MAXUS

Synergizing water, food and energy policy

R. (Rogier) E. A. Burger

On the cover is a picture that I took on field research in Ghana. The women depicted had been working the whole day to harvest, while 100 meters down the road, a combined harvester cleared the field at three meters per second. Upon asking if I could take a picture, they smiled at me and one of them asked: "Only if you give us all a bottle of water". By chance, I happened to have one bottle of water and gave it to them. Then I felt it was the right moment to ask, if they found it unfair that the neighbour had a machine. They said: "We shouldn't be doing this, but it will change." And then they continued working.

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by

R. E. A. Burger

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Field trip visit to Dalun, Ghana

SUMMARY

Population growth, meat-focused diets and emerging industries are increasing stress on water, energy and food (hereafter: WEF) supply around the globe. As stress on the resources rises, the interdependencies between the sectors become more apparent and often lead to unforeseen chain reactions. An example of which is: a drought leads to disappointing hydropower generation that leave groundwater pumps inoperable, which in turn lead to disappointing harvests.

Because of these chain effects, synergizing water, food, and energy policy is no easy task. Unconnected institutional entities further complicate this. Farmers are promoted to grow water intensive rice while at a nearby city faces a drinking water crisis. Sustainability regulations encourage the replacement of food crops by biofuel crops while elsewhere forests are cut to make place for food production.

The 'Nexus', that is an acronym for the interrelated WEF system, and the need to obtain integrated policies was globally advocated. Several analytical Nexus models where developed but left a lot to be desired according to critics. The main critique of these models so far has been that many cannot serve as a decision support tool because they lack the ability to investigate specific governance actions or the implementation of technical interventions. These models generally have intensive data requirements and are not scalable and flexible enough to perform for many Nexus studies within a single model framework.

In this study an optimization model framework is proposed, titled 'MAXUS', specifically designed to address the shortfalls of current models. It was built to customize a model for a specific Nexus study. To test the methodology of MAXUS it was applied to a case study for Ghana and Burkina Faso. Allocation of water and land resources for the final supply of WEF was optimized over space and time, for the objective and constraints given.

It demonstrates how sectors could respond in harmony to changes occurring in one of the sectors. The model shows non-trivial, multi-sectoral, spatial and temporal trade-offs for operational management and infrastructural planning of WEF sectors. For example, changing locations of proposed irrigation capacity because of an increase in electricity demand.

Moreover, the case study demonstrated how it can support in decision making on cross-border cooperation by means of separate optimization for Ghana and Burkina Faso. It showed how sharing resources and open trade would lead to a large reduction in infrastructural requirements. In case of non-cooperation, it would be beneficial for Burkina Faso to expand reservoir storage capacity and irrigation capacity on a much larger basis than in case of cooperation. Mainly because it would not benefit from hydropower production generated in Ghana in case of non-cooperation. It also showed how thermal power production would have to fill up the gap in electricity supply and how food imports would need to compensate for the loss in food production.

MAXUS is built to serve in a wide range of nexus studies. Hence, it is scalable in time and space, has an adaptable data structure and allows customization of objectives, balances, constraints dimensions and decision variables.

Using Maxus to customize a model for a specific cases study requires broad expertise. It requires engineers to set-up the equations for the model, experts in different sectors that understand the interactions, and local experts that now the conditions that apply in the case study area. Furthermore, it demands policymakers to think through their ambitions, their preferences, their range of possible interventions and governance actions, and the influences of their decisions on each of the WEF sectors. Exploring strategies for responding to developments in the WEF sectors requires cooperation of all sectors.

CONTENT

NOMENCLATURE

Name	**Short description**	**Dimensions**	**Units**	**Type**
SW_{Stocks}	surface water collection storage term	i,t	Mm^3/season	variable
SW_{Ava}	surface water availability collection term	i,t	Mm^3/season	variable
SW_{Con}	surface water consumption collection term	i,t	Mm^3/season	positive variable
SW_{Unused}	trapped surface water	i,t	Mm^3/season	positive variable
SW_S	reservoir water storage	i,t	Mm^3	positive variable
$SW_{S_{loss}}$	reservoir water loss factor	i,t	-	parameter
$SW_{S.Cap.Existing}$	existing reservoir storage capacity	i	Mm^3	parameter
$SW_{S.Cap.New}$	new reservoirs storage capacity	i,t	Mm^3	positive variable
SW_{Ex}	surface water export	i,t	Mm^3	positive variable
SW_{Im}	surface water import	i,t	Mm^3	positive variable
$SW_{Ex.Cap}$	surface water export capacity	i	Mm^3/season	parameter
SW_{Irr}	surface water irrigation	i,t	Mm^3/season	positive variable
GW_{Stocks}	groundwater storage collection term	i,t	Mm^3/season	variable
GW_{Ava}	groundwater availability collection term	i,t	Mm^3/season	variable
GW_{Con}	groundwater consumption collection term	i,t	Mm^3/season	positive variable
GW_{ImEx}	groundwater import/export collection term	i,t	Mm^3/season	variable
GW_S	groundwater storage	i,t	Mm^3	positive variable
GW_{Re}	groundwater recharge ratio	-	-	parameter
GW_{Nat}	groundwater uptake ratio	-	-	parameter
GW_{Irr}	groundwater irrigation	i,t	Mm^3/season	positive variable
$W_{Con.Fg}$	crop water consumption	i,c,e,w,t	Mm^3/tonnes/season	parameter
W_P	precipitation	i,t	mm/season	parameter
W_{ET0}	crop reference evaporation	i,t	mm/season	parameter
W_{evap0}	natural evaporation	i,t	Mm^3/season	positive variable
W_{CR}	crop replacement factor	-	-	parameter
W_{KC}	crop evaporation factor	i,t	-	parameter
$W_{KC.Nat}$	natural evaporation factor	i,t	-	parameter
W_{Sup}	water supply	i,t	Mm^3/season	positive variable
W_D	water demand	i,t	Mm^3/season	parameter
E_{Stocks}	electricity storage collection term	i,t	MWh/season	variable
E_{Ava}	electricity availability collection term	i,t	MWh/season	variable
E_{Con}	electicity consumption collection term	i,t	MWh/season	variable

Name	**Short description**	**Dimensions**	**Units**	**Type**
E_{Stocks}	electricity storage collection term	i,t	MWh/season	variable
E_{Ava}	electricity availability collection term	i,t	MWh/season	variable
E_{Con}	electicity consumption collection term	i,t	MWh/season	variable
E_{ImEx}	electricity import/export collection term	i,c,t	tonnes/season	variable
$E_{Prod.Thermal}$	thermal power production	i,t	MWh/season	positive variable
$E_{hydro.W_T}$	hydrowater generation from water transport	i,i	MWh/Mm^3	parameter
$E_{hydro.W_{Ex}}$	hydrowater generation from water export	i	MWh/Mm^3	parameter
E_T	electricity transport	i,i,t	MWh/season	positive variable
$E_{T_{loss}}$	electricity transport loss factor	i,i	-	parameter
E_{Im}	electricity import	i,t	MWh/season	positive variable
E_{Ex}	electricity export	i,t	MWh/season	parameter
E_{Sup}	electricity supply	i,t	MWh/season	positive variable
E_D	electricity demand	i,t	MWh/season	parameter
$E_{Prod.Thermal.Cap}$	thermal power production capacity	i	MWh/season	parameter
F_{Stocks}	food storage collection term	i,c,t	tonnes/season	variable
F_{Ava}	food availability collection term	i,c,t	tonnes/season	positive variable
F_{Con}	food consumption collection term	i,c,t	tonnes/season	positive variable
F_{ImEx}	food import/export collection term	i,c,t	tonnes/season	variable
F_S	food storage	i,c,t	tonnes	positive variable
$F_{S_{loss}}$	food storage loss factor	i,t	-	parameter
F_G	food production	i,c,e,w,t	tonnes/season	positive variable
$F_{G_{loss}}$	food production loss factor	i,t	-	parameter
F_{Sup}	food supply	i,c,t	tonnes/season	positive variable
F_T	food transport	i,i,c,t	tonnes/season	positive variable
$F_{T_{loss}}$	food transport loss factor	i,i,t	-	parameter
F_{Im}	food imports	i,t	tonnes/season	positive variable
F_{Ex}	food exports	i,t	tonnes/season	parameter; positive variable
$F_{S.Cap}$	food storage capacity	i	tonnes	parameter
F_D	food demand	i,c,t	tonnes/season	parameter
$F_{D.Unsatisfied}$	unsatisfied food demand	i,t	tonnes/season	positive variable
F_{K_y}	yield response factor	c	-	parameter
L_{Ava}	land availability collection term	i,t	hectares	parameter
L_{Use}	land use term	i,t	hectares/season	positive variable
$L_{agr}(i,t)$	available agricultural land	i,t	hectares	parameter

Name	Short description	Dimensions	Units	Type
$L_{Use.Irrigated}$	irrigated land use	i,t	hectares/season	positive variable
$L_{Req.F_G}$	food land requirement	i,c,e,w	hectares/tonnes/season	parameter
L_{Tot}	total area	i	hectares	parameter
$L_{Irr.Cap.Existing}$	exisiting irrigation capacity	i	hectares	parameter
$L_{Irr.Cap.New}$	new irrigation capacity	i,t	hectares	positive variable
C_{Tot}	total costs	-	US$	variable
$C_{SW_{S.Cap.New}}$	reservoir construction cost factor	i	US$/$Mm^3$	parameter
$C_{Unsatisfied}$	unsatisfied demand cost factor	-	US$/tonnes; US$/Mm^3; US$/MWh	parameter
$C_{GW_{Irr}}$	groundwater irrigation cost factor	-	US$/$Mm^3$	parameter
C_{F_G}	food production cost factor	c,e,w	US$/hectares	parameter
C_{F_T}	food transport cost factor	i,i	US$/tonnes	parameter
$C_{F_{Im}}$	food import cost factor	c,t	US$/tonnes	parameter
$C_{E_{Prod.Thermal}}$	thermal power production cost factor	-	US$/Mwh	parameter
$C_{E_{Im}}$	electricity import cost factor	-	US$/Mwh	parameter
$C_{L_{Irr.Cap.New}}$	new irrigation capacity cost factor	-	US$/hectares/season	parameter

Name	Dimension type	Set type	Set size	Unit
i	spatial	set	23	administrative region
j	spatial	subset	23	administrative region
t	temporal	set	4	precipitation season (half a year)
c	agricultural production	set	12	crop type
e	agricultural input	set	3	input level
w	agricultural watering	set	2	watering method

Picture 1 : Crop circles, Al Jawf; source AXELGLOBE[110]

1. INTRODUCTION

In the year 2012 a power outage caused half of India's population, more than 600 million people, to be without electricity. A drought that year had affected hydropower production, while at the same time pushed farmers to draw increased power from the grid for running pumps for irrigation. The demand had grown too strong for the supply to keep up and after some mismanagement the grid collapsed.[4]

Energy, water, and food (hereafter: WEF) supply are interdependent, and their interdependency is strong. The food and energy sector together account for 86% of the world's water withdrawals[5]; roughly 90% of global power generation is water intensive[1] and about 30% of the world's produced energy is on behalf of the food sector[2].

Understanding these interlinkages is becoming increasingly essential as pressure on the supply of these basic needs increases. Over the last 50 years, land and water management has had to meet rapidly rising demands for food and fibre. Input-intensive, mechanized agriculture and irrigation have contributed to rapid increases in productivity. The world's agricultural production has had to increase between 2.5 and 3 times[6]. A similar rise was seen in energy consumption according to estimates[7].

This rising hunger for WEF resources is not projected to stop any time soon. Driven by population growth, more meat-focused diets and emerging industries, it is estimated that the world of 2050 will demand 50% additional water supply[1], 60% more food supply[2] and 85% more energy supply[3].

Advances in production growth have come with a set of unintended consequences. Globally, only half the nutrients that crops take from the soil are replaced[8] an estimated 20% of the world's groundwater aquifers are now being over-exploited[1] and the sectors account for 50-60% of global GHG emissions* [9]-[11] of today. A sustainable growth is an immense challenge. Efficiency throughout the supply chains of water, food and energy are of utmost importance and since they are interdependent this requires an integrated approach. Over the last decades integrated approaches have gotten increasing attention. The water sector had been the first to increase integration of their policies and given the size of the water market, compared to those of the food and energy markets it has only been natural for them to be the first to make connections[5]. They have established Integrated water resource management (IWRM)[12] as the new standard for modern water sector approaches.

Recently, an increased level of integration has been pleaded for and advocated by the world's most renown development institutions (World Bank [13], FAO [2], UN [1][5], WBCSD [13], ADB [14]). Instead of starting at the water resource when considering interdependencies, an integral approach should ideally consider all elements in an interrelated system. This new approach has become known as the WEF nexus.

The introduction eludes on the concept of the WEF Nexus. It discusses the interlinkages of the WEF Nexus sectors and how these interactions come into play in governance of the WEF sectors. Moreover, it looks at where in the world WEF Nexus studies are most required and for which organizations they are most relevant. It discusses existing models and their shortcomings to convey Nexus studies. Finally, it discusses strategies to address identified shortfalls.

1.1 DEFINING THE WEF NEXUS

Nexus thinking is concerned with addressing externalities across multiple sectors, with a focus on system efficiency, rather than on the productivity of isolated sectors[15]. However, there has been no complete consensus on what sectors to include in nexus thinking. In figure 1 it is shown how different institutions and initiatives have come up with different conceptual frameworks that incorporate land, climate, ecosystems, bio-materials and feed. And there may be more links. To illustrate hypothetically, the power outage of the introduction might also have been affected by an increase in food demand through changing diets, influenced by McDonalds commercials, boosted by an increment in television sales.

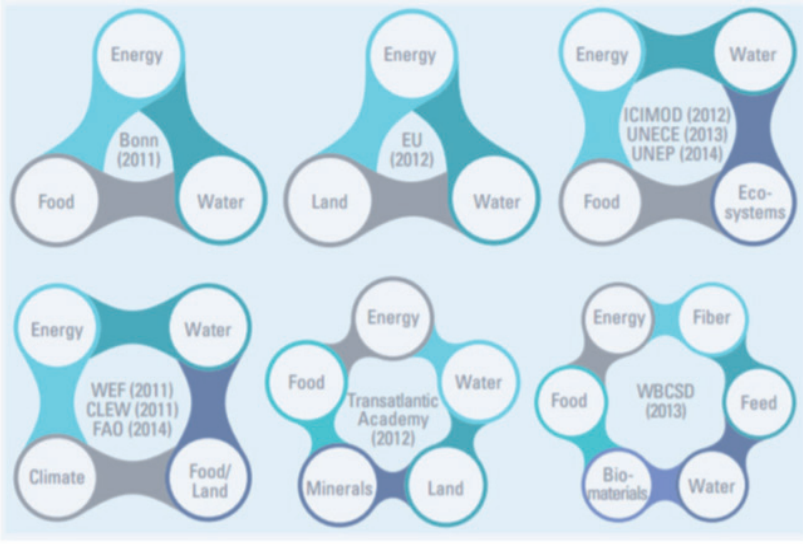


Figure 1: conceptual frameworks proposed by major institutions. EU stands for European Union; ICIMOD for International Centre for Integrated Mountain Development; UNECE for United Nations Economic Commission for Europe; UNEP for United Nations Environment Programme; WEF for World Economic Forum; CLEW for climate, land, energy and water; FAO for Food and Agriculture Organization; and WBCSD for World Business Council for Sustainable Development. Source: ESCWA[16]

The term 'nexus' is used to recognize nothing more than a set of strongly interrelated activities. The WEF nexus therefore represents the strongly interrelated system of water, energy and food. In this study the focus therefore is on the interdependencies of these sectors, but it should not be forgotten that it may have strong links with other elements too.

The need for the WEF nexus approach is apparent. Sustainable Development Goals (SDG's) 2, 6 and 7 as formulized by the United Nations in 2015 show the high priority of improving water, food and energy security[17]. Achieving these SDG's cannot go without integrated understanding. Low levels of water, food and energy security cannot be seen as separate problems. Improving food security may also imply improving water infrastructure for example, or provision energy to operate groundwater pumps. The importance of the WEF nexus approach for achieving the SDGs has been underlined by many[18]-[20].

Connections between Water-Food, Water-Energy and Food-Energy are discussed in more detail in the continuation of this section. Figure 2 shows the most prominent interlinkages graphically.

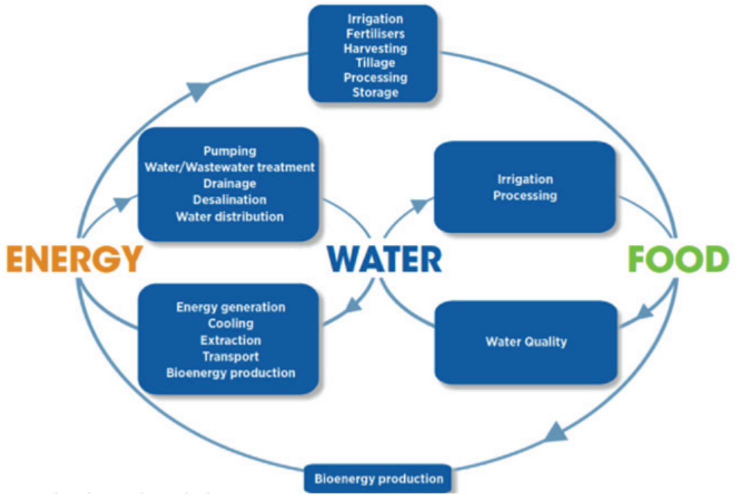


Figure 2 major interlinkages between the WEF sectors; source: Irena[21]

WATER – FOOD
Water is essential for food in a large variety of ways and may the strongest dependency in the WEF nexus. But, food sector inputs in the water sector are limited to fertilizers that affect water quality and that may be the weakest dependency in the WEF sector. This does not mean that this is a one-way link. Food sector decisions are very impactful for the water sector, as are water sector decisions for the food sector.

Water is required to grow and to process food. Agriculture is the world's largest water consumer and agricultural practices have always been greatly influenced by water availability. Decisions on the type of crop to grow, when to grow, whether or not to irrigate and when to harvest, all depend on water resources. Fertilizer application, irrigation and mechanization have radically changed the face of food production and thereby the pressure on water resources. But food production is only one part of the story. The food sector influence water availability in many ways. Food storage, exports and imports all change the temporal and spatial distribution and levels of production. And food demand is in the end what drives production.

Food is not an input in the water sector. The only direct input from the food sector is fertilizer wash-off which affects water quality. Over-extensive use of fertilizers can cause major impacts on water resources. An example that clearly illustrates this is the emergence of the so-called 'dead zone' in the Gulf of Mexico. It is a 20,000 km2 area, previously inhabited by many fish species, but now deprived of fish. This has been mainly a consequence of over-extensive use of fertilizers[22].

WATER – ENERGY
Water and energy rely heavily on one another. Water is required for extraction and production of nearly all types of energy and is the dominant method of storing energy once produced; energy in turn is required for the extraction, treatment and distribution of water, as well as its collection and treatment after use.

Water use in energy is crucial and substantial: thermal energy plant cooling is responsible for 43% of total freshwater withdrawals in Europe and nearly 50% in the USA (more than 50% in several countries), while thermal power plants are responsible for roughly 80% of global electricity production[1]. Hydropower is the leading renewable source for electricity generation globally, supplying 71% of all renewable electricity at the end of 2015[5]. And It is estimated that 99% of the world's electricity storage capacity is in the form of hydropower, including pumped storage[5].

Energy use in the water sector is not just essential, energy consumption is the leading cost factor for drinking water provision and wastewater treatment[14]. Roughly 4% of global power supply is consumed in the water sector. The quality of water is important for the energy requirement of water treatment: heavily contaminated water requires significantly more application of energy to the treatment process; and increasing fresh water scarcity leads to increased devotion to desalination of salt water sources, also requiring heavy energy application. The latter trend is partly responsible for the strong energy demand rise seen in the water sector. The amount of energy used in the water sector is expected to double by 2040[3].

FOOD – ENERGY
Around 30% of global energy supply is consumed in the food sector through many ways[2]. The input of the food sector in the energy sector is limited to the use of biofuels, but this may also induce a competition over land resources.

The application of energy in agriculture is the main reason why agricultural production levels have surged. Irrigation, mechanization, fertilizer application, food storage, food transport, food processing are all energy demanding processes.

> *"The cost and availability of energy in rural areas has had—and will continue to have—a decisive influence on the development of agriculture."*
> *ADB* [14, p. 15]

Sometimes food crops are directly used for the production of biofuels (e.g. sugarcane). Sometimes the non-food crops (e.g. palm oil) used for biofuels are in competition over land with food crops thereby also influencing the food sector. Biofuel production is expected to consume 10.4% and 12% of global coarse grains and vegetable oil production and 22% of global sugarcane production by 2025 [21].

1.2 WEF GOVERNANCE

The interlinkages between the sectors are multifaceted, complex, abundant and sometimes overlooked. Forests are cut for the land to serve in food production while, at the same time, food crops are turned into biofuel crops to serve in sustainable energy production to reduce climate change. Energy is used to desalinate water, while water is used for power generation. According to Rogner[23] water, energy and land-use planning, decision and policy making occurs in separate and disconnected institutional entities. This has its consequences as actions in one sector affect the policies drawn in another sector.

> *"The approach to the energy, water, and food nexus normally depends on the perspective of the policy-maker (Harris, 2002). If a water perspective is adopted, then food and energy systems are users of the resource (see e.g., Hellegers and Zilberman, 2008); from a food perspective energy and water are inputs (see e.g., Mushtaq et al., 2009; UN-DESA, 2011; Khan and Hanjra, 2009); from an energy perspective, water as well as bio-resources (e.g., biomass in form of energy crops) are generally an input or resource requirement and food is generally the output."* Bazilian at al. [21, p.2]

Sometimes, the combination of unlucky circumstances and individual independently determined policies may have heavy consequences. The global food crisis in 2008 is such an example. Higher energy prices, lower crop yields because of worldwide drought and increased production of biofuel crops that replaced food crops led through higher prices to acute food shortages in parts of Asia and Africa. The World Bank estimates that biofuels accounted for about 70% of the food price increase[24].

Due to historical agreements it is not easy to synergize WEF policy. An example from California showed how farmers grow rice in one of the most arid areas of the sates. Rights given to farmers to stimulate agricultural growth in the area in the last century now give them access to water resources beyond reason. But changing those rights is not easy "*because for farmers, it would be as shocking and disruptive as reshuffling land, or bank accounts.*"*Bloomberg* - [23, p.1]

It can also be doubted if WEF interlinkages are taken into consideration in current infrastructure plans. An example from China showed how half of the proposed coal fired power plants are located in areas of high or extremely high water stress[26]. Its analysis is shown in figure 3.

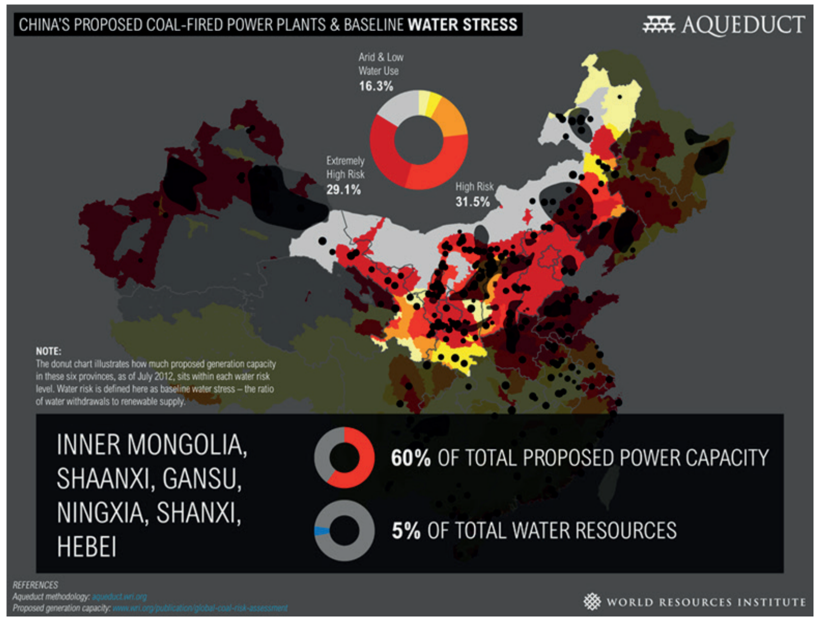


Figure 3 China's proposed coal fired power plants and water stressed regions; source: Water Resources Institute [26]

It is important to align the policies of the water, food and energy institutions. Understanding how decisions taken in one sector affect another is crucial. With little transparency decisions may be taken that may end up having an adverse effect. In textbox 1 an example is given of how this may occur.

textbox 1: Example of complex chain effects in the WEF sector

EXAMPLE OF COMPLEX LINKS

A policy of subsidies on fertilizer production increases food production thereby increasing energy needs and therefore also water needs for energy production. The water required is pumped from a stream through which less water is available downstream. Farmers there start using more groundwater since this is an alternative source and the groundwater reservoirs become saline because of salt intrusion flows that now have more effect. The salinity affects crop production and the farmers now have disappointing harvest despite of the addition of fertilizers.

Stimulation of new sustainable technologies have set foot in society. The fluctuation in production of wind- and solar energy make it hard for coal plants to operate. Because of the long start-up and shut-down processes the coal plants produce energy against negative market prices and finally are forced to shut down. To back up the system more flexible gas power plants are created. These gas power plant rely on import since the region does not have gas resources itself. A drought occurs, and biofuel crops of the supplying region fail, the supplying region now needs its own gas. The low energy availability now causes trouble for desalination plants in the region, they cannot provide in water anymore. The region faces a water and energy shortage.

Nexus issues are global, but at some areas its consequences are apparent. Water stress and water scarcity often form an entry point for nexus case studies as the trade-offs are apparent here [27][28]. Water consumed cannot be consumed somewhere else, which directly causes problems in areas with high water stress (figure 4). One could argue: if a country has water, land and raw energy resources in abundance, is there still a need for a nexus study? Trade-offs could be less present, and therefore a study less relevant. However, reasons to execute a nexus study may vary by region. Even if there is no resource stress, increasing efficiencies could also be for the sake of emission reduction, or even land use reduction. Wherever there is a water, food and energy sector, there is room for cross-sector efficiency improvement.

Reasons may also vary by institution. Businesses may apply case studies to reduce costs or risks for their operations[29]-[32]. NGO's for the sake of water, food and energy security[1][13][32][33]. Governments to reach their CO2 targets[10] . Nexus studies widely vary in scale and goal and both private and public sector are concerned with their execution. In box X an example is given in which an NGO collaborates with a brewer is the imitator for nexus policy. An example of nexus in business is given in textbox 2.

There exist different philosophies along which nexus policy is conveyed. Where there are people that consider access to water, food and energy resources a human right and plead for an allocation along those lines, there are others that believe allocation should be based on economic efficiency. Philosophies also differ on the incorporation of sustainability and environmental care in nexus policy[16]. Should biofuels compete with food or with forest? Should affecting water quality be penalized? Environmental requirements increase cost and may not be economically attractive.

The Nexus really is about finding trade-offs and striking balances. Policymakers would have to find harmony in economic efficiency, supply security, affordability, ecological sustainability and financial sustainability. These trade-offs are everywhere, and their identification is crucial.

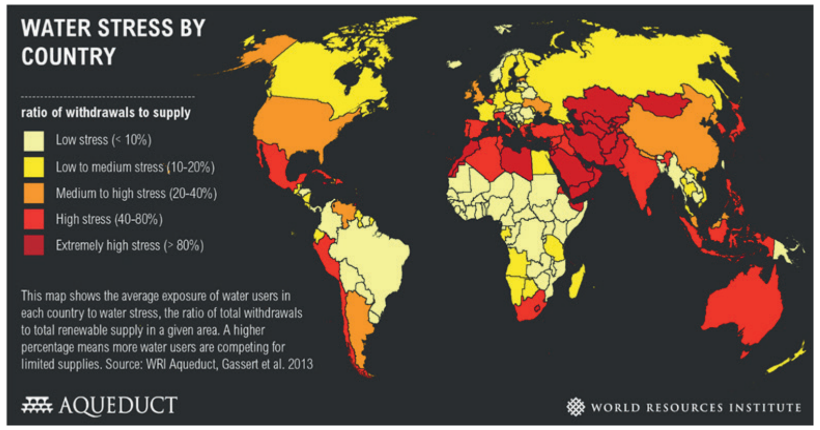


Figure 4: Water stress around the world; Source WRI Aqueduct [34]

textbox 2: Example of nexus in business

NEXUS IN BUSINESS

"The Nature Conservancy (TNC) is one of the leading NGOs in developing and scaling water funds,43 which attracts investment from companies such as SABMiller. An example is the efforts of TNC and SABMiller (whose Bavaria brewery, Cerveceria del Valle, is located near the city of Cali, Colombia) in Colombia. The Water for Life and Sustainability Fund established near Cali, addresses water conservation along the Cauca River, from which SABMiller's Cerveceria del Valle brewery draws water for beverage production. The Cauca River Valley is Colombia's largest sugarcane-producing area, and demand for water for irrigation, a growing population, and industrial use threatens to outstrip supply. The Cauca River is also increasingly contaminated as a result of run-off from sugarcane production, erosion from deforestation for cattle ranching and small-scale agriculture, and a lack of access to modern sanitation in some poor communities.

This fund, driven by SABMiller and a range of other stakeholders, will address the nexus stress by providing water for drinking, agriculture, water and power utilities, and manufacturing, including the SABMiller brewery. The model pools money from downstream water users (such as municipalities, water and power utilities, and companies) and donors into a fund that is used to pay upstream stakeholders who have the ability to impact water quantity and quality, such as farmers, ranchers, community organizations, and environmental groups, and to implement projects and practices to address the community's water, energy, and food needs. The stakeholders and funders for the Cauca River fund aim to reach a total of $15 million; so far, nearly $4.5 million has been raised. Nearly $500,000 has been invested in an endowment fund." - Deloitte [29, p.1]

Picture 2 : rice fields Banaue;
source: Imgur

1.3 CURRENT ANALYSIS MODELS

Planning and decision-making that consider sector optimization or even cross-sector impacts require substantial qualitative and quantitative insight. Qualitative research is required to learn how sectors are linked to each other, what and how stakeholders are involved, how resource availability may be affected in the future and what potential regions may be affected. Quantitative research builds on the data generated by qualitative research and is done to generate estimates of the quantitative impact of decisions made or strategies taken. The focus of this study is on quantitative research in the WEF Nexus.

Developing modelling models to support integrated decision making has been identified as vital in approaching the WEF Nexus[23]. Many models for the analysis of individual systems exist, but only recent advances engage in the holistic synergistic modelling that is required to capture the interdependencies of the WEF sectors[23][35][36]. The models that cover the WEF nexus are given in table 1.

Attempts to reach integrated models have generally concentrated on three types of models: accounting, simulation, and optimization. Accounting models (e.g. AEZ[2] or the FAO-nexus tool[37]) are typically made for a more comprehensible representation or classification of data in the WEF sector, which is useful in this complex environment. Simulation models have been developed to understand interactions between sectors and to investigate scenarios. As opposed to accounting models, simulation models contain mathematical relations that describe WEF interactions (as close to reality as possible). There are many, but the most integrated models are Nexus tool 2.0[38], PRIMA[39], and MUsiasem[40]. Optimization models are created to obtain measures to improve sector collaboration on shared objectives. In addition to the interactions that simulation models contain, they include decision variables that are calculated to maximize utility for a certain objective. The optimization models CLEWs[41] and MESSAGE-GLOBIUM[42] are the most integrated examples covering all sectors of the WEF Nexus.

There is heavy emphasis on the need for decision support systems for policy makers in the discourse on the WEF Nexus. "Theoretically, the perfect modelling tool would allow for the creation of policies that maximize all synergistic efficiencies between the Nexus areas."[35] As pointed out by Dai et al.[36] most simulation models are made for understanding the Nexus interlinkages, rather than supporting "specific governance actions or the implementation of technical interventions". Accounting models simply cannot serve this purpose. Simulation models have more potential on this front and allow to test the impact of scenarios on the WEF Nexus. However, this test does not necessarily imply good solutions are found to resolve negatively impacted components of the WEF Nexus.

