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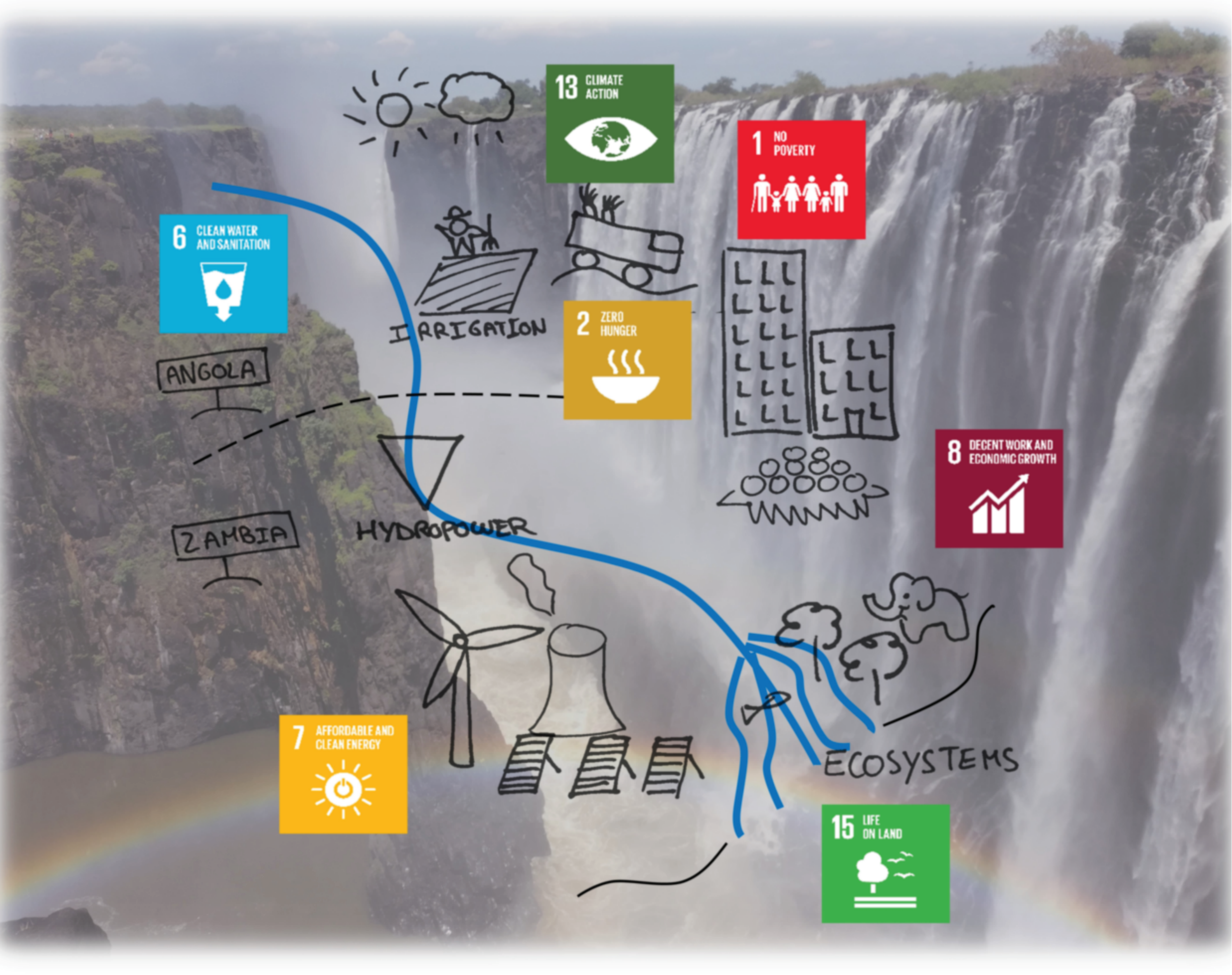

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Preface

The work presented in this industrial PhD thesis was carried out from 1 September 2017 to 30 January 2021, with two leaves: from January to March 2020 and from June to July 2020. It was conducted at the Department of Environmental Engineering at the Technical University of Denmark (DTU) and in the Water Department at COWI A/S. An industrial PhD seeks to address research challenges benefiting society while generating commercial value for the partner company. Professor Peter Bauer-Gottwein was the main supervisor, Kenneth Strzepek (MIT), Silvio Pereira-Cardenal and Mikkel Kromann (COWI) were co-supervisors. A 3 months stay at the National Center for Atmospheric Research (NCAR) in Boulder Colorado was hosted by Kenneth Strzepek. The research was funded by Innovation Fund Denmark (grant no. 7038-00015B), COWIFonden (C-137.02), COWI A/S, the Technical University of Denmark (DTU), and the Massachusetts Institute of Technology (MIT) as an Industrial-PhD project.

The thesis is organized in two parts: the first part puts into context the findings of the PhD in an introductive review; the second part consists of the papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-III**.

I **Payet-Burin, R.**, Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water–energy–food–climate nexus. *HESS*. https://doi.org/10.5194/hess-23-4129-2019, 2019

II **Payet-Burin, R.**, Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., The impact of assuming perfect foresight for investment analysis in water resources systems. *Submitted.* https://doi.org/10.1002/essoar.10504115.1, 2020

III **Payet-Burin, R.**, Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., Silo versus Nexus investment planning under uncertainty. *Submitted.*

In this online version of the thesis, paper **I-III** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

In addition, the following publications, not included in this thesis, were also published during this PhD study:

- **Payet-Burin, R**., Bertoni, F., Davidsen, C., and Bauer-Gottwein, P., Optimization of regional water – power systems under cooling constraints and climate change. *Energy*. https://doi.org/10.1016/j.energy.2018.05.043, 2018

As well as the following presentations and proceedings at international conferences:

- **Payet-Burin, R**., Bertoni, F., Davidsen, C., and Bauer-Gottwein, P., Optimization of regional water -power systems under cooling constraints and climate change. 6th World Congress of Environmental and Resource Economists, 25-29 June 2018, Gothenburg. (Oral Presentation)
- **Payet-Burin, R**., Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., Selecting and scheduling infrastructure investments in the water-energy-food nexus of the Zambezi river basin. EGU General Assembly 2019, 4-12 April 2019, Vienna. (Oral Presentation)
- **Payet-Burin, R**., Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., Using model predictive control in a water infrastructure planning model for the Zambezi river basin. Water: Connecting the World: IAHR 38th World Congress - Panama 2019, CRC Press. https://doi.org/10.3850/38WC092019-1776, 2019
- **Payet-Burin, R**., Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., Selecting water infrastructure investments in the water-energy-food nexus of the Zambezi River basin. AGU Fall Meeting 2019, 9-13 December 2020, San Francisco. (Oral Presentation)
- **Payet-Burin, R**., Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., WHAT-IF, a hydro-economic decision-support tool for infrastructure planning within the Water-Energy-Food Nexus. 21st WaterNet Symposium, 28-30 October 2020, Online. (Oral Presentation)
- **Payet-Burin, R**., Kromann, M., Pereira-Cardenal S.J., Strzepek, K.M., Bauer-Gottwein, P., Climate Change Impacts on the Water-Energy-Food Nexus of the Zambezi River Basin. AGU Fall Meeting 2020, 1-15 December 2020, Online Everywhere. (Oral Presentation available at https://www.what-if-software.dk/documentation)

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Thanks to my roommates in Gråspurvevej, that also became my new "colleagues" as we started working from home, gracias! Thanks for my friends in Copenhagen and abroad, thanks United Compliments for the distraction. Thanks to my family that supports me from distance, maybe I don't often say it, so I won't miss this opportunity, maman, papa, merci. Grazie to Concetta for supporting me during all this time, baccio.

And thanks to you, who is reading this, after all, it is nice to know someone is reading the work.

Summary

Demographic and economic growth lead to important increase in demands for water, energy, and food. To meet these growing demands, multiple water-related infrastructure like hydropower, irrigation, transfer schemes are planned around the world. One challenge for decision-makers is to evaluate the interactions between the potential projects and the existing natural-human system. Interactions are particularly complex because water projects are linked to different sectors: irrigation is related to the food sector, hydropower to the energy sector. The decision-making process is further complicated by uncertainties of climate change and socio-economic growth. Therefore, there is a need for quantitative tools to evaluate impacts of projects considering the inter-dependencies between the water, energy, and food sectors while considering uncertainties.

The aim of this PhD project was to develop an open-source decision support tool for water infrastructure planning, based on early work at COWI. Beyond the development of the tool, the specific aims of this PhD project were: (1) understand the added value of representing the agricultural and power sectors for water infrastructure planning, (2) evaluate the impact of the "perfect foresight" modelling assumption often used in planning models, (3) develop a pragmatic approach to select and prioritize projects under uncertain futures.

The tool developed in this PhD project, WHAT-IF (Water, Hydropower, Agriculture, Tool for Investment and Financing), integrates, in a holistic hydro-economic optimization framework, representations of the water, power and agriculture systems. The tool is generic, open-source and available for community development (https://github.com/RaphaelPB/WHAT-IF).

WHAT-IF was applied to the Zambezi River Basin that spans through eight Southern African countries and supports important economic activities and ecosystems. The population in the basin is expected to grow from 40 million to about 70 million people in 2050. As a result, food demand might double, while electricity demand might triple. Hydropower and irrigation projects could double current hydropower capacity and triple current irrigated land. However, it is unclear whether expanding hydropower and irrigation jointly would lead to trade-offs between the projects and conflicts with environmental flow requirements. Furthermore, the river basin is threatened by uncertain impacts of climate change. The mean annual flow could change by -50% to +30% depending on the climate scenario, which will affect the performance of

the projects. The application of WHAT-IF to the Zambezi case lead to the following insights:

- With an increasing power demand, several hydropower projects are found economically feasible, while being compatible with environmental flow policies. A drying climate would particularly affect existing large plants (Kariba and Cahora Bassa), as well as some projects that are not found beneficial under a drying climate. The introduction of a carbon tax would particularly favor hydropower projects, while likely cost-overrun threatens the feasibility of several projects. Solar and wind power have technically a high potential, this potential should be unleashed in practice.
- With decreasing rainfall and increasing crop demands, there is potential to significantly develop irrigated agriculture. The development is limited by trade-offs with hydropower production, particularly in catchments with large existing abstractions and multiple downstream hydropower plants (e.g. Kafue Flats). Thus, irrigated land is likely to remain a limited share of the total cultivated area. To meet future food demands, fight poverty, and alleviate climate change impacts, countries must also focus on policies and investments improving rainfed agriculture.

When evaluating hydropower and irrigation projects in the Zambezi, the "perfect foresight" modelling assumption is found to have a non-negligible but small impact compared to uncertainties linked to climate and socio-economic change. The representation of the power and agricultural sectors enables to characterize "when, where, and how much" water is needed, and "how valuable" is the water resource under different scenarios. Considering the power and agriculture sectors holistically is expected to be important when considering large projects that will considerably affect the current economic equilibrium.

This work is a contribution to the development of models representing the interrelations between the water, energy, and food sectors. This will be key to support decision-makers consider the full range of solutions that can achieve multiple Sustainable Development Goals (SDGs), including SDG 1, "No poverty", SDG 2 "Zero hunger", SDG 6 "Clean water and sanitation", SDG 7 "Affordable and clean energy", and SDG 13 "Climate Action", while evaluating trade-offs among those objectives.

Dansk sammenfatning

Demografisk og økonomisk vækst fører til en stigende efterspørgslen efter vand, energi og fødevarer. For at imødekomme den stigende efterspørgsel planlægges flere vand-relaterede infrastrukturer globalt, såsom vandkraft, kunstig vanding og vandoverføringsordninger. En udfordring for beslutningstagere er at evaluere interaktionerne mellem potentielle projekter og det eksisterende naturlige-mennepåvirkede system. Interaktionerne er særligt komplekse fordi vandprojekter er forbundet med forskellige sektorer: kunstig vanding er relateret til fødevaresystemet, og vandkraft til energisystemet. Beslutningstagningsprocessen er yderligere kompliceret af usikkerheder forbundet med klimaændringer og samfundsøkonomisk vækst. Der er derfor et behov for kvantitative værktøjer til at evaluere projekters effekter, når man tager den gensidige afhængighed mellem vand-, energi- og fødevaresektoren i betragtning, samt usikkerheder.

Formålet med ph.d.-projektet var at udvikle et open-source beslutningsstøtteværktøj til planlægning af vandinfrastruktur, baseret på tidligere arbejde udført af COWI. Ud over udviklingen af værktøjet, var de specifikke formål med ph.d.-projektet: (1) forstå den øgede værdi af at repræsentere både markedet for landbrug og elektricitet i vandinfrastruktur planlægning, (2) evaluere effekten af modelleringsantagelsen ”perfect foresight”, som ofte er anvendt i planlægningsmodeller, (3) udvikle en pragmatisk tilgang til at udvælge og prioritere projekter under en usikker fremtid. Værktøjet udviklet i dette ph.d.-projekt, WHAT-IF (Water, Hydropower, Agriculture, Tool for Investment and Financing), integrerer systemer for vand, energi og fødevarer igennem en holistisk hydro-økonomisk optimeringsmodel. Værktøjet er generisk, open-source og tilgængeligt for fællesskabsudvikling (https://github.com/RaphaelPB/WHAT-IF).

WHAT-IF var anvendt for Zambezi floden, som flyder igennem otte sydafrikanske lande og understøtter vigtige økonomiske aktiviteter og økosystemer. Det er forventet, at populationen i området vil stige fra 40 millioner til omkring 70 millioner mennesker i 2050. Dette kan resultere i en fordobling af fødevareefterspørgslen og en tredobling af behovet for elektricitet. Projekter med vandkraft og kunstig vanding kan fordoble nuværende vandkraftkapacitet og areal med kunstig vanding. Det er dog uklart hvorvidt en sideløbende ekspanderingen af vandkraft og kunstig vanding vil føre til kompromis mellem projekter eller til konflikter med den miljøregulerende vandforsyning. Derudover

er området truet af usikre effekter som følge af klimaændringer. Den gennemsnitlige årlige vandføring kan ændre sig med - 50% til +30% afhængig af det respektive klimascenarie, hvilket vil påvirke projekternes resultater. Anvendelsen af WHAT-IF til Zambezi casen førte til følgende indblik:

- Med en stigende energi efterspørgsel, er flere vandkraftprojekter fundet økonomisk favorable, og samtidigt i overensstemmelse med miljøregulerende vandkrav. Et tørre klima vil have en effekt på større eksisterende vandkraftværker (Kariba og Cahora Bassa), samt på andre projekter som er sensitive over for klimaændringer. Indførsel af karbonafgift vil favorisere vandkraftsprojekter, mens de forventelige omkostningsoverskridelser vil true flere projekter. Sol- og vindenergi har et højt teknisk potentiale, som burde blive udrullet i praksis.
- Med en reduceret regnmængde og en stigende efterspørgsel af afgrøder, stiger potentialet signifikant for at udvikle landbrug med kunstig vanding. Udviklingen er begrænset af trade-offs med produktionen af vandkraft, især i oplande med store eksisterende vandindvinding, og flere vandkraftsværker nedstrøms (fx Kafue Flats). Det betyder, at arealer, der er kunstigt vandet, sandsynligvis forbliver en mindre del af det samlede opdyrkede område. For at imødekomme fødevareefterspørgsel, bekæmpe fattigdom og reducere klimaændringernes effekter, skal lande fokusere på målsætninger og investeringer, der forbedrer regnvandsbaseret landbrug.

