Will the Benefits Keep Flowing?

Analysing the Effects of an Uncertain World on the Objectives of the Akosombo Dam

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Analysing the Effects of an Uncertain World on the Objectives of the Akosombo Dam

by

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Model files and Jupyter Notebooks for data visualisation are available at
`https://github.com/ArieTieszoon/Volta_opt_reevaluation`

Image on the cover by Barrón (2015)

TU Delft

Preface

After months of hard work, I am proud to present my graduation thesis on the effects of an uncertain world on the Akosombo. This thesis was written to obtain my master's degree in the Engineering and Policy Analysis program at the Faculty of Technology, Policy and Management at The Delft University of Technology.

However, this work was not possible without the help of others. My committee helped a lot in scoping the ambitious plans I had into a thesis-sized topic. Without that, I would likely still be busy for a year to come. I also want to thank my committee for giving me valuable insights when I was stuck, after which I could continue my progress. I specifically want to thank Dr. Jazmin Zatarain Salazar. I am incredibly grateful for your hands-on guidance through the (bi)weekly meetings. During these, you nudged me in the right direction while allowing me to pursue my own interests. This allowed me to stay on course and finish on time but also kept my enthusiasm from fleeting. I sincerely want to thank you for your time because I know you had little to give out. Secondly, I wish to express my gratitude to Prof. Dr. Jill Slinger for going the extra mile as my committee chair. Not only did you provide valuable feedback throughout the process, but you also supported me in going to Ghana and experience the Akosombo context instead of only reading it. This not only led to a better thesis but provided me with valuable personal lessons. Thirdly I want to thank Dr. Nazli Aydin. Although we only met a few times over the course of the thesis, I really appreciated the outsiders' feedback and your flexibility regarding the focus point of the thesis. I also had the great pleasure of working with Afua Owusu. Your help guiding me through your Akosombo model and helping Raoul and me with contacts in Ghana are really appreciated. Lastly, I want to say thank you to the interviewees in Ghana who received us enthusiastically and with whom we had great insightful discussions.

This thesis signifies both an end as well as a new beginning. I will start working, live in a different city, and explore new opportunities. But this text is my final work as a student of the TU Delft. I spent the previous seven years at this university wandering around, learning, exploring, and discovering new interests. I took some detours along the way but ended up at the finish line all the same and with much more experience than I would have otherwise. During this journey, I had many people by my side who I would like to thank. First of all, I am extremely grateful for the support of my girlfriend, my brother and my mother. Thank you for being so supportive when things were tough but also, thank you for the times in which we could share the good moments in life. I also wish to thank my roommates and friends for the fun we had over the years.

Ted Buskop
Delft, July 2022

Executive Summary

Introduction

The Akosombo dam in Ghana's Lower Volta River Basin provides essential economic benefits through hydropower generation, flood protection, and irrigation opportunities. However, since its construction was completed in 1965, the livelihood of the riverine communities drastically changed. The seasonal peak and low flows in the river, which provided environmental services for many downstream households, are now replaced with a stable river flow throughout the year to favour hydropower production. A study on dam reoperation is not only of interest to look into the possibilities of restoring healthy ecosystems but also to look at how current water demands in the basin can be sustained. Climate change and increased water demands for irrigation are expected to strain the water resources in the Lower Volta. Reoperation is also complicated by the absence of water treaties with neighbouring countries. This can result in lower flows from upstream riparian states due to their increasing water needs. In this study, we aim to understand the vulnerabilities of the Akosombo system while finding robust policies that can cope with challenging climate and demographic conditions. This study highlights the challenges in balancing irrigation, environmental, and hydropower goals while also identifying system vulnerabilities and opportunities for robust operations to meet the Lower Volta River water demands under future challenging conditions.

Knowledge gap

Previous literature shows that optimisation has already been performed on the Akosombo dam, and the trade-offs between objectives were analysed. However, to gain a more complete understanding, more uncertainties and levers need to be included in the analysis to find the robustness of policies, limits of operation, and the overall importance of certain factors. The ones deemed relevant for the Akosombo are climate change, upstream water use, treaties, irrigation demand change, extreme flow events, and energy storage. Next to that, the energy reliability objective was added to the simulation. These scenarios are not filled in beforehand but checked afterwards. Next to gaining insight into the Akosombo system, this thesis also addresses a methodological challenge. In current literature, many decisions on risk aversion are made beforehand in the simulation. By putting these decisions on return times, robustness, and system limits near the end of the analysis instead of within the simulation, the decision-maker can more easily change between assumptions and preferences. It will help their understanding of the system and reduce biases from the researcher. Including more uncertainties and being more transparent and flexible in the assumptions provides less biased decision support in the hope of improving stakeholder adoption.

With these insights in mind, the following research question has been researched: *What are the effects of uncertainties and levers concerning climate change, riparian water use, irrigation demands, and energy on optimised release policies for the Akosombo dam using a posteriori decided robustness metrics, climatic return times, and system limits?*

Research approach

To answer the research question, the following five steps were taken. First, the system was researched and described so that it could be translated into a simulation model for the uncertainty evaluation. Second, a selection of the previously optimised release policies from the literature was made. Third, each release policy was subjected to 2400 different scenarios, and the outcomes for each objective were gathered per year within the simulation. Fourth, these results were used to compare the robustness of each policy across different robustness metrics. Fifth, the system was analysed to see which variables are most important in the system and what combination of factors causes below-average system performance for certain return times.

Results

From the results, it becomes clear that the environmental and hydropower objectives trade off against each other across all selected policies across all 2400 scenarios. Whereas the policies prevented flooding in the historical situation, flooding will occur across many of the sampled scenarios. The hydropower policy has better results in the flood objective than the environmental policies. Across these scenarios, it also becomes clear that the currently used maximum hydropower policy has much variation in the energy produced and the reliability of that energy supply. The policies with higher environmental scores have a steady low production and energy reliability in the system. This is argued to be the lack of turbine capacity in the system that prevents energy from being generated at peak flows. Using various robustness metrics to define stakeholder preferences across objectives shows the same trade-offs as in the unmodified objective scores. Environmental policies do not perform well with energy objectives, while the hydropower policies do not work well for the irrigation and environmental objectives.

When looking into the importance of included uncertainties and system levers, it was seen that the water usages of Togo and Côte d'Ivoire play a significant role in the system. These countries, although having a small percentage of the basin area, contribute the largest flows towards the Volta Lake. The influence is negative on the energy and irrigation objectives. However, positive on the environmental and flood objectives. The environmental benefits from having less water during certain parts of the year and peak flows are reduced by the water usage upstream, lowering the flood risk. These abstractions will help (especially during August) since this uncertainty is most influential for the flood risk.

Discussion

Firstly, when considering Ghana's current energy sector, it is deemed unlikely that the environmental objective will be considered soon. Hydropower is a cheap energy source, and political powers want to keep the energy costs low, which is the responsibility of the organisation that operates the dams. With energy storage and extra turbines, things might change, but current technology is not able to store such large amounts of energy. However, the relative influence of the Akosombo is declining over the years due to an increase in other energy sources. At some point, when the relative energy production at Akosombo is limited, environmental flows may be able to be included. Secondly, even though the Volta Basin Authority introduced the Water Charter, the agreements in the currently unsigned document do firmly secure Ghana's water resources. Therefore, it is advised to find opportunities for benefit sharing so upstream states have an incentive to keep flows as they are or change them to benefit both riparian states.

Conclusion

The Akosombo dam performed and still performs a vital function in the Ghanaian energy grid, economic growth, and the lives of many. Also outside of Ghana. However, over the years since its inception, new functions were introduced, and the world has changed and will keep changing. To ensure the dam reaches its full potential and the benefits keep flowing, this study was performed to see what the effects of these changes are on multiple policies, each with different performance preferences over the objectives. From this study, it can be concluded that the uncertainties included in the analysis will alter system functioning. Not only will floods occur with the onset of climate change, but energy production and irrigation potential will also become lower if upstream states start to use more water. The most critical abstractions are those of Togo and Côte d'Ivoire. A benefit of this is that these abstractions also provide some protection against floods. It is therefore wise to create cooperation projects with these countries to safeguard the current benefits of the Akosombo and Kpong dam and create new benefits for all parties.

Limitations

This thesis has several limitations. Firstly, the study only generates what-if scenarios and cannot say anything about the probabilities of scenarios actually happening. The decision-maker or further research will have to assess the relevance of specific scenarios. Secondly, stakeholder preferences on performance return times, robustness and system limits were estimated. Thorough stakeholder engagement is needed to use the model in a more meaningful manner. Thirdly, for some input parameters, historical averages were taken, and it is unclear what the effect of this is on operation results in the future. Fourthly, the policies taken were optimised against historical data, resulting in policies that had zero flooding in the historical situation. Therefore no selection could be based on the flooding objective, meaning that there might be better policies against flooding, but this was not clear from the data.

Contents

1
Introduction

Over the years, water availability and too much or too little of it at the right or the wrong times has been an increasing problem. Extreme discharges in rivers can cause flooding (Cai et al., 2021) while too little can cause agricultural failures (Dewan, 2021) these, in turn, can go as far as creating political instability (Motevalli, 2021). Dams help alleviate this problem by creating reservoirs in a region to reduce water stress due to storage in the reservoir. These dams can also help protect against floods by storing the peak discharge and slowly releasing it again after the extreme event. As a bonus benefit, dams can generate electricity for a large number of households.

Unfortunately, next to these positive attributes of dams, dams can cause harm too. One such case where the implementation of a dam caused both harm and brought benefits is the case of the Akosombo dam in Ghana. The placement of the Aksombo dam in Ghana has been the cause of many current-day problems in the region. Such as coastal erosion, community resettlement, diseases, salt intrusion, seismic activities, weather pattern change, loss of cultures and the loss of jobs needed for livelihoods (Gyau-Boakye, 2001; Addo et al., 2018; Alves et al., 2020). However, the positive sides of the dam implementation should not be dismissed. It provides benefits such as a stable water supply, flood control, drought management, recreation, agriculture and electricity production (Shaktawat & Vadhera, 2021).

To reduce these negative effects, there have been calls to re-optimise the dam (Ntiamoa-Baidu et al., 2017) especially to restore the riverine ecosystems, which in the past were responsible for providing livelihoods for many in the basin (Owusu, Mul, van der Zaag, & Slinger, 2021). According to Owusu, Mul, Strauch, et al. (2021), one of the solutions could be to create new dam release policies for the water in the reservoir, one of which is to include e-flows - dam releases for environmental purposes. However, using a resource for one thing often means it cannot be used for the other, causing difficulties for current water users.

There are arguments to be made for both sides of the discussion on reoperation; however, it is essential to make a conscious and informed decision on the trade-offs between the multiple objectives. Owusu et al. (2022) created a dam optimisation model for the Akosombo dam to see what the best policies are to gain the most utility from the dam.

This research contributes by developing further on the work of Owusu et al. (2022). Their work resulted in a set of optimal policies for the Akosombo dam. However, dam optimisation can be categorised as a wicked problem due to uncertainties, risks, and different perspectives on values (Reed & Kasprzyk, 2009). Therefore, the objective of this thesis was to focus on the performance of optimised policies under deep uncertainty to get a sense of the robustness of each of the proposed policies while also gaining insight into the system behaviour and sensitivities using exploratory modelling (Bankes, 1993). This style of modelling was done to try and increase understanding of the system and provide constructive decision aiding (Tsoukiàs, 2008) to the decision-maker. This knowledge is necessary now that new agreements are on the table with upstream riparian states in the Water Charter of the Volta Basin Authority (, 2018). Additionally, this research contributes to the literature on evolutionary multi-objective direct policy search (EMODPS) for dams by adding flexibility in risk preferences throughout the analysis.

The decision-maker in this thesis is the Volta River Authority (VRA). The VRA is the operator of the dams in Ghana and has the mandate to produce electricity from these dams (Government of Ghana, 1961). This research provides an analysis of the objective outcomes under uncertainty, the robustness of release policies, scenario discovery for set operation limits, and the most important uncertainty factors in the system. Then, using this information, recommendations and insights are given to enhance and secure dam operation for the future.

Water management is arguably a grand challenge, especially when it is involved in carbon-free power generation needed to prevent severe climate change. This thesis is situated in Ghana, but many dams are transboundary and can be classified as an international grand challenge affecting agriculture, industry, drinking water, energy production and flood protection (see the blue Nile basin as an example (Aljazeera, 2021; Mutahi, 2020)). Analysing this challenge, including its uncertainties, multi-actor system, and supporting decision-makers in their choices, is of great importance.

The thesis first analyses current literature on dam optimisation and the Akosombo dam to define the research gap and the main research question (Chapter 2). Then, Chapter 3 introduces the research approach used together with the sub-questions associated with these. The chapter also defines the methods used in the study. Using these methods, the results are generated and shown in 4. Next, Chapter 5 places the results into the larger system context in which the dam operates together with the study's limitations. The final chapter answers the main research question and gives recommendations to the decision-maker, and suggests further angles of research.


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Knowledge gap and main research question

This chapter focuses on gathering relevant literature in the scope of the research topic and finding the knowledge gap in order to generate the main research question. First, the current literature on reservoir optimisation, including robustness and uncertainty, is reviewed to understand these concepts better and discuss them (Section 2.1). Following this, the research gap is defined, resulting in this thesis's main research question (Section 2.2).

2.1. Core concepts

Before describing the knowledge gap, it is important to analyse and discuss some key concepts that apply to this field of research and see where the discussion points are. These key concepts are: 'reservoir optimisation' (2.1.1), 'robustness in reservoir optimisation' (2.1.3), and 'stakeholder adoption ('2.1.4).

2.1.1. Reservoir optimisation

The Water Resource Commission of Ghana proposes to alter the release decisions for the Aksombo dam to increase hydropower and its reliability, improve downstream ecosystems and livelihoods, protect communities against floods, and reduce water-borne diseases (Ofosu et al., 2017). To find the new release policies, optimisation should be done to find the best solutions for these objectives. These new policies can be evaluated and implemented by the Volta River Authority (the dam operator). Since the Akosombo dam was built in 1965, new techniques have been developed to optimise water release policies for many criteria and scenarios. However, Giuliani et al. (2016) state that most reservoirs in the world are still managed using decisions set many years ago. In these decisions, reservoirs were optimised for normal weather conditions and only for a few objectives. However, 'normal' conditions do not always occur in the real world, and climate change could change that even more, more on that in Section 2.1.2. In the meantime, reservoirs increased in complexity over time due to the increase in functions they need to perform. Where the Akosombo dam was primarily built for hydropower (Gyau-Boakye, 2001), it is now trying to balance energy production, irrigation, and flood protection (Ofosu et al., 2017). While old release policies had only one optimisation objective in mind, today's problem is a multi-objective problem. This change requires a new approach to finding a release policy. The optimisation process of 'evolutionary multi-objective direct policy search' (EMODPS) has been found to determine better policies than traditional planning (Giuliani et al., 2016). The optimisation provides a promising technique to deal with the increasing complexity. Owusu et al. (2022) have applied the EMODPS method to the Akosombo system and found a Pareto set of optimal release policies for the historical situation and selected climate scenarios. The authors suggest that more research is required to find robust policies that perform well in future uncertainties such as climate and water use changes.

2.1.2. States of the World

Climate change is altering the water resources flowing into the Volta Basin, causing the monthly runoff into lake Volta to increase in the wet season while a decrease is expected during the dry season (McCartney et al., 2012; Jin et al., 2018; Jung et al., 2012). Meanwhile, the start of the rainy season will shift towards later in the year but keep ending at the same time, causing larger flow intensities (Van de Giesen et al., 2010). Although, Sood et al. (2013) found that overall rainfall will decrease. These studies indicate the climate uncertainty involved in the basin. Next to overall climate change, there is also the uncertainty of inflow extremes in the basin since historical data is often too short to have captured the full range of extremes (Salazar et al., 2017).

However, there are more indications of uncertainties within the basin. Meaning there are more things that can alter the performance of the Akosombo system. One of them is basin cooperation. The six riparian countries have come together in the Volta Basin Authority (VBA) since 2007 to enhance cooperation and consultation regarding new developments, equitable distribution of benefits from the shared source, authorise new projects and contribute to poverty reduction and sustainable development (VBA, 2007b). However, this cooperation is not always as sound as it is made out to be. During the last decade, growing tensions have arisen between Ghana and Burkina Faso due to the creation of large dams upstream, creating problems in stream flow in downstream Ghana, both in terms of flooding as in discharge deprivation (Zakaria & Matsui, 2021). Next to that, Yankey (2019) states that stakeholders start new developments without authorisation and that the VBA has no tools to ensure cooperation or block harmful proposals. Going by the most recent data from FAO (2018), Ghana has not yet secured any water through treaties. Taking this into account, the question that arises is: what will happen when upstream riparian states start to use more water from the river themselves? With described cooperation in the basin, this can entail that upstream riparian states can decide to use water for their own needs. The effects of population growth and an increase in living conditions will lead to more freshwater use Sophocleous (2004). Not only does the larger population need water to drink and basic sanitation, but it also needs water to grow more crops in order to feed inhabitants and livestock, and produce products these citizens need. This gives reason to believe lower inflows into the Volta Lake threaten the operation and functioning of the Akosombo dam.

Increasing temperatures in West Africa (Masson-Delmotte et al., 2021) also cause an increase in crop water usage, on top of overall increasing agricultural demands (McCartney et al., 2012). However, new technologies such as water reuse and efficient irrigation might lead to a decrease in water use in agriculture so that it can be used for other purposes (Perry et al., 2017).

As a final change to the system, energy storage capabilities will start to play a bigger role in sustainable energy systems as this can increase the reliability of these systems (Gallo et al., 2016; Hadjipaschalis et al., 2009). This possibility might also be of interest for the Akosombo case since this can alleviate moments of low production.

Re-evaluating previously optimised policies under uncertainties has been included in the EMODPS study by Quinn et al. (2018). This resulted in a better understanding of how the reservoir system performed under these different States Of the World (SOWs). From these results, they could also gather information about each policy's robustness. In general, it has been found that defining and incorporating more uncertainties and possible futures could help clarify the system's inner workings and contribute to more robust policies (Gong et al., 2017). Therefore, it is reasonable to assume that including different SOWs in the Akosombo case will also bring more insight into the system and result in more robust decisions.

2.1.3. Robustness in reservoir optimisation

Robustness can be defined as the ability of a system to perform well over a large selection of possible futures, and these can be measured using a wide range of performance metrics (McPhail et al., 2018). The current research report on the Akosombo dam by Ntiamoa-Baidu et al. (2017) combines the knowledge of many researchers from a range of disciplines to understand the consequences of reoptimisation better. However, in many chapters, only four different release flow scenarios and only two climate scenarios are used. Also, Owusu et al. (2022) incorporated limited uncertainty in the research process. In total, five climate scenarios were investigated. One could argue that many more futures and options exist in which the dam should and could operate. From a few scenarios, one can not say if a release policy is robust or not.

EMODPS optimisation has been tested to include robustness, even with different perspectives on what robustness is (Quinn et al., 2017; Giuliani & Castelletti, 2016). Giuliani & Castelletti (2016) argue that robustness is a decision-maker's preference and can be captured in metrics ranging from risk-averse to risk accepting. The problem is that decision-makers themselves are not always sure how robust they want a solution to be. These attitudes can subsequently change over time due to the experiences of (model) system failures or (model) system successes. Therefore the authors argue that this robustness metric should also be a parameter in the uncertainty analysis. They found that the different robustness framings can greatly impact the outcomes of a reservoir simulation. Quinn et al. (2017) built on top of the previous article by translating the different robustness metrics into the objective formulas to optimise against in the EMODPS framework, resulting in different optimal policies for different risk attitudes. They found that these different objective functions may also lead to large unintended consequences. These 'rival framings' of the problem can occur due to misinterpretation of the goals or mathematical simplifications and assumptions. Therefore, it is essential to consider both a range of robustness metrics and formulation in the system since one definition does not allow for complete understanding. In both papers, however, risk aversion does not change among the different objectives. Once a stakeholder is risk-averse, it will be risk-averse for all objectives. One could argue that a stakeholder can choose to have high-risk tolerance to hydropower but risk aversion for irrigation.

As argued, perspectives on robustness are essential. However, more uncertainty could be included to make policies even more robust. Salazar et al. (2016) and Giuliani et al. (2016) state that more efforts should be put into the inclusion of more uncertainties in modelling reservoir systems with EMODPS. Recommended uncertainties are societal challenges and climate change. Woodruff et al. (2013) suggests that these uncertainties, as well as the inclusion of multiple objective formulations and model formulations, create a better understanding of the system. This suggestion is close to the argument of (Maier et al., 2014) who argue for optimisation with evolutionary algorithms as a tool for learning instead of providing 'the' answer. One of the ways to learn is through sensitivity analysis (Pianosi et al., 2016), which can also be used to find robust policies as in Quinn et al. (2017). Pianosi et al. (2016) found that in environmental models, sensitivity analyses can increase the understanding of the real-world system by providing information on the influential levers in the system.

2.1.4. Stakeholder adoption

Another topic of interest in the field of reservoir optimisation is the adoption of optimised policies. In the Ghanaian case, the report of the reoptimisation was published in 2017, while at the time of writing this thesis, it is 2022. Slow uptake is something Giuliani et al. (2021) found too in cases worldwide. The authors did a literature review on optimal reservoir control and found that there is low adoption of practitioners in real-life situations even though new optimisation techniques could improve reservoir control and that much of the research focused on creating open-source tools. These open-source tools mean that they are free to use by practitioners. The lack of uptake is argued to be the cause of a preference for simpler tools and the lack of insight into how optimisation processes, such as EMODPS, work. The optimisation method is seen as a 'black box. The recommendations are difficult to understand and explain. These arguments are also given by Ren et al. (2019). The lack of uptake was also noticed by (Salazar et al., 2016).

It must be said that the papers did not focus on making the optimisation explainable or insightful. Instead, the main focus was to prove and show there were better outcomes than any other method. Although explainability is arguably an essential part of decision-making and uptake, very little focus has been put on these aspects in any of the read EMODPS papers.