The most potential to investigate policy actions or technical interventions lies with optimization models. They are made to optimize multiple decision variables from different sectors at the same time, creating ingenious and non-trivial synergistic solutions. The complexity of the WEF Nexus requires such models to assist in finding solutions that could never be found by simulating models with manually included interventions. The analysis of this study therefore devotes itself to optimization models.

Optimization models that combine different sectors are often obtained by the combination of two already existing single sector models (CLEWs[41], MESSAGE-GLOBIUM[42]) . The way that these models are connected gives a second characterization for integrated models, they can be soft-linked or hard-linked. In soft-linked models output of one sub-model is passed on to another and final output is generated iteratively. In hard-linked models (SPATNEX-WE[43]) the sub-models are coupled such that they can be solved simultaneously.

An example of a soft-linked model is CLEWs[41], it combines the water model WEAP[44], the energy model LEAP[45] and the land-use model AEZ[37] in iterative manner. Arguments in favour of such a model with respect to developing a hard-linked model is that it saves time and effort; the distinct models which are already widely in practice can be run by the corresponding experts.

A drawback, however, is that iterations of the connected models may lead to suboptimal solutions. This drawback was confirmed this year by the publishing of the water-energy model SPATNEX[43]. It was shown that hard-links outperformed soft-links for the investigated issues. With hard-links the model considered possible water constraints in energy technology investment straight away, whereas with soft-links an independent investment plan was made and then adjusted through limitations that show up in the water balance. The solution found turned out to be suboptimal and did not evaluate spatial and temporal variations in the water and energy demands and production as effectively. The reason this happened lies in the nature of soft-linked models. In each coupled sub-model, merely local constraints can be evaluated in finding an optimum, while disregarding the constraints of the other sub-models. Not only can the model end at inferior solutions, it can even get trapped in a situation where the solution keeps bouncing between an optimum in one sub-model model, to the optimum of another. In a hard-linked framework or in a single model framework, solutions are only sought after in the solution space and the solution cannot get trapped. However, a singlular model or hard-linked optimization model that covers the domains of water, food and energy does not exist to date.

While there are many different frameworks options and model types, the biggest need for policymakers is "to have a singular framework for performing a 'nexus study' "[36]. To date none of the existing models are considered to have a usability large enough to pass for a 'complete' nexus framework. The ideal nexus model should include short term as well as long term analysis, for local, regional, national and transboundary scales. In addition, users need to be able to adjust "the data structure to achieve a balance between the accuracy of a model and the amount of data available for model building. There needs to be an innovative way balance the trade-off between simplicity and comprehensiveness[35]." Sometimes data intensity is considered the biggest limitation of nexus models[35]. In some of the areas where nexus studies are considered vital, such as developing countries, data availability is generally low.

Another key improvement for a nexus model is: "physical accounting of resources, technology and other requirements and constraints to meet certain needs and services, with the accounting extended far upstream and including externally induced effects (e.g., induced land use change) [23, p.5]." Other studies[46][47] indicated that there is little insight in the spatial patterns and dimensions of resource flow, availability and use.

In summary, to respond to the shortfalls of existing models the following needs were identified. A model should:

- integrate the WEF nexus;
- serve as a decision support tool;
- have an adaptable input data structure;
- perform for different temporal scales;
- perform for different spatial scales;
- allow for physical accounting of resources, technologies and constraints;
- handle and account externally induced effects.

Available full nexus models	**Sector**	**Model Type**	**Link type**	**Distinctive features**
Nexus Tool 2.0[38]	Water, Food, Land, Energy	Simulation, Accounting	Singular	Simple visualization framework
MESSAGE-GLOBIUM[42]	Energy, Food, Land, Climate	Optimization	Soft-linked	Includes competition between different land-use based activities
CLEWs[41]	Water, Food, Land, Energy	Optimization	Soft-linked	Combining LEAP, WEAP and AEZ
PRIMA[39]	Water, Food, Land, Energy	Simulation	Hard-linked	Inclusion of socioeconomics
MuSIASEM[40]	Water, Food, Land, Energy	Simulation, Accounting	Singular	Flows are in relation to funds (e.g. energy input per hour of labour)
The FAO Nexus tool[33]	Water, Food, Land, Energy	Accounting	Singular	Only qualitative framework

Table 1: Water stress around the world; Source WRI Aqueduct [34]

1.4 STRATEGIES FOR AN IMPROVED MODEL

The requirements of a nexus model are substantial. The following core characteristics were identified to serve as the backbone in any nexus optimization model made: integration, coherency, computationally tractability, and flexibility.

Integration of the WEF sectors is simply essential if a model is developed to be applicable for a wide range of nexus issues. As became clear in the introduction, a nexus issue does not always stick to water, food and energy relations. Sometimes links to other sectors may be relevant. A model should allow for adding relations but also for withdrawing others if not relevant anymore. The challenge with modelling nexus of water, food and energy in integrated manner is as described by Brazilian et al.:

> *"to draw system boundaries wide enough to encompass the enormity of the interacting vectors, while maintaining it small enough to be able to conduct useful analysis."* [21, p.5]

Coherency of all mathematical representations of the interactions in a nexus model is necessary. With all the complexity in integrating the nexus, it is of paramount importance that each facet of a model is well-aligned. Therefore, in this study, it is considered essential to create a singular model, rather than hard-linking existing models. To keep a nexus model simple, it should be coherent among all sectors and the easiest way to achieve that is to start building from scratch. Another reason to do this, is to be able to adapt to data availability.

Computationally tractability of a model is indispensable for it to serve as a stable tool. Even if a model is standalone, the type of mathematical equations can still make it to arrive at suboptimal solutions. It is a necessity that the model is robust and solvable. If the problem posed is valid, it need to provide a global optimum. In addition, it is found important that the model can be analysed thoroughly, running it many times, while performing sensitivity analysis. Linear models have the characteristics described, they are quick, always arrive at a global optimum and can be easily analysed on sensitivity. Non-linear models do not have those characteristics intrinsically, however, they do have the opportunity to include non-linear relationships such as reservoir hydro-energy potential or changes in groundwater heads. A linear model is therefore preferred. However, non-linear relationships should not be excluded straight away. If they turn out to be significant, the characteristic should be adapted.

Flexibility is key considering the wide range of nexus issues which may be among different scales in space and time and have different data availability. The framework should 'breath' flexibility in all its components. Users need to be able to select the regions they would want to investigate, process the goal of investigating, adapt to the requirement for detail, decide on the data to include, determine the units of time and space, specify their output, choose a manner of accounting, etc. Flexibility is indispensable for a nexus model.
In conclusion, the desired core characteristics led to the following strategies:

- include all WEF sectors and allow possible extension to other sectors;
- start building form scratch;
- start off by building a linear model; adapt to non-linear if important;
- keep the structure of the model open for adaptations and ensure that the model can be used for different objectives and that it is scalable.

Recent technological advancements may help in meeting the high demanding requirements identified for an improved nexus model. The following key technological advancements have been identified that create opportunities for nexus models.

Remote sensing has given an enormous boost to water management and agricultural monitoring practices. Since the 80s, in which it was discovered that vegetation can be monitored through its spectral reflectance properties, the possibilities to monitor crop growth for example has snowballed[48]. Today, a large range of satellite sensors provide us with multispectral imagery at high spatial resolution that give a detailed insight in crop growth parameters such as crop water use across the growing season, crop land use, achieved crop yield and even attainable crop yields[49]. For water management practices, increasingly detailed information is available open source on precipitation, evaporation, and water level changes. This has a lot of potential for nexus research, data can be obtained significantly easier on regions everywhere on the world.

Geographic Information Systems (GIS) have changed the face of spatial analysis substantially. With GIS systems for storing, managing, and displaying spatial data can be done with ease. An increasing number of spatial databases have become open source and data on power plants, power grids, reservoirs, land cover, soil types, population is freely flowing on the world wide web. This is what the extensive data requirements of nexus models makes achievable and anyone can download it.

Big data and blockchain technology have been the latest technological advancements that could change accountability and precision of Nexus model. Data availability has increased exponentially in the past decade and will most probably continue to do so. Big data sources could shed further light on farmer practices, changing behaviour in energy and food consumption, food and energy demand and trade etc. Promising blockchain technology could keep track of resource flows and emissions. These developments however are too recent and not available nor ready to be easily incorporated in an improved nexus model as this stage. Therefore, this study will abstain from incorporating them in an improved nexus model.

The following key strategies for an improved nexus model have been identified after studying technological advancements:

- explore potential of existing remote sensing data as input for nexus model;
- explore potential of existing free GIS data as input for nexus model.

Picture 3: Lake Bracciano , Italy;
Source: Challenges worldwide[111]

1.5 RESEARCH OBJECTIVE

Summarizing, water, food and energy issues are present on a local and global scale and are likely to become more severe due to increasing demands and changing environments. Currently the WEF sectors address these issues often independently, leaving out the interlinkages with other sectors. To increase cross-sector cooperation and identifying trade-offs, integrated analysis models are required. Some integrated analysis models exist, but these are either formed by merging two or more existing one-sector models or are not capable of performing optimization. The resultant models after merging generate sub-optimal solutions, which is a direct consequence of iteration that these models require inevitably. In addition, most models are very data-intensive, not scalable in scales of time and space and provide little insight in spatial and temporal distribution of flows. Besides, externally induced effects such as climate change or land cover change cannot be included well. An improved model that addresses the shortfalls of current models and suits the desires of policymakers should therefore:

- integrate the WEF nexus;
- serve as a decision support tool;
- have an adaptable input data structure;
- perform for different temporal scales;
- perform for different spatial scales;
- allow for physical accounting of resources, technologies and constraints;
- handle and account externally induced effects.

To realize these goals an improved model was found to require the following characteristics: integration, coherency, computationally tractability, and flexibility. Based on these characteristics the following strategies were determined for the development of a new model:

- include all WEF sectors and allow possible extension to other sectors;
- start building form scratch;
- start off by building a linear model; adapt to non-linear if important;
- keep the structure of the model open for adaptations and ensure that the model can be used for different objectives and that it is scalable.

In addition, key technological advancements in the WEF Nexus analysis were identified: Remote sensing, GIS, big data and blockchain technologies. The first two technologies were found ready to be included in the development of an improved WEF Nexus tool at this stage. The latter two would be for further futuristic approaches. Therefore, two additional strategies follow for the creation of an improved nexus model:

- explore potential of existing remote sensing data as input for nexus model;
- explore potential of existing free GIS data as input for nexus model.

The research objective for the continuation of this study is to create an improved Nexus model that addresses the shortcomings of current approaches. In the following chapter 'MAXUS' a new framework is proposed that has been developed along the lines of the determined strategies. In a case study on Ghana and Burkina Faso the proposed framework is tested. The subsequent chapter 'Discussion' looks at strengths and weaknesses of the proposed framework. The chapters 'Conclusions' and 'Further research' follow with what has been discovered by this study and what prioritizes the agenda for further research.

Picture 4 : Coal fired power plant, China
source:EP-BD [112]

2. MAXUS

In this section the 'MAXUS'-model is presented. Its development was motivated by the need for an improved nexus model that addresses shortcomings of current approaches .

In section "Steps to model a nexus case study" it is discussed how MAXUS can be customized for a case study. Section "Programming framework" follows to discuss what programming environment was used to be able to run and analyse the output of the model. In section "Analyzation methods" it is described how the output should be visualized and analyzed.

MAXUS is an optimization model framework that is built for solving cross-sector optimization problems for the water, food and energy sectors. Its development was motivated by the need for an improved nexus model that addresses shortcomings of current approaches. Requirements of such a model are listed in section 1.5. It was built along the lines of the strategies listed in the same section. MAXUS consists of an objective function, balances, dimensions, constraints and decision variables.

In the **objective function** the goal of the model is set. The model is optimizing whatever is stated in the objective function. This may be a single objective function (e.g. minimizing cost) or it may be a multi-objective function (e.g. maximize supply coverage while minimizing cost and GHG emissions).

The balances formulize how resources in each sector are produced, consumed, stored and traded. If there are any changes in one sector in any of these components, it will affect the other sectors through the quantitative interactions between them.

The **dimensions** are the domains over which the variables and parameters hold a value (e.g. the collection of regions over which the model optimizes is a set of the dimension space.) The number of dimensions may be altered as well as the size of the dimension sets. Subsets of dimensions can allso be made for which special constraints apply (e.g. the collection of regions that contain a harbour forms a subset of the set regions)

The **constraints** form the rules for the system. A constraint is a condition of an optimization problem that the solution must satisfy. Constraints can for instance define minimum and maximum values that variables can take.

The **decision variables** are the variables to be determined by the model. The user may choose which the model should optimize for. The user also may optimize for numerous decision variables at the same time.

Because the model allows for adaptation in objective functions, balances, dimensions, constraints and decision variables, it can be customized to a wide variety of nexus case studies. In the next section it will be discussed how one should define these components when carrying out a case study

2.1 STEPS TO MODEL A NEXUS CASE STUDY

- **Step 1: form an objective**
- **Step 2: create relevant balances**
- **Step 3: select and define the significant interactions**
- **Step 4: define constraints**
- **Step 5: couple balances, interactions and constraints to objective**
- **Step 6: choose decision variables**

STEP 1: FORM AN OBJECTIVE

An objective for a nexus study should contain one or more optimization variables, a spatial and temporal scale and optionally certain conditions. A valid example would be: minimize cost and greenhouse gas emissions for water and energy supply in the Netherlands for the coming five years with existing infrastructure.

STEP 2: CREATE RELEVANT BALANCES

To reach the objective one should consider what quantitative elements are connected to it. Supply of energy requires availability of energy and one can simply not supply more than is available. A balance is required. A balance naturally consists of stocks and fluxes.

In the case of a resource as energy this means storage, production terms, consumption terms and import and export.
If one wants to find trade-offs in water, food, energy. We need to include balances for each of these aspects. This is shown in figure 4.

One could be interested in modelling the Water-Energy Nexus if in a certain region one is convinced the connections between water-food, food-energy do not matter for the objective in that case there could be two balances. This is shown in figure 5.

The number of balances can be expanded if one is convinced it is significant for the objective. A nutrient balance, for instance, may be worth adding when many trade-offs are expected to be centered around fertilizers.This is shown in figure 6.

Now one should consider which of the components matter for the objective and its corresponding timescale. Groundwater transport may be insignificant on a timescale of only a few years for example and can thus be left out.

Moreover, to complete the balances, the subcomponents of each component should be defined. One should explore out of which processes each of these components consist. The first component is given as example here. Storage of water could for example consist of large reservoirs, small reservoirs, pumped storage reservoirs etc. If these need to be separate entities, because they show very different behaviour then these form separate subcomponents of the component storage.

For each of these subcomponents one should decide on dimensions. If it is important to take into account that they differ in space and in time, at least two dimensions are required. When specific subcomponents need to be even more detailed additional dimensions are required. For instance, if one wants to optimize food transport for multiple crops

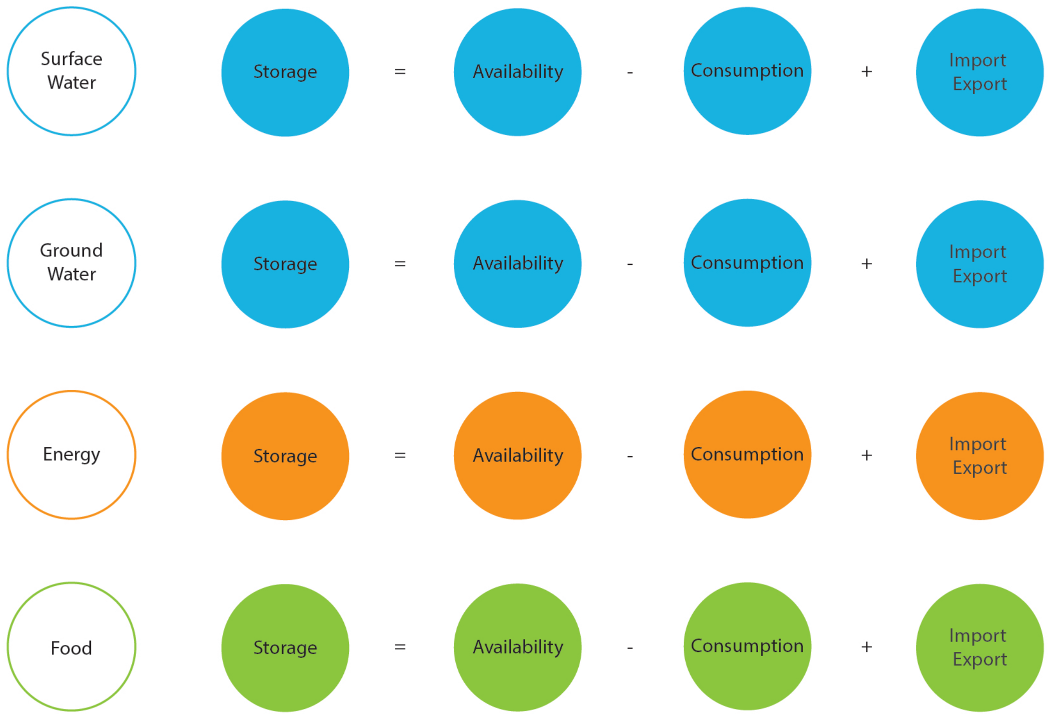


Figure 4: conceptual balances

Figure 5: surface water-energy nexus

Figure 6: nutrient balance

Figure 7: irrelevant groundwater transport

at the same time, another set is required that contains the different crops. Dimensions give additional degrees of freedom, but it makes the system also more complex. The need for dimensions should therefore be considered with care. If certain relations only hold for certain crops, one can create a subset of a dimension. This would be the case if for example some of the crops can be used for biofuels. Biofuel crops could then be a subset of crops.

Units of these dimension sets need also be defined. This choice of unit depends on the objective but also on data availability. One could adopt a spatial unit of a hectare for example, but if one would be interested in finding coarse trade-offs this may not be a good choice. Especially not when data availability is not available on a hectare resolution.

STEP 3: SELECT AND DEFINE THE SIGNIFICANT INTERACTIONS

Trade-offs in the WEF sectors exist because of interactions. They need to be included in the balances. To not miss out on important interactions a systematic approach to select and define interactions is presented here.

To illustrate the process of selecting interactions two components of two balances are picked. One should think of all possible interactions between the components and its subcomponents. Interactions are illustrated in figure 8 as arrows between the components.

By questioning each of these interactions by their DIRECT effect on another component exisiting interactions remain and non-exisitng can be filtered out:

- Is energy DIRECTLY consumed when food is consumed? Yes, cooking.
- Is energy DIRECTLY consumed when food is imported or exported? Yes, in all transport vehicles.
- Is energy DIRECTLY imported or exported when food is consumed? No.
- Is energy DIRECTLY imported or exported when food is imported or exported? No.
- Is food DIRECTLY consumed when energy is consumed? No.
- Is food DIRECTLY consumed when energy is imported or exported? Yes, truck drivers eat food.
- Is food DIRECTLY imported or exported when energy is consumed? No.
- Is food DIRECTLY imported or exported when energy is imported or exported? No.

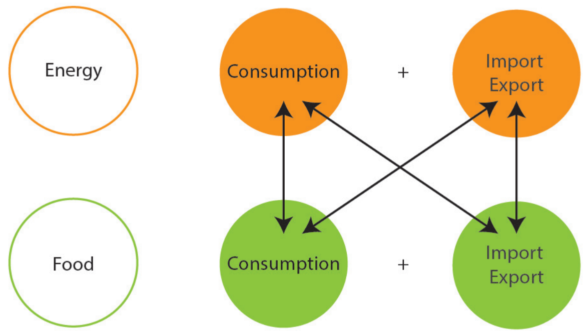
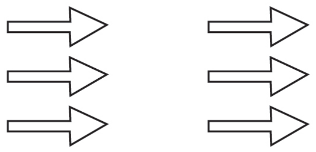


Figure 8: all possible interactions



Now, one should consider the significance of the remaining interactions by questioning their impact on the balance of the other element:

- Is energy HEAVILY consumed when additional food is consumed? Yes, cooking requires a lot of energy. (X% of total energy consumption)
- Is energy HEAVILY consumed when additional food is imported or exported? Yes, transport require a lot of energy. (X% of total energy consumption)
- Is food HEAVILY consumed when additional energy is imported or exported? No, truck drivers have to eat anyway, and won't eat much more.

Even if a interaction may only have little impact on the balance of another element, the impact on the objective function may still be substantial. Imagine one would have an oil balance and producing oil would consume little water but that consumption is essential for its production, Then it could be still worth including that interaction even if it is not affecting heavly in terms of water resources. Therefore a check should be performed on the interactions to be disregarded by questioning their influence on the objective.

- May the consumption of food for energy import or export increase cost substantially? no, in this case not.

Important interactions have remained and can be seen in figure 9.

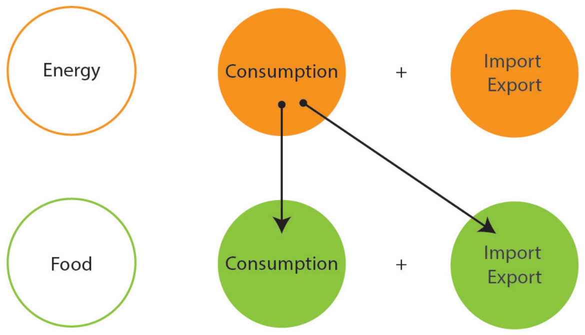


Figure 9: all relevant interactions

Selecting interactions requires expertise. The subjectiveness of the term HEAVILY already reveals the judgement required. But there are also methods that might help in estimating the impact of certain interactions.

The first one is analysing the size of current flows in the region by means of visualization diagrams called 'Sankey diagram'. This can be done for each WEF resource. It is depicted for water in figure 10 and 11. The flows can also be expressed in the unit that impacts the objective. If the objective is minimization of cost, then expressing all flows in terms of cost could detect what the costliest processes are.

The second one is performing sensitivity analysis with the rough formulation of the relation, after which can be decided if one needs a more accurate formulation. Remember, this is an iterative process. Once other relations are added or changed, the relation at issue needs to be considered again.

When important selections are selected they need to be defined. Depending on how significant an interaction is estimated to be, an increased effort should be put into defining the relation more thoroughly.If ¬¬energy for food transport is not that important, it can be modelled as average fuel consumption per kilometre distance. If it would be very important one would perhaps include, type of vehicle, road conditions, wind conditions, load etc. Dimensions of relevant subcomponents need to be reevaluated to check wheter these still fit for the necessary detail level of the interactions.

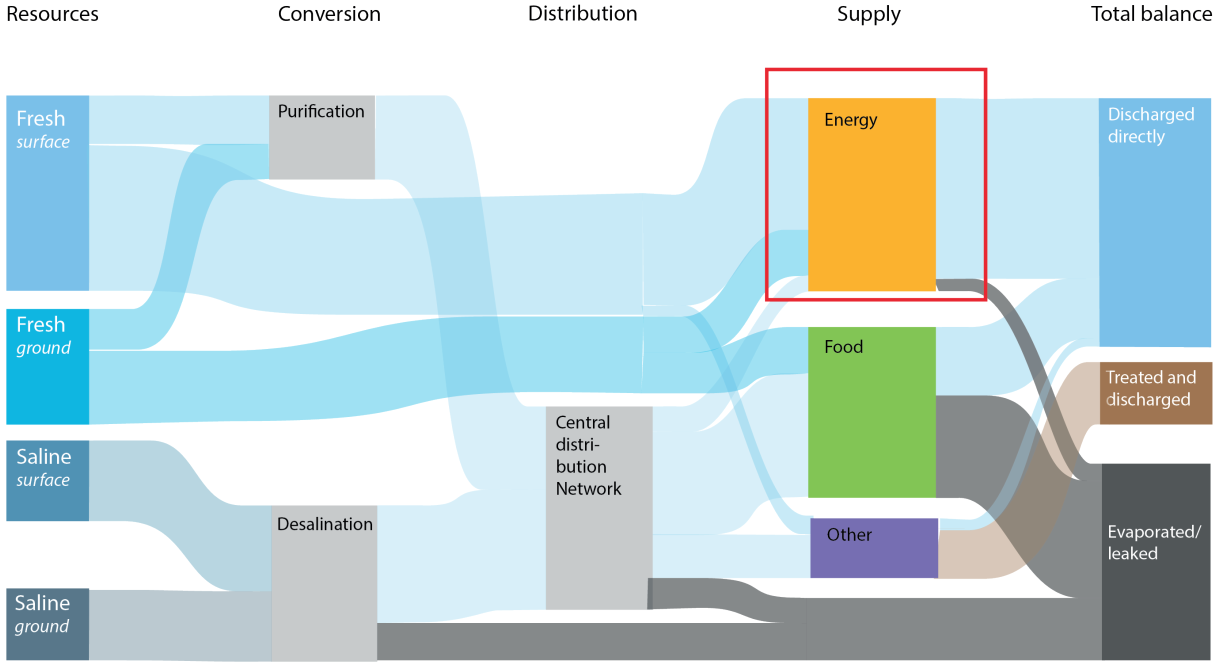


Figure 10: Example Sankey diagram for water

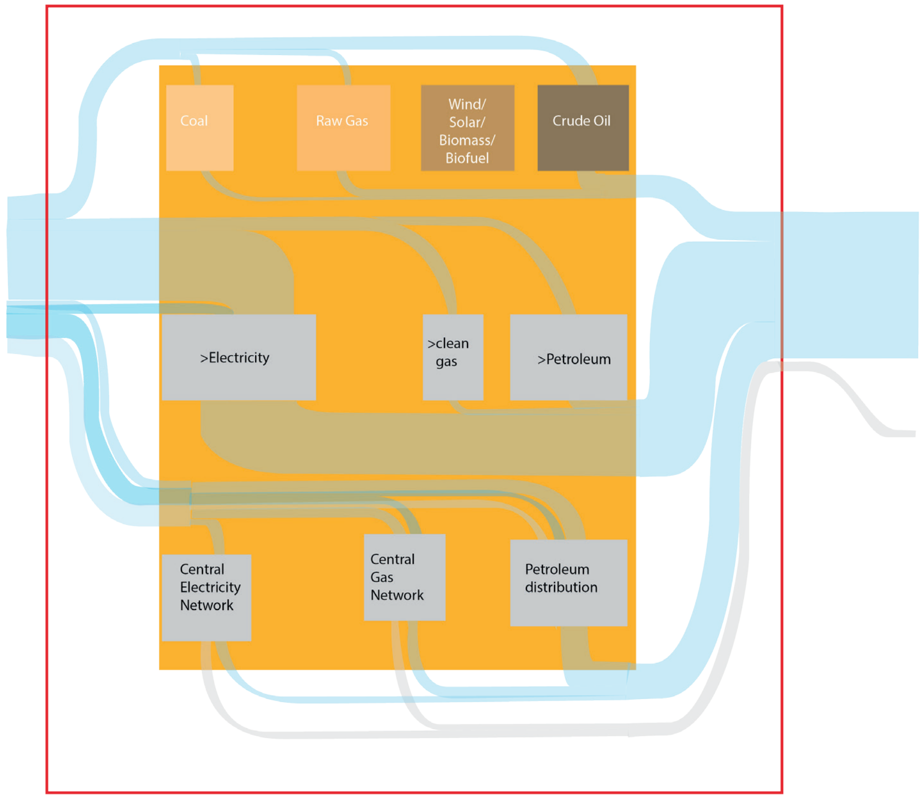


Figure 11: Example Sankey diagram for water in the electricty sector

STEP 4 DEFINE CONSTRAINTS
Constraints consist of natural constraints and adaptable constraints. The natural constraints are those that are formed by physical laws. Adaptable constraints are constraints that can be altered by human intervention. These can be of different types. They can be for instance related to capacities (e.g. reservoir storage cannot be more than reservoir storage capacity) or to regulations (e.g. no more GHG may be emitted as allowed).
In addition, one should define initial conditions. Initial conditions should be defined for all variables that may contain a value at start such as storages of water, food and energy. Initial conditions affect the value of other variables in future time. It matters for the optimization if storages are already present for example. The need for initial conditions depends on the objective. If one wants to see how one can slowly divert away from the current situation it is important. Initial conditions could for example be related to previous production levels, with additional constraints that limit the change of production levels in time.

Boundary conditions define the interactions with the borders of the case study area. They could relate to water, food and energy import and export for example. Here it should be stated if import is allowed, and how much, against what price etc.

STEP 5: COUPLE BALANCES, INTERACTIONS AND CONSTRAINTS TO OBJECTIVE
The system of equations with the relevant balances and interactions is formed. But up to now these balances and interactions are uncoupled from the objective. To be able to say if the objective was reached, first performance indicators are required. These should evaluate if the goal was reached, and if not, how far the solution proposed is off from the goal. In this example, the objective was to satisfy water, food and energy demand against minimal cost. Performance indicators should monitor if water, food and energy demand indeed is met.

In addition, it should be achieved against minimal cost. Everything in the system of equations should be checked whether it brings along cost. Only when all these attributes are known a valid cost optimization can be run.

STEP 6: CHOOSE DECISION VARIABLES
Now the system and objective are linked, the effect of changes in the system can be evaluated. Now, decisions can be made.One can optimize food production, storage or transports. At the same time, water transports and storage or energy transports can be optimized. Optimizing for different variables for different sectors allows to see the influence of one decision on another decision. Irrigation capacity would be built in different places, when storage capacity can also be constructed.

Policymakers should think of which of the subcomponents they can influence. These then can be incoorperated as decision variables. The choice of decision variables also depends on the objective. If one purely wants to optimize food transports Only one decision variable is necessary. However, this requires other levels to be known (e.g. food production). The more decision variables, the less data is required, but also, the harder it may be to implement a found solution.

2.2 PROGRAMMING FRAMEWORK

If the mathematical relations are determined, the optimization problem needs to be able to run and a solution needs to be analysed. The data needs to be pre-processed such that it is in the right spatial and temporal scales and that its units are coherent. Then the data is ready to be passed on to the optimizer which contains the mathematical core and solves the problem posed. Lastly, the solution found by the optimizer needs to be analysed and visualized which is done in the postprocessing phase.

Input data -> preprocessing -> Input data framework -> mathematical optimization kit -> postprocessing -> output data + visualization

To pre-process the data, this study made use of two models: QGIS which visualizes spatial data and does small analysis, such as grouping, summing and averaging; and Python which in turn may process a lot of spatial data at the same time for larger analysis, such as a series of multiplications. The processed data is collected and sorted in an excel-file. The mathematical optimization kit GAMS is utilized to solve the linear problem and extracts the data from the excel-file. GAMS makes use of SIMPLEX in solving the optimization problem, a linear programming algorithm. The output is postprocessed by python to visualize the data, create maps and provide the numbers required by the user.

Used set-up: Input data -> python, qgis -> excel -> gams -> python -> output + visualization

2.3 ANALYZATION METHODS

VISUALIZATION

Physical and temporal accounting of resources has been mentioned as one of the necessary components of a nexus assessment. In the postprocessing of the output therefore the output is visualized and geographically plotted. In addition, each timestep has its own plot as shown in figure 12 which are actual plots of MAXUS.

ACCOUNTING

In addition to spatial plotting. An accounting framework was designed that allows for visualizing an overview of resources through different stages of time based on a Sankey diagram as shown in figure 13 and 14 for food and energy. This has not been coded yet, but the output data is suitable for this graphical type of accounting.

SENSITIVITY ANALYSIS

To discover trade-offs a sensitivity analysis is crucial. MAXUS can contain a large quantity of parameters and therefore a sensitivity analysis needs structure. The sensitivity of a parameter with respect to the objective may be tested (such as the influence of reservoir capacity versus the total profit of the system) but the sensitivity of a variable with respect to another variable can also be tested (such as the influence of reservoir capacity on the use of irrigation). These sensitivities change when any other parameters change. One should therefore start testing sensitivities based on a reference level (which can be representative for the actual situation for example) in which other parameters are kept constant.

Because the model is linear, computational times are generally in the order of seconds with a normal laptop. Sensitivity analysis can therefore be automated and a good understanding in trade-offs can be generated.