Når projekter med vandkraft og kunstig vanding evalueres i Zambezi, har antagelsen om ”perfect foresight” i modellen en ikke-ubetydelige effekt, men betydningen er lille i forhold til de usikkerheder, som er forbundet med ændringer i klima og samfundsøkonomi. Inklusionen af både energi- og landsbrugssektoren gør det muligt at karakterisere ”hvornår, hvor, hvor meget og til hvilken værdi” vandressourceforbrug har til landbrug og vandkraft under nuværende og fremtidige forhold. Holistisk betragtning af energi- og landsbrugssektoren er forventet at have en vigtig betydning for store projekter, som har en signifikant effekt på den nuværende økonomiske ligevægt. Dette arbejde er et bidrag til udviklingen af modeller, som repræsenterer forbindelser mellem vand-, energi- og fødevaresektoren. Dette er en essentiel støtte til beslutningstagere i at finde løsninger, som opfylder flere verdensmål for bæredygtig udvikling (Sustainable Development Goals, SDG), herunder SDG 1, ”Afskaf fattigdom”, SDG 2, ”Stop sult”, SDG 6, ”Rent vand og sanitet”, SDG 7, ”Bæredygtig energi” og SDG 13, ”Klima-indsats”, samtidigt med at evaluere sammenspillet mellem flere af verdensmålene.

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Abbreviations

FAO	Food and Agriculture Organization of the United Nations
IFIs	International Funding Institutions
MPC	Model Predictive Control
RDM	Robust-Decision-Making
SAPP	South African Power Pool
SDGs	Sustainable Development Goals
WEF	Water-energy-food nexus
WHAT-IF	Water, Hydropower, and Agriculture, Tool for Investment and Financing

1 Introduction

1.1 Background and motivation

The UN general assembly (UN General Assembly, 2015) set the objectives to develop an inclusive society increasing people's well-being by defining the Sustainable Development Goals (SDGs). Developing irrigation, hydropower, and water supply while protecting ecosystems will help contribute to multiple and sometimes conflicting goals: SDG 1: No poverty, target 1.1 "By 2030, eradicate extreme poverty for all people everywhere", SDG 2: Zero hunger, target 2.3 "By 2030, double the agricultural productivity and incomes of small-scale food producers", SDG 6: Clean water and sanitation, target 6.1 "By 2030, achieve universal and equitable access to safe and affordable drinking water for all", SDG 7: Affordable and clean energy, target 7.2 "By 2030, increase substantially the share of renewable energy in the global energy mix".

As the Aral Sea disaster reminds us, those objectives are interconnected, and sometimes need to be traded-off**.** In 1960 the decision to divert the Amu Darya and Syr Darya rivers to massively expand cotton irrigation would lead the Aral Sea, once the fourth largest lake on earth, to dry up within the next 40 years causing a major ecological and social disaster (Saidmamatov et al., 2020). On the other hand, the river basins were an example of transboundary cooperation. The upstream countries used to store water during winter to be released in summer so that it could be used for irrigation in the downstream countries. As hydropower is more valuable in winter for heating, the forgone benefits of upstream countries would be compensated through cheap imports of fossil fuels from downstream countries. This mechanism enabled to maximize the economic productivity of the water resource at the basin level. The end of this cooperation with the end of the Soviet Union further increased the pressure on the water resources, as upstream countries did not rely anymore on imports from downstream countries and started release water in winter for hydropower production (Saidmamatov et al., 2020).

These interrelations are conceptualized as the water-energy-food nexus (Albrecht et al., 2018; Bazilian et al., 2011). While it is commonly acknowledged that the interrelations between the water, energy, and food sectors need to be considered to find synergies and avoid unintended consequence, there are few quantitative tools to support decision-makers in that process. Hence, there is a need to develop such tools in order to enable dialogue among stakeholders.

Currently there is a gap between water resources models that have limited representation of the energy and agriculture sectors, and integrated assessment mode, often from the energy or economic communities, that use simplistic and spatially lumped representations of the water sector.

The decision process is further complicated by uncertainties in future climate and socio-technical-economic changes. Indeed, climate change impacts are uncertain (IPCC, 2014), world population could increase to between 8.5 and 10 billion people in 2050 (KC and Lutz, 2017), the cost of solar power could be halved between 2010 and 2030 (IRENA, 2013). Thus, the world is changing fast and the change is uncertain. The recent pandemic illustrates the importance of considering uncertainty, and that unlikely events can have large impacts. This is the underlying philosophy of robust decision making (Lempert et al., 2003): find solutions that are robust to a range of possible futures rather than try to predict the future with precision and find solutions that perform optimally in the predicted future.

To face these challenges when planning water infrastructure and policies, decision-makers need quantitative tools to assess the impact of projects in a transparent and reproducible manner.

1.2 Research questions

Considering the gap between water resource models and integrated assessment models, the goals of this thesis are to:

Build a decision support tool

Provide a decision support tool for water infrastructure investment and policy planning that can tackle several challenges: transboundary issues, intersectoral impacts between the agriculture, energy, water, ecosystems and economy, and uncertainty in climate and socio-economic change. The tool should be able to evaluate many different solutions in an “zero-order” approach rather than few alternatives in a very detailed way, and be able to answer the following questions:

- What are the physical and economic impacts of a project/plan within a river basin across sectors and countries/regions?
- What are the trade-offs or synergies with other sectors, projects, or plans?
- What are the risks linked to climate or socio-economic change, how can robust projects or plans be identified?

The tool should be open-source and flexible so that it can be applied to different problems and cases.

Answer the following research questions

As the Zambezi River Basin is a central study case in this thesis, a question answered throughout the study is:

> **Research question 1** How connected are the water, energy, and food sectors in the Zambezi River Basin, and what are recommendations regarding hydropower and irrigation development? (Paper **I** and **III**)

On a more general note, the development of the tool, leads to the following research question:

> **Research question 2** What is the added value of representing the energy and agricultural sectors beyond their water demand for water infrastructure planning? What are the important spatial and temporal dimensions? (Paper **I** and **III**)

The adopted approach here is to use a hydroeconomic optimization model, assuming "perfect foresight", which is a common assumption in planning models, but also a known limitation.

> **Research question 3** What is the impact of assuming perfect foresight when evaluating project performance? How to avoid this assumption in hydroeconomic optimization models? (Paper **II**)

1.3 Thesis structure

The thesis is organized as follows:

Section 2 describes the context of the problem, (1) what are the dimensions of the planning problem, (2) what are interrelations within the water-energy-food nexus, and (3) what are existing modelling approaches. **Section 3** describes WHAT-IF, the decision support tool developed during this PhD project. **Section 4** describes the Zambezi River Basin, which was the main study case of this thesis. **Section 5** describes the main results of the thesis, answering the different research questions. **Section 6** shows other applications of the tool. **Section 7** provides general conclusions and **Section 8** details future perspectives.

2 Context

2.1 Water infrastructure planning under uncertainty

The decision support process for problems in complex human-natural systems can be divided in four steps that connect five key elements (Moallemi et al., 2020): (1) planning measures (/projects), (2) performance indicators (/objectives), (3) system model, (4) uncertainty, (5) involvement of decision-makers and stakeholders.

Understanding the context of the problem requires to identify the main stakeholders and understand their initial knowledge, assumptions and objectives.

Framing the problem requires to characterize the underlying human-natural system, define performance indicators that reflect the stakeholder's objectives, identify potential measures and possible future scenarios.

Evaluating the problem requires to implement a model that represents the system and links potential decisions, possible futures scenarios, and performance indicators.

Formulating recommendations requires to extract modelling results, translate results to recommendations and present them to stakeholders.

These processes are iterative in the sense that once recommendations have been formulated, stakeholders might consider new objectives, solutions, and scenarios, which will lead to a new problem evaluation and recommendations. Here these dimensions are reviewed in the context of water resource infrastructure planning under uncertainty.

Planning measures/projects

Planning measures (/projects) can be of various nature: infrastructure (e.g. reservoirs, transfer schemes, power plants), insurance, taxes, and water-rights tools (Kasprzyk et al., 2013; Trindade et al., 2019), operating rules (Quinn et al., 2017; Wild et al., 2021), technology improvement (e.g. efficiency or yield increase). The potential measures can be considered as fixed (Erfani et al., 2020; Huskova et al., 2016), or the sizing, timing and other project characteristics can be part of the planning problem through optimization (Bertoni et al., 2019; Hall et al., 2020) or an iterative-participative approach (Ray et al., 2019). A particular case is the identification of indicators used to trigger measures in the case of adaptive planning (Fletcher et al., 2019b; Herman et al., 2020). The planning can be focused on a single project (Bertoni et al., 2019; Ray et al., 2018), compare a few mutually exclusive alternatives (Baker et al., 2014), or consider a portfolio selection problem among a wide range of solutions (Abu-Taleb and Mareschal, 1995; Hall et al., 2020; Trindade et al., 2019). While considering a single project enables a more detailed analysis and provides detailed insights into the performance of that specific project, results may not be realistic because, most probably, other developments and system changes will take place during the project period. Griffin (2008) also claims that performing the cost-benefit analysis of a single project in growing economies usually leads to the conclusion that the project is profitable; however, it does not mean that it is the best possible project.

Performance indicators

The performance indicators are measures of objectives that stakeholders want to achieve. Sustainable development goals are an example of performance indicators. In optimization models, the performance indicators can be integrated in the objective function. A single objective function is often economic (Fletcher et al., 2019a; Ray et al., 2018), while a multi-objective function might look at different aspects such as costs, demand satisfaction or reliability (e.g. water supply, irrigation, ecosystems), power production, or carbon emissions (Beh et al., 2017; Dobson et al., 2019; Kasprzyk et al., 2013).

To assess the aggregated performance of a measure across multiple scenarios, several robustness metrics exist and reflect the risk-appetite of decision-makers. Among others: mean across scenarios, minimum value (*maxmin*), maximum value (*maximax*), the value of a specific percentile (e.g. value reached in at least 90% of the cases), or a weighted combination of the previous. The *maxmin* metric is dependent on the sampled uncertainties and in general does not identify measures that generalize well over a broader ensemble of uncertainties (Lempert and McKay, 2011; Quinn et al., 2017). Another common approach is a *satisficing* metric, meaning a measure is considered successful if it performs above a given threshold objective. Giuliani and Castelletti (2016) show that a measure will be robust in the sense of the robustness metric it was selected with. Because the robustness metrics might not correctly reflect consensus, or the preference of decision-makers might vary in the future, Giuliani and Castelletti (2016) argue that the choice of robustness metric should be treated as an uncertainty, while Beh et al. (2017) integrate it into a multi-objective function.

System model

It is recognized that water resources are interdependent with other resources such as land, ecosystems, or energy. While many water-centered studies consider other sectors in terms of water users (e.g. hydropower production, irrigation demand), it is identified as a major literature gap to better represent those systems and their socio-economic dimension (Herman et al., 2020; Ray et al., 2019). Among the other main research gaps identified are: the representation of groundwater constraints and water quality, the impact of extreme events, the role of institutions (Herman et al., 2020; Ray et al., 2019).

Uncertainty

Uncertainty can be divided in two categories: *aleatory* (or *variability)* and *epistemic* uncertainty (Walker et al., 2003). Aleatory uncertainty is linked to a random variability intrinsic to a process (e.g. weather), while the epistemic uncertainty is linked to a lack of knowledge of the process. Aleatory uncertainty can be statistically characterized, while epistemic uncertainty is harder to characterize.

The epistemic uncertainty can be divided in four categories: *parametric*, *objective*, *structural*, and *contextual* (Dobson et al., 2019). Parametric uncertainty can relate to the parameters of a hydrological model, parameters of the socio-economic context (e.g. population, demands), parameters of a project (costs, construction time). The most studied, and sometimes only, parametric uncertainty for water planning has been climate change (Fletcher et al., 2019a; Huskova et al., 2016; Ray and Brown, 2015). However, it is recognized that other socio-economic uncertainties might have even more impact than climate change (Herman et al., 2020; Ray et al., 2019). Objective uncertainties relate to the *performance indicator* dimension of the planning problem. Quinn et al. (2017) and Giuliani and Castelletti (2016) explore the uncertainty linked to the robustness metrics. Structural uncertainty relates to how interrelationships between different elements are represented, thus the *system interactions* dimension of the planning problem. Contextual uncertainties relate to how the boundaries of the system are defined (Walker et al., 2003). Dobson et al. (2019) include in that category the assumption of cooperation between different infrastructure operations, and showed that in their study case, this assumption is highest source of uncertainty.

The uncertainty is often qualified as "deep" because the likelihood of the potential future state-of-the-world cannot be assessed. When not explicitly stated studies often apply the *principle of insufficient reason* (Giuliani and Castelletti, 2016), meaning all scenarios are assumed equally likely as there is no reason to assume otherwise. A common step is the *scenario exploration*, to understand which parameters of the uncertainty drive the vulnerability of measures. Kasprzyk et al. (2013) uses a systematic method (Patient Rule Induction Method -PRIM) to link uncertainties to vulnerabilities.

Involvement of decision-makers and stakeholders

Many decision-frameworks have the decision-makers at the center of the process as they combine objective and subjective analyses (e.g. Lempert et al., 2003; Ray and Brown, 2015). Furthermore decision-makers might not trust the results if they do not understand the framework (Dobson et al., 2019).

A robust planning needs to address those five dimensions simultaneously. Indeed, considering a wide range of uncertainties, multiple objectives, but a single or limited planning alternatives, will give decision makers good insights about those alternatives, but might not contain the right candidates. Considering a wide range of alternatives, but failing to characterize the uncertainty, might lead to select biased projects among the right candidates. Considering the right candidates, characterizing uncertainty properly, but failing to represent system interrelations, might hide synergies and trade-offs, thus lead to biased decisions. Without including relevant stakeholders, it is unlikely that system interrelations, uncertainties, and planning alternatives will be correctly considered. Even if a "perfect solution" was found, failing to convince decision-makers, would lead this solution to be never adopted in practice. Hence, overall success of a planning exercise will be limited by the biggest limitations in any of those five dimensions, independently how elaborate the other dimensions are. Thus, the biggest challenge in the planning exercise is to find the right balance between those dimensions within limited resources (human, computational, budget, time). This balance will depend on the context of the planning exercise.

In this work the focus is on the model representing the human-natural system which plays a central role in the decision support process. The role of the model is to (1) link the objectives, planning measures and scenarios by (2) representing the system to (3) formulate recommendations to decision-makers. Here the considered system is the interrelations between the water, energy, and food sectors, and their links with ecosystems, climate, and the economy.

