Trans-boundary water management modeling framework

How cooperation impacts water resources in a river basin

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Preface

Dear reader,

Thank you for reading my thesis paper on water management. I have always had an interest in water management with a special focus on hydroelectric dams. During my thesis I have had the possibility expand this interest by researching a whole river basin in which these dams are located. With the use of python I have built a model of this basin that let me explore the effects of different release policies on resources gathered in the basin. With this model I was able to predict the outcomes of different cooperation levels between the countries located in the basin. This has been an exiting and challenging task that I have enjoyed.

The flow and quality of this research has greatly been enhanced by my two supervisors. First, special thanks to Dr. J.(Jazmin) Zatarain Salazar, who was my first supervisor. It was her who introduced the topic of this thesis to me. Furthermore, Jazmin guided me throughout my thesis during regular meetings. This help has been particular usefully since it was my first time constructing a python model from scratch. I am sure that without it the flow of my thesis would have been much less fluid. Jazmin also introduced me to Prof.dr.ir. P.H.A.J.M. (Pieter) van Gelder, who was my second supervisor and was also chair of my graduation committee. Pieter has provided feedback on my thesis during out various meetings. This feedback has greatly enhanced the quality of this thesis.

I want to thank Jazmin for mentoring me during my thesis progress. Furthermore, I want to thank Pieter for being enthusiastic and critical on my work. Moreover, I want to thank them both for having time available and for guiding me through the final challenge of my MSc Engineering Policy Analysis.

I have enjoyed working on this research paper and I hope you enjoy reading it.

Executive summary

This research explores the effects different cooperation levels between countries located in a trans-boundary river basin have on water resources. The water resources that are taken into account are: hydro electricity generated per dam, water that flows to the environment per dam, and irrigation water per station. The Zambezi river basin is selected as study area due to its trans-boundary multi-stakeholder complex character. The cooperation levels that are explored are no cooperation, full cooperation, and section cooperation. No cooperation entails that every hydroelectric dam in the river only tries to maximize its own electricity. With full cooperation the dams releases are adjusted to benefit all the water resources in the whole basin. With section cooperation the dam releases are adjusted to maximize the water resources within the section of the specific dam. A section is a geographical area that is based on borders between the countries in the Zambezi river. A simulation model is built that simulates the Zambezi river in order to explore the effects of the different cooperation levels. The release policies that maximize the water resources for the full and section cooperation levels are found with a multi-objective evolutionary algorithm (MOEA). From this research three findings are extracted. First, this study shows that for the full cooperation level and the section cooperation level policies exist that dominate the no cooperation level policy for every examined water resource. Moreover, the findings indicate that for these water resources the found policies for either full or section cooperation produce similar results. Therefore, this study points out that any of the explored cooperation forms could be more beneficial than no cooperation at all. Second, outcomes of this study indicate that owners of water resources located in the upstream of the river have less possible benefits from entering a cooperation agreement in which their dams have to adjust their release policy. These water resources can only be improved by a relatively small amount compared to water resources located in the downstream of the river. Third, this study shows that policies do exist that are able to perform best for certain water resources, but also cause other water resources to decline to a value lower than their no cooperation value. Therefore, it is key that extra attention goes towards selecting fitting release policies since not every found policy leads to a better solution for every water resource. Last, in this study best performing policies for electricity production and irrigation for both full and section cooperation are compared. It is discovered that adapting the best electricity policy for either one of the cooperation forms would be most beneficial for the involved stakeholders. This is due to the electricity policies having the highest relative resource gains. The best electricity policies perform best for the electricity resource, but has the best or high values for the irrigation resource depending on the section. To conclude, cooperation in a river basin could result in an overall increase in water resources. However, reaching cooperation might prove to be difficult, because of the lower incentives for the stakeholders in the upstream of the river. Furthermore, extra care has to go towards selecting better performing policies, because policies exist that can cause a decline in water resources compared to when there is no cooperation in

the river basin. Moreover, stakeholders are expected to select the policy that maximizes the electricity production, since these policies also perform well for other examined water resources.

Contents

1 Introduction

For centuries mankind has profited from water resources of rivers. Currently, new technologies, like hydroelectric dams, have introduced more options for harnessing a river's resources. Hydroelectric dams allow electricity to be generated by using the rivers flow. This can be a large benefit to the country in which the dam is located. However, these hydroelectric dams also are the cause of a lot of heated debates. This is due to the fact that these damns can alter the flow of the river which often has a direct negative impact on the environment downstream of the river (McCartney & Sally, 2007). Furthermore, during the filling period of a hydroelectric dam reservoir a reduction in flow towards the downstream river will be present. As a result, conflicts often rise between countries that share a river because it is unclear how the rivers resources should be allocated.

Every water conflict case is different. However, cooperation for dividing water resources between two or more countries could be an overall best fitting solution. Trans-boundary disputes are often difficult to solve due to the socioeconomic and environmental differences between the stakeholders that claim ownership of part of the river (Yuan et al., 2020). Research has indicated that risks that are present with the construction and filling of the GERD can be reduced or even avoided with cooperation between the involved countries (Wheeler et al., 2016). This indicates that cooperation between the involved countries could be a solution. Other research by Zeitoun and Warner (2006) shows evidence of power asymmetries between countries involved in a water conflict resulting in unfavorable outcomes. Furthermore, in the same research Zeitoun and Warner (2006) propose a framework that shows how these involved countries might move to cooperation. Through examples from Africa, Central Asia and Latin America cases can be examined for how trans-boundary cooperation between countries can be beneficial for environmental management, benefit-sharing and sustainable use of trans-boundary freshwater resources (Uitto & Duda, 2002). Therefore, it can be concluded that cooperation between countries located in a trans-boundary water conflict could prove to be beneficial.

Water conflicts have been around for a very long time. These water conflicts often are the result of a multitude of reasons. Water logging (e.g. building dams) is among these reasons (Angelakis et al., 2021). Even in ancient times, mankind has tried to avoid water conflicts by creating laws. For example, a Babylonian king in 1792–1750 BC installed water laws for ensuring farmers a fair distribution of water from the empires rivers (Angelakis et al., 2021). However, a situation where two or more countries are involved is more complex. For example, the case of the Grand Ethiopian Renaissance Dam (the GERD). The GERD is a large hydroelectric dam located in Ethiopia. In 1959, Egypt and Sudan agreed to allocate the rivers water resources between the two countries (Abdalla, 1971). Sudan was appointed the right to a certain part of the rivers water and Egypt to the other part. The mayor problem with these kind of solutions is that they do not take the whole system into account. This is also what happened in this case, the upstream countries of the Nile where not taken into account. As a result Ethiopia, started claiming part of the river for its own and constructed the GERD in their upstream part of the Nile.

How water resources should be allocated between involved parties remains a challenge to this day. Current literature on this topic can be divided into two main branches. Either advise is given based on a model or advise is based on data gathered from previous water conflict cases. For example, Abtew and Dessu (2019) create an overview of the consequences of the GERD and suggest filling approaches. Moreover, Yang, Wi, Ray, Brown, and Khalil (2016) suggest a hydro-economic water system model of the Brahmaputra River Basin in South Asia for finding possible development paths. In other research, Zeng, Li, Cai, Tan, and Dai (2019) suggest a hybrid mathematical game theory model for solving water conflicts between two cities. The model provides an indication for locating trans-jurisdictional water rights between the involved stakeholders.

In addition to the research that uses models to suggest cooperation options, other research provides lessons learned from previous cases. For example, Uitto and Duda (2002) show the importance of peaceful cooperation in a river basin with the use of experience gained from cases in Africa, Central Asia and Latin America. Moreover, similar research like Wolf (1997) provide lessons learned per stage of negations in water conflicts. Wolf (1997) uses case studies collected from the Alabama Trans-boundary Freshwater Dispute Database. Also, the Nile river basin is studied for examining the incentive structure of both cooperative and non-cooperative strategies for different countries located in a river basin (Wu & Whittington, 2006). Other research evaluates water cooperation in Europa and applies the lessons learned on the Nile basin case (Reichert, 2019). In addition, Nałecz (2012) indicate actions policy makers could take in order to avoid water conflict.

Currently, very few research provided models can be used in most of the water conflict cases as a base for finding cooperation paths. Research in which this is done is the research of Madani, Zarezadeh, and Morid (2014). In this research Madani et al. provide a framework that is based on economic bankruptcy solving methods for finding solutions for allocating water as a resource during a time where the total water demand is higher than the total supply. Also Yu, Tang, Zhao, Liu, and Mclaughlin (2019) provide a model that can be used in multiple water conflict cases. Yu et al. suggest a repeated game theory model in order to calculate different payoff's for different strategies that the involved countries can use. Furthermore, Berardo and Gerlak (2012) also created a model that can aid in policy making for multiple trans-boundary water conflicts. However, no generic model framework exist that is able to provide a solution space for generic water conflicts cases with hydroelectric dams that takes multiple water resources and multiple cooperation levels into account. Therefore, the main research question of this research will be: *""How can countries located in a trans-boundary river basin that share water resources find a balance in cooperation in order to allocate the rivers resources most efficiently?"*

Based on this research question the following research sub-questions are defined:

- Sub-question 1, What hydro-climatic uncertainties exist and how do they impact the rivers resources?
- Sub-question 2, How can water, agriculture and electricity as resources be balanced between the involved countries?
- Sub-question 3, How do different levels of cooperation impact water, agriculture and electricity as resources in a river's basin.

The main aim of this research is to propose a simulation model that is able to indicate the impact of different water resource allocations based on different levels of cooperation between the countries that are involved. Focus will not only go towards water as a resource but also towards other water resources. The model will be tested using the Zambezi river as case. Te Zambezi river basin will be modeled and possible cooperation policies will be prescribed.

The setup of this paper is as follows. First, a general introduction is given. Second, the Zambezi case is introduced. Third, the research methods are described. Fourth, the model is verified and validated. Fifth, the results presented and conclusions are drawn and discussed.

2 Zambezi River Context

2.1 Basin description

A relevant case is the Zambezi river basin. The Zambezi case is complex due to the large number of existing and planned (hydroelectric) dams located in the river basin. The basin is divided between multiple countries. The river originates in North Zambia, then flows through Angola to South Zambia. From here on, the Zambezi river flows from Zimbabwe to Mozambique where it flows into the ocean. At this moment, three hydroelectric dams operate in the Zambezi river. However, more are planned (Alavian et al., 2010). Furthermore, the existing and planned hydroelectric dams are not only able to have an impact on the rivers resources, but are also themselves vulnerable to external events that impact the climate around the dams (Berardo & Gerlak, 2012). These complex multi-actor properties of the Zambezi river are therefore a case of increasing challenges to correctly manage the river and their basin. Due to these multi-actor complex properties, the Zambezi river case is chosen as case for exploring cooperation paths within a river basin.

The river basin contains multiple hydroelectric dam sites that are either existing, planned or potential hydroelectric dam sites. The modeled part of the river takes the sites into account located in the Zambezi river between Victoria falls and the sea. Furthermore, it also takes the dam sites located in the Kafue river into account. The geographical system with the dam locations is depicted in figure 1.

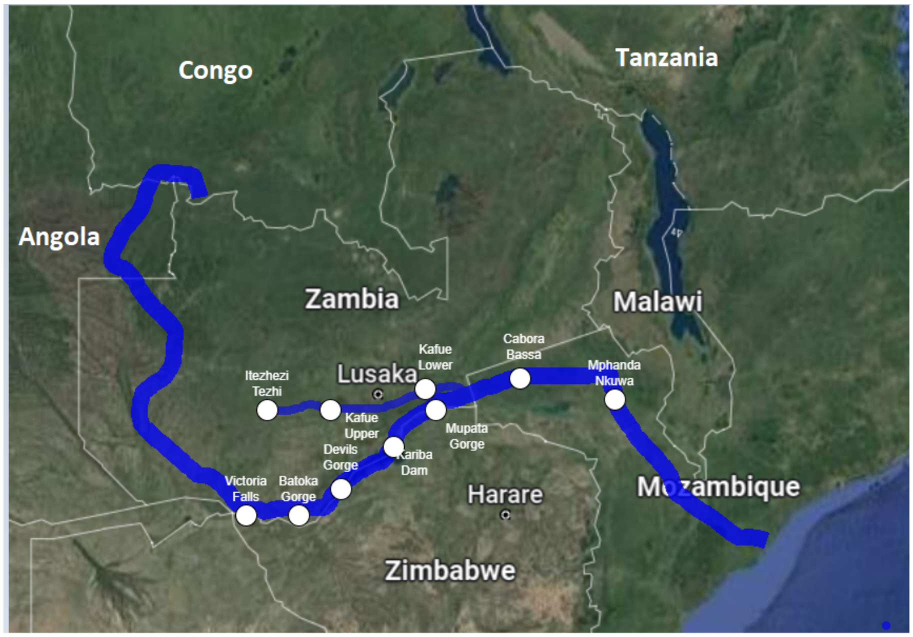


Figure 1: Zambezi basin river dam sites: (*Google Maps*, 2020)

Besides the hydroelectric dams, the Zambezi river also has other rivers flowing into its system. These are: the Upper Zambezi, this is the inflow of the main river, the Gwayi, Sanyayi, Kafue, Chongwe, Luangwa, Manyanne, Luenya and the Shire. The rivers and the size of their discharges are shown in table 1. Moreover, the Zambezi basin also contains irrigation stations from which water is pumped out of the Zambezi system. The described system currently contains 8 irrigation stations. The irrigation demand of these stations is presented in the data section.

River	**Discharge** (m^3/s)
Upper Zambezi	747
Gwayi	84
Sanyati	104
Kafue	336
Chongwe	4
Luangwa	518
Manyane	27
Luenya	180
Shire	162

Table 1: Zambezi river average inflows: (Alavian et al., 2010)

Victoria falls its self does have a power station. However, the Victoria falls power station is not taken into account for the Zambezi river system because it has a negligible impact on the flow of the river (Benn, 1938). Besides the Kafue and Zambezi river also the Shire river houses potential, planned and existing dam sites. The Shire has a middle sized discharge into the Zambezi river of around 162 m^3 per second. Furthermore, the Shire river connects with the Zambezi river after the last dam and is the last river to flow into the Zambezi. Therefore, the influence of the Shire on the Zambezi system is minimal. As a consequence, the Shire river is only taken into account as an inflow, that can alter in size, and not as a whole hydroelectric dam system.

The planned, potential and existing dam sites can be divided into three sections. These sections are based on borders. The sections are as follows: section 1 is the section of Zambia and Zimbabwe. These sites are located on the border between these countries. Section 2 houses dam sites that are only located in Zimbabwe, and section 3 contains dam sites that are only located in Mozambique.

Besides human influence the basin area is also subject to hydro-climatic uncertainties. These are a result of climate trends that are expected to occur in the area. These trends are expected alterations in precipitation, temperature and discharge of rivers in the basin area (Kling, Stanzel, & Preishuber, 2014). Figure 2 shows that precipitation has a cyclic behaviour with only relatively small deviations from the average. Furthermore, the precipitation is not expected to change by a lot in the near future. Also depicted in figure 2 is the temperature. The temperature has a linear behaviour with a large expected increase in the near future of nearly 20 percent. There is no expected future trend for the discharge at Victoria falls, the upper Zambezi inflow. However, there is a trend in existing data that can be observed. The discharge at Victoria falls has a relatively heavy cyclic behaviour ranging from a annual discharge of 400 m^3 per second in dry years to 2300 m^3 per second in wet years (Kling et al., 2014).

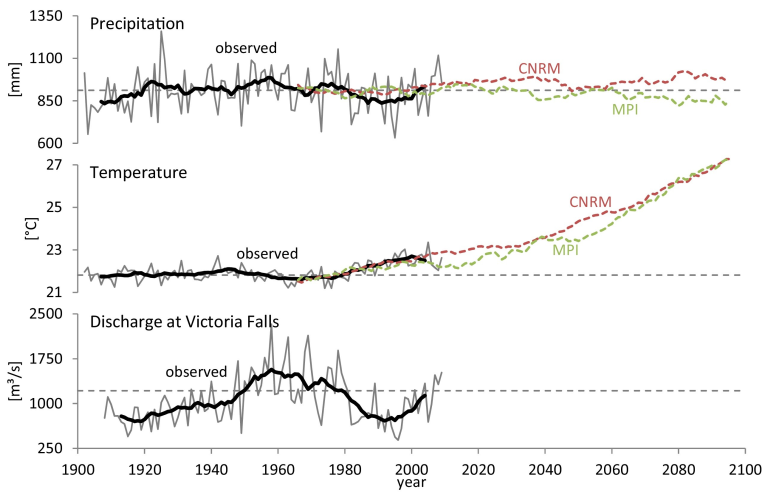


Figure 2: Zambezi basin climate trends: (Kling et al., 2014)

2.1.1 Key concepts

Within the basin the dams and their reservoirs are analysed. The following aspects of the dams are taken into account for this study. First, the water storage capacity of the reservoirs is taken into account. This is the maximum amount of water a reservoir can contain. Second, the effective release of a dam is considered. This is the release a dam needs to match for reaching their maximum electricity production. Third, every dam reservoir has an initial water storage. This is the starting amount of water that is currently in the dam's reservoir. Fourth, every dam has a maximum electricity production. Last, every dam has an effective and current head. The effective head is the water level in the reservoir needed for optimal electricity production. The current head is the current water level of the reservoir. These key aspects are visualised in figure 3.

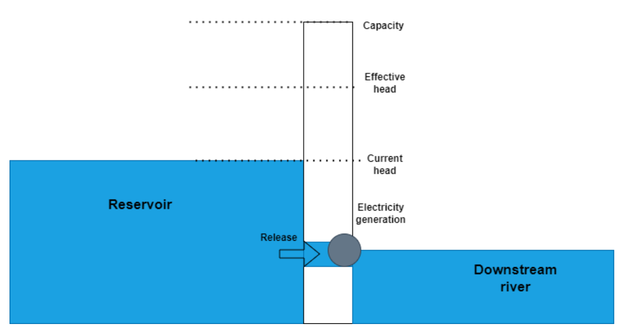


Figure 3: Dam reservoir key aspects

2.2 Model description

As depicted in figure 4 the modelled system contains 9 dams, 9 inflow rivers, and 8 irrigation station divided between 3 sections based on geographical borders. The data gathering process is described in section 2.3. A schematic representation of the basin with their structures and sections is shown in figure 4.

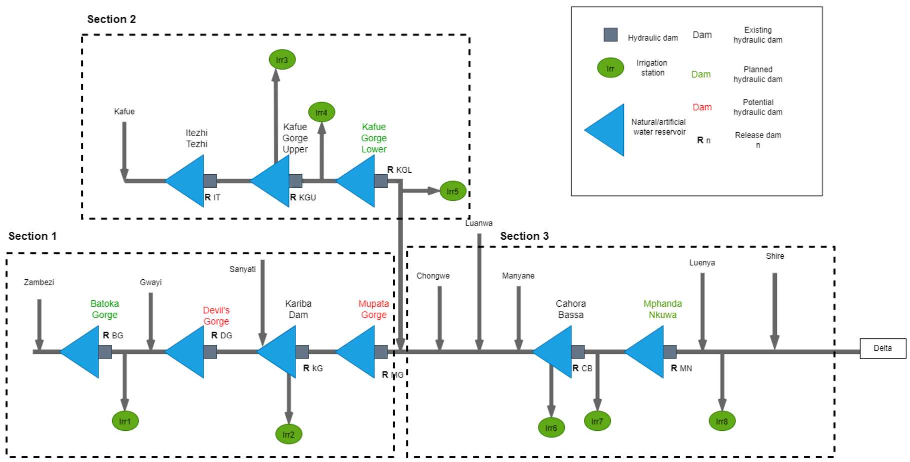


Figure 4: Zambezi basin schematic overview

2.2.1 Operations research model

For the Zambezi model it is important to indicate the difference between the different input values and the output values of the model. To visualize this, a XLRM diagram is constructed. In this diagram the X stands for external factors. In the model these are the described hydro climatic uncertainties. The L stands for the levers. In the model these are the releases of the dams that are adjustable by the stakeholders. The R stands for relations within the system. In this research this is the Zambezi river basin, which is the relation between all the components of the system. M stands for measurements. These are the key performance indicators (KPIs) that indicate the performance of the model under different lever combinations. This is presented in figure 5.

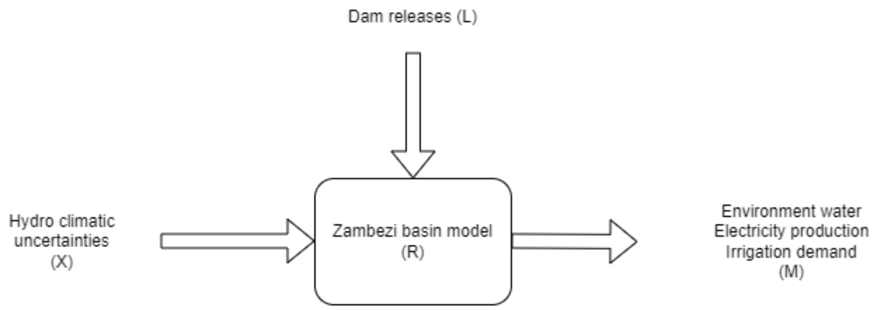


Figure 5: XLRM diagram

The hydro climatic uncertainties are the discharges of the rivers, the evaporation rates and the fluctuations in irrigation demand. The model levers are the releases of all dams. The measurements are the environment water which is the water towards the downstream of all dams, the electricity production per dam and the irrigation demand per irrigation station. The measurements M, are stored as outcomes of the model and used in the analysis of the results. These measures are optimized in this study. The impacts of different cooperation levels will be modeled by selecting different combinations of levers. The scenarios that are examined will be selected by choosing a combination of the mentioned external factors.

2.2.2 Model behaviour

The following equations are used in the model to describe the hydroelectric dams:

$$S_t^k = S_{t-1}^k + \sum_{i=1}^{N}(R_{t-d}^i) + \sum_{j=1}^{M}(Q_{t-d}^j) - E_t^k - R_t^k - \sum_{x=1}^{W}(I_{t-d}^x) \tag{1}$$

$$H_t^k = H_{eff}^k \frac{S_t^k}{C_t^k} \tag{2}$$

$$P_t^k = R_{max}^k \frac{R_t^k * H_t^k}{R_{eff}^k * H_{eff}^k} \tag{3}$$

S_t^k is the current water storage of the k-th dam at moment t.S_{t-1}^k is the water storage of dam k in the previous time step. $\sum_{i=1}^{N}(R_{t-d}^i)$ is the sum of all releases R at the current time step minus the delay d of dams located in the upstream of the river. N is the total of dams in the direct upstream of the reservoir. $\sum_{j=1}^{M}(Q_{t-d}^j)$, the sum of all inflow rivers, is calculated similar to the releases only with the inflow rivers Q. M is the total of direct upstream rivers of the reservoir. The same can be said for the sum of all irrigation water that is taken from the river, $\sum_{x=1}^{W}(I_{t-d}^{x})$. E_t^k is the evaporation at moment t for dam k and R_t^k is the release of the dam k at moment t. W is the total amount of irrigation stations in the direct upstream of the reservoir. The current head of dam k at moment t, which is the height of the water in the reservoir, H_t^k is estimated by multiplying the effective head H_{eff}^k of dam k with the current water storage divided by the total water capacity C_t^k of dam k. P_t^k is the current power generated at moment t for dam k. R_{max}^k is the maximum power capacity of dam k. R_{eff}^k is the effective release of dam k. This is the release at which the maximum power can be generated for dam k. The electricity formula is derived from the general power production formula of hydroelectric plants. However, this formula calculates the electricity produced as a proportion of the maximum electricity that can be produced. This is done because of the derived formula requiring less variables and therefore less data than the general formula.

The most complex dam to model is the Cahora Bassa dam. The large modeling complexity of this dam is due to its location. Its inflow is dependent on the releases of two other dams, 3 rivers and 2 irrigation stations. Moreover, the Cahora Bassa dam is the dam that connects the outflows of section 1 and 2. Within the system there are no other dams that are dependent on the inflow of 2 or more dams in the upstream. Therefore, the water capacity formula is more complicated and is written as follows:

$$S_t^{cb} = S_{t-d}^{cb} + R_{t-7}^{kl} + R_{t-d}^{mg} + Q_{t-d}^{ch} + Q_{t-d}^{lua} + Q_{t-d}^{ma} - E_t^{cb} - R_t^{cb} - I_{t-d}^{5} - I_{t-d}^{6} - I_{t-d}^{7} \quad (4)$$

In the formula, cb represents the Cahora bassa dam, kl the Kafue lower dam, and mg represents the Mupata Gorge dam. Ch,lua and ma represent the rivers Chongwe, Luanwa and Mayanne.

The input values of the system are the required releases of the dam reservoirs. Other possible input of the system, such as the irrigation water demand, are not selected because it is assumed that these demands are more static and harder to alter due to the existence of crops that need a certain amount of water. There are three kinds of KPIs in the system. These are: the electricity generated per dam (in MW), the amount of water released from a dam (in m^3 per second), and the percentage of irrigation demand that is met (in percentage of demand). The amount of water released from a dam, the environment water, is taken into account as KPI because it indicates healthiness of the river downstream, which is an indication of the performance of the model for the quality of the environment. Irrigation demand and electricity are taken into account as KPIs because they both are important economic factors for the countries that are involved.

2.3 Data

For the model to produce realistic results, data is gathered about the Zambezi basin. This data can be grouped into three groups. The first group is dam and reservoir data. The second group is river data and the last group is irrigation data. In this sub-section the gathered data will be discussed and presented. Moreover, gaps in data will be discussed and techniques used for filling these gaps will be presented. Furthermore, assumptions regarding the data are described.

Data about the dam capacity, effective release, initial water storage, max electricity production and their max effective head is gathered. It is assumed that the not yet constructed hydroelectric dams have an initial water storage of 0 because they have not been filled yet once their construction is finished. For the dams with a natural reservoir, these being the Kariba and Itezhezi Tezhi dam, it is assumed that their initial water storage is 50 percent. This is because the Kariba lake levels fluctuate around 50 percent (river authority, n.d.-a). Moreover, there is no information found about the lake levels of the Itezhezi Tezhi. Therefore, since it is the only other natural reservoir dam the initial water storage is also estimated to be 50 percent. For other reservoirs it is assumed that their initial water storage is 100 percent. This is based on the much smaller reservoir size compared to the natural reservoir sizes as can be seen in table 2. As a result, this would indicate that these reservoirs should be easier to fill and therefore likely are full most of the time. Missing data, that either could not be found or is not existent, is filled using logical assumptions. These assumptions are described in appendix A.2 in table A2. The capacity, effective release, max electricity production and their max effective head data sources are presented in table A1 in appendix A.1. These sources combined produced the data presented in table 2 which is used as standard input for the model.

input	Batoka_{Gorge}	Devils_{Gorge}	Kariba_{Dam}	Mupata_{Gorge}	Itezhezi_{Tezhi}	Kafue_{upper}	Kafue_{lower}	Cabora_{Bassa}	$\text{Mphanda}_{N}kuwa$
water capacity (m3)	1,68E+09	1,68E+09	1,8E+13	2,16E+09	6E+12	7E+08	7E+08	5,58E+10	9,7E+10
effective release (m3)	20000	20000	9500	9000	4200	525	6210	7500	9500
init water storage (m3)	0	0	9,00E+12	0	3,00E+12	7E+08	0	5,58E+10	0
electricity capacity (MW)	2400	500	1626	1200	120	900	750	2075	1500
max effective head (m)	167	78	86	78	75	397	171	171	86

Table 2: Reservoir data

Besides reservoir data, data is also gathered about the evaporation rates, irrigation demands, inflow rivers discharges and the delays between the dams. The evaporation rates are gathered from the DAFNE project. The DAFNE project is a project with the objective to establish a decision-analytic framework for participatory and integrated planning within a trans-boundary water system (*DAFNE*, 2020). For the Mupata Gorge dam the evaporation rates are not available and are assumed to be the same as the Kariba dam. This assumption is based on the fact that the evaporation rates within section 1 are all the same. The Evaporation rates are shown in appendix A3 in figure A3. The irrigation demand is based on data gathered from a world bank analysis document by Alavian et al. (2010). In this document data is available about how much water certain crops need per month in the Zambezi basin. Furthermore, it states how many of those crops are in the region of each irrigation station. Combining this data results in monthly irrigation demands per station. These demands are shown in appendix A4 in figure A4. The rivers monthly inflow is also calculated from data gathered from the world bank analysis document created by Alavian et al. (2010). The annual discharges of the inflow rivers is multiplied by the monthly alterations of discharge of the upper Zambezi gathered from Richard Beilfuss (2001). Direct monthly data about all river discharges was not found. Therefore, the river data was estimated as described and is shown in appendix A5 in table A5. Last, the delays are calculated by using the distance between the dams and the average flow speed of the river. The distance between the dams is estimated using google maps. The average flow speed of the Zambezi is 3423 m^3 per second (Richard Beilfuss, 2001). Using the formula depicted below, derived from the liquid flow formula, the flow speed of the river can be estimated. Using this flow speed and the estimated distance between the dam sites the flow delay between the dams can be estimated as depicted in appendix A.6 table A6. The used flow formula is as follows.

$$Speed = discharge/(1/2 * width * depth) \tag{5}$$

3 Methods

Managing complex trans-boundary river basin systems, like the Zambezi river basin, is a complicated process in which simulation optimization models can be beneficial. For finding solutions for dividing river resources mathematical techniques are required (Xevi & Khan, 2005). Moreover, physical modeling, although it has benefits, suffers from several large flaws such as high cost and low geographical flexibility (Mouzelard, Archambeau, Erpicum, & Pirotton, 2001). Besides, physical modeling an other option would be observing current cases and withdrawing lessons learned from them. However, with using these cases the data gathered still needs to be translated to the current case. Moreover, river basin systems are complex and dynamic. Therefore, using only a case study approach might not be a good solution. On the contrast, computational modeling is more flexible, has relatively low cost and can be applied to dynamic cases. Therefore, computational modeling is chosen as main approach. As a result, a computational simulation model is constructed for analysing the Zambezi river case.

