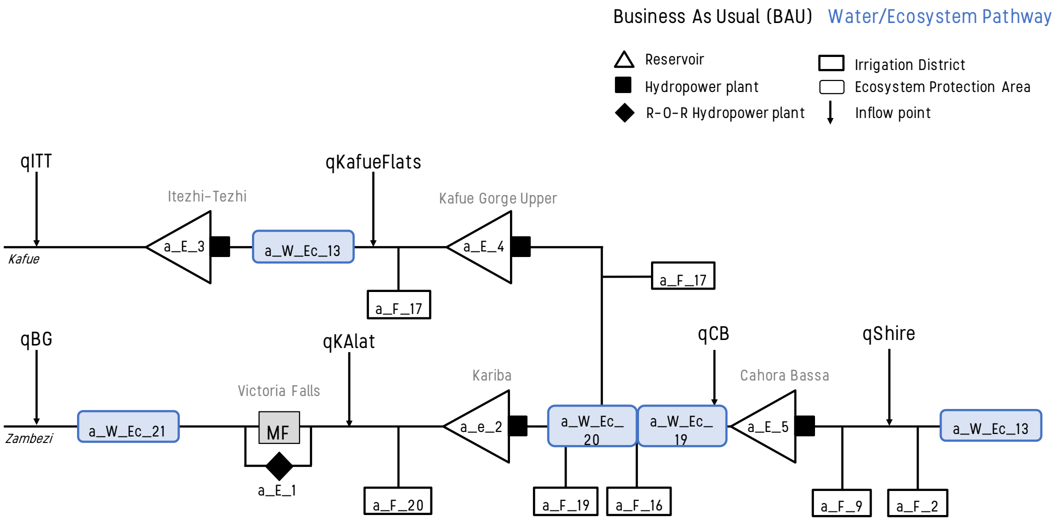

Figure 27 – ZRB water pathway focused on the total preservation of natural ecosystems and hydrological regimes.

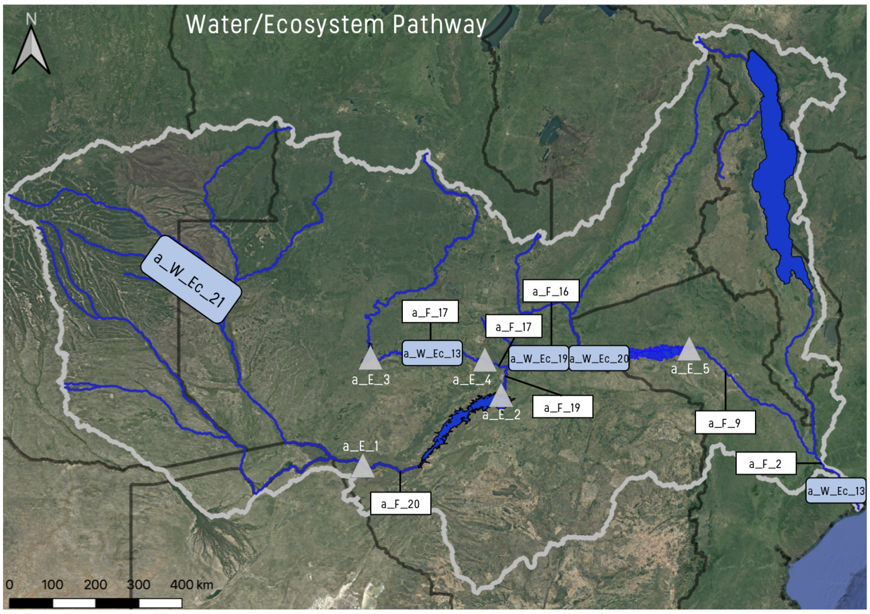

Figure 28 – Geo-referenced location of the planning actions included in the ZRB water pathway, which is focused on the total preservation of natural ecosystems and hydrological regimes.

4. **ZRB full economic expansion** (Figure 29 and Figure 30): Pathway focused on a balanced development of both energy and food sectors, while still preserving the ecosystem requirements. Starting from the existing system configuration, this pathway includes the construction of two hydropower reservoirs (i.e., Kafue Gorge Lower in 2019 and Batoka Gorge in 2026) operated by ZESCO and the development of about 91,000 ha of irrigated land in 2018 (Mozambique/Zimbabwe) and in 2031 (Mozambique/Malawi). Both the existing and planned reservoirs/irrigation water diversion schemes will be operated with respect to a balanced compromise between conflicting objectives, namely hydropower production vs irrigation water supply deficit vs environmental deficit in both the Kafue Flats and the Delta.