2.2 The Water-Energy-Food Nexus

The Bonn 2011 conference called for a "nexus approach" in order to "enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors" (Hoff, 2011). Many studies and report have since explored the nexus: Bazilian et al. (2011), Miralles-Wilhelm (2016), McCarl et al. (2017), Johnson et al. (2019) and Rising (2020) review modelling and research challenges. While water-energy-food nexus is a common term, sometimes shortened to "WEF" or "FEW" nexus, there is no standardized term and it does not correspond to a specific framework. The name might also explicitly contain "land" and "climate" such as "CLEWs" (Climate, Land, Energy, and Water nexus), as well as "economy", "ecosystems", and "health".

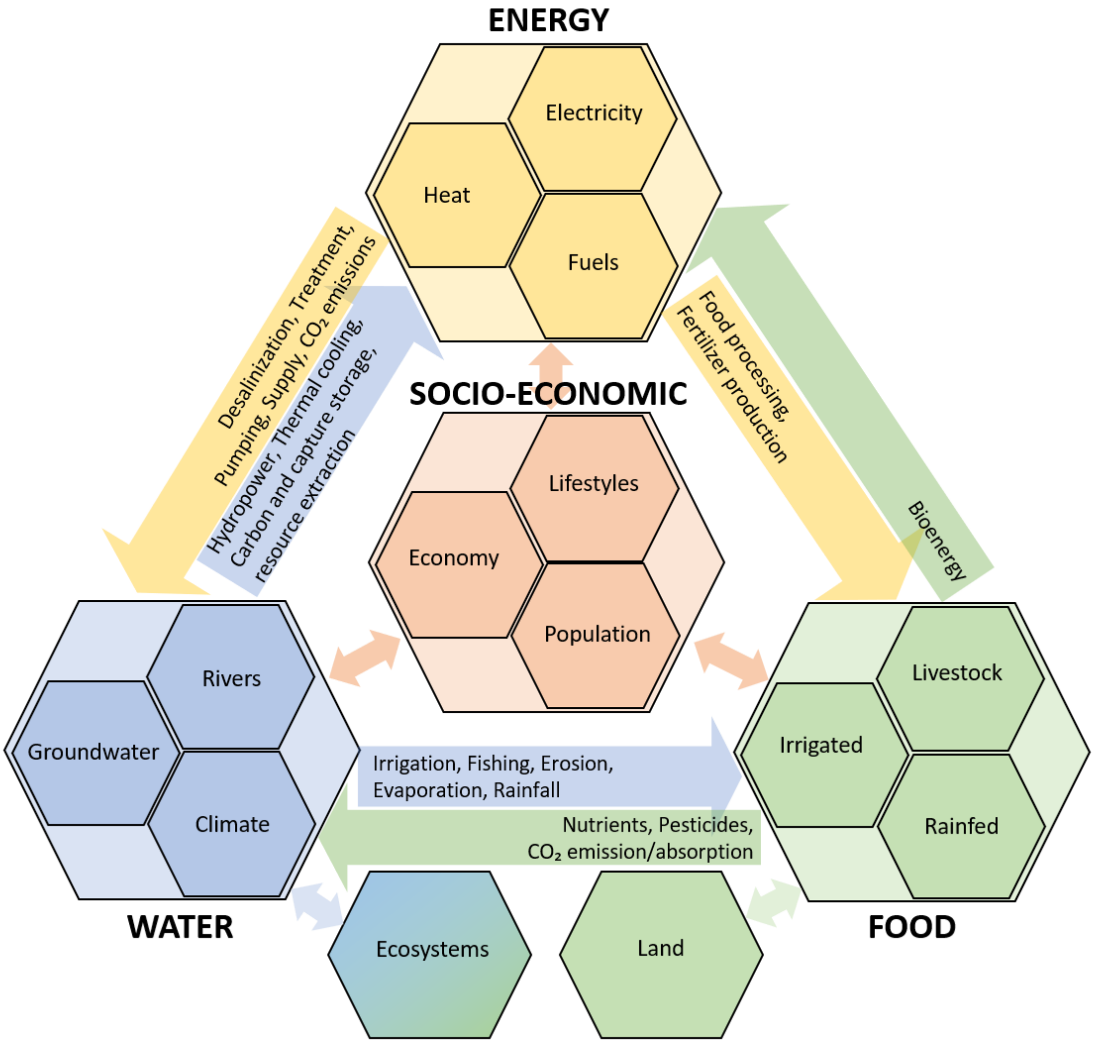


Figure 1. Interrelations in the water-energy-food nexus.

Figure 1 illustrates interrelations within the nexus: About 71% of water withdrawals are for irrigation (McKinsey, 2009), which returns a part of the water to the river, potentially affecting the quality through nutrients and pesticides, and affecting the land, e.g. salinization (Echchelh et al., 2018). Surface water irrigation may require energy, while groundwater irrigation can also affect river flow and is energy intensive (Doukkali and Lejars, 2015). Rainfed and irrigated crops are dependent on climate conditions such as rainfall and temperature (Falkenmark and Rockström, 2006); in turn they also affect the climate through greenhouse gases emissions, and are thus also affected by climate mitigation policies (Van Meijl et al., 2018). Agriculture development consumes land, that often is linked to conversion of pasture and forested area and potentially affects the climate (Lathuillière et al., 2016). Crops or residues of agricultural products can also be used to produce fuels, which potentially can replace fossil fuels and have an important impact on the climate (Mirzabaev et al., 2015), but might threaten the food security of the most vulnerable population (Bonsch et al., 2016).

Electrification can also reduce the use of fuels (cooking and transport), thus reduce the pressure on land, improve the health of populations, but comes at an increased consumption of electricity (Sridharan et al., 2020). The production of electricity relies importantly on water: thermal energy requires water for cooling (Van Vliet et al., 2016; Wang et al., 2019), hydropower plants depend on the river flow (Van Vliet et al., 2016), and carbon capture systems are water intensive (Byers et al., 2014). Electricity and heat production represent 25% of global greenhouse gases emissions (IPCC, 2014) and are thus, an important contributor to climate change. The rapid development of renewable energies (e.g. bioenergy, wind, and solar) could decouple electric production from greenhouse gases emissions (IRENA, 2013). At the same time, it will increase the intermittency in the power system, and can change the current operation of hydropower plants (Chang et al., 2013). The release of water for hydropower production affects withdrawals linked to agriculture and flows to ecosystems like wetlands and deltas (Beilfuss, 2012). Wetlands support basic needs of the population, often the most vulnerable part, as a source for fishing and agriculture (Mccartney et al., 2018). The production of electricity has an important impact on the economy, as it relies on energy to produce and transform goods and provide services (Stern et al., 2018). The economy in turn has impacts on development and access to technologies. Technological developments increasing efficiency, reducing losses and promoting circularity, reduce the consumption of primary resources (Johnson et al., 2019). With a global population that could reach between 8.5 to 10 billion in 2050 (KC and Lutz, 2017), demographic growth has an important impact on the economy and on the demand for water, electricity, food and land. Lifestyles regarding consumption, mobility and environmental awareness can also have important impacts on demands (O'Neill et al., 2017).

Those interrelations do not only connect the different systems, but also the spatial and temporal scale: CO_2 emission and climate affect the entire world and will remain in the atmosphere for decades. Electricity is exchanged over large continental power pools, while rivers connect multiple countries with reservoirs that can store several years of river flow. Crops are exchanged across the entire world, as well as most goods and services, connecting economies in a globalized world.

2.3 Modelling approaches

To understand and quantify these interrelations, models are essential tools supporting the decision-making process. **Table 1** shows different existing models representing interactions within the water-energy-food nexus. This non-exhaustive list aims at illustrating a few methods using different approaches: GCAM (Calvin et al., 2019) belongs to the family of global integrated assessment models; NEST (Vinca et al., 2020) and OSeMOSYS modified (Sridharan et al., 2020) are nexus model originating from the energy sector that use least cost optimization frameworks; Bakhshianlamouki et al. (2020) use a system dynamics framework; Pywr (Tomlinson et al., 2020) is a python based water system simulator; WEAP (Yates et al., 2005) is a widespread water resource management model which has also been coupled to other models in nexus frameworks (e.g. Howells et al., 2013); and WHAT-IF (Payet-Burin et al., 2019) is the model developed in this thesis. While most of these modelling frameworks offer some flexibility in their implementation, they are described here as in the study case of the reference publication. Only quantitative and processed-base models are analyzed here, there are other types of decision support tools that can be used, such as indexes (Simpson et al., 2020), Bayesian networks (Shi et al., 2020), or stakeholder dialogue frameworks (De Strasser et al., 2016).

Table 1. Different modelling approaches. Models that do not claim a specific name, are named after their main publication.

Model	NEST	GCAM	(Howells et al., 2013)	OSeMOSYS modified	Bakhshianlamouki et al, (2020)	WHAT-IF	Pywr	WEAP
Reference(s)	(Vinca et al., 2020)	Calvin et al. (2019)	Howells et al. (2013)	Sridharan et al. (2020)	Bakhshianlamouki et al, (2020)	Payet-Burin et al. (2019)	Tomlinson et al. (2020)	Yates et al. (2005)
Institution(s)	IIASA	PNNL, University of Maryland	KTH	KTH	IHE-Delft	DTU, MIT, COWI	University of Manchester	SEI
Origin	Energy system	Integrated Assessment Model	Energy system	Energy system	Water resources	Water resources	Water resources	Water resources
Goal	Cross-sectorial investments and policies	Emission policies, global impacts	Cross-sectorial investments and policies	Cross-sectorial investments and policies		Water infrastructure and policy planning	Water infrastructure and policy planning	Water infrastructure and policy planning
Type	bottom-up least-cost optimization model, perfect foresight	Global, partial equilibrium model, integrated analytical model, recursive dynamic	Connected models	bottom-up least-cost optimization model, perfect foresight	system dynamic model	bottom-up welfare optimization model, partial equilibrium, perfect foresight	water simulation/optimization multi-objective model	simulation model
Scale	sub-basin, monthly	country-river basin, year	sub-basin, monthly	sub-basin monthly	sub-basin/nodes, monthly	sub-basin, monthly, markets	daily, nodes	daily/monthly, nodes
Sub-models	CWatM, MESSAGEiX		LEAP, WEAP, GAEZ	OSeMOSYS for energy, other sectors "hard" linked				
Decisions	Investments, Trade, Management	Optimized at each time steps (5 years), Investments and technologies	Optimization of management and energy infrastructure decisions, Reservoir operation /allocation iteratively	Optimization of management and infrastructure decisions	input-output rules	Optimization of management decision, optionally investments	Optimization framework wrapped operation rules	Reservoir operation / water allocation, based on operation rule and priority rules
Calibration		Logit functions using observed past data	Manually by user	Crop yield distribution	Rainfall-runoff model	Manually by user: efficiency factors or constraints		Rainfall-runoff model
Land	Land use changes, mainly agriculture versus forest	Land use changes	Agriculture area	Rainfed, irrigated and forested area		Allocation between crops and rainfed/irrigated		
Water	Average decadal monthly as external input, reservoirs, groundwater	Availability constraint by river basin within country	WEAP model	Rainfall, runoff, groundwater availability, but no river network	Lake area and level, groundwater, irrigation and industrial/domestic water use	Hydrology timeseries as exogenous input, reservoirs, groundwater, wetlands	Water allocation, hydrological timeseries, reservoirs, groundwater	Surface and groundwater, different water users, priority rules
Energy	Primary energy resources, energy transformation and energy carrier, energy consumption, CO_2 emissions	Primary energy resources, energy transformation and energy carrier, energy consumption, CO_2 emissions	Primary energy resources, energy transformation and energy carrier, energy consumption, CO_2 emissions	Primary energy resources, energy transformation and energy carrier, energy consumption, CO_2 emissions	Energy demand from water pumps, other agricultural energy uses	Only electric system, production, trade and markets, capacity expansion model, CO_2 emissions	Electric production from hydropower plants	Electric production from hydropower plants
Agriculture	Crop production, land use, residue production	Crop production and global crop market	Crop production	Rainfed, irrigated, and biomass production - no markets	Crop production	Production, yield water response function, crop markets and trade	Irrigation water demand	Irrigation water demand
Climate	Exogenous driver, CO_2 emissions	Exogenous driver, CO_2 emissions	Exogenous hydrology	Exogenous hydrology	Exogenous driver on hydrology	Exogenous driver on hydrology	Exogenous hydrology	Exogenous impact on rainfall-runoff model
Ecosystems	Environmental flow constraints	Environmental flow constraints	-		Lake area as proxy	Environmental flow constraints	Environmental flow constraints	Environmental flow demand
Economics	Total costs, GDP as exogenous driver	GDP (top-down), costs and markets (bottom-up)	Total costs	Total costs	Agricultural benefits	Consumer and producer surplus, no feedback effect	Total costs	
Data	CWatM includes open-source data	Included, current and scenarios linked to SSP's	AEZ for agriculture	AEZ for agriculture	User input	User input	User input	User input
Availability	Open source (https://doi.org/10.5194/gmd-13-1095-2020)	Open source (http://jgcri.github.io/gcam-doc/)	No generic model, build by case	OSeMOSYS is open source (http://www.osemosys.org/)	No generic model, build by case	Open source (https://github.com/RaphaelPB/WHAT-IF)	Open source (https://github.com/pywr/pywr)	License required (www.weap21.org)

Boundary conditions

One challenge is how boundary conditions are represented, in terms of spatial scale and processes. Global models (e.g. GCAM) do not need to define a spatial system boundary as they represent the entire world, while all other models need to work with assumptions regarding interactions with the system spatial boundary. Regarding the water resource, all models in **Table 1** represent the entire river basin and thus avoid assumptions on upstream water use or downstream release requirements. Regarding the energy sector, models representing primary energy resources (e.g. NEST, OSeMOSYS), assume fix import/export costs. With WHAT-IF, in Paper **I,** the entire South African Power Pool (SAPP) is represented to avoid assumptions on potential electricity trade with other countries. Water centered models (e.g. Pywr, Bakhshianlamouki et al. (2020), WEAP), do not represent the power sector and assume exogenous electricity prices. Regarding the agriculture sector, most models assume exogenous import/export prices, while water-centred models usually assume all prices to be exogenous or only consider water demand. The exogenous import/export prices assumption is reasonable if the decisions in the represented area have little impact outside of the model boundaries (e.g. on the global crop market). NEST, that is linked to the global MESSAGEix (Huppmann et al., 2019) integrated assessment model, directly uses as boundary conditions the output from the global model.

Spatial and temporal resolution

The finest spatial and temporal resolution represented in the model has an important impact on interrelations between the different sectors. In fact, interrelations are often driven by scarcity, which might only be visible at a finer temporal or spatial scale (Johnson et al., 2019). The larger the system, the larger the scale: e.g. GCAM as a global model considers countries and river basins as the finest scale. In that case, resource constraints (e.g. water) represent upper boundary conditions. Water centered models like WEAP and Pywr can represent the water resource at the daily scale, while most models represent the water resource at the monthly scale. The spatial scale of water resources models, varies greatly among frameworks: from a few (e.g. Bakhshianlamouki et al., 2020) to a few tens (e.g. NEST, WHAT-IF) of sub-basins of various size. Energy demand and production is usually at the national scale (e.g. Sridharan et al., 2020), while NEST considers intra-national transmission constraints. To represent the (intra-day) variation of the electrical load (/demand), models like

OSeMOSYS and WHAT-IF use "time slices" or "load segments" to divide a monthly/yearly demand into categories (e.g. peak/base demand).