3.1 Tools

For this research a variety of tools are used. First, the model is constructed in python. Python is a computer programming language. Python is chosen as a tool because it allows the model to be built using high level code. Furthermore, Python is also chosen because it excels in editing data and visualising the results, which are a key aspect of this research. Moreover, python is the main language that is needed for the EMA-workbench and Pareto.py. The EMA-workbench is an Python workbench developed by Kwakkel (2022). The workbench supports the users to perform exploratory modeling and analysis on simulation optimization models which is used in this research. Furthermore, this research also uses

Pareto.py created by Woodruff and Herman (2018). Pareto.py is an python bibliography that is available on GitHub. The Pareto.py allows users to reduce full solution sets to smaller non-dominated sets. Non-dominated sets are sets that are Pareto optimums within the found solution space.

3.2 Standard model parameters

The model simulated time will be 20 years. 20 years is chosen because it simulates a period long enough to predict system behaviour. Moreover, 20 years is also short enough to avoid high model uncertainty because a large number of years will increase the unpredictability of the model. As a time step 1 day is chosen because a smaller time step would increase the real run time of the model by too much. A higher time step would make the model more unpredictable because input data such as delays, that are estimated per day, would become more imprecise. For example, a delay of 5 days would be rounded up to 10 days if the time step would be 10 days since the release data is saved per time step. The model will have a warm-up time of 7 days. This is due to the fact that the maximum delay between two dams is 7 days. The delays describe the time water takes from traveling between two dams. Thus for the first 7 days no data is available for previous releases and thus these releases are set to 0. This warm-up time has a very low influence on the KPI's since 7 days is negligible in a total model time of 20 years.

For the directed search A nfe (number of function evaluations) of 90000 is chosen for the directed search. At this value, the search is not stagnated as depicted in figure 6. This indicates that the search keeps returning better solutions. However, figure 6 shows that the search has not yet converged. As a result, it is possible that more promising solutions could be discovered with a higher nfe. Due to computational limitations a higher nfe is not chosen. The goal is to indicate the influence of different levels of cooperation on the KPI's and does not need extremely precise policy data. Therefore, the solutions space generated with 90000 nfe fits for the purpose of this research.

Experiments with different seeds for selecting the starting policies in the directed searches yielded very similar results. Starting policies are the first policies that are selected by the MOEA in the directed search. Because of the similar results between seeds a random seed is used for the EMS-workbench for selecting the starting directed search policy. Furthermore, this is also an indication that the found policies have converged to some extend. The epsilon values chosen to reduce the policy sets in the Pareto.py are chosen so that they reduce the policy sets to contain around 100 policies.

3.3 Worst case scenario

For finding the worst case scenario no direct search over policies is needed. This is due to the expected similar effect the hydro climatic uncertainties have on the KPIs. The effects of the uncertainties are expected to be uni-directional. This means that if a uncertainty increases or increase a decrease or increase in all the

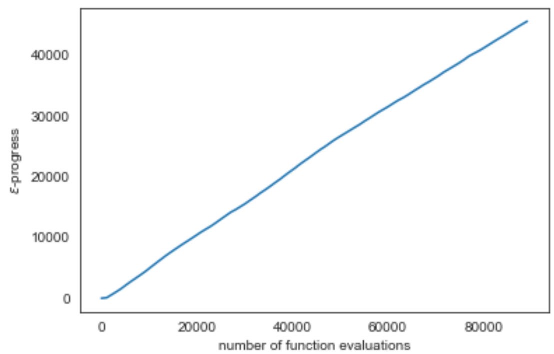


Figure 6: Epsilon progress

KPIs can be expected. It is expected that there is no hydro climatic uncertainty that lowers one KPI and increases an other KPI. The inflow, irrigation demand increase and discharge of the rivers are therefore increased to their maximum expected values in order to find the worst case scenario. According to the climate trends of Kling et al. (2014) in the Zambezi basin the temperature is expected to increase from 22 degrees Celsius to 27 degrees Celsius over the course of 100 years. Therefore, the expected increase of temperature per day in percentages is 0.000006 percent. It is assumed that the evaporation rates and the irrigation demand increase linearly with the temperature. Therefore, the function of increase evaporation rates and irrigation demand is as follows:

$$r_t = 1.0000006 r_{t-1} \tag{6}$$

In this formula the factor with which the irrigation demand or evaporation rate are multiplied every time step, r_t, at time t, is calculated by increasing the previous factor by 0.000006 percent. The discharge behaves more cyclic according to Kling et al. (2014). Depending on the year discharge can increase or decrease by 50 percent at Victoria falls. However, there is no exponential growth or decline predicted. Moreover,, it is assumed that this behaviour is similar for the other rivers in the basin. Therefore, the discharges of the rivers will be multiplied by 0.5 for the worst case scenario.

3.4 Sensitivity analysis

Two sensitivity analysis will be executed. The first sensitivity analysis will be performed by independently and incrementally changing the uncertainties and visualising the result. This generates insight into the performance of the KPIs under alterations in one hydro climatic uncertainty while the other hydro climatic uncertainties have a fixed value. The second sensitivity analysis that will be performed is executed by simultaneously altering all of the uncertainties.

The values of the uncertainties are decided by a stochastic normal distribution. A nominal distribution is chosen because it represents the temperature and discharge data (figure 2) on which the uncertainty values are based best. This is done to examine the performance of the KPIs under different value combinations of uncertainties. The values of the uncertainties for both sensitivity analysis will lie between 0.5 and 1.5 for the discharge uncertainty. For the evaporation and irrigation demand uncertainties the values will alter between 1.000006 and 0.999994. These values are chosen based on the observed trends in the gathered data as described in section 3.3. For the normal distribution a mean value will be chosen that lies between the two described min and max values of the uncertainties. This is the the value 1 for all uncertainties. The standard deviation that is chosen is half the difference between the described values. This is 0.5 for the discharge uncertainty and 0.000006 for the evaporation and irrigation uncertainties.

3.5 Operating policies formulations

In the model the release policies chosen as input for the model have static wanted releases that do not change during the simulated time. A wanted release is the input for a dam to determine its real release. A dam its real release is based on the current head, effective head and the wanted release. If the dam's reservoir current head drops below the effective head by a certain percentage this same percentage is reduced form the eventual release. This secures that the dams almost always have a electricity production with the current inflow of water because dams also focus on refilling their reservoir. Moreover, it is assumed that the stakeholders of the dams do not want to have less than 20 percent water in a reservoir. Therefore, if the water in the reservoir declines below this threshold the real release is set to 0. The formulae for the releases of the dams for the no cooperation level is depicted as follows:

$$R_t^k = R_w^k - R_w^k(\frac{H_{eff}^k - H_t^k}{H_{eff}^k}) \tag{7}$$

In this formulate the real release of dam K at time t, R_t^k, is the wanted release R_w^k minus a fraction of the wanted release that is depended on the height of the current head at time t, H_t^k, and the effective head, H_{eff}^k.

3.6 Model optimization functions

A directed search is performed for generating a solutions space of policies that perform well for the selected KPIs for either the full system or the individual sections. The directed search will be executed using the python EMA-workbench, which is a tool for performing directed searches in python. A directed search is an optimization technique that uses multi-objective evolutionary algorithms

(MOEAs) for selecting either a solution or scenario space for static simulation models. MOEAs imitate biological evolution and natural selection to solve multi-objective problem formulations with starting from a random sample of solution and then iterative improve this set (Salazar, Reed, Herman, Giuliani, & Castelletti, 2016). As described, the model has 3 kinds of KPIs. First, electricity generated per dam. Second, the percentage of irrigation demand that is met. Third, the environment water, which is the water flowing to downstream of a dam. For every KPI means that a higher value would be preferable over a lower value. Therefore, the KPIs are all maximized during the directed search. The KPIs are formulated as follows:

$$P^k = \sum_{t=1}^{T}(P_t^k) \tag{8}$$

$$O^k = \sum_{t=1}^{T}(O_t^k) \tag{9}$$

$$I^k = \sum_{t=1}^{T}(\frac{I_d^k - I_t^k}{I_{max}^k}) \tag{10}$$

P^k, O^k and I^k represent the total generated power, total outflow and total irrigation KPI of a dam k. T is the total amount of simulated days. The KPIs are the sum of their value in a single time step. For the irrigation KPI it is also calculated by how large of a percentage the demand, I_d^k, is met.

The objectives are maximized under a selected worst case scenario. This is done because it is assumed that the involved stakeholders select robust policies that perform well under bad circumstances.

3.7 Policy search process per cooperation level

The main goal of this research is to provide insights into how different levels of cooperation between hydroelectric dams within a rivers basin influence the water resources. For this insights to be generated a multitude of steps need to be taken that are different per level of cooperation. In order to understand the impact of cooperation three different levels of cooperation will be tested. The levels that are analysed are no cooperation, full cooperation and section cooperation.

3.7.1 No cooperation

First, the no cooperation scenario will be explored. For this scenario no policy search is needed because every dam acts independently. Therefore, one simulation run suffices in which every dam only releases an amount of water that efficient for them and nothing more. As a result, every dam adjusts its release policy to maximize its own electricity production. For this cooperation policy dam releases do not take other KPIs, such as irrigation demand of stations nearby, into account for selecting their release policy. This is done because if the dams would take other KPIs into account the focus of this cooperation level would shift towards section cooperation. Therefore, it is assumed that for no cooperation the dams all have an independent stakeholder as owner who are only interested in maximizing their own electricity production. As a result, the wanted releases are the same as the effective releases, since there is no incentive for the dams to release more than needed for maximizing their own electricity production. This secures the dams to have more water in their reservoir which allows the dams to produce more electricity.

For finding the policy that is the result of no cooperation the simulation model is run one time. This is due to the deterministic behaviour of the model. No stochastic elements are embedded into the model. Therefore, every run returns the same results. As model input, the wanted releases of the dams are set to the values of the effective releases. The uncertainties have the worst case scenario values.

3.7.2 Full cooperation

The full cooperation level is simulated by using two similar approaches. First, a directed search is executed that uses constraints as minimum values for the KPIs to generate policies. Second, as comparison directed search is executed with no constraints as comparison. This unconstrained directed search is used as comparison because it might produce policies that perform better for certain groups of KPIs compared to the directed search with constraints. The directed searches will be executed by searching over different dam release combinations and observing the output.

The constraints are selected by examining the described uncertainties and selecting a worst case scenario. A single run is performed that provides KPI outcomes of the worst case scenario during no cooperation as described in the previous section. These outcomes are then used as constraints in the directed search. These constrains are formulated as a minimum value for the certain KPI to be reached otherwise the policy will not be presented as a viable solution. In the EMA workbench constraints are formulated as a function that returns 0 if the constraint is met. The constraints formula is depicted as follows:

$$Constraint = max(0, C - x) \tag{11}$$

In this formula C is the minimum given value for a KPI. This minimum value is the KPI value that is reached with the found no cooperation policy for the worst case scenario. X is the current value of the to be examined function evaluation. If policies are found with this directed search and these constraints it would indicate that cooperation would be beneficial since no KPI performs worse than under no cooperation. On the other hand, if no solutions are found it would indicate that cooperation would be hard to reach within the basin since it would be more beneficial in even the worst case scenario for some dams to operate on their own. The minimum values of the KPI's are shown in appendix

B1 in table B1. Out of the the found solution space by using Pareto.py dominant solutions are selected. These dominant solution are then run trough the model in order to visualize the results. These results are compared with the results from the other levels of cooperation.

3.7.3 Section cooperation

Modeling cooperation per section has a similar approach to the full cooperation approach. Both a directed search is executed with and without constraints. However, first a directed search, with and without constraints, is executed for section 1 and section 2 independently. This can be done since these sections are both in their own independent upstream section of the river's basin and are therefore not depended on other sections within the basin. Out of the found policies for section 1 and 2 policies are selected and used as input for the directed search for section 3. The used policies are selected by examining either their performance on the irrigation KPIs or the electricity KPIs. The water towards the downstream of the river is left out of consideration for the policy selection because the assumption is made that irrigation and electricity production are of a higher concern for the involved stakeholders than the water downstream. Furthermore, the performance of both the best electricity and irrigation policies will be compared for the full cooperation level. Based on this comparison it is decided which one of the policies will be used as input for section 3. Afterwards, by using the found releases of section 1 and 2 a last optimization is executed. This is done by optimizing the KPIs of section 3. Finally, also for section 3 suitable policies are chosen. Afterwards, the found policies per section are combined and are compared to the other levels of cooperation. This full process is depicted in figure 7

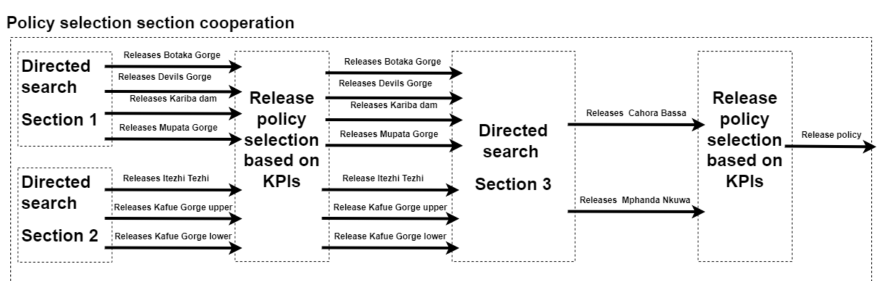


Figure 7: Directed search setup section cooperation

4 Verification and Validation

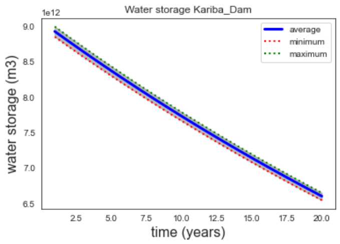
In this section the results of the verification and validation test are presented. The model is verified for researching if the model works well. The model is validated for describing if the model is usable for making statements about the real world.

4.1 Verification

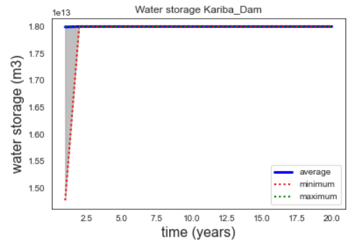
For the verification of the model the following extreme value tests are performed. For these tests extremely large or small input values are used to determine if the model functions accordingly. During the verification test, all other input is set to their base no cooperation scenario values. This means that the wanted releases are set to the values of the effective releases and the hydro climatic uncertainties have the value 1. Extreme low and high discharges are chosen for these test because alterations in discharges affect every KPI. Therefore, model non functioning can be detected during these text. All of the results are represented in appendix C1 and C2.

4.1.1 Extreme high discharges

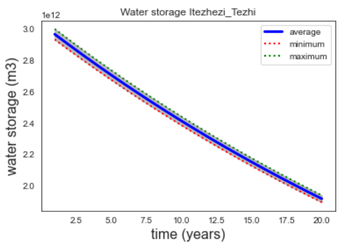
For this test, the discharges of the inflow rivers are set to an extreme high number. It is expected that with an extreme high inflow all the reservoirs should be filling up and that the KPIs also increase compared to the base no cooperation scenario. The uncertainty inflow factor will be set to 1000000 for this run. This means that the discharges are 1000000 times higher. The results from this run are as expected and are depicted in appendix C1. In the base no cooperation run, the Kariba and Itezhi Tezhi dam reservoirs are slowly drying up. However, with extreme high inflows the reservoirs remain full at their max capacity as depicted in figure 8. Furthermore, all irrigation KPIs reach 100 percent of their demand all the time which is also an indication that the model works correctly.



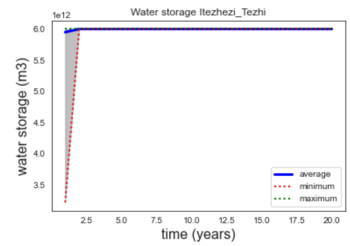
(a) Base no cooperation



(b) Extreme high discharges



(c) Base no cooperation

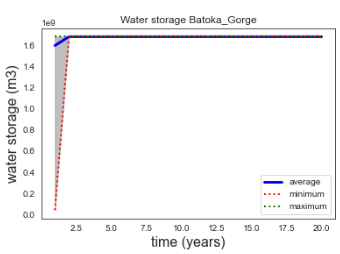


(d) Extreme high discharges

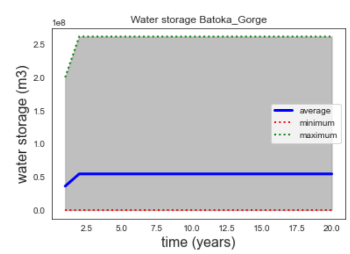
Figure 8: Kariba and Itezhi Tezhi dam yearly average, maximum and minimum water water storage

4.1.2 Extreme low discharges

For this test the inflow rivers discharges will be set to 0. This means that no water will be flowing into the system. It is expected that the reservoirs dry up and that eventually every KPI reaches 0. This seems to be true in some cases. The results are depicted in appendix C1. However, for most cases the KPIs behave differently. For example the reservoir of the Batoka Gorge does stay empty but fills partly up. This is due to the negative evaporation rates. The evaporation rates can be negative in the data gathered from the DAPHNE research.



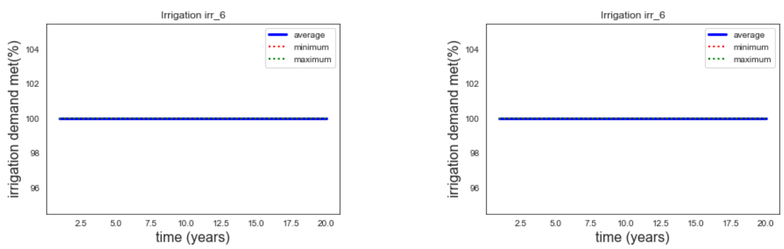
(a) Base no cooperation



(b) Extreme low discharges

Figure 9: Botaka Gorge water storage yearly average, maximum and minimum water water storage

Moreover, some KPIs still perform well as depicted in figure 10. This is due to partly the negative evaporation rates and partly to the water that still exists in the system. The reservoirs who are already constructed have water in them at the beginning of the simulation. Therefore, they keep the water flow active until they dry up. Because some the size of some of the reservoirs this flow can be kept active for a long period. This is behavior that indicates that the model works accordingly.



(a) Base no cooperation (b) Extreme low discharges

Figure 10: Irrigation station 6 yearly average, maximum and minimum water demand met

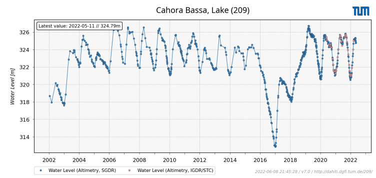
To conclude, the models behaviour is as predicted for either one of the performed extreme value test. Therefore, it can be concluded that the model is constructed accordingly.

4.2 Validation

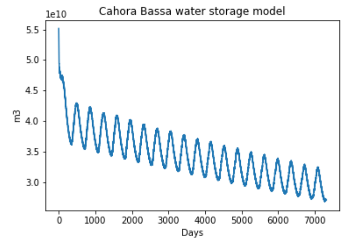
For validating the model the models values are validated against real world data. Trends visible in the model are compared to real word trends for this test.

4.2.1 Value validation

For this validation technique the trends of reservoir water levels are compared to real world data. This is done because data is more widely available about reservoir data than for other elements of the system. Moreover, all reservoirs water levels in the system have a relation with other reservoirs because rising water levels in one reservoir would mean a lower discharge downstream and thus lower water levels downstream. Therefore, the behaviour of the whole system can be validated by comparing key reservoirs to their real life version. First, the water levels of the real Cahora Bassa are compared to the generated model data of the base case with no cooperation as shown in figure 11. Cahora Bassa is chosen as reservoir because, as previously described, is it the only reservoir that has the outflow of two other reservoirs, of different sections, as inflow. Therefore, validation of this reservoir would be an indication that the whole model is valid. Furthermore, it is an already constructed dam and therefore lake levels are available. Trends in storage levels are the same as trends in lake levels and can therefore be compared.



(a) Real data: (*Cahora Bassa, Lake, Water Level Time Series (Altimetry)*, 2022)

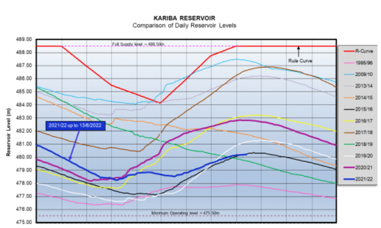


(b) Model data

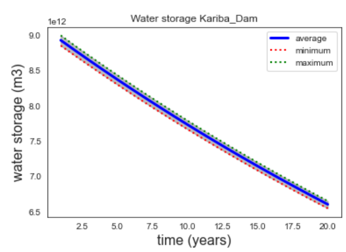
Figure 11: Cahora Bassa monthly water levels

From comparing the data three statements can be formalized. First, both data shows cyclic behaviour. This is an indication that the model generates real worlds cyclic behavior of the reservoir levels correctly. Second, the both data show a decline in values. Note that the real data describes data of a shorter period that has already occurred instead of the model describing a longer period period that still has to occur. Therefore, the decline might not be exactly similar. However, it can be said that both data set show a decline in water levels. Third, there is a difference between the data. In the real data after a rare (assumed) spontaneous decline the lake levels tend to increase more than with the model data. A possible explanation is that the model data predicts a period that has yet to occur and therefore could have different behaviour from earlier periods.

An other reservoir that is also compared to real data is the Kariba dam. This dam is chosen because it has one of the largest reservoirs of the system. The expected modeled trends and real trends are depicted in figure 12.



(a) Real data: (river authority, n.d.-a)



(b) Model data

Figure 12: Kariba dam monthly water levels

Two statements can be made by comparing the data. First, both data sets indicate an decline in water levels. Second, the real data indicates more fluctuations in water levels per year.The real data of 2021 - 2022 is higher than that of 2022 -2023 so far. This is not shown in the model data. This could be explained due to the difference in period the two data sets describe. To conclude, the the real world data and the model data do seem to have similar key features. However, some trends of the real world data are not visible in the data that is generated by the model.

5 Results

In this section the results are presented. First, the results of the sensitivity analyses will be presented. Second, the results of the no cooperation strategy will be described. Third, the results of the full cooperation will be presented and compared to the previously described results of no cooperation. Last, the sections cooperation level results will be discussed. Also, these results will be compared with the no and full cooperation strategies.

5.1 Sensitivity analysis

As described, two sensitivity analysis are executed. First, a random sensitivity analysis is performed to explore the effects different combinations of uncertainties have on the KPIs. Second an independent sensitivity analysis is performed in order to explore the effects independent uncertainties have on the KPIs. These two analysis are performed for the no cooperation level.

5.1.1 Random sensitivity analysis

A random sensitivity analysis is executed. The result are depicted in appendix D.1. The no cooperation level is run under different randomly chosen uncertainty input sets. The values of the uncertainties are chosen with a normal distribution. Three plots per KPI are constructed that plot the values of the uncertainties on the x-axis and the values of the KPI on the y-axis. The y-axis depicts the sum of the values of the KPI after the total run time of 20 years. Thus 7300 for the irrigation KPI means 7300 / 20 / 365 = 100 percentage of the demand met per day on average. Furthermore, a regression line is plotted to get insight into the correlation between the KPI and the uncertainty.

By observing the results the following statements can be made. First, irrigation KPIs 2,3, 6,7 and 8 do not correlate with any of the uncertainties. An example of this is plotted in figure 13 in which KPI 8 is presented . The other mentioned KPIs have very similar plots. As can be seen, non of the uncertainties have any effect on irrigation KPI 8. This can be explained due to the position the KPIs have in the river. Irrigation KPI 2,3,6 and 8 directly withdraw their water from the reservoirs of dams. Therefore, it is allot harder for these demands to not be met since the reservoirs have almost always, except under extreme conditions, enough water in them. Irrigation KPI 7 is located just after the Cahora Bassa dam which has an enormous reservoir that is very hard to deplete fully of its water storage. This is also the reason why the demand of irrigation station 7 is always met.

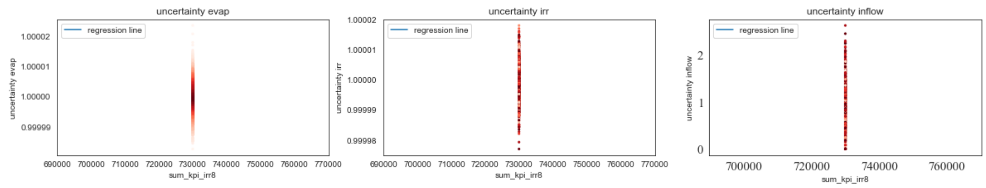


Figure 13: Influence of hydro-climatic uncertainties on irrigation station 8 total demand met.

Second, for the other irrigation KPIs the irrigation uncertainty seems to have the most influence on the total values. These are KPI 1,4 and 5. KPI irrigation 4 is plotted in figure 14. Irrigation KPI 1 and 5 behave similarly. As can be seen in the figure, a very low correlation exist between the other uncertainties and the KPI. Furthermore, a high correlation exist between the irrigation KPI and the irrigation uncertainty. Again, this is due to the position the irrigation stations have in the river. They are all positioned after reservoirs. Which means they are less dependent on the inflow of rivers since the reservoirs often have a more stable release of water. Therefore, they are more influenced by the irrigation uncertainty since this means that their irrigation demand rises or decreases which affects the percentage of the irrigation demand met.

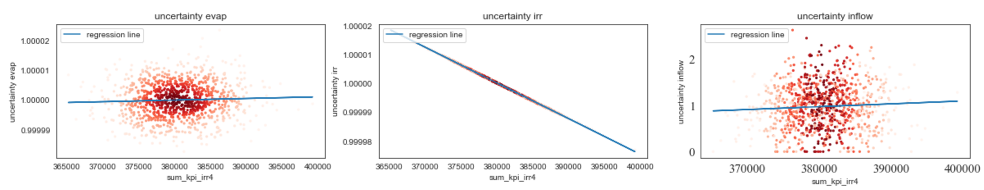


Figure 14: Influence of hydro-climatic uncertainties on irrigation station 4 total demand met.

For the other KPIs the inflow uncertainty has the highest correlation. An example of this is provided in figure 15 and figure 16. These two figures represent the total irrigation demand met and the total electricity production of all corresponding KPIs. It can be stated that of the three uncertainties the inflow uncertainty has the highest correlation. Therefore, the statement can be made that for these KPIs the changes in the inflow of rivers weight heaviest on their outcomes compared to the other uncertainties.

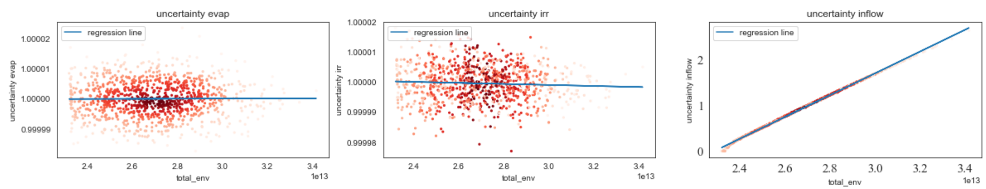


Figure 15: Influence of hydro-climatic uncertainties on sum of all environment water.

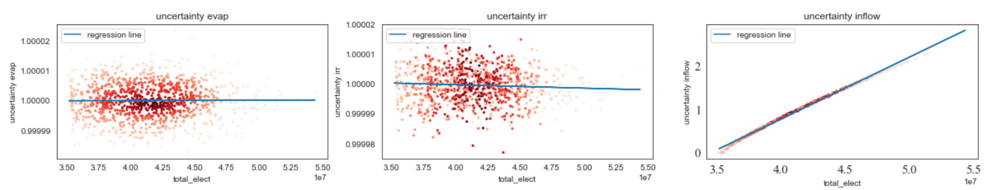


Figure 16: Influence of hydro-climatic uncertainties on sum of all electricity production.

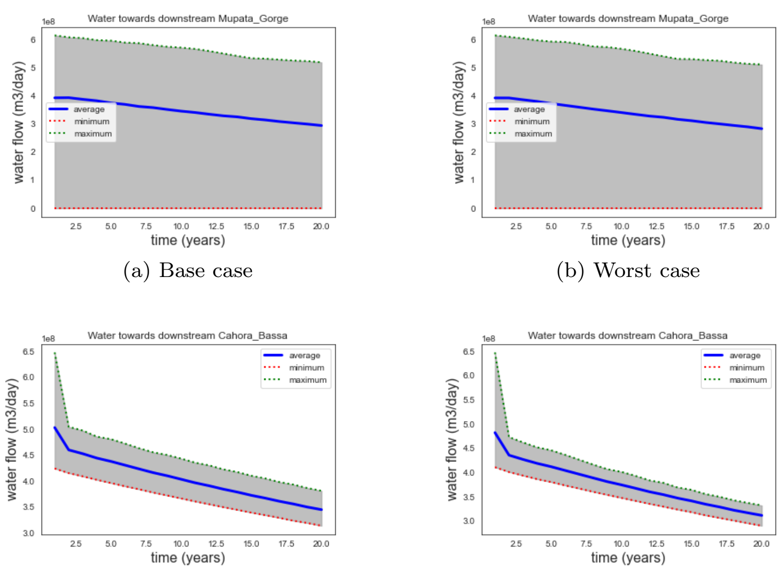
In conclusion, most irrigation KPIs are not heavily influenced by changes in any of the KPIs. Furthermore, the irrigation KPIs that are influenced by uncertainties are mostly influenced by the irrigation uncertainty. The other KPIs electricity production and water towards the downstream are mostly influenced by the inflow uncertainty. This means that these KPIs depend most on the discharge of the inflow rivers.

5.1.2 Independent sensitivity analysis

A independent sensitivity analyses is performed. This is done for generating insights about how sensitive the model KPIs react to changes in a hydro climatic uncertainty independent from changes in the other hydro climatic uncertainties. This is performed by altering one of the uncertainties while the other uncertainties remain fixed. The results are presented in appendix D.2. The results show that almost all KPIs react linearly to changes in the uncertainties. For example, a higher evaporation rate means a lower outcome of the KPI. As a result, the conclusion can be made that well performing policies under the base no cooperation scenario also perform well under different scenarios and visa versa. Therefore, selecting well performing policies can be done by observing the performance of policies for one uncertainty scenario, such as the worst case.