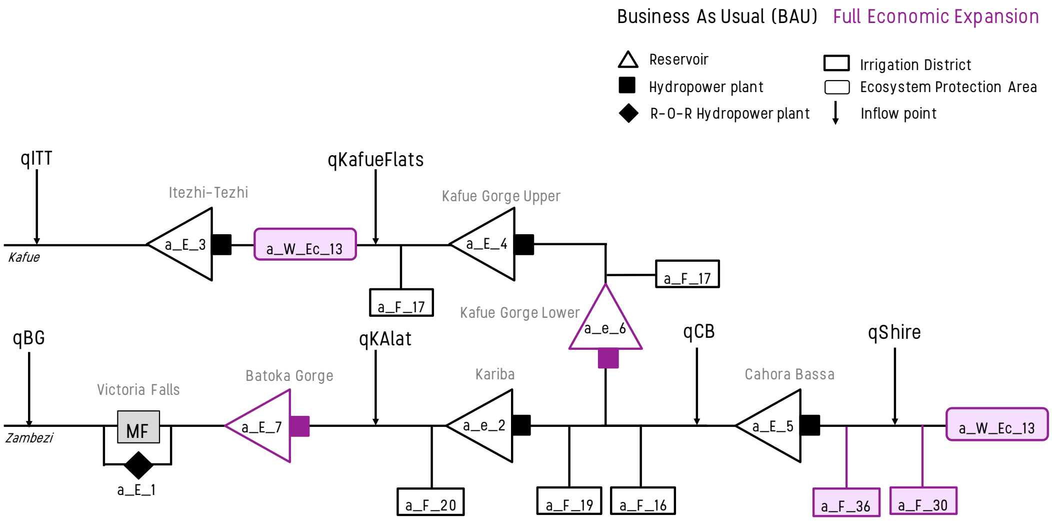

Figure 29 – ZRB full economic expansion pathway focused on a balanced development of both energy and food sectors, while still preserving the ecosystem requirements.

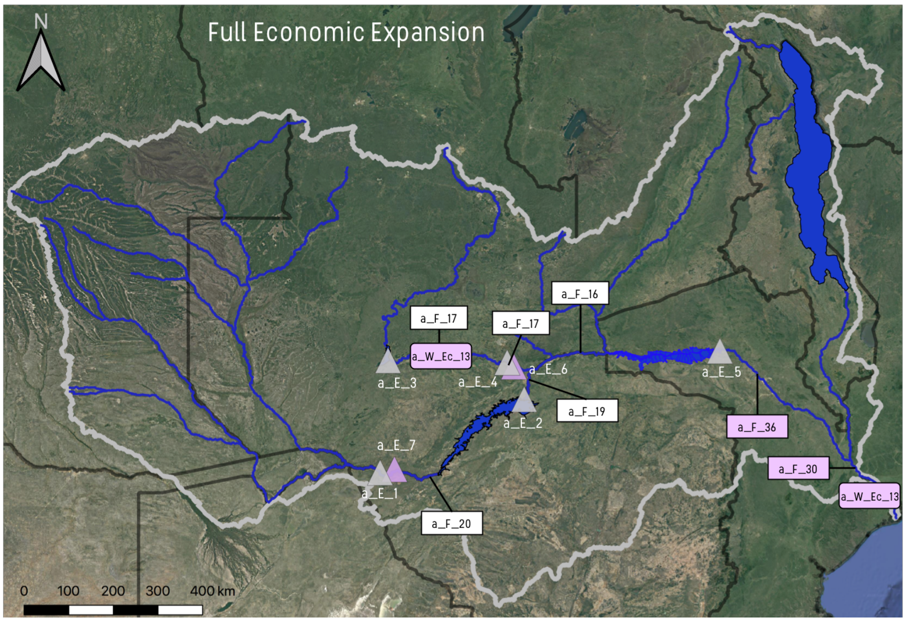

Figure 30 – Geo-referenced location of the planning actions included in the ZRB full economic expansion pathway, which is focused on a balanced development of both energy and food sectors, while still preserving the ecosystem requirements.