Operation of infrastructure and technological choices

The representation of infrastructure and technologies is usually defined by the engineering characteristics (capacity, costs, efficiency, connections, etc.). The challenge is to represent operation of infrastructure and choice of technologies (e.g. storage and release from reservoirs, cropping decision, type of energy generation, trade). There are two main approaches: (1) the use of operating rules based on physical or economic indicators (e.g. at month *m*, if reservoir level is above *x*, and electricity price is above *p*, release water *q*), (2) the optimization of infrastructure operation and technological choices. Pywr, WEAP, and Bakhshianlamouki et al. (2020) use operating rules, while the other models use an optimization framework or a blend of both.

By using an optimizing framework, one can identify how improved management can lead to additional benefits (Pereira-Cardenal et al., 2016). Furthermore, when evaluating scenarios that considerably change the system conditions, optimizing decisions simulates how infrastructure operation and technological choices can adapt to new conditions. Vinca et al. (2020) compare optimal future energy mixes under different objectives; Sridharan et al. (2020) observe how the optimal distribution between rainfed and irrigated area evolves with increasing electricity prices. Some optimization frameworks use "perfect foresight", in the sense that decisions are optimized assuming a perfect knowledge of the future (e.g. WHAT-IF, NEST, and OSeMOSYS modified). GCAM uses a recursive dynamic framework where decisions are optimized for each time step. In Paper **II**, a recursive dynamic framework is implemented in WHAT-IF by using model predictive control and the impact of the perfect foresight assumption is evaluated.

The advantage of operation rules is that they might better reflect how infrastructure is currently operated. However, when analyzing future scenarios where the system is considerably changed, the current operation rules might not be adapted and may lead to considerable under-performance of the infrastructure. In Pywr, in order to remediate this, the rules can be optimized by wrapping the simulation framework with an (multi-objective) optimization algorithm (see also Bertoni et al., 2019; Gonzalez et al., 2020; Hadka and Reed, 2013; Kasprzyk et al., 2013). This does not only enable the evaluation of planning alternatives, but also gives insights on how specific infrastructure can be operated. The downside is that it can lead to computational barriers when analyzing a large range of scenarios for complex systems: Quinn et al. (2017) use a total of 1.7 million computing hours with such a framework applied on the Red River basin.

Calibration

A calibration step enables tuning of the model to reproduce observed system behavior. For example, GCAM reproduces past technological choices (e.g. power, crops), by calibrating a logit function that is based on option costs and a preference parameter. Models that base choices solely on option costs (e.g. OSeMOSYS modified, WHAT-IF, NEST) might neglect other factors not represented in the model (preference, knowledge, political) and usually require some manual calibration. Those calibrated parameters might however become driving factors when evaluating the system under future conditions (e.g. maximal increase of renewable power sources per year in GCAM).

Coupling models

Some models combine existing single system models: NEST combines CWatM (Burek et al., 2020) and MESSAGEiX (Huppmann et al., 2019); Howells et al. (2013) combine OSeMOSYS (Howells et al., 2011), WEAP, and GAEZ (Fischer et al., 2008). The advantage of using established models is that they are approved and understood by experts in their respective fields, facilitating the dialogue between sectors. Existing models might also already include data (e.g. MESSAGEiX). The coupling can be "hard", in the sense that the framework processes the sub-models simultaneously in a holistic framework (e.g. NEST, OSeMOSYS modified), or "soft", in the sense that models feed each other in a cascade or iterative process (e.g. Howells et al., 2013). The first option might be challenging in terms of model development, while the second might neglect feedback effects and/or require many iterations before reaching equilibrium if sectors are strongly connected.

Data availability

Data availability is often the main driver for (not) considering inter-linkages and for choosing the spatial and temporal scales. The development of satellite observations, global models such as CWatM (Burek et al., 2019), and global databases (e.g. ISMIP https://data.isimip.org/search/) offers an important opportunity for models to systematically assimilate data. **Table 2** lists examples of global data sources that are relevant for modelling the water-energy-food nexus.

Table 2. Examples of global data sources relevant for modelling interactions in the Water-Energy-Food nexus.

Data	**description** **resolution**	**link**
Water system		
Global dam database	Dams with a storage above 0.1 km³	https://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01
Groundwater	Groundwater maps	https://www.whymap.org/whymap/EN/Maps_Data/Gwr/gwr_node_en.html
River discharge	Observed river discharge at stations	http://www.rivdis.sr.unh.edu/ https://www.bafg.de/GRDC/EN/02_srvcs/21_tmsrs/210_prtl/prtl_node.html
Runoff	Gridded runoff monthly 1902-2014	https://www.research-collection.ethz.ch/handle/20.500.11850/324386
Precipitation / ET0	Gridded monthly/daily	https://crudata.uea.ac.uk/cru/data/hrg/ https://wapor.apps.fao.org/catalog/1
Lake and wetlands	Area occupied by wetlands	https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database
Water use by sector	Gridded use by sector, monthly 1971-2010	https://hess.copernicus.org/articles/22/2117/2018/hess-22-2117-2018.html
Energy system		
Energy data	Various type of energy data	https://energydata.info/
Solar potential	Gridded solar potential	https://solargis.com/maps-and-gis-data/download
Transmission network	Shapefile of transmission lines	https://datacatalog.worldbank.org/dataset/derived-map-global-electricity-transmission-and-distribution-lines
Global power plants database	Power plants by type	https://datasets.wri.org/dataset/globalpowerplantdatabase
Agriculture system		
Crop calendar	Crop calendars per crop	http://www.fao.org/aquastat/en/databases/crop-calendar/
FAO stats	Crop production, yield, price, area, trade at yearly and country level	http://www.fao.org/faostat/en/#data/QC
SPAM	Gridded crop area, yield, production, value in 2010	https://www.mapspam.info/data/
Socio-economic		
Population	Gridded population, past and present	https://landscan.ornl.gov/ https://data.jrc.ec.europa.eu/dataset/0c6b9751-a71f-4062-830b-43c9f432370f
SSP's	Shared socio-economic pathways	https://tntcat.**II**asa.ac.at/SspDb
Trade	Trade between countries by year	https://comtrade.un.org/labs/

3 The WHAT-IF tool

WHAT-IF: Water, Hydropower, Agriculture Tool for Investment and Financing was developed to analyze water-related investments in an economic context considering the interactions with the agriculture and power sectors. The model belongs to the family of hydroeconomic optimization models (Bauer-Gottwein et al., 2017; Harou et al., 2009), where water is allocated according to an economic objective.

The original description of the model is available in Paper **I**, the non-perfect foresight framework is detailed in Paper **II**, the investment selection framework is available in Paper **III**. The latest model developments are available in a git repository (https://github.com/RaphaelPB/WHAT-IF). The repository also contains a wiki, a tutorial to set-up WHAT-IF, a description of its various features, and the complete model equations. The following paragraphs summarize the model and its functionalities.

3.1 Representation of the water-energy-food nexus

The representation of the water-energy-food nexus in WHAT-IF is centered around the representation of domestic/industrial water users, irrigation, reservoirs, hydropower and ecosystems (**Figure 2**).

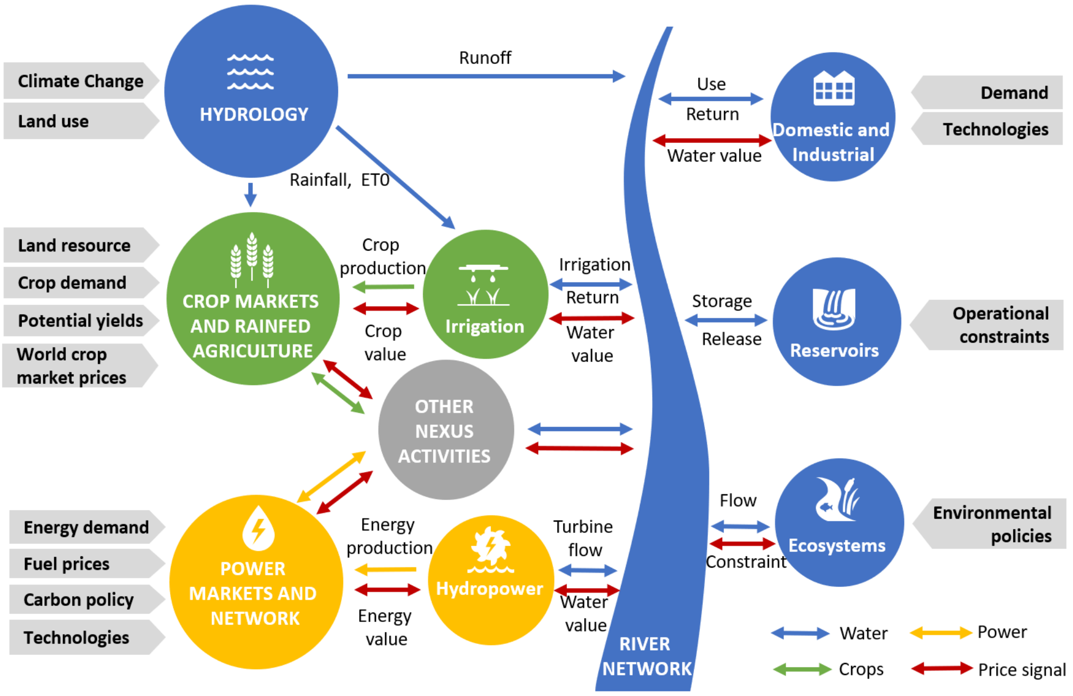


Figure 2. WHAT-IF conceptual framework. All flows are solved holistically to maximize consumer and producer surplus.

The water resource availability is typically represented by an exogenous rainfall-runoff model, while the natural (e.g. river network, lakes) and engineered (e.g. reservoirs, transfer schemes) flow network is represented internally at the sub-basin and monthly scale. Water users (except hydropower and irrigation) are represented through their demand/value, while ecosystems are represented through environmental flow constraints.

The agriculture sector is represented by rainfed and irrigated agriculture, that produce within crop markets (typically at the national scale), while trade occurs between markets (including e.g. a world market). Crop demand is represented per market considering own-price elasticity. The main links with the water resources are rainfall, surface and groundwater supply to agriculture, using mainly the FAO 33 (Doorenbos and Kassam, 1979) and FAO 56 (Allen et al., 1998) for irrigation requirement and yield water response functions.

Power plants (e.g. hydropower, thermal, renewables), produce within power markets (typically at the national scale), that trade through transmission lines, while greenhouse gas emissions are traced. A capacity expansion model represents the development of generic power technologies. Power demand is represented as inelastic, but different load segment (sometimes called "time slices") that sub-divide the monthly demand can be defined (e.g. peak and base demand). Capacity factors for power plants can be defined at the monthly and load segment scale and represent limited availability of power plants. For example, capacity factors can be used to represent seasonal and intraday variability of renewable energies. Hydropower production is dependent on river flow and reservoir releases.

While the previously described processes are predefined in the model (with a flexible implementation), a general activity module represents any other process that consumes and/or produces one or several commodities (land, water, power, and crops) connecting sub-basins, crop markets, power markets and agriculture land. This can represent various processes such as: desalinization (consumes energy and produces water), livestock (consumes land, water and crops and produces another food commodity), food processing (consumes energy, water and crops and produces another commodity), and bioenergy (consumes crops or crop residues and produces energy).

The main exogenous drivers are demand for commodities (water, crops, electricity), technology development (e.g. power technologies, yields, efficiencies), external markets (import/export prices), policies (e.g. environmental constraints, food security policies, carbon taxes), and climate change.

Operation of infrastructure (e.g. releases, water supply, energy production, trade, cropping) is solved simultaneously considering physical and policy constraints to maximize welfare benefits. Welfare benefits are the sum of consumer and producer surplus (see Krugman and Wells, 2005). The optimization framework simulates how operation and management responds to new infrastructure and exogenous climate change and socio-economic drivers. As the model is solved in a single iteration for the entire planning horizon, this results in assuming "perfect foresight" in represented infrastructure operation.

3.2 Model predictive control framework

While the assumption of perfect foresight is common to many long-term planning models, and recognized as a limitation, few studies have analyzed its effect (Dogan et al., 2018). Paper **II** describes how a Model Predictive Control (MPC) framework is integrated to WHAT-IF to overcome this assumption by iteratively running the perfect foresight model with forecasts. Model predictive control simulates how infrastructure can be operated in practice by repetitively answering the question "What are the decisions to take now considering the information we have about the current system state and the prediction of the future?" In fact, this is how the Colorado reservoirs are operated. Every month, the "24-Month study" (Bureau of Reclamation, 2019) predicts the expected behavior of the water system for the next two years to draw the operation rules for the current month. This is particularly relevant for the water system as hydrologic parameters are characterized by a strong variability and uncertainty. It is also relevant for renewable energy production, as well as any uncertain socio-economic parameter such as population growth, demand changes, and technological development. In Paper **II**, the framework is applied to reservoir operation while assuming perfect knowledge of non-hydrologic parameters, but the method can be extended to other parameters and infrastructure operation.

3.3 Investment selection and scheduling

The investment module developed in Paper **III**, represents potential investments with the investment decision integrated into the economic objective function of the model. This is equivalent to an implicit cost-benefit analysis performed within the model that selects and schedules investments according to physical and economic constraints. It can represent how actors adapt to changing conditions (e.g. farmers equip fields for irrigation) or be used to find projects that exploit synergies and avoid trade-offs (Paper **III)**.

4 Zambezi River Basin

The Zambezi River Basin was the central study case of this thesis, and was used in Papers **I, II,** and **III**. The Zambezi River Basin extends over 1.4 million square kilometers over eight countries: Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe. The population was estimated around 40 million people in 2015, and is expected to reach 51 million in 2025 and 70 million in 2050 (SADC et al., 2015). Paper **I** describes the status of the water, energy, and agriculture sectors in the Zambezi River Basin, reviews past studies and projections for the future. The key points are summarized here.

Water

Average precipitation in the river basin is 950 mm, with important variation as the northern and eastern parts receive approximately twice as much rain as the southern part. Average net runoff is around 110 000 Mm^3 per year (Beilfuss, 2012). The main consumptive uses of water are the large man-made reservoirs (Kariba and Cahora Bassa) with around 8 000 Mm^3 per year; irrigation consumptive use was around 3000 Mm^3 per year in 2010, while domestic and industrial consumption, mainly from coal mines, represent a minor share with around 800 Mm^3 per year (World Bank, 2010). The Zambezi River supports vital ecosystems, including the Kafue Flats and the Barotse Plain in Zambia, the Mana Pools in Zambia and Zimbabwe, and the Zambezi Delta in Mozambique.

Energy

The main source of energy is biomass, covering about 80% of the energy demand. Most of the population does not have access to electricity: access rates vary from 12% in Zambia to 40% in Zimbabwe (SADC et al., 2015). The countries in the river basin are member of the South African Power Pool (SAPP). Malawi, Tanzania and Angola are not yet fully connected but projects are under development (SAPP, 2018). While the power pool is dominated by South Africa (80% of power demand) and coal-fired power plants (77% of production), in the Zambezi River Basin, hydropower is the main source of electricity production (World Bank, 2010).