5.2 No cooperation

To predict the performances of the no cooperation strategy both the base case and worst case results are simulated. The final model outcomes of both scenarios are presented in appendix D3 in table C1. Furthermore, the behaviour over time of the KPIs is examined. From the data of the two scenarios two characteristics of the relation between the sets become clear. First, the base case performs better or the same for every KPI expect for irrigation demand 4. This is expected since the worst case scenario has less favourable uncertainty input. The reason why the worst case scenario performs higher on KPI irrigation demand 4 is because of the negative evaporation used as input for the model. As a result, the irrigation demand 4 receives a bit more water than under normal circumstances. Furthermore, the behaviour of the KPIs over time in both scenarios is very similar. A example of both characteristics is the electricity generated over time at the Devils Gorge and the water towards downstream at Mupata Gorge as depicted in figure 17. The behaviour is very similar between both scenarios and the base case performs higher compared to the worst case.



(a) Base case

(b) Worst case

(c) Base case

(d) Worst case

Figure 17: Behaviour comparison scenarios no cooperation yearly average, maximum and minimum KPI values

What also can be derived from observing both scenarios is that except KPI irrigation 5, all irrigation station perform relatively well. Irrigation KPI 2,3,6,7 and 8 perform even at their maximum for both scenarios as can be seen in table C1 in appendix D. Only KPI irrigation 1 seems to alter relatively heavily between the scenarios with a average demand met of 88 percent for the base case and 47 percent demand met in the worst case. An explanation is that irrigation station 1 lies at the beginning of the river and is therefore more heavily influenced by the rivers inflow. The other stations have more reservoirs in their upstream. These reservoirs still release water even though less inflow is available. As a results, these irrigation stations are less depended on the inflow of rivers and thus on the models uncertainties.

To summarize, the worst case and base case lead to very similar behaviour for most KPIs. Moreover, except for irrigation KPI 1, the irrigation KPIs tend to reach the same or very similar results regardless of the scenario being chosen. The main difference between the base and worst case results is the height of the KPI values. In the base case more preferable circumstances,the uncertainty combinations, are modeled. Therefore, the base case produced higher KPI results. Although the behaviour of the KPIs over time is very similar.

5.3 Full cooperation

As described a directed search over all the KPIs is executed for the worst case scenario. As a result, a set of over 10000 policies is found. This set is reduced to a set of around 100 non-dominated policies using the Pareto.py module. The results are visualized in parallel coordinate plots. These plots visualize the found policies and solutions as a single line. Every larger, or more wanted, value of the KPIs in the coordinate plots are plotted with the same direction, which is up. This means that a visual increase of a plotted solution for a KPI is also a positive increase in the KPIs value. Four coordinate plots are computed. One for every kind of KPI and one for the releases. Within the coordinate plots the results of the directed search with and without constraints are plotted. Furthermore, the values of the no cooperation policies are also plotted in the coordinate plots together with the best policy for irrigation and electricity. These best policies are selected by computing the sum of the electricity and irrigation KPIs and then selecting the maximum values.

The found release policies for the full cooperation level are presented in figure 18. From this figure the following characteristics of the computed data can be observed. First, almost every found policy requires a larger wanted release for every dam compared to the no cooperation level. In the no cooperation level dam reservoirs do not release more water than needed. As a result, there is allot of improvement room for other KPIs if the releases are increased as shown. Second, the policies that are found with the directed search with constraints are located in the top of the found policies. This means that these policies require larger releases on average than the release policies that are found with the no constraints directed search. Third, the policies for best irrigation and best electricity are very similar regarding their wanted releases. Last, the wanted releases for the Mphanda Nkuwa dam increase by the largest percentage compared to to the other dams with both directed searches. A reason for this could be that this dam is located at the end of the river. Thus, increasing the Mphanda Nkuwa wanted release by a large amount would be the only measure to increase the Mphanda Nkuwa water towards the downstream KPI and the irrigation KPI of station 8, which are taking into account for the full cooperation level.

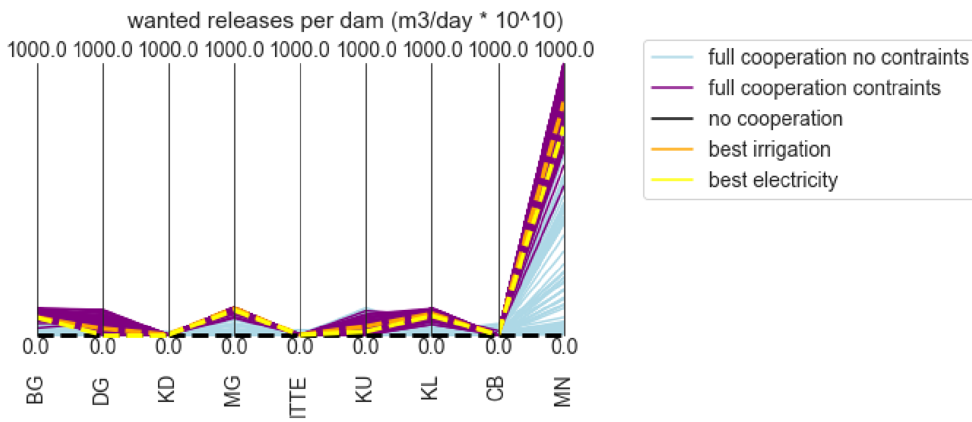


Figure 18: Wanted releases full cooperation parallel coordinate plot

The found policies for the full cooperation level are presented in figure 19 for the electricity KPIs. The following characteristics of the computed data can be observed. First, choosing for the best irrigation policy results in a visually lower performance of most electricity KPIs. Second, the directed search with constraints produces the best values for all the electricity KPIs. Last, most hydroelectric dams that are located more in the downstream of the river have a larger possibly to increase their total generated electric by shifting from no cooperation to full cooperation. This could be due to more water being available for these dams because the dams also take the electricity production into account of dams in the downstream of their river by selecting their releases.

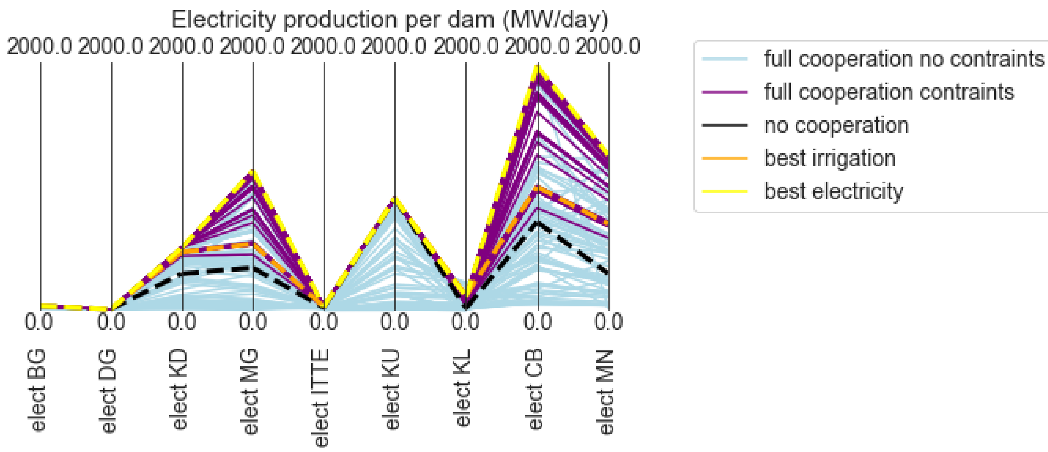


Figure 19: Electricity production full cooperation parallel coordinate plot

The found policies for the full cooperation level are presented in figure 20 for the irrigation KPIs. The following characteristics of the computed data can be observed. First, the best irrigation policy performs similar to the best electricity policy for the presented irrigation KPIs but score a little bit higher. However, this is only by a relative small amount compared to the difference in the electricity KPIs visible in figure 19. Second, only the KPI of irrigation station 5 is able to improve by a large amount compared to the no cooperation level. Furthermore, if no constraints are provided the directed search is able to improve the KPI of irrigation station 1 by most. This means that for these policies at least one other KPI scores lower than their value for the no cooperation level. Because, if this was not the case these policies would have been found with the constraints directed search.

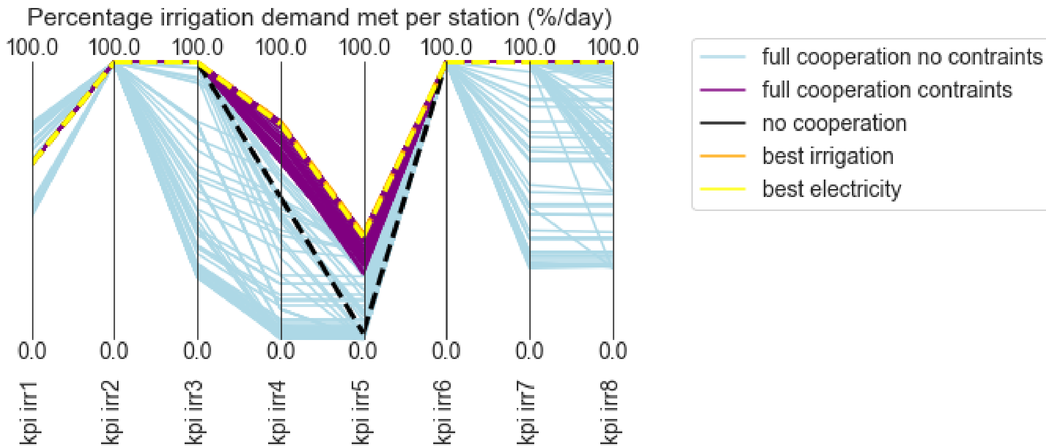


Figure 20: Irrigation demand met full cooperation parallel coordinate plot

The found policies for the full cooperation level are presented in figure 21 for the water towards the downstream KPI. The following conclusions of the computed data can be concluded. First, the same conclusion can be drawn about the water towards to downstream KPI improvement possibilities as for the electricity KPI. This means that the dams located higher upstream of the river have less room for improving their KPI by switching to the full cooperation level. Second, for this KPI the performance of the best electricity and irrigation policies are very similar. Last, for the Kafue lower, Cahora Bassa and the Mphanda Nkuwa some policies are available that allow their KPI to increase to the highest value. However, this is only with the no constraints directed search. Thus, as a consequence at least one other KPI would decrease lower than their no cooperation level value.

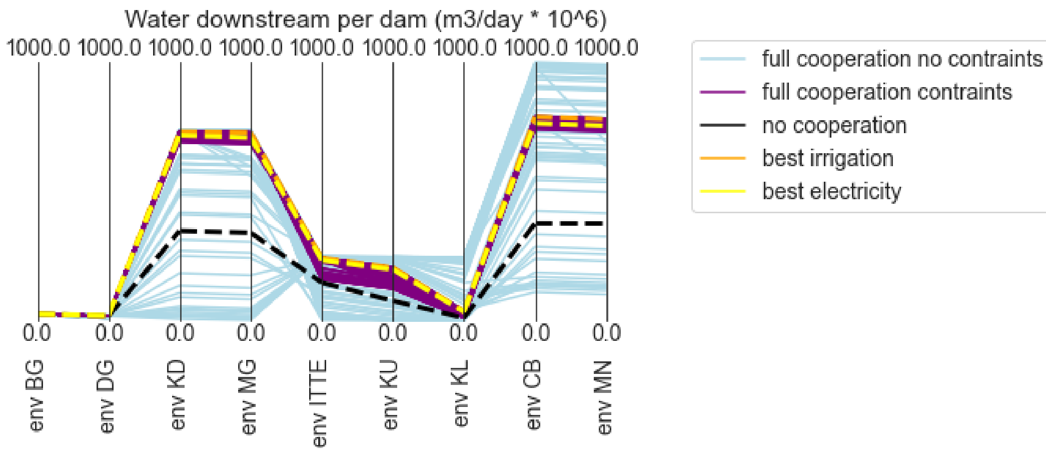


Figure 21: Water downstream per dam full cooperation parallel coordinate plot

To summarize, by examining the results of the directed searches with and without constraints for the full cooperation levels the following conclusions can be made. First, owners of water resources located in the upstream of the river have less room for increasing their KPIs by adapting the full cooperation level compared to the water resources located more in the downstream. Second, applying constraints to directed search resulted for some KPIs in a lower maximum possible increase. However, these policies would also result in a lower performance than the no cooperation level for other KPIs. Third, the difference between the best irrigation and electricity policy is mostly noticeable in the electricity KPI. As a result, It would would be expected that a stakeholder would choose the best electricity policy over the irrigation policy since for electricity the largest relative value increases can be expected.

5.4 Section cooperation

As described directed searches over all the KPIs are executed for the worst case scenario per section. As a result, a large set of policies per section is found. These sets are reduced to sets of around 100 non-dominated policies using the Pareto.py module. The results are visualized in parallel coordinate plots. These plots visualize the found policies and solutions as a single line. Every larger, or better, value of the KPIs in their coordinate plots are plotted with the same direction, which is up. This means that an visual increase of a plotted solution for a KPI means also a positive increase in the KPIs value. Four coordinate plots are computed per section. One for every kind of KPI and one for the releases. Within the coordinate plots the results of the directed search with and without constraints are plotted. Furthermore, the values of the no cooperation policies are also plotted in the coordinate plots together with the best policy for irrigation and electricity. These best policies are selected by computing the sum of the electricity or irrigation KPI and then selecting the maximum values. First both directed search optimizations with and without the described constraints (table B1) for both section 1 and 2 is executed independently. The found policy sets of section 1 and section 2 are used in the the Pareto.py to produce a set of non-dominated policies. Out of these policy sets the best performing policies for electricity are selected. Electricity is chosen as policy selection KPI since it would be the priority of the countries as it is the reason the hydroelectric dams where constructed. Furthermore, the irrigation KPI performs well under the worst case no cooperation scenario and therefore needs less improvement. Moreover, results from both the full cooperation level and, the to be discussed, section cooperation show that the difference between the policies for either best electricity and best irrigation is minimal except for the electricity KPI. Thus, it would be logical to assume that stakeholders would select the best electricity . As a result, the electricity KPIs are chosen as a policy selection KPIs.

5.4.1 Section 1

The found release policies for the section 1 are presented in figure 22. The following can be concluded. First, a large amount of policies have the same maximum irrigation KPI outcome. Thus, there is more room for other KPIs, such as electricity, to be taken into account for the best policy selection. Second, both the first and the last dam have to increase their wanted releases by a relatively large amount compared to the other dams for an overall increase in the KPIs in section 1.

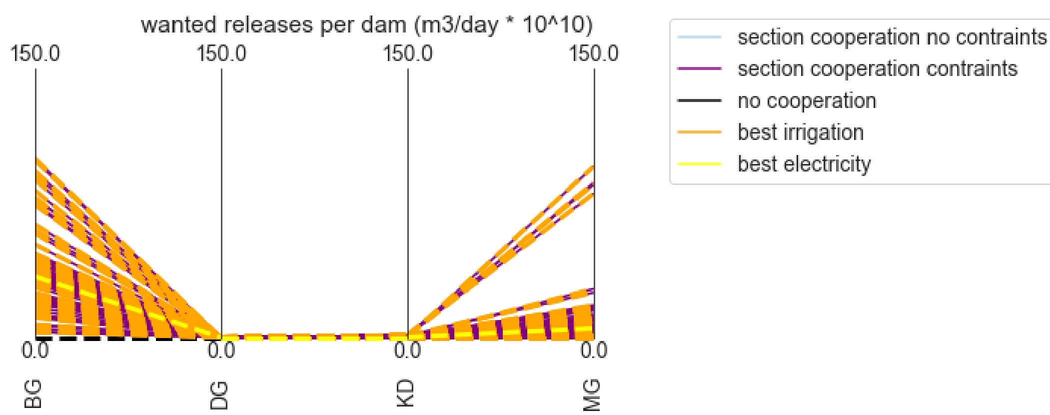


Figure 22: Wanted releases section 1 cooperation parallel coordinate plot

The found policies for the section 1 are presented in figure 23 for the electricity KPIs of the section. The following conclusions can be drawn. First, the best irrigation and best electricity policies can perform different for the electricity KPIs but a policy exists that performs best for both electricity and irrigation. Therefore, this contributes to the assumption that for section 1 the best electricity policy will be chosen as input for section 3. Furthermore, there are no policies that perform better under no constraints than with constraints for the directed searches. Third, similar to the results of full cooperation it can be observed that dams located in the upstream of the river have less room for improving their electricity production by switching to a form of cooperation. Last, compared to the full cooperation level no large difference can be observed in the maximum performance of the electricity production of the dams.

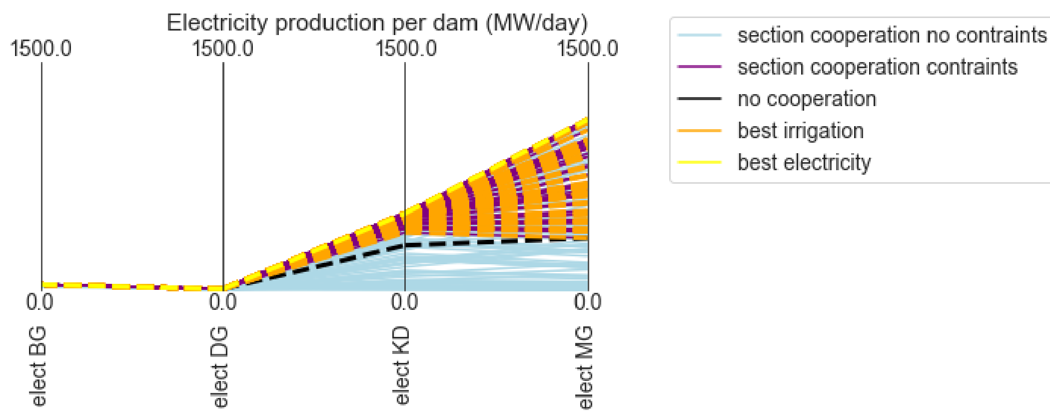


Figure 23: Electricity production section 1 cooperation parallel coordinate plot

The found policies for section 1 are presented in figure 24 for the irrigation KPIs of the section. The following can be concluded by observing the plot. First, the best irrigation and electricity policy performance do differ for irrigation KPi 1. However, compared to the electricity KPIs of section 1 this is a relative smaller difference. Thus, even with the best irrigation performing better than the best electricity policy for the irrigation KPIs the assumption can still be made that stakeholders of section 1 will choose the best electricity policy over the best irrigation policy. Last, there are policies found with the directed search without constrains that perform better than the policies found with the constraints for the irrigation KPIs. This means that these policies do perform worse than the no cooperation level for other KPIs.

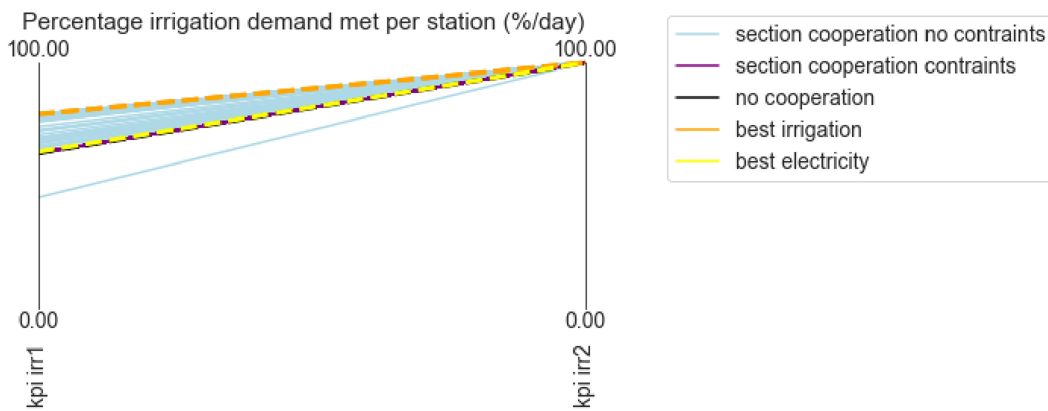


Figure 24: Irrigation demand met section 1 cooperation parallel coordinate plot

The found policies for the section 1 are presented in figure 25 for the water downstream KPI of section 1. The following conclusion can be made. First, The directed search with constraints produces the best results. Second, the best irrigation and electricity policies can be chosen that they both perform the same for this KPI. Third, the directed search without constraints produces policies that perform lower than the no cooperation values. Last, the best electricity and irrigation policies do result in a larger flow towards the downstream. Which can be seen because there is an increase in the KPI water towards the downstream of Mupata Gorge.

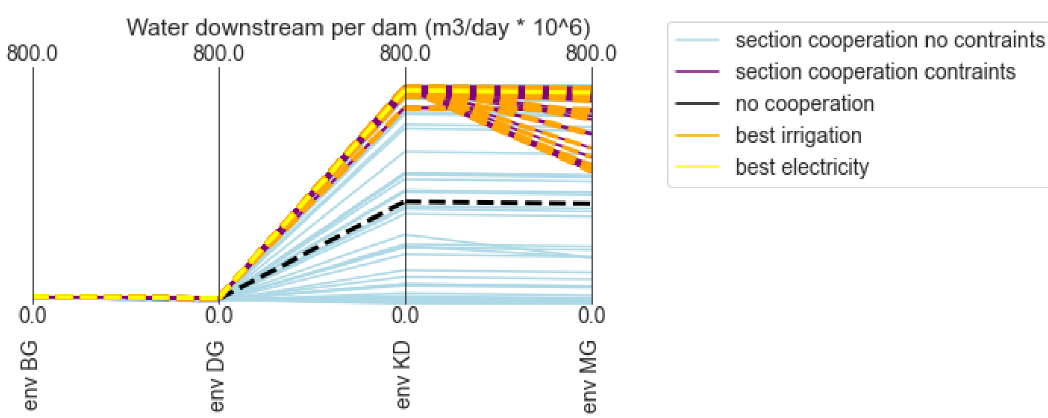


Figure 25: Water downstream per dam section 1 cooperation parallel coordinate plot

To conclude, for the directed searches for section 1 all of the KPIs are able to improve compared to the no cooperation level. The no constraints directed search policies are in some cases able to out perform the constraints directed search KPIs for this section. However, by selecting these policies other KPIs would reduce to values below their no cooperation level values. Furthermore, the best electricity and best irrigation policies perform similar for most KPIs. Although there are differences. However, the assumption can still be made that a stakeholder would select the best electricity policy for this section because it results in a relatively higher electricity increase compared to the increase in irrigation KPIs for the best irrigation policy.

5.4.2 Section 2

The found release policies for the section 2 are presented in figure 26. The following can be concluded. First, the Kafue upper dam has to increase its release by the relative largest amount for both directed searches. The Kafue lower dam can also increase its wanted releases. However, by doing so certain KPIs would perform under the no cooperation level. Last, the difference between the best irrigation policy and best electricity policy is best visible in the releases of Kafue upper.

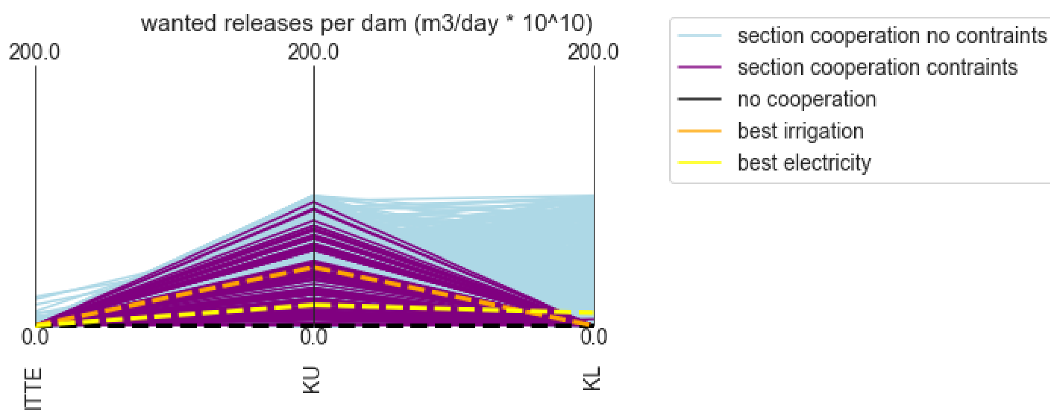


Figure 26: Wanted releases section 2 cooperation parallel coordinate plot

The found policies for the section 2 are presented in figure 23 for the electricity KPIs of the section. The following conclusions can be concluded. First, the electricity production of the first and last dams do seem to produce no electricity. They produce relatively less electricity but not 0 electricity. However, this is less visible due the large amount of electricity the Kafue upper is able to generate. Second, both the best electricity and best irrigation policies perform similar with the best electricity policy producing slightly better results for the Kafue lower dam. Last, section 2 electricity KPIs are only able to slightly increase their values for cooperation within this section compared to the no cooperation level values.

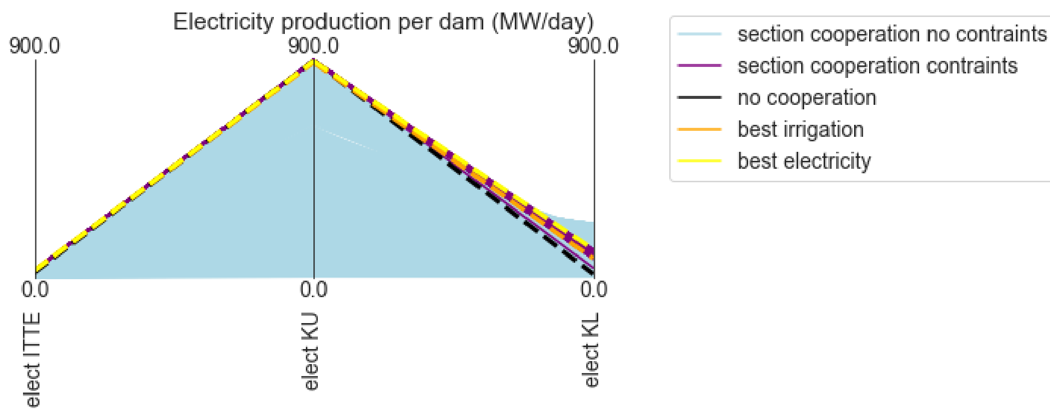


Figure 27: Electricity production section 2 cooperation parallel coordinate plot

The found policies for the section 2 are presented in figure 28 for the irrigation KPIs of the section. The following can be concluded by observing the plot. First, both the best electricity and best irrigation policies perform similar. Moreover, these two policies also produce the best result for the irrigation KPIs in this section. Second, no policies of the directed search without constraints are found that outperform the policies found with constraints.

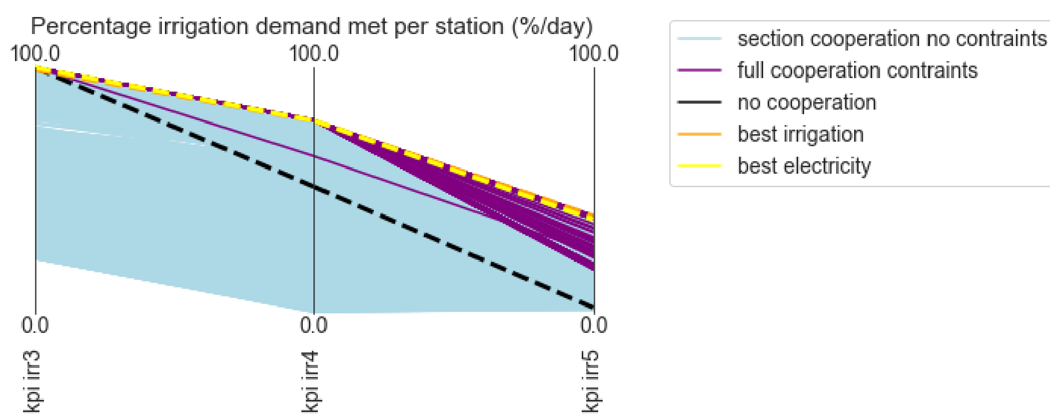


Figure 28: Irrigation demand met section 2 cooperation parallel coordinate plot

The found policies for the section 2 are presented in figure 29 for the water downstream KPI of section 2. The following conclusion can be made. First, for this KPI the directed search without constraints produced the best values. Second, the best electricity and irrigation policies perform similar for this KPI. Last, every directed search produces results that are better than the no cooperation values.

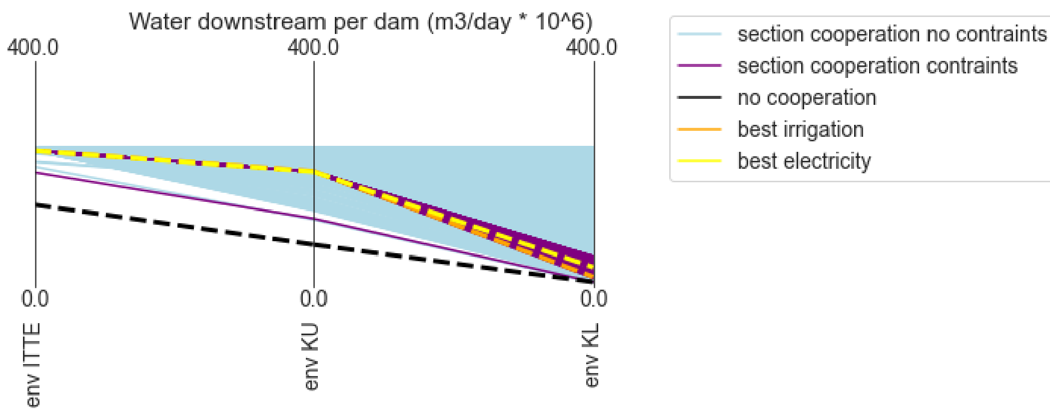


Figure 29: Water downstream per dam section 2 cooperation parallel coordinate plot

To conclude, for the directed searches for section 2 all of the KPIs are able to improve compared to the no cooperation level. The no constraints directed search policies are in some cases able to out perform the constraints directed search KPIs for this section. However, by selecting these policies other KPIs would reduce to values below their no cooperation level values. Furthermore, the best electricity policy is chosen as input for the directed search of section 3. The reason for this is that both the electricity and irrigation policies perform very similar with the electricity policy performing a bit better for the electricity KPIs.