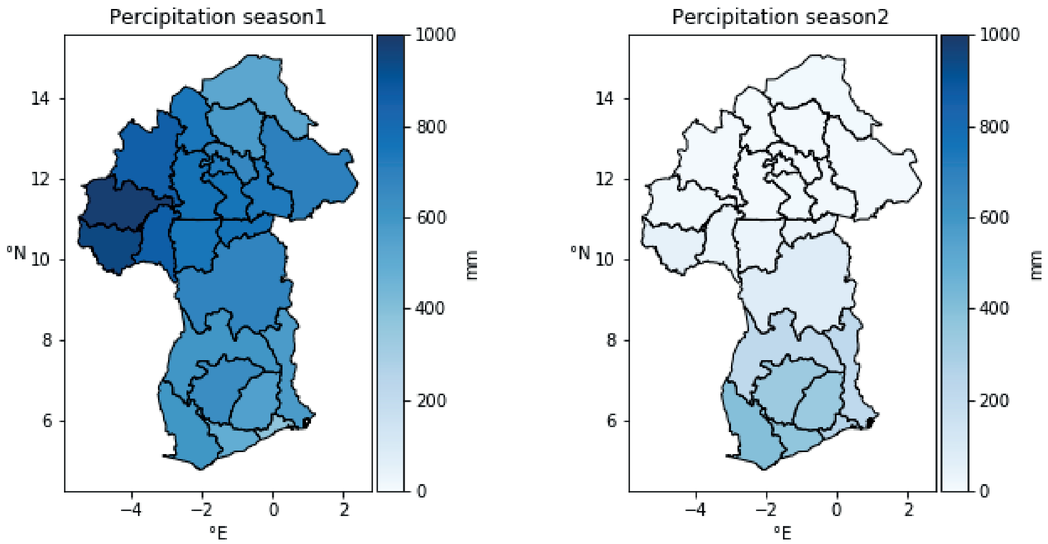


Figure 12: Spatial and temporal visualization for precipitation in Maxus

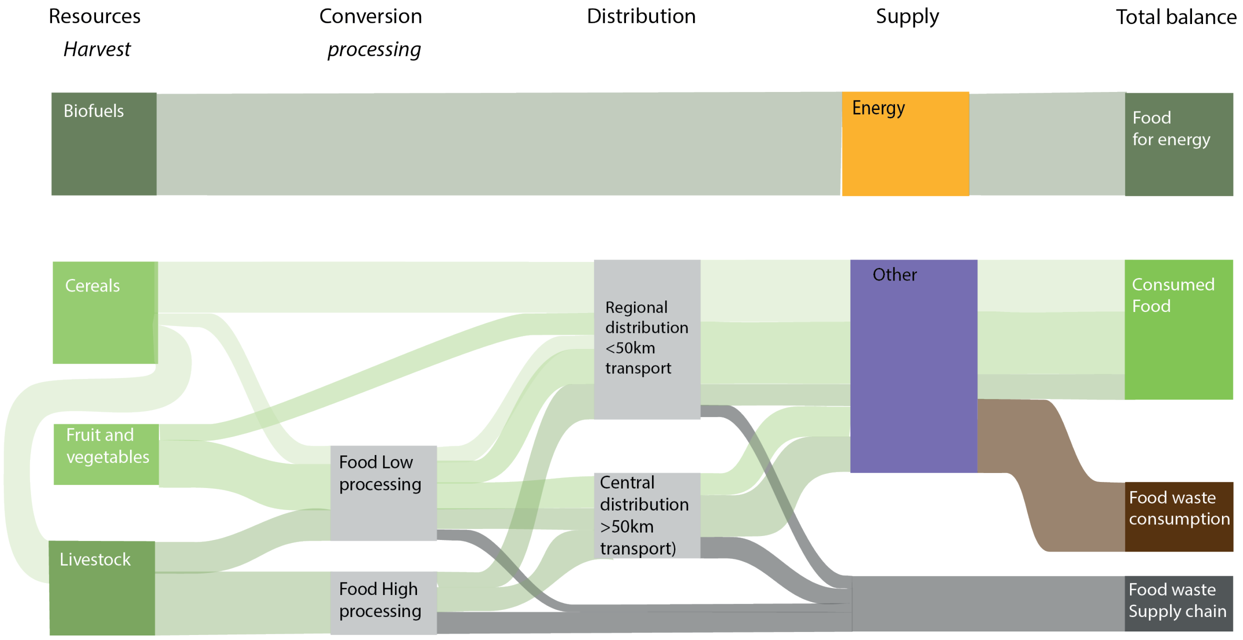


Figure 13: Example Sankey diagram for food

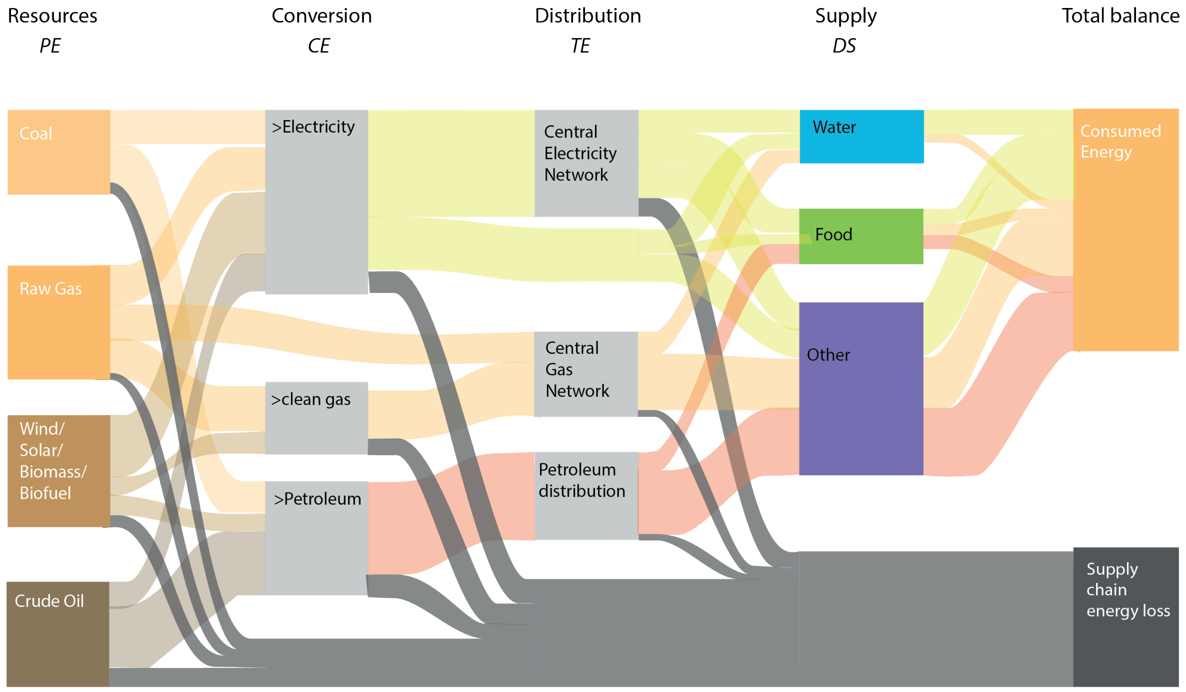


Figure 14: Example Sankey diagram for energy

3. CASE STUDY

In this section MAXUS is used to investigate the WEF nexus for Ghana and Burkina Faso.

In this case study a qualitative study is done to understand the WEF challenges in the area and what interactions seem most critical. After that the steps as described in MAXUS are followed to delineate a model to generate quantitative insight in the interactions, trade-offs and challenges. In addition, used data and assumptions are given. Then results of using MAXUS are given and discussed. At last a conclusion follows and recommendations to improve the specific case study.

Ghana and Burkina Faso have fast growing populations[1] and strong growing economies[2] . Demand for WEF is rising and it thus has become an even bigger challenge to increase WEF security. The area furthermore forms a good case study area because WEF interactions and limitations are strong. Even though the area is rich in resources, the strong seasonality in water availability combined with the dependency of energy and food on water supplies, make it had to have year-round accessibility. This case study aims to show how MAXUS can be used to explore how developments in one sector may affect decisions to be taken in another sector.

3.1 QUALITATIVE STUDY GHANA & BURKINA FASO

The agricultural sector in Ghana and Burkina Faso employs 45% and 85%of labour force respectively mostly on small-scale farms and therefore its growth is essential for the growth of the economy as a whole[50][51]. Agricultural production has expanded quickly in Ghana. It realized an even quicker agricultural production growth than population growth, which made Ghana achieving the Millennium Development Goal of halving poverty and hunger before 2015[52][53]. In Burkina Faso the number of undernourished people rose, even though it invested heavily in agriculture [54].

The agricultural expansion of the last decades has been mainly realized by agricultural land expansion. The land footprint of agriculture has risen from 13% of total land cover of Ghana in 1975 to 32% in 2013 and in Burkina Faso from 15% to 39% over the same period[55][56]. Natural vegetation thereby suffered. Forested area lost 25% of their original land occupation in Ghana and 30% in Burkina Faso[55][56].

To keep expanding agricultural production, Ghana und Burkina Faso seek refuge in intensification of agriculture rather than increasing land expansion. More mechanization, irrigation and fertilization should be the new drivers for agricultural growth.

The contribution of agriculture to national GDP varies from year to year, in part due to low yields resulting from drought[54].The high seasonality in rainfall make rainfed farming hard. Storage of water is key in the area for a steady food production, but irrigation capacity is very limited and local infiltration losses are quite substantial[57]. Increasing irrigation capacities is seen as one of the top priorities for improving food security[58][59].

[1] *Population growth - Ghana 2.2% (2016), Burkina Faso 2.9% (2016), world average of 1.2% (2016)[82]*

GDP growth - Ghana: 9% (2017), Burkina Faso 5.5% (2017), world average 2.5% (2016)[83]

Burkina Faso is one of the few countries in Africa (13 out of 54) that in most years since 2003, have achieved the Comprehensive Africa Agriculture Development Programme (CAADP) target to allocate at least 10 percent of the national budget to agriculture.[54]

Picture 5: Aksombo dam, Ghana; source: Pinterest[113]

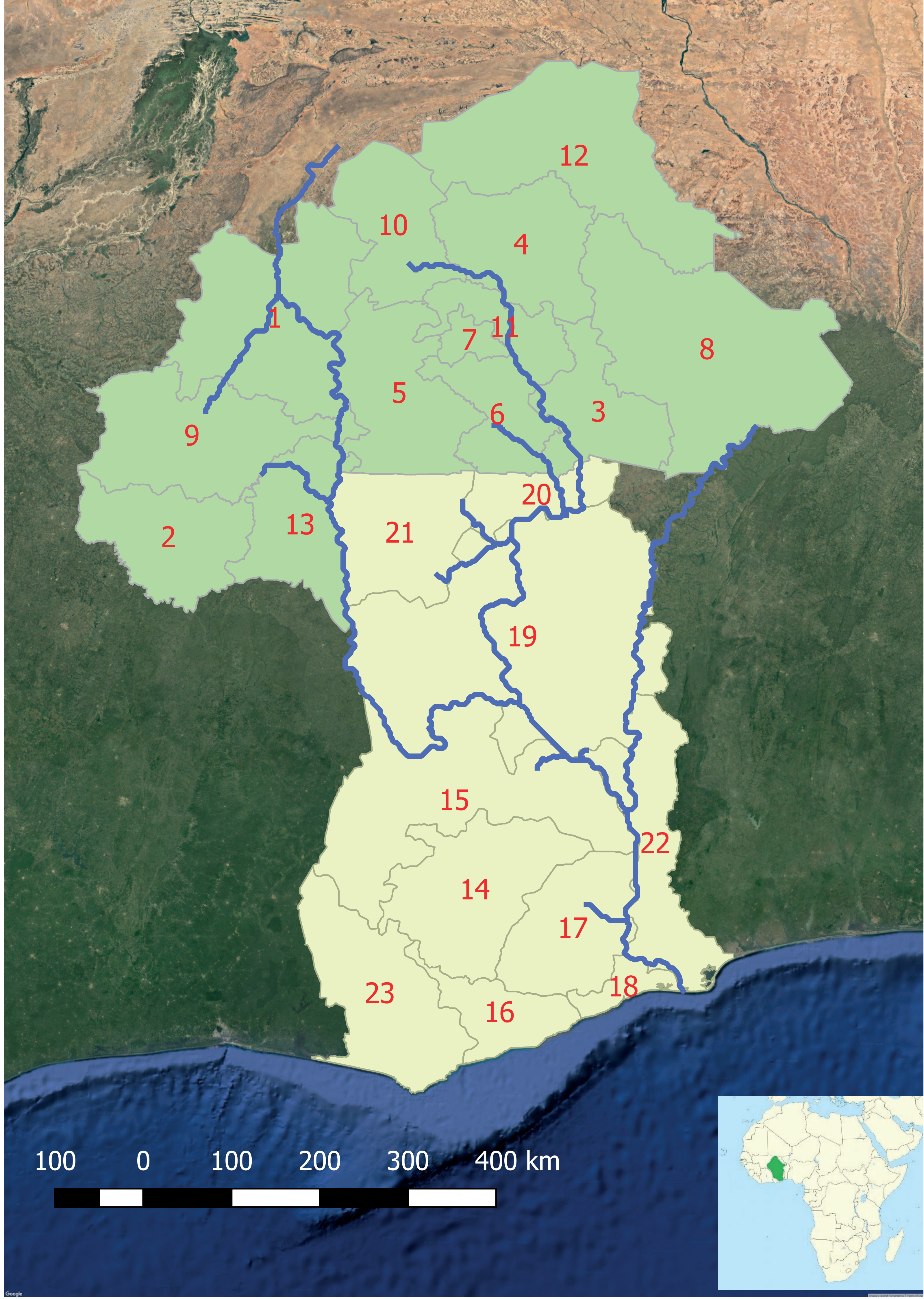


Figure 15 : Case study, Ghana and Burkina Faso

Instead of storing water for the sake of irrigation, groundwater application may be the remedy. It was shown that less than 1% of the sustainable recharge rate of groundwater was abstracted in the Volta Basin[60]. The challenge with the application of groundwater is accessibility of the financial resources to drill and in addition medium to large scale pumping requires fuel or electricity.

Instead of water storage, food storage is another alternative to bridge the gap in seasonality of water availability. After harvest, food can be bagged and stored in warehouses to respond to temporal and spatial price differences. However, at least in some areas, warehouse management in both community warehouses as large-scale governmental facilities was identified as extremely poor, leading to physical deterioration and waste[61]. Food losses are high, up to 15% pre-harvest losses and 40% post-harvest losses[62]. In a dry year, especially Burkina Faso relies on international food aid[54].

The availability of water does not just play a role in food production in Ghana and Burkina Faso, it is also crucial for power production. More than 50% of power production in the region depends on hydropower[63]. The largest share of power production is generated in the Akosombo Dam in Ghana, located in region 17 in figure 15, which has seen water levels drop consistently below acceptable operational levels[64].

With the recent increase in energy demand (52% over the period 2006-2016 in Ghana), significant amounts of thermal power generation sources have been introduced into the sector. Both countries now heavily rely on large international thermal power contracts, that leave some reliability to be desired[64]. Because of intermittent power supply it is estimated that Ghana loses between 2% and 6% of GDP annually[65]. The ratios of energy prices to purchasing power in both countries belong to one of the highest in the world[66]. Aside from intermittent supply, losses in transmission and distribution form other reasons why the prices are so high. These losses are on average 22% in Ghana and a staggering 60% in Burkina Faso[63][67]. Both Burkina Faso and Ghana are looking to expand power production facilities and plan for new hydropower dams to become less dependent on import. Solar and wind energy may form new opportunities for power production[64][68].

With the high dependency on water, geopolitical tensions exist between the two countries. Burkina Faso expanding its water withdrawals in the upper basin through dam building and irrigation development may lead to disappointed hydropower production in Ghana. It is important to understand the implications of such interventions.

The coming decades Ghana and Burkina Faso have significant challenges when it comes to WEF security. It will be of utmost importance to well consider how to apply governmental budgets.

- To what extent should Ghana and Burkina Faso stimulate the intensification of agriculture not to harm forests any further?

- Should water be used for agriculture or for hydropower and when and where?

- Where should food and energy programs aim to increase the counties own production of food and energy to decrease the dependency on imports?

- Should food policy focus on improving and reducing losses in food, or should it focus on increasing water availability? By means of water storage or by groundwater irrigation?

3.2 METHODS & METHODOLOGY

To investigate trade-offs in the WEF sectors of Ghana and Burkina Faso, a model is costumized by means of using the methodology of MAXUS. These are:

- **Step 1: form an objective**
- **Step 2: create relevant balances**
- **Step 3: select and define the significant interactions**
- **Step 4: define constraints**
- **Step 5: couple balances, interactions and constraints to objective**
- **Step 6: choose decision variables**

STEP 1: FORM AN OBJECTIVE

To demonstrate the presence of trade-offs the objective of the case study is chosen to be to satisfy water, food and electricity demand at minimal cost. It is pretended as if water, food and energy supply would be a pure economic question, but this already gives a lot of trade-offs.

$$\underset{decision\ variables*}{\text{minimize}} \quad \underbrace{C_{Tot}}_{\text{total costs}}$$

while satisfying demand of water food and electricty

The reason that the study is limited to electricity when it comes to energy is that a lot of the cross-sector Nexus trade-offs for energy described concern electricity rather than oil, fuels and gas. Remember that this is an example. For a more complete WEF analysis one could choose not to neglect these types of energy.

Two modes were investigated. In the first one costs are minimized for WEF operations given existing infrastructure. In the second one, infrastructure can be expanded, and investment cost are incorporated in the objective function. The latter is to illustrate how decisions in infrastructural decisions of one sector may be influenced by developments in another sector.

Next to that, it has also been investigated how optimization would differ if the two countries would maximize their own utilities, compared to the situation in which the countries would share and optimize the use of their water and land resources for the benefit of WEF supply. In this case the same objective function is in fact used twice but for different areas.

The temporal scope has been set to two years for this case study. This is deemed appropriate for an analysis on operations and infrastructure. Figure 16 provides an illustration of this step.

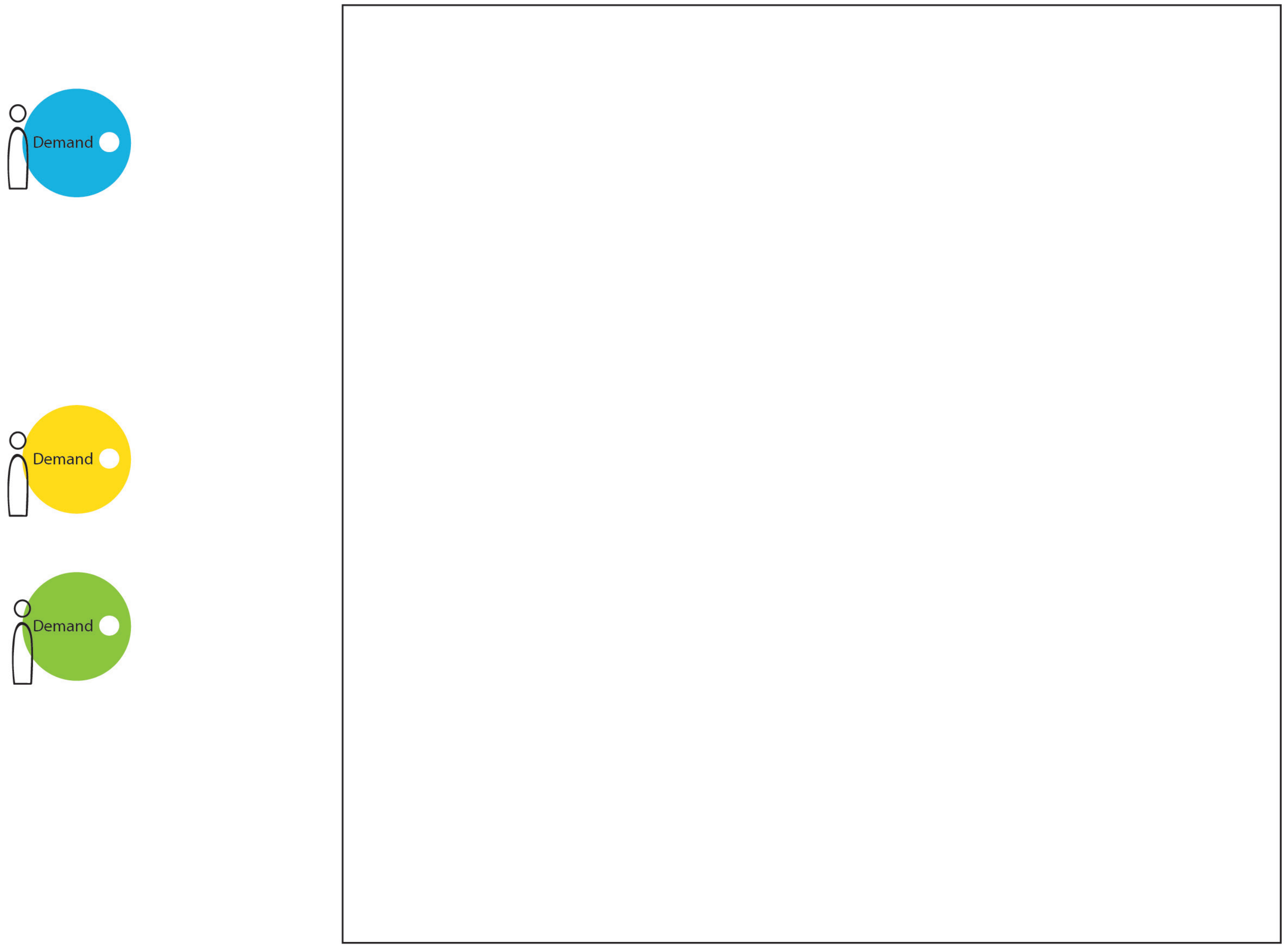


Figure 16: setting an objective

STEP 2: CREATE RELEVANT BALANCES

In the qualitative study the most important trade-offs were found to be in surface water, groundwater, land, food and electricity. These are the balances that are used in this case study. One could expand this nexus, but that would also make it more complicated. Expanding to fossil fuels, would require balances for each resource, coal, oil, gas etc. These balances may not have too many large-scale interactions with the food and water sector. In Burkina Faso for example agriculture plays a minor role in the energy use (less than 0.1%). Though if deemed necessary for WEF interactions they can be added in future research. Land decisions are limited to available agricultural land. Land use trade-offs concerning the energy sector and water sector are not considered. Compared to agriculture they use negligible amounts of land. The Volta lake, the largest manmade lake on earth and largest lake of the area uses 3.5% of Ghanaian land. For the bigger picture this is neglected. The balances are given in figure 17.

$$\underbrace{SW_{Stocks}(i,t)}_{\text{SW storage}} = \underbrace{SW_{Ava}(i,t)}_{\text{SW availability}} - \underbrace{SW_{Con}(i,t)}_{\text{SW consumption}} + \underbrace{SW_{ImEx}(i,t)}_{\text{SW import/export}}$$

$$\underbrace{GW_{Stocks}(i,t)}_{\text{GW storage}} = \underbrace{GW_{Ava}(i,t)}_{\text{GW availability}} - \underbrace{GW_{Con}(i,t)}_{\text{GW consumption}} + \underbrace{GW_{ImEx}(i,t)}_{\text{GW import/export}}$$

$$\underbrace{F_{Stocks}(i,c,t)}_{\text{food storage}} = \underbrace{F_{Ava}(i,c,t)}_{\text{food availability}} - \underbrace{F_{Con}(i,c,t)}_{\text{food consumption}} + \underbrace{F_{ImEx}(i,c,t)}_{\text{food import/export}}$$

$$\underbrace{E_{Stocks}(i,t)}_{\text{elec. storage}} = \underbrace{E_{Ava}(i,t)}_{\text{elec. availability}} - \underbrace{E_{Con}(i,t)}_{\text{elec. consumption}} + \underbrace{E_{ImEx}(i,t)}_{\text{elec. import/export}}$$

$$\underbrace{L_{Ava}(i,t)}_{\text{land availability}} \geq \underbrace{L_{Use}(i,t)}_{\text{used land}}$$

Groundwater transport between regions are neglected since groundwater transport is in the ranges of meters per year [69]. This is negligible compared to river flow.

Electricity storage is also neglected. There are no real electricity storage facilities in the region. Energy storage happens in the form of water storage, such that hydropower can be generated on a later stage. Also, electricity storage is not a process that is used to bridge months, but rather hours or days.

$$\mathrm{GW}_{ImEx}(i,t) = 0$$

$$\mathrm{E}_{Stocks}(i,t) = 0$$

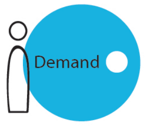


Figure 17: creating relevant balances

SURFACE WATER SUBCOMPONENTS

Water storage happens exclusively in reservoirs. No distinction is made between large and small reservoirs. Surface water is produced by rainfall. A part of that goes to groundwater. Apart from the food sector and energy sector surface water is consumed by natural evaporation and by water supply to other sector such as industry, domestic or livestock etc. Water may be transported between regions but also in- or outside the case study area.

$$\underbrace{SW_{Stocks}(i,t)}_{\text{SW storage}} = \underbrace{SW_{Ava}(i,t)}_{\text{SW availability}} - \underbrace{SW_{Con}(i,t)}_{\text{SW consumption}} + \underbrace{SW_{ImEx}(i,t)}_{\text{SW import/export}} + \underbrace{SW_{Unused}(i,t)}_{\text{modelling artifact}}$$

$$\mathrm{SW}_{Stocks}(i,t) = \underbrace{SW_S(i,t) - (1 - SW_{S_{loss}}(i,t)) * SW_S(i,t-1)}_{\text{reservoir storage change}}$$

$$\mathrm{SW}_{Ava}(i,t) = \underbrace{W_P(i,t)}_{\text{rainfall}}$$

$$\mathrm{SW}_{Con}(i,t) = \underbrace{W_{Sup}(i,t)}_{\text{water supply}} + \underbrace{(1 - GW_{Nat}) * W_{evap0}(i,t)}_{\text{natural vegetation evaporation}}$$

$$\mathrm{SW}_{ImEx}(i,t) = \underbrace{\sum_j (SW_T(j,i,t))}_{\text{net internal import}} - \underbrace{\sum_j SW_T(i,j,t)}_{\text{internal export}} + \underbrace{SW_{Im}(i,t)}_{\text{external import}} - \underbrace{SW_{Ex}(i,t)}_{\text{external export}}$$

$$\mathrm{W}_{Evap0}(i,t) = \underbrace{W_{KC}(i,t) * W_{ET0}(i,t) * L_{Tot}(i)}_{\text{Natural vegetation evaporation}}$$

GROUNDWATER SUBCOMPONENTS

No distinction is made between different groundwater storage types. Groundwater is produced and consumed by surface water interaction that will follow later. Groundwater transport is considered irrelevant.

$$\underbrace{GW_{Stocks}(i,t)}_{\text{GW storage}} = \underbrace{GW_{Ava}(i,t)}_{\text{GW availability}} - \underbrace{GW_{Con}(i,t)}_{\text{GW consumption}} + \underbrace{GW_{ImEx}(i,t)}_{\text{GW import/export}}$$

$$\mathrm{GW}_{Stocks}(i,t) = \underbrace{GW_S(i,t) - GW_S(i,t-1)}_{\text{groundwater storage change}}$$

$$\mathrm{GW}_{Ava}(i,t) = 0$$

$$\mathrm{GW}_{Con}(i,t) = \underbrace{GW_{Nat} * W_{evap0}(i,t)}_{\text{natural vegetation evaporation}}$$

$$\mathrm{GW}_{ImEx}(i,t) = 0$$

ELECTRICITY SUBCOMPONENTS

Electricity cannot be stored. It can be produced by thermal power production. Electricity may be supplied to other sectors than water and food. Like food and water, electricity may be transported between regions but also in- and outside the case study area via import and export. However, there may be losses in transport.

$$\underbrace{E_{Stocks}(i,t)}_{\text{electricity storage}} = \underbrace{E_{Ava}(i,t)}_{\text{electricity availability}} - \underbrace{E_{Con}(i,t)}_{\text{electricity consumption}} + \underbrace{E_{ImEx}(i,t)}_{\text{electricity import/export}}$$

$$\mathrm{E}_{Stocks}(i,t) = 0$$

$$\mathrm{E}_{Ava}(i,t) = \underbrace{E_{Prod.Thermal}(i,t)}_{\text{thermal power production}}$$

$$\mathrm{E}_{Con}(i,t) = \underbrace{E_{Sup}(i,t)}_{\text{electricity supply}}$$

$$\mathrm{E}_{ImEx}(i,t) = \underbrace{\sum_j ((1 - E_{T_{loss}}(j,i)) * E_T(j,i,t))}_{\text{net internal import}} - \underbrace{\sum_j E_T(i,j,t)}_{\text{internal export}} + \underbrace{E_{Im}(i,t)}_{\text{external import}} - \underbrace{E_{Ex}(i,t)}_{\text{external export}}$$

FOOD SUBCOMPONENTS

Food may be stored, though there may be losses. Food is produced by harvesting though there may be losses. Food may be supplied. Food may be transported between regions but also in- and outside the case study area via import and export. However, there may be losses in transport.

$$\underbrace{F_{Stocks}(i,c,t)}_{\text{food storage}} = \underbrace{F_{Ava}(i,c,t)}_{\text{food availability}} - \underbrace{F_{Con}(i,c,t)}_{\text{food consumption}} + \underbrace{F_{ImEx}(i,c,t)}_{\text{food import/export}}$$

$$\mathrm{F}_{Stocks}(i,c,t) = \underbrace{F_S(i,c,t) - (1 - F_{S_{loss(i,t)}}(i)) * F_S(i,c,t-1)}_{\text{warehouse storage change}}$$

$$\mathrm{F}_{Ava}(i,c,t) = \underbrace{\sum_{e,w} ((1 - F_{G_{loss(i,t)}}) * F_G(i,c,e,w,t))}_{\text{net harvest}}$$

$$\mathrm{F}_{Con}(i,c,t) = \underbrace{F_{Sup}(i,c,t)}_{\text{food supply}}$$

$$\mathrm{F}_{ImEx}(i,c,t) = \underbrace{\sum_j ((1 - F_{T_{loss(j,i,t)}}) * F_T(j,i,c,t))}_{\text{net internal import}} - \underbrace{\sum_j F_T(i,j,c,t)}_{\text{internal export}} + \underbrace{F_{Im}(i,c,t)}_{\text{external import}} - \underbrace{F_{Ex}(i,c,t)}_{\text{external export}}$$

AGRICULTURAL LAND SUBCOMPONENTS

Agricultural land is not used or consumed other than by agriculture.

$$\underbrace{L_{Ava}(i,t)}_{\text{land availability}} \geq \underbrace{L_{Use}(i,t)}_{\text{used land}}$$

$$\mathrm{L}_{Ava}(i,t) = \underbrace{L_{agr}(i,t)}_{\text{available agricultural land}}$$

$$\mathrm{L}_{Use}(i,t) = 0$$

Now the dimensions of all subcomponents need to be determined and the size and units of the dimension sets. Since finding spatial and temporal trade-offs is an aim of this study, these dimensions are required. The spatial dimension unit was chosen to ben an administrative region. This is estimated to represent rough spatial trade-offs well. The dimension set therefore includes 13 administrative regions of Burkina Faso and 10 of Ghana. Going to smaller units than regions, data availability becomes low. Sub-basins could also form spatial units of similar size, but data of the energy sector and food sector is not given for sub-basins but for administrative regions. To be able to compare it had been deemed more practical to use administrative regions. Table 2 provides an overview of the dimensions, their size and their units.

The temporal dimension set exists of 4 timesteps each representing a dry or wet season of two consequential years. A time step of half a year was required to at least represent the seasonality of rainfall well. Going to a timestep smaller than that makes representing crop growth more complicated. It would require non-linear constraints to account for the crop growth durations. Crop growth has been such an important factor in the optimization process that a bad representation could not be allowed.

With food production the dimension crop type is required. In the dimensions set twelve crops have been included, nine subsistence crops (millet, maize, sorghum, rice, cassava, yam, plantain, cocoyam and groundnuts) and three cash crops (cotton, cacao and palm oil). These are the principle crops in Ghana and Burkina Faso[50][53][54].

As mentioned before, crop yields were discretized over three input levels (high, intermediate, low) and two water levels (rainfed, irrigated). These both form additional dimension sets. More dimensions have not been deemed necessary.

For every variable and parameter, one should decide on dimensions. Two examples illustrate this decision process:

- The parameter W_P which represents rainfall should be able to represent spatial differences and temporal differences. Therefore, W_P requires two dimensions: i and j forming W_P (i,t) representing rainfall per region per season.
- The variable F_T which represents food transport should not just show when food is transported and from what region. In addition, it should tell to which region is transported and what food type is transported. F_T therefore requires four dimensions i, i, c and t forming F_T(i,i,c,t). One could desire more level of detail, for example what lorry type food is transported with or if the food was cooled or not during transport. This would require additional dimensions.