Agriculture and land

Most of the area is covered by bush (75%), cropland represents 13% of the area. Only 5% of the cultivated area is irrigated (SADC et al., 2015), with sugar cane being the most irrigated crop representing 33% of irrigated area (FAO, 2018), while the most common cultivated crop is maize, covering 43% of cultivated area. A majority of the agriculture is smallholder farming, and average yields are far below standard yields (World Bank, 2010). Informal charcoal production for use as cooking fuel, leads to progressive deforestation and land erosion (SADC et al., 2015).

Economy

Gross Domestic Product (GDP) per capita ranges from about 1000 $ in Malawi to 18 000 $ in Botswana. While services represent the biggest share of GDP in all countries, agriculture is still a major contributor in Tanzania, Malawi and Mozambique and is the main labor occupation in all countries (CIA, 2020). Coal, copper, and gold extraction represent an important part of GDP in Angola, Botswana, and Zambia. For example in Zambia, 50% of the electricity consumption is from the mining industry (SADC et al., 2015).

Future scenarios

Under climate change the annual runoff could vary between -50% to +30% (Cervigni et al., 2015). Carbon taxes might be introduced in the power system (IRENA, 2013), while the capital costs of renewable energies are predicted to decrease (IRENA, 2013). As a result, about 80% of new power investments could be renewable energy investment. Average crop yields are expected to double by 2050 due to improved agricultural practices (OECD and FAO, 2017). With population increase and economic development, crop demand is expected to increase by 60% from 2010 to 2030 (IFPRI, 2017), while energy demand could increase by 90% in the same period (SAPP, 2015).

Development plans

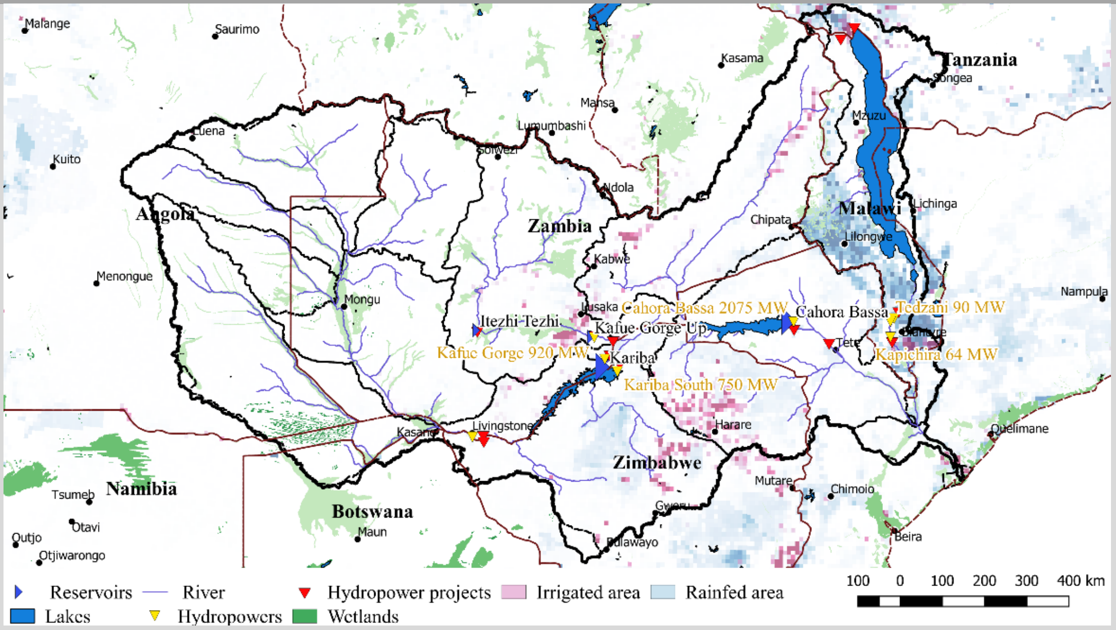
To accommodate the growing demands in the Zambezi, hydropower and irrigation development plans (World Bank, 2010) contain 15 hydropower projects totaling 7.2 GW adding to the existing 5 GW, and 336 000 ha of irrigation projects that could triple current area under irrigation.

BOX 1. The Zambezi River basin in maps.

Wetlands, hydropower, irrigation and rainfed agriculture

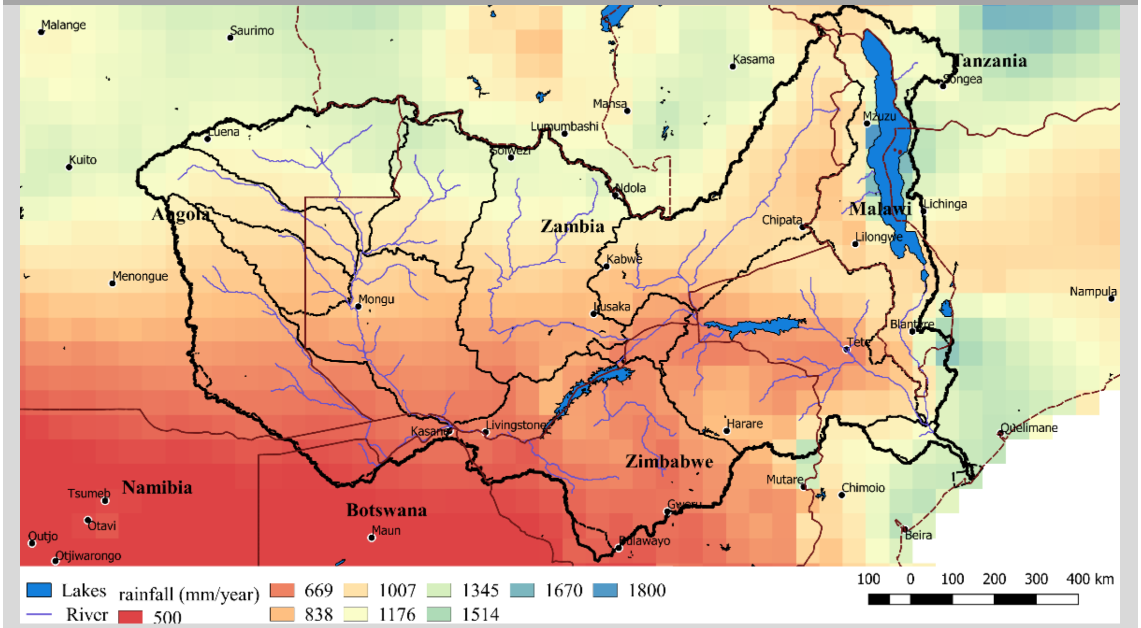
Agriculture area: (IFPRI and IIASA, 2017)

Wetlands: (Lehner and Döll, 2004)



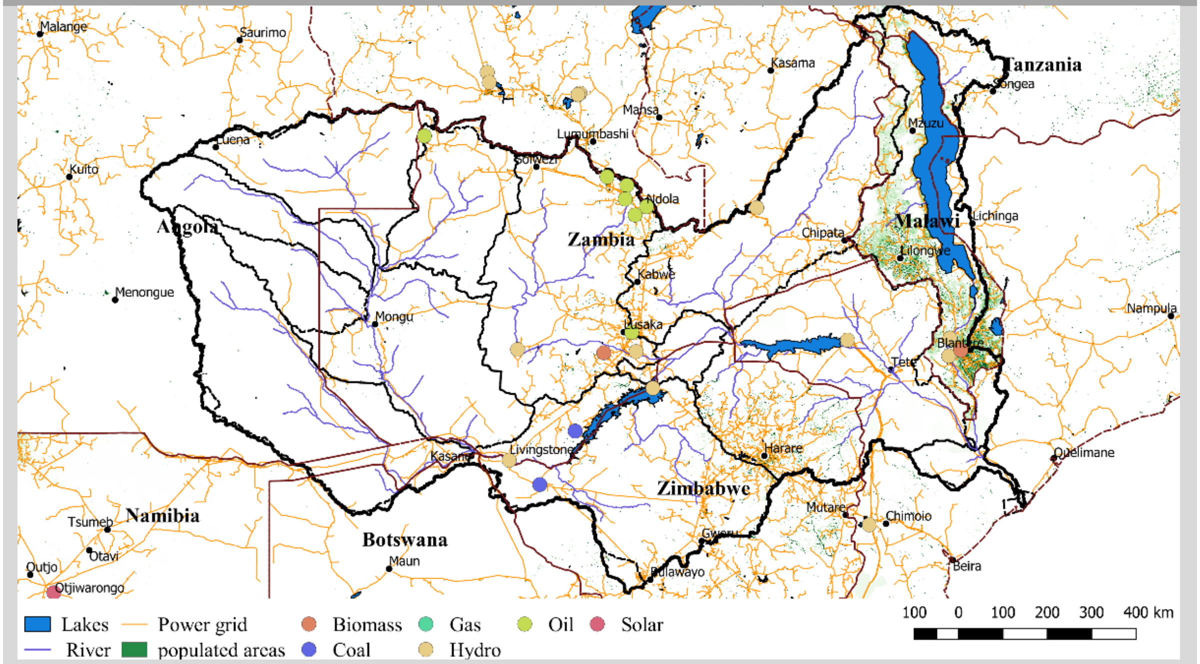
Precipitation distribution in the river basin

Precipitation: (FAO, 2021)



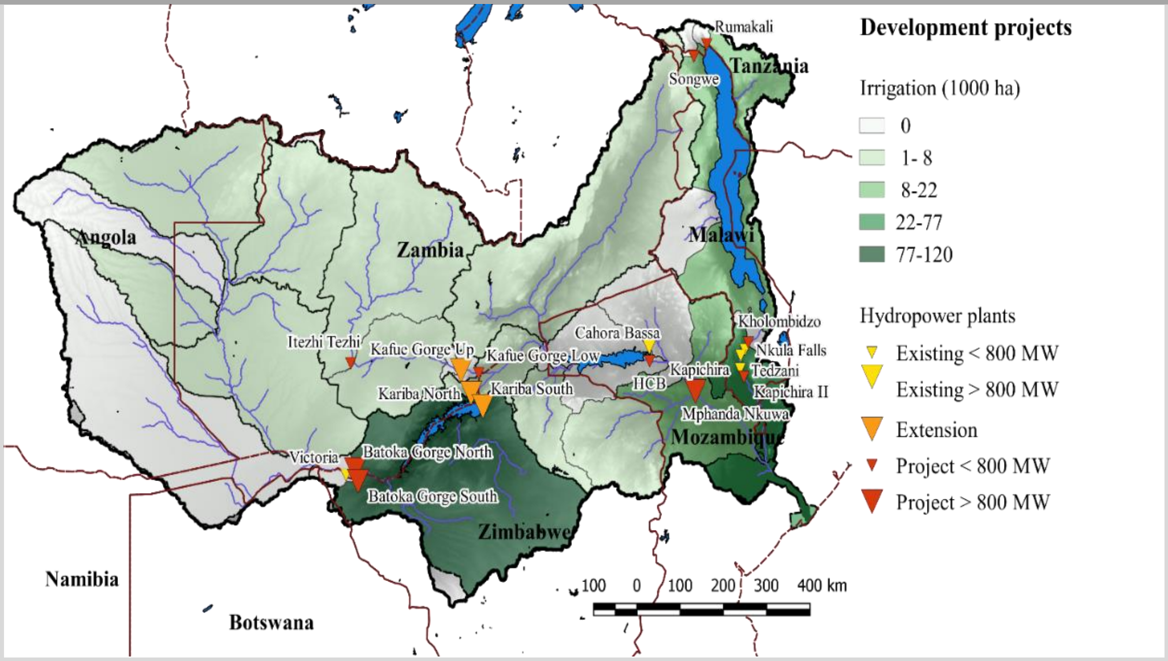
Population distribution, power plants and power grid

Power plants: (Byers et al., 2019)
Power grid: (Fox, 2020)
Populated areas: (Schiavina et al., 2019)



Hydropower and irrigation development projects

reproduced from Paper **I** (Payet-Burin et al., 2019) under Creative Commons Attribution 4.0 License



5 Results and Discussions

This section answers the research questions based on the application of WHAT-IF to the Zambezi River Basin. Firstly, it is shown how the model can evaluate the performance of hydropower and irrigation development projects in the Zambezi River Basin. Secondly, the discussion is enlarged to what are the benefits of representing the agricultural and power sectors, and what are the implications of the "perfect foresight" assumption. As the central study case is the Zambezi River Basin, throughout this section the following question is answered:

Research Question 1 How connected are the water, energy, and food sectors in the Zambezi River Basin, and what are recommendations regarding hydropower and irrigation development? (Paper **I** and Paper **III)**

5.1 Economic evaluation of development plans

As stated in the research objectives, a central question is how WHAT-IF can answer the following questions:

- What are the physical and economic impacts of a project/plan within a river basin across sectors and countries/regions?
- What are the trade-offs or synergies with other sectors, projects or plans?
- What are the risks linked to climate or socio-economic change, is a project/plan robust to an uncertain future?

In Paper **I**, after validating the model set-up on the baseline scenario, with-without analyses of the hydropower and irrigation development plans under different scenarios are performed to answer these questions. In Paper **III**, hydropower and irrigation projects as well as other power plants and transmission lines are considered individually, and investment decisions are integrated in the economic objective function of the model. While in Paper **I** uncertainties are evaluated by changing one parameter at a time, in Paper **III** scenarios are Monte-Carlo sampling of uncertainties.

What are the physical and economic impacts of a project/plan within a river basin across sectors and countries/regions?

In paper **I**, the hydropower development plan is found to produce an additional 30 000 GWh per year, doubling the current hydropower production, which is in accordance with (World Bank, 2010). New projects do not significantly affect reservoir evaporation, as they include small reservoirs compared to the large existing ones (Kariba and Cahora Bassa). The additional hydropower production mainly supplies growing demands in Zambia, Zimbabwe and Malawi, but is fully exported in Mozambique. New projects increase power trade in the South African Power Pool. Economic benefits could reach about one billion dollars per year, with an internal rate of return of around 15%. Benefits are mainly on the producer surplus side, as power prices would be marginally affected. Hydropower projects could save about 23 million tons of CO_2 emissions per year in the River Basin, which roughly corresponds to the combined fossil fuel emissions of Malawi, Mozambique, Zambia, and Zimbabwe.

The irrigation development plan could generate a crop production worth about 700 million dollars per year, which corresponds to an internal rate of return of 26%. About 80% of the irrigation development value is generated through exports, thus the impact on crop prices is not significant, particularly as most of crop production is rainfed. The development plan results in an additional irrigation consumption of 5200 Mm^3 per year (currently 3400 Mm^3), increasing irrigation water use to about half of the total consumptive water use in the river basin.

What are the trade-offs or synergies with other sectors, projects or plans?

In Paper **I**, the additional water consumption of the irrigation development plan is found to reduce hydropower production by 1200 GWh/year (4% of current production). This represents an economic impact of about 50 million dollars per year which corresponds to 7% of the additional irrigated crop production value.