5.4.3 Section 3

As input for the directed searches of this section it is assumed that section 1 and 2 choose the policy that performs best for the electricity KPI. The reasons for this assumption are provided in the subsection for section 1 and 2 above.

The found release policies for the section 3 are presented in figure 30. The following can be concluded. First, every found policy with the directed search with constraints leads to the highest irrigation KPI values. Furthermore, it can be concluded that releases of the Mphanda Nkuwa dam have to increase by a relatively larger amount compared to the Cahora bassa releases if there is a switch to section cooperation.

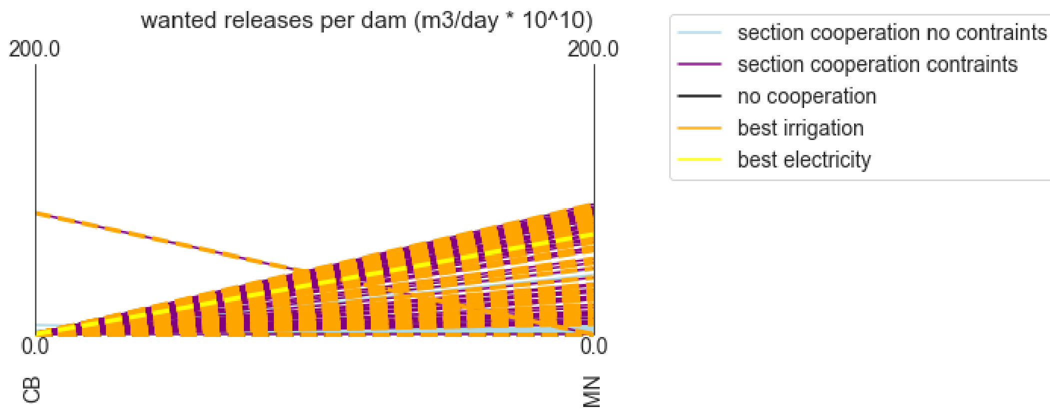


Figure 30: Wanted releases section 3 cooperation parallel coordinate plot

The found policies for the section 3 are presented in figure 31 for the electricity KPIs of the section. First, policies are found that produce better results than the no cooperation policy for every KPI. This means that even for section 3 engaging in any form of cooperation would be beneficial. Second, in this case, a best irrigation policy exist that is also aligned with the best electricity policy. Therefore, the conclusion can be made that also for this section a stakeholder would choose for the best electricity policy.

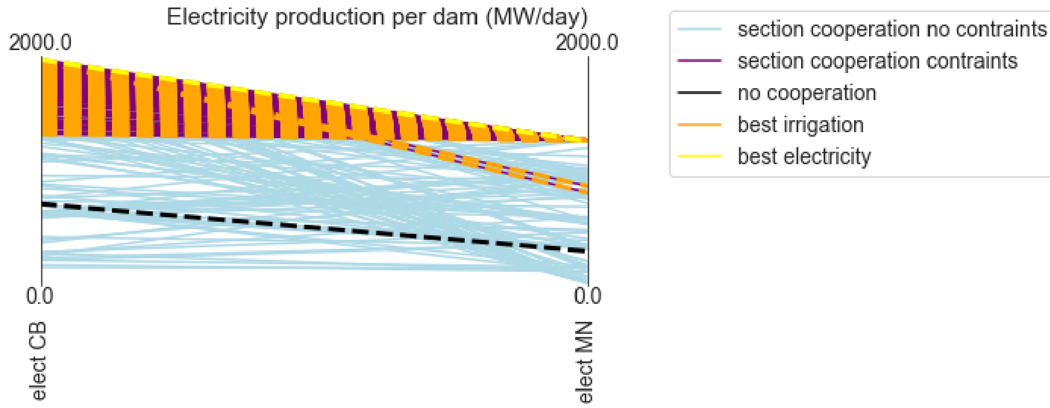


Figure 31: Electricity production section 3 cooperation parallel coordinate plot

The found policies for the section 3 are presented in figure 32 for the irrigation KPIs of the section. The following can be concluded by observing the plot. For this KPI the no cooperation, best electricity and irrigation policies are all aligned together with the policies found with the directed search with constraints. All of these policies produce the maximum irrigation KPI values for this section. This means that the irrigation demand is always met.

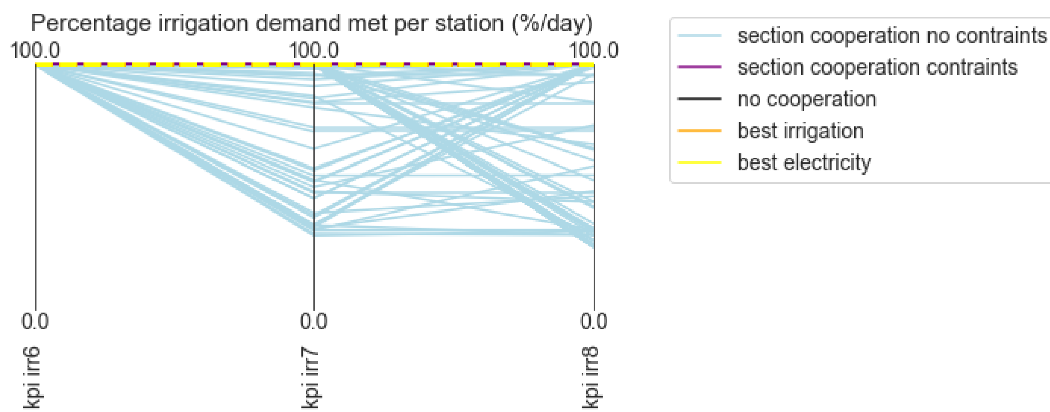


Figure 32: Irrigation demand met section 3 cooperation parallel coordinate plot

The found policies for the section 3 are presented in figure 33 for the water downstream KPI of section 3. The following conclusion can be made. For these KPIs the best irrigation, best electricity and policies found with the directed search with constraints perform the not only same but also produce the highest values. Moreover, every policy found with either one of the directed searches produces better values for the KPIs. This indicates that for these KPIs section cooperation would always be an improvement.

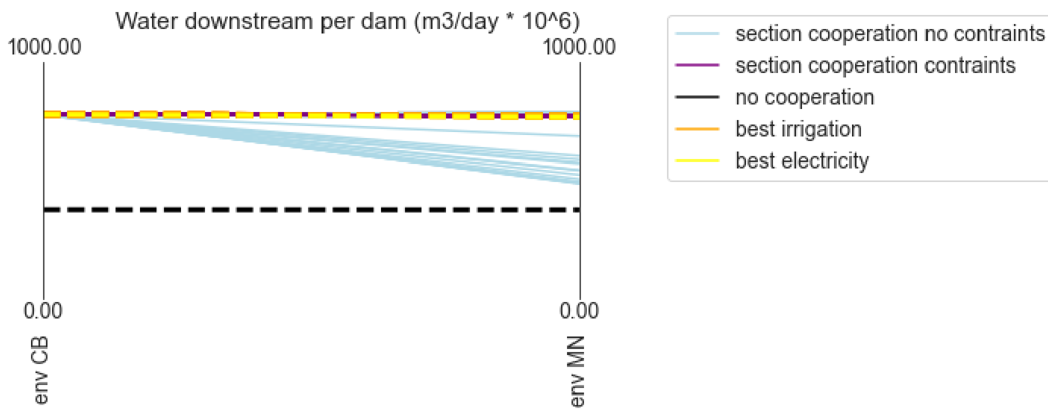


Figure 33: Water downstream per dam section 2 cooperation parallel coordinate plot

To conclude, for the directed searches for section 3 all of the KPIs are able to improve compared to the no cooperation level. Furthermore, the policies perform relatively the same for the KPIs in this section cooperation compared to the full cooperation level. This indicates that for section 3 any kind of cooperation would be beneficial. Even if section 1 and section 2 choose not to cooperate with section 3 it would still add value to cooperate within section 3. Furthermore, multiple policies exist that produce the best irrigation results for this section. Out of these policies one policy is also able to produce the best electricity results. Therefore, electricity would be chosen by stakeholders as policy selection KPI.

6 Discussion

In this section the findings of this research are discussed. First, the key findings and interpretations are presented. Second, both the scientific and societal relevance is discussed. Last, the limitations of this research are discussed.

6.1 Key findings and interpretations

The mayor contribution of this research is to explore the effects of different cooperation levels on the resources of rivers that are shared between countries located in the rivers basin. This research uses the Zambezi river as a case to explore the effects of these different cooperation levels. This is done trough simulation modeling in which a simulation model is built that mirrors the Zambezi river basin. The resources that are examined are generated hydroelectric electricity, water that flows to the downstream of the river and irrigation water demand met. Moreover, this research explores the effects of three different cooperation levels. The first cooperation level that is examined is no cooperation. With this level there is no cooperation between the hydroelectric dams and other aspects of the river. This means that the dams only try to maximize their own electricity production and adjust their releases accordingly. The second cooperation level that is simulated is full cooperation. With this cooperation level the releases of all the dams in the modeled rivers basin are adjusted to optimize all of the rivers resources. The third cooperation level that is examined is the section cooperation level. In this cooperation level the river basin is divided into sections based on the borders of the countries located in the basin. In this cooperation level the releases of the dams are only adjusted to optimize the rivers resources located in the same section of the dams. This research has shown that full cooperation could be an overall fitting solution. Full cooperation scores well because dam release combinations for all dams exist that outperform the no cooperation level on every resource gathered within the basin for this cooperation level. Furthermore, the same can be said for section cooperation. Compared to the no cooperation level section cooperation is also able to produce higher values for all of the mentioned resources in the whole basin if the right policies are selected. Moreover, section cooperation produces very similar results compared to the full cooperation level. This is due to two factors. First, the Zambezi river is divided into three sections for this research of which two lie in their own upstream river and one lies in the downstream of these other sections. One could assume that if the first two section would individually try to optimize their own resources instead of also taking the resources of the last section into account this would result in less water resources for the last section. However, in the Zambezi river, the last section is very independent regarding the discharges of the upstream sections. This is due to the fact that a large part of inflow into the last section find its origin in rivers such as the Chongwe, Luanwa and the Mayane. These rivers have no hydroelectric dams in them and therefore produce a steady inflow of water regardless of the release policies selected by the upstream sections. Furthermore, one of the water resources that is taking into account is measured by the amount of water that flows to the downstream of a dam. No flow towards the downstream of a dam would be bad for the section in which the dams is located as well. Therefore, if the sections optimize their resources they also optimize the water towards the downstream of the last dam in their section. As a result, a steady discharge is released from the upstream sections. These two reasons combined are the reason that the last section is less depended on the release policies of the other sections. As a result, the downstream section is still able to perform well regardless of the upstream release policies. What more came forward from the results was that besides policies that exist that outperform the no cooperation policies for all of the water resources also policies exist that allow for an even larger increase in some of the resources gathered. However, the costs of this increase would mean a reduction in other resources gathered below the no cooperation level values. Thus, for the Zambezi case it can be concluded that by taking produced electricity, irrigation demand and water towards the dams stream of a dam into account any of the explored levels with cooperation would result in better results than no cooperation. However, extra care has to be taken to select the right policies that cause a rise in all of the resources and no reduction compared to a no cooperation scenario. Besides the effects of the cooperation levels an other mayor aspect of hydroelectric dams in a river has become visible in the results. This is the trend that hydroelectric dams located in the upstream of the river and the resources gathered around these dams increase less by adapting cooperation policies compared to dams located in the lower basin of the dams. As a result, this trend shows that in negotiations it might prove to be more difficult to also include these dams in the release policies. For the cooperation levels two strategies are also explored. These strategies either maximize the produced electricity or the percentage of irrigation demand that is met. The results from both the full cooperation and cooperation within the described sections are similar. Both the best irrigation policies and best electricity policies produce values for all of the rivers resources that are close together. In almost all cases a best irrigation policy exist that also is the best electricity policy. In the cases where this does not occur the best electricity policy scores only relatively a bit lower on the irrigation policy compared to the best irrigation policy. As a result, it can be concluded that stakeholders would choose the best electricity policy since it produces relative more electricity while still scoring well on the irrigation demands.

6.2 Societal relevance

This research has shown that cooperation within a river basin is better than no cooperation. These findings show the need for cooperation. Furthermore, this research has indicated that no involved country has to experience a decline in resources gathered by entering a cooperation agreement. Currently, in the world many water conflict exist today besides the Zambezi case such as conflict between Ethiopia, Sudan and Egypt in the Nile where Egypt is treating with military actions (Ibrahim, 2021). An other example of a water conflict is in the Mekong river, in which newly constructed dams cause international disputes (Wei et al., 2021). These, together with the Zambezi case, are all cases that are currently proving to be a massive challenge and are subject to numerous rounds of negotiations that have often concluded to either no agreements or failed agreements. The findings of this study could prove to be beneficial for these negotiation processes due to two main reasons. First, the findings of this research can be used to start negotiations in future possible water disputes. As described, this study showed that stakeholders can improve all of their resources gathered by entering a cooperation agreement. However, this research has also shown that for this to happen extra care has to go to the selection of these release policies because some policies can also result in a decline in water resources. This puts more focus on the importance of well coordinated negotiations. Furthermore, the findings provide a motivation for the stakeholders for entering and keeping up with these negotiations because the end goal would be beneficial to them. Second, This research has shown that more than one cooperation level exists that has policies that provide better values for all the resources gathered compared to no cooperation. As a result, there is more room in the negotiations. Furthermore, if one stakeholder would leave the negotiations it shows that this would not necessarily mean the end of the negotiations because other cooperation forms that also produce good results might still be reached. To conclude, the finding of this research could aid in water conflict negotiations by showing that cooperation works best and that in-between cooperation forms also might prove to be effective.

6.3 Scientific relevance

For answering the research question a computer model was built that simulated the Zambezi river basin with its hydroelectric dams. Solutions where found by applying a MOEA. This process has been done before. However, this research is unique in that it combined independent directed policy searches by slicing up a model into different sections and using the found policy set of one section as input for the directed search of an other section. By doing so, this research has been able to explore the effects of different cooperation levels on the resources gathered in a basin, for which no scientific literature exist to this date.

6.4 Limitations

In this study multiple limitations are present due to a multitude of reasons. First, due to the time limitation data gathered was less precise. Assumptions had to be made for missing data that might have been found if more time was available. As a result, the behaviour of the model is still usable but the precise results might differ from the real world system. Therefore, the same conclusions of this research can still be drawn but the precise found policies of the model might not be fully usable. The same can be said about to the computing limitations that limited the amount of number of function evaluations that could be performed. As a consequence, the found policies might still have been improved. Lastly, this research focuses on three main KPI's, these being electricity, water to the environment and irrigation water. This is a limitation because within a river basin many more resources are gathered from the river, such as fishery, transport etc. Another limitation is the limitation that arises by using the multi-objective evolutionary algorithm trough the EMA-workbench. The EMA-work bench provides a solutions space of possible policies that can be implemented. However, these policies are static in the model. This means that during the simulated time the releases of the dams are not adjusted. In real life this is not the case.

7 Conclusions

The main aim of this study is to answer the research question: "How can countries located in a transboundary river basin that share water resources find a balance in cooperation in order to allocate the rivers resources most efficiently". This question is answered by answering the following sub-questions:

- Sub-question 1, What hydro-climatic uncertainties exist and how do they impact the rivers resources?
- Sub-question 2, How can water, agriculture and electricity as resources be balanced between the involved countries?
- Sub-question 3, How do different levels of cooperation impact water, agriculture and electricity as resources in a river's basin.

To answer these question the Zambezi river basin is studied as a case and a simulation model of this river is built. For KPIs (the key performance indicators) the electricity generated per dam, water to the environment per dam and irrigation water per station are selected because they indicate important economic and environmental aspects of the river basin. By exploring existing literature it is concluded that hydro-climatic uncertainties exist. The evaporation rate, the discharges, and the irrigation demands are the hydro-climatic uncertainties that are found. A sensitivity analysis shows that the relation these uncertainties have with the KPIs is very linear. As a result, lower uncertainty values, such as lower discharges, have almost always worse KPI values. Thus, the effect of the hydro-climatic uncertainties can be predicted, because it is the same for every KPI. Therefore, the conclusion can be drawn that well performing policies perform well over different scenarios and can be selected relatively independently from the scenarios that are based on the hydro-climatic uncertainties. Furthermore, this research showed that changes in the discharges of inflow river seem to have to highest impact on the electricity and water to the environment KPIs. The irrigation demand KPIs is split up between KPIs that are hardly influenced by changes in the described uncertainties and KPIs that correlate most with changes in the irrigation demand uncertainty.

Water, agriculture and electricity can be balanced between the involved countries depending on three explored cooperation levels. The first level is no cooperation. On the no cooperation level no dam within the Zambezi basin cooperates with any other structure in the basin. This means that the dams only focus on increasing their own generated electricity. As a result, the dams only want to release the effective discharge at which the dam produces the most electricity. Furthermore, if the dam reservoir is lower than the max effective head, the water level that enables highest electricity production, a percentage of water is withdrawn from the discharge to fill up the reservoir. The next cooperation level that is explored is the full cooperation level. Full cooperation is the level at which the dams releases are adjusted to maximize all of the KPIs within the modeled river basin. The third cooperation level that is explored is the section cooperation level. At this level the releases are adjusted to maximize the KPIs within the same section of their dam. The sections within the Zambezi river are geographical areas that ere based on the boundaries between the countries located in the basin.

For answering how different levels of cooperation impact the described water resources the results of the simulations are examined. Result of the full cooperation level indicated two mayor findings. First, a policy set was found that out performs the no cooperation level for every water resources that was taken into account. Thus, if the whole system releases would cooperate every resource gathered will either stay the same or improve. Second, the KPIs of dams higher upstream of the river, such as the Batoka and Devils Gorge, have relatively less room for improvement by cooperation than than the KPIs of dams located more in the downstream of the river. This was also the case for the section cooperation level. Moreover, the results of the section cooperation level are very similar to the full cooperation level in which every resource gathered is able to increase by entering a cooperation agreement. This shows that any cooperation form could be more beneficial than no cooperation at all. Furthermore, this research has shown that for the either the full or section cooperation strategies selecting a policy that performs best for electricity might be a better option for stakeholders compared to selecting a policy that performs best for irrigation. This is due to that the best performing electricity policies also perform best or high for irrigation water demand. Also, data showed that extra attention has to go towards selecting a fitting policy because not all found policies for either full or section cooperation necessarily perform better than the no cooperation form. To conclude, cooperation in a rivers basin could result in a overall increase in resources gathered. However, reaching cooperation might prove to be difficult because of the lower resource gains that are possible in the upstream of the river.

8 Future work

This research shows that cooperation is more beneficial than no cooperation within a river basin. Future work that continues on this research could look towards ways to ensure this cooperation. A possible framework for this would be to follow the 8 design principles of stable local common pool resource management of Ostrom (1990). These are principles that are present in a stable system that is shared between multiple stakeholders for its resources. The first principle states that there is a need for: 'Clearly defined group boundaries (and effective exclusion of external un-entitled parties) and contents of the common pool resources'. Future research could focus on this principle by performing an in-depth actor analysis. From this actor analysis it should become clear how many actors, countries or other stakeholder, lay claim to the to be analysed river. Furthermore, this future research should then focus on to how much resources the involved parties are entitled. Other research could focus on the second design principle that states the need for: 'The appropriation and provision of common resources that are adapted to local conditions'. This research would study the specific rules that apply to the water resources in the to be examined river basin. For example, this study could focus on how many water resources are present and how these water resources should be measured.

Furthermore, this research could look towards restrictions that apply for consuming these water resources. For example, it could be discovered that during a certain season a minimal water flow is required in the river and that consuming more water is not possible. Future research could also focus on the third design principle which entails that there is a need for: 'Collective-choice arrangements that allow most resource appropriators to participate in the decision-making process'. This research would explore how the negotiation process should be setup in ways that ensure all involved parties to participate. Moreover, from the eighth design principles principles most focus should go towards the forth, fifth and sixth principle as these are a larger issue than the other principles. First, the forth principle should be ensured by ensuring effective monitoring by monitors who are part of or accountable to the appropriators. In the case of a rivers basin this would be implemented by installing a trans-boundary organisation that monitors both the resources gathered by the involved stakeholders and the releases of the hydroelectric dams. This is necessary for checking if the cooperation policy is still being met or that stakeholders are acting independently. If during the monitoring it is discovered that a stakeholder has derived from the cooperation policy sanctions against these stakeholders should be held, which is the fifth design principle. Furthermore, mechanisms of conflict resolution that are cheap and of easy access should be present, which is the sixth principle. Thus, future research could explore what kind of sanctions could be applicable in such cases, how the monitoring should be executed and how conflicts should be resolved in such cases. The seventh design principle future research could look in to for water resource related cases is the need for: 'Self-determination of the community recognized by higher-level authorities'. This means that research could explore how the appropriators should gain full authority within a river basin. Finally, research could look at the eighth design principle that described a rule for large common-pool resources that applies for water resources. This principle described the need for: 'organization in the form of multiple layers of nested enterprises'. This entails that future research could explore how the appropriator organisation that is established trough a cooperation agreement should be constructed from smaller nested organisations.

Other research could look into the incentives stakeholders need to join cooperation agreements. This research has shown that owners of dams that are located upstream have less incentive to join a cooperation agreement because their water resources have less potential to benefit from it. However, this research also shows that these water resources do not have to decline. Furthermore, this research has also shown that other water resources that are located downstream will experience growth due to cooperation. Therefore, the countries in the downstream of the basin will experience an economic growth due to cooperation. This might be enough incentive for countries upstream to join cooperation agreements since they would also indirectly, trough trade for example, benefit from cooperation. However, it can also be expected that these upstream stakeholders expect compensation for entering a cooperation agreement because otherwise they benefit less. As a result, other research could explore how the rises in these resources should be divided and how countries that experience less growth should be compensated.

9 Link Master: Engineering Policy Analysis

The central focus of Engineering Policy Analysis (EPA) is to educate its scholars in solving complex problems that involve politics trough the means of simulation modeling. The main focus of this thesis study is to prescribe cooperation advise to stakeholders located in a trans-boundary river basin, which entails the politics aspect. This trans-boundary river basin is a complex system with multiple components and has multiple stakeholders involved. Therefore, water conflicts in such a river basin can be described as complex problems. Moreover, this thesis study found solutions by using simulation modeling as a tool. As a result, all key characteristics of EPA are represented in this thesis study.

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Appendices

A Data

A.1 Data sources

In table A1 the hydroelectric dam characteristics data sources are presented used for this research. A - sign means that no data has been found about this input parameter. This is mostly due to the fact that most dams have not been constructed yet and are therefore missing data. Sources used are gathered from broad variety of data sources such as official government websites, journals and news papers.

	water capacity	eff release	electricity capacity	eff head
BG	(Vasanthi, 2020)	(Vasanthi, 2020)	(Vasanthi, 2020)	(Carmen, 2020)
DG	-	-	(Carmen, 2021)	-
KD	(river authority, n.d.-a)	(*Kariba South Power Station*, n.d.)	(*Kariba South Power Station*, n.d.)	(ns energy, n.d.)
MG	(river authority, n.d.-b)	-	(river authority, n.d.-b)	(river authority, n.d.-b)
ITTE	(power development, 1994)	(power development, 1994)	(power development, 1994)	(power development, 1994)
KU	(power development, 1994)	(power development, 1994)	(power development, 1994)	(power development, 1994)
KL	-	(Duddu, 2020)	(Duddu, 2020)	(Duddu, 2020)
CB	(Britannica, 2021)	(Britannica, 2021)	(Britannica, 2021)	(*Cahora Bassa increases discharges*, 2001)
MN	(*Mphanda Nkuwa Hydropower Project*, n.d.)	-	(*Mphanda Nkuwa Hydropower Project*, n.d.)	(*Mphanda Nkuwa Hydropower Project*, n.d.)

Table A1: Reservoir data source

A.2 Data assumptions

In table A2 the assumptions are presented that are made to fill the gaps in missing data. Most of the assumptions are based on the main assumption that hydroelectric dams that are close to each other tend to have similar aspects.

Structure: Hydroelectric Dam	**Assumptions**
Batoka Gorge	1. Effective head main is same as effective head north dam 2.planned dam means no reservoir thus 0 water level.
Devils Gorge	1. Height dam is max effectve head 2. Missing other values copied from batoka gorge because it is most close.
Kariba Dam	1. Head south and north dam are the same same.
Mupata Gorge	1. Height dam is effective head. 2. simulair MW to Kariba dam thus similar effective release.
Itezhezi Tezhi	1. Height dam is effective head 2. Max discharge is design capacity.
Kafue upper	1. Gross head is effictive head.
Kafue Lower	1. Maximum discharge is max effective discharge 2. Length dam is max effective head 3. Max water capacity copied from kafue upper because similar dams
Cabora Bassa	1. Dam height is effective head
Mphanda Nkuwa	1. Dam height is effective head 2. Values simular to Kariba dam so max effective discharge also same.

Table A2: Reservoir data assumptions

A.3 Evaporation rates

In table A3 the evaporation rates are presented per reservoir. It is assumed for Mupata Gorge to have the same rates as other dams in section 1 because they are the same. This data is collected from the DAPHNE research.

Structure: Hydroelectric Dam	data available/ month	1	2	3	4	5	6	7	8	9	10	11	12
Victoria falls	no	-38	-41	23	96	118	107	112	130	162	181	117	-23
Batoka Gorge	yes	-38	-41	23	96	118	107	112	130	162	181	117	-23
Devils Gorge	yes	-38	-41	23	96	118	107	112	130	162	181	117	-23
Kariba Dam	yes	-38	-41	23	96	118	107	112	130	162	181	117	-23
Mupata Gorge	no	-38	-41	23	96	118	107	112	130	162	181	117	-23
Itezhezi Tezhi	yes	-90	-80	20	110	120	90	120	140	170	190	50	-60
Kafue upper	yes	-66	-60	48	136	144	108	144	168	204	232	78	-32
Kafue Lower	yes	-66	-60	48	136	144	108	144	168	204	232	78	-32
Cabora Bassa	yes	-7	19	93	159	192	208	249	193	139	113	43	-30
Mphanda Nkuwa	yes	-7	19	93	159	192	208	249	193	139	113	43	-30

Table A3: Evaporation rates per reservoir (m3/s)

A.4 Irrigation demand

In table A4 the irrigation demand per irrigation station are presented. This data was gathered from the world bank (Alavian et al., 2010) by combining data from crops water demand and crops amount per irrigation station.

station	name/month	1	2	3	4	5	6	7	8	9	10	11	12
1	Between Batoka and Kariba	3262333	2432000	2974667	7452333	11830667	15336667	24669667	24521667	30078667	22326667	12358333	5670000
2	Kariba dam	8669667	7689333	8996667	16963667	27424000	38767333	63618667	61735333	73026333	48424667	25297000	12634667
3	Kafue Sugar extension	2500000	3500000	5500000	23000000	26500000	21500000	28000000	38000000	51500000	63500000	43000000	15000000
4	Lower Kafue after Kafue Gorge Lower	10560000	10240000	11200000	0	2880000	11200000	24640000	12800000	19520000	0	0	0
5	Mupata	53315333	53810667	64473667	1,24E+08	1,75E+08	2,14E+08	3,44E+08	3,37E+08	4,39E+08	3,45E+08	2,09E+08	84467333
6	Cahora Bassa	0	0	0	66666,67	173333,3	183333,3	230000	303333,3	403333,3	246666,7	0	0
7	Between Cahora Bassa and Mphanda Nkuwa	0	0	0	37333,33	68666,67	65000	129666,7	167666,7	217666,7	258666,7	152000	5333,333
8	Tete	1420667	480000	466666,7	1474000	3459333	4010000	5680667	7081333	8509333	5810000	1026667	33333,33

Table A4: Irrigation demand monthly per station (m3/day)

A.5 River discharge data

In table A5 data is presented about the monthly discharges from rivers. This data was gathered constructed by using existing data from the world bank (Alavian et al., 2010). The mean annual discharges were found and adjusted to a monthly discharge by using the upper Zambezi monthly discharge (which was only available).

dam/month	1	2	3	4	5	6	7	8	9	10	11	12
Upper Zambezi	41490514,29	69150857	110641371	165962057	1,38E+08	82981029	41490514	27660343	24894309	22128274	22128274	27660343
Gwayi	4665600	7776000	12441600	18662400	15552000	9331200	4665600	3110400	2799360	2488320	2488320	3110400
Sanyati	5776457,143	9627428,6	15403885,7	23105828,6	19254857	11552914	5776457	3850971	3465874	3080777	3080777	3850971
Kafue	18662400	31104000	49766400	74649600	62208000	37324800	18662400	12441600	11197440	9953280	9953280	12441600
Chongwe	222171,4286	370285,71	592457,143	888685,714	740571,4	444342,9	222171,4	148114,3	133302,9	118491,4	118491,4	148114,3
Luangwa	28771200	47952000	76723200	115084800	95904000	57542400	28771200	19180800	17262720	15344640	15344640	19180800
Manyane	1499657,143	2499428,6	3999085,71	5998628,57	4998857	2999314	1499657	999771,4	899794,3	799817,1	799817,1	999771,4
Luenya	9997714,286	16662857	26660571,4	39990857,1	33325714	19995429	9997714	6665143	5998629	5332114	5332114	6665143
Shire	8997942,857	14996571	23994514,3	35991771,4	29993143	17995886	8997943	5998629	5398766	4798903	4798903	5998629

Table A5: River discharge monthly data (m3/day)

A.6 Delay data

In table A6 data is presented about the water delays between the dams. This data was gathered constructed by using google maps (*Google Maps*, 2020). Using the liquid flow formulate, and general aspects of the Zambezi river the delays are estimated.

trajject	km	delay (days)
victoria falls, batoka gorge	42	0,842545
batoka gorge, devils gorge	73	1,464424
Devils Gorge, Kariba dam	270	5,416362
kariba dam, mupata gorge	190	3,811514
itezhi tezhi, kafue upper	270	5,416362
kafue upper, kafue lower	19	0,381151
kafue lower, cabora bassa	340	6,820605
mupata gorge cabora bassa	180	3,610908
cabora bassa, mphanda nkuwza	230	4,613938

Table A6: Delay data (days)

B Model input

B.1 Constraints

In table B1 data is presented about the constraints used in the directed search. These constrains where gathered by running the model with the worst case no cooperation scenario.