For each of the four candidate pathways manually identified and described above, Table 19 summarizes the corresponding planning (e.g., hydropower infrastructures and irrigated areas expansion) actions and their associated timing.

Table 19 – Summary of the actions considered in the characterization of the BAU, and the four candidate pathways identified for the ZRB. Each action is detailed with the relative sector, id, and additional specifics. New planned actions are highlighted with a background color.

Business As Usual (BAU)					
Sector	**Action Id**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	RoR power plant	108 MW	Completed	Existing
Energy	a_E_2	Dam + power plant	1830 MW	Completed	Existing
Energy	a_E_3	Dam + power plant	120 MW	Completed	Existing
Energy	a_E_4	Dam + power plant	990 MW	Completed	Existing
Energy	a_E_5	Dam + power plant	2075 MW	Completed	Existing
Food	a_F_2	Irrigation district	23899 ha	Completed	Existing
Food	a_F_9	Irrigation district	17611 ha	Completed	Existing
Food	a_F_16	Irrigation district	2825 ha	Completed	Existing
Food	a_F_17	Irrigation district	45539 ha	Completed	Existing
Food	a_F_19	Irrigation district	30030 ha	Completed	Existing
Food	a_F_20	Irrigation district	10 ha	Completed	Existing
Energy Pathway					
Sector	**Action Id**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	RoR power plant	108 MW	Completed	Existing
Energy	a_E_2	Dam + power plant	1830 MW	Completed	Existing
Energy	a_E_3	Dam + power plant	120 MW	Completed	Existing
Energy	a_E_4	Dam + power plant	990 MW	Completed	Existing
Energy	a_E_5	Dam + power plant	2075 MW	Completed	Existing
Energy	a_E_6	Dam + power plant	750 MW	2019	Planned

(Table 19 continued)

Energy	a_E_7	Dam + power plant	2400 MW	2026	Planned
Energy	a_E_8	Dam + power plant	1200 MW	2029	Planned
Energy	a_E_10	Dam + power plant	1500/2040 MW	2026	Planned
Socio-Economy	a_SE_14	Copper mine	-	2018	Planned
Food	a_F_2	Irrigation district	23899 ha	Completed	Existing
Food	a_F_9	Irrigation district	17611 ha	Completed	Existing
Food	a_F_16	Irrigation district	2825 ha	Completed	Existing
Food	a_F_17	Irrigation district	45539 ha	Completed	Existing
Food	a_F_19	Irrigation district	30030 ha	Completed	Existing
Food	a_F_20	Irrigation district	10 ha	Completed	Existing
Food Pathway					
Sector	**Action Id**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	RoR power plant	108 MW	Completed	Existing
Energy	a_E_2	Dam + power plant	1830 MW	Completed	Existing
Energy	a_E_3	Dam + power plant	120 MW	Completed	Existing
Energy	a_E_4	Dam + power plant	990 MW	Completed	Existing
Energy	a_E_5	Dam + power plant	2075 MW	Completed	Existing
Food	a_F_17	Irrigation district	45539 ha	Completed	Existing
Food	a_F_30	Irrigation district	74443 ha	2031	Planned
Food	a_F_36	Irrigation district	16533 ha	2018	Planned
Food	a_F_41	Irrigation district	6466 ha	2018	Planned
Food	a_F_44	Irrigation district	6078 ha	2019	Planned
Food	a_F_46	Irrigation district	283 ha	2019	Planned
Food	a_F_48	Irrigation district	210 ha	2019	Planned
Food	a_F_49	Irrigation district	135237 ha	2019	Planned
Water Pathway					
Sector	**Action Id**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	RoR power plant	108 MW	Completed	Existing
Energy	a_E_2	Dam + power plant	1830 MW	Completed	Existing
Energy	a_E_3	Dam + power plant	120 MW	Completed	Existing
Energy	a_E_4	Dam + power plant	990 MW	Completed	Existing
Energy	a_E_5	Dam + power plant	2075 MW	Completed	Existing
Food	a_F_2	Irrigation district	23899 ha	Completed	Existing
Food	a_F_9	Irrigation district	17611 ha	Completed	Existing
Food	a_F_16	Irrigation district	2825 ha	Completed	Existing
Food	a_F_17	Irrigation district	45539 ha	Completed	Existing
Food	a_F_19	Irrigation district	30030 ha	Completed	Existing
Food	a_F_20	Irrigation district	10 ha	Completed	Existing
Water	a_W_Ec_13	E-flow	-	Completed	Existing
Water	a_W_Ec_19	TFCA	29860 km^2	2018	Planned
Water	a_W_Ec_20	TFCA	17789 km^2	2018	Planned
Water	a_W_Ec_21	TFCA	16289 km^2	2018	Planned
Full Economic Expansion					
Sector	**Action Id**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	RoR power plant	108 MW	Completed	Existing
Energy	a_E_2	Dam + power plant	1830 MW	Completed	Existing
Energy	a_E_3	Dam + power plant	120 MW	Completed	Existing
Energy	a_E_4	Dam + power plant	990 MW	Completed	Existing