In Paper **III**, hydropower and irrigation investments are evaluated under two frameworks: (1) considering the agriculture and the energy sectors jointly, (2) considering them separately, ignoring their respective water uses. Planning irrigation development while ignoring the (non-consumptive) use of water for hydropower, leads to find economically beneficial 22% more irrigated area than with the integrated framework. This shows that significant trade-offs exist between the use of water for hydropower and irrigation.

Paper **I** explores the opportunity costs of an environmental policy that intends to restore the natural flooding regime of the river by forcing an important water release during the flood period. For an environmental flow below 7000 m^3/s

the policy is found to have little impact on the hydropower and irrigation sectors, while a policy of 10 000 m^3/s generates opportunity costs of around 100 million dollars/year in the current climate. Here environmental benefits of the policy are not evaluated.

What are the risks linked to climate or socio-economic change, how can robust projects or plans be identified?

While the previous results were expressed for the baseline scenario, many uncertainties exist in future projections.

Under the worst climate change scenario, current hydropower production is halved, while new projects produce around 20% less hydropower (Paper **I)**. This shows that, on average, new hydropower projects are more robust to climate uncertainty than the existing ones. In particular, the Kariba and Cahora Bassa dams are found to be over-sized under a drying climate. In Paper **III**, for the most optimistic climate scenarios, an average of 4 GW of new hydropower projects are found economically beneficial. This reduces to only 2 GW under the driest scenarios (**Figure 3**). This shows that not all projects are robust to a drying climate.

The driving factor for the value of hydropower projects is the potential introduction of a carbon tax (assuming the tax reflects a cost to society). The value of hydropower projects is doubled if a 50\$/t-CO_2 tax is introduced compared to no CO_2-tax (Paper **I**). In Paper **III,** it is found that a carbon tax of 25\$/t-CO_2 would increase the share of hydropower projects found beneficial on average by about 50%, while increasing the tax from 25 to 50 \$/t-CO_2eq has little effect (**Figure 3**).

Trade-offs with ecosystems significantly increase under a drying climate: opportunity costs of an ambitious environmental flow policy are multiplied by a factor 4, reaching 800 million dollars per year for a 10 000 m^3/s policy in the driest climate scenario (Paper **I**). Climate change is also found to affect trade-offs between hydropower and irrigation: under the driest scenario the hydropower curtailment generated by additional irrigation represent 10% of the value of the irrigation development plan (Paper **I**). Paper **III** confirms these results: while in the baseline scenario ignoring trade-offs with hydropower production increases the share of irrigation projects deemed profitable by 22%, under the driest climate projections, this figure goes up to 50%.

The value of irrigation projects mainly relies on exports; thus, projects are found sensitive to international crop prices. The projected yield growth is the driving factor, as stagnating yields would reduce the plan's value by around 30% (Paper **I**).

Financial parameters are also found to be driving factors (Paper **III)**, small variations in the discount rate significantly impact the share of irrigation and hydropower projects that are deemed profitable (**Figure 3**). Under high discount rates, thermal power is favored over hydropower and other renewables, as it has higher operational costs but lower capital costs. Construction costs of large hydropower projects are likely to be higher than expected (Ansar et al., 2014; Awojobi and Jenkins, 2015). In Paper **III**, some hydropower projects are found to not be robust to likely cost-overrun.

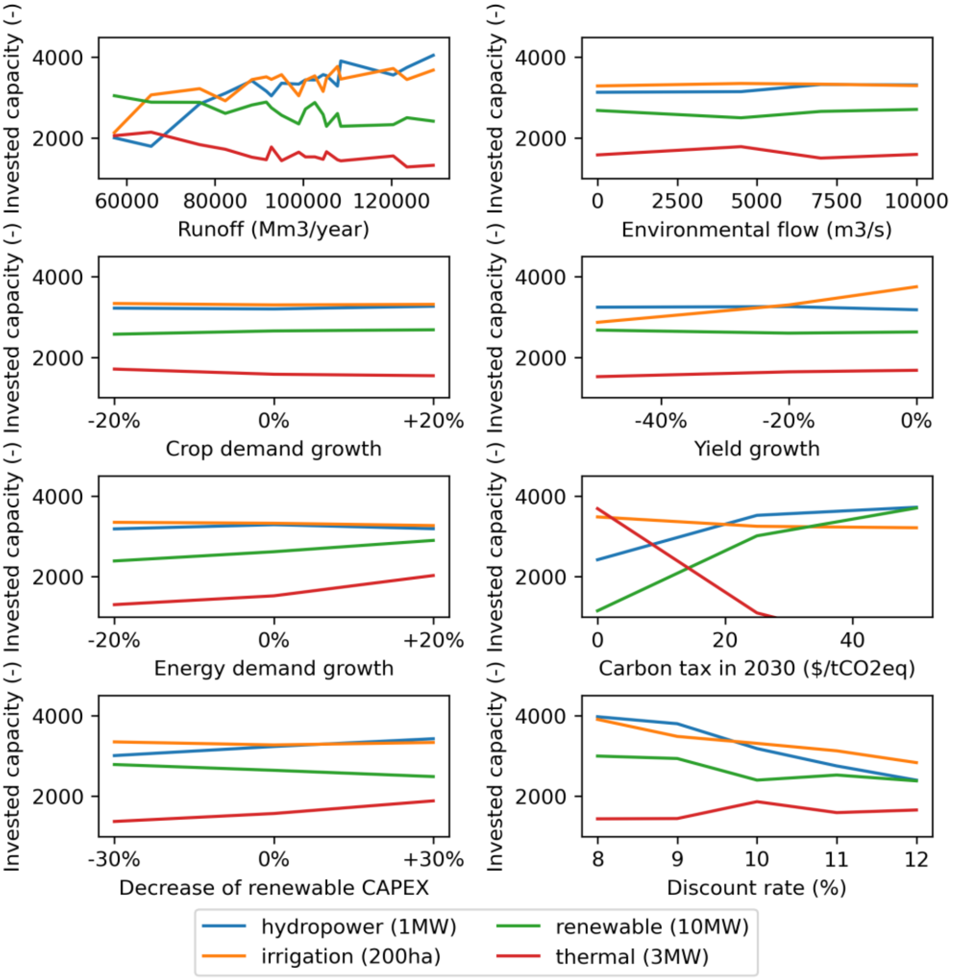


Figure 3. Impact of uncertainties on optimal investments in hydropower, irrigation, thermal and renewable power over the 2020-2050 planning horizon. Invested capacity is the average invested capacity across Monte-Carlo sampled scenarios.

5.2 Representing the agriculture and power sectors

A central question is whereas the previous analysis could have been carried without representing the agriculture and power sectors, simplifying model assumptions. In water-centered models (e.g. Bertoni et al., 2019; Dogan et al., 2018; Tomlinson et al., 2020; Yates et al., 2005) irrigation is considered as a water demand, and hydropower is modelled as a non-consumptive water user generating power that is sold at exogenous prices. However, other producers, demand and elasticity, markets, and trade/transmission are usually not considered.

Research Question 2 What is the added value of representing the power and agricultural sectors beyond their water demand for water infrastructure planning? What are the important spatial and temporal dimensions? (Paper **I** and **III)**

Representing the agriculture and power sector enables: (1) characterizing the water uses (how much, when, where, what value?), (2) representing alternatives reaching the same objectives as water infrastructure/policies, and (3) representing feedback effects with the agriculture and power sectors and finding synergies.

Characterizing the water use and value

In WHAT-IF, using the FAO-56 method (Allen et al., 1998) combined with cropping patterns enables calculating irrigation demands corresponding to the climatic conditions. Considering an average demand would neglect the interannual variability and the potential effects of climate change. The value of crops also dependents on the demand-supply equilibrium, thus representing all producers (i.e. including rainfed) enables representing supply-demand equilibrium variations (and thus price variations) with climatic conditions. However, this could also be addressed by exogenously calculating crop water demand time series and crop prices.

Similarly, representing the power system enables understanding when, how much, and how valuable is water for hydropower production. Currently hydropower is used as a baseload production, also hydropower in the region is usually valuated in terms of "firm" and "secondary" energy (World Bank, 2010). Firm energy, production that can be guaranteed most of the time (e.g. 95%), is more valuable than production that is variable (secondary energy). In fact, in

Paper **I**, modelled current hydropower production by optimizing producer/consumer surplus in the power market leads to similar results in terms of firm and secondary energy as the World Bank (2010) study. However, this is likely to change with the higher penetration of renewable energies, as hydropower can be used to compensate the intermittency in renewable production (Palmintier, 2013). In WHAT-IF, the representation of the power sector enables representing how impacts on other power producers affect the value of hydropower (e.g. carbon taxes and exogenous decrease in capacity costs of renewables in Papers **I** and **III**). Again, the use of exogenous models could also reproduce these effects.

Representing alternatives

As stated by Griffin (2008), when performing cost benefit analysis of water infrastructure projects in growing economies, it is important to consider alternative solutions, as most projects are likely to be found beneficial. Thus, the question is not only if a project is economically feasible, but also if it is the best alternative. For example, the value of equipping an area for irrigation, depends on the productivity of the same area under rainfed agriculture. In Papers **I, II,** and **III** irrigated agriculture is represented as replacing rainfed areas. In the Zambezi, it would be interesting to also evaluate the impact of alternative measures beyond irrigation, like improving soil moisture and fertility management. Similarly, the value of hydropower projects depends on the alternative costs of renewable or fossil power plants. In Papers **I** and **III**, the economic value of hydropower development is found negatively affected by decreasing capital costs of solar and wind power.

Feedback effects and synergies

Feedback effects are observed when water-related infrastructure impact the existing agriculture or power market equilibrium which affect them in turn. A feedback effect is observed between the development of hydropower and renewables. While capital costs of renewable power were found to influence the value of hydropower, the development of hydropower is also found to influence the development of renewable energy (**Figure 4**). Flexible hydropower production compensates intermittent renewable production.

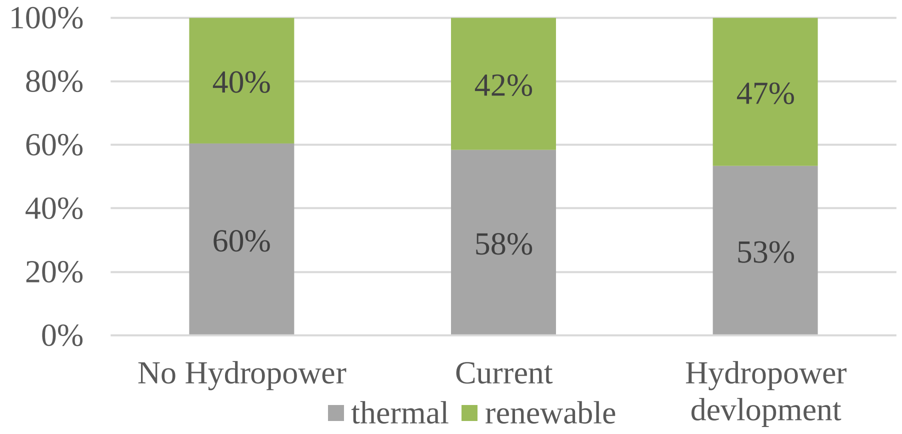


Figure 4. Power investments under different hydropower development scenarios. Thermal and renewable (excl. hydropower) investments are found using the investment selection module. For the analysis to be consistent, in the "No Hydropower" and "Current" scenarios the plants from the "Hydropower development" scenario are modelled with a fix capacity independent from the water resource.

Another example of feedback effect can be observed when evaluating food security constraints in Paper **I**. The irrigation development plan reduces crop imports by 50 million dollars per year under the current climate, but 100 million dollars per year under a drying climate as rainfed production is affected. Thus, an increasing water scarcity affects rainfed agriculture, which increases the value of irrigation, which in turn, stabilizes agricultural markets. Yet, in the Zambezi the effect is limited, as a large share of irrigated crops are produced for export and the irrigation projects remain a small portion of the total cultivated area.

An example of synergy can be found in Paper **I**, as developing the power transmission network positively impacts the hydropower development. The connection of Malawi to the power pool through Mozambique export excess production from Malawi (about 20%), while new transmission lines between Mozambique and South Africa export of all additional production from Mozambique (**Figure 5**).

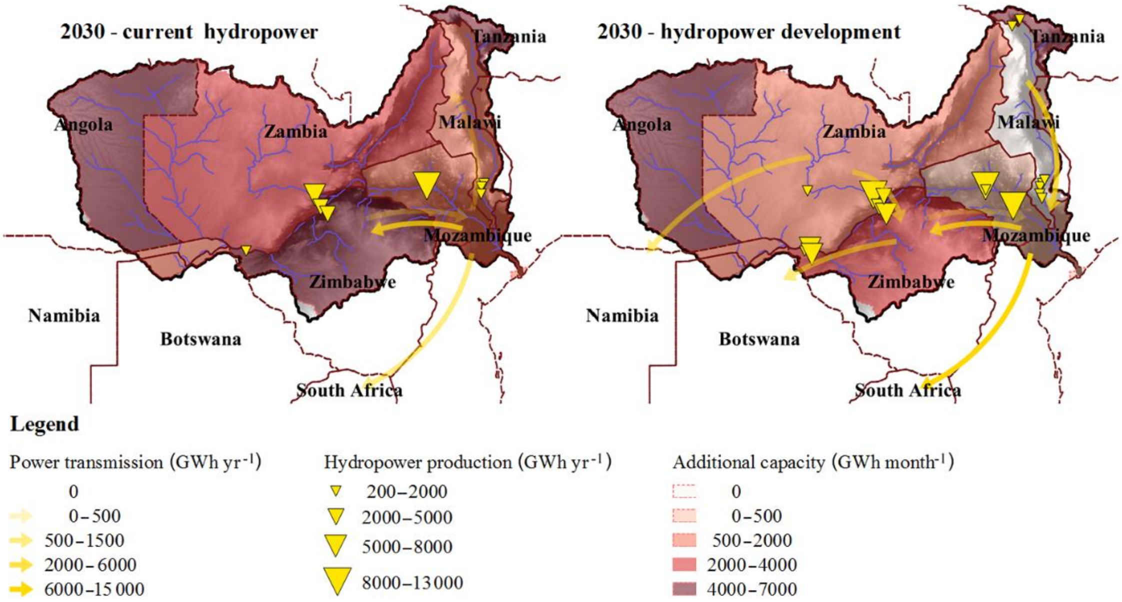


Figure 5. Power trade with and without hydropower development. The figure is reproduced from Paper **I** (Payet-Burin et al., 2019) under Creative Commons Attribution 4.0 License.