The more dimensions, the more data is required to be able to run the optimization. Data availability especially matters for the parameters. For all parameters a level of data was selected, based on usefulness and availability. These can be found in Annex A.

Name	Dimension type	Set type	Set size	Unit
i	spatial	set	23	administrative region
j	spatial	subset	23	administrative region
t	temporal	set	4	precipitation season (half a year)
c	agricultural production	set	12	crop type
e	agricultural input	set	3	input level
w	agricultural watering	set	2	watering method

Table 2: Dimensions

STEP 3: SELECT AND DEFINE THE SIGNIFICANT INTERACTIONS
In the following points, only the significant interactions are listed and discussed. An illustration of the step is given in figure 18.

- Water consumption is mainly through agriculture and natural vegetation (99.7%)[70]. Water consumption in agriculture comes back in the equation as interaction (1). Natural vegetation also consumes water. If agriculture changes land cover (2), natural vegetation is replaced and therefore its water consumption (3).

- Part of surface water infiltrates to groundwater (4) but it can also be pumped up for irrigation (5) Groundwater pumping plays a minor role, in water supply, but is important in the production of food at dry locations.

- Electricity is produced by either hydropower or thermal power[63]. Hydropower comes back in equations through the interaction of surface water import/export (6). Thermal power production is in the component energy availability.

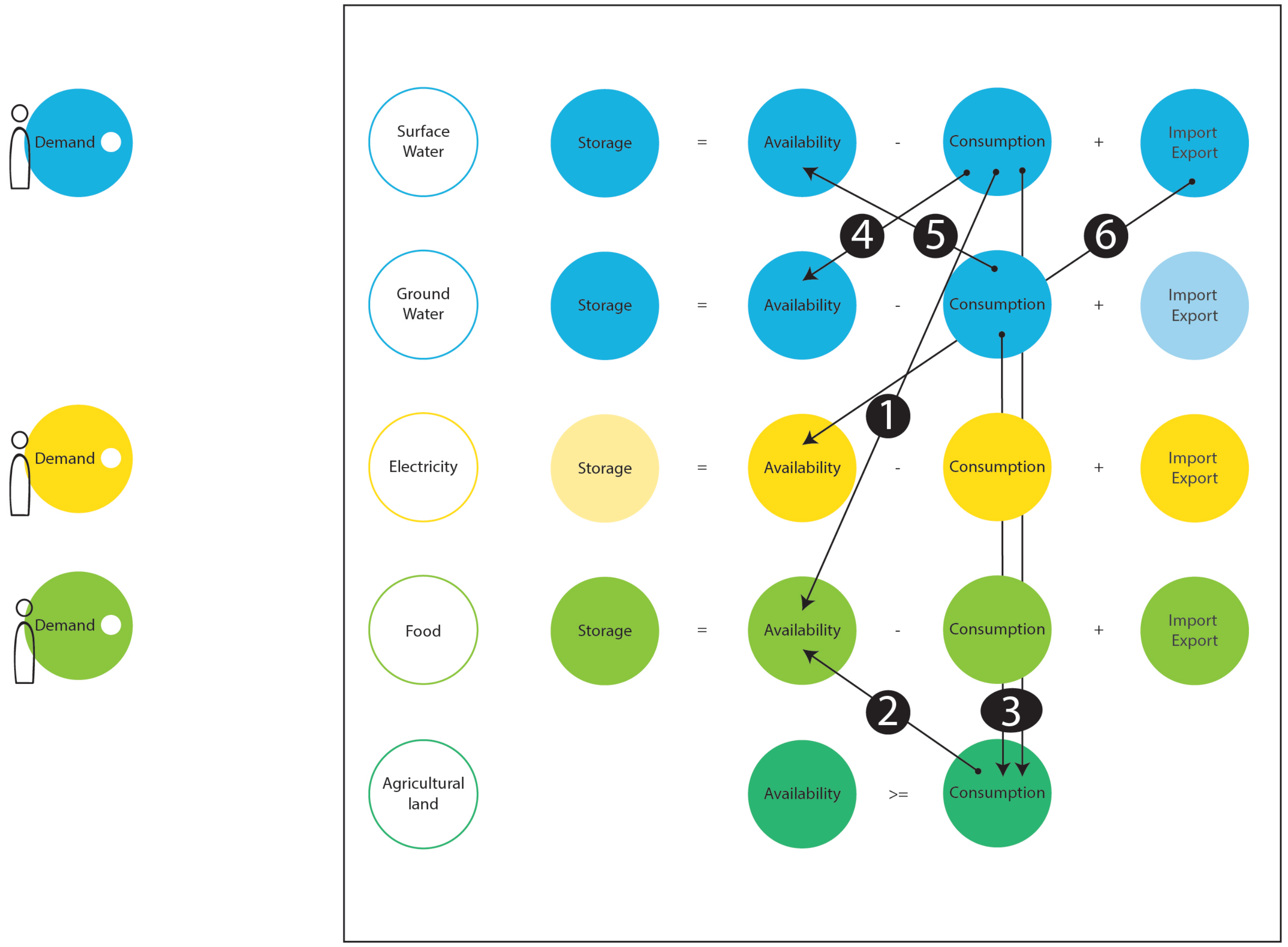


Figure 18: selecting and defining interactions

Interaction (1) is an important interaction as a major part of water is consumed in agricultural production. The water consumption of agriculture is in fact evaporation of crops. The actual evaporation of a crop Eta that is realized with actual yield (Ya) can be related to the maximum evaporation of that crop (ETx) when the crop grown also reaches maximum yield (Yx) with a crop response factor (Ky).

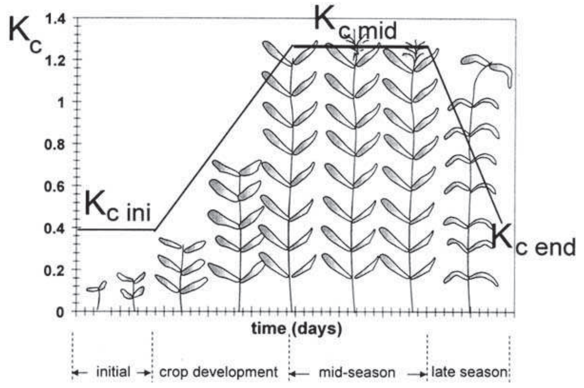
$$\text{FAO formula:}\quad (1-\frac{Y_a}{Y_x}) = K_Y(1-\frac{ET_a}{ET_x})$$

$$\mathrm{W}_{Con.F_G}(i,c,e,w,t) = \underbrace{((\frac{L_{F_G.Req}(i,c,e_{high},w_{irr})}{L_{F_G.Req}(i,c,e,w)}-1)*\frac{1}{F_{K_y}(c)})+1)}_{\text{real yield / maximum yield * yield response factor}} * \underbrace{W_{KC}(c)*W_{ET0}(i,t)}_{\text{maximum crop evaporation}}$$

$$\mathrm{SW}_{Con}(i,t) = ... + \underbrace{\sum_{c,e,w}(W_{Con.F_G}(i,c,e,w,t)*F_G(i,c,e,w,t))}_{\text{crop evaporation}}$$

The maximum evaporation of a crop is described by the following equation. With a crop-coefficient it can be described how much a crop evaporates compared to reference-crop evapotranspiration (ETo). The crop-coefficient varies throughout the growth stages of a crop as depicted in figure 19. In this case study an average crop-coefficient is determined for each crop over the growth stages.

$$\text{FAO formula:}\quad ET_x = K_c\, ET_o$$



Figuur 19 crop coefficient curve; source: FAO[71]

Interaction (2) describes the land requirement of grown crops, in other words, the inverse of yields. Yields that are obtained in a region are ideally calculated based on the water diverted to that crop. In addition, one should link attainable yields to applied nutrients and applied production methodologies for the crops. Since there is not a continuous relation that links that all due to the heterogeneity in production methodologies, in the current model crop yields are discretized by making use of GAEZ data which has determined attainable yields for grid cells of 10km squared for three established input levels of production methodologies and nutrients and considers soil quality and climatic constraints[37]. In this case study these yields are averaged over the available agricultural land per region per input level.

$$\mathrm{L}_{Use}(i,t) = ... + \underbrace{\sum_{c,e,w} L_{Req.F_G}(i,c,e,w)*F_G(i,c,e,w,t)}_{\text{combined irrigated and rainfed land use}}$$

The maximum attainable yield is determined as obtainable yield in the area without water or nutrient constraints. Therefore, maximum attainable yield (Yx) is best described by high input level yield on a irrigated area. However, irrigated yields are not known for the whole area, mostly because the area contains negligible irrigation capacity. Irrigated yields thus have been established as being equal to the highest rainfed yield of all the regions. Although there are some differences in soil quality, the main spatial differences in rainfed crop yields come from differences in water availability. It is therefore assumed that the irrigated yield is equal to the rainfed yield of the region where the highest rainfed yield is observed rainfed under the assumption that here water limitations are not present.

Interaction (3) describes the change in natural water evaporation. When crops are grown, evaporation of the land on which is grown is affected. Evaporation of natural vegetation is modelled similarly to crop evaporation but then with different crop factors.

If the land cover changes because crops replace natural vegetation the evaporation of natural vegetation is affected by the following relation:

$$\mathrm{W}_{Evap0}(i,t) = ... - \underbrace{\sum_{w,c,e}(L_{F_G.Req}(i,c,e,w)*F_G(i,c,e,w,t))}_{\text{land use of crops}} * \underbrace{W_{KR}*W_{KC.Nat}(i,t)*W_{ET0}(i,t)}_{\text{evaporation of vegetation replaced}}$$

In which Wcr is a factor that relates to which natural vegetation is replaced. On agricultural land it is most likely shrubs or herbs that grow when agricultural land is not used. Not evergreen forest. In a region with a lot of forest, the average Wkc of natural vegetation is high, and therefore Wcr should be lower than one. In a region with a lot of barren ground it is unlikely that rainfed agriculture will replace barren ground. In that case Wcr could be higher than one.

Interaction (4) describes surface water infiltration to groundwater. This effect in included as a consumption term of surface water and a production term of groundwater. An infiltration factor represents the ratio of infiltration. The amount that is infiltrated is expressed in terms of rainwater.

$$\mathrm{GW}_{Ava}(i,t) = ... + \underbrace{GW_{Re}*W_P(i,t)}_{\text{groundwater recharge}}$$

$$\underbrace{W_{Sup}(i,t)}_{\text{water supply}} = ... + \underbrace{GW_{Re}*W_P(i,t)}_{\text{groundwater recharge}}$$

Interaction (5) describes the pumping of groundwater for irrigation. In this case study the interaction includes an amount of water that is consumed from groundwater and an availability term for surface water

$$\mathrm{SW}_{Ava}(i,t) = ... + \underbrace{GW_{Irr}(i,t)}_{\text{GW irrigation}}$$

$$\mathrm{GW}_{Con}(i,t) = ... + \underbrace{GW_{Irr}(i,t)}_{\text{GW irrigation}}$$

Interaction (6) is hydropower generation and is modelled based on the following equation. In which n is the efficiency of the turbines, ro is the density of water, Q is the discharge, g s the gravity constant, and h is the hydraulic head Hydraulic heads and gravity are assumed constant for the dams to keep the equation linear. The discharge is assumed to be equal to the transport of water through the dam. Ehydro.Wt represents the hydropower generation per unit volume.

$$\text{HYDROPOWER formula:}\quad \int_{t=0}^{t=end} \eta\rho(t)Q(t)gh(t)$$

$$\mathrm{E}_{Ava}(i,t) = ... + \underbrace{\sum_j(E_{hydro.W_T}(i,j)*W_T(i,j,t))}_{\text{hydropower production}} + \underbrace{E_{hydro.W_{Ex}}(i)*W_{Ex}(i,t)}_{\text{hydropower production cross-border transport}}$$

STEP 4 DEFINE CONSTRAINTS

Constraints form the conditions for the optimization problem. There are four types as depicted in figure 20, natural constraints, adaptable constraints, initial conditions and boundary conditions.

The natural constraints consisting of more terms are given here. Rainfed crops cannot grow if water requirements are not met. Crop production can only occur when water consumption is positive. The other natural constraints are written for variables that cannot be negative (e.g. storage and transports of water, food). In the nomenclature can be seen which are constrained to be positive.

$$\underbrace{F_G(i,c,e,w_{RF},t)}_{\text{rain fed crop production}} * \left(\underbrace{\frac{W_P(i,t)}{L_{Tot}(i)}}_{\text{rainfall per unit area}} - \underbrace{W_{Con.F_G}(i,c,e,w,t)}_{\text{water consumption crop per unit area}} \right) \geq 0$$

$$\underbrace{F_G(i,c,e,w,t)}_{\text{crop production}} * \underbrace{W_{Con.F_G}(i,c,e,w,t)}_{\text{water consumption crop per unit area}} \geq 0$$

The adaptable constraints of this case study are related to infrastructure. Upper bounds for water storge, irrigated land use, surface water export, food storage and thermal power production are given by reservoir storage capacity, irrigation capacity, surface water export capacity, warehouse storage capacity and thermal power production capacity respectively.

When optimizing with having the possibility of infrastructural expansion, two constraints are made dynamic in this case study. Irrigation capacity can be expanded, and reservoir capacity can be expanded.

$$\underbrace{SW_S(i,t)}_{\text{reservoir storage}} \leq \begin{cases} \text{Operations:} & \underbrace{SW_{S.Cap.Existing}(i)}_{\text{existing reservoir storage capacity}} \\ \text{Planning:} & \underbrace{SW_{S.Cap.Existing}(i)}_{\text{existing reservoir storage capacity}} + \underbrace{SW_{S.Cap.New}(i,t)}_{\text{new reservoir storage capacity}} \\ & \underbrace{SW_{S.Cap.New}(i,t)}_{\text{new reservoir storage capacity}} \geq \underbrace{SW_{S.Cap.New}(i,t-1)}_{\text{new reservoir storage capacity of previous timestep}} \end{cases}$$

$$\underbrace{L_{Use.Irr}(i,t)}_{\text{land use for irrigated crops}} \leq \begin{cases} \text{Operations:} & \underbrace{L_{Irr.Cap.Existing}(i)}_{\text{existing irrigation capacity}} \\ \text{Planning:} & \underbrace{L_{Irr.Cap.Existing}(i)}_{\text{existing irrigation capacity}} + \underbrace{L_{Irr.Cap.New}(i,t)}_{\text{new irrigation capacity}} \\ & \underbrace{L_{Irr.Cap.New}(i,t)}_{\text{new irrigation capacity}} \geq \underbrace{L_{Irr.Cap.New}(i,t-1)}_{\text{new irrigation capacity of previous timestep}} \end{cases}$$

$$\underbrace{SW_{Ex}(i,t)}_{\text{xternal export}} \leq \underbrace{SW_{Ex.Cap}(i)}_{\text{external export capacity}}$$

$$\underbrace{\sum_c F_S(i,c,t)}_{\text{varehouse storage}} \leq \underbrace{F_{S.Cap}(i)}_{\text{warehouse storage capacity}}$$

$$\underbrace{E_{Prod.Thermal}(i,t)}_{\text{hermal energy production}} \leq \underbrace{E_{Prod.Thermal.Cap}(i,t)}_{\text{thermal energy production capacity}}$$

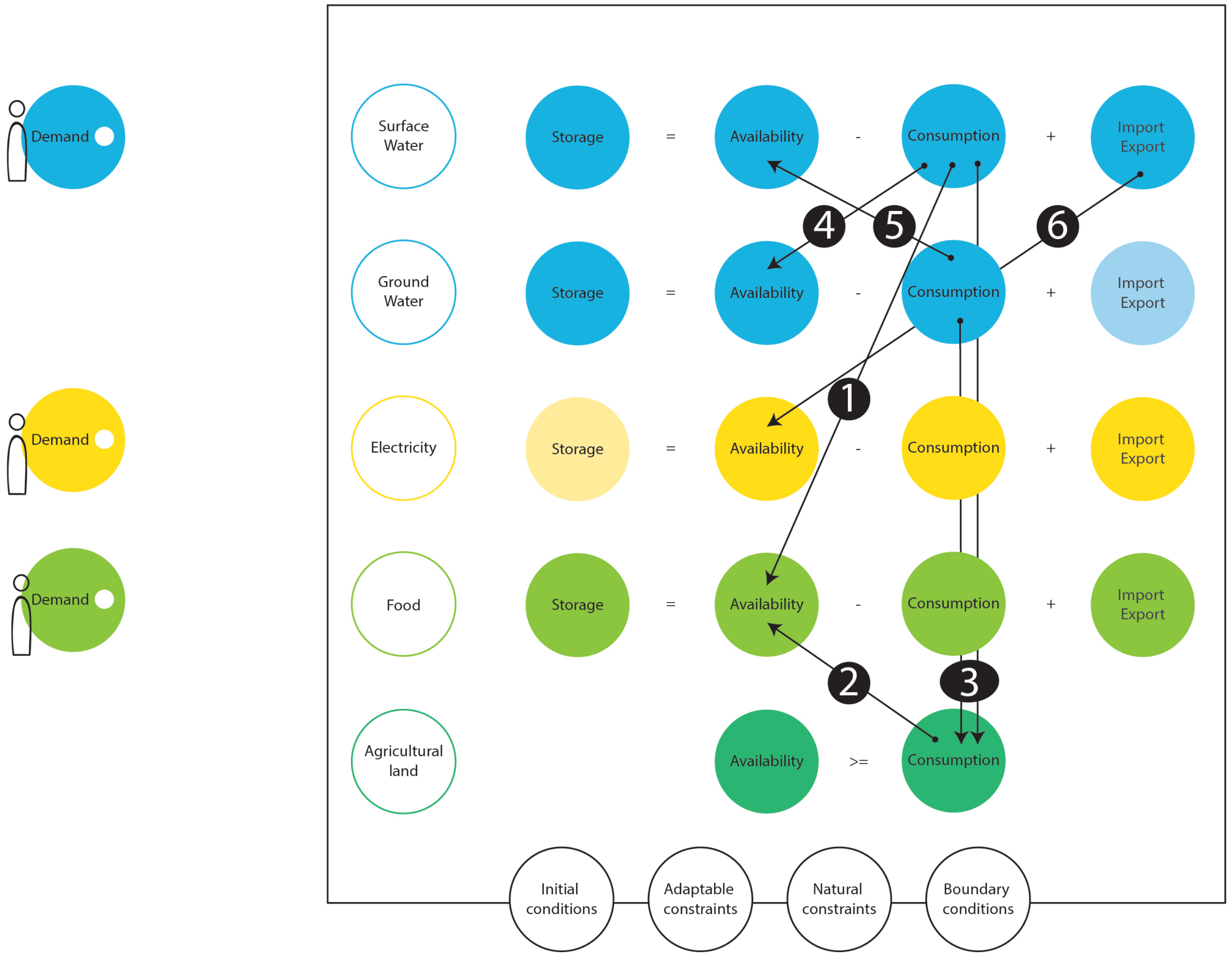


Figure 20: forming constraints

The initial conditions are necessary for the terms that include a previous timestep: food storage, surface water storage and ground water storage. All three were initially zero. No initial storage was assumed.

$$\underbrace{SW_S(i,t=0)}_{\text{initial surface water storage}} = 0$$

$$\underbrace{GW_S(i,t=0)}_{\text{initial groundwater storage}} = 0$$

$$\underbrace{F_S(i,c,t=0)}_{\text{initial food storage}} = 0$$

Boundaries are set-up such that WEF demands can in almost any case be satisfied. Food and electricity can always be imported, and the penalty is much higher than the cost to import. There is never a problem that water demand cannot be satisfied even though it cannot be imported. Since water demand mainly comes from agriculture, lowering agricultural production compensates for in case there are water shortages.

Since there are no rivers entering or leaving the area of Burkina Faso and Ghana there is no possibility to significantly export or import water. There may be some trucks carrying water over the borders, but this is insignificant. Water leaving the area leaves to sea. This however should be formulized.

Food and electricity exports are fixed based on export data in terms of quantity and price. The reason the quantity is fixed is that different runs of the model become more comparable. If the amount to be supplied also becomes variable they are harder to compare.

$$\underbrace{SW_{Ex}(i,t)}_{\text{external export}} \leq \underbrace{SW_{Ex.Cap}(i)}_{\text{external export capacity}}$$

$$\underbrace{\sum_{i,t} F_{Ex}(i,c,t)}_{\substack{\text{food exports of all}\\ \text{regions and timesteps}}} = \underbrace{F_{Ex}(c)}_{\text{total food exports per crop}}$$

$$\underbrace{\sum_{i,t} E_{Ex}(i,t)}_{\substack{\text{electricity exports}\\ \text{of all regions}}} = \underbrace{E_{Ex}(t)}_{\text{total electricity exports in timestep}}$$

STEP 5: COUPLE BALANCES, INTERACTIONS AND CONSTRAINTS TO OBJECTIVE

Having defined our constraints, it should be checked whether the objective is feasible. Performance indicators are defined to monitor wheter water, food and energy demand can be satisfied and if not, how far the best option is off from reaching the objective. This is shown in figure 21.

$$\underbrace{W_{D.Unsatisfied}(i,t)}_{\text{unsatisfied water demand}} = \underbrace{W_D(i,t)}_{\text{water demand}} - \underbrace{W_{Sup}(i,t)}_{\text{water supply}}$$

$$\underbrace{E_{D.Unsatisfied}(i,t)}_{\text{unsatisfied elec. demand}} = \underbrace{E_D(i,t)}_{\text{elec. demand}} - \underbrace{E_{Sup}(i,t)}_{\text{elec. supply}}$$

$$\underbrace{F_{D.Unsatisfied}(i,c,t)}_{\text{unsatisfied food demand}} = \underbrace{F_D(i,c,t)}_{\text{food demand}} - \underbrace{F_{Sup}(i,c,t)}_{\text{food supply}}$$

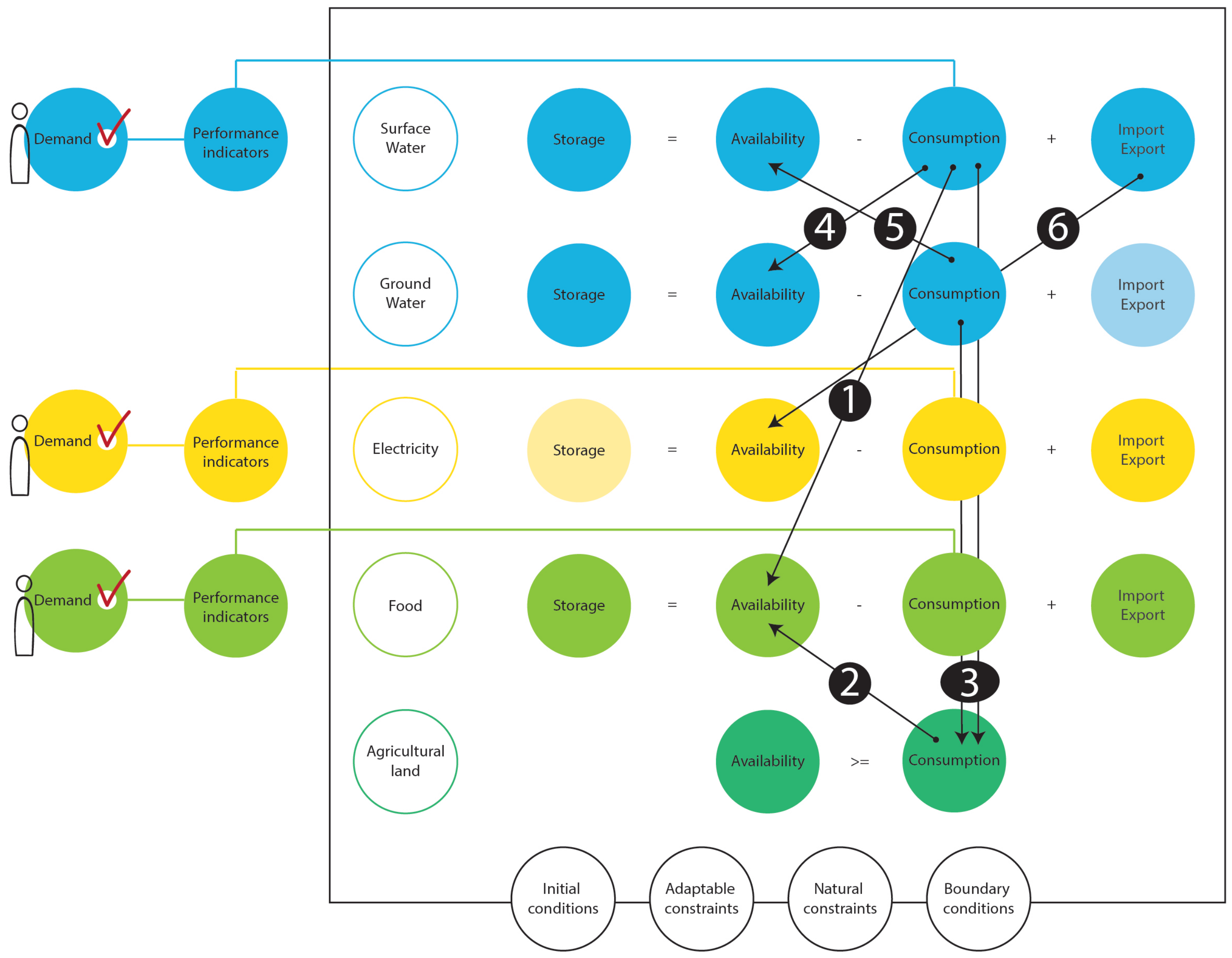


Figure 21: linking balances, interactions and consraints to goal and monitor by performance indicators

To make sure the demand is satisfied when possible, unsatisfied demand should be penalized. Moreover, when there are actually many options to satisfy the demand, it needs to be determined what the best way is to do so. This is stated in the objective, in this case, minimizing cost while satisfying demands. Each subcomponent (of components) that may bring along cost should be attributed a cost level such that decisions can be made how to supply that water, food and energy. This is illustrated in figure 22. The most important cost identified by the author are summed up in table 3. For each cost term the dimensions need to be set. This depends on the level of detail required and desired.

- reservoir construction cost are assumed to be linear with construction vulume. Regions along the river have a lower cost per unit volume then regions that are not.
- unsatisfied water is penalized linear with its volume.
- groundwater irrigation cost are assumed equal for every region and linear with the volume drawn.
- thermal power production cost are linear with the power produced. The cost are assumed to be equal for every power plant.
- elecectricty import cost are assumed to be linear with the amount imported. The cost are equal for every region.
- unsatisfied electricity demand is penalized with its volume.
- food production cost are dependent on crop type, input level and watering method. They are assumed linear with land utilized.
- food transport cost are assumed to be linear with distance transported and does not depend on crop type.
- unsatisfied demand of food is penalized with its volume.
- irrigation capacity construction cost are assumed to be linear with the amount constructed and the cost per unit area constructed does not depend on region.

cost term	**cost factor**	**in expression**
reservoir construction cost	$C_{SW_{S.Cap.New}}(i)$	$\sum_{i}(C_{SW_{S.Cap.New}}(i) * SW_{S.Cap.New}(i, t = end))$
unsatisfied water demand penalty	$C_{Unsatisfied}$	$\sum_{i,t}(C_{Unsatisfied} * W_{D.Unsatisfied}(i, t))$
groundwater irrigation cost	$C_{GW_{Irr}}$	$\sum_{i,t}(C_{GW_{Irr}} * GW_{Irr}(i, t))$
thermal power production cost	$C_{E_{Prod.Thermal}}$	$\sum_{i,t}(C_{E_{Prod.Thermal}} * E_{Prod.Thermal}(i, t))$
electricity import cost	$C_{E_{Im}}$	$\sum_{i,t}(C_{E_{Im}} * E_{Im}(i, t))$
unsatisfied electricity demand penalty	$C_{Unsatisfied}$	$\sum_{i,t}(C_{Unsatisfied} * E_{D.Unsatisfied}(i, t))$
food production cost	$C_{F_G}(c, e, w)$	$\sum_{i,c,e,w,t}(C_{F_G}(c, e, w) * F_G(i, c, e, w, t) * L_{Req.F_G}(i, c, e, w))$
food transport cost	$C_{F_T}(i, j, t)$	$\sum_{i,j,c}(C_{F_T}(i, j, t) * F_T(i, j, c, t))$
food import cost	$C_{F_{Im}(c,t)}$	$\sum_{i,c,t}(C_{F_{Im}}(c, t) * F_{Im}(i, c, t))$
unsatisfied food demand penalty	$C_{Unsatisfied}$	$\sum_{i,t}(C_{Unsatisfied} * F_{D.Unsatisfied}(i, t))$
irrigation capacity construction cost	$C_{L_{Irr.Cap.New}}$	$\sum_{i}(C_{L_{Irr.Cap.New}} * L_{Irr.Cap.New}(i, t = end))$

Table 3:objective function with linked subcomponents

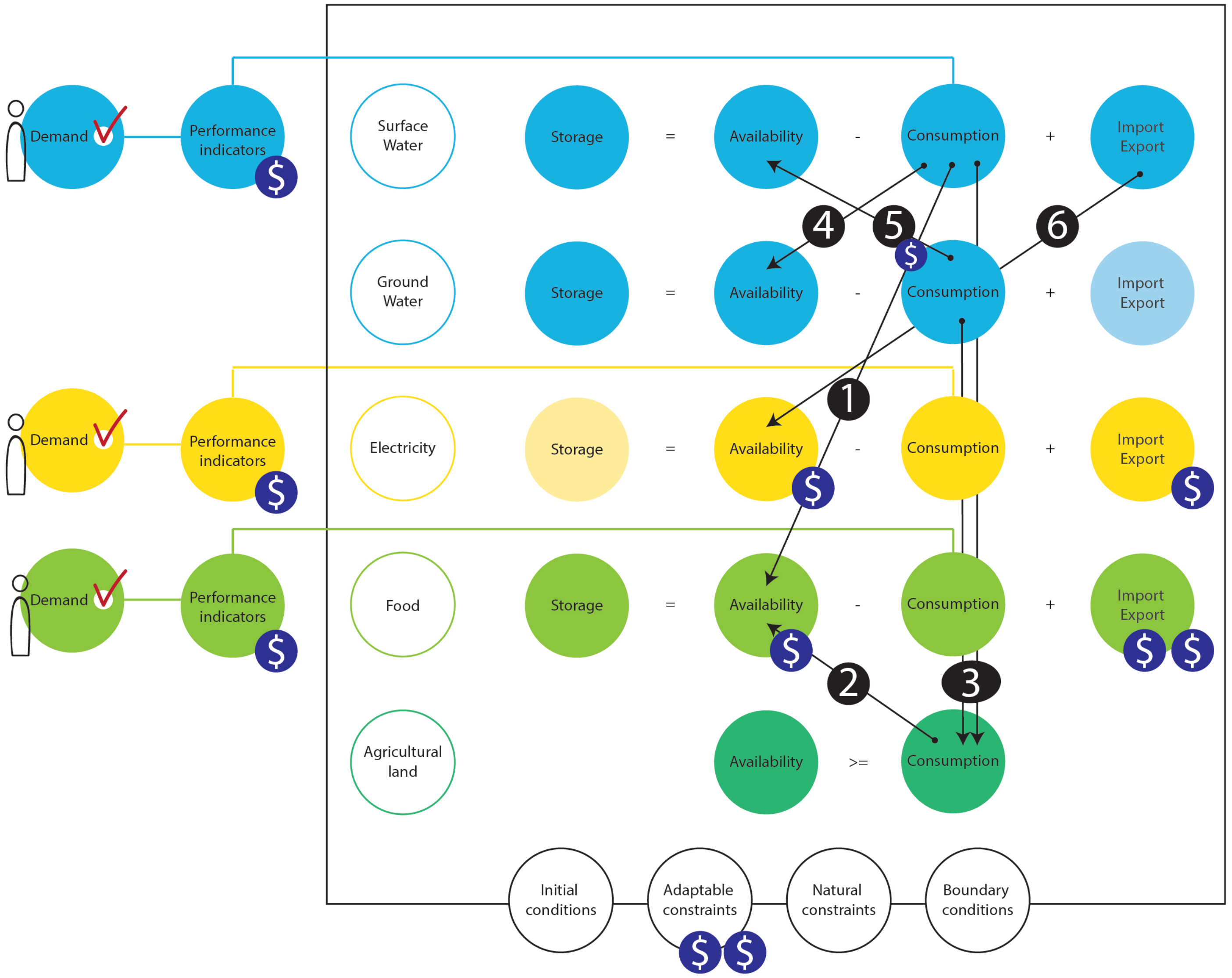


Figure 22:attributing weight/cost factors tha to link subcomponent to objective.