The importance of insight and explainability of the models and results of water systems is given by Dobson et al. (2019) who state that stakeholders tend not to trust optimisation study results if they are not fully aware of or distrust the model's assumptions. In the study, the authors try to increase credibility by checking system performance under uncertainty. Unfortunately, this does not address the decision-maker's awareness or trust towards the actual assumptions. Mahmoud et al. (2009) argue that uncertainty can only be communicated if the stakeholders trust the scenarios shown and deem them credible. One way to do this is by being transparent to stakeholders and involving them in the process. Where stakeholder inclusion is already included in many forms in System Dynamics (SD) modelling, the dam optimisation literature has not. Examples of SD stakeholder inclusion are group model building (Vennix, 1996), mediated modelling (Van den Belt, 2004), or stakeholder consultation (Nava Guerrero, 2016), model as a boundary object (Luna-Reyes et al., 2019) modelling in the muddled middle (Clifford-Holmes et al., 2017). Unfortunately, these types of collaboration are not apparent in the EMODPS framework. A difficulty with the EMODPS method, compared to SD, is that essential model settings need to be set a priori to the optimisation process. Only then can the optimisation algorithm find the best release policies. The optimisation takes a long time, so a change in stakeholder preferences can not instantly be discussed and explored with that stakeholders. This delay becomes a problem when stakeholders change their preferences when presented with the consequences of their previous preferences. Therefore it is argued to be fruitful to move from a priori decided model settings to a posteriori decided models settings before finding the most optimal policy for those preferences. This way, the decision-maker can learn more in a short amount of time because they can change their preferences on the fly with some optimal 'trial' release policies.

2.2. Knowledge gap and research question

The literature in Section 2.1.1 has shown that previously unincluded objectives in the Akosombo dam can benefit from reoptimisation. An effective way to do this is through EMODPS since these find the best solutions for the set robustness metrics and scenarios. The Akosombo dam operation has been optimised by Owusu et al. (2022) and created a set of Pareto optimal policies. However, current research has not looked extensively at uncertainties stated in Section 2.1.2 and the associated set of different scenarios in which the dam needs to operate. The uncertainties that can play a role in the Akosombo system are the changes in irrigation demand, climate change, upstream water use, water treaty implementation, and energy storage. Including these uncertainties can enhance system understanding and lead to more robust policies.

Section 2.1.3 shows that no robustness test of Akosombo release policies has been performed. These tests are important as it provides a learning opportunity for decision-makers and enhances their system understanding. It has also been found that it is important to include multiple robustness metrics in the evaluation since decision-makers are not always sure of their preferences beforehand and can change their preferences after being faced with the outcomes. One way of enhancing this learning is by including sensitivity analysis to find the most critical levers in the system so more robust policies can be created.

From the above, it can be concluded that the gap that currently exists in the Akosombo reoptimisation is that there is no information on the system's vulnerabilities nor on the robustness of release policies when climate, riparian water use, energy storage uncertainties and levers are included. The gap in optimisation literature is that more choices should be made by decision-makers and allow them to quickly interact with the results for them to learn the consequence of certain choices. This thesis will focus on postponing decisions for robustness metrics, preferred return times of outcomes due to climatic events, and system limits, to the final analysis instead of within the simulation. This way, biases from the researcher will be reduced, and stakeholder preferences will be revealed more quickly. This will give the decision-maker quick control of what the requirements and assumptions are and indicate the effects these decisions have to learn what it actually wants while also trusting the outcomes better. Once the requirements are set a posteriori of the simulation through stakeholder interaction, the optimisation can be done again to find the best policy for those preferences to find the exact best policy.

When taking the many objective robust decision making (MORDM) framework of Kasprzyk et al. (2013) (see Figure 2.1), literature has already focused on creating an initial model for the Akosombo and Kpong dam system, generated optimised policies (in this case with EMODPS), and has also analysed the trade-offs apparent in the system. However, what is still missing are the uncertainties that play a role in the system together with levers to allow for uncertainty analysis and scenario discovery. That is why this thesis aims to support decision-making by filling these gaps.

This research will help the Volta River Authority make decisions on new release policies considering different future states of the world. More specifically, this thesis will aim to provide more insight into the robustness of previously defined optimal policies under uncertainties while maintaining a flexible method in which robustness risk attitudes and return times can easily be adapted after the simulation runs, intending to enhance system understanding and trust in the outcomes of EMODPS policies. This thesis, therefore, has the following research question.

What are the effects of uncertainties and levers concerning climate change, riparian water use, irrigation demands, and energy on optimised release policies for the Akosombo dam using a posteriori decided robustness metrics, climatic return times, and system limits?

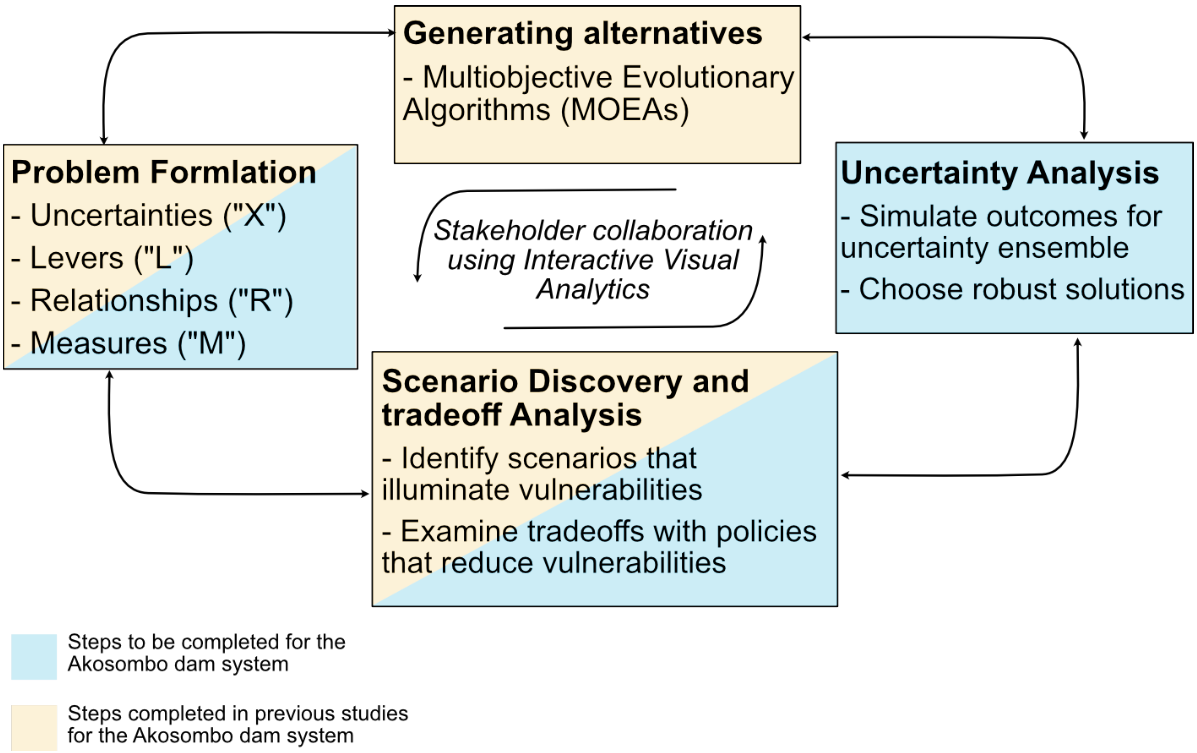

Figure 2.1: The MORDM framework of Kasprzyk et al. (2013) with an indication of the steps that are completed for the Akosombo case in previous studies and which ones will be completed in this study

3
Research approach and methods: From historical to future

This chapter details how the main research question (as formulated in section 2.2) will be answered. The research approach is defined together with what is done in each research phase. Each research phase answers the associated sub-research question.

3.1. Research approach

This research aims to give policymakers insight into the trade-offs and vulnerabilities that exist in the Akosombo dam system. This is done by exploring the behaviour and trade-offs in the objectives under different uncertainties and robustness preferences. These insights will allow decision-makers to decide which release policy is most suitable for their goals and what vulnerabilities they need to monitor. A modelling approach allows for easily testing a range of release policies and scenarios to explore potential solutions to a problem. These results can be used to advise or interactively discuss with policymakers. Using scenarios helps decision-makers test their assumptions and alter their mental models accordingly (Wack, 1985a,b). As a consequence, system understanding is enhanced (Gilbert et al., 2018). Scenario-based modelling has also shown to lead to more robust decision-making when compared to forecasting models (Gong et al., 2017). The combination of large-scale experimentation, enhancing understanding, and robust decision-making, make the scenario modelling approach applicable for this thesis.

The exploratory modelling approach will be used in this thesis since the approach aims to explore the system under varying assumptions and uncertainties Bankes (1993). Moallemi et al. (2020) describes two sub-approaches of exploratory modelling that apply to the goals of this thesis: the many-objective optimisation and the stress testing approaches. In the stress testing approach, a previously defined set of policies is tested against a sampled set of uncertainties resulting in ranges of good operation. The many-objective optimisation approach tries to find policies that perform well across multiple objectives in one specific scenario. This thesis will combine these two approaches by using many-objective optimisation to find promising policies that will then be subjected to the stress testing approach. These approaches can be filled into the taxonomy of robustness frameworks created by (Herman et al., 2015). The resulting framework, as seen in Figure 3.1, is adapted from Quinn et al. (2018) who used the framework of Herman et al. (2015) to first find policies that perform well through EMODPS (multi-objective optimisation) and then stress test the policies by re-evaluating them. Step 1 of Figure 3.1 has been added to provide an in-depth analysis of the Akosombo system and its inner workings. Step five has also been slightly adapted to, next to scenario discovery, include feature scoring in the analysis to provide more insight into the system.

3.1.1. Sub-questions

This approach of five steps results in the following five sub-questions that help answer the main research question:

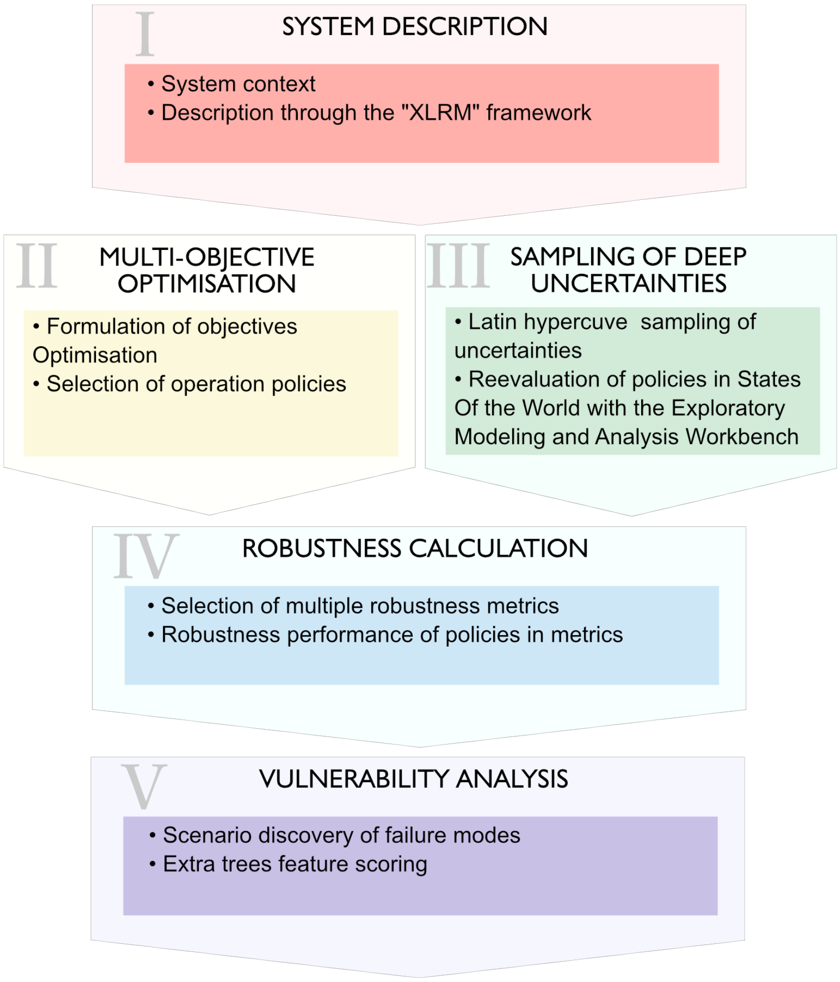

Figure 3.1: Method used in this thesis (adapted from Quinn et al. (2018) and Herman et al. (2015))

1. What are the factors that influence the re-operation of the Akosombo dam, and how do these interact?
2. What are optimal release policies for the Akosombo dam under historical conditions?
3. How does the Akosombo dam perform under a wide range of uncertainties?
4. How do optimised release policies perform under different robustness metrics?
5. What factors or combination of factors cause vulnerabilities in the functioning of the Akosombo dam?

3.2. System description

Before finding and testing policies, this thesis first describes the Akosombo system is described through the XLRM framework (Figure 3.2) of Lempert (2003). This is done to provide a clear overview of the parameters that can change in phase three of the research. The section will highlight the essential parts of the system that are modelled to create enhanced system understanding. The section also aims to give a general introduction to the Akosombo system with the help of literature and interviews done with stakeholders and actors in the system (see Appendix B). The interviews were done under the approval of the Delft University of Technology Human Research Ethics Committee for the PhD research of A. Owusu. The interviews did not provide input for the modelling, as these were done after the modelling phase. However, they provide essential information to the context of this research and are used to validate certain modelling choices. Information from interviews is indicated with "(Interviews, 2022)".

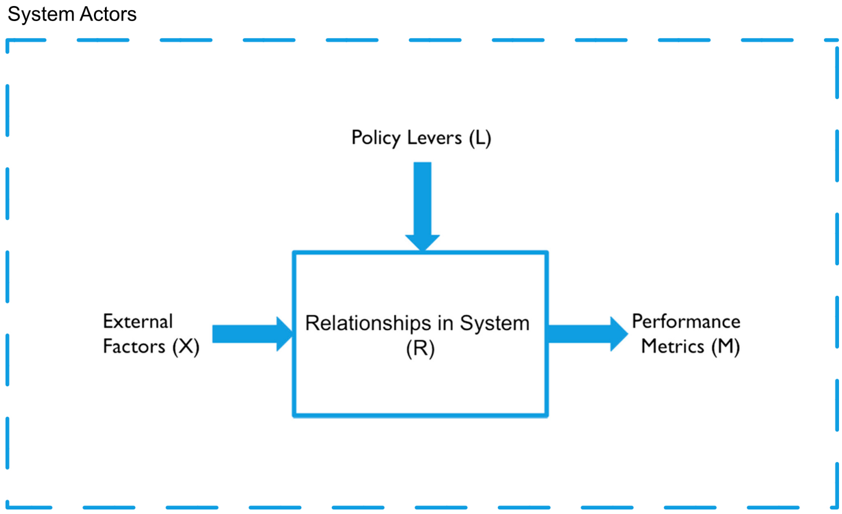

Figure 3.2: The XLRM framework adapted from Kwakkel (2017a), based on the system diagram of Enserink et al. (2010). The dashed blue box indicates the system boundary on which the actors exert influence. The actors are placed outside the boundary since they are not limited to the system under consideration and can perform actions outside of the considered system.

The system description will be based on the previous study by Owusu et al. (2022), supplemented by literature and grey literature. The literature will provide a general functioning of the Lower Volta Basin and the operation of the Akosombo and Kpong dams, together with the associated uncertainties. This system description is used to define the adapted simulation model (See appendix C). This formalisation is done according to the filled-in XLRM framework found in phase 1 of the research since this allows for easy adaptation of the model for running scenarios (Lempert, 2003) in phase three of the study.

The following section first gives some context of the system and is then structured according to the XLRM framework presented in Figure 3.2. The system boundary is set first. From here, the actors in the system are described. Then the performance metrics are described in section 3.2.4. This is followed by levers available within the system to try and reach the best performance (Section 3.2.5). From here, the external factors are defined in section 3.2.6 and the uncertainty associated with these. These previous steps are then used in section 3.2.7 to describe the inner workings of the system and how the inputs are translated to outputs. Figure 3.8 presents the XLRM framework used in this study.

3.2.1. System context

This section aims to give a general introduction to the Akosombo system with the help of literature and interviews done with stakeholders and actors in the system (see Appendix B). The interviews were done under the approval of the Delft University of Technology Human Research Ethics Committee for the PhD research of A. Owusu.

The Akosombo dam is located in Ghana, creating the largest man-made lake in the world in terms of area (Shahin, 2002). The dam is situated in the Lower Volta Basin near the Gulf of Guinea all the way downstream of the Volta river basin. The amount of people living in the basin is about 31 million (Baah-Kumi & Ward, 2020). However, the amount of people affected by it is much larger due to electricity generation from built dams being used in areas outside the basin area (WAPP, 2020) and causing blackouts when the dam is disrupted (GIBBAH, 2019). The same can be assumed about industrial and agricultural activities made possible by the inflows affecting many more outside of the basin when considering that the capital of Ghana, Accra, falls outside the basin.

The dam is currently used for multiple services, such as hydropower production, irrigation, and flood protection. The current discussion focuses on also adding environmental flows to that list of services.

Kpong dam

The Akosombo dam works in tandem with the smaller Kpong dam, which is a bit further downstream and provides a reservoir for future irrigation (Interviews, 2022). The current release policy of the Kpong dam is to have a 'fixed head' or 'run of the river' policy. This means there is a fixed water level in the reservoir, and everything that comes in goes out. Everything released from the Akosombo dam is either used for irrigation or flows through the Kpong dam. It either flows through the turbines for hydropower production or is spilled when there is too much release from Akosombo for the turbines. Spillage happens quite often during big releases of Akosombo, and these high releases also interfere with the 'fixed head' of Kpong (Interviews, 2022).

Tributaries of Lake Volta

A river basin is an area in which the precipitation that falls in that area contributes to the discharge of a particular river, also known as the drainage area (Uereyen & Kuenzer, 2019). In the case of the Volta River Basin, this area spans six countries in West Africa: Burkina Faso, Mali, Benin, Côte d'Ivoire, Togo, and Ghana. In this thesis, Mali is not considered since the Volta basin has a limited area in Mali and no significant rivers flowing from it into Ghana. Together with the fact that rainfall decreases from north to south in the basin(McCartney et al., 2012), Mali is assumed to have little influence on the Ghanaian water resources. The Volta river basin consists of multiple rivers contributing to the Lake Volta reservoir. In this thesis, the rivers considered are the Oti, Black Volta, and White Volta rivers. These rivers account for about 81% of the Volta lake inflow, while another 17% is attributed to the Lower Volta tributaries (Goes, 2005).

The influence of each river on inflow into Ghana and lake Volta has been investigated and is shown in Table 3.1. The stations have been chosen as close to the border as possible to quantify the amount of water that enters Ghana from other countries. Using data from the Global Runoff Data Centre (GRDC, 2022), which has both monthly and daily discharge data for 52 Volta basin stations and maps of the catchment area that concentrates to the station. The stations selected are Ousessa, Nangodi, Yarugu, Tagou, Arly, Porga, Bamboi, Sabari, and Senchi. See Figure 3.3 for their locations. Except for Senchi, each of these stations is located near a country's border and therefore giving an indication of the Ghanaian water dependency. Senchi is selected to give an indication of how much water flows into the Volta lake. For Senchi, only data before 1964 is used as the Akosombo dam was built after this date and altered the outflow. See appendix A for the full details. The total amount of water that is out of control of the Ghanaian government is equal to the sum of discharges in Nangodi, Yarugu, Bamboi, and Sabari. In total, this is 23.0 $km^3/year$ or 60.18% of the total inflow into the Volta lake.

Table 3.1: Volta Basin discharge stations, their flows, and contributions to the Volta lake

Station	Mean annual discharge [$km^3/year$]	Water collected between stations [$km^3/year$]	Flow of total inflow of Lake Volta [-]	Water collection of total inflow Lake Volta [-]
1. Ouessa	1.38	1.38	3.61	3.61
2. Nangodi	0.69	0.69	1.81	1.81
3. Yarugu	2.31	2.31	6.04	6.04
4. Tagou	0.29	0.29	0.76	0.76
5. Arly	0.31	0.31	0.81	0.81
6. Porga	1.78	1.18	4.66	3.09
7. Bamboi	8.52	7.14	22.29	18.68
8. Sabari	11.48	9.7	30.04	25.38
9. Senchi	38.22	15.22	100.00	39.82

Basin cooperation

Since 2007 the six riparian countries come together in the Volta Basin Authority (VBA) to enhance cooperation and consultation in the basin regarding new developments, equitable distribution of benefits coming from the shared source, authorise new projects and contribute to poverty reduction and sustainable development (VBA, 2007b). However, this cooperation is not always as sound as it is made out to be. During the last decade, growing tensions have arisen between Ghana and Burkina Faso due to the creation of large dams upstream, creating problems in streamflow in downstream Ghana, both in terms of flooding as in discharge deprivation (Zakaria & Matsui, 2021). Burkina Faso has a large

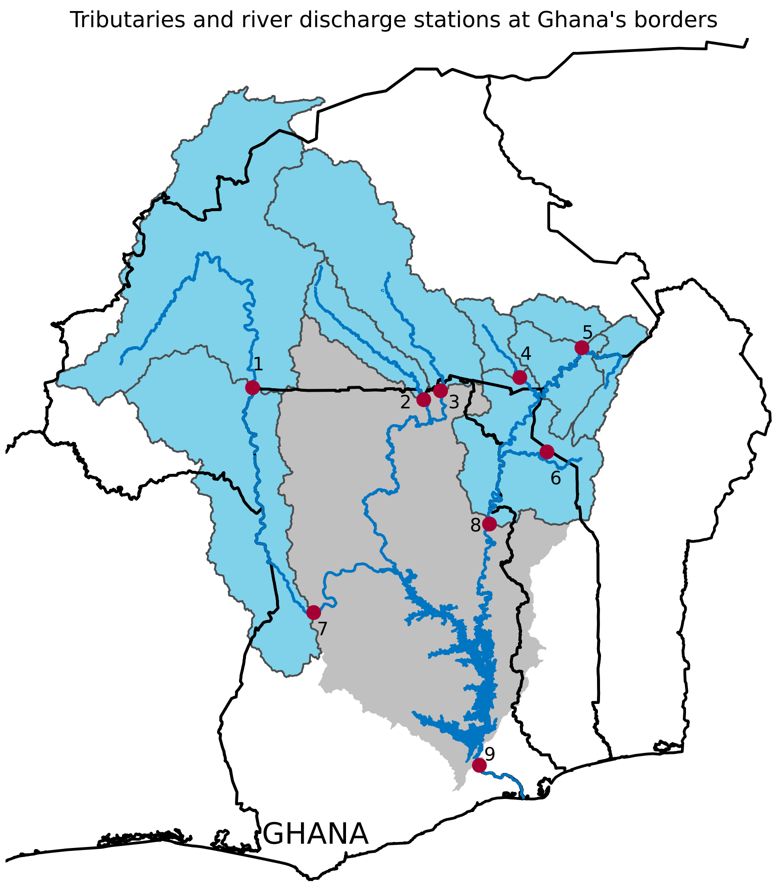

Figure 3.3: The Volta basin tributaries that lie (mainly) outside of Ghana. In light blue is the catchment area of the stations. In red are the stations considered. The country borders are black, and the water bodies are dark blue. The grey area represents the rest of the Volta basin area. (1:Ouessa, 2:Nangodi, 3:Yarugu, 4:Tagou, 5:Arly, 6:Porga, 7:Bamboi, 8:Sabari, 9:Senchi)

basin area but does not contribute much to flow, see Section 3.2.1. Nevertheless, (Interviews, 2022) indicate that the VRA still sees Burkina Faso as one of Ghana's main threats to water resources. Lack of cooperation was also found by Yankey (2019) who states that stakeholders start new developments without authorisation and that the VBA has no tools to ensure cooperation and block harmful proposals. Going by the most recent data from FAO (2018), Ghana has not yet secured any water through treaties. This is one of the reasons why the Ghanaian Water Resource Commission appointed transboundary cooperation as one of its priorities (WRC, 2021).