(Table 19 continued)

Energy	a_E_5	Dam + power plant	2075 MW	Completed	Existing
Energy	a_E_6	Dam + power plant	750 MW	2019	Planned
Energy	a_E_7	Dam + power plant	2400 MW	2026	Planned
Food	a_F_16	Irrigation district	2825 ha	Completed	Existing
Food	a_F_17	Irrigation district	45539 ha	Completed	Existing
Food	a_F_19	Irrigation district	30030 ha	Completed	Existing
Food	a_F_20	Irrigation district	10 ha	Completed	Existing
Food	a_F_30	Irrigation district	74443 ha	2031	Planned
Food	a_F_36	Irrigation district	16533 ha	2018	Planned
Water	a_W_Ec_13	E-flow	-	Completed	Existing

4.4.2 Omo-Turkana Basin

In this section we list 4 manually constructed pathways relative to the OTB case study, namely the Energy, Food, Water/Ecosystem, and Full development pathways. The **Business As Usual (BAU) pathway** in the OTB is represented in Figure 31, by means of a topological representation (left panel), and the relative position on a map (right panel). The BAU comprises infrastructural elements and protected areas currently present in the OTB. In particular, the Gibe reservoirs cascade (Gibe I and III reservoirs and power plants, and Gibe II power plant), existing irrigation districts, and the Omo National Park. The irrigation districts are represented in the map as grey colored areas in correspondence of their location and extension, however irrigated areas are very small in the BAU scenario, and therefore are hardly visible in the map.

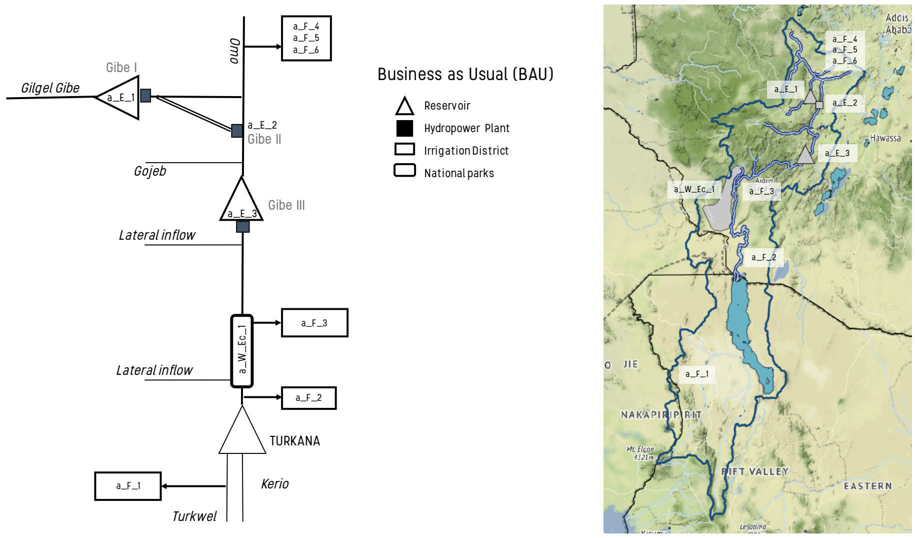

Figure 31 – Business as Usual in the OTB. On the left, the topological scheme of the system, and on the right the georeferenced representation of the elements on a map. Elements are labelled according to the relative action id.