STEP 6: CHOOSE DECISION VARIABLES

To change the cost of supplying water, energy annd food, interventions need to be taken. The decision variables are ther variables that may be set by the model. These are the variables that is optimized for. For each subcomponent one should consider if the policymaker has influence on that variable and if it wants to allow it to be changed. In figure 23 they are illustrated with an exclamation mark. The decision variables in this study for the optimization of WEF operations for given existing infrastructure are given in table 4 on the top.

All of it is optimized in one go in the case study. One could also optimize with less variables but then data is required for the other variables which then become parameters. This has not been done in the case study, since data availability was low.

For optimizing operations and infrastructure expansion two additional decision variables which are the last two in the table. There may be many more infrastructural developments such as power production facilities or groundwater pumping facilities, but in this case study these two variables are deemed enough to reach the aim of demonstrating how developments in one sector may affect infrastructural choices made in another.

The model is now complete for this case study. A full list if equations is given in Annex B.

Name	Short description	Dimensions	Units
SW_S	reservoir water storage	i,t	Mm^3
SW_T	surface water transport	i,i,t	Mm^3/season
GW_{Irr}	groundwater irrigation	i,t	Mm^3/season
$E_{Prod.Thermal}$	thermal power production	i,t	MWh/season
E_T	electricity transport	i,i,t	MWh/season
E_{Im}	electricity import	i,t	MWh/season
F_S	food storage	i,c,t	tonnes
F_G	food production	i,c,e,w,t	tonnes/season
F_T	food transport	i,i,c,t	tonnes/season
F_{Im}	food imports	i,t	tonnes/season
F_{Ex}	food exports	i,t	tonnes/season
$SW_{S.Cap.New}$	new reservoirs storage capacity	i,t	Mm^3
$L_{Irr.Cap.New}$	new irrigation capacity	i,t	hectares

Table 4:decision variables

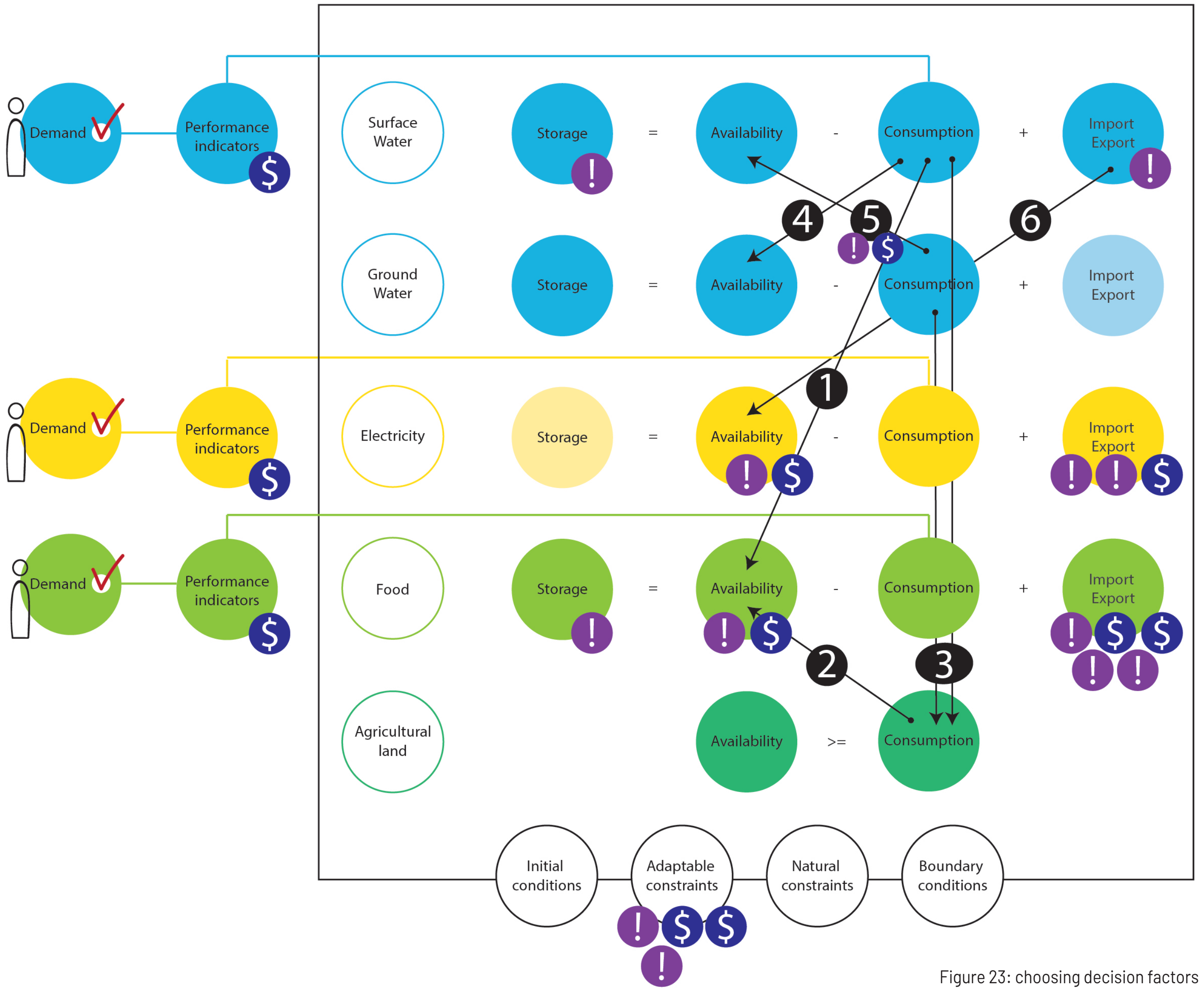


Figure 23: choosing decision factors

ASSUMPTIONS

In this case study assumptions were necessary. Firstly, because simplifications need to be made when dealing with a complex system of this sort. As was discussed in the introduction the challenge with modelling nexus of water, food and energy in integrated manner is as described by Brazilian et al.: "to draw system boundaries wide enough to encompass the enormity of the interacting vectors, while maintaining it small enough to be able to conduct useful analysis" [21, p.5]. Secondly, because the linear nature of the model forces non-linear relations to be linearized and thirdly, this study had to build on open source data which is available to a limited extent for the case study area. A list of assumptions is given below:

Surface water
- Storage losses of a reservoir is linear with its volume
- Reservoir storage can be built in every region, also when it is not along the main branch of the Volta River
- Storage construction cost are linear with volume, but the price per unit volume is different for regions along the main branch of the Volta river.
- Surface water consumed has no price tag.
- The wet season starts in May and ends in October.
- The dry season start in November and ends in April.
- Water can only be transported if the Volta river as depicted in figure 15 flows through the region.
- Water can only be transported downstream.
- Surface water cannot be imported or exported when there is no river crossing the border.
- Surface water irrigation can happen everywhere as long as there is irrigation capacity.
- Water demand that is not from the food or energy sector is zero.

Ground water
- Groundwater is always accessible as long as one is prepared to pump.
- Groundwater irrigation cost are equal in every region and are linear with the amount of water pumped.
- Groundwater is recharged by a part of rainfall.
- Groundwater transport and import and export are zero.
- If vegetation evaporates more than available rainfall it consumes from groundwater.

Electricity
- Electricity storage is not possible.
- Electricity production can occur in two ways, thermal production and hydropower production.
- The capacity of thermal power production is based on installed capacity and is not limited by available energy sources.
- Electricity losses are linear with distance and based on national average distribution and transmission losses.
- Electricity transport can reach anywhere where there is demand.
- Electricity can be imported by every region and its price is fixed and equal for every region.
- Electricity export is zero.
- Electricity demand is based on population and average consumption per capita for Ghana and Burkina Faso.

Food
- Food storage can occur everywhere, capacity is unbounded.
- Food storage losses are linear with the volume stored and crop type does not matter.
- Food-processing does not occur.
- Food production losses are similar for every crop and every region in every season.
- food production cost are dependent on crop type, input level and watering method. They are assumed linear with land utilized.
- Crops have a crop growth duration of half a year.
- Cropping seasons are equal to rainfall seasons.
- Food production can occur at three input levels that account for fertilizers, mechanization etc.
- Irrigated crop yields are equal for every region and its value is determined by the highest rainfed yield of all regions.
- Food transport losses are linear with the volume transported and the weight is equal for every crop for every distance.
- Food transport cost are linear with the distance bridged and does not depend on crop type.
- Food import prices are fixed.
- Food export is fixed in terms of quantity.
- Food demand is based on population and diet per capita.

Land
- The availability of agricultural land is fixed. It cannot be expanded.

DATA

Data that has been collected is given for this study is given in Annex A. It is described how it was determined or pre-processed. It provides an estimation by the author on the accuracy level of the data, the year the data represents and the source.

Figure 24: Food demand

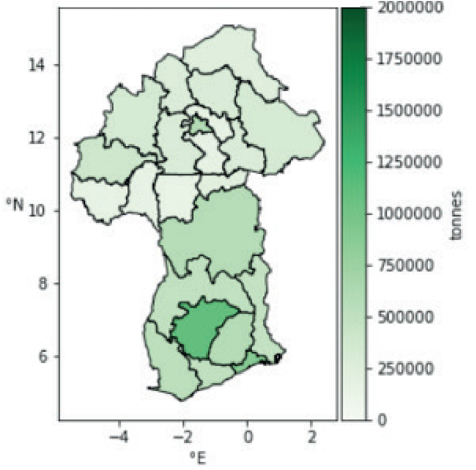


Figure 25: Electricty demand

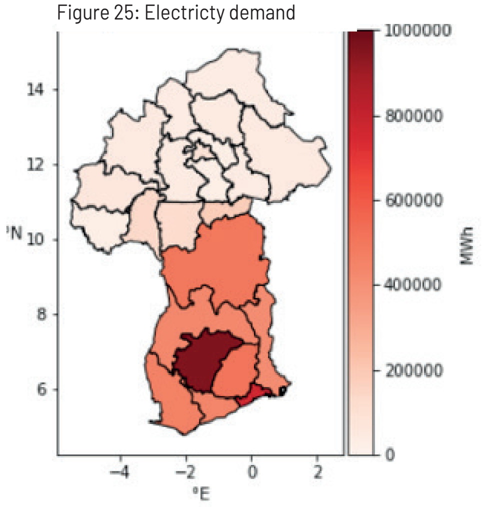
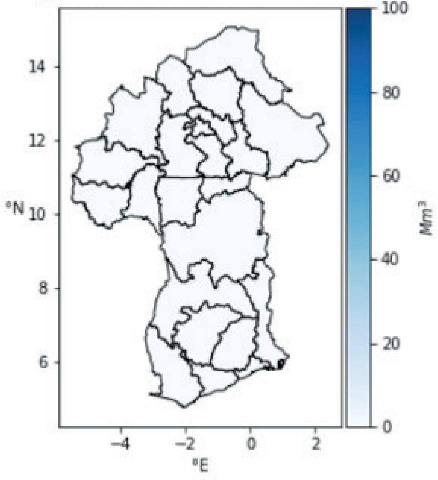


Figure 26:Water demand



3.2 RESULTS

MAXUS optimizes the allocation of water, energy and land resources for the final supply of water, food and energy over space and time, for the objective and constraints given. The objective is to satisfy water, food and electricity demands at minimal costs. WEF demands as defined are shown in figures 24, 25 and 26. The time span is two years. This section will show:

- optimization for current infrastructure
- optimization for a given infrastructural expansion
- optimizing infrastructural expansion
- optimization for different agents

The development of MAXUS has been a continuous process of building and testing. This section will show testing results that have been obtained with the latest version of MAXUS. Several examples are presented that increase in complexity.

3.2.1 OPTIMIZATION FOR CURRENT INFRASTRUCTURE CHANGING COST

If cost factors change, one would expect the outcome to be affected in most cases. Figures 27, 28 and 29 show the situation for decreased food prices, which should translate to domestic production becoming less attractive. Land used for the production of all crops relative to the total available agricultural land per region is plotted for the basin. A clear pattern can be discerned, indeed if food import prices are reduced, in this case from three times the farmgate prices to two and one and a half, generally land utilization decreases. However, when taking a closer look, one can see some regions' land utilization increasing. It is not trivial in what regions the highest margins are obtained. Production may also be taken over by other areas when conditions change (At "changing demands" a clear example of this phenomena is explained). This is related to many aspects: yields, types of crops, transport distances, demand centres, land constraints, but also changing water balances because of changing production, the whole system's dynamics is important.

In the next example food transport cost is reduced. Now, land utilization resurges as one would expect. The increase of production, however, is highest in the south. With the decrease in transport costs, it becomes more lucrative to produce in the south where higher yields can be obtained than in the north, where the largest disparity is in demand and production. This is a pattern that can be clearly seen in figures 33, 34 and 35, which show domestic/internal transports. The north is increasingly importing (green areas), and the south increasingly exporting (red areas) as the cost decreases.

Figure 27: land use; import prices 3 x farmgate prices

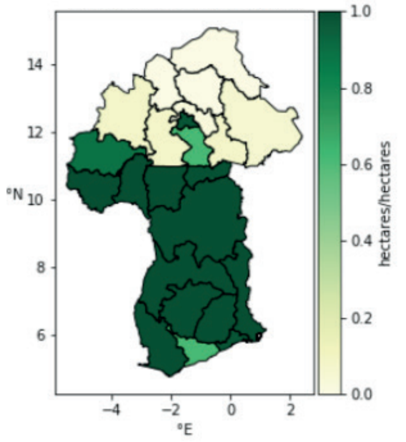


Figure 28: land use; import prices 2 x farmgate prices

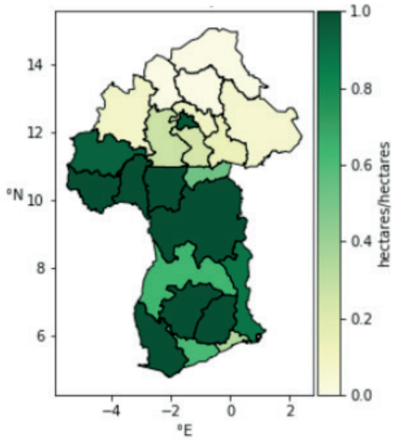


Figure 29: land use; import prices 1.5 x farmgate prices

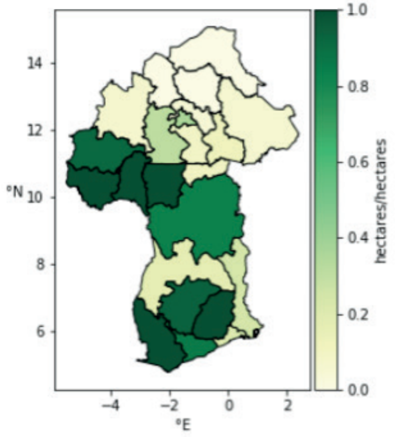


Figure 30: land use; 1 x normal transport prices

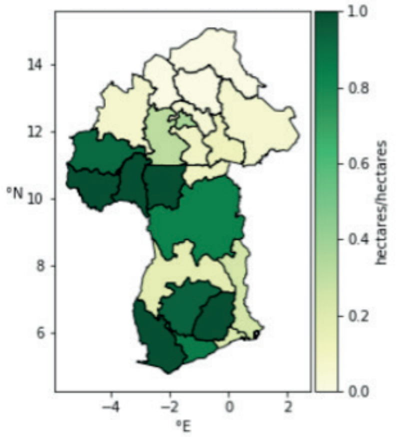


Figure 31: land use; 0.5 x normal transport prices

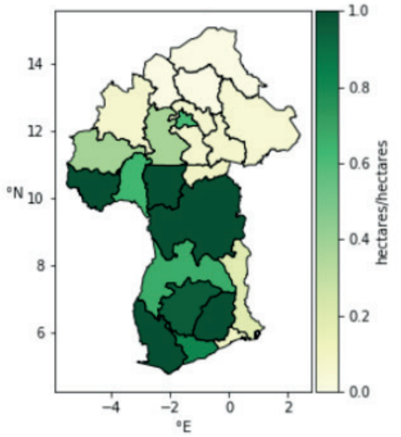


Figure 32: land use; 0.25 x normal transport prices

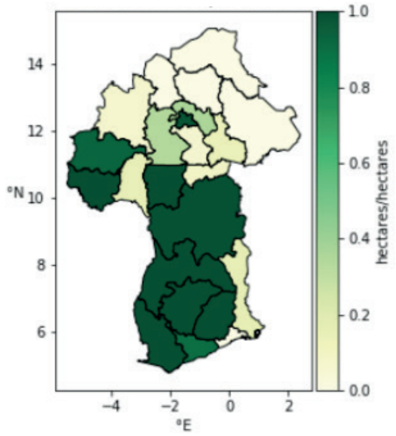


Figure 33: food transport; 1 x normal transport prices

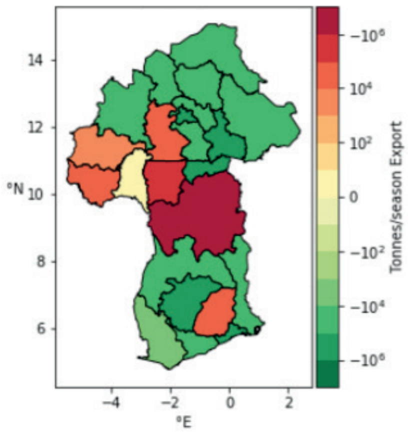


Figure 34: food transport; 0.5 x normal transport prices

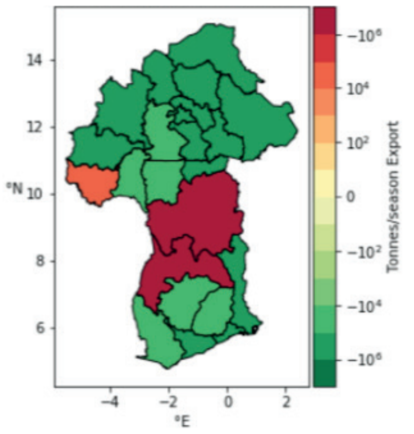
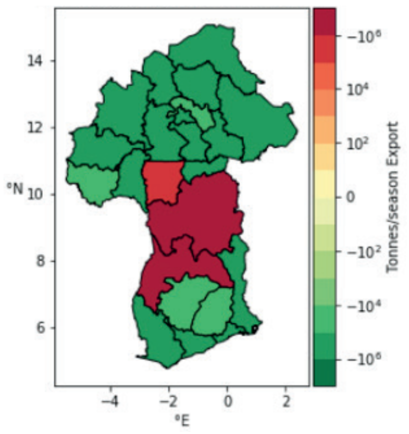


Figure 35: food transport; 0.25 x normal transport prices



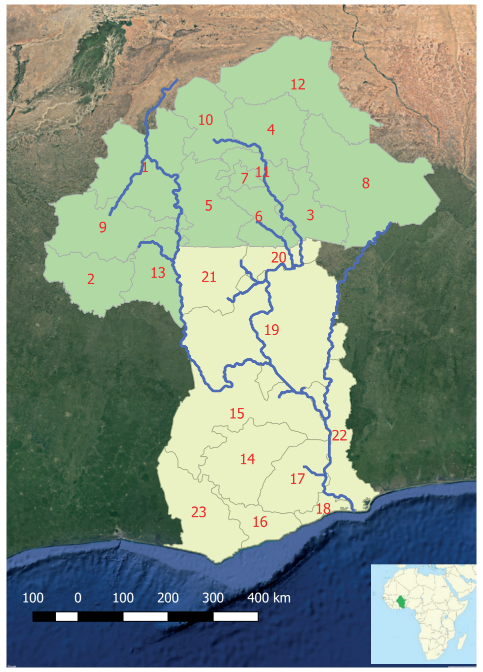


Figure 36: regions case study

3.2.2 OPERATIONAL CHANGE INDUCED BY DEVELOPMENT IN OTHER SECTOR In the previous examples it was shown how the food sector responded to changes in its own sector. In this section the food sector response to changes in the electricity sector is investigated. In the scenario illustrated in figures 37, 38 and 39 the electricity demand has been increased. In figure 37 the same starting position as in the previous example is depicted, now with the hydropower produced beneath it. As energy demand increases, the trade-off of using water for food production instead of using it for hydropower takes centre stage. If the hydropower is not produced, electricity should either be produced by thermal power plants, or be imported. The cost difference between hydropower and the alternatives is compared to the cost of production and supplying food versus importing food on each location with all the given constraints. As the energy price increases, land use for food production is diminished from regions that are connected to the river, to give room for hydropower production. In some other regions, land use for food prodruction increases. One example is region 18 (see figure 36) which is home to the capital of Ghana, Accra. The reason food production increases here is that water used here cannot be used for the production of hydropower. It is thus lucrative to move production to this region, even though obtained yields are lower than in the neighbouring regions that are upstream of hydropower dams.

Figure 37: landuse; 1x normal electricity demand

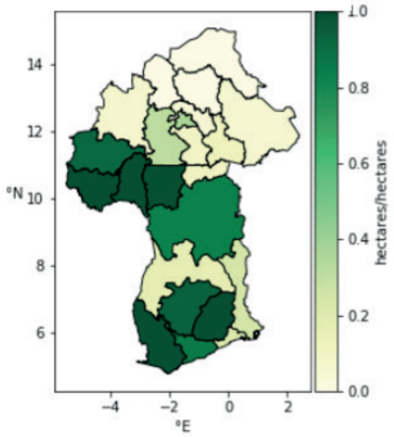


Figure 38: landuse; 1.5 x normal electricity demand

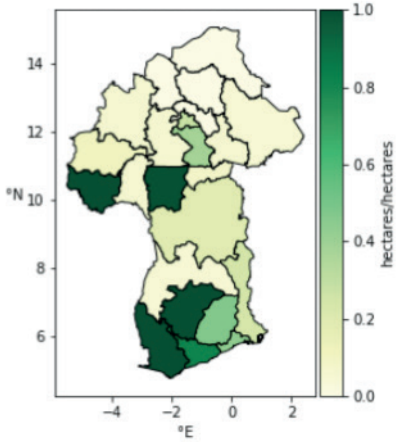


Figure 39: landuse; 2 x normal electricity demand

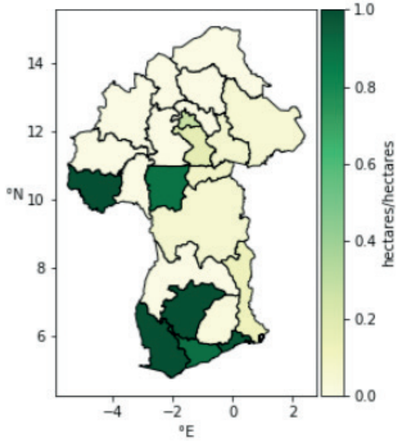


Figure 40: hydropower; 1x normal electricity demand

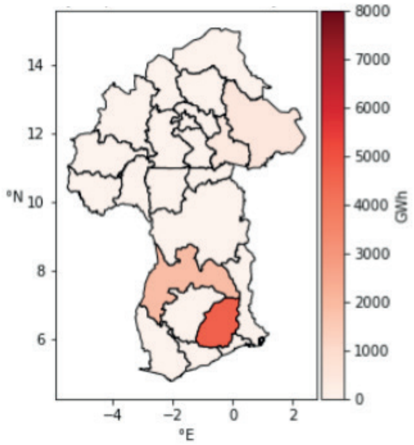


Figure 41: hydropower; 1.5 x normal electricity demand

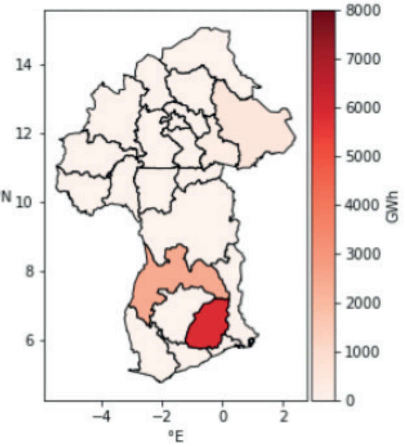
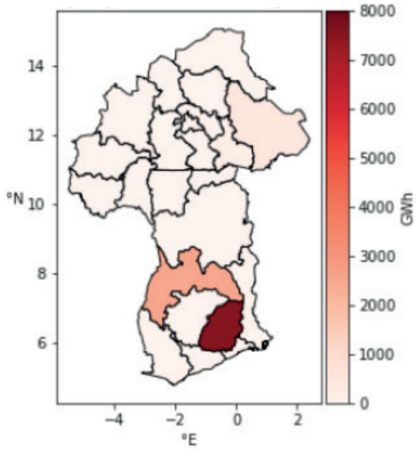


Figure 42: hydropower; 2 x normal electricity demand



3.2.3 MULTIPLE TIMESTEPS

In the next examples the results are presented for multiple timesteps. In Ghana and Burkina Faso there is very strong seasonality in precipitation. Figures 45 and 46 shows the collection of rain in the months May to October (hereafter: the wet season) and November to April (hereafter: the dry season) on the left and right respectively. In the dry season, the amount of rain is so low that in most parts rainfed crop production is not even possible (figure 44). There is only a couple of regions in the south with some crop production. To still supply enough to satisfy food demand in the dry season, one can use storage of water and food.

Figure 45: precipitation; wet season

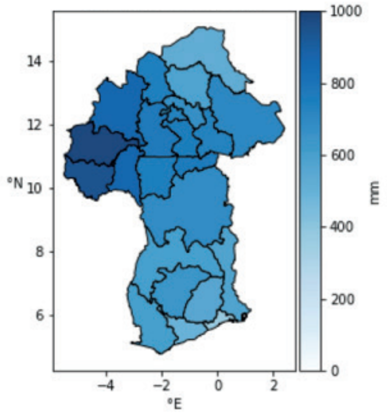


Figure 43: rainfed land use; wet season

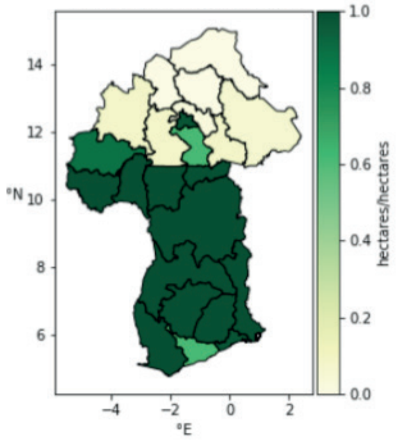


Figure 44: rainfed land use; dry season

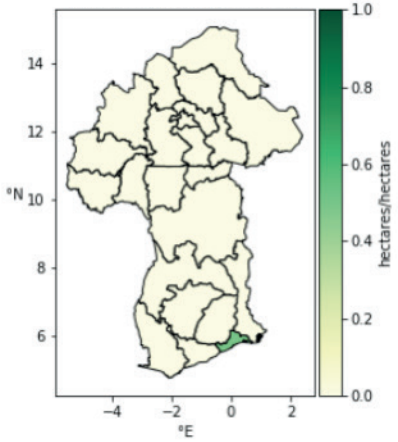
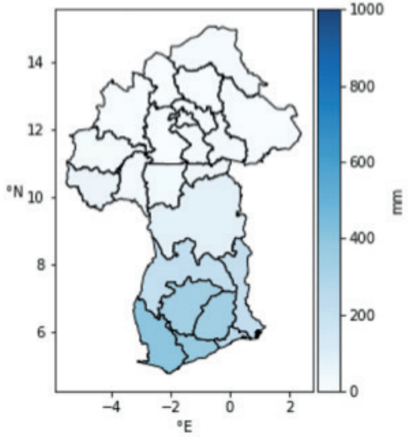


Figure 46: precipitation; dry season



Herewith comes an interesting dilemma: should one produce food in a wet season and store it for the dry season or should one store that water instead, to be able to produce in the dry season? There could be a difference in losses between the two. But this is not the only thing to consider. Storage of water would only be half the work, to be able to produce one also requires irrigation capacity, which is very limited in Ghana and Burkina Faso. It therefore makes no sense to store water for food production in this case. Nonetheless, looking at the proposed amount of food storage and water storage by the framework, shown in figures 47 and 48, there is still significant amount of water stored. This water however, serves a different purpose, it is used for hydropower generation in the dry season. Again, the trade-off includes all three sectors. And this is not the only link here. If there would be irrigation capacity installed, it gets even more of an integral decision. One could pump from a river, a reservoir or even from an aquifer, all of which require energy and have associated cost which varies per location. Besides, food can also be imported.

Figure 47: food storage; from wet to dry season

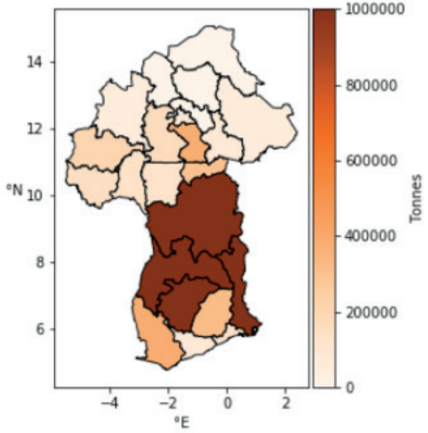
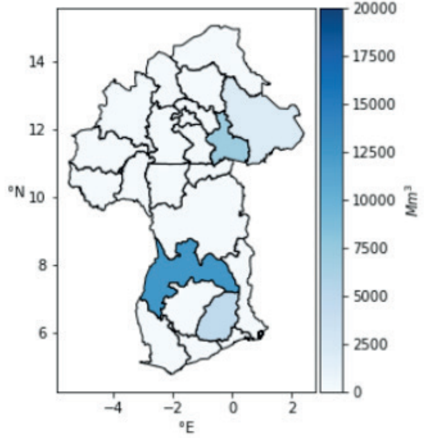


Figure 48: revevoir storage; from wet to dry season



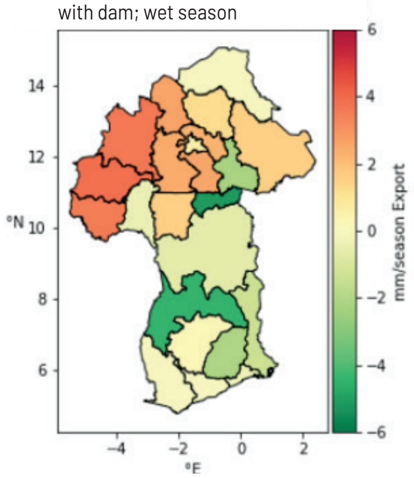


Figure 49: nett water transport; with dam; wet season

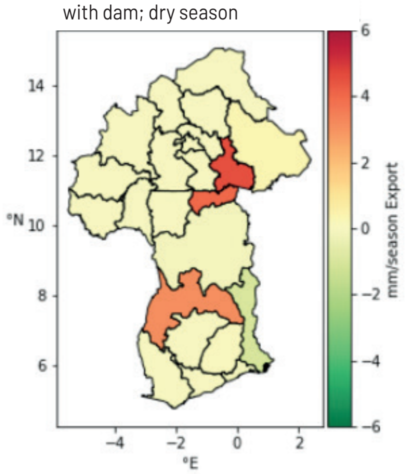


Figure 50: nett water transport; with dam; dry season

3.2.4 OPTIMIZATION FOR A GIVEN INFRASTRUCTURAL EXPANSION

The first thing required to store water and food is infrastructure. Up to now optimization has only been done for existing infrastructure, however, one could also expand infrastructure. To plan infrastructure, one should understand the impact of building infrastructure. The following section discusses how to similate infrastructure expansion.

In Ghana, plans have been made for the construction of a multipurpose dam, near Pwalagu, region 20[72]. It is to serve for hydropower, as well as irrigation. To investigate the benefits of such a construction, the proposed extra water storage capacity and irrigation capacity is added to region 20. An optimization now is run with the new infrastructure.

In figures 49 and 50, the obtained net water transports are given for the wet season and the dry season respectively. It can clearly be seen how the new dam is used to store water coming from the northern regions in the wet season and to discharges in the dry season. Part of the discharged water is used for irrigation in the region itself, as becomes clear from figure 51 which shows land use for irrigation relative to the total available agricultural land in the area. With land being cropped, water is also being evaporated. This is shown in figure 52. Also, some crop evaporation is seen in the south, but this is due to rainfed production. On the right, cross-border export is depicted. The irrigation capacity in region 20 is used to produce crops that have the highest margin (and thereby save most cost). Therefore, cacao and palm oil* are produced and exported. This is shown in figure 53.