3.2.2. System boundary

The system boundary can largely be defined by geographical boundaries and the four envisioned objectives in the system. These objectives are hydropower generation, flood control, environmental flows, and irrigation (Owusu et al., 2022). As seen in Figure 3.4, the Akosombo is situated in the Lower Volta Basin and generates its benefits locally or downstream. The electricity generation happens at Akosombo and Kpong itself and is distributed from there. The environmental flows are released at Akosombo and Kpong to serve downstream ecosystems. The Irrigation project sources its water upstream of Kpong. Lastly, flooding occurs in the region. Outside this geographical region, the upstream states are also considered in the system boundary as these provide Ghana with most of its water resources (see Section 3.2.1). With the inclusion of these countries, their water usages and social relations with Ghana also need to be included in the analysis.

Factors left outside of the system boundary in this study consist of changes in factors over time, such as demand growth. Next to that, Ghanaian upstream influences and planned infrastructure are left out of the modelling scope. Second-order effects of changes in metric outcomes are left out of the thesis. Examples of these are increased electricity prices when there is less hydropower or decreased food security due to irrigation demands not being met. Other than the availability or absence of environmental flows, no negative side effects of the Akosombo and Kpong were modelled. Another set of factors that are not modelled are the power relations between countries, except for upstream and downstream relations. This means that, for example, the larger energy system is not modelled and therefore does not include the power dynamics between electricity exporting Ghana and importing Togo WAPP (2020).

3.2.3. System actors

Within the set system boundary, multiple actors are active, and each has their own set of actions they can perform. The actors are placed outside of the system boundary since each of them has more systems in which they are active.

Volta River Authority

The Volta Basin Authority is mandated to produce power in the Ghanaian power grid (Government of Ghana, 1961) and controls the dams in Ghana and other types of power plants such as thermal and renewable (VRA, n.d.-b). They also plan how much energy should come from which source and when. The VRA is, therefore, the main decision-maker on the release policies in the system. Within the XLRM-framework, they are assumed to also decide the performance metrics, energy storage, and advice in creating treaties. See Section 3.2.4 and 3.2.5 for more detail on the performance metrics and levers.

Upstream states

As discussed in Section 3.2.1, the upstream countries provide Ghana with many water resources. These countries could alter inflows if their own water needs increase. Therefore, their action in the defined system is to take out water for consumptive use to satisfy their needs. Meanwhile, they are also part of the treaty-building process. The upstream riparian states considered in this thesis consist of Burkina Faso, Benin, Côte d'Ivoire and Togo. See Section 3.2.5 and 3.2.6 for more information on the treaties and water usages.

Volta Basin Authority

The Volta Basin Authority (VBA) is an organisation formed by the six riparian countries. The VBA aims to promote consultation between countries, equitable distribution of the benefit of water usage, authorise impactful projects, and contribute to poverty reduction and sustainable development of the

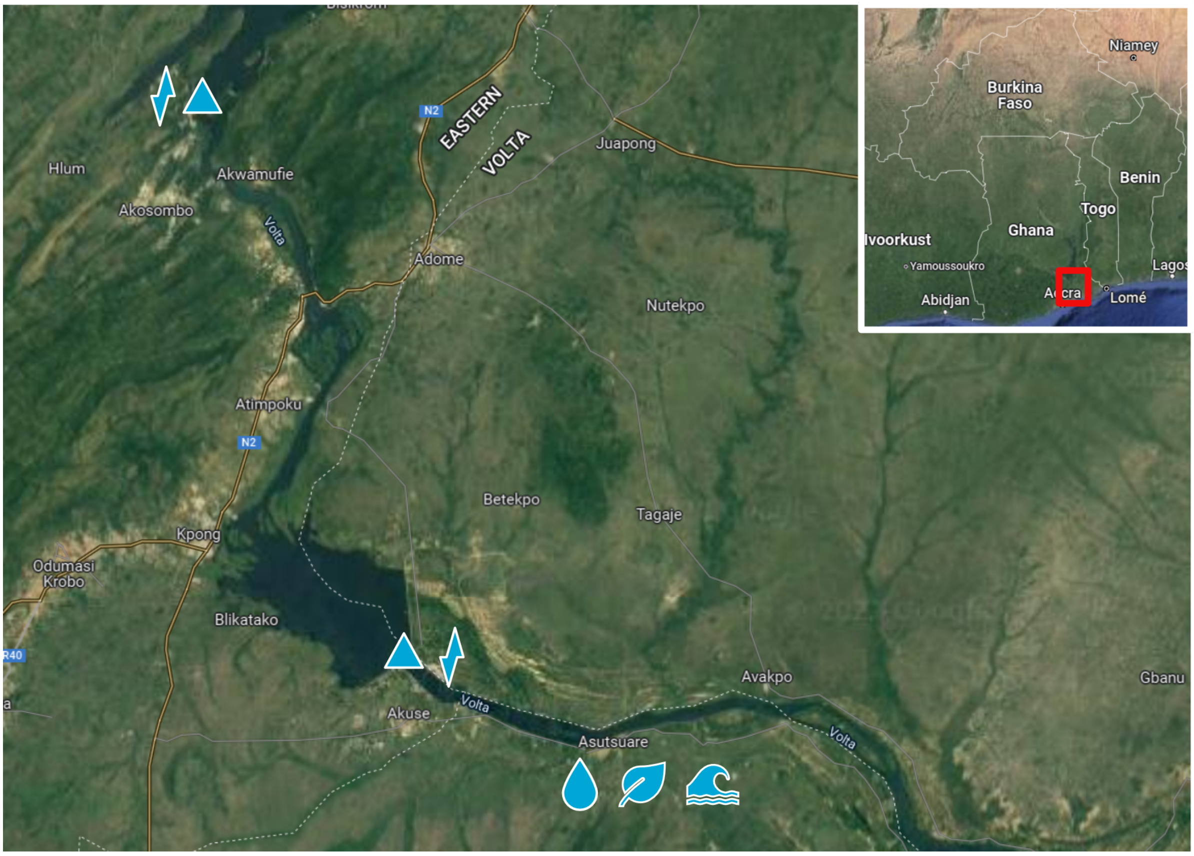

Figure 3.4: The geographical overview of the Akosombo and Kpong dams (indicated by the triangles). The objectives are indicated by their respective indicator at their respective location. Electricity is generated at both Kpong and Akosombo. The environmental flow, flood protection and irrigation objectives are situated downstream of Kpong.

basin (VBA, 2007a). The VBA is, therefore, the assigned actor to mediate, implement and control treaties within the basin. The VRA can use their expertise to guide Ghanaian representatives within the VBA. See Section 3.2.5 for more information

3.2.4. Performance Metrics

The VRA is in charge of the dam and is therefore assumed to set the performance metrics. Owusu et al. (2022) has defined four performance metrics for the Akosombo: flooding, annual hydropower generation, environmental flows, and irrigation. From these metrics, the environmental objective is currently not a goal of the VRA. However, this study looks into the possibilities, and it might become a goal of the VRA in the future. Next to these metrics, this thesis also uses the energy reliability metric. All the metrics are stored per year in the simulation run to get a better view of low metric outcomes in a specific year instead of averaging over the whole simulation run. Using these extra data points, below-average performance can be found in the vulnerability analysis.

Flooding

The flooding objective is defined as the average flood that occurs over a year in a simulation run (Owusu et al., 2022). This, generally, results in a low number since the flood mechanism has only been used twice in the historical records. However, the floods that occurred had a significant impact. The higher the outcome, the higher the number of floods that have occurred or have occurred with a higher intensity.

$$J_{flood} = \sum_{t}^{365} \frac{\max(Q_{actual,t} - Q_{flood}, 0)}{Q_{flood}} \tag{3.1}$$

where: J_{flood} = Average flow exceedance through Akosombo in simulation run of Q_{flood} [−]
$Q_{actual,j,i}$ = Actual downstream releases through the turbines and spillways on day t of the year $[m^3]$
Q_{flood} = The release of a day at which flooding occurs (2300 m^3/s average) $[m^3]$

Annual Hydropower

The hydropower performance metric is the average annually generated hydropower.

$$J_{hydro} = \sum_{i}^{365} HP_i \tag{3.2}$$

where: J_{hydro} = The mean annual hydropower in the system $[GWh]$
HP_t = Hydropower production on day t $[GWh]$

Environmental flows

Following Mul et al. (2017), Owusu et al. (2022) defined the following e-flow requirement where there is limited flooding, and a higher flow is permitted in the dry season. It is deemed more likely that this is a requirement that decision-makers can agree with when compared to others proposed by Owusu et al. (2022). The e-flow target in September up to and including October is 2300 m^3/s minimally. During the rest of the year, a 700 m^3/s is the maximum.

$$J_{eflow} = 1 - \frac{d_{missed}}{d_{eflow}} \tag{3.3}$$

where: J_{eflow} = The fraction of days where the eflow requirement is met [−]
d_{missed} = The number of days where the e-flow target is missed over the total length simulation $[day]$
d_{eflow} = Number of days where there was an e-flow target to be met over the total length of the simulation $[day]$

Irrigation

Although current irrigation from Kpong has only reached a very small percentage of the planned (ca.) 200 000 hectares (Interviews, 2022) it is still included in this thesis as the thesis is looking into future developments. The irrigation metric is defined by Owusu et al. (2022) as the daily average mean fraction of water received and what was needed per day. The daily irrigation demand is taken to be a constant 38 m³/s throughout the year to account for future expansion of the Kpong irrigation project.

$$J_{irrigation} = \frac{\sum_{t}^{365} \frac{Q_{actual,t}}{Q_{demand,t}}}{365} \tag{3.4}$$

where: $J_{irrigation}$ = The mean fraction of water releases meeting irrigation demands $[-]$
$Q_{actual,t}$ = Actual releases through the turbines and spillway on day t $[m^3]$
$Q_{demand,t}$ = Water demand for irrigation on day t $[m^3]$

Hydropower reliability

Although not included in Owusu et al. (2022), the reliability of energy supply by the Akosombo and Kpong dam is arguably an important metric since this will allow decision-makers to steer towards certain energy policies outside of the dam system. Annor et al. (2017) describe the situation in 1997 where insufficient energy was generated, and an energy crisis followed. Since then, thermal energy plants have been built, but these have higher energy costs than hydropower and are therefore less favourable. Taking the annual expected hydropower projection of 4415 GWh/year (Annor et al., 2017) and converting this into a daily demand from the dam (12.1 GWh/day), the following metric function can be defined. The deficit is squared to punish large deficits more than small deficits.

$$J_{reliability} = \sum_{i}^{365} HP_{deficit,i}^2 \tag{3.5}$$

$$HP_{deficit,i} = HP_i - HP_{demand} \tag{3.6}$$

where: $J_{reliability}$ = The mean squared daily hydropower missed in the system $[GWh^2]$
$HP_{deficit,i}$ = Hydropower deficit on day i $[GWh]$
HP_i = Hydropower produced by Akosombo and Kpong on day i $[GWh]$
HP_{demand} = Daily demand of 12.1 GWh

3.2.5. Levers

This thesis uses the following policy levers to optimise the performance metrics mentioned earlier. The first lever is the release policy for the dam. This release policy is set by the VRA. The second lever is the implementation of energy storage by the VRA. Energy storage is becoming an interesting option when looking towards the future and the increased need for renewable energies worldwide to reduce climate change. Finally, as a third lever, treaties between countries are also looked at due to their current absence and Ghanaian dependency on foreign waters. These treaties will be defined in cooperation with the VBA, VRA, and the upstream countries.

Release policy

The Volta River Authority can steer towards certain performance of the dam system by deciding when and how much the water passes through Akosombo. Not only the total quantity can be determined but also how much is released for what purpose. The Volta River Authority can decide to release for four reasons: hydropower generation, environmental flows, irrigation, and spillage. In general, the Kpong dam passes the exact same amount of water as the Akosombo releases to perform its function as a run of the river dam. The exception is when irrigation water is released. That water is taken out just before the Kpong dam is used in the fields. The other exception is when too much water is released from Akosombo for Kpong turbines to handle. Then the water is stored or spilled. This storage is not explicitly accounted for and taken as spillage. Figure 3.7 gives a schematic overview of the system. The decision formula of actually releasing and its quantity is described in Chapter 3.3.

However, the equations below describe the release volumes of both the Akosombo and Kpong through their respective release purposes.

$$r_{Ak} = r_{hydropower} + r_{environment} + r_{irrigation} + r_{spill} \tag{3.7}$$

$$r_{Kp} = r_{Ak} - r_{irrigation} \tag{3.8}$$

where: $r_{hydropower}$ = Release volume for hydropower purposes $[m^3]$
$r_{environment}$ = Release volume for environmental purposes $[m^3]$
$r_{irrigation}$ = Release volume for irrigation purposes $[m^3]$
r_{spill} = Release volume for flooding purposes $[m^3]$
r_{Kp} = The volume of water that is passed through the Kpong dam $[m^3]$

Energy storage

With the increased need for more sustainable solutions to halt climate change, it has been pointed out that these energy sources are not always as reliable as traditional ones. However, energy storage has been said to provide a promising solution to overcome this problem of reliability (Gallo et al., 2016; Hadjipaschalis et al., 2009). Dams already serve the function of energy storage by collecting water in their reservoir for later energy generation with their turbines. However, as shown before, this has large consequences on ecosystems downstream. The idea of including energy storage is to allow for a more natural flow of the river while still meeting the energy reliability metric in conditions of low inflows. Table 3.2 shows the range in which the energy storage can be taken. The energy storage could likely be limited to storing half a year's worth of energy due to low flows in the dry months and excess energy in the rainy season. However, to see the effects of larger storages in, for example, multiple dry years, the maximum is set to be able to store about a year's worth of the energy produced by the Akosombo dam with a hydropower optimised release policy of Owusu et al. (2022)

$$HP_{storage}(t) = HP_{storage}(t-1) + HP_{produced}(t) - HP_{needed}(t) \tag{3.9}$$

$$0 <= HP_{storage}(t) <= HP_{max,storage} \tag{3.10}$$

where: $HP_{storage}(t)$ = hydro power stored at day t $[GWh]$
$HP_{storage}(t-1)$ = hydro power stored at day $t-1$ $[GWh]$
$HP_{produced}(t)$ = hydro power produced at day t $[GWh]$
$HP_{needed}(t)$ = the need for hydro power at day t $[GWh]$
$HP_{max,storage}$ = maximum energy storage capacity $[GWh]$

Table 3.2: Lever ranges energy storage.

Lever	Unit	Low	High	Source
$HP_{max,storage}$	$[GWh]$	0	5000	assumption

Treaties

As shown in section 3.2.1, Lake Volta is for 60% dependent on foreign water. Currently, this amount is not secured in treaties (FAO, 2018) and can therefore legally be used by upstream riparian countries. To secure inflow, the government of Ghana can try to engage in treaties with other nations in the VBA. There are multiple ways to set up treaties. The list includes, but is not limited to: annual or seasonal quota, percentage-based allocation of annual or daily flows, water use without harm to downstream countries, and variable water quota based on climate conditions (Transboundary Freshwater Dispute Database, 2018). For this thesis, a percentage-based allocation of daily flow is implemented. The modelled treaties guarantee a minimum percentage of the inflow that must be passed through the border stations shown in Figure 3.3. This agreement can be made per country in which the station is situated.

$$Q_{outflow,j}(t) = (Q_{in,j}(t) + Q_{collected,j}(t)) * \sigma_{treaty,j} \tag{3.11}$$

where: $Q_{outflow,j}(t)$ = The amount of water flowing from station j to downstream stations on day t $[m^3/s]$

$Q_{in,j}(t)$ = The amount of water that came from station(s) upstream of j on day t $[m^3/s]$

$Q_{collected,j}(t)$ = The amount of water flowing into the river between the upstream station(s) of station of j and station j itself on day t $[m^3/s]$

$\sigma_{treaty,j}$ = The agreed upon percentage of flow at station j that needs to be passed through $[-]$

Table 3.3: Lever ranges treaties.

Lever	Unit	Low	High	Source
$\delta_{Treaty,Benin}$	$[-]$	0	1	assumption
$\delta_{Treaty,BurkinaFaso}$	$[-]$	0	1	assumption
$\delta_{Treaty,CoteIvoire}$	$[-]$	0	1	assumption
$\delta_{Treaty,Togo}$	$[-]$	0	1	assumption

3.2.6. External factors

This section describes the part of the system that the decision-maker has no direct influence on and is part of the external factors in the XLRM framework. There are two parts to this section. First, the external historical factors are described, and then future uncertainties are motivated.

Historical

Owusu et al. (2022) use several climatic external factors in the optimisation. The inputs for these climatic factors are from historical records. These historical records are used during the optimisation process. The historical data used for the optimisation is a set with 29 years of data from 1984 until 2013. This data set encompasses water levels in the Volta lake, the tailwater level of Akosombo, daily inflows, evaporation rates, and the head at Kpong.

Inflow

Hydrology plays an important factor in the basin. Inflows determine the storage in the reservoir and, consequently, the decision that will be made on the releases. The inflow is not something decision-makers can influence and is therefore considered external. Historical inflow data have been generated on the daily inflow into the Volta reservoir.

Evaporation

Evaporation is also considered external for the same reason as inflows. Decision-makers are not able to influence the evaporation caused by climatic conditions. Evaporation has also been included through daily historical data.

Tailwater

The tailwater of the Akosombo, in combination with the reservoir level, determines the head and, therefore, the energy production in the system. No proper relation between downstream water levels and releases could be found due to complex downstream conditions playing a prominent factor. Daily historical data has been used to account for it.

Uncertainty

This thesis expands the model of Owusu et al. (2022) by incorporating multiple uncertainties in the system. The inclusion of uncertainties is important to determine how historically optimised release

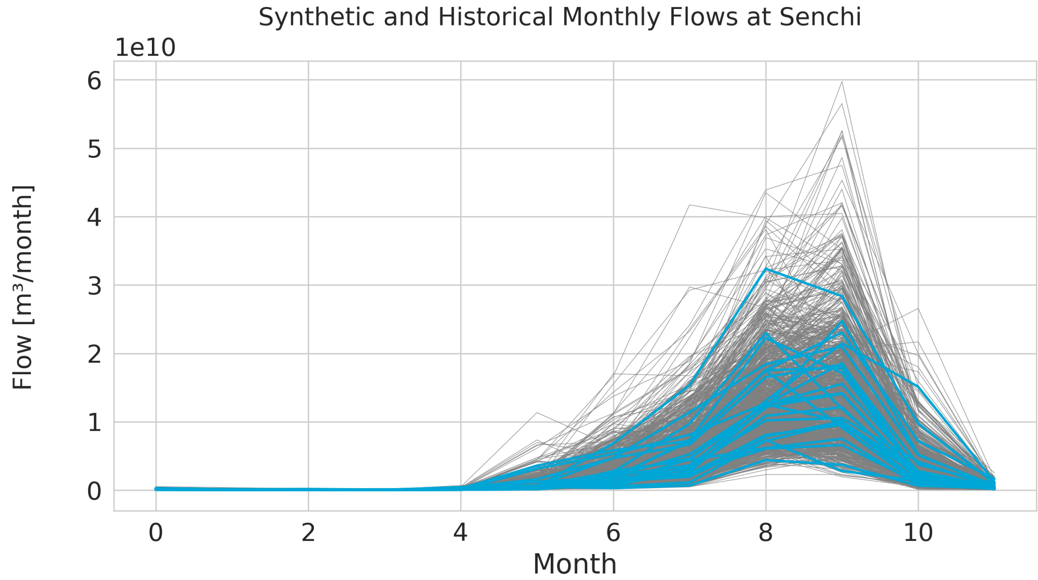

Figure 3.5: Synthetic streamflows (grey) plotted compared to historical flows at Senchi before 1964 (blue). Average monthly flows are plotted per month. Month 0 is January and 11 is December.

policies will hold up in the face of uncertain futures. The uncertainties and the motivation for including them are detailed here.

Extreme flow events

In the optimisation process, historical data are used. However, concerns exist if this historical data set is comprehensive enough since extreme events are rarely captured in relatively short time spans, underestimating the impact of extreme hydrological conditions (Salazar et al., 2017). To overcome this concern, the Kirsch Nowak streamflow generator of Giuliani et al. (2022) is applied as this has been used successfully in multiple studies on reservoir optimisation (Giuliani et al., 2017; Quinn et al., 2017; Salazar et al., 2017; Quinn et al., 2018).

This study chooses a simulation length of 20 years to minimise the impact of initial conditions in the reservoir (Quinn et al., 2017). This will be done for 50 simulations to map diverse climatic sequences. However, there is a downside to this sampling method. Low metric scores in a year can be masked by high metric score years in the 20-year period due to averaging over the complete simulation period (Quinn et al., 2017). This 'information hiding' is overcome by storing each year's simulation results and only later sampling the outcomes in the analysis phase. This means that, for example, the worst-case performance can be found per year instead of per simulation of 20 years. For the validation of the synthetic streamflow generation method, see A.

Figure 3.5 shows the sampled flows, and it can be seen that more extreme values are included in the simulation than in the historical data set. Extremes include both higher flows as well as lower flows.