1. **OTB energy pathway** (Figure 32): the energy pathway foresees a great development of the energy sector in the Omo-Turkana basin. This pathway considers the construction of Koysha (action a_E_4) dam on the Omo river by 2021, as envisioned in the Ethiopia Growth and Development plan. Reservoir operations will be designed (action a_E_5) to favor the maximization of the energy production over other operating objectives, with the implementation of a hydropower prone policy. On the contrary, a_E_6 will not be implemented as it considers forced releases to reproduce natural hydrological pattern with detrimental effects on hydropower production. Production of energy will increment in the region from a mix of sources, e.g., biogas, solar, wind,

and other large hydropower projects in neighboring basins (e.g., Grand Ethiopian Renaissance Dam). Conjunctively, energy transmission grid will be significantly potentiated within EAPP, in order to allow the national and international distribution of the produced energy.

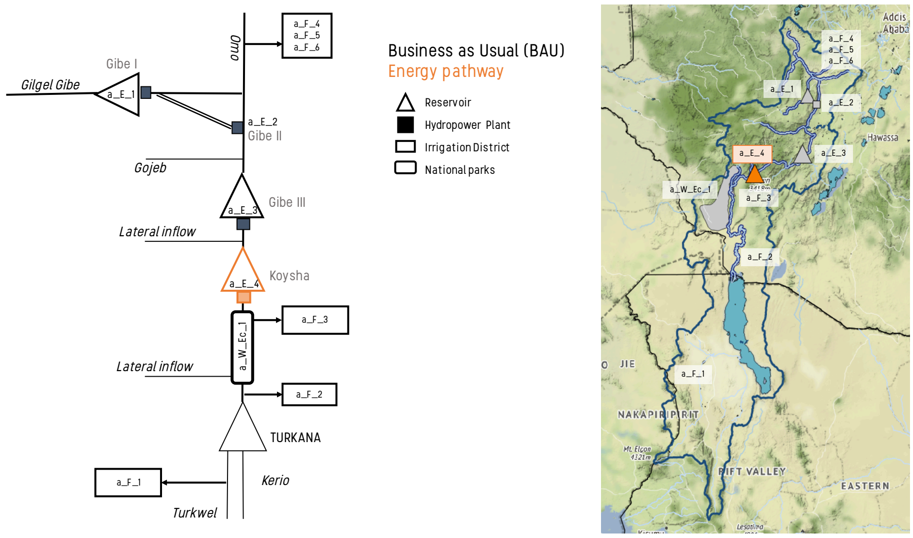

Figure 32 – Energy pathway in the OTB. On the left, the topological scheme of the system, and on the right the georeferenced representation of the elements on a map. Elements are labelled according to the relative action id. Orange elements represent the new infrastructural actions introduced in the Energy pathway with respect to the BAU.

2. **OTB food pathway** (Figure 33): the food pathway considers a large irrigation development in the near future. To the already existing agricultural districts (actions from a_F_ 1 to 6) other approximately 242,000 ha will be constructed since 2025 across Ethiopian and Kenyan territory (actions a_F 7 to 13). In particular, actions a_F_8 and a_F_9 are relative to the expansion of existing districts a_F_2 and a_F_3, while the remaining actions are relative to the construction of new districts. The reservoirs operating policy (action a_E_5) will select an objectives tradeoff which primarily aims at the minimization of the normalized irrigation deficit in the agricultural districts. Areas from the Omo National Park, Tama Wildlife Reserve and Mago National Park will lose their protection status and will be absorbed in the Kuraz Sugar development as in action a_W_Ec_7.