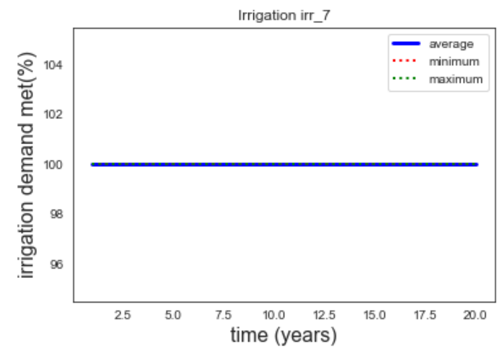
sum elect BG	254946,2
sum elect DG	43232,34
sum elect KD	2141267
sum elect MG	2489410
sum elect ITTE	148567,4
sum elect KU	6550761
sum elect KL	250742,8
sum elect CB	5533675
sum elect MN	2293368
sum kpi irr1	343410,8
sum kpi irr2	730000
sum kpi irr3	730000
sum kpi irr4	448477,9
sum kpi irr5	45404,03
sum kpi irr6	730000
sum kpi irr7	730000
sum kpi irr8	730000
sum env BG	1,76E+11
sum env DG	1,43E+11
sum env KD	2,53E+12
sum env MG	2,48E+12
sum env ITTE	1,08E+12
sum env KU	8,14E+11
sum env KL	1,51E+11
sum env CB	2,83E+12
sum env MN	2,82E+12

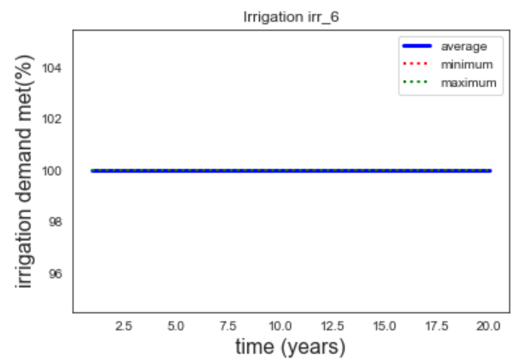
Table B1: Constraints

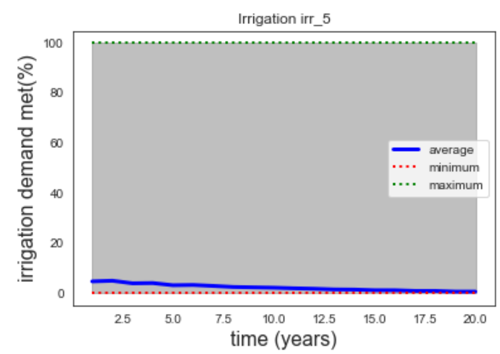
C Verification

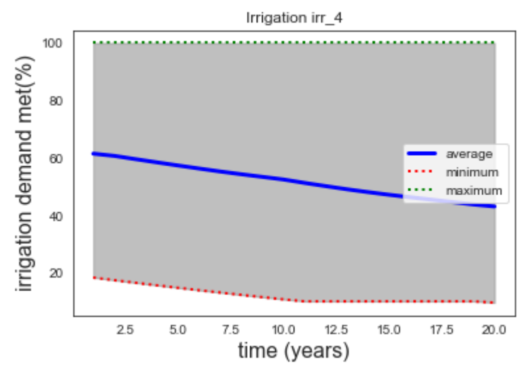
C.1 Extreme low discharges

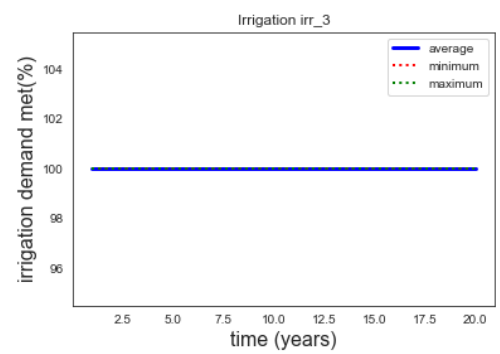
The results in this section show the outcomes of the model for the extreme low discharges verification test. In the figures below the behaviour of the KPIs over time is presented. The yearly averages are depicted together with the yearly maximum and minimum reached values.

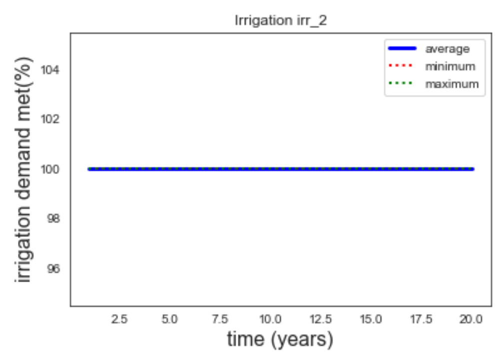

Irrigation irr_7
irrigation demand met(%)
time (years)
average
minimum
maximum

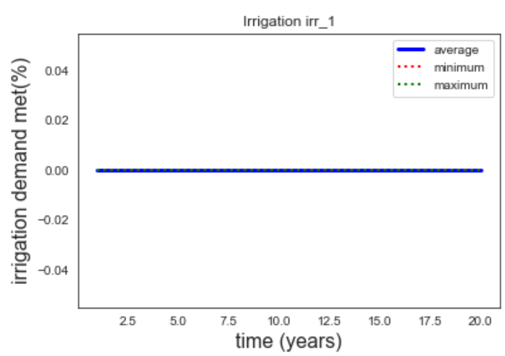

Irrigation irr_6
irrigation demand met(%)
time (years)
average
minimum
maximum

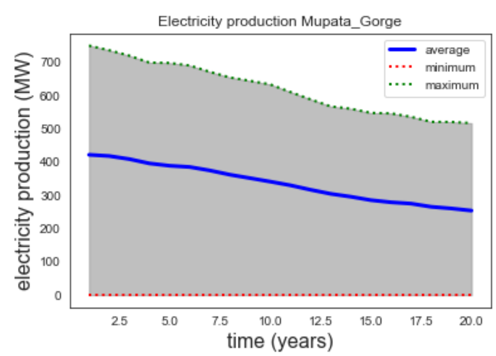

Irrigation irr_5
irrigation demand met(%)
time (years)
average
minimum
maximum

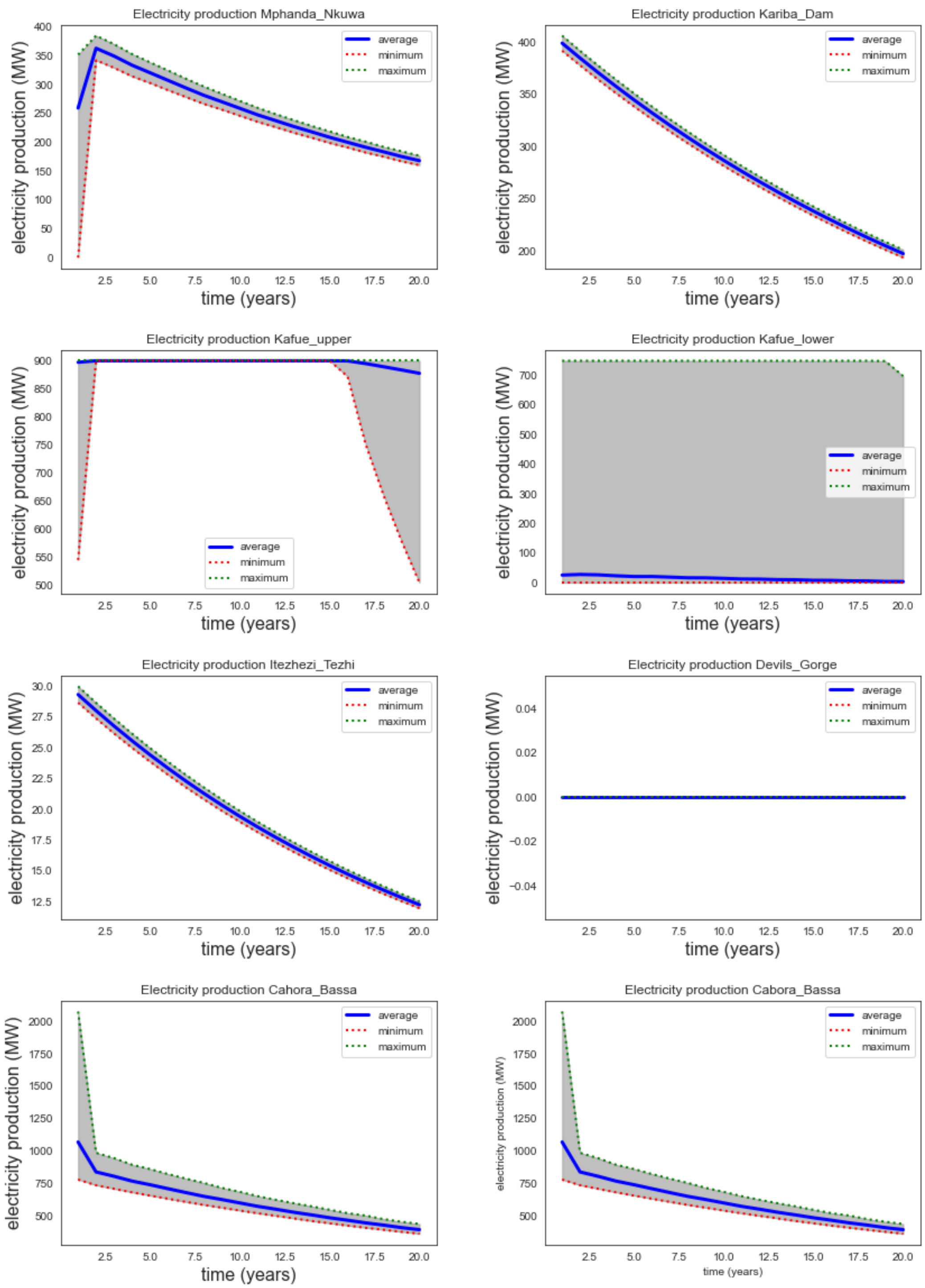

Irrigation irr_4
irrigation demand met(%)
time (years)
average
minimum
maximum

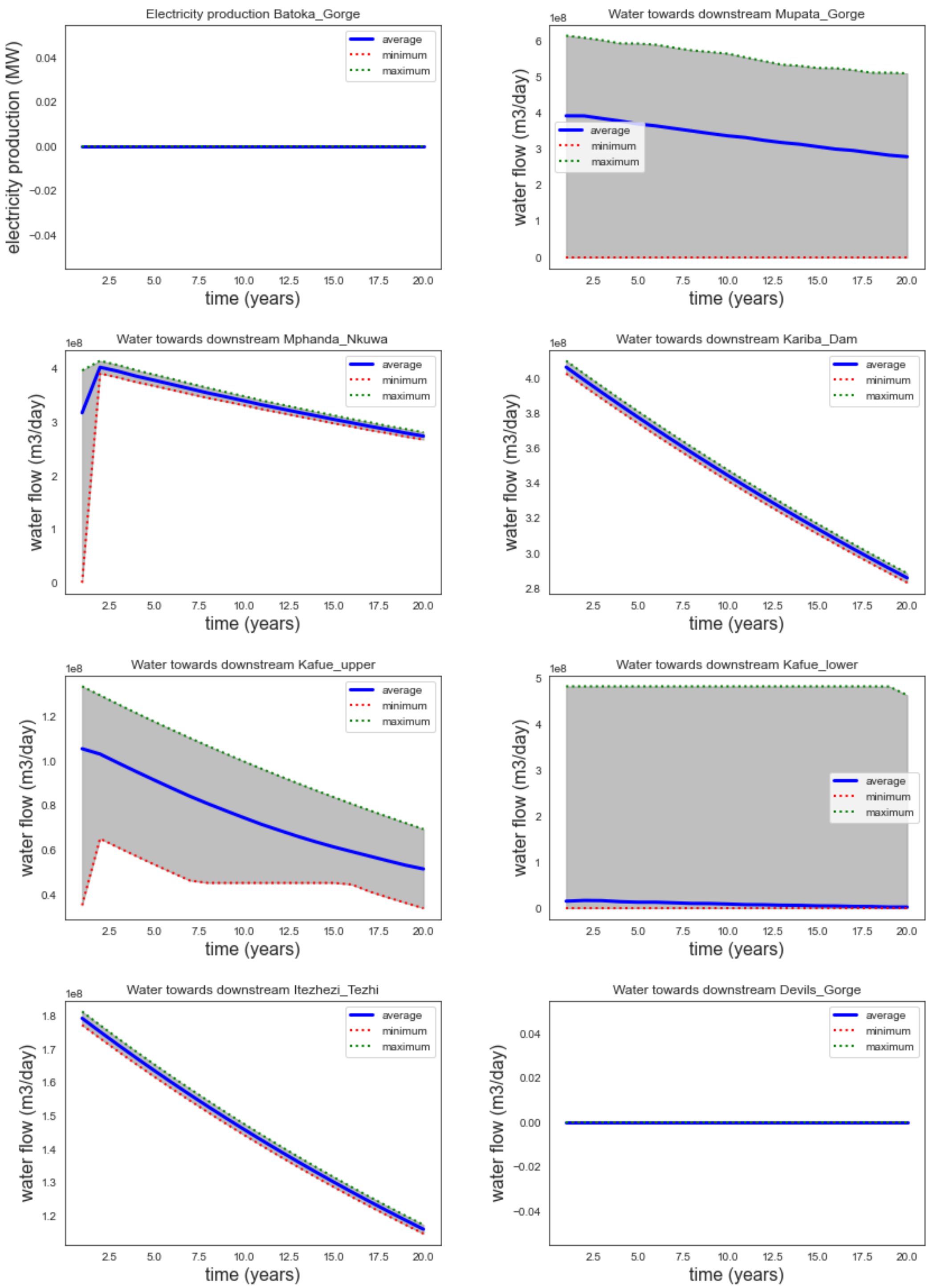

Irrigation irr_3
irrigation demand met(%)
time (years)
average
minimum
maximum

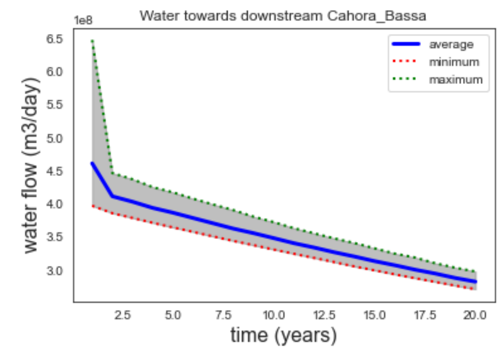

Irrigation irr_2
irrigation demand met(%)
time (years)
average
minimum
maximum

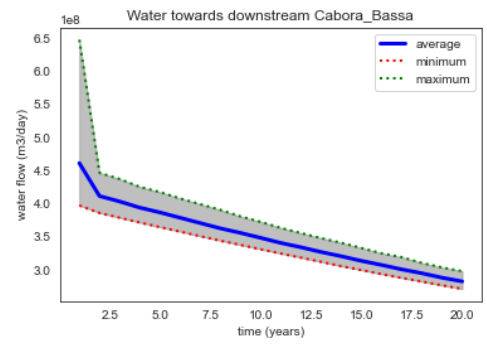

Irrigation irr_1
irrigation demand met(%)
time (years)
average
minimum
maximum

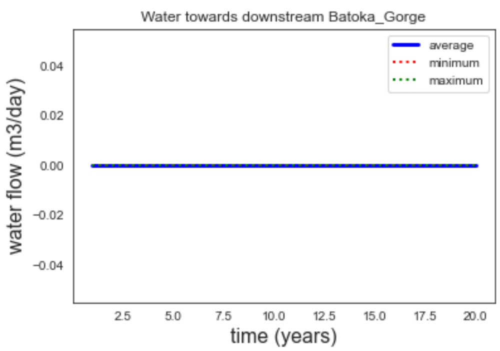

Electricity production Mupata_Gorge
electricity production (MW)
time (years)
average
minimum
maximum

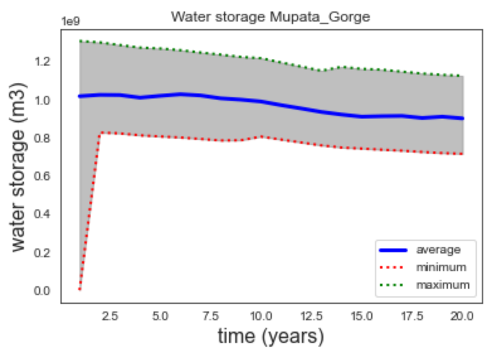

Electricity production Mphanda_Nkuwa
Electricity production Kariba_Dam
Electricity production Kafue_upper
Electricity production Kafue_lower
Electricity production Itezhezi_Tezhi
Electricity production Devils_Gorge
Electricity production Cahora_Bassa
Electricity production Cabora_Bassa
electricity production (MW)
time (years)
average
minimum
maximum

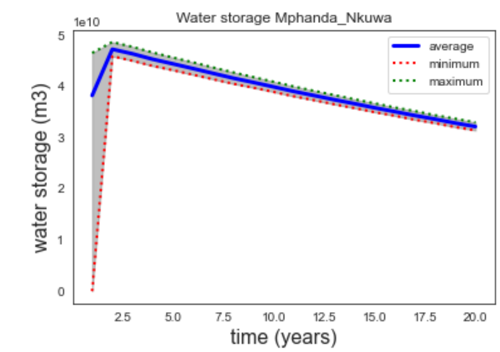

Electricity production Batoka_Gorge
electricity production (MW)
time (years)
average
minimum
maximum
Water towards downstream Mupata_Gorge
1e8
water flow (m3/day)
time (years)
Water towards downstream Mphanda_Nkuwa
Water towards downstream Kariba_Dam
Water towards downstream Kafue_upper
Water towards downstream Kafue_lower
Water towards downstream Itezhezi_Tezhi
Water towards downstream Devils_Gorge

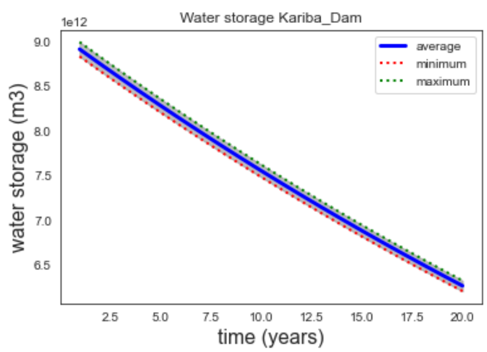

Water towards downstream Cahora_Bassa
1e8
water flow (m3/day)
time (years)
average
minimum
maximum

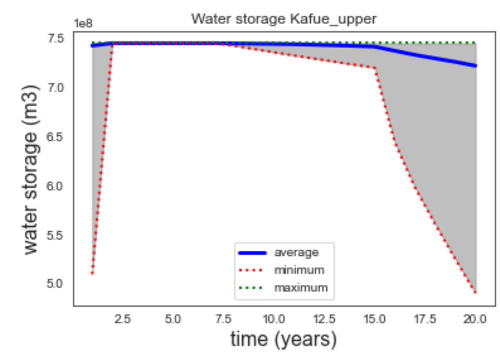

Water towards downstream Cabora_Bassa
1e8
water flow (m3/day)
time (years)
average
minimum
maximum

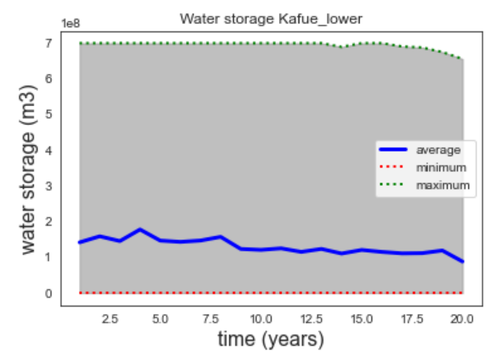

Water towards downstream Batoka_Gorge
water flow (m3/day)
time (years)
average
minimum
maximum

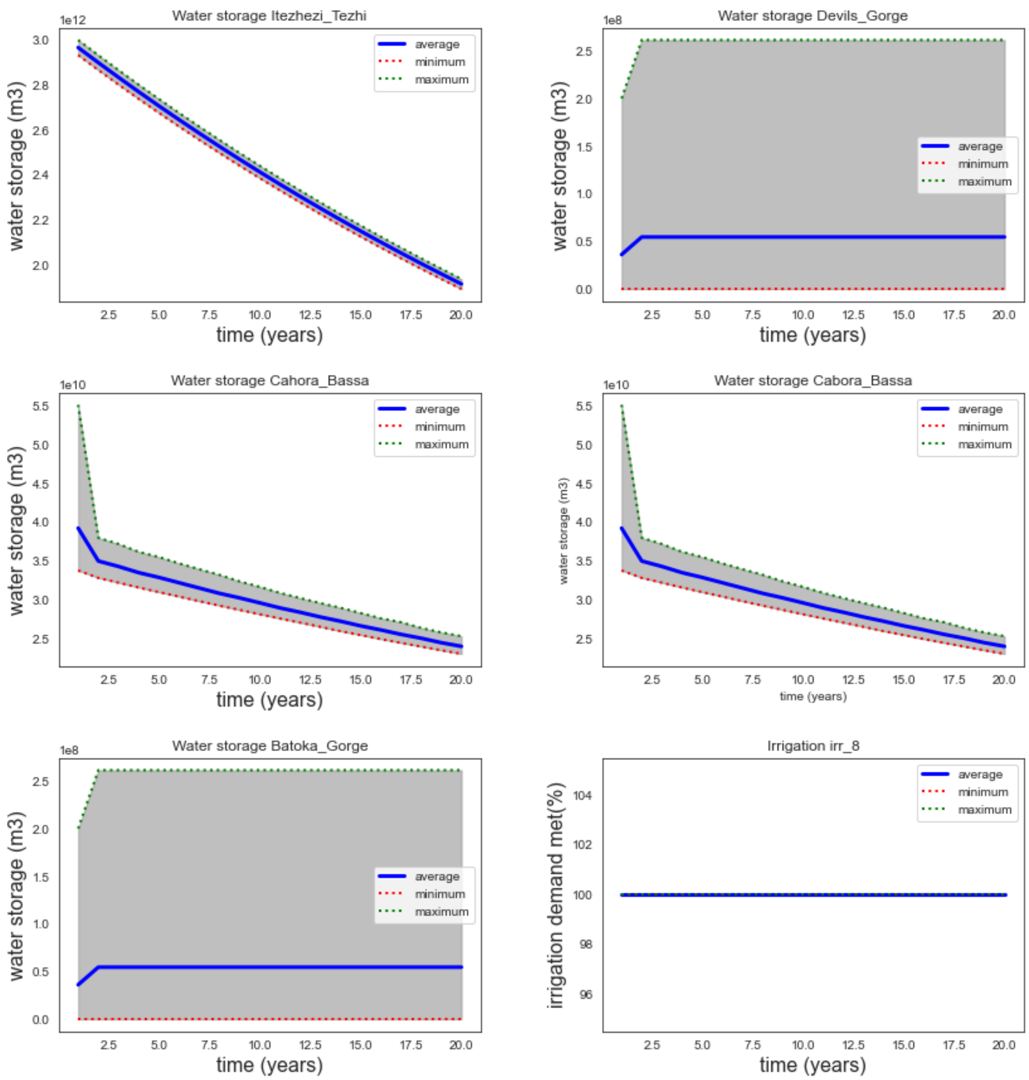

Water storage Mupata_Gorge
1e9
water storage (m3)
time (years)
average
minimum
maximum


Water storage Mphanda_Nkuwa
1e10
water storage (m3)
time (years)
average
minimum
maximum


Water storage Kariba_Dam
1e12
water storage (m3)
time (years)
average
minimum
maximum

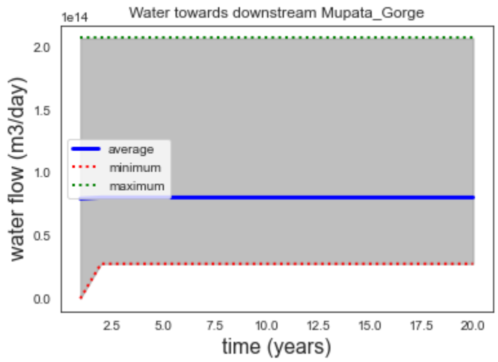

Water storage Kafue_upper
1e8
water storage (m3)
time (years)
average
minimum
maximum

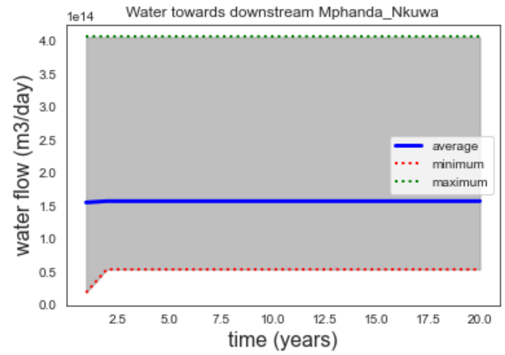

Water storage Kafue_lower
1e8
water storage (m3)
time (years)
average
minimum
maximum

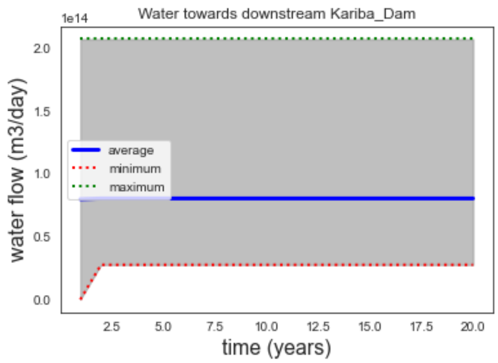

Water storage Itezhezi_Tezhi
Water storage Devils_Gorge
Water storage Cahora_Bassa
Water storage Cabora_Bassa
Water storage Batoka_Gorge
Irrigation irr_8
water storage (m3)
irrigation demand met(%)
time (years)
average
minimum
maximum
1e12
1e8
1e10

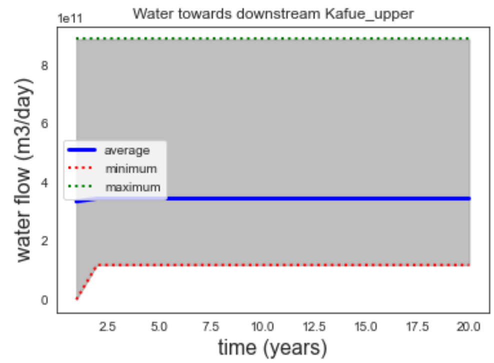
C.2 Extreme high discharges

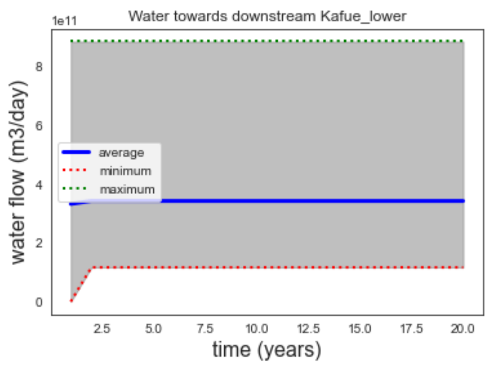
The results in this section show the outcomes of the model for the extreme high discharges verification test. In the figures below the behaviour of the KPIs over time is presented. The yearly averages are depicted together with the yearly maximum and minimum reached values.