Climate Change

Climate change is an important factor to consider as this could affect the inflow in Lake Volta. However, it is unclear how this change will unfold. Some argue that monthly flows in the basin will increase until 2050, (Jin et al., 2018) while Sood et al. (2013) has shown that the water yield, the net amount of water contributing to streamflow in the reach, will drop over the years. In this thesis, the ranges defined by Kunstmann & Jung (2005) and Jung et al. (2012) are used because they specifically researched the change in inflow into lake Volta due to climate change. In this thesis, climate change is assumed to not alter the water distribution among the different discharge stations but will decrease the flow in all stations by an equal percentage.

$$Q_{collectedCC,j}(t) = Qcollected,j(t) * \sigma_{month} \tag{3.12}$$

where: $Q_{collectedCC,j}(t)$ = The amount of water flowing into the river between the upstream station(s) of station of j and station j itself under climate change conditions on day t $[m^3/s]$

$Q_{collected,j}(t)$ = The amount of water flowing into the river between the upstream station(s) of station of j and station j itself under current climate conditions on day t $[m^3/s]$

σ_{month} = The basin wide streamflow change factor of that month due to climate change $[-]$

Table 3.4: Uncertainty ranges climate change.

Uncertainty	Unit	Low	High	Source
$C_{january}$	$[-]$	-0.10	1	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{february}$	$[-]$	-0.25	0.03	Kunstmann & Jung (2005); Jung et al. (2012)
C_{march}	$[-]$	-0.25	0.03	Kunstmann & Jung (2005); Jung et al. (2012)
C_{april}	$[-]$	-0.25	0.03	Kunstmann & Jung (2005); Jung et al. (2012)
C_{may}	$[-]$	-0.10	0.20	Kunstmann & Jung (2005); Jung et al. (2012)
C_{june}	$[-]$	0.10	0.55	Kunstmann & Jung (2005); Jung et al. (2012)
C_{july}	$[-]$	-0.15	-0.10	Kunstmann & Jung (2005); Jung et al. (2012)
C_{august}	$[-]$	-0.08	0.25	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{september}$	$[-]$	0.25	0.40	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{october}$	$[-]$	0.18	0.45	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{november}$	$[-]$	0.05	0.20	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{december}$	$[-]$	-0.75	0	Kunstmann & Jung (2005); Jung et al. (2012)

Upstream usage

As discussed in 3.2.1, Ghana has limited water resources within its borders. This means that Ghana is vulnerable to diminishing inflow due to increased upstream riparian water use. One example of where concerns exist is the dispute between Ethiopia and Egypt (Mutahi, 2020). Upstream Ethiopia has built infrastructure with which it can reduce water supply to Egypt by using more themselves, resulting in disputes. With no treaties, Ghana could potentially fall to the same fate. The locations of water extraction are indicated in 3.6. To simulate the impact of such upstream changes, this uncertainty is included.

The water use upstream is defined as a factor of what a riparian country historically expects the flow to be into that region for that month. This does mean that in low flow months, a country can decide to take out all water in a river but not more than that. Equation 3.11 can be rewritten as follows.

$$Q_{outflow,j}(t) = Q_{in,j}(t) + Q_{collected,j}(t) - Q_{average,j}(t) * \sigma_{waterUseRate,j} \tag{3.13}$$

$$Q_{outflow,j}(t) >= 0 \tag{3.14}$$

where: $Q_{outflow,j}(t)$ = The amount of water flowing from station j to downstream stations on day t $[m^3/s]$

$Q_{in,j}(t)$ = The amount of water that came from station(s) upstream of j on day t $[m^3/s]$

$Q_{collected,j}(t)$ = The amount of water flowing into the river between the upstream station(s) of station of j and station j itself on day t $[m^3/s]$

$Q_{average,j}(t)$ = The expected amount of water based on historical records at station j on day t $[m^3/s]$

$\sigma_{waterUseRate,j}$ = The percentage of water used from what is historically expected flow of station j $[-]$

Irrigation demand

Not only can the amount of water flowing into the basin change. The requirements for dam operation

Table 3.5: Uncertainty ranges upstream water use.

Uncertainty	Unit	Low	High	Source
$\delta_{WaterUseRate,Benin}$	[−]	0	1	assumption
$\delta_{WaterUseRate,BurkinaFaso}$	[−]	0	1	assumption
$\delta_{WaterUseRate,CoteIvoire}$	[−]	0	1	assumption
$\delta_{WaterUseRate,Togo}$	[−]	0	1	assumption

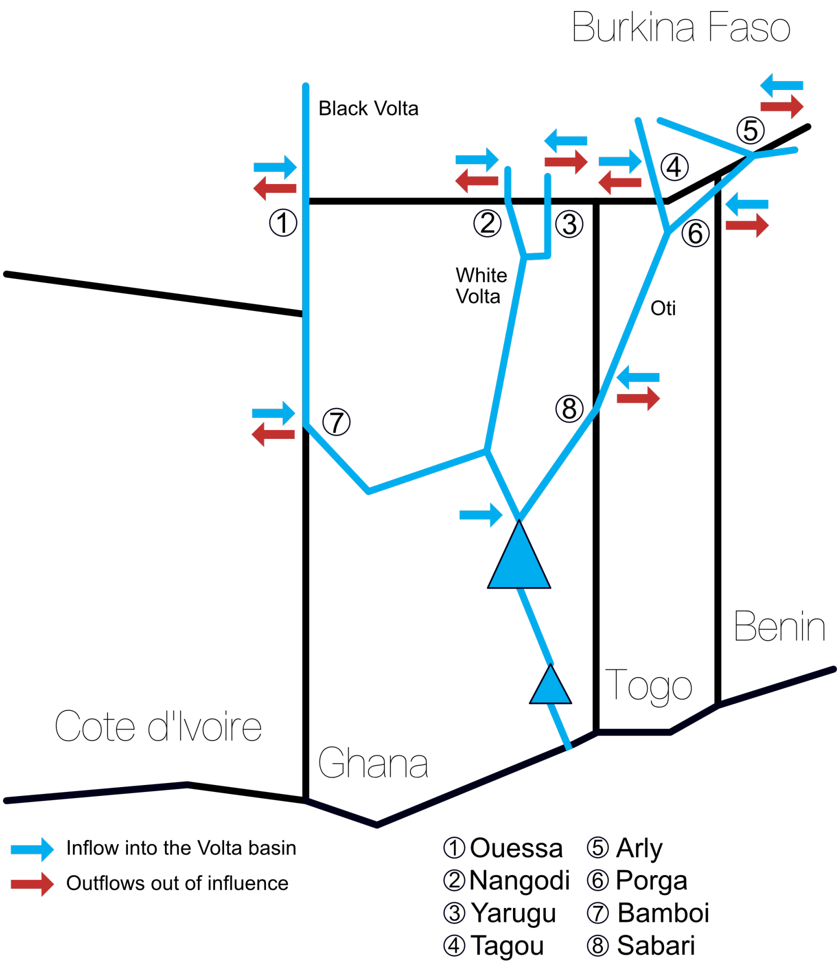

Figure 3.6: The Volta River Basin schematic overview of inflows and outflows at border flow stations considered. Blue arrows indicate the flow of a tributary into the Volta lake if not obstructed or depleted by others. Red arrows indicate the outflow due to consumptive country usage in, for example, industrial, domestic and agricultural sectors. What is left either flows into lake Volta or to the next flow station.

Table 3.6: Uncertainty ranges irrigation

Uncertainty	Unit	Low	High	Source
$D_{irrigation}$	$[m^3/s]$	0.5	3	FAO (2021); McCartney et al. (2012)

can also change due to increased irrigation demands. McCartney et al. (2012) argue for a full development scenario in which the irrigation demand will triple by the end of the century when compared to current development. The top range of the uncertainty is that the Kpong reservoir tries to keep up in this situation of full development and increases the irrigation plots to triple the original amount. On the other hand, Irrigation needs can decrease due to technological innovation, which requires less water than currently needed. Using the FAO Net Biomass Water Productivity indicator, one finds that the irrigated area near the Kpong dam currently has a productivity of about 1.5 kg/m^3 while the highest productivity found in the area is 3.2 kg/m^3 (FAO, 2021). The indicator indicates how effectively crops transfer water into yield. Indicating irrigation could be halved. This uncertainty can be described by rewriting $Q_{demand,j,i}$ in Equation 3.4.

$$Q_{demand,j,i} = Q_{historicalDemand,j,i} * \sigma_{IrrigationDemandMultiplier} \tag{3.15}$$

where: $Q_{demand}(t)$ = Water demand for irrigation on day t $[m^3/s]$
$Q_{historicalDemand}(t)$ = Historical water demand for irrigation on day t $[m^3/s]$
$\sigma_{IrrigationDemandMultiplier}$ = Change in water productivity or irrigation expansion

3.2.7. Relationships in the system

The external factors, levers and performance metrics can now be used to serve as inputs and outputs of the system. The way the system handles these inputs to get to the outputs is described below.

Power generation

The Akosombo has six turbines that can together handle a maximum flow capacity of 1600 m^3/s. The Kpong dam has only four turbines but can handle the same amount of water flow through them. The turbines can not generate more power and can also not let more water through when at their maximum. The hydropower generation at Kpong and Akosombo can be described as the sum of power generation by each turbine. Where the following describes each turbine.

$$HP_{t,turbine} = \eta * g * \rho_w * h_t * Q_t^{turbine} * 10^{-9} \tag{3.16}$$

$$Q_t^{turbine} <= 1600/n \ m^3/s \tag{3.17}$$

where: $HP_{t,turbine}$ = Hydropower produced through the turbine on day t $[GWh]$
η = Turbine efficiency [–]
g = gravitational constant of 9.81 m/s^2
ρ_w = The density of fresh water of 1000 kg/m^3
h_t = Head difference between dam level and tailwater level $[m]$
$Q_t^{turbine}$ = The flow trough a turbine on day t $[m^3]$
n = The total number of turbines installed at Akosombo (6) or Kpong (4) [–]

Water storage and releases

The amount of water stored in the Akosombo reservoir is an important indicator for making a release decision. The amount of storage in the reservoir can be deducted from the storage level in the reservoir through a storage-area-level relationship. The Akosombo must use its spillways when dam levels reach 84.12 meters. At this moment, the floodgates open, and water does not go through the turbines but is diverted to the downstream river directly. These releases of the Akosombo reach the Kpong dam, where releases with irrigation purposes are removed from the total release. The remaining water will

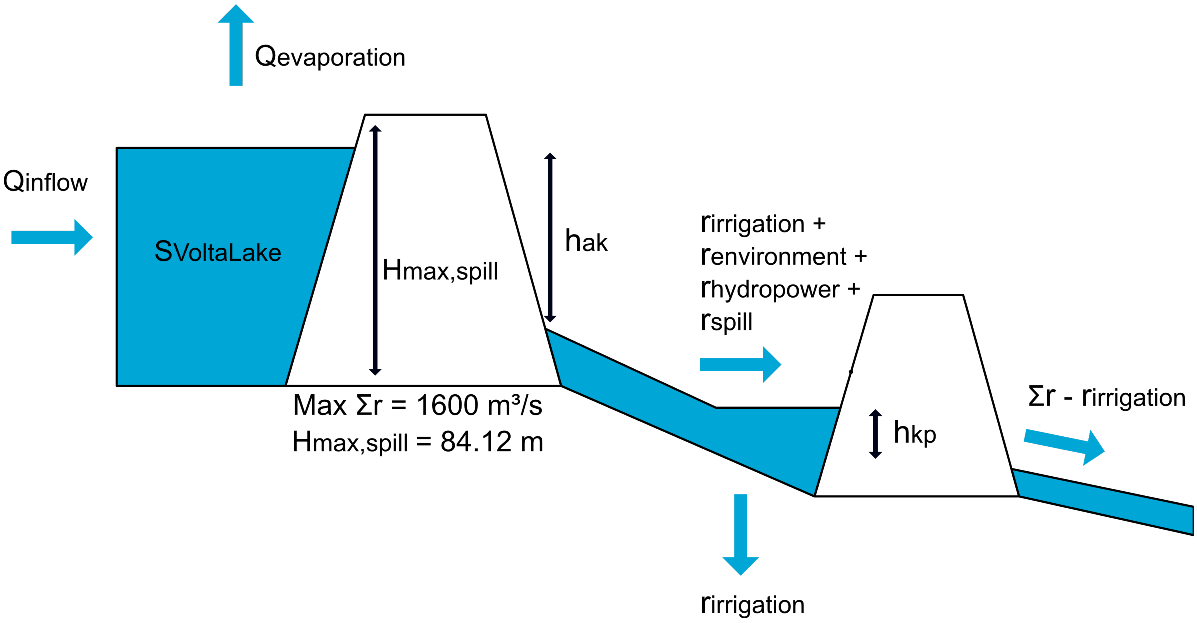

Figure 3.7: Schematic of flows and operation of the Akosombo dam in combination with the Kpong dam

flow through the Kpong dam, either through the turbine or through the spillways when there is too much for the turbines to handle. A schematic has been provided in Figure 3.7. The storage in Lake Volta can be defined as a mass balance:

$$S_{VoltaLake,t} = S_{VoltaLake,t0} + Q_{inflow} - r_{Ak} - Q_{evaporation} \tag{3.18}$$

where: $S_{VoltaLake,t}$ = The storage in the Akosombo reservoir at day the end of t $[m^3]$
$S_{VoltaLake,t0}$ = The initial storage in the Akosombo reservoir at the beginning of day $t[m^3]$
Q_{inflow} = Inflow of water from all tributaries during day t $[m^3]$
r_{Ak} = The volume of water that is passed through the Akosombo dam during day t $[m^3]$
$Q_{evaporation}$ = The volume of evaporation in the reservoir during day t $[m^3]$

3.2.8. Akosombo system XLRM framework

The information from the system description can be summarised in the XLRM framework in Figure 3.8.

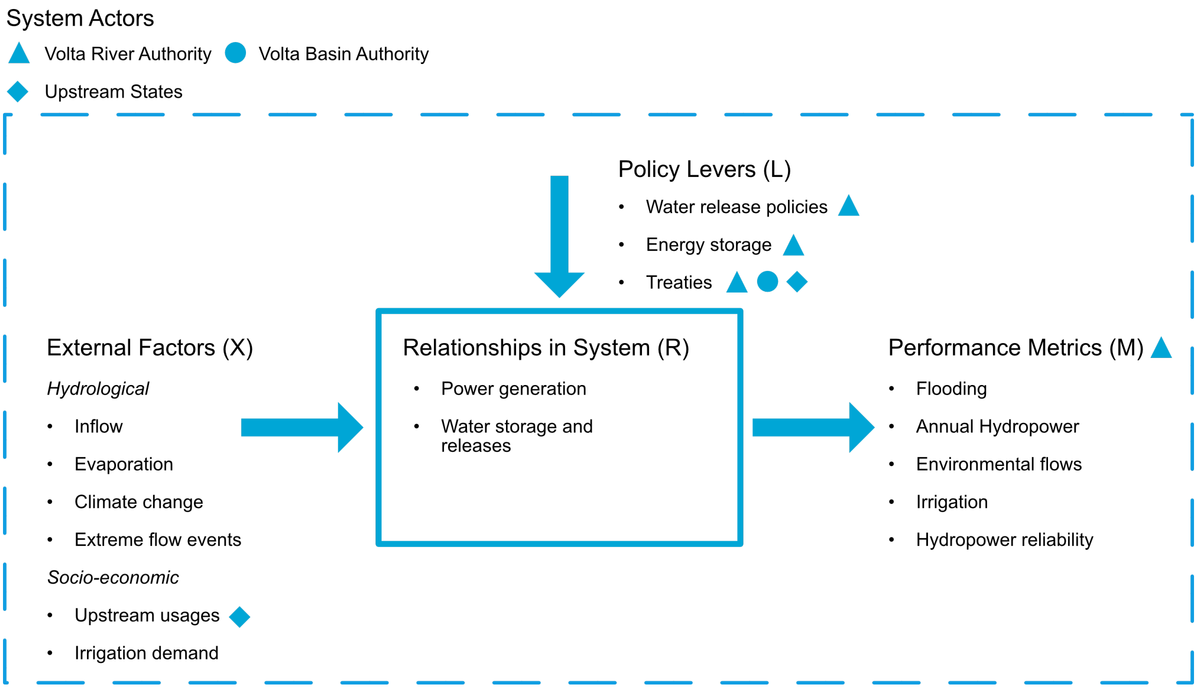

Figure 3.8: An overview of the XLRM framework for the Akosombo-Kpong system (adapted from Kwakkel (2017a))

3.3. Multi-objective optimisation

In the second phase of the thesis, optimal policies to be used in the rest of the research will be found. The optimisation for this system has already been performed by Owusu et al. (2022) who studied the Akosombo and the implication of the inclusion of e-flows. They set up the optimisation in a similar fashion as done in previous EMODPS studies such as Giuliani et al. (2016); Giuliani & Castelletti (2016); Quinn et al. (2017, 2018). However, different objective functions were used than in those studies. The literature review in section 2.1.1 has shown that this will have found the ideal release policy set from a reference scenario, in this case, the historical case. The policies resulting from the optimisation of Owusu et al. (2022) are analysed in this thesis.

3.3.1. Optimisation setup

The optimisation process of Owusu et al. (2022) found the optimal set of Radial Basis Functions (RBF) parameters Θ that are used for the generation of release rules u_t (Equation 3.20) which together form the release policy p over the simulation time horizon as depicted in Equation 3.19. The optimisation process finds the optimal set of variables $(\Theta *)$ which form the optimal release policy $(p*)$. For simplification, the thesis will refer to 'the optimised policy'.

$$p = [u_t(t_0, x_t), \dots, u_{t-1}(t, x_t)] \tag{3.19}$$

$$u_t(t, x_t) = [\varphi_1(\Theta), \dots, \varphi_4(\Theta)] \tag{3.20}$$

where:
p = The release policy
u = The release decision function at time t
t = Time of the simulation
x_t = The storage in the reservoir at time t
$\varphi_1(\Theta)$ = RBF function with input parameters Θ
Θ = input parameter to create the set of RBF functions

Historical data

The historical data used for the optimisation in (Owusu et al., 2022) is a set with 29 years of data from 1984 until 2013. This data set encompasses water levels in the Volta lake, the tailwater level of Akosombo, daily inflows, evaporation rates, and the head at Kpong.

Used objectives

The objectives that are optimised are adapted from the performance metrics described in Section 3.2.4 so that the objective optimises against the mean outcome over the simulation horizon. The reliability objective is not optimised as this was not included in the study of Owusu et al. (2022). Owusu et al. (2022) also used multiple objective functions for the environment and performed multiple optimisations. This study only uses one of the environmental objective functions, as defined in Section 3.2.4. In the system, the flooding objective needs to be minimised since high values mean flooding. The environmental, irrigation and hydropower objectives are to be maximised to ensure maximum benefits in the system. The optimal release policy is described in Equation 3.21. The optimal policy ($p*$) is the one that creates the best combination of the defined objectives.

$$p* = \begin{cases} \arg\min_p J_{flood}, \\ \arg\max_p J_{hydro,Ak}, \\ \arg\max_p J_{hydro,Kp}, \\ \arg\max_p J_{eflow}, \\ \arg\max_p J_{irrigation}, \end{cases} \tag{3.21}$$

3.3.2. Policy selection

The optimisation resulted in a set of Pareto optimal release policies. Due to computational limitations, not all of these can be sampled. Instead, a selection is made based on policy performance from the optimisation. This 'thinned' solution set is used in the next step of the thesis. The part of the thinned set contains the best performing policies of the hydropower Akosombo, irrigation and environment objective. These policies have stark trade-offs associated with them. To capture more information, policies that perform relatively well across multiple objectives are also selected to form the second part of the thinned set. The satisficing criteria for the policies are as follows. The policies should have 80% of the maximum hydropower performance at Akosombo and 75% of the other best objective outcome for the optimisation set. Hydropower has a higher threshold than the other objectives since current dam operator preferences are focused on energy production.

3.4. States of the world

In phase three of the thesis, the uncertainties and levers are sampled to generate scenarios representing different states of the world (SOWs) in which the dam could operate (Section 3.4.1. After the simulation, a specific return time per objective is chosen to investigate the policy performance in challenging climate situations (Section 3.4.2).

3.4.1. Uncertainties and levers

The uncertainties of the Akosombo system, defined in phase one, are implemented. Using the Exploratory Modelling and Analysis (EMA) Workbench (Kwakkel, 2017b), the adapted model is used to re-evaluate the chosen release policies under a selection of scenarios. The selection of scenarios is made through Latin Hypercube sampling. This sampling method has the advantage of providing a more complete set of possibilities with fewer samples than other known sampling methods such as Monte Carlo sampling (Data Science Genie, n.d.). This is important since every run in the simulation model itself is computationally expensive, while the exploration of a good range of uncertainties is paramount to understanding what can possibly happen in the future. However, there is no general rule for the total number of scenarios needed except that there should be no gaps in the scenario space. Therefore, the vulnerability analysis requirement is taken as in 3.6, 2400 per release policy. After visual analysis of the scenario space plotted in Figure D.1 of Appendix D there are no gaps in the experiment space.

Table 3.7: Uncertainty and lever ranges used in scenario sampling.

Uncertainty	Unit	Low	High	Source
$C_{january}$	$[-]$	-0.10	1	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{february}$	$[-]$	-0.25	0.03	Kunstmann & Jung (2005); Jung et al. (2012)
C_{march}	$[-]$	-0.25	0.03	Kunstmann & Jung (2005); Jung et al. (2012)
C_{april}	$[-]$	-0.25	0.03	Kunstmann & Jung (2005); Jung et al. (2012)
C_{may}	$[-]$	-0.10	0.20	Kunstmann & Jung (2005); Jung et al. (2012)
C_{june}	$[-]$	0.10	0.55	Kunstmann & Jung (2005); Jung et al. (2012)
C_{july}	$[-]$	-0.15	-0.10	Kunstmann & Jung (2005); Jung et al. (2012)
C_{august}	$[-]$	-0.08	0.25	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{september}$	$[-]$	0.25	0.40	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{october}$	$[-]$	0.18	0.45	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{november}$	$[-]$	0.05	0.20	Kunstmann & Jung (2005); Jung et al. (2012)
$C_{december}$	$[-]$	-0.75	0	Kunstmann & Jung (2005); Jung et al. (2012)
$\delta_{Treat,Benin}$	$[-]$	0	1	assumption
$\delta_{Treat,BurkinaFaso}$	$[-]$	0	1	assumption
$\delta_{Treat,CoteIvoire}$	$[-]$	0	1	assumption
δ_{Togo}	$[-]$	0	1	assumption
$\delta_{WaterUseRate,Benin}$	$[-]$	0	1	assumption
$\delta_{WaterUseRate,BurkinaFaso}$	$[-]$	0	1	assumption
$\delta_{WaterUseRate,CoteIvoire}$	$[-]$	0	1	assumption
$\delta_{WaterUseRate,Togo}$	$[-]$	0	1	assumption
$D_{irrigation}$	$[m^3/s]$	19	114	FAO (2021); McCartney et al. (2012)

The uncertainties and levers are taken together in the scenario sampling instead of separately sampling the levers and uncertainties and evaluating every combination of the two. This is done for two reasons. The first is that this way, the computational costs are reduced. The second is that for this thesis, the influence of each factor is of interest and that this can still be found with simultaneous sampling. The limitation of the process is that it is hard to identify a set of levers and their performance in a range of scenarios to allow for comparison.