Effect of timescale

Another important dimension of the nexus interrelations is the time scale. While most nexus models opt for a monthly timestep and represent seasonal variation, the interannual variability is often neglected. Interannual variability in hydrology is expected to play an important role for water scarcity. In **Figure 6**, the impact of climate change on crop and hydropower production is evaluated by (1) using a time series of climate projections (of runoff, precipitation and potential evapotranspiration), (2) using seasonal rolling average of these projections, keeping only the average climate change effect. Using averaged time series is found not only to underestimate the interannual variability in maize yields, but also to find higher average yields across time series. In WHAT-IF, the endogenous impact of climate on yields is represented through the FAO 33 yield water-response function: lower rainfall will negatively impact yields while higher rainfall positively impacts yields only up to a given threshold. The variability has important impacts on crop prices and thus food security. For cereals the effect is less important as a large share of cereals are irrigated, hence the variability in rainfall can be compensated by irrigation. Hydropower production is found similar for the average and original projections. As most hydropower plants are supported by large reservoirs, the reservoirs can compensate the interannual variability.

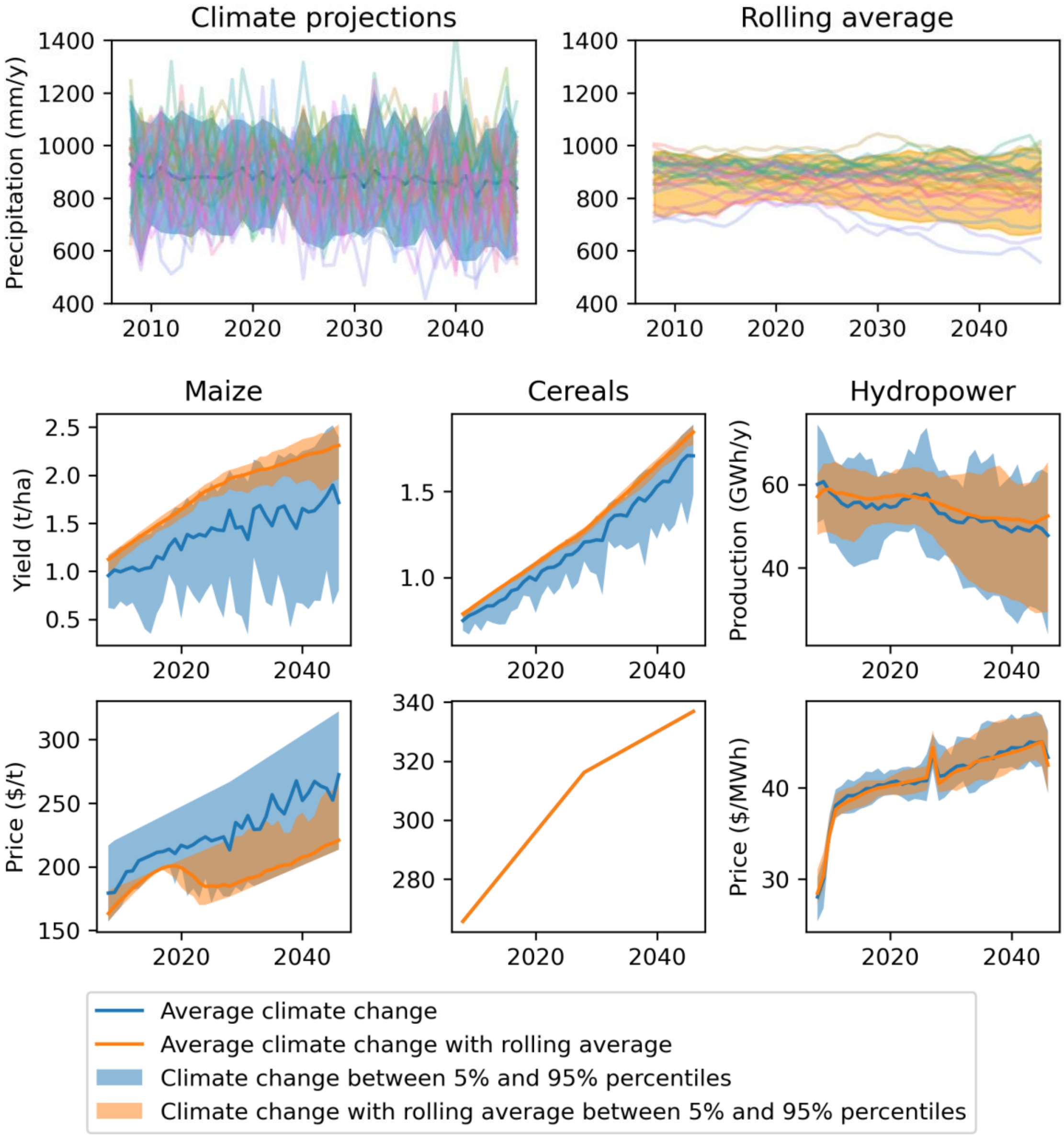


Figure 6. Effect of interannual variability of hydrologic parameter on crop yields and hydropower production. The climate projections consist of 30 different scenarios. The rolling average is the average over the past 2 and future 2 years for the same months.

In the power sector, the resolution of "load segments" (or "time slices") that subdivide the monthly power demand in for example peak and base load is found to have an important impact on the power price. This is found particularly important when evaluating renewable energies with variable availability.

5.3 The impact of assuming perfect foresight

The previous results are presented using a "perfect foresight framework", in the sense that decision variables in the model are solved at once, considering the entire planning horizon. In practice, infrastructure operation and choices are made with a limited foresight of the future, thus this modelling assumption might lead to biased results.

Research Question 3 What is the impact of assuming perfect foresight when evaluating project impacts? How to overcome this assumption in hydroeconomic optimization models? (Paper **II)**

Paper **II** shows how to overcome this assumption by using the perfect foresight model within a Model Predictive Control (MPC) framework. With MPC, the decisions are solved at each time step (month/year) in an iterative process, using a forecast for the future. The perfect foresight framework is found to anticipate high and low flow conditions, by storing or releasing more water. Implementing the MPC framework leads to more realistic reservoir operation.

Paper **II** compares the perfect foresight and MPC frameworks when evaluating economic impacts of different hydropower and irrigation projects under different climate change scenarios (**Figure 7**).

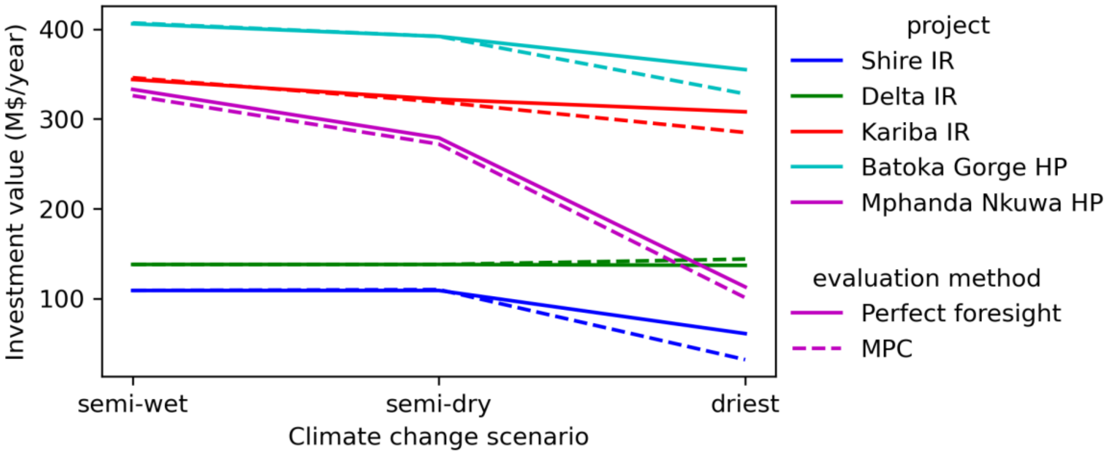


Figure 7. Impact of perfect foresight on the economic analysis of infrastructure development under different climate change scenarios.

In the Zambezi case, the study finds that the value of hydropower and irrigation projects is overestimated with perfect foresight (mostly below 10%). The effect is found more important under a drier climate change scenario. However, when comparing the sensitivity of project value to the evaluation method (with or without perfect foresight) compared to the sensitivity of projects to climate change, it appears that climate change is the driving factor and that perfect foresight plays a secondary role. Furthermore, Paper **I** and Paper **III** show that socio-economic uncertainties can have even more significant impacts on project performance. Thus, in the Zambezi River Basin, the conclusions reached in Paper **I** and **III** under perfect foresight can be considered valid, and not particularly sensitive to the perfect foresight assumption.

In general, perfect foresight can impact the evaluation of project performance, particularly in a context of water scarcity. Using a method like Model Predictive Control makes it possible to overcome the assumption while still using the original model. However, when evaluating the robustness of investments, the bias introduced by perfect foresight might be small compared to the impact of multiple uncertainties. Thus, a balance needs to be found between increased computational costs to overcome the perfect foresight assumption and exploration of uncertainties.

6 Other applications of the tool

The tool adopted a generic framework so that it could be used in other study cases and for COWI's consulting activities. The following sections briefly describe other applications of WHAT-IF.

6.1 Supporting IFIs and River Basin Organizations

The thesis is part of an industrial-PhD project; thus, outcomes are expected to have a commercial significance. Besides, consultancy companies are often an important actor in the planning process. COWI expects business opportunities of around 10 million DKK within the next four years in model-based services to International Funding Institutions (IFIs). Expected beneficiaries are River Basin Organizations and Ministries in low- or middle-income countries. An example of such projects is the "Development of a regional hydrological platform and a multi-sector nexus model for the Amazon basin". COWI and The Nature Conservancy, will use WHAT-IF to support the Amazon River Basin Organization (OCTA) and the Inter-American Development Bank to identify investments needs and their inter-linkages in the water-energy-food nexus. In this task, it was required to use a model with an endogenous representation of the energy and agriculture sectors.

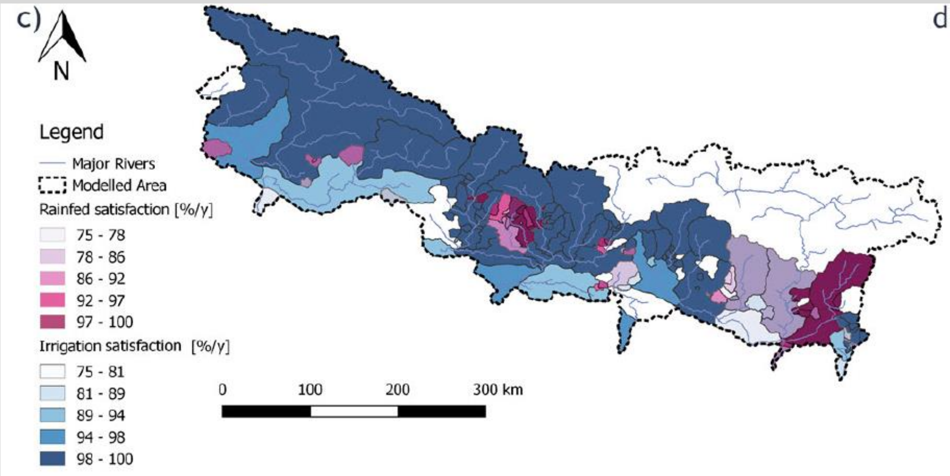
To promote the model and its potential applications, a website has been developed (https://www.what-if-software.dk/).

6.2 Bachelor and master theses

The WHAT-IF tool has been used for several Bachelor and Master theses that have contributed to the modelling framework (**BOX 2**).

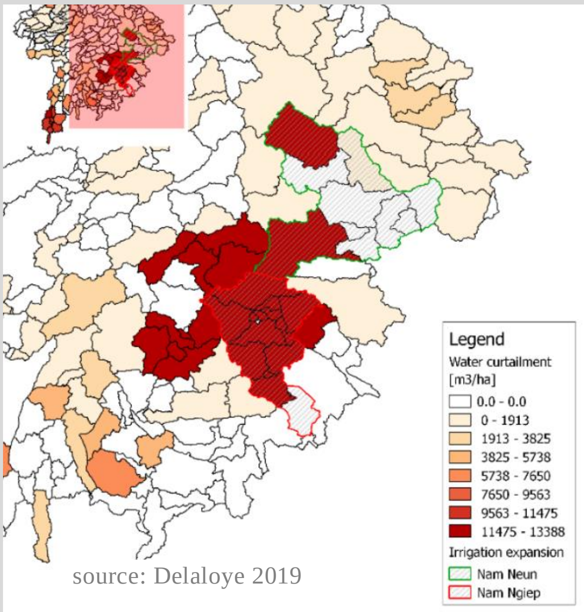
BOX 2. Bachelor and Master theses using WHAT-IF

Modeling the Water-Energy-Food nexus in **Nepal** for water infrastructure investment planning (Thorvaldsdottir, 2018)



The study evaluates several irrigation, hydropower, and transmission lines projects in Nepal. The study performs a cost-benefit analysis for all projects and identifies the feasible projects. Co-investment in hydropower and transmission lines is found to be an important factor for the feasibility, irrigation projects are found to be beneficial mainly in the downstream areas. Additionaly, the better connection of cultivated fields to crop markets would enable increasing agricultural productivity.

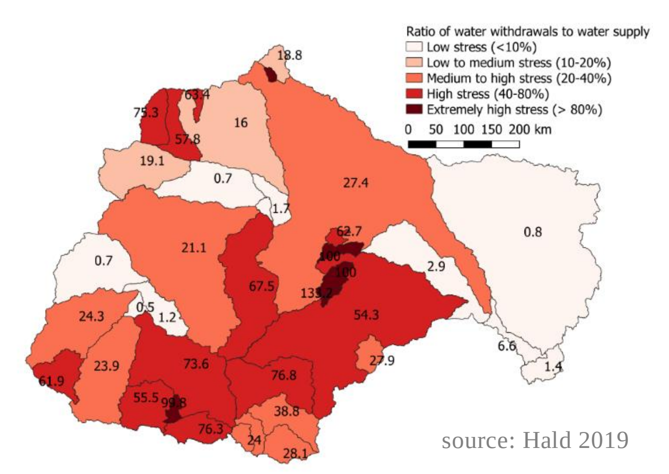
A hydroeconomic optimization model to support water resources management in **North-Eastern Laos** (Delaloye, 2018)



source: Delaloye 2019

The study evaluates several hydropower and irrigation projects in the North-Eastern Laos. In general, the study finds that hydropower projects have higher economic return than irrigation projects. Some irrigation projects found beneficial without hydropower development become non profitable with hydropower extension. Thus, the development of hydropower and irrigation should be coordinated to avoid trade-offs.

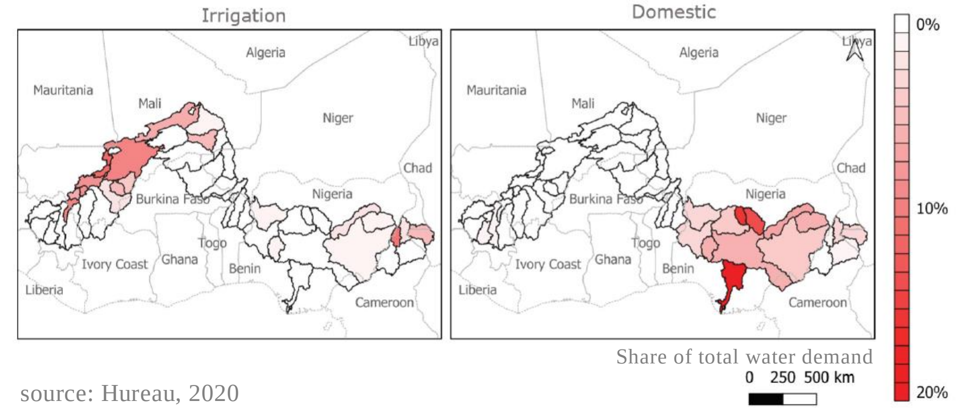
Hydroeconomic analysis of the **Limpopo River basin** (Hald, 2019)



source: Hald 2019

The study evaluates the water use in the Limpopo river basin. The water resource is found to be very scarce, as in several catchments more than 80% of the runoff is allocated to irrigated agriculture. The river basin is thus particularly sensitive to droughts and climate change.