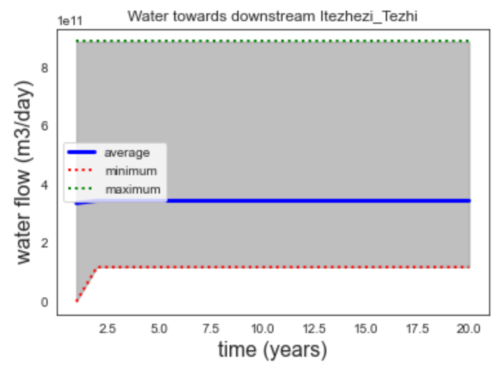

Water towards downstream Mupata_Gorge
1e14
water flow (m3/day)
time (years)
average
minimum
maximum

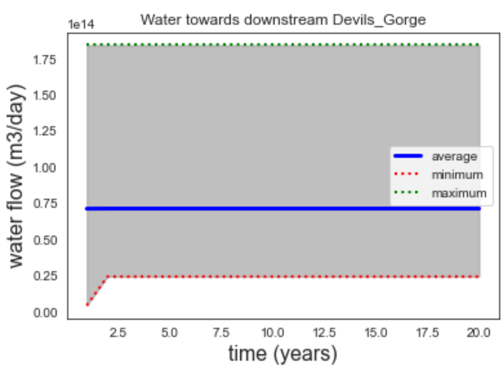

Water towards downstream Mphanda_Nkuwa
1e14
water flow (m3/day)
time (years)
average
minimum
maximum

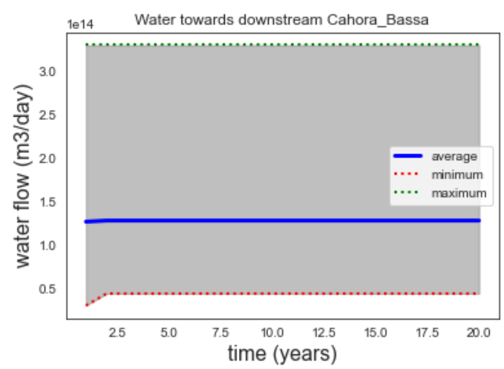

Water towards downstream Kariba_Dam
1e14
water flow (m3/day)
time (years)
average
minimum
maximum

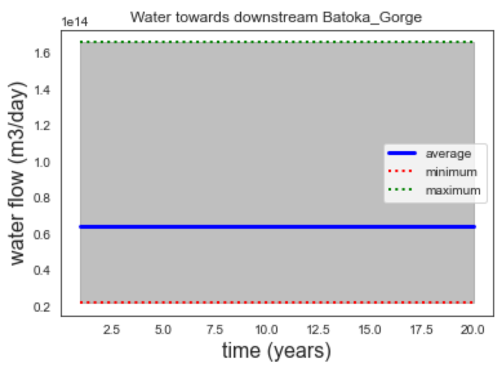

Water towards downstream Kafue_upper
1e11
water flow (m3/day)
time (years)
average
minimum
maximum

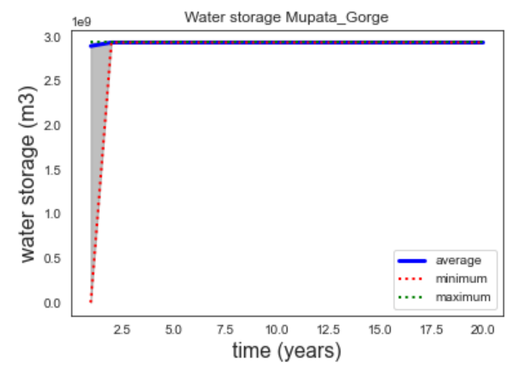

Water towards downstream Kafue_lower
1e11
water flow (m3/day)
time (years)
average
minimum
maximum

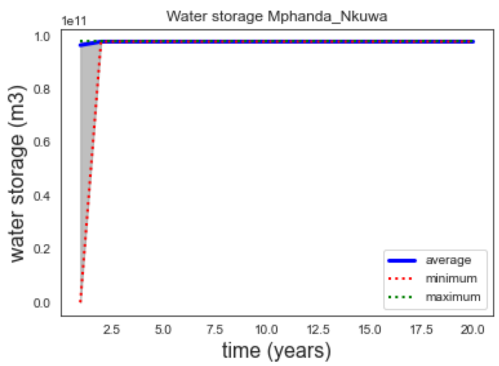

Water towards downstream Itezhezi_Tezhi
1e11
water flow (m3/day)
time (years)
average
minimum
maximum

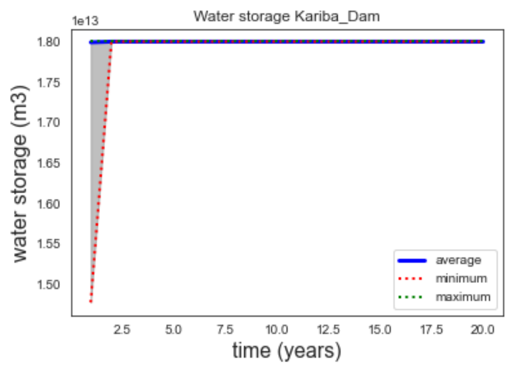

Water towards downstream Devils_Gorge
1e14
water flow (m3/day)
time (years)
average
minimum
maximum

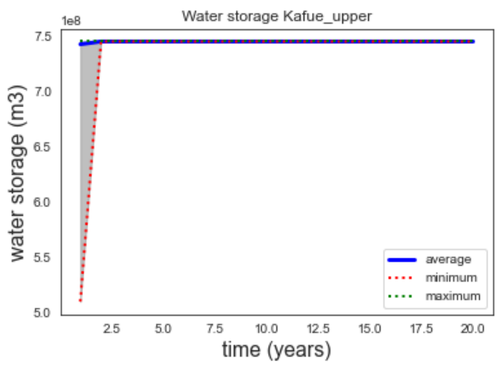

Water towards downstream Cahora_Bassa
1e14
water flow (m3/day)
time (years)
average
minimum
maximum

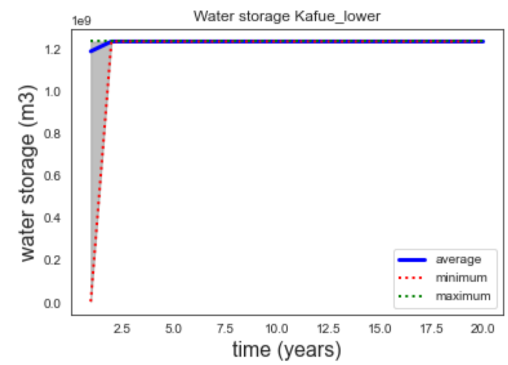

1e14
Water towards downstream Batoka_Gorge
water flow (m3/day)
time (years)
average
minimum
maximum

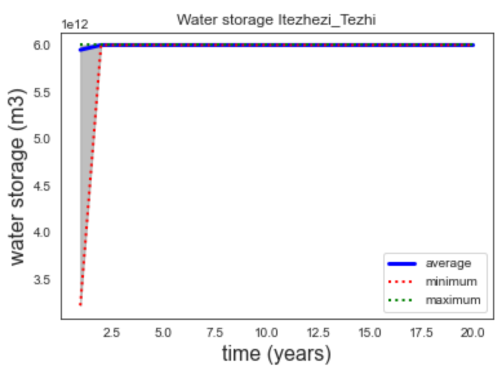

1e9
Water storage Mupata_Gorge
water storage (m3)
time (years)
average
minimum
maximum

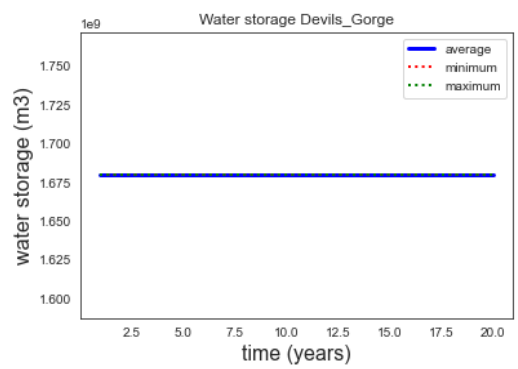

1e11
Water storage Mphanda_Nkuwa
water storage (m3)
time (years)
average
minimum
maximum

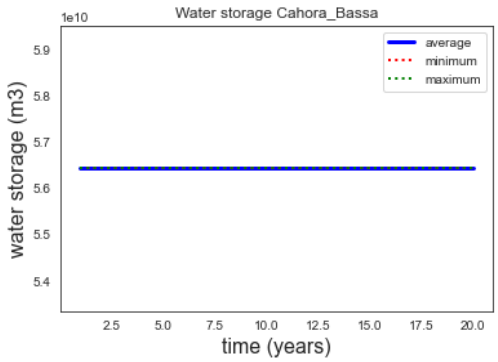

1e13
Water storage Kariba_Dam
water storage (m3)
time (years)
average
minimum
maximum

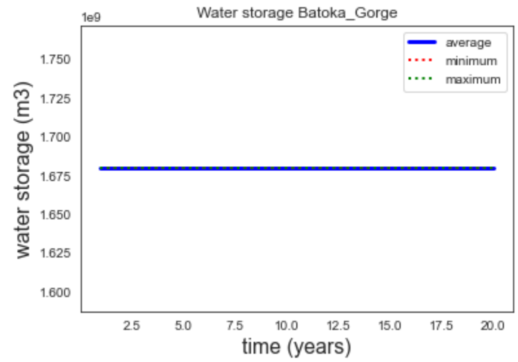

1e8
Water storage Kafue_upper
water storage (m3)
time (years)
average
minimum
maximum

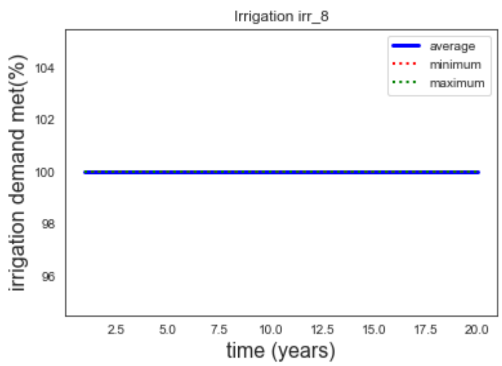

1e9
Water storage Kafue_lower
water storage (m3)
time (years)
average
minimum
maximum

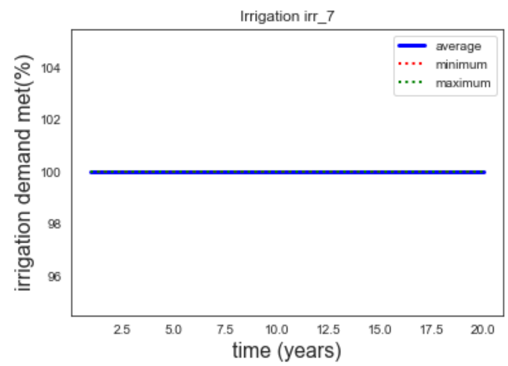

1e12
Water storage Itezhezi_Tezhi
water storage (m3)
time (years)
average
minimum
maximum

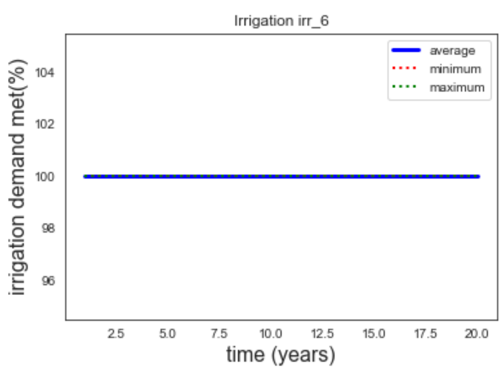

1e9
Water storage Devils_Gorge
water storage (m3)
time (years)
average
minimum
maximum

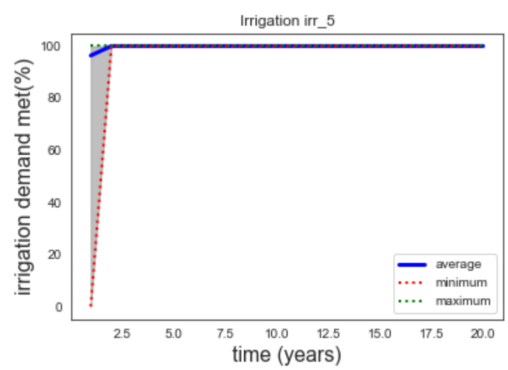

Water storage Cahora_Bassa
1e10
water storage (m3)
time (years)
average
minimum
maximum

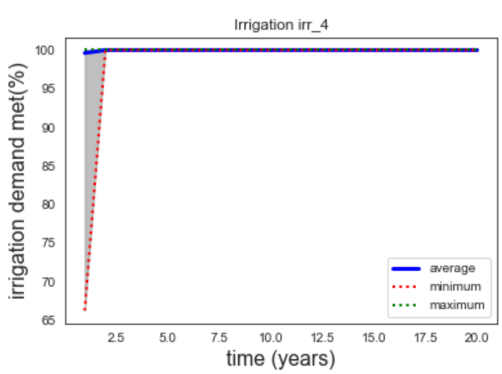

Water storage Batoka_Gorge
1e9
water storage (m3)
time (years)
average
minimum
maximum

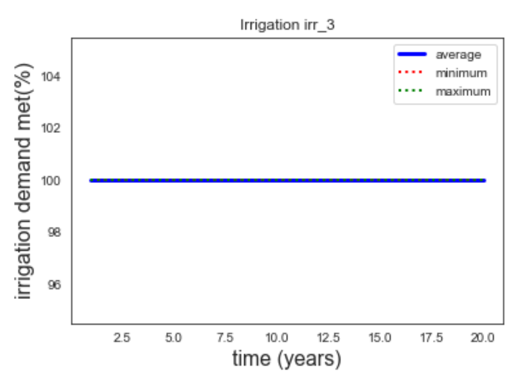

Irrigation irr_8
irrigation demand met(%)
time (years)
average
minimum
maximum

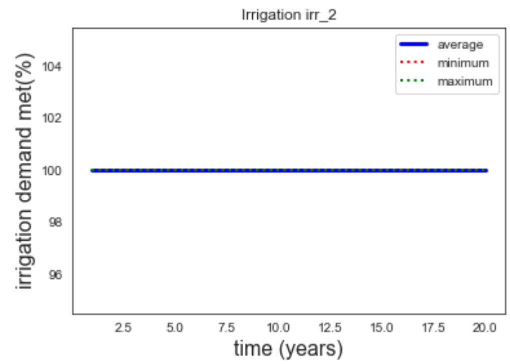

Irrigation irr_7
irrigation demand met(%)
time (years)
average
minimum
maximum

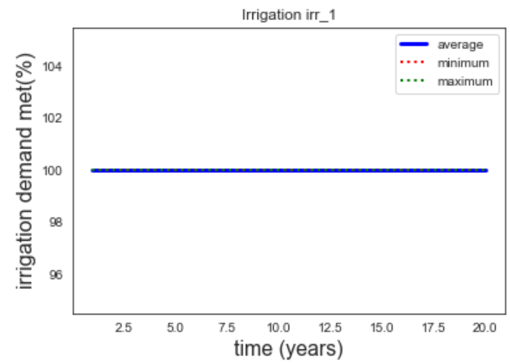

Irrigation irr_6
irrigation demand met(%)
time (years)
average
minimum
maximum

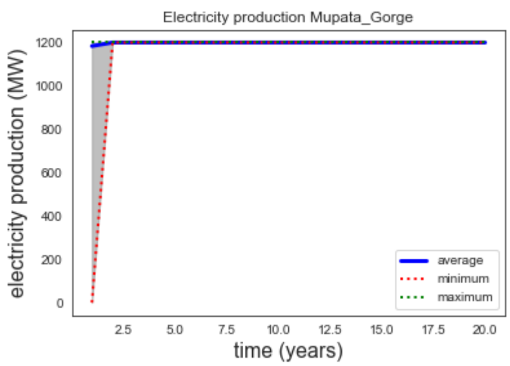

Irrigation irr_5
irrigation demand met(%)
time (years)
average
minimum
maximum

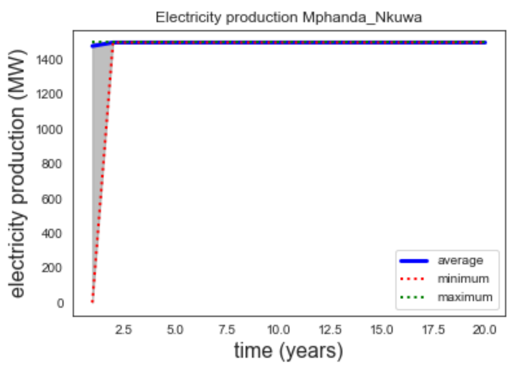

Irrigation irr_4
irrigation demand met(%)
time (years)
average
minimum
maximum

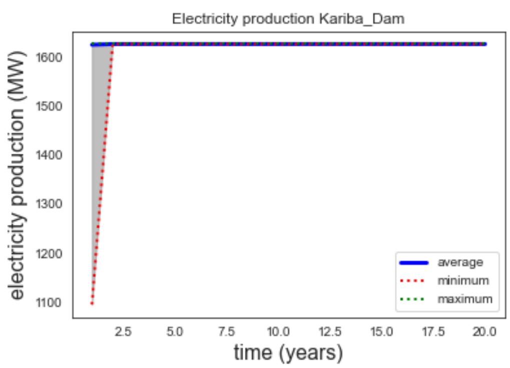

Irrigation irr_3
irrigation demand met(%)
time (years)
average
minimum
maximum

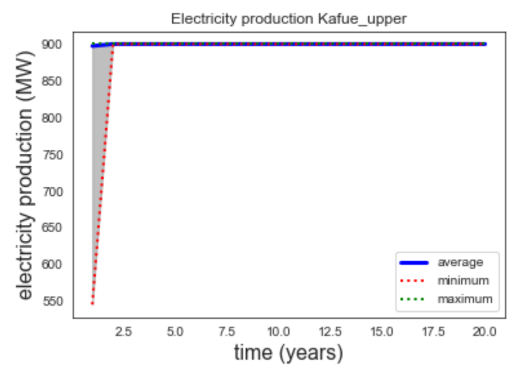

Irrigation irr_2
irrigation demand met(%)
104
102
100
98
96
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum

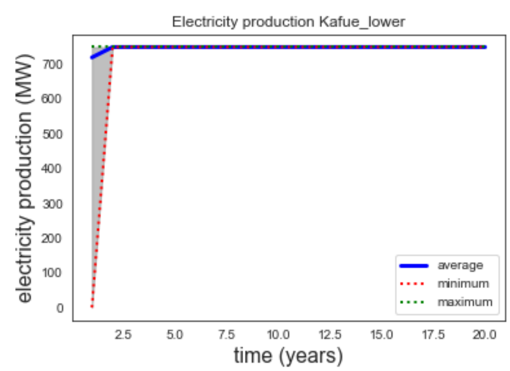

Irrigation irr_1
irrigation demand met(%)
104
102
100
98
96
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum

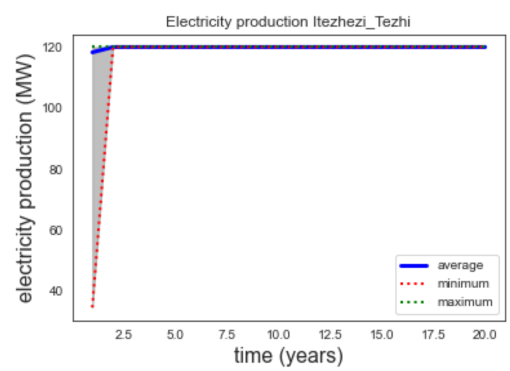

Electricity production Mupata_Gorge
electricity production (MW)
1200
1000
800
600
400
200
0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum

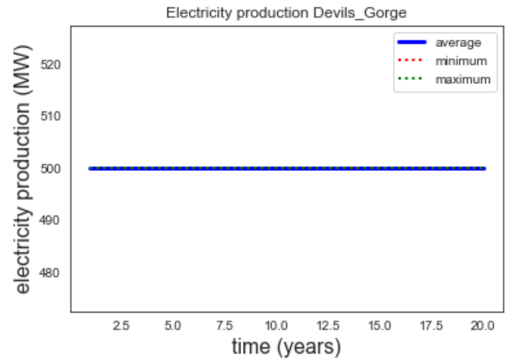

Electricity production Mphanda_Nkuwa
electricity production (MW)
1400
1200
1000
800
600
400
200
0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum

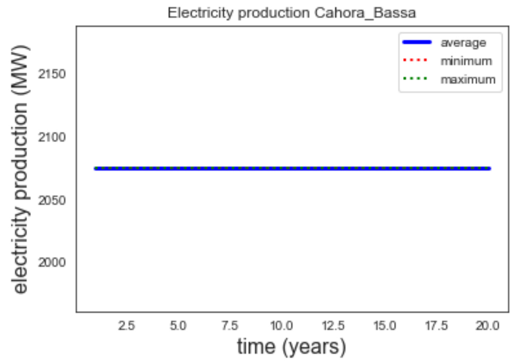

Electricity production Kariba_Dam
electricity production (MW)
1600
1500
1400
1300
1200
1100
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum

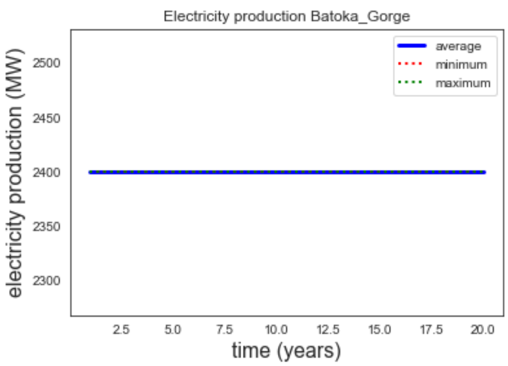

Electricity production Kafue_upper
electricity production (MW)
900
850
800
750
700
650
600
550
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum


Electricity production Kafue_lower
electricity production (MW)
700
600
500
400
300
200
100
0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum


Electricity production Itezhezi_Tezhi
electricity production (MW)
120
100
80
60
40
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)
average
minimum
maximum


Electricity production Devils_Gorge
average
minimum
maximum
electricity production (MW)
520
510
500
490
480
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)

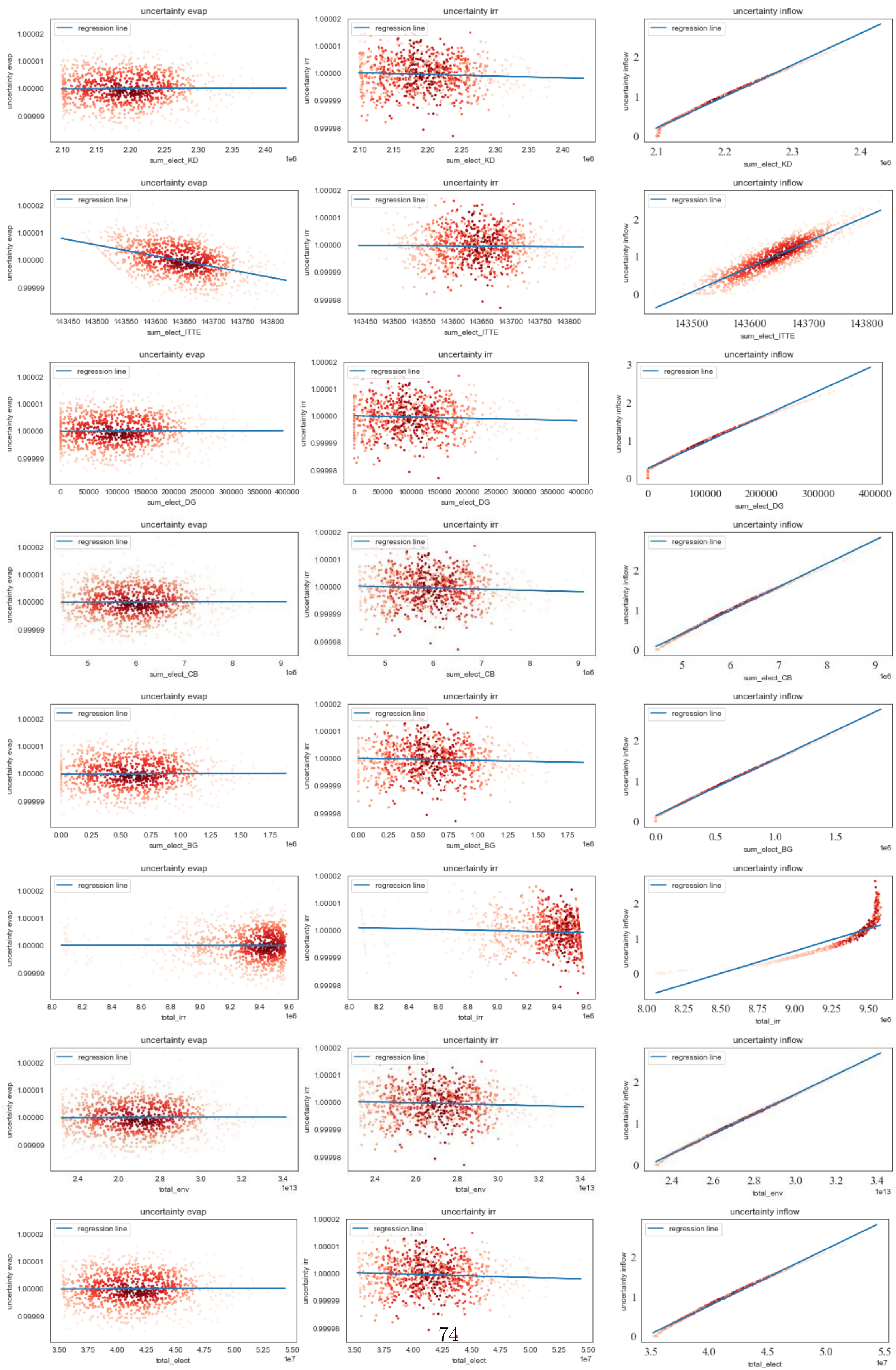

Electricity production Cahora_Bassa
average
minimum
maximum
electricity production (MW)
2150
2100
2050
2000
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)


Electricity production Batoka_Gorge
average
minimum
maximum
electricity production (MW)
2500
2450
2400
2350
2300
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
time (years)