Uncertainty ranges

From the information in Sections 3.2.6 and 3.2.5 Table 3.7 summarises the ranges in which these uncertainties and levers will be sampled in the different states of the world (SOW's).

3.4.2. Synthetic flow return times

As described in 3.2.6 the experiments will be run for 50 simulations over 20 years. The results of the objectives are stored per year and only processed afterwards in the analysis instead of in the model. This post-processing is done by obtaining values for set return times (transformed to percentile values) from the whole set. Since these flows are created from a flow probability curve (see Appendix A), return times can be attributed to these flows. Therefore, the decision-maker can decide what return times are preferred when analysing the data. The return times used in this thesis are listed in Table 3.8. To find the outcome for a set return time in a scenario, the percentile value of the 20x50 outcome set is taken.

This phase concludes with the performance of each policy across a range of scenarios. This performance is used in the next phase to check for the robustness of the policies and in the last phase to see the influence each of the uncertainties and levers has.

Table 3.8: Return times for objectives that want to be investigated

Objective	Return time
Hydropower Akosombo	$\frac{1}{20}$
Hydropower Kpong	$\frac{1}{20}$
Energy reliability	$\frac{1}{10}$
Environment	$\frac{1}{30}$
Irrigation	$\frac{1}{30}$
Flood control	$\frac{1}{100}$

3.5. Robustness calculation

The different SOWs of step three contribute to finding release policies that work in many different situations. The better an optimised policy from section 3.3 performs in a range of situations; the more robust one can call that policy when compared to another. From Section 2.1.3 it was found that the way one defines robust can have a significant impact on the resulting policy performance (Quinn et al., 2017; Giuliani & Castelletti, 2016; McPhail et al., 2018; Herman et al., 2015). These different definitions of robustness metrics should be chosen according to stakeholder preferences, which can change over time (Giuliani & Castelletti, 2016). There are metrics for risk-averse decision-makers and different metrics for risk-tolerant ones. That is why in this thesis, multiple robustness metrics will be tested among the different objectives to help decision-makers understand what different metrics do to the system performance.

3.5.1. Different metrics different meanings

To allow the decision-maker to get a comprehensive overview of the impact of a certain risk tolerance, a diverse set of metrics is chosen to allow comparison. The set has been chosen to range from slightly more tolerant than neutral to almost entirely risk-averse. The minimax metric has not been chosen as Quinn et al. (2017) found that focusing on the worst-case situation can lead to unintended failures, does not provide insight into the trade-offs and result in unstable policies being favoured. Therefore this thesis will use the worst first percentile approach instead. Using the risk classification of the robustness metrics given by McPhail et al. (2018) the following have been selected (risk-averse to risk-tolerant): the worst first percentile, 90^{th} percentile minimax regret, mean-variance, and percentile-based peakedness.

3.5.2. Worst first percentile

This robustness metric defines the most robust policy the one that performs best in the lowest percentile bad case scenario. Figure 3.9 shows a set of outcomes for a policy and indicates the worst first percentile value. The combination of the worst first percentiles of all objectives results in the robustness scores of that policy.

For an objective optimised for maximisation, the worst first percentile is the 1st percentile lowest value. The policy that performs best in this situation is marked as the best. For an objective optimised for minimisation, the worst first percentile is defined as the 99th percentile highest value, and the policy with the lowest value is deemed best.

$$p^* = \begin{cases} arg \min\limits_{p} J^{WP1}_{\text{objective}}, & \text{minimisation} \\ arg \max\limits_{p} J^{WP1}_{\text{objective}}, & \text{maximisation} \end{cases} \tag{3.22}$$

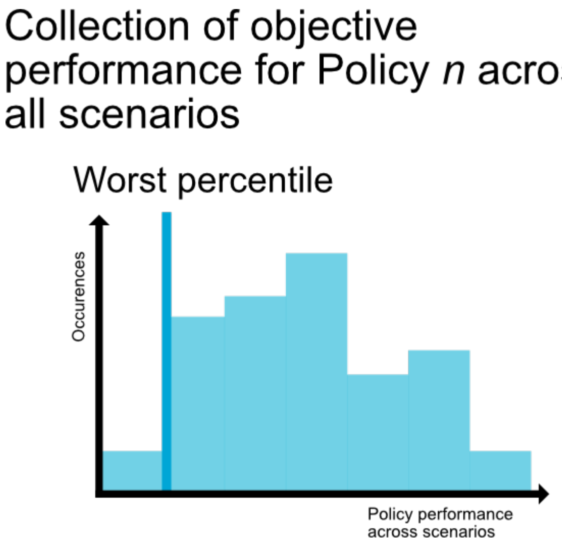

Figure 3.9: Visualisation of the worst first percentile metric. The robustness value is the value at the worst percent of the performance distribution among experiments, indicated by the blue vertical line.

$$J^{WP1}_{\text{objective}} = \begin{cases} \underset{i\in(1,\ldots,N)}{\text{quantile}} \{J_{\text{objective}}(i), 0.99\}, & \text{minimisation} \\ \underset{i\in(1,\ldots,N)}{\text{quantile}} \{J_{\text{objective}}(i), 0.01\}, & \text{maximisation} \end{cases} \tag{3.23}$$

where: $J^{WP1}_{\text{objective}}$ = the policy performance of an objective in the worst first percentile situation a

N = the amount of simulation runs of one year

$J^{all}_{\text{objective}}(i)$ = the set of N performance values of which the percentile will be taken

3.5.3. 90th percentile minimax regret

Giuliani & Castelletti (2016) define minimax regret as minimising the maximum regret over all different future scenarios. The policy that has the least regret is the most robust policy. For the metric used, the 90th percentile regret will be used to allow for a more risk-tolerant stakeholder.

Figure 3.10 shows that regret is calculated by taking the best-performing policy outcome and subtracting the outcomes of other policies. This calculation is done for each scenario and stored in a set. The 90th percentile regret value of this set is taken as the final robustness metric. This is repeated for each objective.

$$p^* = arg\min_p(r^{R90}_{\text{objective}}) \tag{3.24}$$

$$r^{R90,j}_{\text{objective}} = \underset{i\in(1,\ldots,N)}{\text{quantile}} \left\{r^j_{\text{objective}}(i), 0.90\right\}, \tag{3.25}$$

$$r^j_{\text{objective}}(i) = |\max_p(f(p,w_i)) - f(p_j,w_i)| \tag{3.26}$$

where: p^* = the most robust policy

$r^{R90,j}_{\text{objective}}$ = 90^{th} percentile regret of policy p_j

w_i = SOW i

$r^j_{\text{objective}}$ = The absolute regret value of policy p_j in SOW i

$f(p,w_i)$ = the performance of p_j in state of the world w_i

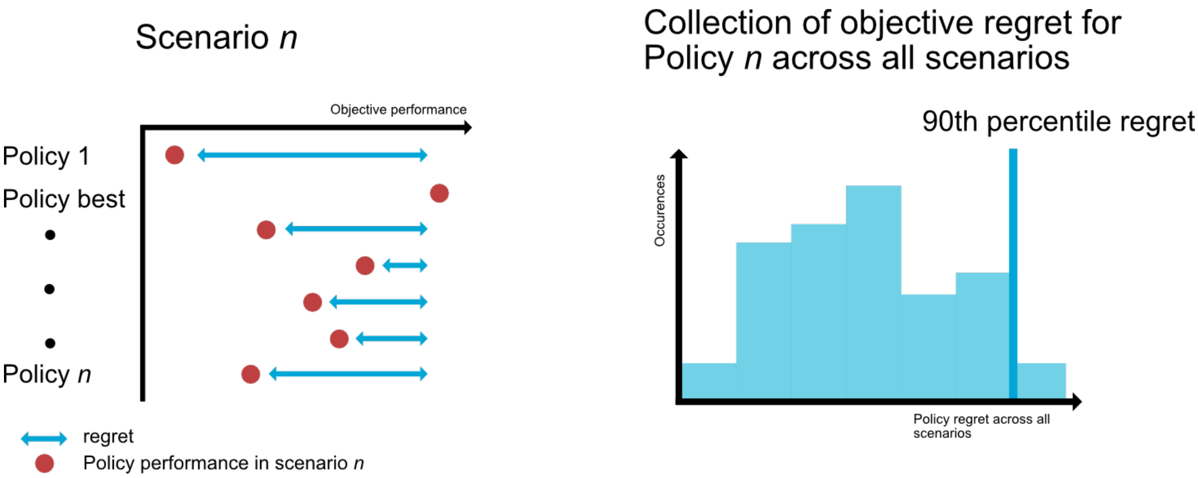

Figure 3.10: Visualisation of the 90th percentile regret metric. The difference between the outcome of the best-performing policy and another policy is called regret. The collection of regrets of all scenarios creates a distribution. The 90th percentile, indicated by the blue vertical line, is the robustness value. The lower the value, the better it is.

3.5.4. Mean-variance

The metric tries to decrease the amount of variation in the outcomes of the policy under deeply uncertain scenarios. Making the outcomes more reliable and certain no matter how the future changes Hamarat et al. (2014). This metric is similar to the signal-to-noise ratio but is adapted to avoid dividing by zero (Hamarat et al., 2014). For minimisation objectives, a lower mean and variance are preferred. For maximisation objectives, a high mean and low variance is preferred.

$$p^* = \begin{cases} arg\ \min\limits_p(f_{\text{objective}}), & \text{minimisation} \\ arg\ \max\limits_p(f_{\text{objective}}), & \text{maximisation} \end{cases} \tag{3.27}$$

$$f_{\text{objective}} = \begin{cases} (\mu + 1) * (\sigma + 1), & \text{minimisation} \\ \frac{(\mu+1)}{(\sigma+1)}, & \text{maximisation} \end{cases} \tag{3.28}$$

where: $p*$ = The most robust policy for the mean-variance metric.
$f_{\text{objective}}$ = The mean-variance robustness metric of a policy for an objective.
μ = The average performance of a policy for an objective.
σ = The standard deviation of a policy for an objective.

3.5.5. Peakedness

Kwakkel et al. (2016) introduces the Kurtosis metric as in Equation 3.29. The higher the peakedness of an objective, the higher the density is around the mean. In a robust policy, more values lie close to the mean than a low peakedness value. Next to that, a high mean value is preferred for maximisation objectives, while low mean values are preferable for minimisation objectives.

$$f_{\text{objective}} = \begin{cases} -\mu_i, \frac{q_{90}-q_{10}}{q_{75}-q_{25}}, & \text{minimization} \\ \mu_i, \frac{q_{90}-q_{10}}{q_{75}-q_{25}}, & \text{maximization} \end{cases} \tag{3.29}$$

There is a problem with this metric, which is that there are two outcomes for the value, the mean and the peakedness. To strike a combination between the two, Equation 3.30 has been defined similarly to the mean-variance objective. The difference between the peakedness and the mean-variance metric is that the peakedness metric is more tolerant towards deviations. As an additional rule, single-valued outcome policies are set at a peakedness value of four. This is done since, with a single value, the peakedness equation divides by zero, which is impossible.

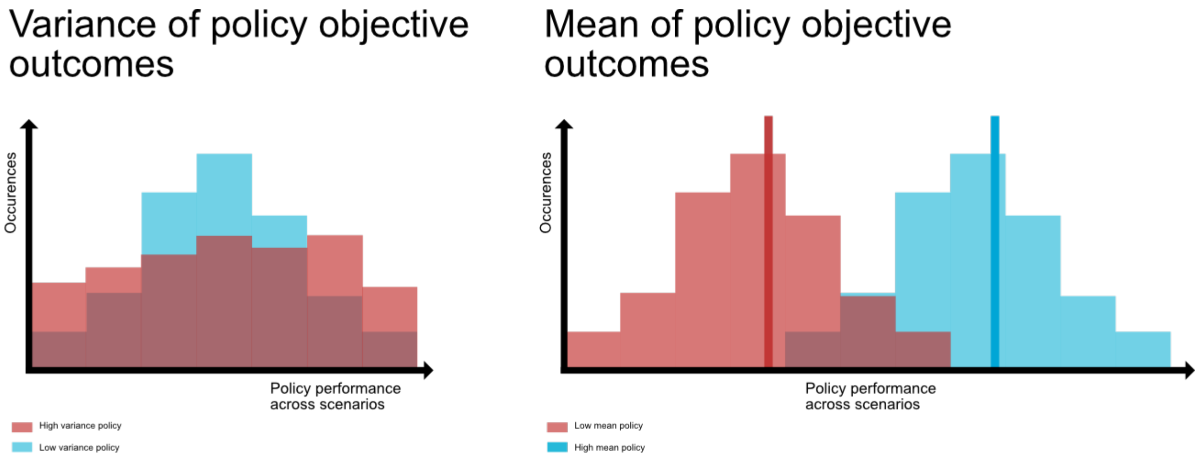

Figure 3.11: Visualisation of the mean-variance metric. When the variance is higher the distribution is flatter, meaning less reliable outcomes. A high reliability is preferable. The mean, indicated by the vertical lines. A high or low mean can be equally preferred depending on the objective.

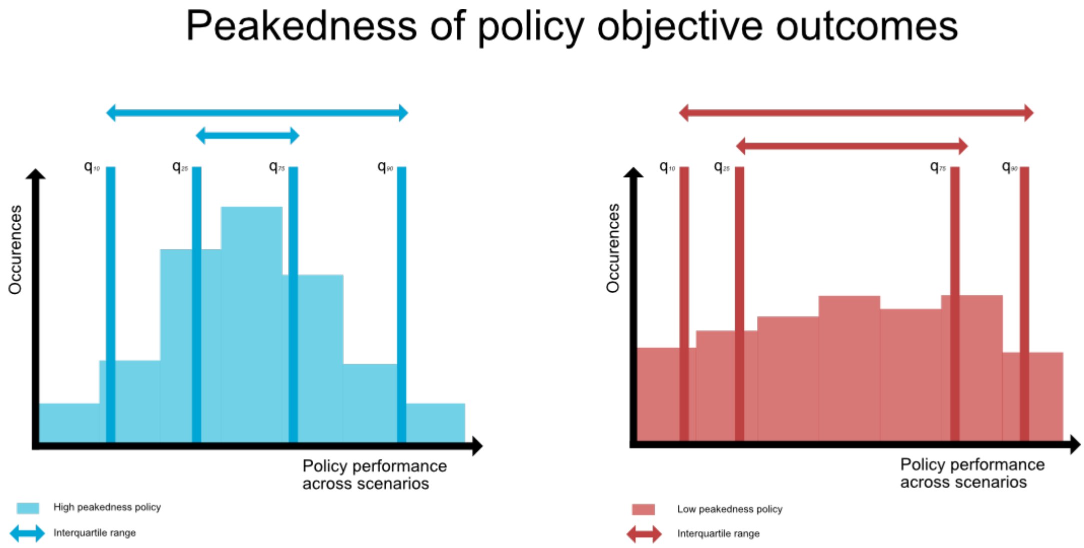

Figure 3.12: Visualisation of the percentile based peakedness metric. the smaller the range of the 25-75th percentile compared to the 10-90th percentile the more reliable the policy is.

Figure 3.12 illustrated the peakedness value. If a policy is peaked, the range between the 10th - 90th percentiles is much bigger than that of the 25th-75th percentiles. If the policy is not peaked, the differences between these ranges are smaller.

$$f_{\text{objective}} = \begin{cases} -\mu \;/\; \frac{q_{90}-q_{10}}{q_{75}-q_{25}}, & \text{minimization} \\ \mu * \frac{q_{90}-q_{10}}{q_{75}-q_{25}}, & \text{maximization} \end{cases} \tag{3.30}$$

$$p^* = \begin{cases} arg\ \min_p(f_{\text{objective}}), & \text{minimisation} \\ arg\ \max_p(f_{\text{objective}}), & \text{maximisation} \end{cases} \tag{3.31}$$

where: $p*$ = The most robust policy for the peakedness metric.
$f_{\text{objective}}$ = The mean-variance robustness metric of a policy for an objective.
μ = The average performance of a policy for an objective.
q_n = The n^{th} quantile value of the distribution of outcomes.

Table 3.9: Chosen robustness metrics for the objectives

Objective	Robustness metric
Hydropower Akosombo	90th percentile regret
Hydropower Kpong	90th percentile regret
Energy reliability	Mean-variance
Environment	Peakedness
Irrigation	Mean-variance
Flood control	WP1

3.5.6. Comparing policies with different metrics for the outcomes

To select the policies that will be analysed in Section 3.6 a parallel axis plot will be created using different robustness metrics per objective to include different robustness requirements of the objectives. The hydropower objectives from Kpong and Akosombo are selected using the 90th percentile regret formulation to allow decision-makers to see how much electricity generation they will miss out on compared to the maximum in that situation. This gives an illustration of their losses and how much extra energy generation capacity they would need to install to achieve the same electricity generation as the best policies. A more risk-tolerant metric is chosen for the energy shortage. Energy shortages are to be expected but can be covered by backup capacity or storage. That is why the mean-variance metric is selected. For irrigation, mean-variance is also taken in which more supply deficit can occur and therefore failed harvests. However, this risk is deemed acceptable. For the environmental objective, the peakedness objective is chosen. The risk tolerance that comes with the peakedness metric is considered acceptable since, currently, the environmental objective is not considered at all. Lastly, flood control is set to the worst first percentile objective since extremes in this objective are to be prevented due to the high impact of an extreme flood occurrence.

3.6. Vulnerability analysis

The last step in the thesis is to take the performance of the optimised policies under uncertainty (the outcome of phase 3) and explore the system's vulnerability. Vulnerability aims to discover the influence of uncertainties and policy levers on the success or failure of the system, and there are two popular analyses (Kwakkel & Haasnoot, 2019).

One way of doing this is through scenario discovery as described in (Bryant & Lempert, 2010). Scenario discovery provides insight into the combinations of factors most influential for certain outcomes in the system through subspace partitioning. These subspaces are the combination of factors in which a policy most likely fails or succeeds. In this thesis, situations are found for which the system performance is below average for that policy. Each of the Patient Rule Induction Method boxes is created to have at least an 80% density of 'true' values to attribute importance to the dimensions of the box. This will provide insight into the main factors causing below-average performance.

The second analysis is sensitivity analysis. It can provide insight into factor prioritisation to reduce dimensionality in further studies by discarding uninfluential uncertainties and levers. It also helps to design new policies focused on the influential inputs (Kwakkel & Haasnoot, 2019). The best way to perform sensitivity analysis is a global sensitivity analysis to account for second-order effects of interactivity between inputs (Saltelli et al., 2019). However, the techniques used to perform such an analysis are computationally expensive. Luckily methods exist that approach the measure of sensitivity fairly well while being less computationally intensive. One such method is feature scoring using the Extra Trees algorithm of Geurts et al. (2006) (Jaxa-Rozen & Kwakkel, 2018). The extra trees feature scoring method only needs 10% of the evaluation of a Sobol sensitivity analysis to accurately find the influence of a factor (Jaxa-Rozen & Kwakkel, 2018). Using the sampling size needed for a Sobol test as defined in Saltelli et al. (2010) with a $N = 1000$ in the authors proposed formula: $N_T = N(k+2)$ the total runs are: 1000 * (22+2) = 24000 runs needed per policy. For this thesis, using the Extra Trees method, 2400 experiments are performed. The outcome is a list of all the levers and uncertainties with their relative influence on model outcomes.

4
Results

This chapter presents the results of the research using the methods discussed in Chapter 3. First, release policies are selected to be used for the rest of the study (Section 4.1). Secondly, the results of sampling these policies under uncertainty are discussed in Section 4.2. Thirdly, the robustness performance of these policies is presented in 4.3. Lastly, Section 4.4 presents the vulnerability analysis of the Akosombo system. These results will be put into their larger context in Chapter 5.

4.1. Multi-objective optimisation

4.1.1. Optimal release policies

From the optimisation of Owusu et al. (2022), a Pareto optimal set is obtained and plotted in a scatter plot in Figure 4.1. The plot displays an objective per axis, and each dot represents the average yearly outcome of a release policy for a combination of two objectives. The hydropower produced at Akosombo is indicated using the hue of the dots. Good outcomes are the ones with combinations of high values for the hydropower Akosombo, hydropower Kpong, environment, and irrigation objective. The flood control outcome should be low. Looking at the scatter plot of this Pareto front of outcomes in Figure 4.1, one can see a significant trade-off between Hydropower generation at Akosombo and the environmental objective. The set of optimised policies also has a large correlation between the hydropower produced at Aksombo and Kpong. The trade-off that is apparent from this image is that the hydropower objectives have difficulty in also performing well when the environment objective is doing well. The optimisation has not come up with a policy that performs well in all of these three objectives. On the other hand, the irrigation objective does not show a direct trade-off. It can meet irrigation demands while also having high power production for Kpong and Akosombo. Apparently, the power production at Kpong does not suffer significantly from water being abstracted from the river flow. With the knowledge of Section 3.2.1 it can be explained because the flow coming from Akosombo to Kpong is often higher than the dam can handle, and water needs to be spilled anyway. Also, the irrigation flows are relatively low (38 m^3/s) when compared with the mean annual flow of Kpong (1160 m^3/s (VRA, n.d.-a)). Irrigation can also be high while also having a good environment score. However, it can be seen that irrigation and environment cannot be combined to have a large hydropower production at Akosombo, as indicated by the light shade of blue in the top right axis of the irrigation-environment scatter plot. Lastly, the figure shows no trade-offs in the flood control objective. This is because all the policies have zero flooding in them.