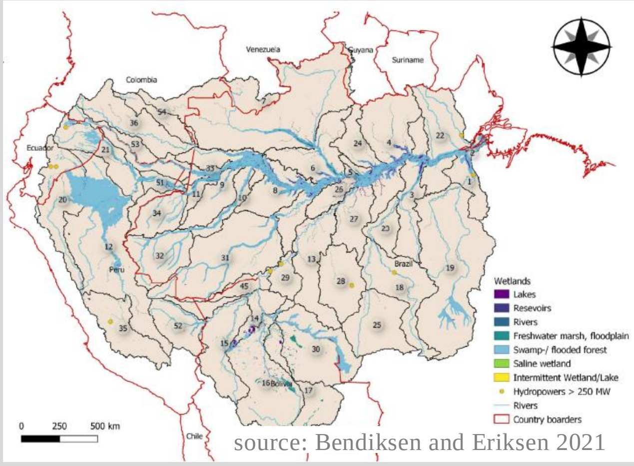
Hydro-economic analysis of infrastructure investment options within the Water-Energy-Food nexus in the **Niger River basin** (Hureau, 2020)



source: Hureau, 2020

The study evaluates irrigation and hydropower development plans in the Niger basin. No trade-offs are found between the development of hydropower and irrigation plans. Unless massive irrigation expansion far beyond the current plans, the Niger Inner Delta is more threaten by climate uncertainty than human activity.

Hydroeconomic analysis of the water-energy-food nexus in the **Amazon Basin** (Bendiksen and Eriksen, 2021)



source: Bendiksen and Eriksen 2021

The study analyses the trade-offs between environmental flows, hydropower production, livestock and soybean agriculture in the Amazon. Water is not found scarce. Measures that intensify rather than expanding livestock production could enable increasing crop production without increasing deforestation.

7 Conclusions

A decision support tool for water infrastructure planning with a holistic representation of the power and agriculture sectors was developed. WHAT-IF is open-source and has a flexible implementation, thus, it can be applied to other river basins for water infrastructure and policy planning studies.

The modelling framework developed here is a contribution to bridge the gap between water-centered models that do not represent the agriculture and power sectors, and integrated assessment models that have a simplistic representation of the water resource. Many similar efforts are currently going on.

In the Zambezi River Basin, the tool was applied to evaluate irrigation and hydropower development under climate and socio-economic uncertainties. The main findings can be summarized as follow:

- Given that the demand for crops will considerably increase in the next decades with a growing population, and that climate change will have major impacts on the current rainfed production, there is potential to develop irrigation. However, irrigation development is constrained by trade-offs with hydropower production and eventually ecosystems. Thus, irrigation will only be a limited share of the solution. To feed the growing population and adapt to climate change, enhancing rainfed agriculture will also be key.
- Given that the demand for electricity will grow even faster than the food demand, there is potential for hydropower development. Climate change will particularly impact the performance of existing hydropower plants, and not all new hydropower projects are robust to a drying climate. The new hydropower projects are compatible with environmental flow policies, yet no local environmental impact assessment was performed here. Another major risk for large hydropower dams comes from financial parameters, under likely cost overruns and delays some projects are found to potentially not be beneficial. Technically, wind and solar power have important potential in the area, it is important that this potential is unleashed in practice.

In general, representing the agriculture and power sectors characterizes the water uses (e.g. irrigation and hydropower): when is the water needed, where is it needed, how much is needed, and how valuable is it? This is particularly important when analyzing a large range of scenarios that divert from the current system state.

This could also be achieved by linking to exogenous, sector-specific, models. Exogenous models might require more efforts but can have a more detailed representation of the power and agriculture sectors. However, when evaluating projects that might considerably change the existing equilibrium, important feedback effects can take place and should be considered. For example, irrigation can stabilize variability in crop supply linked to climate variability, hydropower plants can stabilize intermittency constraints or seasonal variation in the power sector. Thus, a balance should be found between the level of accuracy of the power and agriculture sectors representation, and the level of integration. This balance is likely to be case dependent. Finally, considering the energy and agriculture sectors enables considering a larger range of solutions that can achieve the goals pursued by water-related infrastructure.

Uncertainty is an essential aspect of the planning process. The optimization framework enables to simulate how operation and management decisions could adapt under radically different scenarios. A simulation framework is likely to have a more accurate representation of the current state but might face challenges when exploring scenarios. The "perfect foresight" assumption of the optimization framework is found to have a non-negligible but small impact compared to uncertainties linked to climate and socio-economic changes. An alternative to the "perfect foresight" assumption is to run the model with a Model Predictive Control framework which was implemented here.

This work focused on the importance of the energy and agriculture sectors for water infrastructure planning. However, it also revealed that it might be important to reframe the question from "how to plan water infrastructure/policies considering the food and energy sectors ?" to "how to plan water, energy and food infrastructure/policies considering their inter-linkages?". While this would require important institutional changes, answering this question will be key to identify solutions that tackle the challenges posed by climate and socio-economic changes, considering the full range of trade-offs and synergies.

8 Future perspectives

Measuring the Sustainable Development Goals

While it has been mentioned that planning water infrastructure within a water-energy-nexus framework can evaluate the synergies and trade-off between multiple SDGs, few specific SDG indicators have been used in this analysis. Several studies have qualitatively shown the interlinkages between the SDGs (e.g. Baldassarre et al., 2019; Nerini et al., 2019; Zhou and Moinuddin, 2017), but few studies have used quantitative approaches (Van Vuuren et al., 2015).

BOX 3 lists the most relevant goals and indicators for water-related infrastructure and how they can be assessed with WHAT-IF or how they could be integrated with further development.

Land and ecosystems

The work highlighted how rainfed agriculture in the Zambezi is threatened by climate change and at the same time the limits of irrigation. Falkenmark and Rockström (2006) show that globally satisfying future food demand cannot fully be achieved by increasing irrigation but requires a more efficient "green water" management. Representing the green water cycle, would enable modelling solutions like increasing rainwater capture and improving soil moisture and fertility management, such as conservation agriculture (SDG target 2.4).

Then, large land use changes can impact the hydrological cycle (Lathuillière et al., 2016; Schilling et al., 2008), which would in turn affect water uses. Furthermore, major trade-offs between ecosystems and agriculture are likely to be on the land resource (Johnson et al., 2019). Evaluating these effects would require a more detailed representation of the land resource and to integrate in (or out of) the model the link between land use and the hydrological cycle. This could be used to assess the impacts of converting forested area or wetlands to cultivated area (SDG target 15.1).

Demand side measures

The work showed how representing demand can be important to the evaluation of supply-side infrastructure. It also enables representing demand side measures, as an alternative or complement to supply infrastructure. One can investigate the benefits of shifting energy load from peak to off-peak periods (Strbac, 2008), improvement in electricity transmission and distribution losses (Sadovskaia et al., 2019), and improvement in irrigation efficiency related to

SDG 6.4 (Bakhshianlamouki et al., 2020; Dubreuil et al., 2013). All these measures can also have feedback effect on other sectors and are thus particularly relevant in an integrated framework like WHAT-IF.

Data sources

In many cases, a limitation to represent more interactions or a finer spatial/temporal scale is the lack of data or the cost of data assimilation. Satellite observations and global databases offer an important opportunity to systematically collect data. Some automated data collection was developed (using e.g. SPAM and GRUN), yet a fully automated basic set-up of the model for any river basin(s) would be of great value. The basic set-up could be used as a starting point to initiate discussion among stakeholders and then be updated with local data according to the identified needs. This would also enable having a continental/global scale model that would be particularly relevant to evaluate inter basin transfer, connection of power pools or crop trade policies.

Groundwater and water quality

While groundwater can be represented in the model through simple linear reservoirs it has not been evaluated in the Zambezi River Basin. Representing groundwater enables representing alternatives to surface water irrigation (MacDonald et al., 2012), withdrawal sustainability issues, and connections with energy policies (Turner et al., 2019). In some regions, energy subsidies are found to lead to groundwater overdraft, while subsidies on irrigation efficiency improvement could reach similar goals while generating co-benefits for other water users.

Water quality can be an important factor of water scarcity (Van Vliet et al., 2017) and is considered a major research gap for water planning (Herman et al., 2020; Ray et al., 2019), related to SDG target 6.3. Here, we only considered the quantitative aspect, but various approaches could be implemented: coupling the model to a water quality model (e.g. Boehlert et al., 2015; Wild et al., 2021), using static water quality classes (e.g. Martinsen et al., 2018), or using Artificial Neural Networks as surrogate models for high fidelity water quality models (Shaw et al., 2017). This would represent quality constraints on the water use or on operation of reservoirs, as well as the impact of new projects (e.g. reservoirs, agriculture expansion) and climate change. This could also be used to prioritize interventions on water quality (e.g. wastewater treatment plants, change in agricultural practices) while considering the full range of impacts on the water, agriculture, and energy sectors.

Economywide impacts

WHAT-IF is a partial equilibrium model (of the water, power, and agricultural sectors) which implies that sectorial economic impacts are not further propagated to other sectors of the economy. Additionally, the aggregated utility function (total consumer and producer surplus) implies that distributional effects are ignored.

Computable General Equilibrium (CGE) models represent all economic flows between actors and markets. The combination of a microeconomic framework and macroeconomic rules enables representing the impact of policies and infrastructure both at the household level (including distribution effects) and the macro level. Thus, coupling WHAT-IF to CGE models would lead to better assess economy-wide impacts of planning measures (Luckmann et al., 2014; Nielsen et al., 2016). This would particularly improve representation of SDG targets 1.1 and 8.3. For example, Robinson and Gueneau (2013) coupled a CGE model to a water model to assess economywide impacts of the Basha dam on the Indus river.

Role of institutions and humans

While the model is limited to the representation of the natural-engineered system, institutions and humans play a key role in efficient resource management (Baldassarre et al., 2019). Agent-based models represent these interactions by explicitly representing the behavior of individual agents (Magliocca, 2020). In WHAT-IF all agents are implicitly assumed to be rational and maximize utility within perfect markets for the water, electricity, and crop commodities. Using agent-based modelling, one could represent various actors (e.g. farmers, hydroelectric producers, water allocation agencies) that have different objectives and knowledge. This can help identify the sphere of influence of different stakeholders and where external interventions can improve the situation (e.g. remove capital barriers). The assumption of full cooperation could be also treated by representing different agents (e.g. upstream/downstream countries) maximizing their individual profit (e.g. Britz et al., 2013; Quinn et al., 2017; Tilmant and Kinzelbach, 2012) which would enable evaluating the impact of transboundary agreements (SDG target 6.5).

BOX 3. Implementing SDG indicators in WHAT-IF. Status: + and ++ indicate the level of development required by the implementation of the SDG target.

Goals and targets (UN General Assembly, 2015)	**Indicators**	**Status**	**How to measure/implement in WHAT-IF**
Goal 1. End poverty in all its forms everywhere			
1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day	1.1.1 Proportion of the population living below the international poverty line by sex, age, employment status and geographic location (urban/rural)	++	Consider distributional effects to measure impacts on the poorest.
1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	1.4.1 Proportion of population living in households with access to basic services	+	Consider impacts of projects on basic services (e.g. water and sanitation, electricity)
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture			
2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES)	+	The scale is a questionnaire, but commodity prices, or productivity of subsistence agriculture could be used as a proxy.
2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	2.3.1 Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size		Divide agriculture production by classes (available)
	2.3.2 Average income of small-scale food producers, by sex and indigenous status		Producer surplus of small-scale producers.
2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	2.4.1 Proportion of agricultural area under productive and sustainable agriculture	+	Include a more detailed soil moisture and management representation
2.b Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round	2.b.1 Agricultural export subsidies		Represent taxes as a cost in the objective function, to see impacts on trade, prices, consumer and producer surplus.
Goal 6. Ensure availability and sustainable management of water and sanitation for all			
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Proportion of population using safely managed drinking water services	+	Use as an indicator or constraint when evaluating investments needs.
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1 Proportion of domestic and industrial wastewater flows safely treated	+	Use as an indicator or constraint when evaluating investments needs.
	6.3.2 Proportion of bodies of water with good ambient water quality	++	Represent water quality and use as indicator/constraint.
6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.1 Change in water-use efficiency over time		Measure water productivity of agriculture.
	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources		Use as indicator
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation	+	Measure benefits of cooperation by modelling with and without cooperation.

BOX 3. Implementing SDG indicators in WHAT-IF. Status: + and ++ indicate the level of development required by the implementation of the SDG target.

Goals and targets (UN General Assembly, 2015)	**Indicators**	**Status**	**How to measure/implement in WHAT-IF**
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	6.6.1 Change in the extent of water-related ecosystems over time		Measure impact of projects on wetland area. Add as a constraint or objective.
6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan		Use as an indicator when establishing investment plans.
6.b Support and strengthen the participation of local communities in improving water and sanitation management	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management	++	Would require representing the role of institutions/agents.
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all			
7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.1 Proportion of population with access to electricity	+	Use as an indicator or constraint on investments.
	7.1.2 Proportion of population with primary reliance on clean fuels and technology	+	Represent the impact of electrification on the impact of clean fuel use
7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption		Use as an indicator/constraint on investments.
7.3 By 2030, double the global rate of improvement in energy efficiency	7.3.1 Energy intensity measured in terms of primary energy and GDP		Use as an indicator/constraint on investments.
7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support	7.b.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)		Use as an indicator/constraint on investments.
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all			
8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services	8.3.1 Proportion of informal employment in total employment, by sector and sex	++	Represent impact of projects in terms of employment
Goal 12. Ensure sustainable consumption and production patterns			
12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	12.3.1 (a) Food loss index and (b) food waste index	+	Assess impacts of reducing market losses.
Goal 13. Take urgent action to combat climate change and its impacts			
13.2 Integrate climate change measures into national policies, strategies and planning	13.2.2 Total greenhouse gas emissions per year	+	Represented for electricity, extend to agriculture
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss			
15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	15.1.1 Forest area as a proportion of total land area	+	Use as an indicator/constraint on investments (e.g. agriculture expansion)
15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	15.3.1 Proportion of land that is degraded over total land area	+	Use as an indicator/constraint on investments (e.g. agriculture expansion)

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Papers

I WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water–energy–food–climate nexus

II The impact of assuming perfect foresight for investment analysis in water resources systems

III Silo versus Nexus investment planning under uncertainty

In this online version of the thesis, **paper I-III** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from:

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