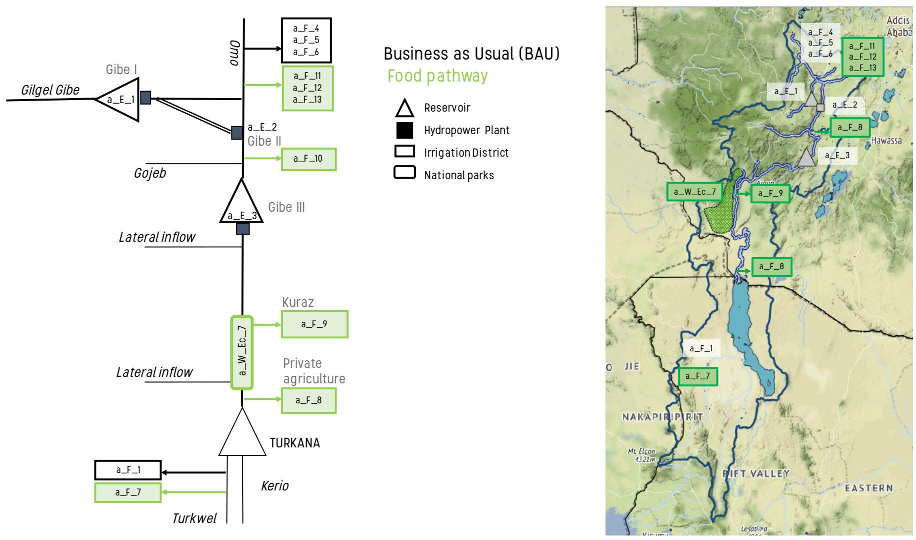

Figure 33 – Food pathway in the OTB. On the left, the topological scheme of the system, and on the right the georeferenced representation of the elements on a map. Elements are labelled according to the relative

action id. Green elements represent the new infrastructural actions introduced in the Food pathway with respect to the BAU.

3. **OTB water/ecosystem pathway** (Figure 34): this pathway considers the preservation of the natural ecosystems and hydrological regimes in the basin. Actions a_E_6 will be implemented to force releases from Gibe III and ensure the survival of the recession agriculture practice. Action a_E_5 will favor a balanced reservoir regulation aimed at preserving natural hydrological regimes in the Omo Delta and Lake Turkana. Currently protected areas will maintain their status (action a_W_Ec 1), proposed transboundary conservation areas will be established via a multilateral conservation agreement (a_W_Ec_2 to 4 and a_W_Ec_6) [9].

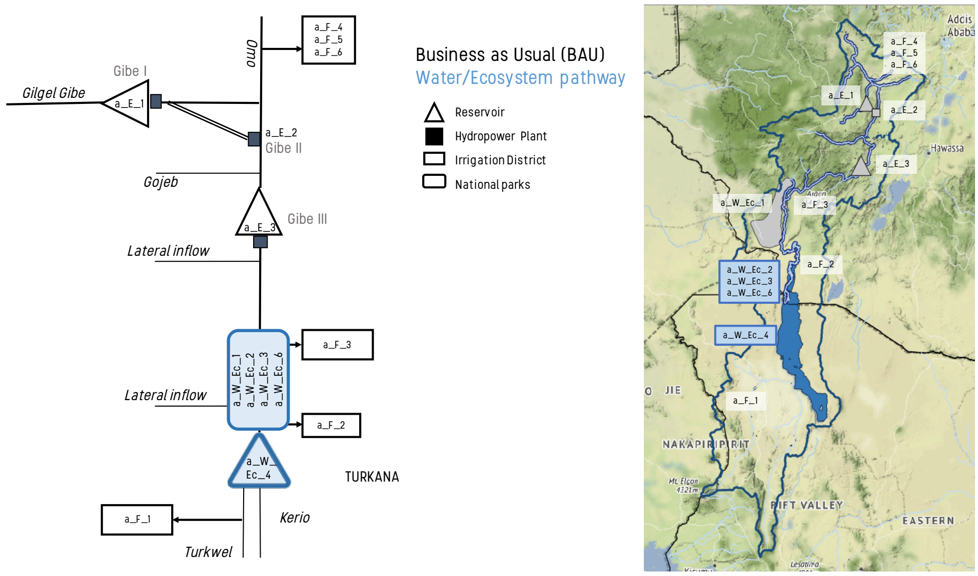

Figure 34 – Water/Ecosystem pathway in the OTB. On the left, the topological scheme of the system, and on the right the georeferenced representation of the elements on a map. Elements are labelled according to the relative action id. Blue elements represent the new legislative actions introduced in the Water/ecosystem pathway with respect to the BAU.

4. **OTB full development pathway** (Figure 35): this pathway foresees a full infrastructural development considering the construction of Koysha Dam in 2021 (a_E_4) and of the planned irrigation districts in 2025 (actions a_F 7 to 13). The reservoirs operating policy (action a_E_5) will favor hydropower production and irrigation needs in the choice of the preferred objectives tradeoff. Portions of the currently protected areas will lose their status and be absorbed by the Kuraz Sugar development as in action a_W_Ec_7.

A summary of all actions considered in the different candidate pathways is reported in Table 20, divided in BAU and Energy, Food, Water/Ecosystem, and Full Development Pathway.