Using the parallel axis plot, Figure 4.2, these trade-offs can be seen by following the lines, each representing a release policy, across the objective axes. The higher the line on the objective axis, the better a policy performs in that objective. Horizontal lines show that there is no trade-off between the adjacent objectives, while a steep diagonal line shows a large trade-off. For all policies, the hydropower objectives show horizontal lines indicating a trade-off is absent. Meanwhile, the environment objective is limited to steep diagonal lines indicating no policies that perform well in both objectives. Irrigation has a mix of diagonal and horizontal lines with the environmental objective and, therefore, indirectly also with the hydropower generation objectives. However, the best irrigation policy works best when electricity generation is low and environmental flows are met. The trade-offs are highlighted by showing

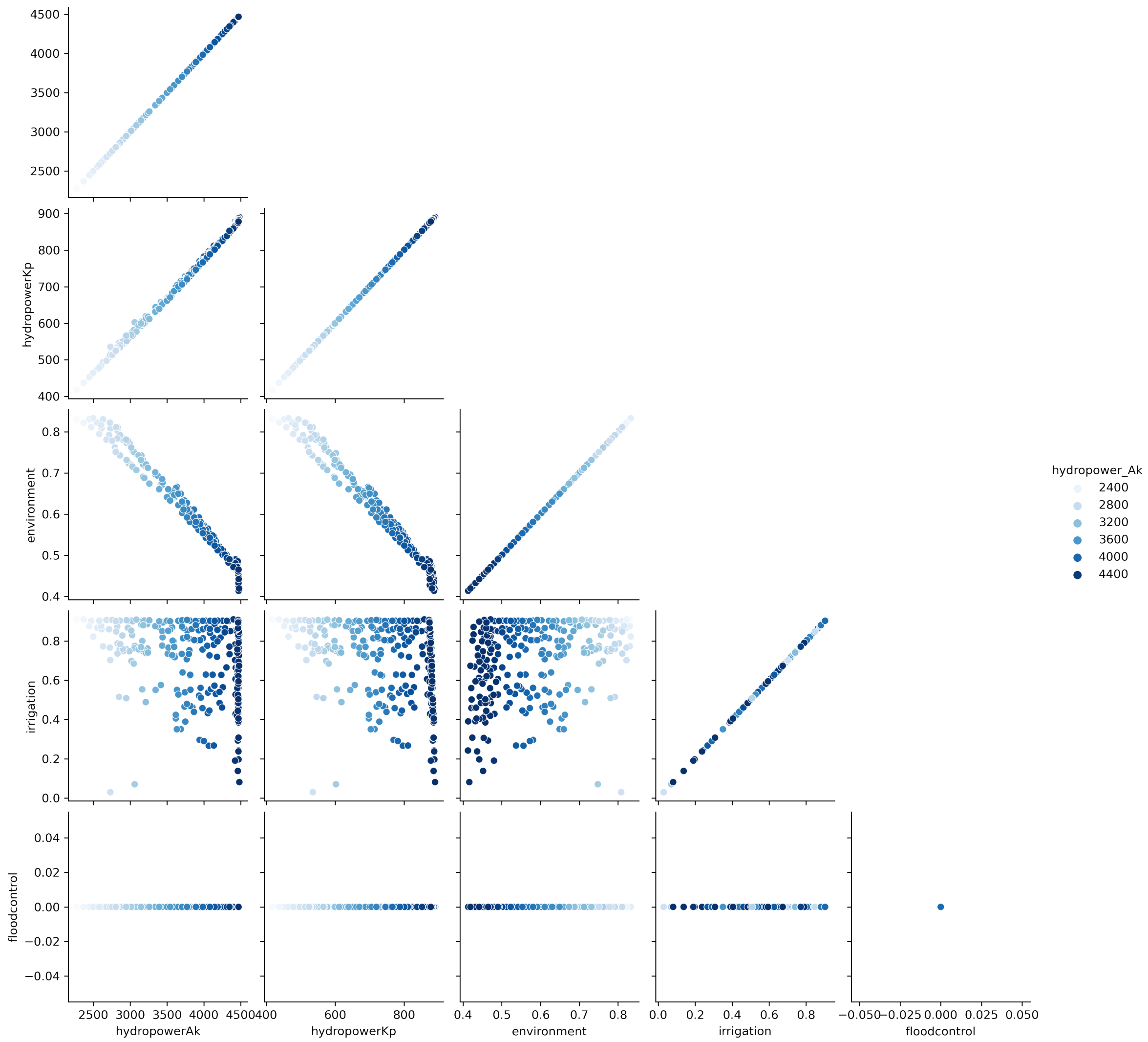

Figure 4.1: Average yearly outcomes of the historically optimised Pareto front policies on historical data. The blue hue indicated the hydropower generated at Akosombo. Good outcomes are the ones with combinations of high values for the hydropower Akosombo, hydropower Kpong, environment, and irrigation objective. The flood control outcome should be low.

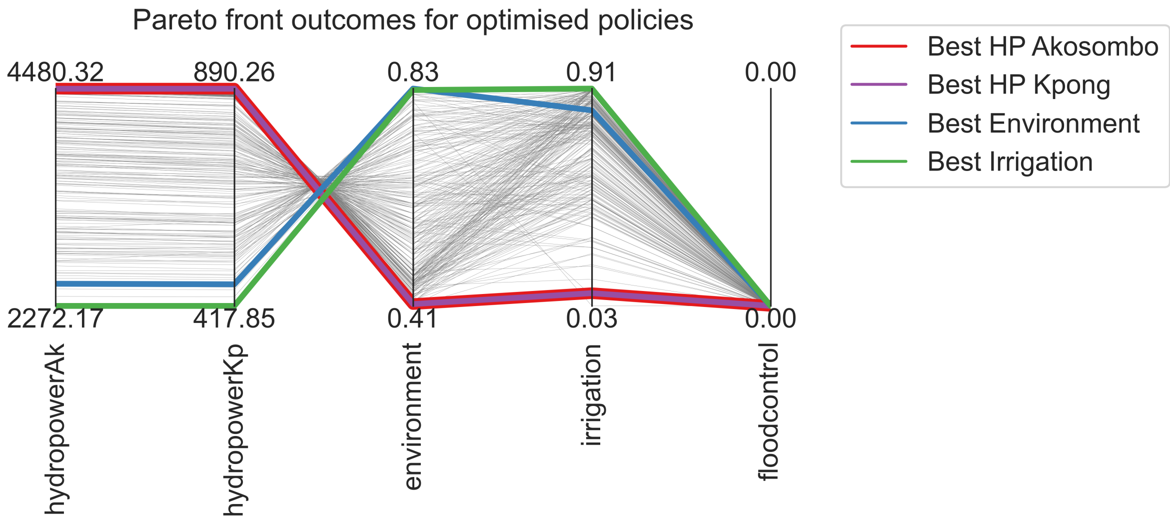

Figure 4.2: Parallel axes plot of all historically optimised Pareto policies in grey, and the best historical release policy per objective is highlighted in colour. Each of the axes represents a different objective, and the higher the line, the better the policy performs. When the line is horizontal across the axes, no trade-offs exist. When a line is diagonal, trade-offs do exist.

the best-performing policies for each objective, except for the flood objective since these are all zero.

4.1.2. Policies used in next analysis

Using the best performing policies for each goal and the ones that perform 80% of the maximum Akosombo result and 75% of the other objective maxima, the following policies are selected for further analysis. The best performing metrics are shown by ReleasePol1-3 in Figure 4.3. The other selected policies, seen in Figure 4.3, all seem to perform quite similar except for the irrigation objective, where a bit of spread can be seen among the objective. The satisficing can also be called a compromise policy since the hydropower objective is reduced in favour of the environmental and irrigation policies. Again, the outcome preference direction is to the axes' top side.

4.1.3. Conclusion

There are no policies that perform well over all objectives in the historical situation. This means a choice needs to be made in policies. Either the decision-maker needs to focus on full hydropower and low environmental flows or the other way around. The irrigation and flood control objectives can be achieved in either decision. A decision-maker can also choose a release policy that balances the policy performance between the hydropower and the environmental objectives.

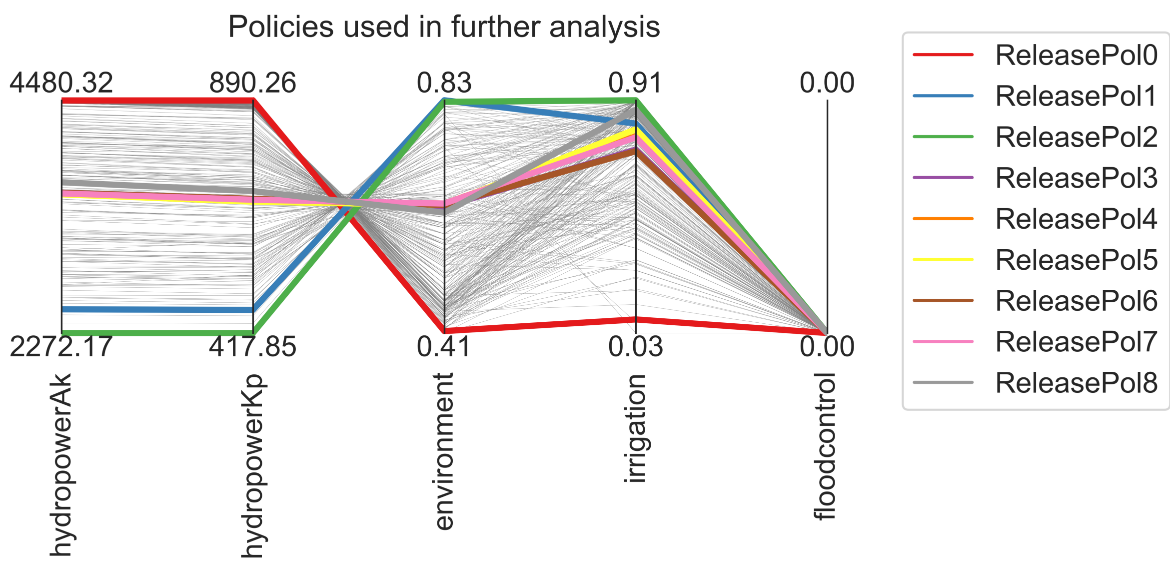

Figure 4.3: Selected policies for further analysis. Parallel axes plot of all historically optimised Pareto policies in grey. The selected policies are in colour. The policies are the best policy per objective and the satisficing policies. Each of the axes represents a different objective, and the higher the line, the better the policy performs. When the line is horizontal across the axes, no trade-offs exist. When a line is diagonal, trade-offs do exist.

4.2. Sampling of deep uncertainties

Figure 4.4 is created by using the Latin Hypercube sampling for scenario generation and performing the experiments on each of the selected optimised policies from 4.1. Figure 4.4 contains three parts. The first part is the top parallel axis plot. The plot shows the different objectives along the different axes for each selected policy in all the sampled scenarios. The better a policy performs, the higher it is located on the graph. Figures 4.5, 4.6, 4.7, and 4.8 allow for more detailed information since the top graph of Figure 4.4 contains several overlapping policies, making it though to analyse on an individual basis. The second graph, in the middle, contains a kernel density estimate (KDE) plot that indicates the number of outcomes for all policies. In this plot, the axes show the different outcome metrics, similar to the parallel axis plot. This plot indicates the complete range of the outcomes across release policies. Lastly, the figure contains a KDE plot for each policy to differentiate the performance and range of each policy.

After re-evaluation of each policy, some spread can be seen among the outcomes of the different experiments. Especially the hydropower objectives, j_hyd_ak, j_hyd_kp, j_energy_reliability, have quite some variation over the scenarios. The satisficing policies (Pol3-Pol8) are fairly similar to the best hydropower policy (Pol0) when considering the hydropower objectives. Pol 1 and 2 have a limited uncertainty range for hydropower. This can be explained by the limited hydropower generation that occurs when flows for the environment are released, which can easily be reached across scenarios. This, in combination with the inability to turn all the flows into hydropower during peak environmental flows due to limited turbine capacity, cause the outcomes to be low but stable. Figure 4.5 shows that the energy reliability can be low even though much hydropower is generated. Sometimes the energy reliability is lower when a large amount of hydropower is generated than when less hydropower is generated.

Overall, the irrigation and environment objectives have smaller outcome ranges per policy than the energy-related objectives meaning it is more difficult for policies to perform consistently for the energy objectives across scenarios than it is to perform consistently in the irrigation and environmental objective.

Pol1 and Pol2 seem to have almost the same environmental objective, although Pol2 is better at irrigation. This seems to come at the cost of hydropower production. Lastly, the satisficing policies have a single value for the environment objective for all scenarios.

One important result is that for each of the policies, flood control is not 0 as in the historical situation. The number of 0.19 means that the once in a hundred-year flood, the average daily flood in a year is 19% of 2300 m^3/s. This can cause trouble in the downstream basin. Especially since this is the daily average, but it is focused within a few events of big flooding. From the environmental favouring policies, this was to be expected since these try to implement a pre-dam condition with peak flows in the rainy season. However, also in the hydropower favoured policy, floods can occur even though they should supply a steady regime throughout the year to produce electricity. In contrast, the irrigation environmental policy aims to supply a little bit of flooding each year since this is good for the ecosystem.

4.2.1. Conclusion

Three noticeable conclusions can be drawn from the results to answer the sub-question of how the policies for the Akosombo perform in a range of uncertainties. First, the hydropower objective is the most variable objective for policies focused on generating the most hydropower. The policies focused on other objectives consistently perform low on the energy objectives, argued to be because of the missed power production potential due to turbine limitations during peak flows. Secondly, the flooding objective reoccurs in the system even though in the historical optimisation, none of the policies had floods. Thirdly, the scenarios give numerical shifts, but there are no scenarios in which the policies perform well in all objectives. The trade-offs in the system remain under all scenarios in the set climatic return times.

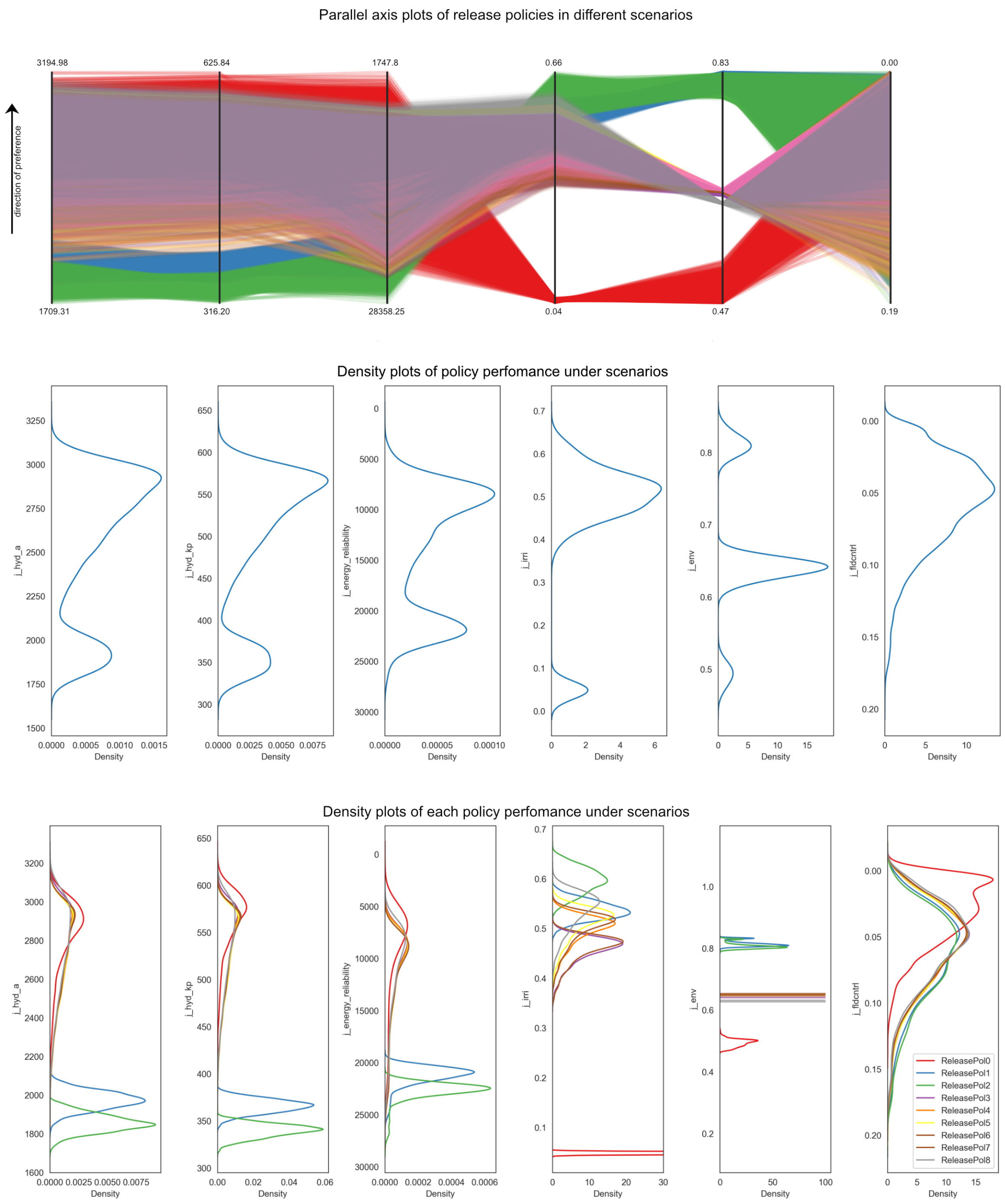

Figure 4.4: Policy performance under uncertainty (top), outcome prevalence of all policies (middle) and per policy (bottom) in the form of kde plots. Each axis is an objective and the desired situation is to have all objectives near the top of the graphs and closely grouped together.

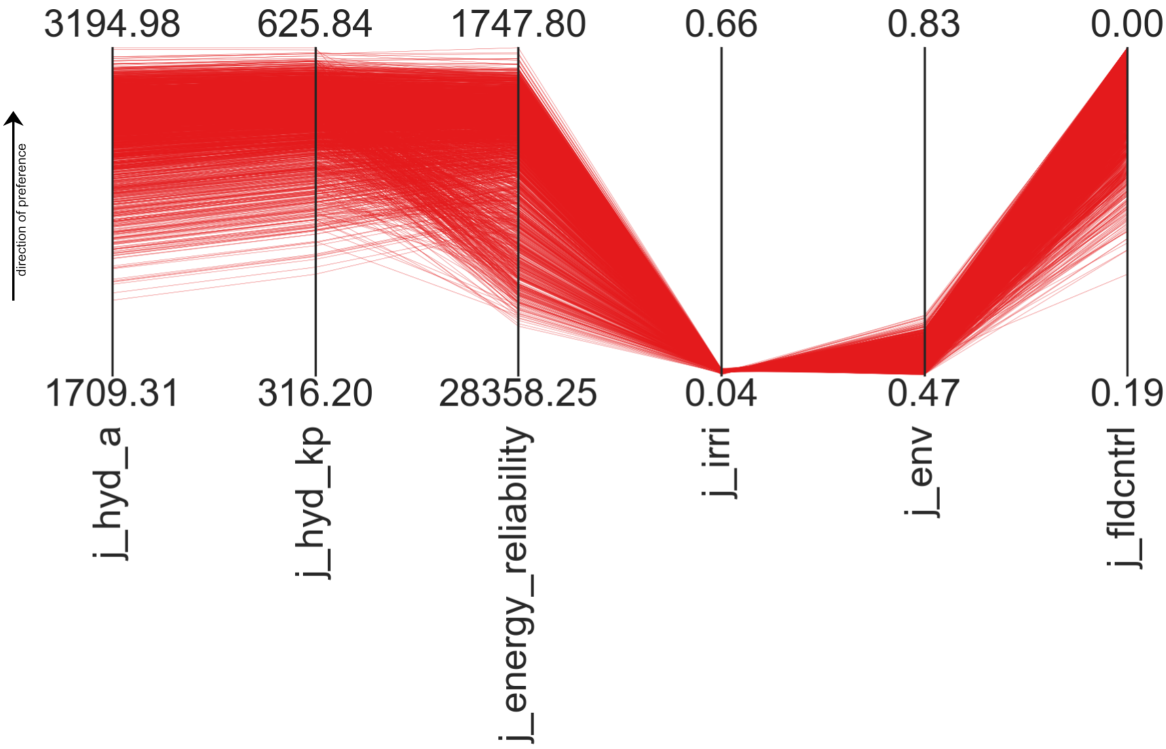

Figure 4.5: Performance of policy 0 (best hydropower) under uncertainty.

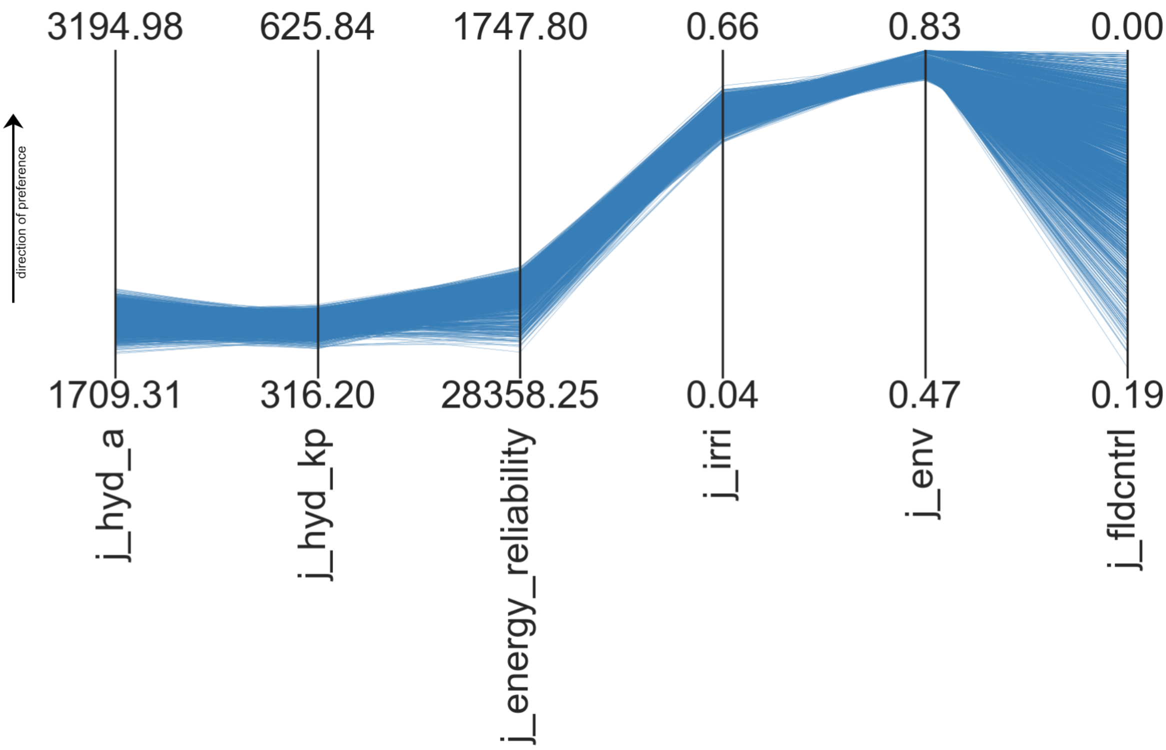

Figure 4.6: Performance of policy 1 (best environment) under uncertainty.