The new production of hydropower is shown in figures 54 and 55 for the dry season. Figure 54 shows how region 20 now also produces hydropower. However, it also shows that hydropower production in the south is less* than without the dam. Because of a significant change in crop evaporation, the total hydropower production has decreased, even though additional hydropower capacity was installed.

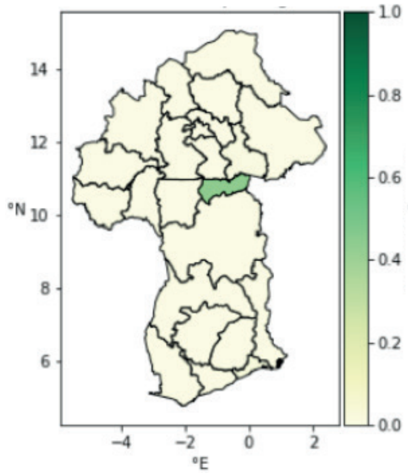


Figure 51: irrigated land use as % of total available land; dry season

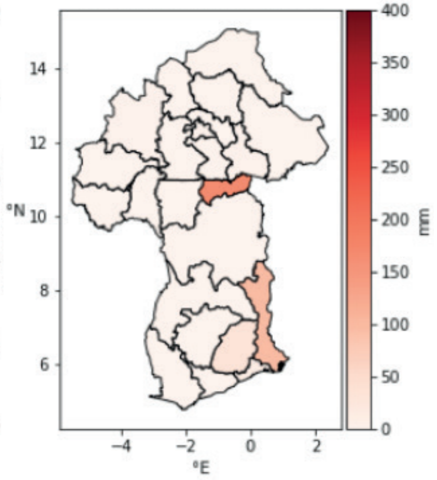


Figure 52: crop evaporation; with dam; dry season

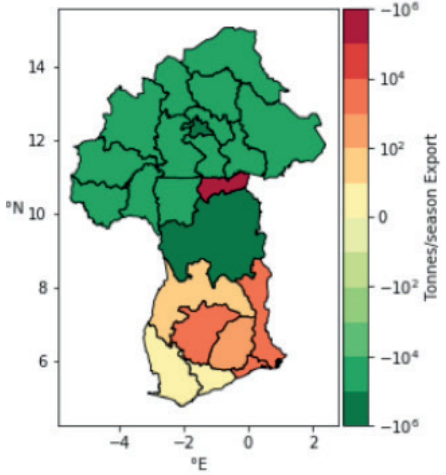


Figure 53: food export and import; with dam; dry season

Comparing the two situations in terms of cost, illustrated in figure 56, one can see that the main effect of adding storage and irrigation capacity is the ability to strongly reduce imports. Cost of food transport has been reduced too, food production can be higher in the dry north, where production normally is difficult. Therefore, food is produced closer to where the highest disparity is in production and demand. Someone with a keen eye for detail would notice how the requirement for thermal energy even has reduced. This is remarkable, even though less hydropower is produced after the construction of the dam, thermal energy production is no longer required. Because of the relocation of hydropower generation, from south to north, transmission losses could be reduced, and consequently, nett more is left. The power now produced is closer to the demand. The cost of food production has increased, because of the higher production, but altogether, yearly cost is lower with the dam. Ideally, the difference in operational cost should be weighed against investment of the dam to determine if it is worth it. Of course, this is only useful if one could easily adopt the proposed operations.

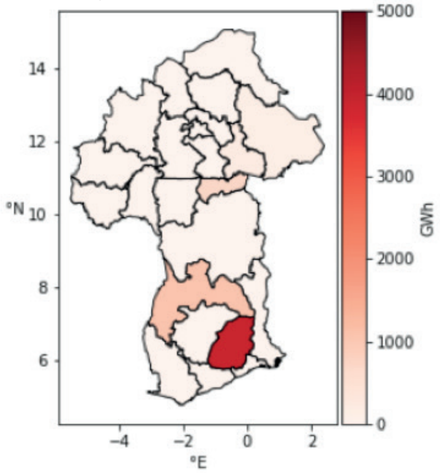


Figure 54: hydropower; with dam; Generation = 6072 GWh

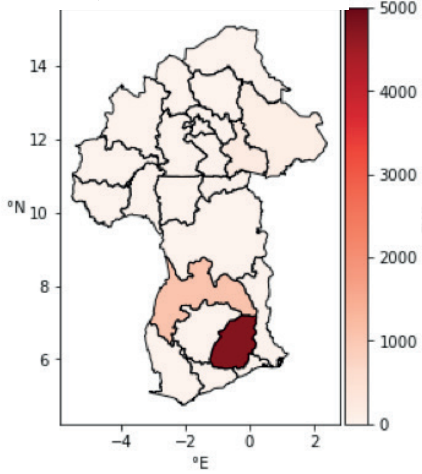
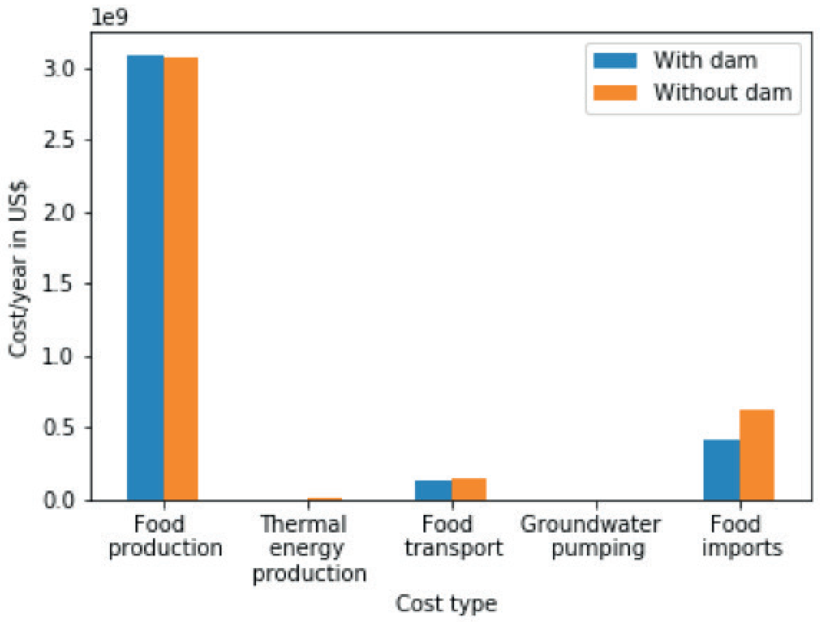


Figure 55: hydropower; without dam; Generation = 6187 GWh

Figure 56: cost optimization; with dam and without dam



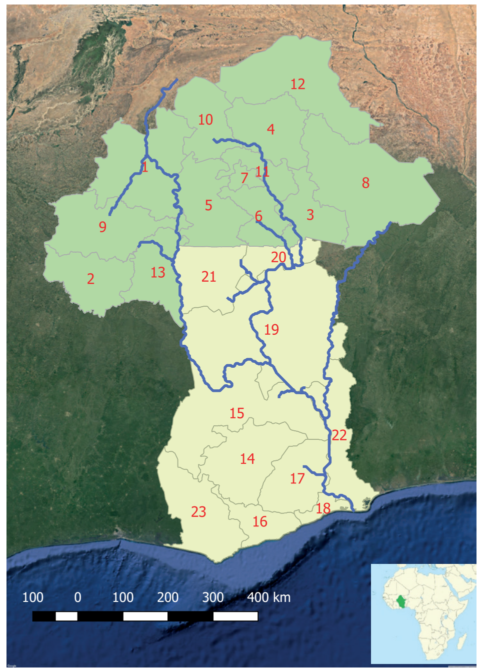


Figure 57: regions case study

3.2.5 OPTIMIZING INFRASTRUCTURE EXPANSION

As seen in the previous example, infrastructure can be manually expanded at certain locations to investigate how it could affect the water food energy system of a region. But if the impact of infrastructure expansion can be determined by the model, a new question arises: where (and when) is infrastructure worth the investment? To answer that, in this section, a new strategy is adopted. By making infrastructure expansion part of the optimization problem, the model determines where infrastructure is beneficial against a certain cost. This is a feature that makes optimization so valuable compared to simulation.

Figures 59, 60 and 61 present the results of when irrigation capacity and storage capacity were allowed to expand by including them to the decision variables. Hydropower capacity could not be expanded. On the top one can see how irrigation capacity is built, and on the bottom how storage is expanded. On the left the old capacities are depicted. As mentioned, existing irrigation capacity is very limited and is not even visible on the scale on which new irrigation capacity is constructed. Existing storage capacity is already large compared to the proposed new storage to be constructed, which is depicted in the centre. On the right extra irrigation capacity constructed compared to the total available agricultural land is depicted.

Figure 58: existing irrigation capacity

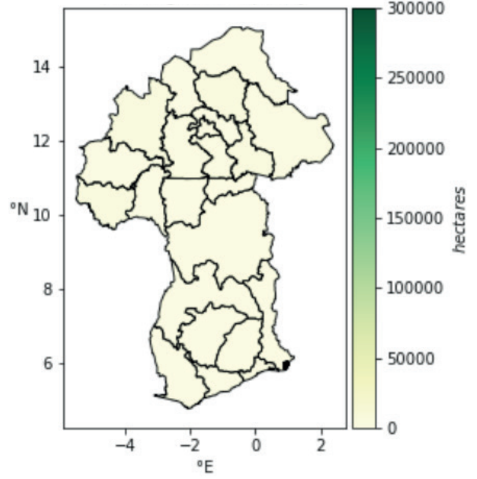


Figure 59: constructed irrigation capacity relative to available land

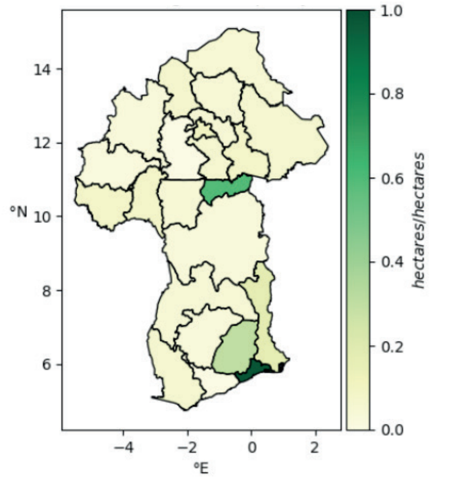


Figure 60: constructed irrigation capacity

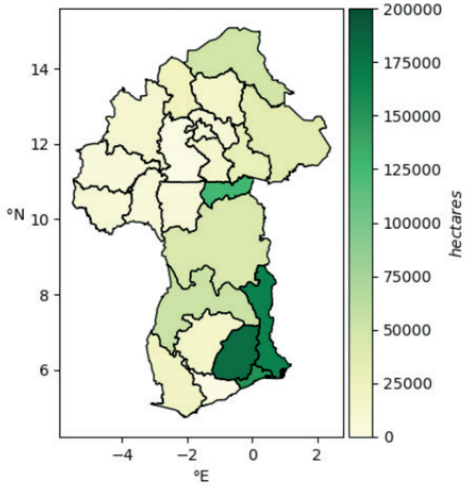
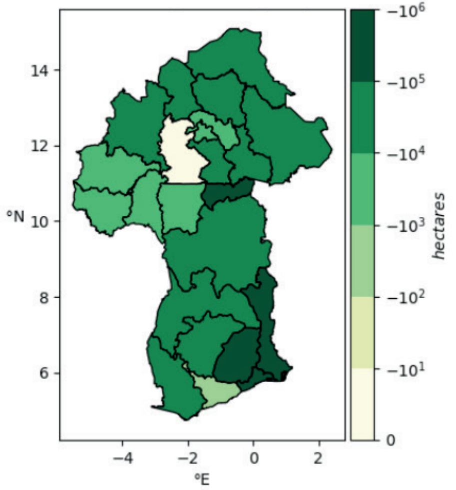


Figure 61:constructed irrigation capacity on a logaritmic scale



As figure 59 shows, two regions become for the larger part equipped with irrigation capacity. Region 18, the region of the capital of Ghana, and region 20, the region for which new plans are proposed. This is no coincidence. Both region 18 and 20 are just downstream of a hydropower dam and below water storage. In region 18 water has benefitted from all possible hydropower production before it is used for irrigation purposes and on top of that is close to a large centre of food which is the capital. Region 20 is home to a large river junction, located relatively close to Ouagadougou the capital of Burkina Faso, another node of large demand. This region becomes key in supplying the north. Besides region 18, neighbouring areas in the south also get a lot of irrigation capacity constructed. Since all agricultural land availability downstream of the last and largest hydropower dam has been equipped, little further upstream areas come into the picture. Here water has still benefitted from significant hydropower production and the production is still close to demand. With no cost-difference in storage construction along the river, storage is built mostly in the northern areas. Here, there is relatively little storage capacity and building it provides essential water for irrigation. This is sown in figure 63.

The costs, depicted in figure 64, reflect the findings, by building irrigation capacity and storage, food imports, -transports and -production costs can be lowered. Food is produced with higher yields, on the right locations, requiring less food storage and transport, through which food losses decrease. Another interesting feature is that, hydropower production now increased, even though irrigation capacity has increased. The reverse was true in the previous example. Now, the combination of a reduction in crop evaporation, by needing to produce less, and extra water retaining capacity, resulted in enough discharge on the right locations to increase hydropower production.

The difference in total operational cost between before and after construction of infrastructure is given on the right. Dividing the initial investment by the difference in cost gives the rate of return (on average) for the infrastructure built. (which in this example is 2.0 years, with irrigation capacity and storage reservoirs having a lifespan of 10 and 50 years respectively.)

Figure 62: existing storage capacity on a logaritmic scale

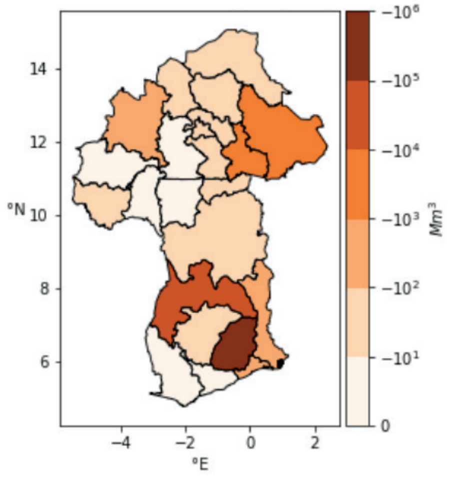


Figure 63: constructed storage capacity on a logaritmic scale

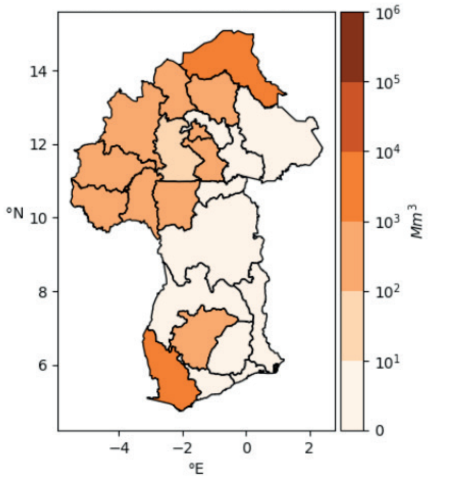
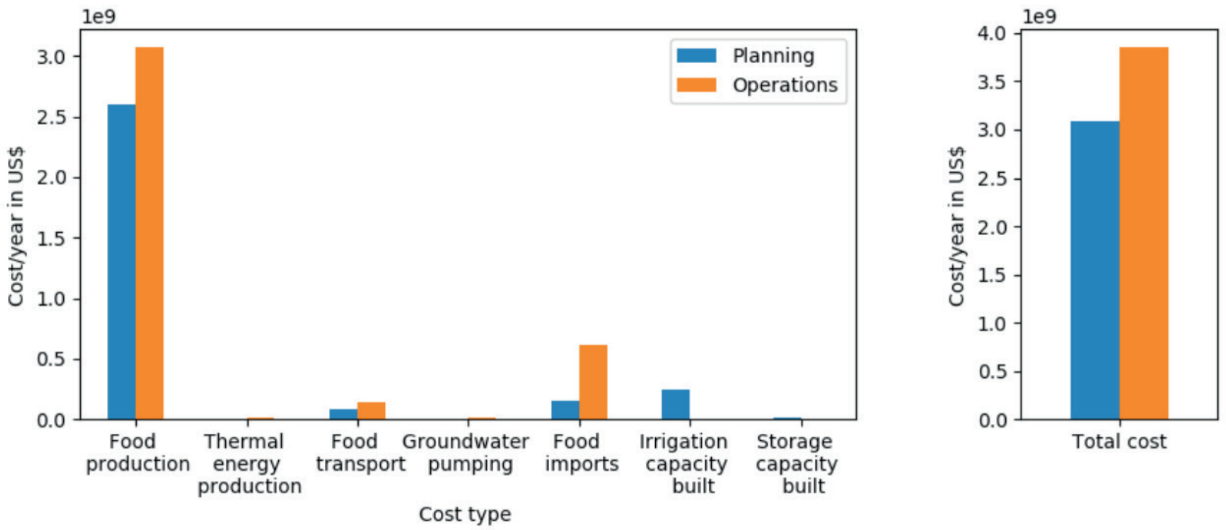
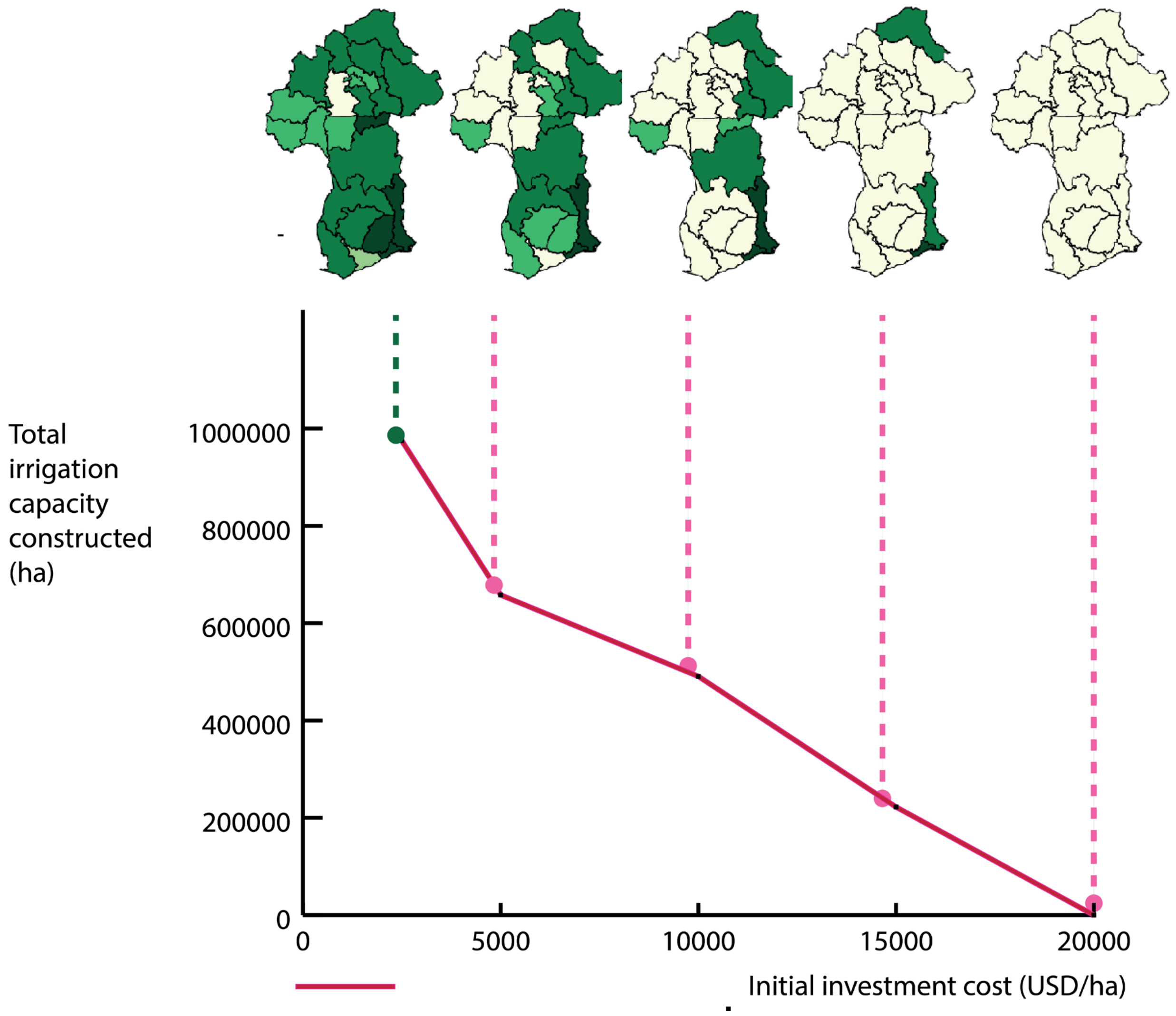


Figure 64: cost optimization; with constructed infrastructure and without



Increasing the investment cost from 2500 USD/ha to 15000 USD/ha is used as input for the scenario above. Figure 65 shows the total amount constructed for all regions at different rates of construction. It can be seen how the overal amount of irrigation capacity construction decreases when the cost increases. From 20000 USD/ha construction ceases to be profitable. The spatial patterns show how some regions are quickly eliminated from the list of options once the rate goes up. Region 20 is such an example. Region 12 shows a modest amount of construction at a low rate, but it stays attractive even when the price goes up. This is because it is unconnected to the river and hence is not in trade-off with hydropower, and in addition forms a good base for northern food supply. Note that, if expansion is only allowed in one region, the region might show a complete different behaviour as is shown by the graph.

Figure 65: constructed irrigation capacity on a logaritmic scale for different amounts of initial investment cost



3,2,6 OPTIMIZATION FOR DIFFERENT AGENTS

Planning often occurs on different levels of society. Regions, countries, basins, all have their separate planning instritutions. For a cohesive planning, it is important to be able to understand each agents interest. Besides one should understand how this varies amongst different scales.

A well know challenge is the management of transboundary rivers. The complex nature of the dependencies on water make it extremely hard to have a 'fair' distribution of water resources. Is water allocated based on equal benefits form the water, or an equal share of water, or something else? And what are exactly the benefits of water? Ideally, countries cooperate on the river to get the most benefits from the river system, but how often is this really the case? Generally, upstream countries have more influence on their downstream counterparts, however sometimes the reverse is true.

In this example it is investigated how the optimization problem would be solved if it was to be solved for the two countries seperately. Lets assume the upstream country, Burkina Faso is given the right to plan storage capacity and irrigation capacity construction first, regardless of how it would influence Ghana. Then Ghana may built infrastructure, based on the new levels of river discharge that is entering Ghana.

Figure 66: constructed irrigated capacity; optimization for Burkina Faso

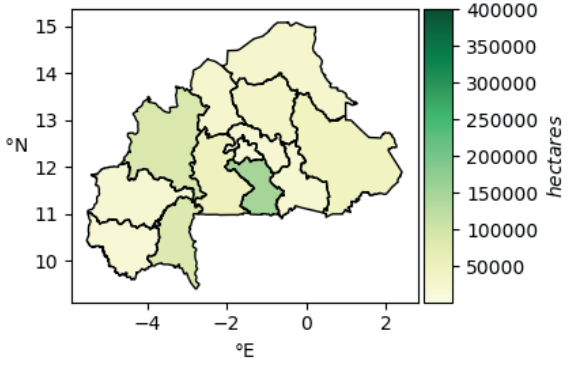


Figure 67: constructed reservoir storage capacity; optimization for Burkina Faso

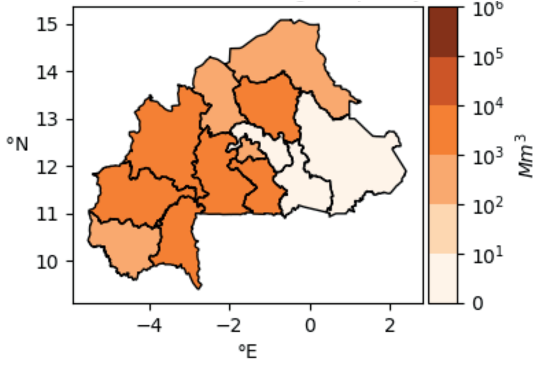


Figure 68: constructed irrigated capacity; optimization for Ghana

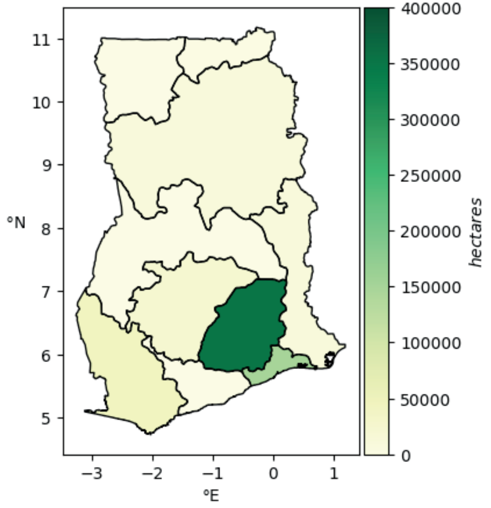
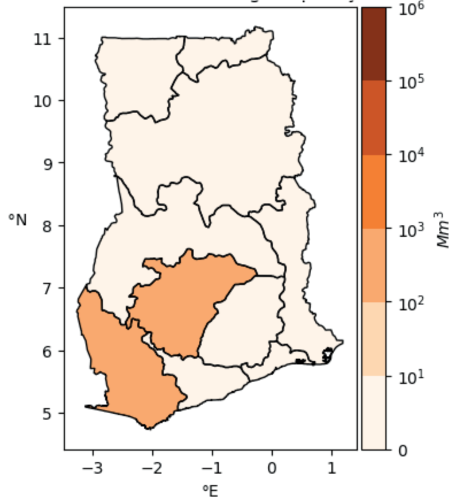


Figure 69: constructed reservoir storage capacity; optimization for Ghana



Figures 66 and 67, 68 and 69 show the separate optimization for Burkina Faso and Ghana and in figures 70 and 71 this result is combined into one graph, figures 72 and 73 show the basin scale optimization. Comparing seperate optimzation with basin scale optimization, it is clear that storage and irrigation capacity is built in Burkina Faso in much larger proportions. It does not benefit from hydropower generated in Ghana and therefore water is retained and used for irrigation. Burkina Faso now manages to meet its own food demand without the need of much import. For Ghana it's a different story. The river discharges entering the country are substanially lower than before and that hits Ghana's food and hydropower production.

Figure 70: constructed irrigation capacity; seperate optimization

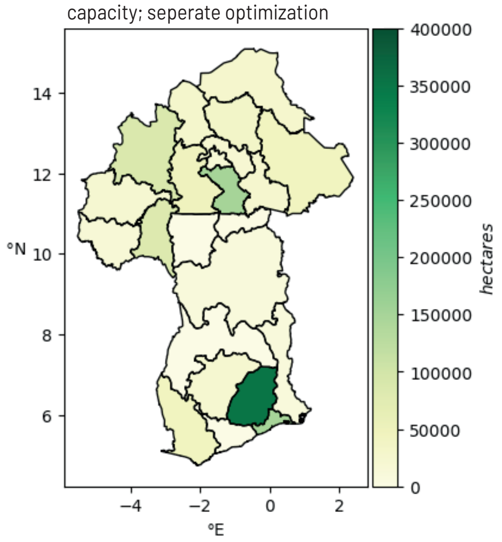


Figure 71: constructed reservoir storage capacity; seperate optimization

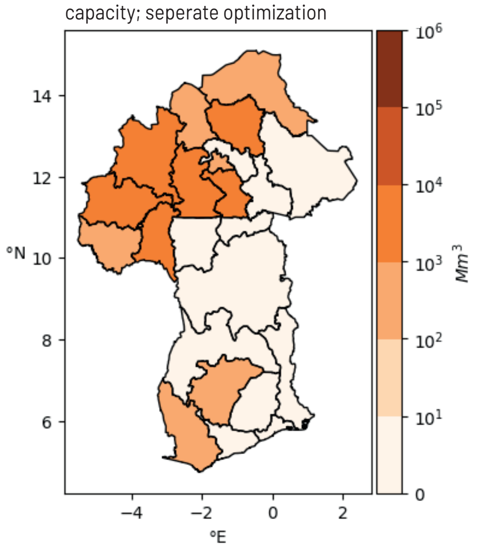


Figure 72: constructed irrigation capacity; single optimization

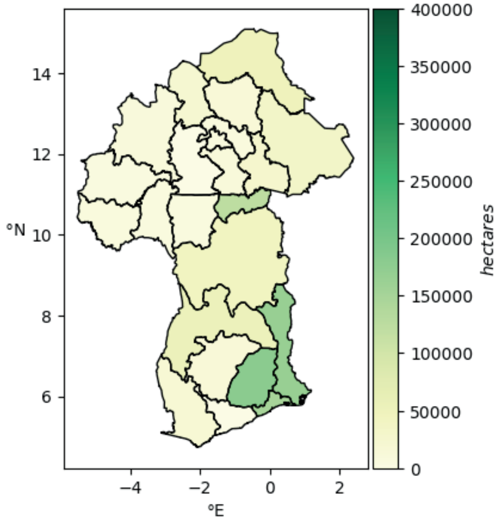


Figure 73: constructed reservoir storage capacity; seperate optimization

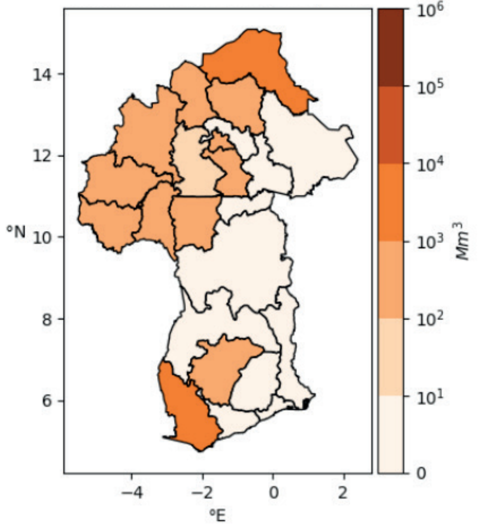


Figure 74: thermal power production;
seperate optimization; wet season

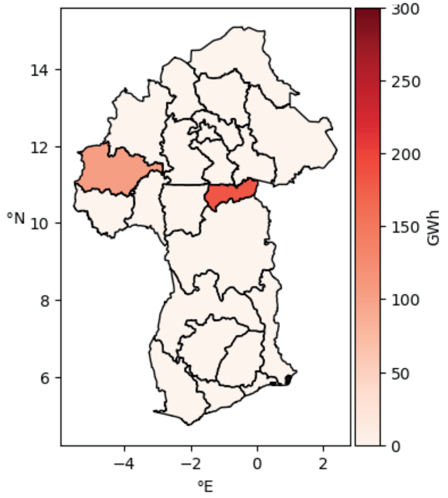
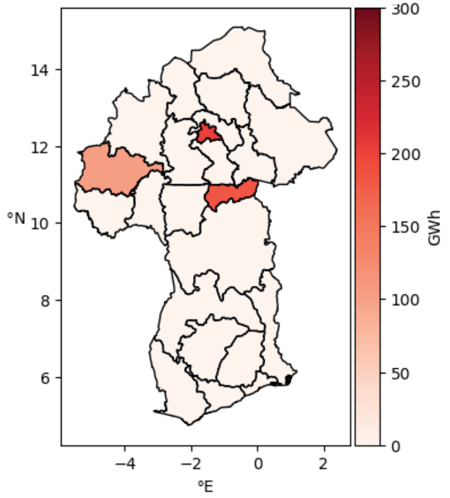


Figure 75: thermal power production;
seperate optimization; dry season



Ghana has to import large amounts of food which is shown in 80, while it would have been an exporting country when is optimized for the basin as can be seen figure 79.

Because of the strong reduction in hydropower production in the basin, both countries have to find other means to meet energy demand. Both countries now actuate thermal power plants. This is depicted in figures 74 and 75 .