[9] Action a_W_Ec_5 regarding sediment flushing from dams is also potentially interesting for this pathway. However, I am not aware of any research within the project concerning sediment deposition and flushing in reservoirs. In my understanding, ETHZ is working on modeling sediment transport in fluvial reaches, but not dams. If so, maybe we should rediscuss this action.

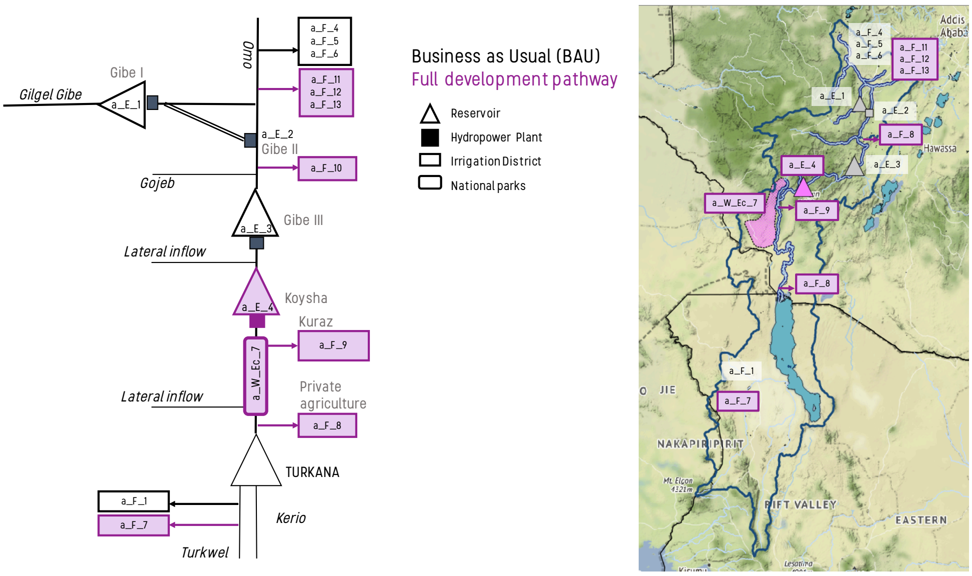

Figure 35 – Full development pathway in the OTB. On the left, the topological scheme of the system, and on the right the georeferenced representation of the elements on a map. Elements are labelled according to the relative action id. Violet elements represent the new infrastructural actions introduced in the full development pathway with respect to the BAU.

Table 20 – Summary of the actions considered in the characterization of the BAU, and the four candidate pathways identified for the OTB. Each action is detailed with the relative sector, id, and additional specifics. New planned actions are highlighted with a background color.

Business As Usual (BAU)						
Sector	**Action Id**	**Name**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	Gibe I	Dam + PP	184 MW	Completed	Existing
Energy	a_E_2	Gibe II	PP	420 MW	Completed	Existing
Energy	a_E_3	Gibe III	Dam + PP	1870 MW	Completed	Existing
Food	a_F_1	-	Irrigation district	3878 ha	Completed	Existing
Food	a_F_2	-	Irrigation district	149 ha	Completed	Existing
Food	a_F_3	-	Irrigation district	3382 ha	Completed	Existing
Food	a_F_4	-	Irrigation district	480 ha	Completed	Existing
Food	a_F_5	-	Irrigation district	750 ha	Completed	Existing
Food	a_F_6	-	Irrigation district	628 ha	Completed	Existing
Water	a_W_Ec_1	Omo National Park	Protected area	4346 ha	Completed	Existing
Energy Pathway						
Sector	**Action Id**	**Name**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	Gibe I	Dam + PP	184 MW	Completed	Existing
Energy	a_E_2	Gibe II	PP	420 MW	Completed	Existing
Energy	a_E_3	Gibe III	Dam + PP	1870 MW	Completed	Existing
Energy	a_E_4	Koysha	Dam + PP	2200 MW	2021	Planned
Food	a_F_1	-	Irrigation district	3878 ha	Completed	Existing
Food	a_F_2	-	Irrigation district	149 ha	Completed	Existing
Food	a_F_3	-	Irrigation district	3382 ha	Completed	Existing
Food	a_F_4	-	Irrigation district	480 ha	Completed	Existing
Food	a_F_5	-	Irrigation district	750 ha	Completed	Existing
Food	a_F_6	-	Irrigation district	628 ha	Completed	Existing