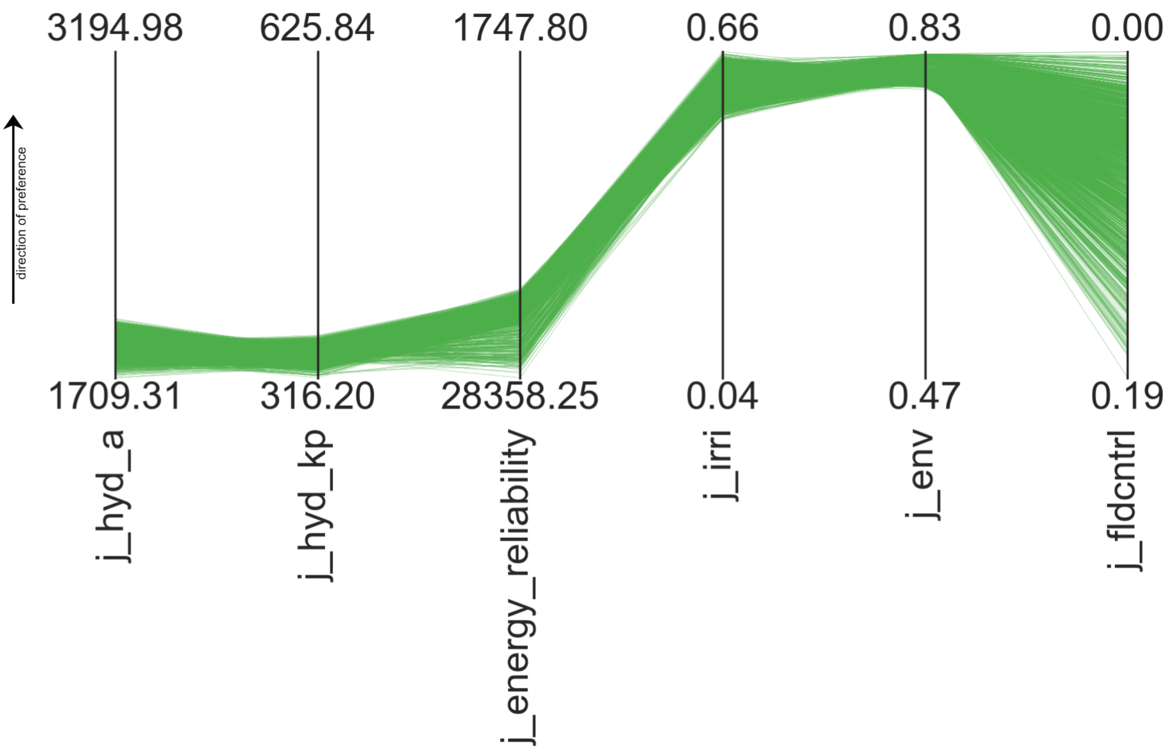

Figure 4.7: Performance of policy 2 (best irrigation) under uncertainty.

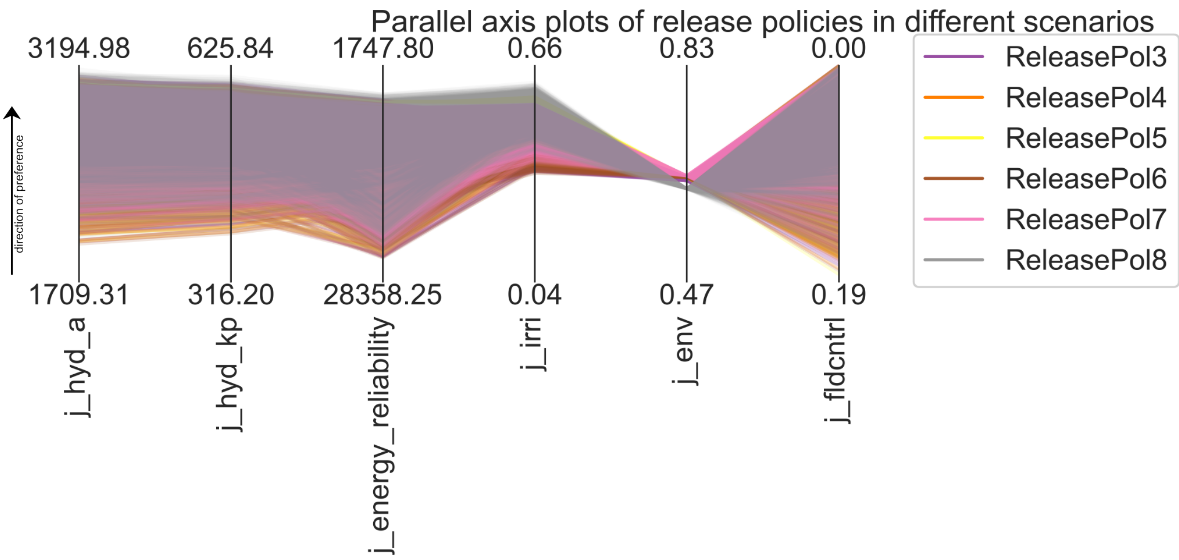

Figure 4.8: Performance of policies 3 to 8 (satisficing policies) under uncertainty.

4.3. Robustness

The parallel axis plot in Figure 4.9 shows the trade-offs in robustness among the policies. These trade-offs can be seen by following the lines, each representing a release policy, across the objective axes. The higher the line on the objective axis, the better a policy performs in that objective. Horizontal lines show that there is no trade-off between the adjacent objectives, while a steep diagonal line shows a large trade-off.

The parallel axis plot depicts that with a combination of different robustness metrics, there is no consensus on what the best policy should be selected from a robustness perspective. There are still trade-offs between the energy production at Kpong and Akosombo and the environmental objectives. New is that the robustness of energy reliability is higher in the best irrigation and environment policies (Pol2 and 1). Figure 4.4 shows that Pol 0 (best hydropower) produces more energy than the other objectives, but the spread is large, giving it a low overall robustness score.

Pol 1 and 2 (best environment and irrigation) have similar performance with robustness metrics as with the performance in Section 4.1 and 4.2 except for the energy reliability and the environmental objective. The policies perform better in the energy reliability metric than what one would expect from the actual performance in the previous section. Meanwhile, the environmental metric performs worse than one would expect from the actual performance. This has to do with the single value outcome of the satisficing policies, meaning an unbeatable high peakedness for these policies.

The satisficing policies perform very similar to Pol 0 (best hydropower) but have a higher irrigation and environment robustness metric score while having a lower flood control score.

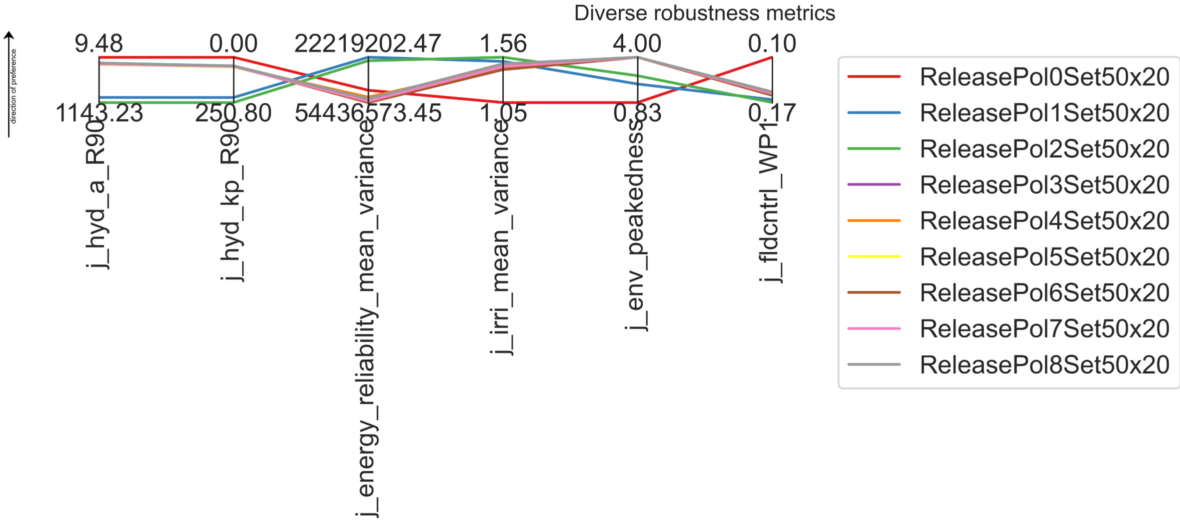

Figure 4.9: Robustness performance of policies with different robustness metrics across objectives (the different axes) to capture different risk attitudes across objectives. Each line represents a policy and the direction of prefference is up.

4.3.1. Conclusion

Returning to the sub-question of how the policies perform under different robustness metrics, one can conclude that the performance is fairly similar to what one would expect from actual performance scores. However, trade-offs still exist even when choosing a policy through different robustness preferences. What stands out is that the energy reliability scores lower in the hydropower favoured policy. This means that hydropower policies, even though they produce more energy, have a tough time producing a constant amount. Meaning it is not a good policy if one would like to create an energy system in which one knows what extra energy is consistently needed to support the power grid.

A second observation is that the environmental and irrigation policies perform lower in terms of robustness of the environmental objective than the satisficing policies. Although, when combining this information with the fact that other objectives have zero variation, the policy still performs reasonably.

4.4. Vulnerability

The vulnerability analysis is done for pol0 (best hydropower) since this is close to current operation objectives. The other policy used in this analysis is Pol8 (satisficing policy) since this performs well on both energy production as well as irrigation and environment. This can be a promising alternative and therefore deserves extra attention.

4.4.1. Scenario Discovery

The figures used in this section are the result of the Patient Rule Induction Method (PRIM). The method looks for the combination of factors in different states of the world in which the system performs below average. The method then provides the factors and ranges most indicative of the below-average performance in the form of a multi-dimensional box. It was chosen that the density of these boxes, the number of below-average cases to total cases in the box, should be at least 80%. The resulting coverage, the percentage of total below-average cases in the box, is indicated in the analysis. The figures show the factors given by the PRIM algorithm and plot these against each other. From here, the ranges of the box are plotted with a red border. If a case is within the border area of the shown multi-dimensional box, it is likely a case with below-average performance.

Figure 4.10 shows that electricity production at Akosombo mostly depends on the water use and treaties of both Côte d'Ivoire and Togo. The combination of no treaties and increased water use shows that the system performs poorly if water usage is high while treaties are low. Especially Togo seems to have a considerable influence, as seen by the quick histogram change at the treaties. These vulnerabilities are relatively similar for both policies. Except that pol0 (best hydropower) has the PRIM box set at 20% of Togo water use while Pol8 (satisficing policy) has it set at 30%, meaning Pol8 (satisficing policy) is less sensitive to the changes. Also, the coverage of the PRIM box of pol0 (best hydropower) is 70.2% while that of Pol8 (satisficing policy) is 66.4%. These numbers indicate that Pol8 (satisficing policy) is a bit less vulnerable to upstream water uses in achieving the mean energy production than pol0 (best hydropower). For Kpong, the results are similar except for the fact that the PRIM box coverage is lower for pol0 (best hydropower), 65.1%. This indicates that other factors have a more prominent role in these objectives than in that of the Akosombo.

The energy reliability can be significantly increased for pol0 (best hydropower) by increasing the energy storage between 1000-2000 GWh. The PRIM box covers 80% of the cases just with this variable. For Pol8 (satisficing policy), storage is less critical since the big factors are still water usage and agreements between Togo and Côte d'Ivoire. The coverage of these factors is relatively low compared to other objectives, with 41.3% for both policies. This means other factors also have an influence.

When using pol0 (best hydropower), the irrigation objective also strongly depends on water inflows from Togo and Côte d'Ivoire. The PRIM box covers 70.8% of all cases of below-average performance. However, in this objective, the water usage by Côte d'Ivoire is less important than in other objectives. In pol0 (best hydropower), the variable is not included in the box, and in Pol8 (satisficing policy), the water usage only becomes important after 26%, instead of the smaller 10% water usage. Noticeably, the irrigation demand multiplier does not play a large role in average performance of pol0 (best hydropower). However, in Pol8 (satisficing policy), the irrigation demand multiplier does show up in the PRIM box. Even with a decrease in irrigation demand, the policy has a tough time supplying the demand. Only when the irrigation demand is 75% of the current demand does the scenario fall outside of the PRIM box. The total coverage of the PRIM box is 60.4%.

The environmental objective for pol0 (best hydropower) performs especially poorly when inflows in June are too high or water usages in other countries are too low. This suggests that the policy performs below average when too much water is available and performs better when less water is available, especially in June. Also, when Togo and Côte d'Ivoire use more than 80 % and 90 %, respectively, the environmental objective is better off. These three uncertainties have a PRIM box coverage of 60.1%. No vulnerability could be analysed for Pol8 (satisficing policy) since the policy performed constantly over all scenarios.

Flood control for both pol0 (best hydropower) and 8 (satisficing policy) performance drops below average when climate change generates high inflows, from 30% increases, in October. However, this effect can be reduced by the water use of Côte d'Ivoire and Togo. Their development could benefit the flood control objective by using more water in peak seasons. These factors have a 68.8% coverage for both policies.

4.4.2. Feature scoring

The results in this section show the combination of uncertainties and levers and the importance of these on the system performance metrics in the form of a table. The tables contain a hue and a number. The darker and higher the number is, the higher the importance of that factor in the objective. In total, the columns, levers and uncertainties, of an objective sums to one.

Figure 4.12 shows the importance of uncertainties in the simulation on the objectives. The most important uncertainties for the energy objectives are the water use of Togo and Côte d'Ivoire. In which Togo plays a more prominent role, almost double, than Côte d'Ivoire. For the irrigation objective, pol0 (best hydropower) is most vulnerable to the climate change factor in August and, to a smaller extent, water usage by other countries. For Pol8 (satisficing policy), the irrigation demand is the main factor, together with water usages. This can be reasoned by the fact that the way the objective function is defined. The irrigation objective can be compensated in periods of high flows. For pol0 (best hydropower), irrigation is compensated in August, while Pol8 (satisficing policy) releases more water throughout the months, which it cannot always provide. The environmental objective of pol0 (best hydropower) is most sensitive to the June climate change factor, with some importance attributed to the upstream water usage. There is no data available for Pol8 (satisficing policy) since the outcomes are all the same. For both policies, the flood control objective is primarily affected by the increase in water in October and the water usage in Togo.

Figure 4.13 illustrates that the levers have similar influences on the outcomes for both policies. The treaties for Togo and Côte d'Ivoire have a considerable influence on hydropower production and irrigation supply. The energy reliability objective is very dependent on the energy storage lever, for pol0 (best hydropower) even more so than Pol8 (satisficing policy). The levers do not seem to affect the flood and environmental objective much.

What is notable is that the treaties have a larger influence than the water usage of the countries. This has to do with how the water use and treaties are set up. The water use assumes partial consumption of average flow while the treaties have a percentage of absolute flow.

4.4.3. Conclusion

This section looked to find the factors or combination of factors that cause the Akosombo system to be vulnerable to bad system functioning. Poor functioning is described as below-average performance in set climatic return times. The following observations are made:

- From both analyses, it becomes apparent that Togo and Côte d'Ivoire play an important role. The water they consume strongly alters the energy production, irrigation, and flood control objectives. Especially Togo has a large influence, being double that of Togo.
- Energy storage plays an important factor in the reliability of energy supply, especially when operating with pol0 (best hydropower).
- Irrigation is also largely dependent on water usage upstream while the demand multiplier has a lower influence. However, the PRIM of pol0 (best hydropower) shows that the irrigation objective also has a tough time succeeding even when the future demands are lower than current-day demands. The change in August flows also has a large impact on the objective for pol0 (best hydropower).
- The environmental objective is mostly disturbed by high inflows in June, and upstream usages could help with succeeding more often.
- The flood control objective shows that increases in inflow in August make flood control difficult. However, water use by riparian countries can decrease the effect due to the lowering of the peak flow.

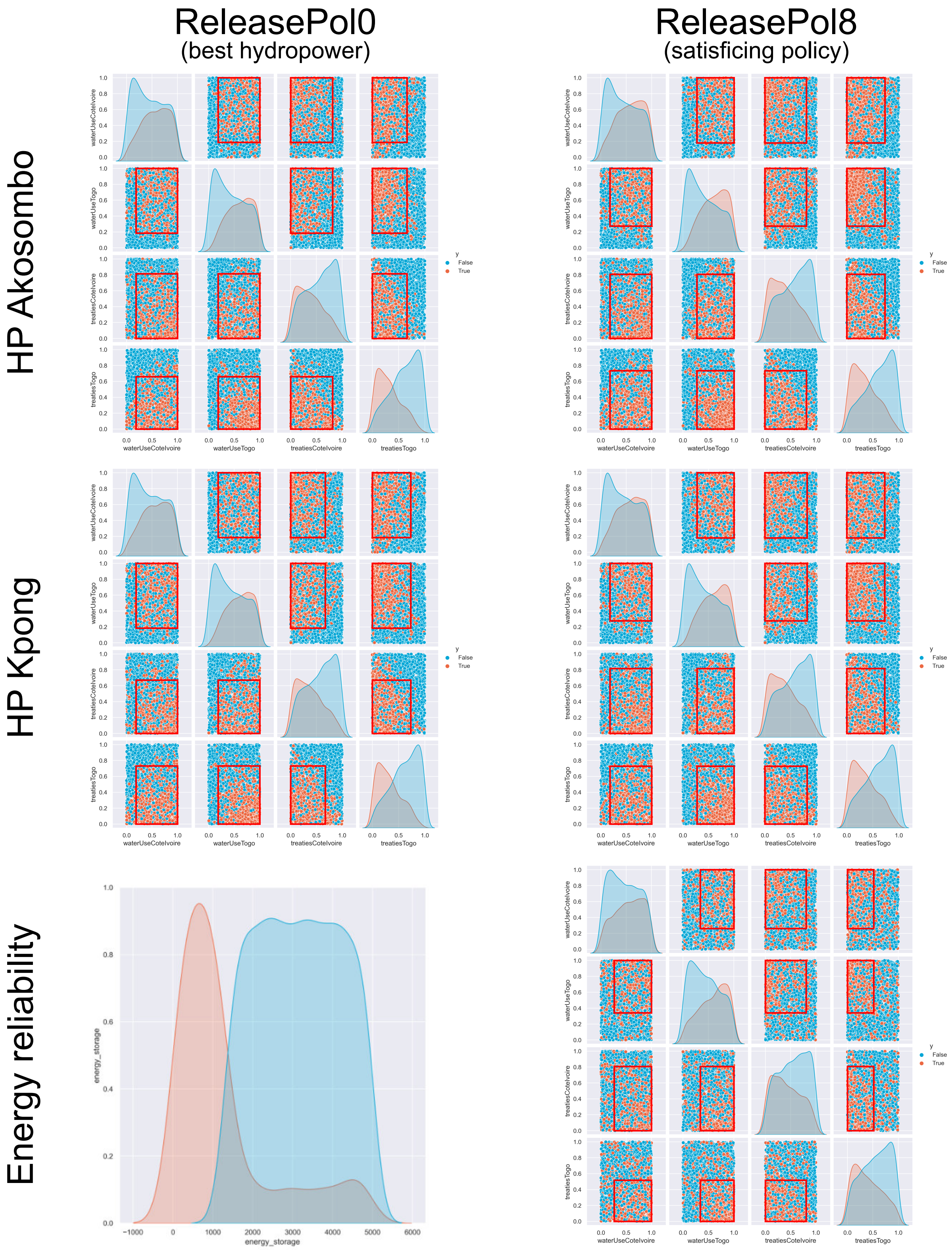

Figure 4.10: Patient Rule Induction Method boxes for release pol0 (best hydropower) and release Pol8 (satisficing policy). Each dot represents a scenario outcome for the specified policy. Orange dots indicate below-average performance, while blue dots indicate above-average performance. The ranges of the boxes are specified per objective pair by the red box. The chosen density is at least 80%. [1/2]

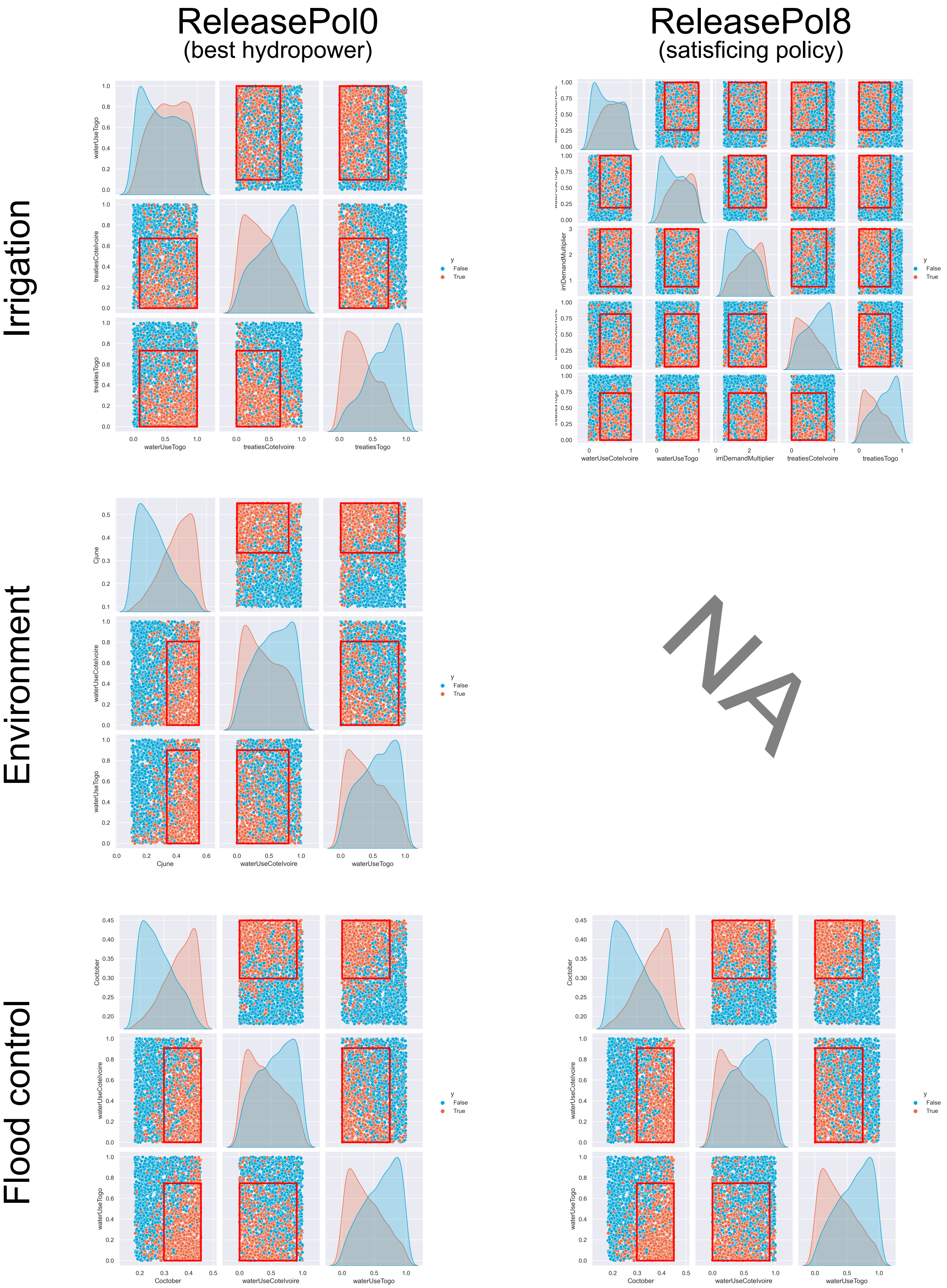

Figure 4.11: Patient Rule Induction Method boxes for release pol0 (best hydropower) and release Pol8 (satisficing policy). Each dot represents a scenario outcome for the specified policy. Orange dots indicate below-average performance, while blue dots indicate above-average performance. The ranges of the boxes are specified per objective pair by the red box. The chosen density is at least 80%. [2/2]

Figure 4.12: Extra trees feature scores of uncertainties in the system for pol0 (best hydropower) and Pol8 (satisficing policy). A higher and darker score means that that factor has a large influence on the outcome. The columns sum to one in combination with the levers table.