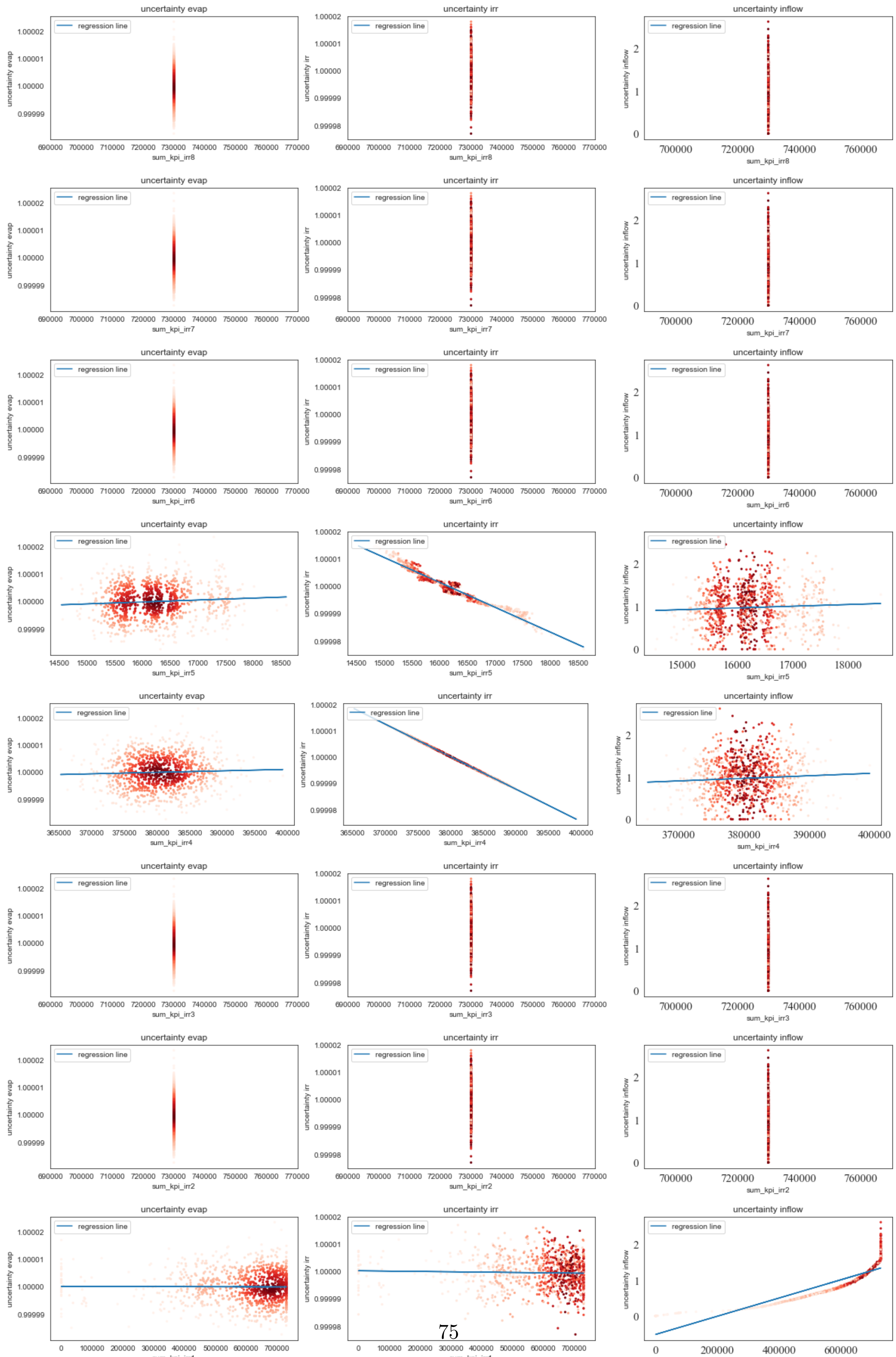
D Results

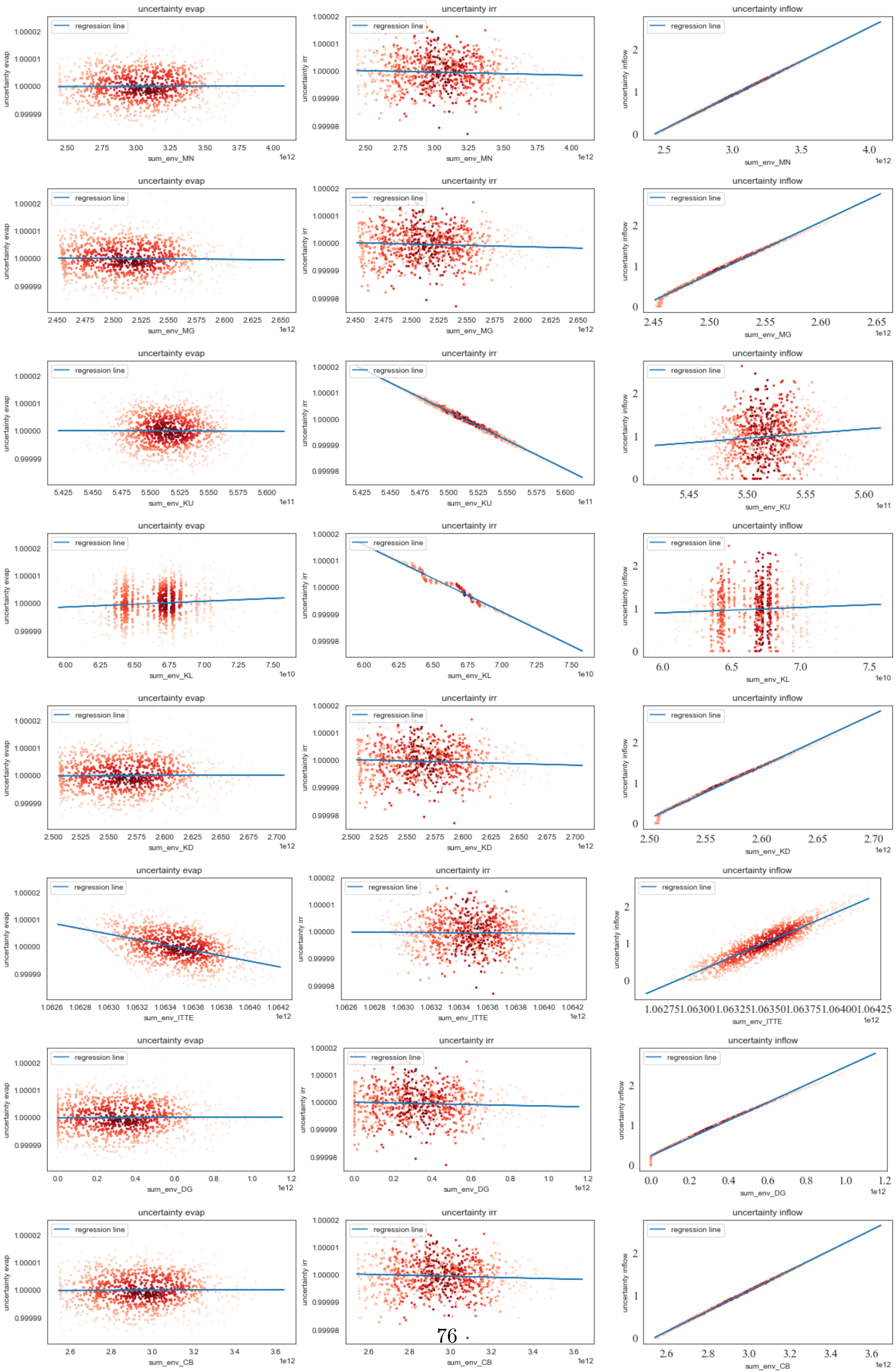
D.1 Random sensitivity analysis

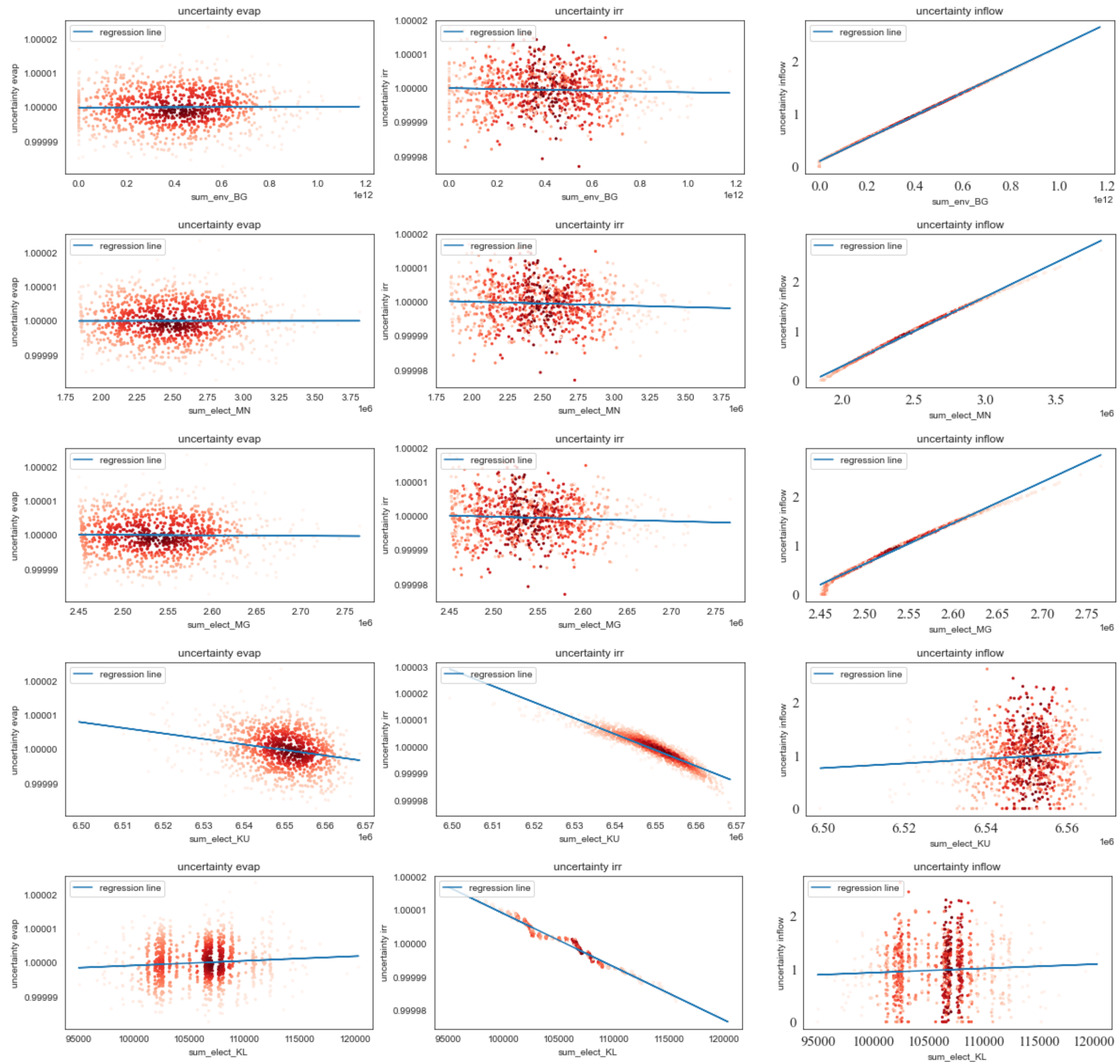
The results shown in this section show the distribution between the found outcomes of the random sensitivity analysis.



uncertainty evap
uncertainty irr
uncertainty inflow
regression line
uncertainty evap
uncertainty irr
uncertainty inflow
sum_elect_KD
sum_elect_ITTE
sum_elect_DG
sum_elect_CB
sum_elect_BG
total_irr
total_env
total_elect
1e6
1e13
1e7


uncertainty evap
regression line
uncertainty evap
sum_kpi_irr8
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr8
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr8
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr7
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr7
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr7
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr6
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr6
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr6
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr5
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr5
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr5
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr4
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr4
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr4
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr3
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr3
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr3
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr2
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr2
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr2
uncertainty evap
regression line
uncertainty evap
sum_kpi_irr1
uncertainty irr
regression line
uncertainty irr
sum_kpi_irr1
uncertainty inflow
regression line
uncertainty inflow
sum_kpi_irr1


uncertainty evap
uncertainty irr
uncertainty inflow
regression line
sum_env_MN
sum_env_MG
sum_env_KU
sum_env_KL
sum_env_KD
sum_env_ITTE
sum_env_DG
sum_env_CB
1e12
1e11
1e10


uncertainty evap
regression line
uncertainty evap
sum_env_BG
uncertainty irr
regression line
uncertainty irr
sum_env_BG
uncertainty inflow
regression line
uncertainty inflow
sum_env_BG
uncertainty evap
regression line
uncertainty evap
sum_elect_MN
uncertainty irr
regression line
uncertainty irr
sum_elect_MN
uncertainty inflow
regression line
uncertainty inflow
sum_elect_MN
uncertainty evap
regression line
uncertainty evap
sum_elect_MG
uncertainty irr
regression line
uncertainty irr
sum_elect_MG
uncertainty inflow
regression line
uncertainty inflow
sum_elect_MG
uncertainty evap
regression line
uncertainty evap
sum_elect_KU
uncertainty irr
regression line
uncertainty irr
sum_elect_KU
uncertainty inflow
regression line
uncertainty inflow
sum_elect_KU
uncertainty evap
regression line
uncertainty evap
sum_elect_KL
uncertainty irr
regression line
uncertainty irr
sum_elect_KL
uncertainty inflow
regression line
uncertainty inflow
sum_elect_KL

D.2 Independent sensitivity analysis

D.2.1 Irrigation uncertainty

In figure D1 the results of the sensitivity analysis for the irrigation demand uncertainty are visualized. Al the KPI's show a linear relation between this uncertainty and the KPI as can be seen in the figure.

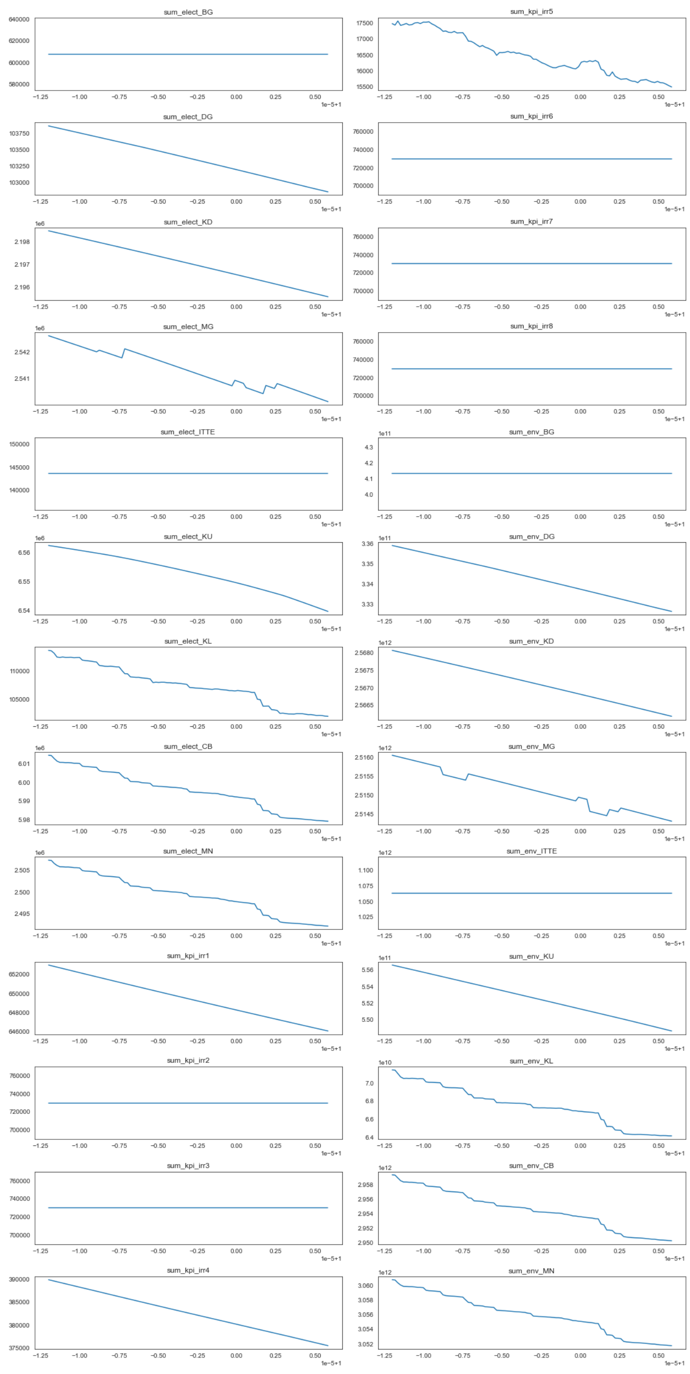


Figure D1: Sensitivity analysis uncertainty irrigation

D.2.2 Inflow uncertainty

In figure D2 the results of the sensitivity analysis for the inflow uncertainty are visualized. Al the KPI's show a linear relation between this uncertainty and the KPI as can be seen in the figure.

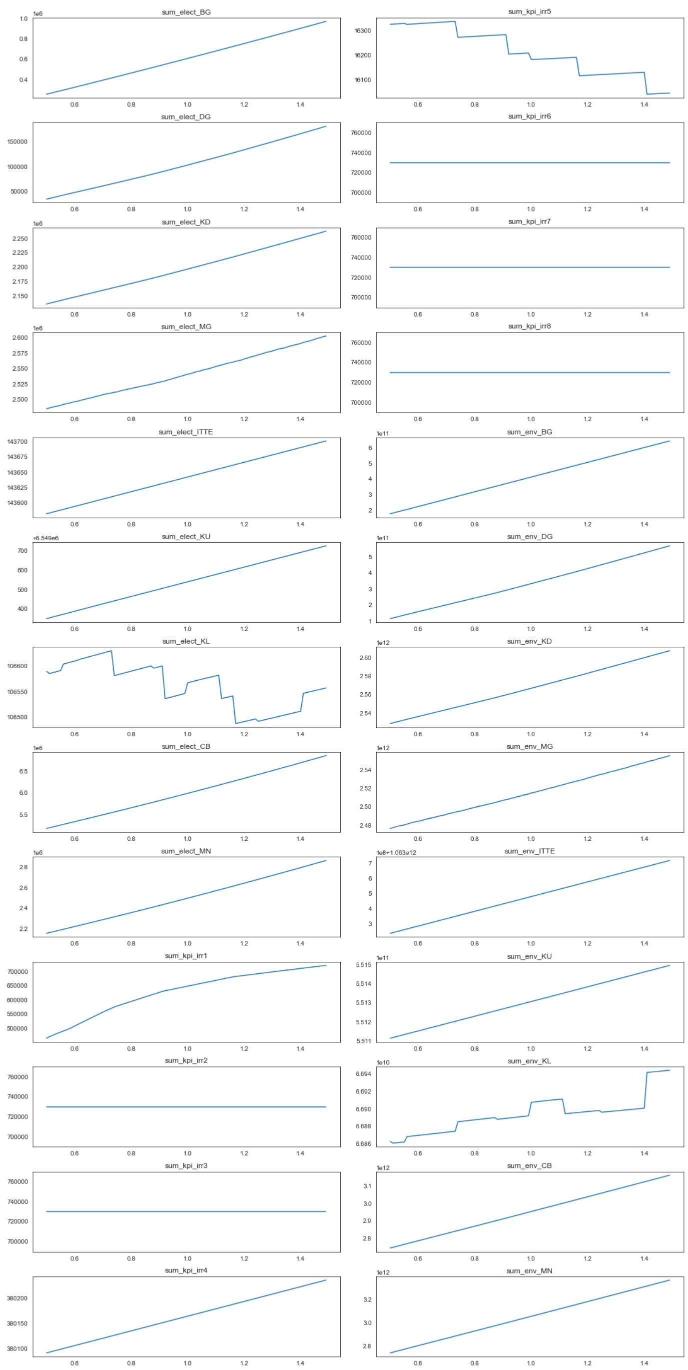


Figure D2: Sensitivity analysis uncertainty inflow

D.2.3 Evaporation uncertainty

In figure D3 the results of the sensitivity analysis for the evaporation uncertainty are visualized. Al the KPI's show a linear relation between this uncertainty and the KPI as can be seen in the figure.

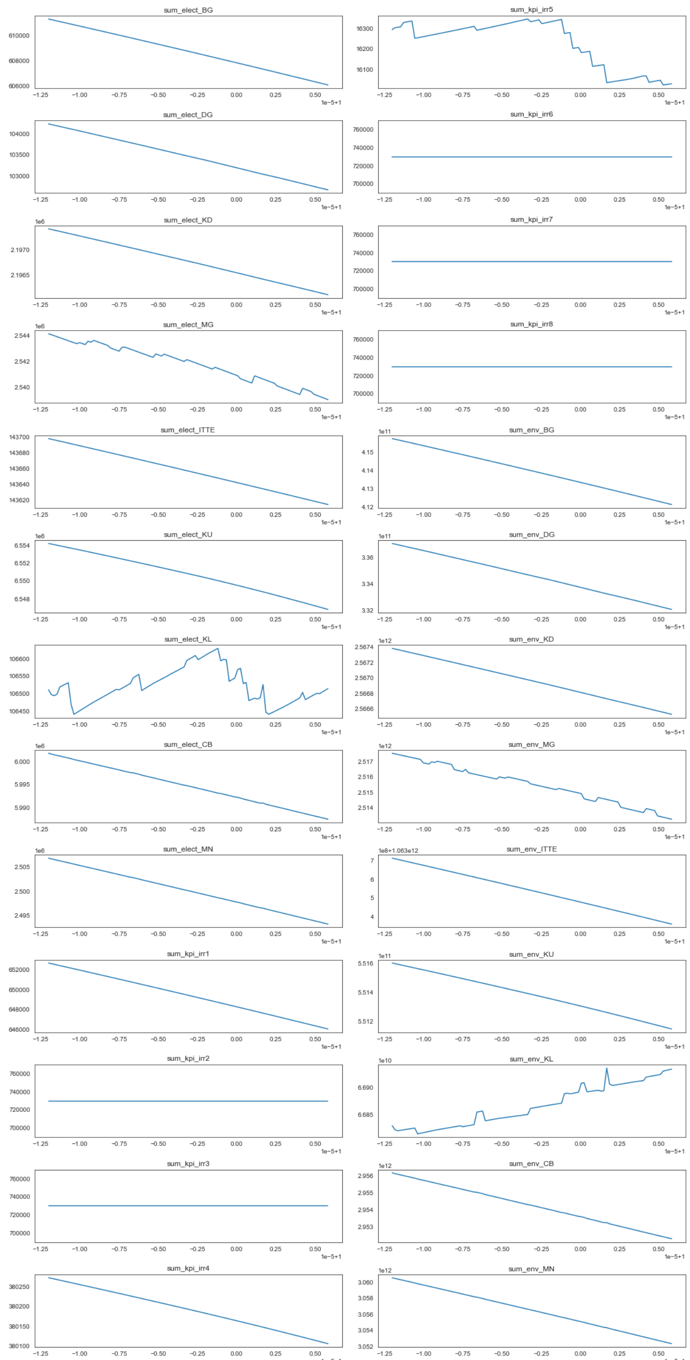


Figure D3: Sensitivity analysis uncertainty evaporation

D.3 No cooperation results

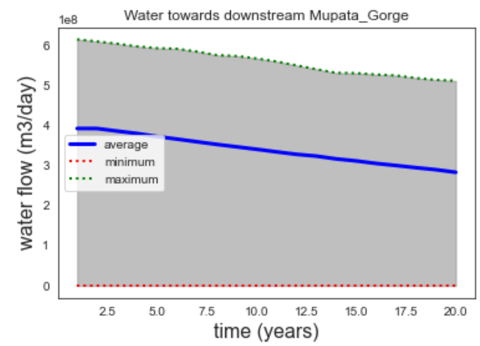
In table C1 the model results of both the worst and base case are displayed. As can be seen out performs the base case the worst case on nearly every KPI.

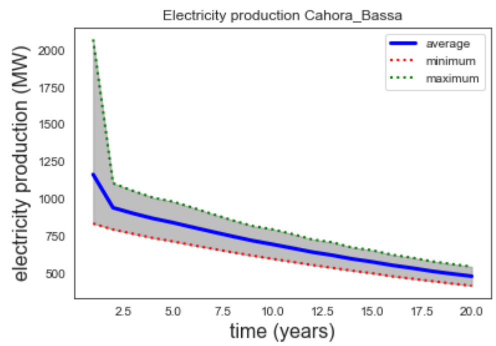
KPI	base case	worst case
elect BG	83,26441	34,92414
elect DG	14,13686	5,922238
elect KD	300,8962	293,3242
elect MG	348,0716	341,015
elect ITTE	19,67703	20,3517
elect KU	897,1971	897,3646
elect KL	14,59825	34,34833
elect CB	820,8633	758,0377
elect MN	342,1676	314,1599
kpi irr1	88,80512	47,04257
kpi irr2	100	100
kpi irr3	100	100
kpi irr4	52,07726	61,43533
kpi irr5	2,216705	6,219731
kpi irr6	100	100
kpi irr7	100	100
kpi irr8	100	100
env BG	56623718	24171846
env DG	45717225	19616494
env KD	3,52E+08	3,47E+08
env MG	3,45E+08	3,4E+08
env ITTE	1,46E+08	1,48E+08
env KU	75521521	1,11E+08
env KL	9165412	20718151
env CB	4,05E+08	3,88E+08
env MN	4,19E+08	3,87E+08

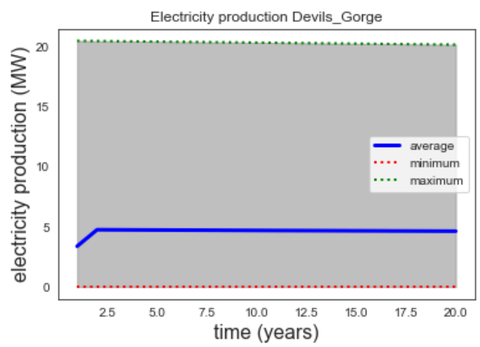
Table C1: No cooperation KPI values (per day)

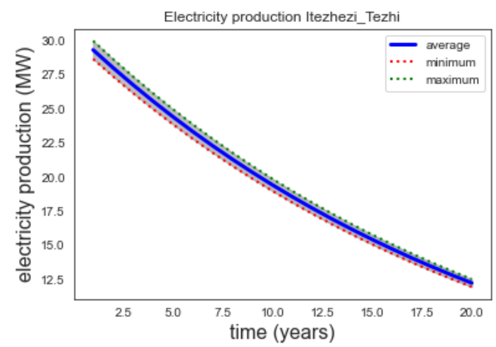
D.3.1 Base case no cooperation

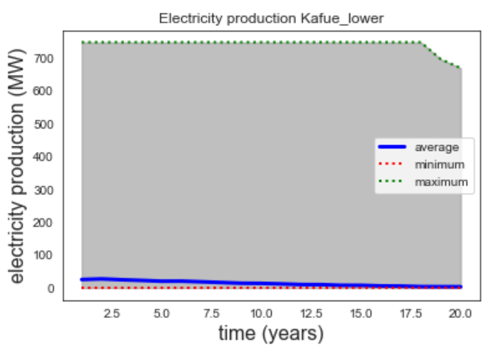
In the figures below the behaviour of the KPIs over time is presented. The yearly averages are depicted together with the yearly maximum and minimum reached values.

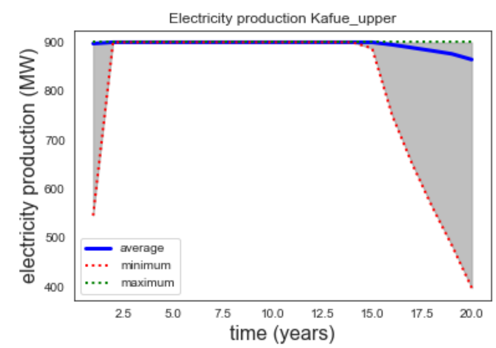

Water towards downstream Mupata_Gorge
1e8
water flow (m3/day)
time (years)
average
minimum
maximum

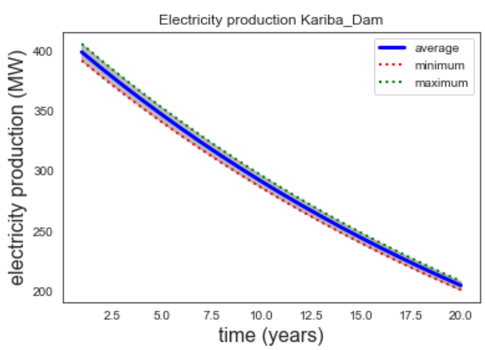

Electricity production Cahora_Bassa
electricity production (MW)
time (years)
average
minimum
maximum

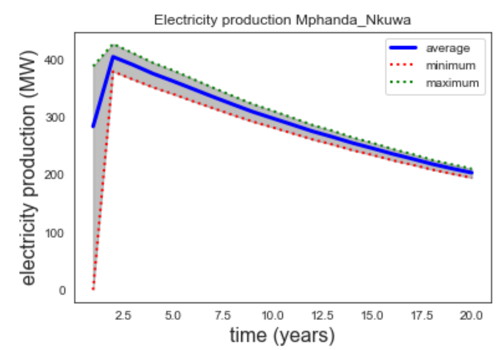

Electricity production Devils_Gorge
electricity production (MW)
time (years)
average
minimum
maximum

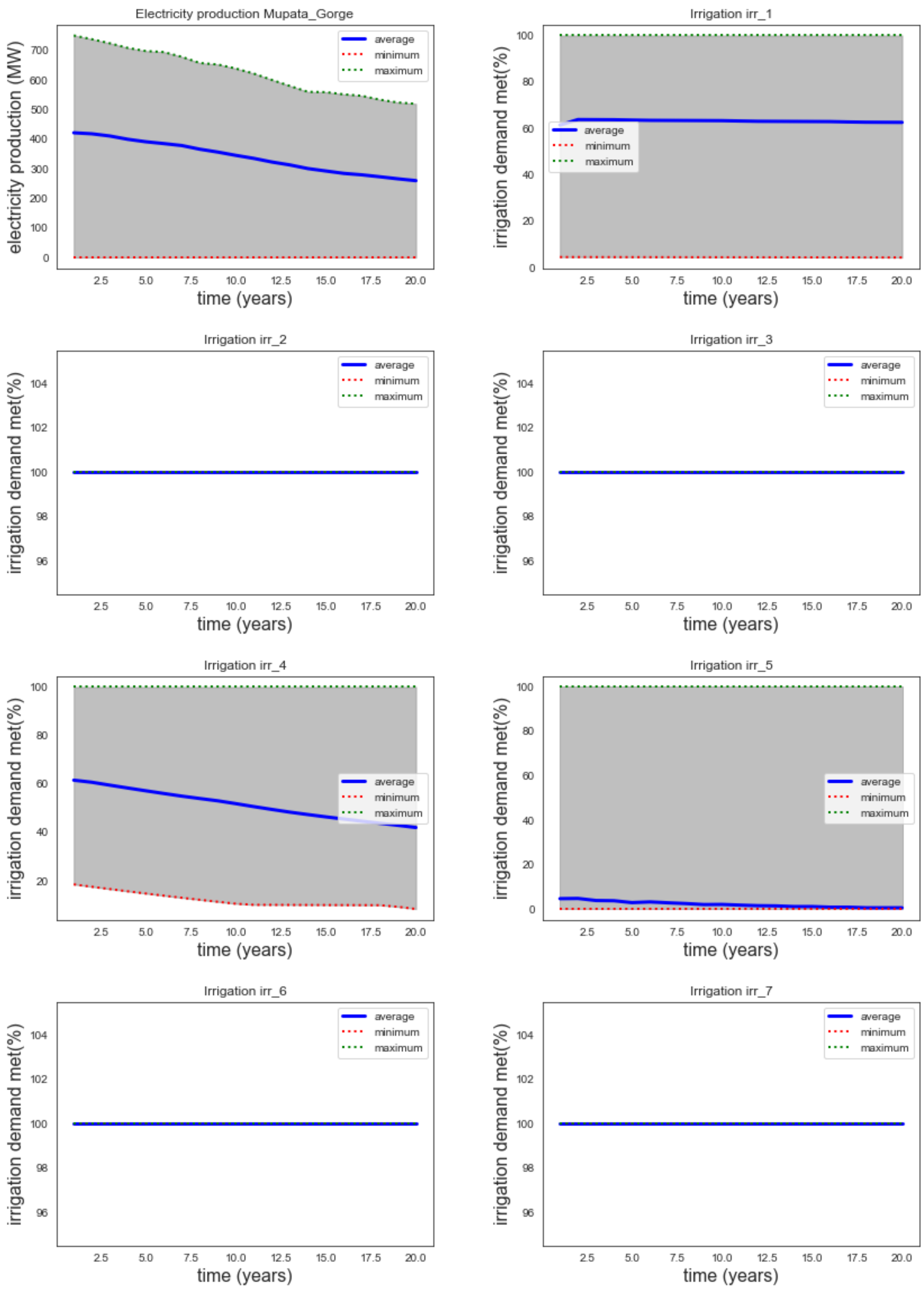

Electricity production Itezhezi_Tezhi
electricity production (MW)
time (years)
average
minimum
maximum

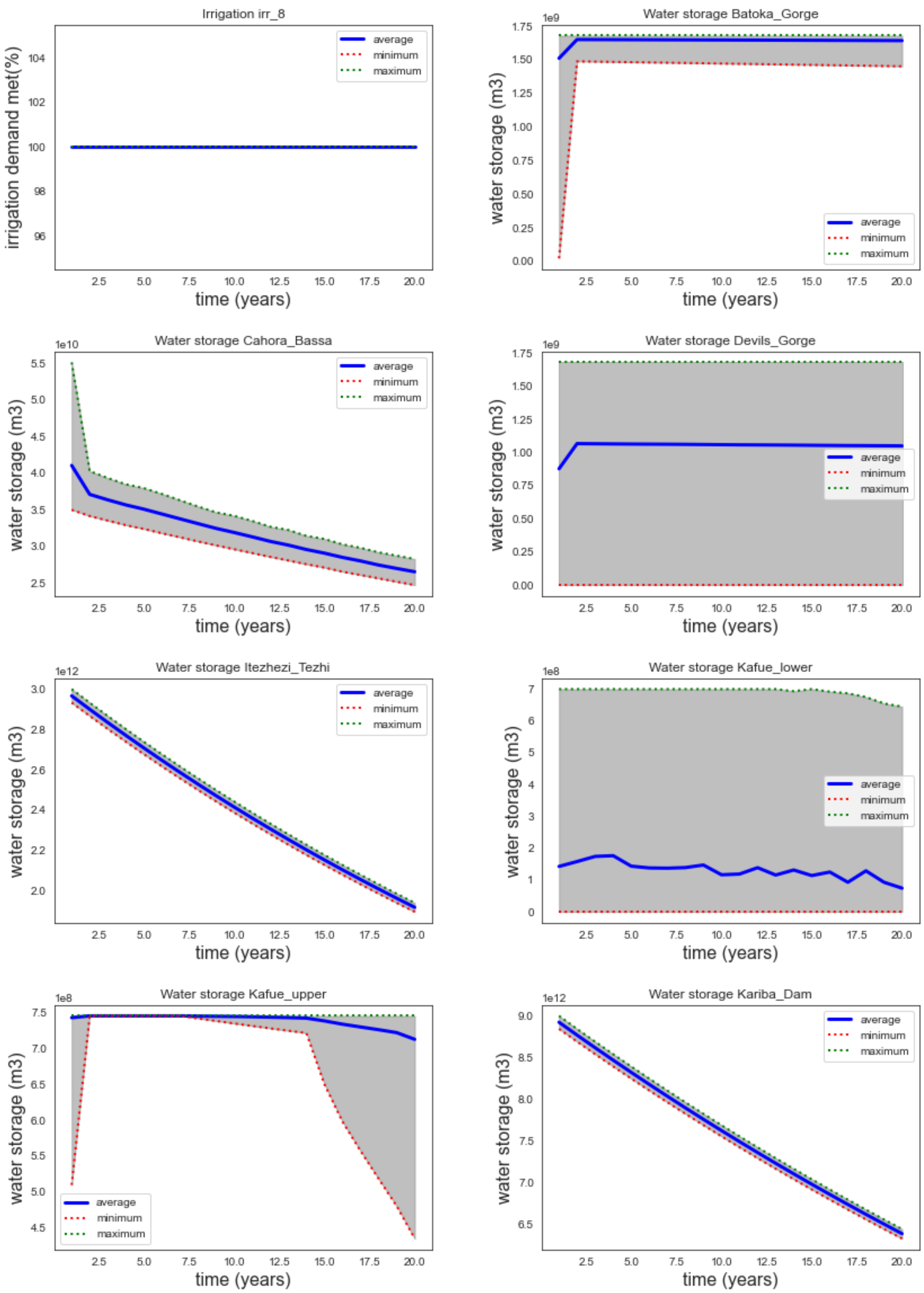

Electricity production Kafue_lower
electricity production (MW)
time (years)
average
minimum
maximum