(Table 20 continued)

Water	a_W_Ec_1	Omo National Park	Protected area	4346 ha	Completed	Existing
Food pathway						
Sector	**Action Id**	**Name**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	Gibe I	Dam + PP	184 MW	Completed	Existing
Energy	a_E_2	Gibe II	PP	420 MW	Completed	Existing
Energy	a_E_3	Gibe III	Dam + PP	1870 MW	Completed	Existing
Food	a_F_1	-	Irrigation district	3878 ha	Completed	Existing
Food	a_F_2	-	Irrigation district	149 ha	Completed	Existing
Food	a_F_3	-	Irrigation district	3382 ha	Completed	Existing
Food	a_F_4	-	Irrigation district	480 ha	Completed	Existing
Food	a_F_5	-	Irrigation district	750 ha	Completed	Existing
Food	a_F_6	-	Irrigation district	628 ha	Completed	Existing
Food	a_F_7	-	Irrigation district	12585 ha	2025	Planned
Food	a_F_8	-	Irrigation district	10000 ha	2025	Planned
Food	a_F_9	Kuraz	Irrigation district	195515 ha	2025	Planned
Food	a_F_10	-	Irrigation district	6000 ha	2025	Planned
Food	a_F_11	-	Irrigation district	2200 ha	2025	Planned
Food	a_F_12	-	Irrigation district	15037 ha	2025	Planned
Water	a_W_Ec_7	Omo National Park	Deforestation	1000 km^2 affected	Ongoing	Ongoing
Water/Ecosystem pathway						
Sector	**Action Id**	**Name**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	Gibe I	Dam + PP	184 MW	Completed	Existing
Energy	a_E_2	Gibe II	PP	420 MW	Completed	Existing
Energy	a_E_3	Gibe III	Dam + PP	1870 MW	Completed	Existing
Food	a_F_1	-	Irrigation district	3878 ha	Completed	Existing
Food	a_F_2	-	Irrigation district	149 ha	Completed	Existing
Food	a_F_3	-	Irrigation district	3382 ha	Completed	Existing
Food	a_F_4	-	Irrigation district	480 ha	Completed	Existing
Food	a_F_5	-	Irrigation district	750 ha	Completed	Existing
Food	a_F_6	-	Irrigation district	628 ha	Completed	Existing
Water	a_W_Ec_1	Omo National Park	Protected area	4346 ha	Completed	Existing
Water	a_W_Ec_2	Lower Omo	Protected area	-	NA	Proposed
Water	a_W_Ec_3	Omo Delta	Protected area	-	NA	Proposed
Water	a_W_Ec_4	Lake Turkana	Protected area	-	NA	Proposed
Water	a_W_Ec_6		Forest restoration	-	NA	Proposed
Full development pathway						
Sector	**Action Id**	**Name**	**Type**	**Features**	**Time**	**Status**
Energy	a_E_1	Gibe I	Dam + PP	184 MW	Completed	Existing
Energy	a_E_2	Gibe II	PP	420 MW	Completed	Existing
Energy	a_E_3	Gibe III	Dam + PP	1870 MW	Completed	Existing
Energy	a_E_4	Koysha	Dam + PP	2200 MW	2012	Planned
Food	a_F_1	-	Irrigation district	3878 ha	Completed	Existing
Food	a_F_2	-	Irrigation district	149 ha	Completed	Existing
Food	a_F_3	-	Irrigation district	3382 ha	Completed	Existing
Food	a_F_4	-	Irrigation district	480 ha	Completed	Existing

(Table 20 continued)

Food	a_F_5	-	Irrigation district	750 ha	Completed	Existing
Food	a_F_6	-	Irrigation district	628 ha	Completed	Existing
Food	a_F_7	-	Irrigation district	12585 ha	2025	Planned
Food	a_F_8	-	Irrigation district	10000 ha	2025	Planned
Food	a_F_9	Kuraz	Irrigation district	195515 ha	2025	Planned
Food	a_F_10	-	Irrigation district	6000 ha	2025	Planned
Food	a_F_11	-	Irrigation district	2200 ha	2025	Planned
Food	a_F_12	-	Irrigation district	15037 ha	2025	Planned
Water	a_W_Ec_7	Omo National Park	Deforestation	1000 km^2 affected	Ongoing	Ongoing

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