Rainfed yields are generally better in the south, and hydropower is also generated in the south. When both countries cooperate it is therefore beneficial to increase production in the south and transport food and energy to the north. This shown in figure 77. In seperate optimization this opportunity is not there (figure 78). In that case, as becomes clear by figure 76, food import costs and investment costs in infrastrcuture can greatly be reduced, with a little more transport and food production costs. Cooperating would save in this case 43% of the total costs.

Figure 76: cost optimization;
single optimization (cooperation) vs seperate optimization (non-cooperation)

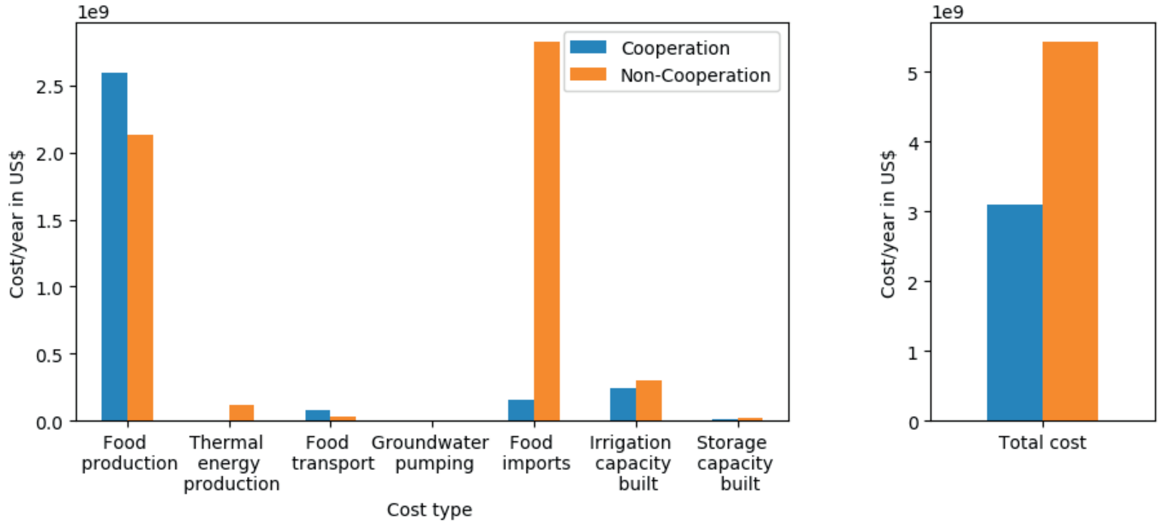


Figure 77: internal food transports;
single optimization; wet season

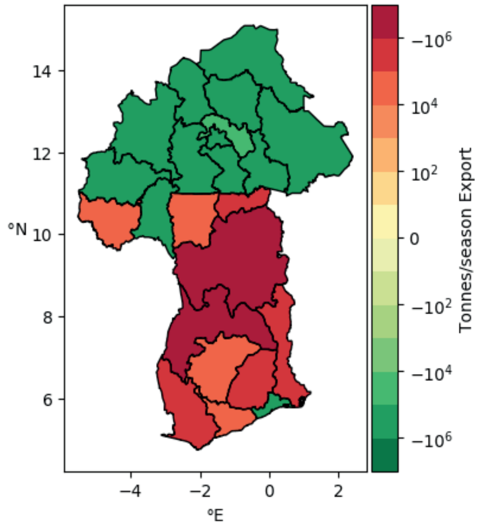


Figure 78: internal food transports;
seperate optimization; wet season

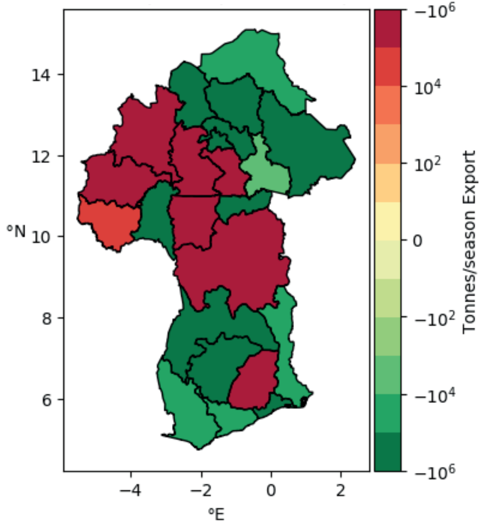


Figure 79: food exports;
single optimization; wet season

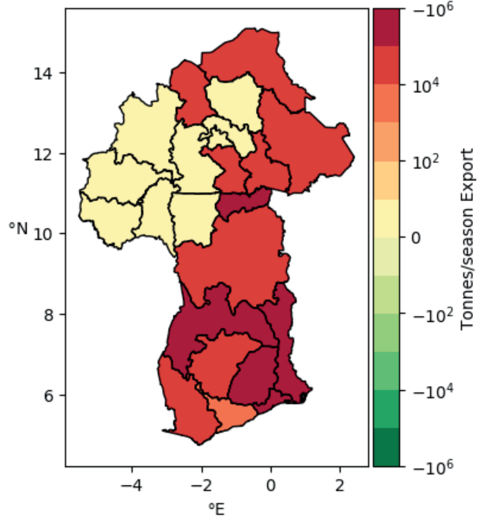
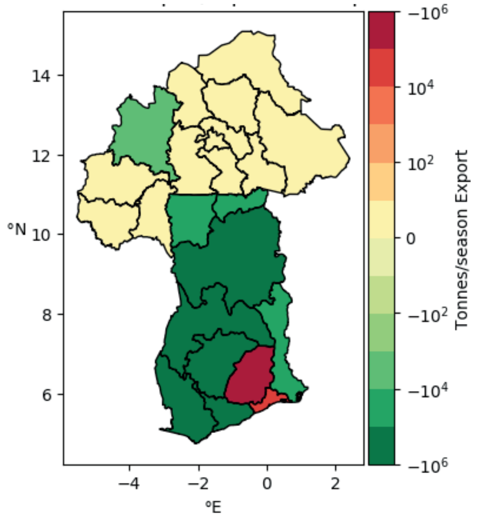


Figure 80: food exports;
seperate optimization; wet season



3.4 DISCUSSION

DOES THE MODEL SHOW HOW DEVELOPMENTS IN ONE SECTOR AFFECT CHOICES IN OTHER SECTORS?

Trade-offs were clearly seen throughout the analysis. Section 3.2.1 showed how the food sector could respond to price changes by weighing import and production under various constraints. It is not trivial how agriculture should ideally respond to price changes. There is so much to take into consideration, demand, transport, land availability, water availability, energy prices etc. The model showed to be able to quickly balance all these aspects and find an optimal situation.

Section 3.2.2 demonstrated how a change in one sector caused other sectors to reorganize. An electricity demand increase caused agriculture to respond by moving productions of different crops to different locations. Water allocation was adapted accordingly.

In section 3.2.4 addition of a multipurpose dam caused not only regional but national WEF sectors to respond. It showed secondary effects that were all but trivial: less hydropower was generated even though additional capacity was added. This had been due to additional water consumption from crops. Nonetheless, it turned out to be positive for the electricty balance. That smaller quantity of hydropower was better distributed over the regions and therefore less electricity was lost in transmission and distribution.

Section 3.2.6, where separate optimization was executed for Burkina Faso and Ghana, it was shown how trade-offs and choices made might differ for different parties. In case of non-cooperation, it would be beneficial for Burkina Faso to expand reservoir storage capacity and irrigation capacity on a much larger basis than in case of cooperation. Mainly because it would not benefit from hydropower production generated in Ghana in case of non-cooperation. It also showed how thermal power production would have to fill up the gap in electricity supply and how food imports would need to compensate for the loss in food production. It is clear the model shows how developments in one sector might affect choices in other sectors.

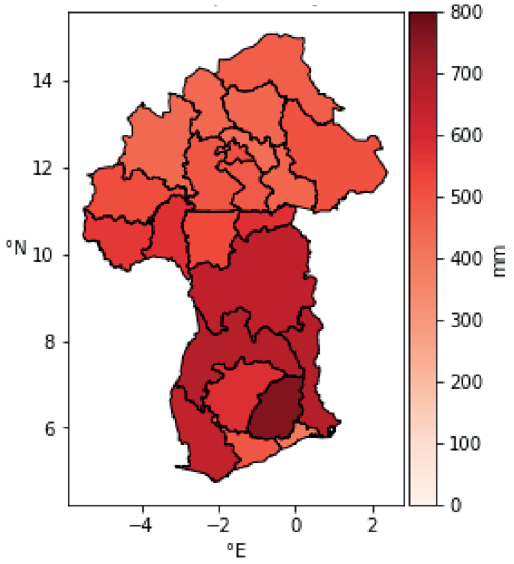
IS THE CASE STUDY MODEL RELIABLE?

It is hard to conclude if the system of equations chosen for this case study is reliable. To verify the reliability of an optimization model, one should ideally take a case that is fully transparent such that all required input data is known and accurate, no variably is a decision variable and model output data can be compared. In fact, this would be simulation. If now the model output data is different from the actual, the model contains model errors. One should agree with the size of these model errors, perhaps perform a sensitivity analysis, and settle on the reliability of the model.

In absence of a case that is fully transparent which is the case for Ghana and Burkina Faso, one can check if the order of magnitudes is right and if patterns observed are about right. An example is actual evaporation which is calculated by the model. It is given in figure 81. Evaporation seems to have the right pattern and is in the right order of magnitude, but its values are consistently lower than the actual values.

Figure 81: determined actual evapo(trans)piration; source: NSTG[73]

Figure 82: actual evapo(trans) piration determined in optimization for existing infrastructre by the case study model



A consequential effect is observed for discharge. Discharges are consistently higher in the range of 50-100%. In figure 84 observed discharged are given for various branches of the river. The red line showing discharge at Akosombo is around 1000 m³/s on average. This is around 1500 m³/s in the model. Aksombo is in region 17 which can be seein in figure 83.

This model contains lots of assumptions but the most plausible reason that the evaporation is underestimated and the recharge to groundwater underestimated. Since the relation of water consumption for crops as captured in interaction 1 is well established it is expected to be due to cropping seasons are not well represented by a time step of half a year. Quite a lot of crops for example are only cropped for a couple of months and these could not grow in the model since water constraints would prevent them from growing. This would lead to underestimation of crop evaporation. This however remains educated guessing at this stage and requires much more research. In the following section the equations used in this case study model are discussed on their completeness and reliability.

Figure 83: regions in case study; Akosombo is in region 17; Kpong is in region 18; Oti is thre river that start in region 8; Blackvolta is the river that flows through 4 and 13; White Volta is the river that starts in region 10;

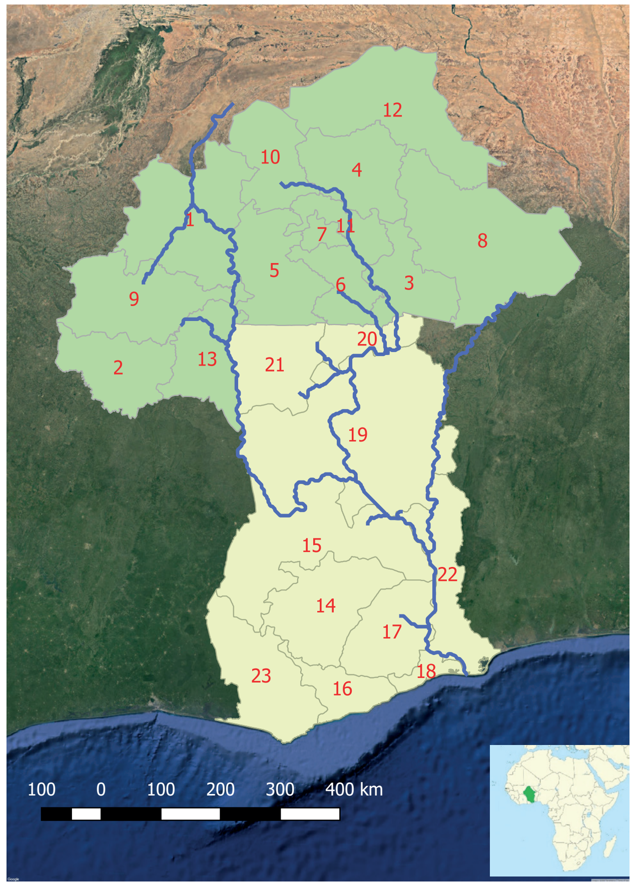


Figure 84 observer river discharges; source: C. Ndehedehe at al. [74]

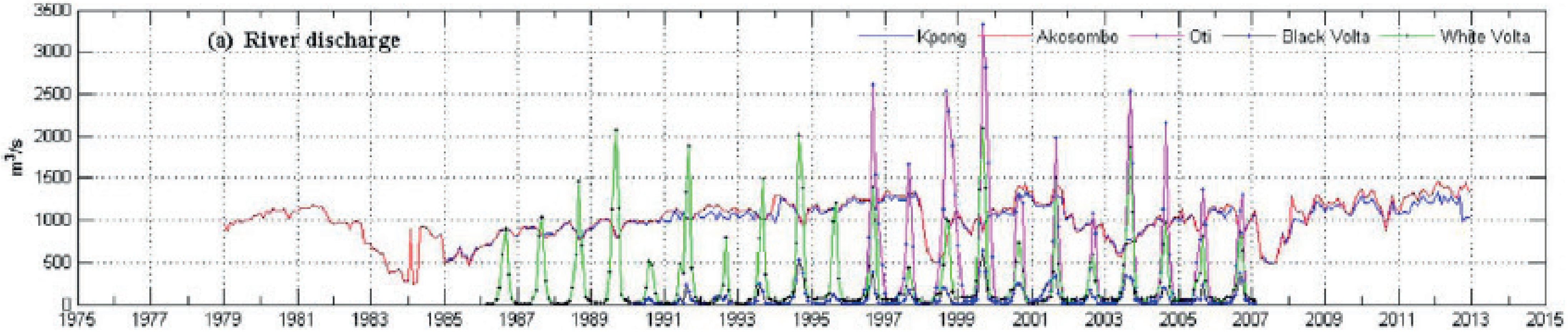


Figure 85: modelled river discharge; for existing ifrastructure; wet season;

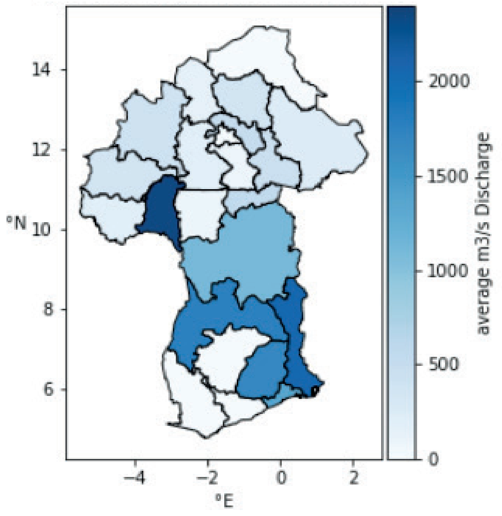
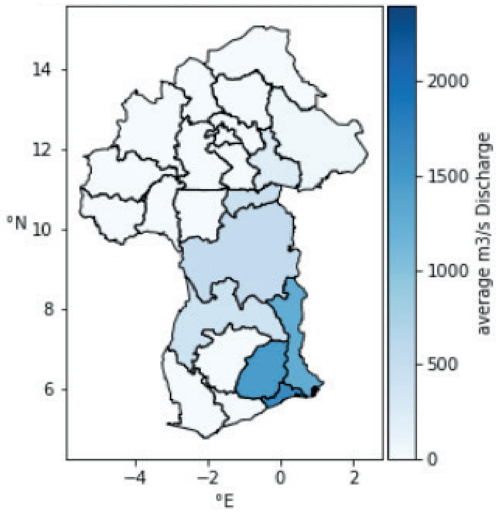


Figure 86: modelled river discharge; for existing ifrastructure; dry season;



This section discusses the balances, their subcomponents and assumptions taken in formulizing them. Estimated impact on the objective is given. The number refers to the corresponding equation in Annex B.

Trapped water
If a region does not contain a river and limited water storage capacity, it has no possibility to get rid of excessive water. In that case water gets trapped. This happens in small amounts, but it needs to be captured with the model otherwise it would become infeasible. In reality, it would either flow through small streams or infiltrate in the ground. This should be investigated such that the water balance is correct and does not need a modelling artefact. This has not the highest priority but is still important to improve.

1 ●●○○○

Linear reservoir water losses
Reservoir storage losses should represent open water evaporation of the reservoir. However, since the relationship between area and storage volume is non-linear this could not be incorporated easily in the model. In this case it is assumed that a certain percentage of storage evaporates. Even though these weights could be adapted this is a simplistic assumption. A better approximation would be to assume that a fixed amount would evaporate depending on the average area of the lakes. However, then one would also have to have initial levels of reservoir or at least restrict evaporation when the storages are empty.

2 ●●●○○

Invariable potential yields
In the model crop growth by means of water and nutrients is discretized by making use of GAEZ data which has three input levels[37]. Because climate constraints are already incorporated with calculating potential yields in GAEZ and are not adapted in the MAXUS model for this case study, changing rainfall in the model would not result in an adaptation of potential yields. If one would want to investigate the effect of climate change, potential yields would have to adapt, and one would have to calculate potential yield again with the GAEZ model. A variable yield is not easy, a continuous function linking biomass growth to input level and water is not feasible. Input level varies in so many ways, from fertilizer input to mechanization, weeding etc. One would really have to investigate well how best incorporate this.

3 ●●●○○

Doubtful replacement of natural vegetation
If no crop is grown on agricultural land natural vegetation would grow on that land. This means evaporation originating from that land changes. But how much? What type of natural vegetation would grow and how would evaporation develop over time? In this case it is assumed that low natural vegetation covers the agricultural land if no crop is grown, shrubs or herbs. The factor WKR should then represent the evaporation of shrubs or herbs relative to the average evaporation of natural vegetation. In this case it is fixed at 70% for every region but this should be calculated more accurate. This is a weak assunption. In any case, this should be looked at in detail since it is an important factor in water availability.

4 ●●●●○

●●●○○ Impact on objective

0 equation in Annex B

Simplistic food storage losses
Food storage losses are not only crop specific, they also depend on the facility in which they are stored and the time they are stored. In addition, often they are stored when they are processed. Not only the raw material. All of these aspects are not included in the model for now. This was infeasible as data on availability on food storage facilities was not found, food processing is not included in this case study, and the timestep of the case study was half a year and therefore storage is bound to half a year. It should be really considered well to what level of detail one wants to go. Food production is quite a large factor and therefore food losses are important. It is recommended to get this to higher detail level.

5 ●●●●○

Simplistic food growth losses
Food growth losses are a similar story as food losses. They at least depend on the type of crop and the input level. Food production loss is even more important to know more accurate than food storage loss, since it affects all food produced. More accurate values are very important for making the model more representative.

6 ●●●●●

Simplisitic food transport losses
Food transport losses also depend on crop type as well as method of transport. Currently food transport losses are deemed equal for every crop for every distance. This is of course not the case. Since much food is transported, more accurate estimation of transport losses is important.

7 ●●●●○

Spationally unconnected food import and export
Food imports and export are modelled such that every region can do so. In reality, most export and import would go through either important roads or harbours. This would require an additional constraint. In the section future research an example is given.

8 ●●○○○

Unbounded electricity transmission and distribution
Electricity may yet be transported over all the regions, since the demand of electricity is determined per capita and population is in every region. In reality there is not that much electrification and the grid is not that extensive, such that it contains only limited ways of transportations. Transmission and distribution happens via specific pathways each with their own character for transportation losses. This also holds for import and export of electricity to outside the case study area borders.

9 ●●●○○

Simplistic hydropower generation
Hydropower is generated based on a fixed hydraulic head. A water level change does not matter for the production. But it does matter in reality. In addition, reservoirs have minimum operating levels and maximum operating levels. With a temporal unit of half a year these cannot be monitored but it might mean that some of the water should be spilled.

10 ●●○○○

Unbounded food storage

Food storage capacity is currently virtually unbound. No data was found to accurately estimate food storage capacities. Food is probably stored at many different facilities, of which some are at the farm itself and some are organized communal or rented out private facilities. The type of facility required also depends on the crop. It is important to investigate the possibility of storage. This has high impact on the optimization solution. Importing food is expensive and if food storage facilities in reality are limited one would have to import food. Investigation on capacities has high priority for improving the representation of the model for reality.

11 ●●●●●

Unable to capture uncertainty in electricty production

Power generation capacity is now based on installed capacity of available plants. But it also depends on availability of the resources. In reality, it is actually one of the problems that gas supply via the West African Gas Pipeline is unreliable [64]. If this problem was to be investigated in more detail adaptation of this constraint is definitely necessary. However, this might also require a more sophisticated approach that includes stochastic modelling and uncertainties.

12 ●●○○○

Unreal initial water storage

Initial surface water storage was assumed to be zero. In reality, there would be lake Volta, Bui and Bagré which all would have remaining storage after the dry season is over. Not taking into account this storage in the model may not have too large consequences; lake volume does not matter much for hydropower in the model since hydraulic head is fixed. However, not considering initial storage matters for evaporation, though this can be partly compensated for in the loss factors. This should be investigated in more detail. It has an intermediate priority

13 ●●●●○

Unreal initial ground water storage

Initial ground water storage could also affect the problem but again to a limited extent. Having initial groundwater storage would remove constraints of groundwater availability for pumping for irrigation. But as groundwater pumping capacity is very low, groundwater storage availability is not constraining.

14 ●○○○○

Fixed demand

Demands of water, food and electricity are fixed now and in the model the cost to provide it is minimized. Demands however in reality vary based on the price and the availability of resources. A more complete analysis should discuss elasticities of water, food and electricity prices. This is up for future research.

15 ●●○○○

Unrealistic high penalty on unsastisfied demand

The penalty on unsatisfied demand is very large in the case study. However, in reality, it may be sometimes beneficial not to supply in terms of cost. This depends on the added value of supplying. Investigating this in more detail would be an interesting case but has low priority.

16 ●○○○○

●●●○○ Impact on objective

0 equation in Annex B

unrealistic storage construction cost

The cost of storage is assumed to be linear with the volume. This assumption is very simplistic, since water storage is non-linear with the dam size. The impact on the choice where storage is built is quite significant. This could be improved in a linear model by discretizing such that there are different dam options per area with estimated cost by experts. A model could then decide on which combination of dams would be optimal. If the model is going to be extended to also include non-linear constraints, one should determine per area a continuous function that describes how much storage would require what investment. In case reservoir storage is to be investigated in detail this has high priority.

17 ●●●●○

Simplisitc groundwater cost

The cost of ground water is assumed to be linear with volume and for every region the same. In reality, this would differ per region largely, because of the suitability of the soil and the depth of the groundwater aquifer. The model in the current state allows surface water irrigation in every region. But in many areas groundwater irrigation would be much cheaper than surface water irrigation. This should be accounted for by adapting the price of surface water irrigation. This is discussed in the section further research.

18 ●●●●○

Simplisitc food production cost

The cost of food production has been based on detailed crop calculations for maize and rice. For other crops it is also essential to have better food production cost estimations. This has high priority because food production cost is very important in the optimization. Food production cost may also vary per region. This requires detailed investigation.

19 ●●●●●

Simplisitc food import cost

The cost of food imports is fixed for unit quantity of a crop and though the dimensions are such that it could change in time, the collected data did not allow for such a detailed representation. It is important to know food import prices well, since it has a lot of impact on the optimization. Food import cost may be very high.

20 ●●●●○

Simplisitc thermal power production cost

Cost of thermal power production is fixed in the model but in reality, it matters which power plant is used. Increasing the level of detail here would have some impact on the optimization but not too much. Thermal power production is still a relative small component of the total cost.

21 ●●●○○

Simplisitc electricity import cost

The cost of electricity import is assumed to be fixed here, but in reality, it varies per connection to the border countries ad may also change with time. More accurate estimation of the import cost might not even impact the optimization. The installed capacity of thermal power and hydropower together is in most of the runs enough to supply in electricity. Though, when import becomes cheaper than production it would matter.

22 ●●○○○

● = term in balance

● = constraint

● = performance indicator

● = cost factor

Picture 6: near Tamale, Ghana; Own picture

3.6 CONCLUSIONS

The case study was done to show how MAXUS can be used to explore how developments in one sector may affect decisions to be taken in another sector. Even though a lot of simplifications and assumptions were required in the delineation of the interrelated WEF system of Ghana and Burkina Faso, the model has shown spatial and temporal trade-offs that involve all sectors.

It has shown to be usable in exploration of operational management improvement as well as infrastructural development with only small adaptations. It showed that operational changes were not jsut proposed in the water sector or in the food and electricty sectors seperately, instead it showed substantial shifts in food production, water allocation and electricity distribution at the same time. However, most of the trade-offs have centered around the use of water for food and electricity production.

It showed how the model was able to determine strategic locations for storage and irrigation capacity within the constaints posed and for the objective given. The location of irrigation capacity determined coincided with actual plans for building irrigation capacity. Also storage was built in the locations where the amount of small reservoirs are quickly expanding, in the north of Burkina Faso.

The model has showed that seperate optimization is possible with the same framework with relative ease. This showed trade-offs and synergies for cooperation on WEF sector management between Ghana and Burkina Faso. When cooperating countries can make use of the hydropower generation production capaciy and the cropland with the highest yields in an optimal way. Burkina Faso would have to built less storage and irrigation capacity and Ghana would have to compensate Burkina Faso for their loss. This woulds save a lot of needless thermal power production and food imports.

In its optimization logical patterns were seen and its output values have shown to be in the right order of magnitude. Even though the model variables show logical behaviour, solutions found were not trivial. It has proven to require analyzation and expertise to understand the decisions taken by the model.

3.7 FURTHER RESEARCH

Food processing
Food production is not just agriculture, but also processing. There are lots of ways to process, each requiring different amounts of electricity and water and all factories distributed over the regions. In a more realistic this should be incorporated if one would want a broader coverage. It would be an additional layer on top of the present model. Consumption of food should then be represented by raw crop consumption partly by sellers and distributors of food but also by the demand of the processing factories. This has not high priority but has the potential to be an interesting feature. Building food processing factories is one of the greater ambitions of the government[75] and it would therefore be interesting to investigate.

●●○○○

Irrigation efficiency
With irrigating there is always more water required than the consumption of the crops. In case irrigation is applied via surface water this is important since that water is taken from the river or storage reservoirs and excessive water leaks to groundwater. There might even be additional soil evaporation because of this leakage. It is relatively easy to include this in the model and should be done. It has high priority since it matters a lot for the allocation of water resources.

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Livestock
Livestock is a relative large consumer of food, land and water. Since there is also quite a lot of meat consumption. The effect of increasing meat production could be captured if livestock would be included. Livestock would be an addition to the model. Without having a livestock balance its demand could already be included in the model by adding it up to food demand and water demand.

●●●○○

Land expansion
This case study refrains from expansion of agricultural land. In this case study it is investigated how to best use the available land. But this could be an interesting feature.

●●○○○

Hydrologic processes
increasing the reliability of hydrological processes is essential. Crops only consume water when water is in their reach. This requires distinction of different groundwater layer such as soil moisture in the root zone or deep quifers. Overall, this needs more investigation.

●●●●○

Hydropower production capacity
Hydropower is generated based on hydraulic head and water transport in the model and is not capped. Hydropower can therefore exceed the hydropower capacity which is installed in reality. This would also require a new interaction, such that water transport is split in water that generates hydropower and water that is spilled.

●●●●○

Crop schedules
Crops all have different crop growth durations. To get to a more realistic water consumption pattern it is important to have a better representation crop growth duration. This however requires a smaller temporal dimension unit. One needs to go to months instead of seasons. It also requires non-linear constraints. However, it is a very important feature to improve.

●●●●●

Food and electrity import
It is assumed here, that food and electricity demands can always be satisfied by means of import, although the cost may be way higher. The same may hold for food imports. Food and electricity can also not be imported and exported from anywhere. A constraint holding for a subset could only give access to those areas with a harbour for food import, or a electricity grid line connection with another country.

●●○○○

Surface water irrigation cost
There is no additional cost for supplying surface water for irrigation on top of the cost for irrigated food production. However, surface water irrigation could be very expensive if the land to be irrigated is far from a stream or reservoir. Sometimes groundwater irrigation may be much more attractive. Having a cost factor for surface water is therefore worth investigating.

●●●●○

Food storage cost
Food storage has no cost. It is assumed that much food storage happens at the farm and that the cost of it is expressed in losses. But depending on the facility there should be a cost associated with food storage. This should be investigated.

●●●●○

Picture 7: river Volta, Ghana;
Own picture

4. DISCUSSION

In this section, it is discussed to what extent the needs for an improved model are addressed by developing MAXUS.

In the development of MAXUS, the following needs for an improved nexus model were identified:

- *Integrate the WEF nexus; Serve as a decision support tool;*
- *Have an adaptable input data structure;*
- *Perform for different temporal scales;*
- *Perform for different spatial scales;*
- *Allow for physical accounting of resources, technologies and constraints;*
- *handle and account externally induced effects;.*

INTEGRATE THE WEF NEXUS;
In the case study, MAXUS was used to develop a customized model for water, food and electricity for Ghana and Burkina Faso. Complex spatial and temporal trade-offs were seen that involved each sector. For example, rainfed crops were grown in a region with lower attainable yields than in neighbouring areas, only because, opposed to those other areas, it was downstream of a hydropower dam. The construction of irrigation capacity, changed the face of thermal power drastically and electricity transports had to be completely adapted, which in turn affected distribution losses.

In addressing this required amount of integration, the strategy for MAXUS had been to model from scratch. As a result, the water, food and electricity sectors formed a coherent interrelated system in which evaluated constraints of all sectors at the same time. As the model was built computationally tractable this always led to an optimal solution for the objective defined. An integrated model having the ability to optimize for the WEF nexus an interconnected system evaluating all constraints at the same time did not exist before (see “current analysis tools”).

Chapter ‘Introduction’ showed that several conceptual frameworks were proposed that want to take issues even wider than the WEF sectors[16][41]. To allow for extension whenever necessary MAXUS was built to be flexible. Additional balances can be included such as nutrients, forests, biomaterials etc. These balances could be coupled to the balances of water, food, electricity, gas etc. by means of interactions. Possibilities are endless. Nonetheless, one should not assume adding balances is also added value for the policymaker. Additional balances also require definitions, data and also complicates the analyzation of results. The of shaping a model is captured well by Bazilian et al. “to draw system boundaries wide enough to encompass the enormity of the interacting vectors, while maintaining it small enough to be able to conduct useful analysis.”[21, p.5]

SERVE AS A DECISION SUPPORT TOOL
One of the main points of critique on the current models is that they serve to understand nexus interlinkages, rather than serve to analyse specific governance decisions or technical interventions[35][36][76].

Decision variables allow to explore a wide range of possible interventions. The interventions may be tested separately or in combination with each other, by selecting one or multiple decision variables. To illustrate that: food transport is optimized differently when food production is optimized as well; and again differently when water transport is also optimized.

By analysing the results, one can come up with suitable governance actions. The case study demonstrated that, while minimizing cost, an increase in the demand for electricity pushes agricultural production to more downstream regions. WEF sectors can anticipate on this phenomenon. If the difference in cost is large indeed, one could already invest in agriculture in the downstream regions. If this is expected to be a long-lasting phenomenon, one could respond by building infrastructure such as food storage facilities or governance actions such as introducing subsidies or schooling programs that enable the required adaptation.

Adaptable constraints can also be set to the preference of the policymakers. In case the government does not regard the shift of agricultural production as a suitable option, they should accept the loss in hydropower and find other solutions for the necessary increase in electricity supply. In this case they could constrain the agricultural production from change and look for new optima. A possible measure could be to add electricity production facilities. Adapting the input data for the capacity constraint of thermal power production facilities allows increasing capacity or adding additional electricity production facilities to be explored as a solution.

Another way to explore this solution would be to make the constraint dynamic and set the capacity as a decision variable. This was done in the case study for reservoir storage and irrigation capacity. By performing sensitivity analysis, the robustness of infrastructure at specific proposed locations can be checked. If infrastructure would always be chosen to be built on the same location under various conditions, one may find reason to explore this location further. Section 3.2.6 demonstrated how construction of storage and irrigation capacity would geographically distributed depending on location and investment cost.

Exploring strategies for responding to developments in the WEF sectors requires cooperation of all sectors. Decisions and planning should work in harmony. MAXUS requires expertise from all sectors to agree on shared objectives, required balances and interactions, constraints that apply which may also include their preferences and decision variables that represent their range of measures. MAXUS requires but also therefore supports this cooperation.