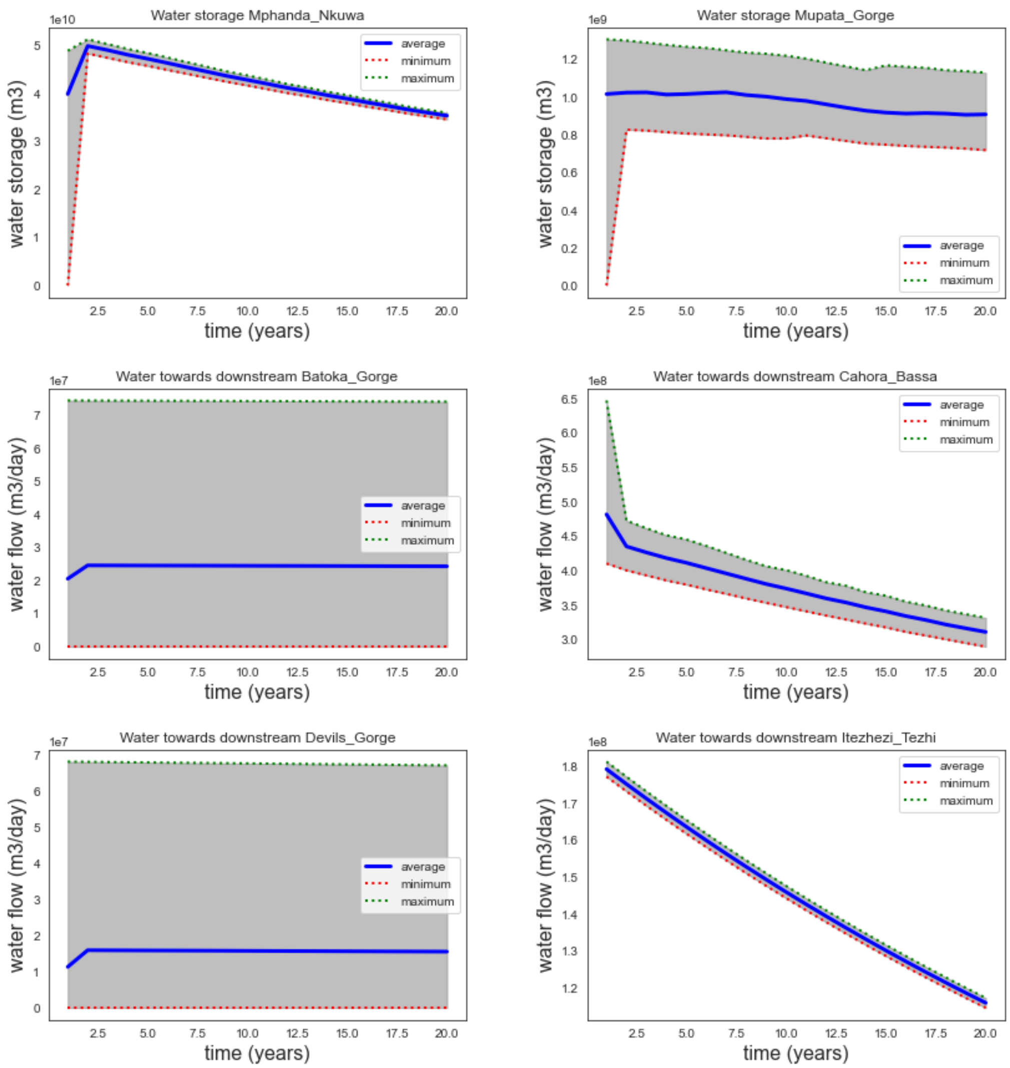

Electricity production Kafue_upper
electricity production (MW)
time (years)
average
minimum
maximum

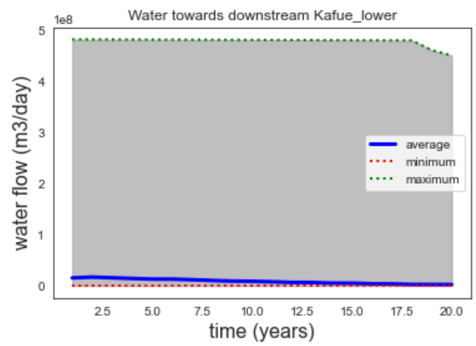

Electricity production Kariba_Dam
electricity production (MW)
time (years)
average
minimum
maximum

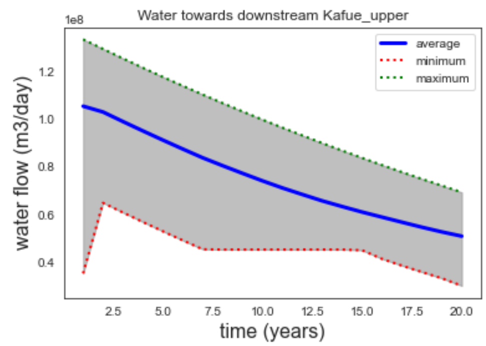

Electricity production Mphanda_Nkuwa
electricity production (MW)
time (years)
average
minimum
maximum

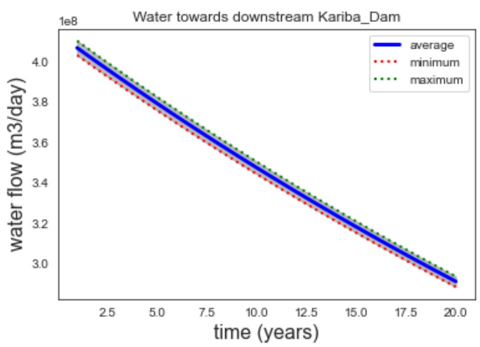

Electricity production Mupata_Gorge
electricity production (MW)
time (years)
average
minimum
maximum
Irrigation irr_1
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_2
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_3
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_4
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_5
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_6
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_7
irrigation demand met(%)
time (years)
average
minimum
maximum

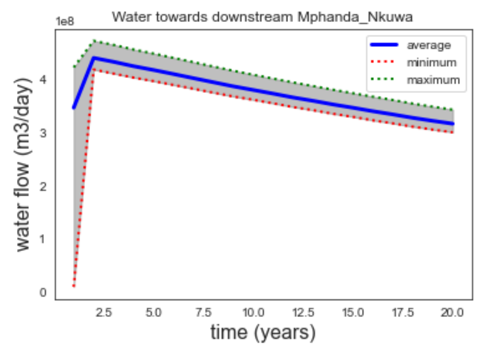

Irrigation irr_8
irrigation demand met(%)
time (years)
average
minimum
maximum
Water storage Batoka_Gorge
Water storage Cahora_Bassa
Water storage Devils_Gorge
Water storage Itezhezi_Tezhi
Water storage Kafue_lower
Water storage Kafue_upper
Water storage Kariba_Dam
water storage (m3)


Water storage Mphanda_Nkuwa
1e10
water storage (m3)
time (years)
average
minimum
maximum
Water storage Mupata_Gorge
1e9
water storage (m3)
time (years)
average
minimum
maximum
Water towards downstream Batoka_Gorge
1e7
water flow (m3/day)
time (years)
average
minimum
maximum
Water towards downstream Cahora_Bassa
1e8
water flow (m3/day)
time (years)
average
minimum
maximum
Water towards downstream Devils_Gorge
1e7
water flow (m3/day)
time (years)
average
minimum
maximum
Water towards downstream Itezhezi_Tezhi
1e8
water flow (m3/day)
time (years)
average
minimum
maximum


Water towards downstream Kafue_lower
1e8
water flow (m3/day)
time (years)
average
minimum
maximum
0
1
2
3
4
5
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

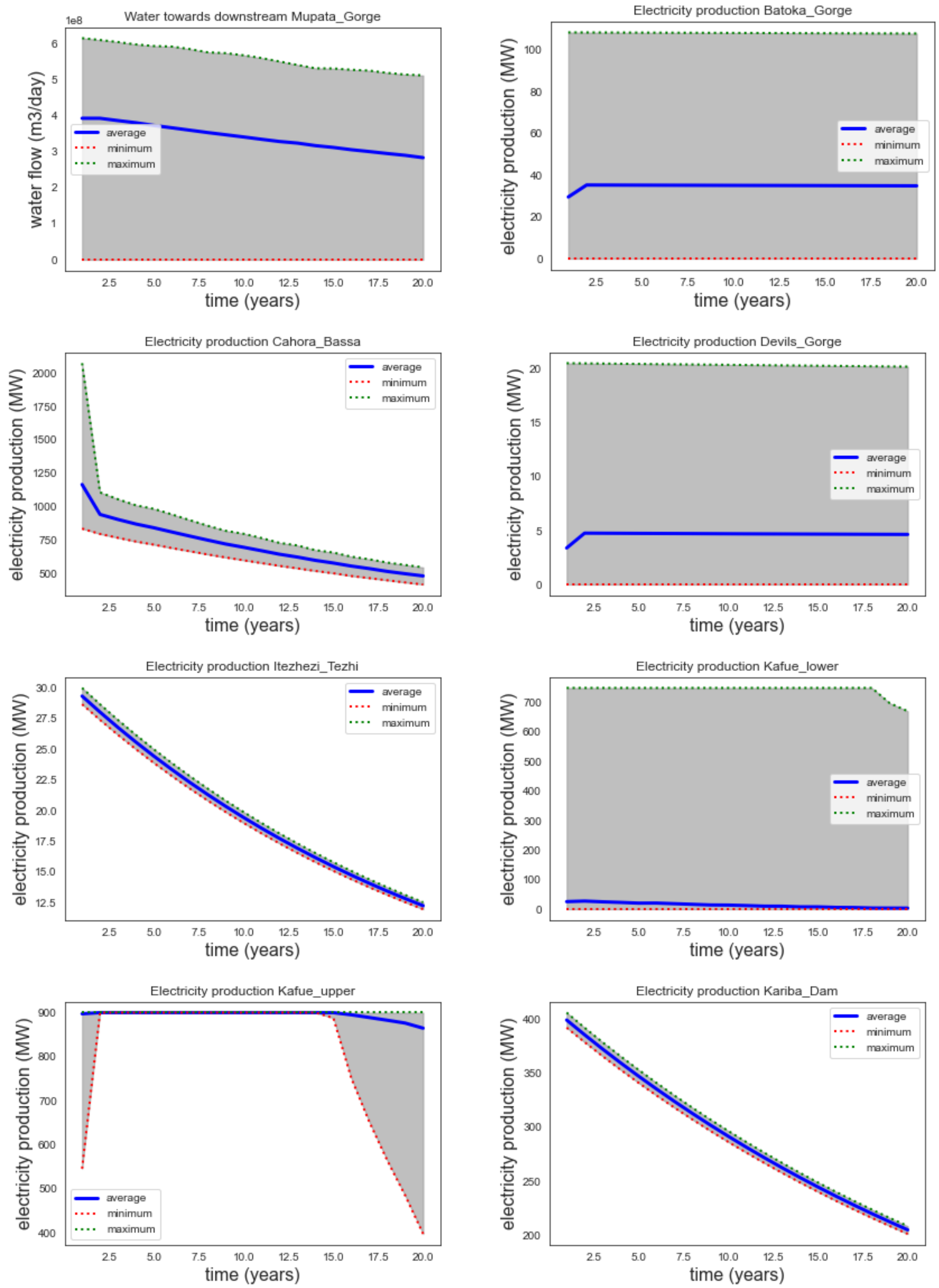

Water towards downstream Kafue_upper
1e8
water flow (m3/day)
time (years)
average
minimum
maximum
0.4
0.6
0.8
1.0
1.2
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0


Water towards downstream Kariba_Dam
1e8
water flow (m3/day)
time (years)
average
minimum
maximum
3.0
3.2
3.4
3.6
3.8
4.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

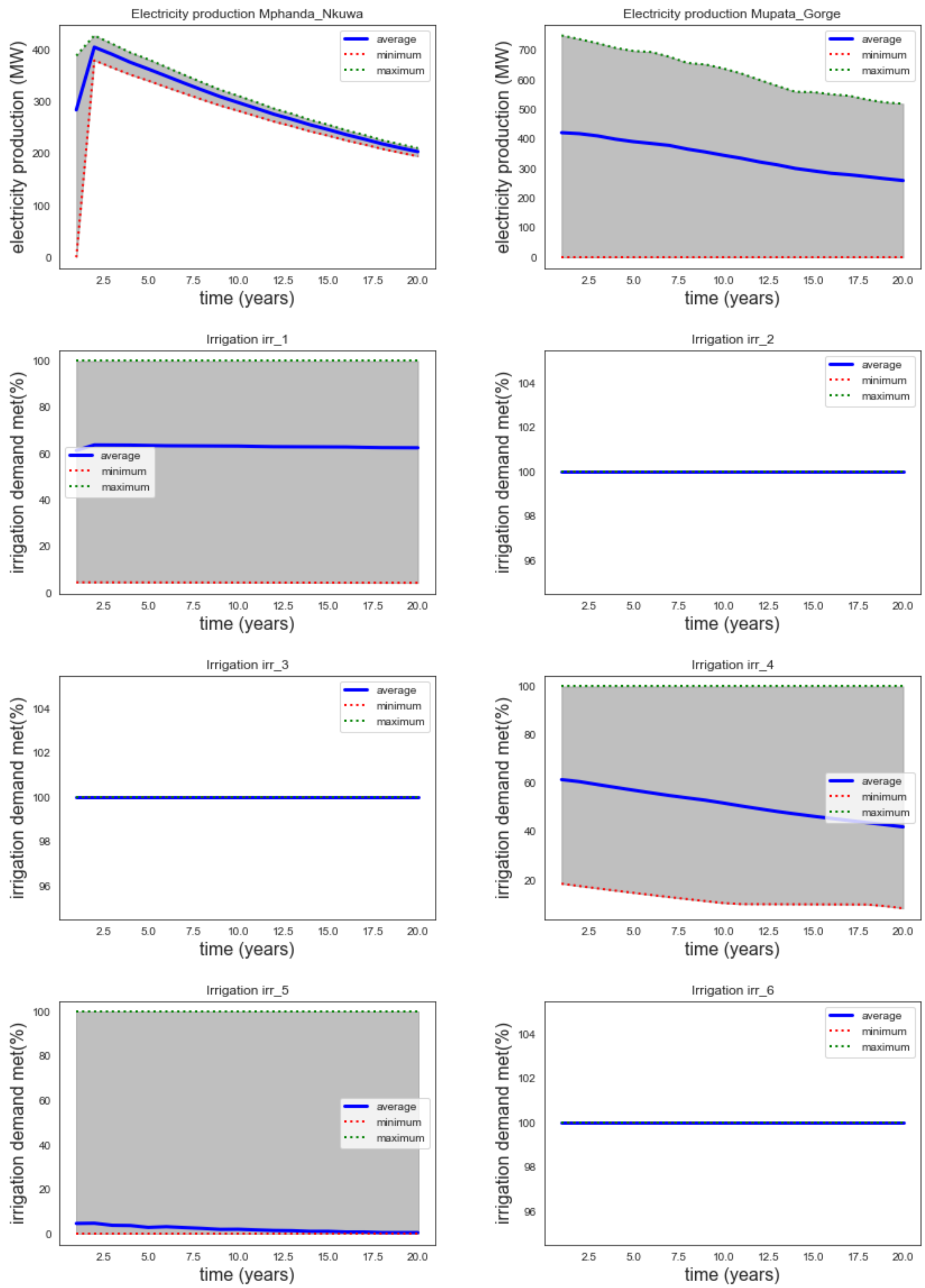

Water towards downstream Mphanda_Nkuwa
1e8
water flow (m3/day)
time (years)
average
minimum
maximum
0
1
2
3
4
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

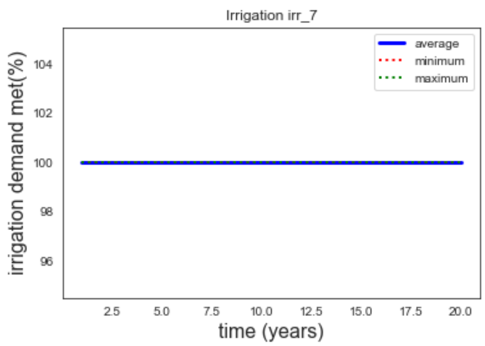
D.3.2 Worst case no cooperation

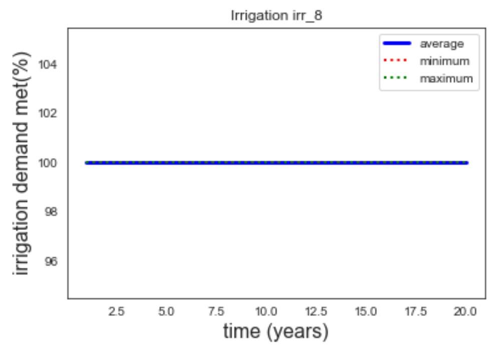
In the figures below the behaviour of the KPIs over time is presented. The yearly averages are depicted together with the yearly maximum and minimum reached values.

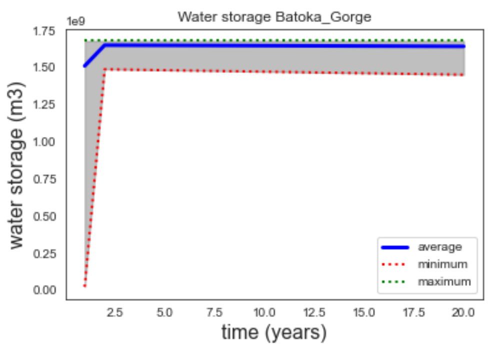


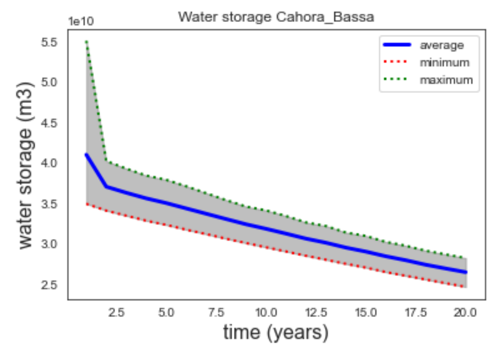
Water towards downstream Mupata_Gorge
1e8
water flow (m3/day)
time (years)
Electricity production Batoka_Gorge
Electricity production Cahora_Bassa
Electricity production Devils_Gorge
Electricity production Itezhezi_Tezhi
Electricity production Kafue_lower
Electricity production Kafue_upper
Electricity production Kariba_Dam
electricity production (MW)
average
minimum
maximum

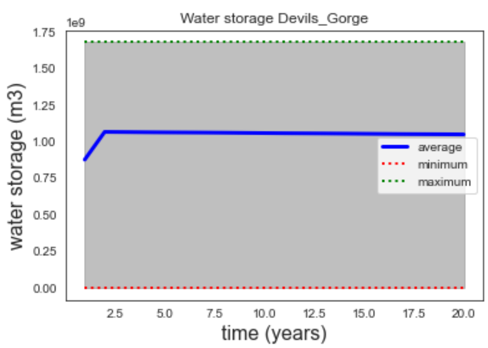

Electricity production Mphanda_Nkuwa
electricity production (MW)
time (years)
average
minimum
maximum
Electricity production Mupata_Gorge
electricity production (MW)
time (years)
average
minimum
maximum
Irrigation irr_1
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_2
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_3
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_4
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_5
irrigation demand met(%)
time (years)
average
minimum
maximum
Irrigation irr_6
irrigation demand met(%)
time (years)
average
minimum
maximum

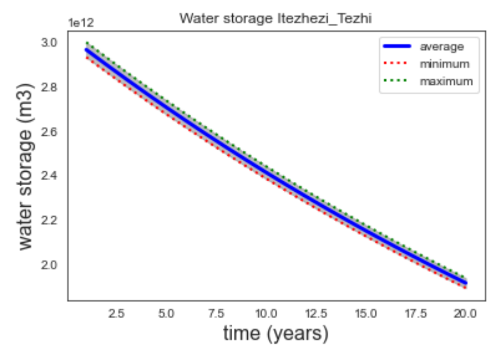

Irrigation irr_7
irrigation demand met(%)
time (years)
average
minimum
maximum

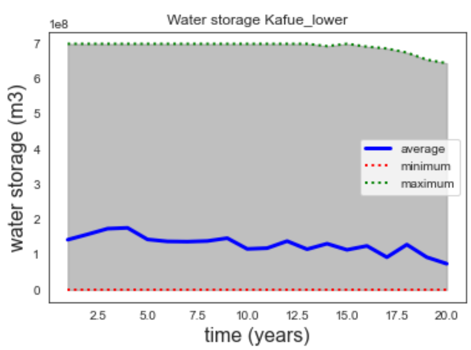

Irrigation irr_8
irrigation demand met(%)
time (years)
average
minimum
maximum

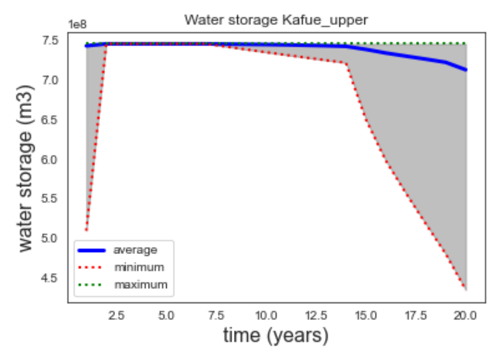

1e9
Water storage Batoka_Gorge
water storage (m3)
time (years)
average
minimum
maximum

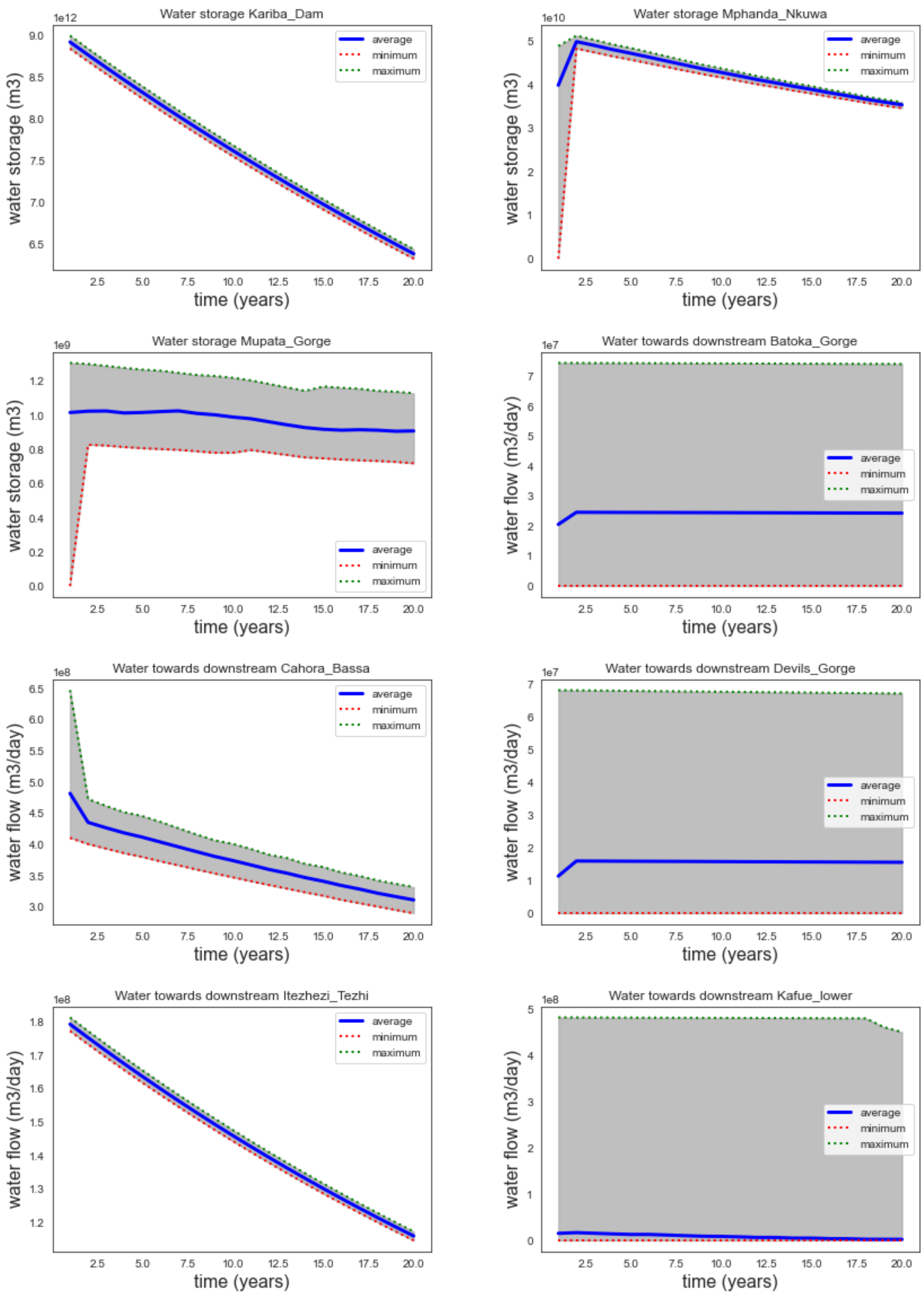

1e10
Water storage Cahora_Bassa
water storage (m3)
time (years)
average
minimum
maximum

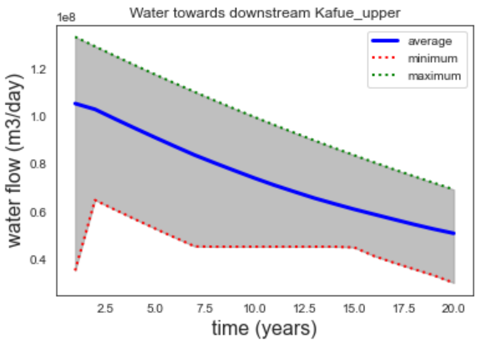

1e9
Water storage Devils_Gorge
water storage (m3)
time (years)
average
minimum
maximum

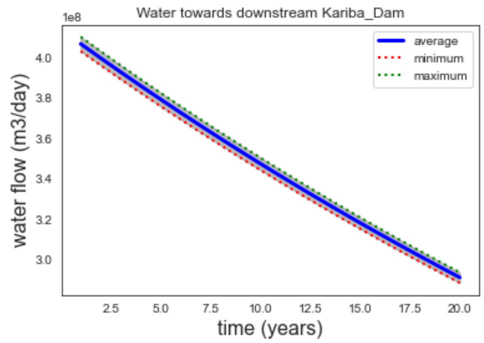

1e12
Water storage Itezhezi_Tezhi
water storage (m3)
time (years)
average
minimum
maximum

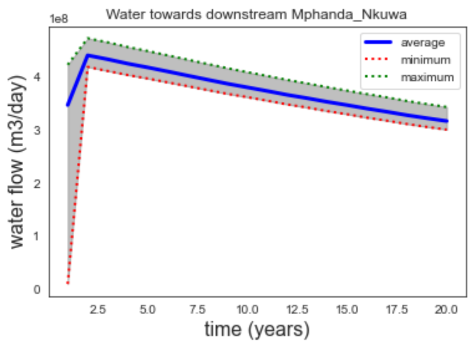

1e8
Water storage Kafue_lower
water storage (m3)
time (years)
average
minimum
maximum


1e8
Water storage Kafue_upper
water storage (m3)
time (years)
average
minimum
maximum


Water storage Kariba_Dam
1e12
water storage (m3)
time (years)
Water storage Mphanda_Nkuwa
1e10
water storage (m3)
time (years)
Water storage Mupata_Gorge
1e9
water storage (m3)
time (years)
Water towards downstream Batoka_Gorge
1e7
water flow (m3/day)
time (years)
Water towards downstream Cahora_Bassa
1e8
water flow (m3/day)
time (years)
Water towards downstream Devils_Gorge
1e7
water flow (m3/day)
time (years)
Water towards downstream Itezhezi_Tezhi
1e8
water flow (m3/day)
time (years)
Water towards downstream Kafue_lower
1e8
water flow (m3/day)
time (years)
average
minimum
maximum


Water towards downstream Kafue_upper
1e8
water flow (m3/day)
time (years)
average
minimum
maximum


Water towards downstream Kariba_Dam
1e8
water flow (m3/day)
time (years)
average
minimum
maximum


Water towards downstream Mphanda_Nkuwa
1e8
water flow (m3/day)
time (years)
average
minimum
maximum