MAXUS may also support geopolitical discussions. Due to its ability to optimize for multiple regions separately, differences for cooperation and non-cooperation can be investigated. In the case study it was shown how infrastructure would be built on different locations and in different proportions when Burkina Faso and Ghana would optimize WEF infrastructure planning in non-cooperative manner and cooperative manner. WEF infrastructure development in Burkina Faso and its effect on Ghana has been topic of discussions between Burkina Faso and Ghana[77][78]. In addition, MAXUS could map how different solutions proposed by different parties with different interests would play out in the water, energy, food system. Further possible uses for the proposed framework are yet to be explored.

Nonetheless, the optimization of MAXUS should not be interpreted an optimum in all aspects. In optimizing decisions, MAXUS takes into consideration whatever is formulated as objectives and constraints. However, some issues are hard to describe in equations. Two such examples are presented here:

Social/cultural/ethical reasoning
Perhaps some social/cultural/ethical preferences could be translated to constraints, such as: crop production in the poorer north should be at least equal to that in the richer south; or everybody needs to have access to electricity; or part of food production still needs to be produced with low level of fertilizers etc. However, some considerations would be very hard to formulate using equations. Labour availability could for example be an important factor on where to build what crops, farmers could have family sentiment to stick to a certain crop or simply do not have the education levels required for a change in crops and perhaps they don't even want to, even if they would be better off[79]. There could be all sorts of things why a certain change in the system is not preferred, think of traditions, access to credit, corruption etc.[80][81]

Ecosystems
An economically efficient allocation might be very harming for ecosystems[82]. Ecosystem requirements are hard to include. Some examples that could be captured with constraints would include: land of national parks should remain untouched and its water needs ensured; dam construction should be limited; or a high biodiversity of crops in a region is required. Such quantitative constraints are relatively straightforward to include. However, when it comes down to water quality requirements it becomes really hard to capture in constraints. Examples include: the temperature of water may not rise above X degrees for conservation of fish communities; or the concentration of nutrients in surface water as a consequence of run-off may not exceed X Moles/L. What may be optimal in quantitative terms may not be in qualitative terms. Solutions may be proposed, that largely affect the water quality.

In case relations as described in the above turn out to be important after a qualitative study of a certain case were to be conveyed, one should sit with experts to see what constraints could be added and what not. The flexible character of MAXUS in which objectives, constraints, dimensions, units, scales, input and output requirements can be specified, could serve in many nexus issues.

PERFORM FOR DIFFERENT TEMPORAL SCALES;

The time scale in MAXUS is adaptable and could be manually set. The temporal unit to adopt should depend on multiple aspects: relations included in the model should have a similar timescale; the unit adopted should suit the objective; and the unit would need to comply with data availability.

A meaningful time scale for regional to national nexus analysis is expected to vary from days to years. A time scale of days could matter in operational issues or for peak capacity requirements of storage, of power production etc. A time scale of years would more relevant for global infrastructure development. In the case study a unit of a half year was adopted. Differences in precipitation were significant for the dry season and the wet season each taking about half a year in the region under investigation. Crop rotations were of a similar time scale. The temporal units of available data were sometimes smaller and sometimes larger. Data was therefore aggregated or disaggregated, but overall, a season seemed an appropriate unit of time.

When the temporal unit would decrease to a month, unrealistic crop rotation times could be adopted by the model. This could only be prevented if additional non-linear constraints were included. Since it was decided to limit the scope of this study to linear modelling and food production turned out to be a leading cost factor for the case study, it was decided to abstain from a monthly unit of time.

A time unit of a month, however, would also give many opportunities. Being able to model shorter crop rotations is also an opportunity. Some crops indeed have rotation times of a couple of months[83]. And cropping seasons can also be better represented with a monthly unit of time. Some crops are planted in March, and others in April for example. And to include monthly variations in precipitation could also be consequential. For storage operations or infrastructure expansion, this would be very relevant. It is therefore recommended to see how the case study result would differ, when a monthly scale is adopted by including non-linear constraints.

It is important that the temporal and spatial scale are aligned and meaningful for the objective of the study. As stated, a meaningful time scale for regional to national nexus analysis is expected to vary from days to years. A meaningful time scale in a nexus research aimed at a city scale would be a time scale of hours to days[84]. The equations now included in MAXUS would be too coarse. It would require complete different relations. Nonetheless, a similar model structure could be adopted which is optimizing for different variables at the same time for complex temporal and spatial trade-offs.

PERFORM FOR DIFFERENT SPATIAL SCALES;

The choice of the spatial unit is comparable to the choice of the unit of time. It is dependent on the goal, data availability and the relations of the nexus study. One could try to maximize output for one province, but also for multiple countries. The choice for the case study to stick to administrative regions as a spatial unit had as main argument that data collection had been easiest on the regional level. It also suited the coarse level on which the intersectoral relations were aimed to be evaluated.

But, the choice may also depend on physical boundaries. To know where rainfall will end up, it might be preferable to work with basins as spatial units instead of administrative regions. Otherwise modelled water flows could potentially be far off from reality. In the case study, this was mitigated by having a larger loss factor for regions that contributed only partly to the flow. But one needs to consider this. If the data availability allows for it, one could also get more reliable by adopting smaller spatial units.

Dams are other examples of physical boundaries. Hydropower could be generated if it flows through the dam. In the model it is linked to water transport from one region to another. This implies that the dam is always modelled at the end of a region, even if it were in the centre. This could give a misrepresentation for the amount of discharge that is able to get through the generators and thereby a misrepresentation in hydropower generation. One could therefore also reduce the size of regions here such that one obtains a region direct upstream from the dam and the other directly downstream.

If the course of rivers is important, which had been the case in the case study, spatial units should be small enough to be able to reflect that. If not, water transport may be modelled too coarse for the objective. A simple example for the case study shows how that may affect the outcome. In optimizing where to build irrigation capacity the model considered that irrigation capacity could be supplied with surface water should it be available. Everywhere within the same region it is irrigated at the same cost. For regions covering several dozens of kilometres this is obviously not realistic. Surface water can only be brought there if there are streams, canals or pumps, should the geographic position of the agricultural site allow for it. There are several options to work around this in the model: one could limit the amount of land suitable for irrigation in a region; one could increase the price of irrigation capacity in regions once the amount increases, to take into account that some irrigation sites are preferable above others; Or, again, one could decrease the unit of space.

The smaller a spatial unit gets, the more precise the optimization can be. But, in return, one must acquire more data and should accept an increasing computational time. If the problem is solved with linear mathematics, this is not directly a problem, but if non-linear equations were taken into account, the computational time may build up strongly and computational complexity may become infeasibly large.

Picture 7: Illinois biufuel power plant; source: ISTC [114]

HAVE AN ADAPTABLE INPUT DATA STRUCTURE;
Adapting of spatial and temporal units can only be done if the data input structure allows for it. As is the case too for including additional relations, adding extra regions, changing units etc. The data structure should completely depend on the specifics of the nexus case study under investigation. The user should be able to adapt it to the governing data availability. The value of flexibility cannot be overestimated. The structure of MAXUS allows for adaptable data input. In the current set-up, data has to be inserted in excel, but one can think of database software which checks upfront if all the parameters required to solve the problem are given and if given values are valid. If one adapts the problem, this software should also adapt the check.

ALLOW FOR PHYSICAL ACCOUNTING OF RESOURCES, TECHNOLOGIES AND CONSTRAINTS;
In MAXUS all parameters and variables are stored. By visualizing it in a Sankey diagram as proposed, It could show how water is distributed over different processes in the food and energy sector; how energy is used in the water and food sector etc. To improve accounting, there are many visualization methods yet to be explored.

HANDLE AND ACCOUNT EXTERNALLY INDUCED EFFECTS.
The framework allows for inclusion of externally induced effects such as land cover change, climate change or population growth, but this depends how the model is customized. In the case study potential yields were retrieved from GAEZ with had determined them with inclusion of climatic constraints. If rainfall patterns change, these potential yields should be adapted as well. If one wants to investigate the effect of climate change, other potential yields for different climatic scenarios should be adopted. The GAEZ has already calculated these for different climatic scenarios and hence it should pose no problems. Other external effects such as land cover change, diet changes, or population growth, could be incorporated rather easily in the case study. Input data can be adapted, a suitable timeframe can be selected, a spatial distribution of the developments can be covered, etc.

Boundaries are also made flexible, this is something that should be well considered. Should import be at a fixed price? Or, should there be seasonal variation? Should there be caps on the amount of imports and exports? Should the locations from which import from outside the model borders be fixed, such as a harbour area? And if export is included, should export be a decision variable? Should it then optimize profits based on projected prices? Shaping the boundaries, is part of shaping the optimization problem.

Next to that, one should also take into account initial conditions. From what moment should one change agriculture? Should one pretend nothing grows before optimizing, or should one determine which crops are growing currently before optimizing? What would be the difference? Should reservoir levels be measured before optimizing and what about soil moisture? The effect of initial conditions on the outcome of the model are yet to be explored. They will be different for every objective, timescale, scale of space, and set of relations etc.

Picture 8: Vietnam rice production; source: Sunsurfer [115]

5. CONCLUSIONS

This study has addressed the quantification of WEF sector interactions in order to assess possible trade-offs and synergies. A framework was proposed to address the shortcomings of existing analysis models that fail to capture the complex chain reactions found in the WEF system. By the incorporation of WEF interactions in an integral, coherent, computationally tractable, flexible optimization framework MAXUS has shown that:

- it can find non-trivial, multisectoral, complex spatial and temporal trade-offs and synergies for operational management and infrastructural planning;
- it can detect collaboration opportunities through better mobilization of resources and infrastructural planning by optimizing for regions separately.
- it can be customized to a wide range of nexus studies; allowing adaptation objective functions, balances, decision variables, constraints and dimensions; it is therefore scalable in time and space;
- it provides, by means of physical accounting, insight in spatial and temporal patterns of resource flows, use of technologies, and constraints;
- it allows for inclusion of externally induced effects such as climate change, land cover change, changing consumption patterns and population growth;

Using Maxus to customize a model for a specific cases study requires broad expertise. It requires engineers to set-up the equations for the model, experts in different sectors that understand the interactions, and local experts that now the conditions that apply in the case study area. Furthermore, it demands policymakers to think through their ambitions, their preferences, their range of possible interventions and governance actions, and the influences of their decisions on each of the WEF sectors. Exploring strategies for responding to developments in the WEF sectors requires cooperation of all sectors.

6. FURTHER RESEARCH

Performing analysis on the interaction in the WEF sectors is still at an early stage. Data collection technologies have developed quickly in recent years and that is the main reason why analysis on these complex systems started to become more accurate and hence feasible. The development of MAXUS has anticipated on more advances in data acquirement and is flexible enough to include a higher data level in its model customization.

MAXUS has shown to capture multisectoral, spatial and temporal trade-offs and this is a vital step toward more integral analysis of the WEF sectors. This could shed new light on the validity of well-known performance indicators in WEF policy such as water productivity, water footprint, ecological footprint etc. If interdependencies between sectors prove to be crucial, these individual performance indicators could be overvalued in allocation and application of resources. This doubt is reflected by existing literature[85][86].

There lies potential in expanding MAXUS on at least a couple of terrains and these are given in the order of priority to develop. Firstly, the sensitivity analysis should be automated. The programming framework used for the case-study does not allow to work in batch-processes. Increasing the operationality of the software scripts could solve this issue. Replacing GAMS with Pyomo[87] may ensure that all scripts are in one programming language and the software can be run in one go. There should be checks on the input data that give a warning when the input is wrongly formatted or when values are missing to be able to run. The usability of the model could be greatly improved.

Secondly, non-linear solvers may enhance the reliability of MAXUS. The case study showed the importance of non-linear equations for the representation of crop schedules, groundwater irrigation, hydropower generation and reservoir evaporation losses. Inclusion of non-linear equations might also enhance the approximation of cost levels such as reservoir storage construction cost. Non-linear solvers have the drawback to not always arrive at a global optimum but rather a local optimum. Hence, it becomes harder to assure that the found solution is a good one.

Thirdly, stochastic analysis could support decision making. Instead of having rainfall fixed or having always reliable electricity import, having probability distribution functions coupled to rainfall and electricity import could give a much more realistic view on decision making. If one is unsure about the rainfall to come or about the resources available for import, one tends to build buffers in the system such as storages or diverts away from risky operations. Risk-averseness could really impact decisions in operations and infrastructure, and thus should be given weight in the analysis.

Lastly, agent-based modelling could be interesting for understanding decisions in the WEF sectors better. Instead of optimizing for all sectors combined, one could optimize utility of individual agents. Separate optimization has already been done for regions as shown in the case study, but it could also be done for agent in different sectors such as farmers, power plants etc. This could give additional insights on what is constraining the agents in cooperation.

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ANNEX A: DATA USE

Name	**determination method**	**accuracy level**	**year of data**	**Institutional author**	**Source**
$SW_{S_{loss}}$	estimate by assuming reservoir to have invariable area over the height; potential evaporation divided by depth of reservoir	low	2009	CGIAR	[97]
$SW_{S.Cap.Existing}$	sum of capacities of reservoirs in dataset	high	2011	GranD	[98]
$SW_{Ex.Cap}$	based on where river may cross the borders (parameter in fact functions as state variable)	high	-	-	
GW_{Re}	for wet season estimate based on literature; for dry season water must be allowed to be taken up from the ground otherwise natural vegetation could not grow	low	1991; 2002		[97]
$W_{Con.Fg}$	based on FAO formula that relates actual evaporation of a crop with the maximum evaporation, maximum yield and actual yield	medium	-	-	
W_P	dataset for the year 2015 of rainfall per month averaged over season and averaged per region	medium	2015	Nasa TRMM	[99]
W_{ET0}	potential evaporation data per month was averaged per region per season; reference evaporation was found by dividing potential evaporation by literature based reference evaporation factor of water	high	2009; 2007	CGIAR; -	[97]
W_{CR}	arbitrarily set	-	-	-	
W_{KC}	factor per growth stage of crop; averaged over total crop growth duration	high	1998	FAO	[83]
$W_{KC.Nat}$	factor per land cover class; land cover based on sattelite data; averaged over region	high	2007	-	[97]
W_D	set to 0	-	-	-	
$E_{Con.W_T}$	estimated by hydropower equation that relates hydraulic head, generation efficiency and discharge to power production; hydraulic heads were found or estimated based on literature	medium	-	GranD	[98]
$E_{Con.W_{Ex}}$	similar to $E_{Con.W_T}$; but now based on where water crossing the borders would generate hydropower for the region	medium	-	-	
$E_{T_{loss}}$	estimated by having the transport loss to be proportional with distance between regions	low	2000-2013; -	Energy comission of ghana; -	[63][67]

Name	**determination method**	**accuracy level**	**year of data**	**Institutional author**	**Source**
E_{Ex}	set to 0	-	-	-	
E_D	estimation based on multiplying population and energy demand per capita	low	2010 - 2017	World Bank	[100]
$E_{Prod.Thermal.Cap}$	sum of intalled capacities as provided by datatset	high	2007	Energy commission of Ghana	[63]
$F_{S_{loss}}$	estimated based on literature				[62]
$F_{T_{loss}}$	estimated based on literature				[62]
$F_{G_{loss}}$	estimated based on literature				[62]
$F_{S.Cap}$	has been set to infinity	-	-	-	
F_D	estimation based on multiplying population and diets		2010	MOFA, Ghana	[50]
F_{K_y}	based on literature	high	2012	FAO	[83]
L_{Ava}	sum of agricultural land as defined by dataset	high	2000	-	[101]
$L_{Req.F_G}$	yields were retrieved from data base, multiplied by available agriculturual land, and averaged per region; irrigation yields per region were set equal to highest rainfed yield of all regions	low	2012	GAEZ	[37]
L_{Tot}	found by summing the area within admistrative borders of dataset	high	2005	Sedac	[102]
$L_{Irr.Cap.Existing}$	based on literature dataset	medium	2000	FAO	[103][104]
$C_{SW_{S.Cap.New}}$	estimated based on literature; values were set lower for those regions crossed by the volta river;	medium	2012	IMWI	[105]
$C_{Unsatisfied}$	set to very high	-	-	-	
$C_{GW_{Irr}}$	estimated based on literature	high	1995	FAO	[106]
C_{F_G}	cost of rize and maize were based on detailed cost calulation from literature. Other food production cost were scaled to maize relative to farmgate prices	low	2012	MOFA, Ghana	[107][50]
C_{F_T}	estimated based on fuel price and carry load of lorries and an additional factor for overhead cost	medium	2018	-	
$C_{F_{Im}}$	estimated value by multiplying farmgate prices	low	2010	MOFA, Ghana	[50]
$C_{E_{Prod.Thermal}}$	estimated based on literature	medium	2013	IAE	[66]
$C_{E_{Im}}$	estimated value by multiplying thermal production prices	low	-	-	
$C_{L_{Irr.Cap.New}}$	based on literature	high	2014	FAO	[59]

ANNEX B: MODEL

Surface water balance

$$\underbrace{SW_{Stocks}(i,t)}_{\text{SW storage}} = \underbrace{SW_{Ava}(i,t)}_{\text{SW availability}} - \underbrace{SW_{Con}(i,t)}_{\text{SW consumption}} + \underbrace{SW_{ImEx}(i,t)}_{\text{SW import/export}} + \underbrace{SW_{Unused}(i,t)}_{\text{modelling artifact}}$$ ①

$$\mathrm{SW}_{Stocks}(i,t) = \underbrace{SW_S(i,t) - (1 - SW_{S_{loss}}(i,t)) * SW_S(i,t-1)}_{\text{reservoir storage change}}$$ ②

$$\mathrm{SW}_{Ava}(i,t) = \underbrace{W_P(i,t)}_{\text{rainfall}} + \underbrace{GW_{Irr}(i,t)}_{\text{GW irrigation}}$$

$$\mathrm{SW}_{Con}(i,t) = \underbrace{W_{Sup}(i,t)}_{\text{water supply}} + \underbrace{(1 - GW_{Nat}) * W_{evap0}(i,t)}_{\text{natural vegetation evaporation}} + \underbrace{GW_{Re} * W_P(i,t)}_{\text{groundwater recharge}} + \underbrace{\sum_{c,e,w}(W_{Con.F_G}(i,c,e,w,t) * F_G(i,c,e,w,t))}_{\text{crop evaporation}}$$ ③

$$\mathrm{SW}_{ImEx}(i,t) = \underbrace{\sum_j(SW_T(j,i,t))}_{\text{net internal import}} - \underbrace{\sum_j SW_T(i,j,t)}_{\text{internal export}} + \underbrace{SW_{Im}(i,t)}_{\text{external import}} - \underbrace{SW_{Ex}(i,t)}_{\text{external export}}$$

$$\mathrm{W}_{Con.F_G}(i,c,e,w,t) = \underbrace{((\frac{L_{F_G.Req}(i,c,e_{high},w_{irr})}{L_{F_G.Req}(i,c,e,w)} - 1) * \frac{1}{F_{K_y}(c)}) + 1)}_{\text{real yield / maximum yield * yield response factor}} * \underbrace{W_{KC}(c) * W_{ET0}(i,t)}_{\text{maximum crop evaporation}}$$

$$\mathrm{W}_{Evap0}(i,t) = \underbrace{W_{KC}(i,t) * W_{ET0}(i,t) * L_{Tot}(i)}_{\text{Natural vegetation evaporation}} - \underbrace{\sum_{w,c,e}(L_{F_G.Req}(i,c,e,w) * F_G(i,c,e,w,t))}_{\text{land use of crops}} * \underbrace{W_{KR} * W_{KC.Nat}(i,t) * W_{ET0}(i,t)}_{\text{evaporation of vegetation replaced}}$$ ④

Groundwater balance

$$\underbrace{GW_{Stocks}(i,t)}_{\text{GW storage}} = \underbrace{GW_{Ava}(i,t)}_{\text{GW availability}} - \underbrace{GW_{Con}(i,t)}_{\text{GW consumption}} + \underbrace{GW_{ImEx}(i,t)}_{\text{GW import/export}}$$

$$\mathrm{GW}_{Stocks}(i,t) = \underbrace{GW_S(i,t) - GW_S(i,t-1)}_{\text{groundwater storage change}}$$

$$\mathrm{GW}_{Ava}(i,t) = \underbrace{GW_{Re} * W_P(i,t)}_{\text{recharge}}$$

$$\mathrm{GW}_{Con}(i,t) = \underbrace{GW_{Irr}(i,t)}_{\text{GW irrigation}} + \underbrace{GW_{Nat} * W_{evap0}(i,t)}_{\text{natural vegetation evaporation}}$$

$$\mathrm{GW}_{ImEx}(i,t) = 0$$

Electricity Balance

$$\underbrace{E_{Stocks}(i,t)}_{\text{electricity storage}} = \underbrace{E_{Ava}(i,t)}_{\text{electricity availability}} - \underbrace{E_{Con}(i,t)}_{\text{electricity consumption}} + \underbrace{E_{ImEx}(i,t)}_{\text{electricity import/export}}$$

$$\mathrm{E}_{Stocks}(i,t) = 0$$

$$\mathrm{E}_{Ava}(i,t) = \underbrace{E_{Prod.Thermal}(i,t)}_{\text{thermal power production}} + \underbrace{\sum_j(E_{hydro.W_T}(i,j) * W_T(i,j,t))}_{\text{hydropower production}} + \underbrace{E_{hydro.W_{Ex}}(i) * W_{Ex}(i,t)}_{\text{hydropower production cross-border transport}}$$ ⑩

$$\mathrm{E}_{Con}(i,t) = \underbrace{E_{Sup}(i,t)}_{\text{electricity supply}}$$

$$\mathrm{E}_{ImEx}(i,t) = \underbrace{\sum_j((1 - E_{T_{loss}}(j,i)) * E_T(j,i,t))}_{\text{net internal import}} - \underbrace{\sum_j E_T(i,j,t)}_{\text{internal export}} + \underbrace{E_{Im}(i,t)}_{\text{external import}} - \underbrace{E_{Ex}(i,t)}_{\text{external export}}$$ ⑨

Food balance

$$\underbrace{F_{Stocks}(i,c,t)}_{\text{food storage}} = \underbrace{F_{Ava}(i,c,t)}_{\text{food availability}} - \underbrace{F_{Con}(i,c,t)}_{\text{food consumption}} + \underbrace{F_{ImEx}(i,c,t)}_{\text{food import/export}}$$

$$\mathrm{F}_{Stocks}(i,c,t) = \underbrace{F_S(i,c,t) - (1 - F_{S_{loss}(i,t)}(i)) * F_S(i,c,t-1)}_{\text{warehouse storage change}}$$ ⑤

$$\mathrm{F}_{Ava}(i,c,t) = \underbrace{\sum_{e,w}((1 - F_{G_{loss}(i,t)}) * F_G(i,c,e,w,t))}_{\text{net harvest}}$$ ③ ⑥

$$\mathrm{F}_{Con}(i,c,t) = \underbrace{F_{Sup}(i,c,t)}_{\text{food supply}}$$

$$\mathrm{F}_{ImEx}(i,c,t) = \underbrace{\sum_j((1 - F_{T_{loss}(j,i,t)}) * F_T(j,i,c,t))}_{\text{net internal import}} - \underbrace{\sum_j F_T(i,j,c,t)}_{\text{internal export}} + \underbrace{F_{Im}(i,c,t)}_{\text{external import}} - \underbrace{F_{Ex}(i,c,t)}_{\text{external export}}$$ ⑦ ⑧

Land balance

$$\underbrace{L_{Ava}(i,t)}_{\text{land availability}} \geq \underbrace{L_{Use}(i,t)}_{\text{used land}}$$

$$\mathrm{L}_{Ava}(i,t) = \underbrace{L_{agr}(i,t)}_{\text{available agricultural land}}$$

$$\mathrm{L}_{Use}(i,t) = \underbrace{\sum_{c,e,w} L_{Req.F_G}(i,c,e,w) * F_G(i,c,e,w,t)}_{\text{combined irrigated and rainfed land use}}$$

Surface water constraints

Storage constraints

$$\underbrace{SW_S(i,t)}_{\text{reservoir storage}} \leq \begin{cases} \text{Operations:} & \underbrace{SW_{S.Cap.Existing}(i)}_{\text{existing reservoir storage capacity}} \\ \text{Planning:} & \underbrace{SW_{S.Cap.Existing}(i)}_{\text{existing reservoir storage capacity}} + \underbrace{SW_{S.Cap.New}(i,t)}_{\text{new reservoir storage capacity}} \\ & \underbrace{SW_{S.Cap.New}(i,t)}_{\text{new reservoir storage capacity}} \geq \underbrace{SW_{S.Cap.New}(i,t-1)}_{\text{new reservoir storage capacity of previous timestep}} \end{cases}$$

$$\underbrace{SW_S(i,t=0)}_{\text{initial surface water storage}} = 0$$

⑬

Availability constraints

$$\underbrace{\sum_c (W_{Req.F_G}(i,c,e,t) * F_G(i,c,e,w_{Irr},t))}_{\text{water use of irrigated crops}} \geq \underbrace{GW_{Irr}(i,t)}_{\text{GW irrigation water}}$$

Import/Export constraints

$$\underbrace{SW_{Ex}(i,t)}_{\text{external export}} \leq \underbrace{SW_{Ex.Cap}(i)}_{\text{external export capacity}}$$

Groundwater constraints

Storage constraints

$$\underbrace{GW_S(i,t=0)}_{\text{initial groundwater storage}} = 0$$

⑭

Electricity constraints

Availability constraints

$$\underbrace{E_{Prod.Thermal}(i,t)}_{\text{thermal energy production}} \leq \underbrace{E_{Prod.Thermal.Cap}(i,t)}_{\text{thermal energy production capacity}}$$

⑫

Import/Export constraints

$$\underbrace{\sum_{i,t} E_{Ex}(i,t)}_{\text{electricity exports of all regions}} = \underbrace{E_{Ex}(t)}_{\text{total electricity exports in timestep}}$$

Land constraints

Availability constraints

$$\underbrace{L_{Use.Irr}(i,t)}_{\text{land use for irrigated crops}} \leq \begin{cases} \text{Operations:} & \underbrace{L_{Irr.Cap.Existing}(i)}_{\text{existing irrigation capacity}} \\ \text{Planning:} & \underbrace{L_{Irr.Cap.Existing}(i)}_{\text{existing irrigation capacity}} + \underbrace{L_{Irr.Cap.New}(i,t)}_{\text{new irrigation capacity}} \\ & \underbrace{L_{Irr.Cap.New}(i,t)}_{\text{new irrigation capacity}} \geq \underbrace{L_{Irr.Cap.New}(i,t-1)}_{\text{new irrigation capacity of previous timestep}} \end{cases}$$

$$\underbrace{L_{Use.Irr}(i,t)}_{\text{irrigated crop land use}} = \underbrace{\sum_{c,e,w} L_{Req.F_G}(i,c,e,w_{Irr}) * F_G(i,c,e,w,t)}_{\text{land use}}$$

Food constraints

Storage constraints

$$\underbrace{\sum_c F_S(i,c,t)}_{\text{warehouse storage}} \leq \underbrace{F_{S.Cap}(i)}_{\text{warehouse storage capacity}}$$

⑪

$$\underbrace{F_S(i,c,t=0)}_{\text{initial food storage}} = 0$$

Availability constraints

$$\underbrace{F_G(i,c,e,w_{RF},t)}_{\text{rain fed crop production}} * \left(\underbrace{\frac{W_P(i,t)}{L_{Tot}(i)}}_{\text{rainfall per unit area}} - \underbrace{W_{Con.F_G}(i,c,e,w,t)}_{\text{water consumption crop per unit area}} \right) \geq 0$$

$$\underbrace{F_G(i,c,e,w,t)}_{\text{crop production}} * \underbrace{W_{Con.F_G}(i,c,e,w,t)}_{\text{water consumption crop per unit area}} \geq 0$$

Import/Export constraints

$$\underbrace{\sum_{i,t} F_{Ex}(i,c,t)}_{\text{food exports of all regions and time-steps}} = \underbrace{F_{Ex}(c)}_{\text{total food exports per crop}}$$

Performance indicators

$$\underbrace{W_{D.Unsatisfied}(i,t)}_{\text{unsatisfied water demand}} = \underbrace{W_D(i,t)}_{\text{water demand}} - \underbrace{W_{Sup}(i,t)}_{\text{water supply}}$$

⑮

$$\underbrace{E_{D.Unsatisfied}(i,t)}_{\text{unsatisfied elec. demand}} = \underbrace{E_D(i,t)}_{\text{elec. demand}} - \underbrace{E_{Sup}(i,t)}_{\text{elec. supply}}$$

⑮

$$\underbrace{F_{D.Unsatisfied}(i,c,t)}_{\text{unsatisfied food demand}} = \underbrace{F_D(i,c,t)}_{\text{food demand}} - \underbrace{F_{Sup}(i,c,t)}_{\text{food supply}}$$

⑮

Objective function

$$\underset{decision\ variables*}{\text{minimize}} \ \underbrace{C_{Tot}}_{\text{total costs}} \ \text{while satisfying water food and energy demand}$$

cost term	cost factor	in expression
reservoir construction cost	$C_{SW_{S.Cap.New}}(i)$	$\sum_{i}(C_{SW_{S.Cap.New}}(i) * SW_{S.Cap.New}(i,t=end))$ ⑰
unsatisfied water demand penalty	$C_{Unsatisfied}$	$\sum_{i,t}(C_{Unsatisfied} * W_{D.Unsatisfied}(i,t))$ ⑯
groundwater irrigation cost	$C_{GW_{Irr}}$	$\sum_{i,t}(C_{GW_{Irr}} * GW_{Irr}(i,t))$ ⑱
thermal power production cost	$C_{E_{Prod.Thermal}}$	$\sum_{i,t}(C_{E_{Prod.Thermal}} * E_{Prod.Thermal}(i,t))$ ㉑
electricity import cost	$C_{E_{Im}}$	$\sum_{i,t}(C_{E_{Im}} * E_{Im}(i,t))$ ㉒
unsatisfied electricity demand penalty	$C_{Unsatisfied}$	$\sum_{i,t}(C_{Unsatisfied} * E_{D.Unsatisfied}(i,t))$ ⑯
food production cost	$C_{F_G}(c,e,w)$	$\sum_{i,c,e,w,t}(C_{F_G}(c,e,w) * F_G(i,c,e,w,t) * L_{Req.F_G}(i,c,e,w))$ ⑲
food transport cost	$C_{F_T}(i,j,t)$	$\sum_{i,j,c}(C_{F_T}(i,j,t) * F_T(i,j,c,t))$
food import cost	$C_{F_{Im}(c,t)}$	$\sum_{i,c,t}(C_{F_{Im}}(c,t) * F_{Im}(i,c,t))$ ⑳
unsatisfied food demand penalty	$C_{Unsatisfied}$	$\sum_{i,t}(C_{Unsatisfied} * F_{D.Unsatisfied}(i,t))$ ⑯
irrigation capacity construction cost	$C_{L_{Irr.Cap.New}}$	$\sum_{i}(C_{L_{Irr.Cap.New}} * L_{Irr.Cap.New}(i,t=end))$

Decision variables

Name	Short description	Dimensions	Units
SW_S	reservoir water storage	i,t	Mm^3
SW_T	surface water transport	i,i,t	Mm^3/season
GW_{Irr}	groundwater irrigation	i,t	Mm^3/season
$E_{Prod.Thermal}$	thermal power production	i,t	MWh/season
E_T	electricity transport	i,i,t	MWh/season
E_{Im}	electricity import	i,t	MWh/season
F_S	food storage	i,c,t	tonnes
F_G	food production	i,c,e,w,t	tonnes/season
F_T	food transport	i,i,c,t	tonnes/season
F_{Im}	food imports	i,t	tonnes/season
F_{Ex}	food exports	i,t	tonnes/season
$SW_{S.Cap.New}$	new reservoirs storage capacity	i,t	Mm^3
$L_{Irr.Cap.New}$	new irrigation capacity	i,t	hectares

Dimensions

Name	Dimension type	Set type	Set size	Unit
i	spatial	set	23	administrative region
j	spatial	subset	23	administrative region
t	temporal	set	4	precipitation season (half a year)
c	agricultural production	set	12	crop type
e	agricultural input	set	3	input level
w	agricultural watering	set	2	watering method