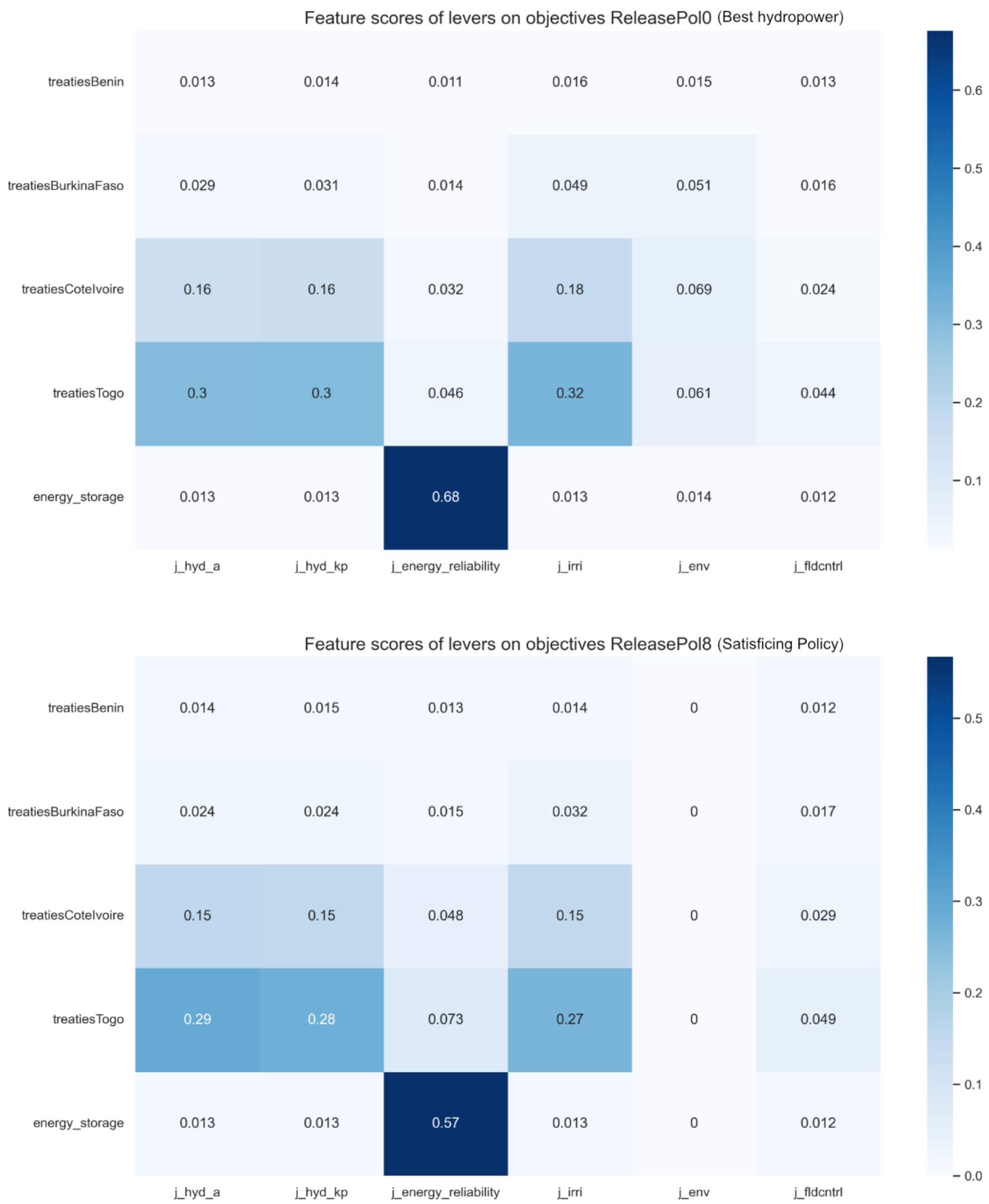

Figure 4.13: Extra trees feature scores of levers in the system for pol0 (best hydropower) and Pol8 (satisficing policy). A higher and darker score means that that factor has a large influence on the outcome. The columns sum to one in combination with the uncertainties table.

5

Discussion

This chapter first summarises the research findings (Section 5.1) to place the found results into its larger system context in order to provide a better understanding of their implications and meaning (5.2). Lastly, the limitations of this research are presented (5.3).

5.1. Research findings

The literature has shown that EMODPS is a promising technique for finding new policies in the dam multi-objective reoperation problem of the Akosombo. Reoperation of the dam has been looked at before; however, current studies have not looked extensively at performance under uncertainties that play a role within the system and the robustness of release policies. In general, the EMODPS method in the literature has not included a flexible posterior way of navigating stakeholder preferences regarding robustness and climatic return times of flows. That is why the following research question has been defined: *What are the effects of climate change, riparian water use, and energy uncertainties and levers on optimised released policies for the Akosombo dam using a posteriori decided robustness metrics, climatic return times, and system limits?*

The method to answer this question has been to: 1) describe the system at hand. 2) find optimal policies to re-evaluate 3) re-evaluate these policies in different states of the world. 4) analyse these results for a range of robustness metrics. 5) Explore the vulnerability of the policies.

The system description (Chapter 3.2) revealed that the current Akosombo and Kpong systems are subjected to uncertainty regarding inflows due to climate change, more extreme events, inflow changes due to upstream water use, and irrigation demand changes. The levers that could help the dam operation were defined to be treaties between riparian states and energy storage to improve energy reliability.

Using this description, historically optimised policies are taken and analysed. However, since there are no policies that perform well over all objectives in the historic situation, a choice needed to be made in policies. Therefore, the best policies per objective and those that satisfied all objectives well were chosen for further analysis.

The re-evaluation of selected policies shows that the hydropower objective is subjected to large variation over the different scenarios. Next to that, the flooding objective is not zero anymore, meaning downstream communities will deal with flooding of their lands. Lastly, the trade-offs remain in the system. There are no scenarios in which the policies perform well in all conditions. This means that these policies do not perform well for all metrics, even in the best situations. What is holding back hydropower production is the fact that during high flow releases for the environmental objective, the flows are too high for the turbines, and water has to go over the spillways. This does not only limit hydropower production but also the energy reliability objective since, at this point in time, no energy can be stored for later use.

The robustness tests show that the trade-offs remain even when a decision-maker has different risk attitudes towards the objectives. Next to that, the hydropower policies have a tough time generating the same amount of energy constantly across scenarios.

The vulnerability shows how important Côte d'Ivoire and especially Togo are for the Akosomsbo dam. They alter the energy production significantly negatively when their water use increases. When taking the electricity production of the Ghanaian Bui dam on the Black Volta into account, Côte d'Ivoire will play a more prominent role than is currently portrayed. However, at the same time, the countries can also reduce flooding when their water use increases, especially during peak flows in August. These countries can also improve the environmental objective when their water use increases due to less water being available to the Akosombo, creating dryer conditions in which nature thrives.

5.2. Placement into the larger context

5.2.1. The energy sector

Even though the talks on the Akosombo dam reoperation have existed already in 2017, there have been no changes in operation. Although Giuliani et al. (2021) mentioned that the uptake of EMODPS has been slow due to incomprehensibility, it can also be argued that there is no political will to do this. What can be seen at the VRA in Ghana is that their mandate, since the beginning, has been, and still is, to provide energy to Ghana (Government of Ghana, 1961; Interviews, 2022). Interviews (2022) revealed the political pressure to produce hydropower over other energy sources since this is the cheapest form of energy. Especially the last few years in which the price of fuels for thermal power plants has undergone large increases. The gasoline price within the country doubled (Doris Dokua Sasu, 2022).

While the Akosombo and Kpong dam currently generate 54% of the energy by the VRA (VRA, 2019), the percentage used to be a 100% and exports. Due to demand increases and the inability to produce more with what they can, the Akosombo becomes less relevant in terms of relative power production. In Interviews (2022) the interviewees also mentioned that the Akosombo dam's role will get smaller with increased energy demand in the country. However, the Akosombo dam is said to always serve critical functions within the energy system, and no decommissioning is planned since maintenance will keep the dam working for longer.

Not only is the dam essential for power production within Ghana but also outside of Ghana. Ghana has a tied second place with Côte d'Ivoire, behind Nigeria, as the largest energy exporter in the West African Power Pool (WAPP). Ghana exports ten times the amount of energy that it imports. Togo and Benin, on the other hand, are the largest importers of energy within the WAPP (WAPP, 2020). One could argue that Togo and Benin have a large incentive to protect the Akosombo dam power production. However, it can also be argued that these imports do not come cheap and that it is an incentive to create their own production through hydropower. Togo is situated along the river with the highest flow, the Oti, which could generate a lot of electricity.

Lastly, the current worldwide energy sector is not yet ready for energy storage at the proposed capacity of over 1000 GWh. The world's largest battery energy storage system is currently 1.6 GWh (Colthorpe, 2021). This is 0.16% of the needed capacity. Although current technology is not yet available, it is worth keeping an eye on future developments.

5.2.2. The Water Charter

Currently, the six riparian states of the Volta Basin are working on a Water Charter by the Volta Basin Authority (VBA) that aims to prevent and settle inter-state arguments regarding the use of shared water resources while also promoting good governance of these resources (, 2018). This is a good step to enhance basin cooperation. However, the Water Charter does not yet provide strict target flows for downstream states except that at least basic human needs should be provided. There is also the term 'equitable and reasonable utilisation of the resources'. Currently, Ghana benefits greatly from the water flowing into their country, and it would be painful if Ghana lost these resources. However, the question arises if this is a strong enough reason for other basin countries to refrain from finally reaping the benefits of these water resources themselves. Is it equitable to prevent harm to others and keep yourself down, or is it equitable to develop one's own country as Ghana has benefited in the past?

The Water Charter describes that the VBA will try to mediate in the dispute but wields no hard power to stop disputed actions of member states. When the VBA cannot settle the dispute, it brings the case to the e Economic Community of West African States and the African Union. If these also fail to settle the dispute, the case will be brought to the International Court of Justice of the United Nations. However, this last option brings its own set of challenges as only Togo and Côte d'Ivoire recognise the jurisdiction of the court, while Burkina Faso, Ghana and Benin do not (International Court of Justice, 2022).

The lack of flow requirements and definition of equitability and the absence of written consequence in the Water Charter make it that Ghana's water resources are not firmly established for the future. Next to these issues, it has been found that treaties usually maintain the status quo and that the weaker party agrees under the fear of losing all, leading to issues later on (Zeitoun & Warner, 2006).

5.2.3. Shared benefits

To prevent unilateral actions in the basin, it hypothesised that benefits in the basin could be shared to enlarge the benefits for everyone. For example, the Oti river brings in a lot of water, but the river's midsection lies on the border of both Togo and Ghana. A shared cross-border reservoir could enlarge both countries' energy production and irrigation potential while also sharing the burden. The same is true for Côte d'Ivoire. Another mutual benefit that can be agreed upon is that the water treaty engages in different flow scenarios. As seen, the water usage of upstream states can prevent flooding in the Lower Volta basin in extreme flows. This could provide upstream states with the chance to store the excess water for later use.

The benefits do not have to be restricted to dams either. The Sogakope-Lomé transboundary drinking water transfer project (African Development Bank, 2013) is an example of a project in which benefits are shared by first passing water through to Ghana to be used for electricity production and later transferred towards Togo again to supply the capital with fresh water.

5.3. Limitations

- In this thesis, the system's vulnerability was analysed; however, no specific system operation boundaries were found. It can be of interest to redo the analysis with stakeholders to find more significant results that relate to true scenarios to avoid.
- This study used certain return times for the objectives under different climatic conditions. However, these were not decided together with stakeholders meaning that certain outcomes might be worse or better than one would find with the decision maker's preferences.
- The same argument can be used for the choice in robustness metrics. No stakeholders have been engaged on this topic. They might find average performance more important than worst percentile or regret.
- The uncertainties and levers were sampled together in setting states of the world. This decision was made to reduce computational costs, however, it also reduces the amount of information one can retrieve from the analysis. The current data can not answer the question of what combination of levers delivers the best performance across the scenarios.
- The uncertainties in this thesis were set to find extremes in the system. However, the probabilities of these happening are low. It is not likely that Togo will use 100% of all water in the Oti river. Together with stakeholders, more specific ranges for the uncertainties and levers can be described with a different scenario sampling method to include probabilities of a scenario actually happening.
- The chosen policy set has limited variation within its outcomes. Selecting a more diverse set to show more possibilities to the decision-maker is interesting.
- The current model only takes into account a strategy. However, the actual operation can differ due to political pressure or demand changes in the grid. These factors are not considered, and therefore actual operation will look different.
- In the study, the Ghanaian internal water resource dynamics were considered outside the system boundary since it was deemed under the control of local authorities. The outcomes will likely change when these factors are taken into account. One example of a change upstream is the Pwalugu dam in the White Volta.
- The Oti and Black Volta rivers lie for a large part on the border of Ghana and Togo and Côte d'Ivoire. This means it is hard for these countries to actually develop large infrastructures. Even when taking out water from the river, Ghana could do the same but a little bit further upstream. Therefore, it is worth investigating the discharges before the border is shared.

- The stochastic sets of evaporation, tailwater levels and head at Kpong are taken to be a repetition of the mean value of that day of the year from the 29-year historical data set. The change in evaporation of Lake Volta is considered out of scope, and an average over the historical years was deemed good enough to have an indication of the seasonal pattern. However, with climate change, this might become an important factor in the future.
- As discussed in Section 3.2.6 the tailwater levels of Akosombo are hard to connect to releases of the Akosombo due to the influence of downstream conditions, and historical averages were taken. However, with new operation of the Akosombo dam, the behaviour of the Kpong levels can also change.
- Historical optimisation succeeded in obtaining release policies that have zero floods. However, when faced with different inflows, floods start to occur since the flood objective stopped optimising when zero floods occurred and did not anticipate other flows anymore. Therefore, a new optimisation requirement could be formulated to indicate near flooding instead so the optimisation can keep optimising on that objective.

6 Conclusion

As discussed in Chapter 2 the construction of the Akosombo dam brought along many negative side effects. Recent research has been focused on finding optimal release policies to try and minimise these effects for ecosystems downstream of the dam. To complement that research, this study took these optimal policies to subject them to a range of scenarios. These new states of the world included climate change, upstream water use, treaties, irrigation demand change, extreme flow events, and energy storage. The aim was to gain insight into the system and the release policies by subjecting the optimal policies to unknown future states of the world while moving the analyses to the end of the process to stay flexible with regard to changing preferences of the decision-maker and further studies. This chapter will answer the main question of this study: "*What are the effects of uncertainties and levers concerning climate change, riparian water use, irrigation demands, and energy on optimised release policies for the Akosombo dam using a posteriori decided robustness metrics, climatic return times, and system limits?*"

From previous research it was already known that trade-offs exist between the hydropower objective and the environmental objective. When re-evaluating release policies, these trade-offs do not go away. There was not a scenario that was found in which both hydropower generation and environment scored well.

Secondly, the more a policy is focused on hydropower, the less stable the result is across the scenarios. The amounts produced vary while the energy reliability also shifts up and down. With the environmental and irrigation release policies, the energy outcomes are low but stable. Depending on the decision-maker's preferences, this unreliability might pose a problem. For example, when it needs to decide on how much extra capacity to install in the grid. Next to this issue, flooding poses a problem for each of the policies. Plans will need to be made on how to deal with these floods in the future.

Thirdly, the robustness of the policies varies per objective, also when having different metrics per objective. Therefore, to decide on a robust policy, the decision-maker must decide what objectives they find most important for robustness.

Lastly, the currently used maximum hydropower policy and a more balanced policy that performs better for the irrigation and the environment objective while also having about 80% of the current hydropower production have their threats. Although their percentual size of the Volta basin is small, the biggest threat is the water use of both Togo and Côte d'Ivoire. This is because most of the water in the basin flows through these countries. Consequently, their water usage can significantly influence the hydropower objectives of the Akosombo and Kpong, especially Togo. However, their water usage also provides possibilities. Their water usage can help reduce peak flows in August and, therefore, flood events in the Lower Volta. Another opportunity arises when these countries hold back water. The environmental objective benefits from this since dry seasons will be dry again. Regarding energy reliability, energy storage can help reduce shortages. However, during high peak flows, the turbines cannot handle all discharges and spillways are opened. This leads to energy losses that cannot be used for another moment in time. Increasing the turbine capacity or amount of turbines might improve electricity production during high flows and energy reliability, creating better energy outcomes for the environmental release policies. However, current technology in the sector is not ready for such large capacities yet.

Overall, when considering the current context, the dam's reoperation for environmental flows will come at the high price of lower energy production. In the future, this price might be relatively lower when the percentual contribution of the Akosombo dam becomes lower and energy storage possibilities are higher. However, even when not reoperating the dam for ecosystem services, the benefits are threatened by water use by upstream states. The Water Charter is a good step towards cooperation in the basin but still has its flaws and is not expected to establish firm water security. Sharing benefits and cooperating in shared projects within the basin could benefit both Ghana and upstream riparian states more than strict treaties.

6.1. Recommendations to policy makers

1. A conscious decision needs to be made between what policies are acceptable that trade-off the hydropower and environment objectives since both are not possible.
2. There is potential flooding with the chosen policies and extreme flow events. Try to get people out of the flood plain and have plans available for when a flood occurs so harm is minimised.
3. Since there is variation in the system, it is worth it to create flexible systems. For example, thermal plants already backup the energy grid when low flows occur. Try to find similar solutions for the irrigation and environmental objective to either substitute flows from Akosombo or minimise damages.
4. Find agreements with Togo and Côte d'Ivoire that secures certain flows over the months. However, also secure maximum flows during high flow months to reduce flood risk.
5. The Oti is the river with the largest flow in the basin. Therefore, working together with Togo on developing infrastructure along the shared border could be beneficial for both countries.
6. Keep an eye on the development in the field of energy storage. Although it is currently not possible at a large scale, energy storage can increase the energy reliability of the system by storing energy when it is not needed and releasing it when it is. This might also open doors for environmental flows.
7. Do not entirely depend on treaties and agreements as these can be broken. Sharing benefits in the basin could increase the security of Ghanaian water resources.

6.2. Scientific contribution

Studies on the Akosombo dam and potential new release policies to minimise the impacts on environmental systems have been done before (Ntiamoa-Baidu et al., 2017; Owusu et al., 2022). This research builds upon that research by exploring how optimised release policies perform under a wide range of uncertainties to which the Volta Basin is subjected. This way, the first cycle of the many objective robust decision-making framework (Kasprzyk et al., 2013) is completed. This full cycle provides more understanding of the system, and these first results can be used in future work.

Next to specific insights into the Akosombo, the work also introduces a flexible analysis to EMODPS literature in which return times, robustness metrics, and system performance limits can be decided a posteriori in the analysis instead of a priori in the simulation. This way, decision-makers can easily alter their risk preferences per objective.

6.3. Recommendations for future research

1. From literature, it was found that decision-makers find the outcomes of optimisation techniques difficult to understand. Further research should be done on effective communication of the optimisation method to stakeholders.
2. Choices for parameters of the analysis phase needed to be made without having literature to substantiate those choices. The application of the research could be enhanced by working on the model together with decision-makers and allowing them to work with the results interactively. One suggestion is to create an interactive decision support system where decision-makers can change performance metrics, return times, robustness metrics and system limits in real-time.

Literature suggests this could enhance their understanding of the system while also finding better solutions.

3. The research has focused on postponing decisions to after the simulation (a posteriori). However, in this study, the decision on objective functions was made beforehand (a priori). For example, the irrigation objective is the mean demand deficiency over a year. However, one could also argue that the missed demand per month is important since crops could die if demand is missed in the middle of the growing season. One way to postpone the decision in policy re-evaluation is to store the flows during the simulation and afterwards apply a metric to it. This would postpone decisions and enhance unbiased decision support.

4. This study focused on what-if scenarios with little regard for the political consequences for upstream countries when their water use increases. A stakeholder study could be done to see if the sketched scenarios are realistic. These should include benefits and the costs for an upstream state when it decides to abstract water from the rivers.

5. Research into the future of the Akosombo could be done to explore its relevance in the future when it produces relatively little energy for the system. An analysis could be made when new possibilities open up for the other objectives in the system.

6. Further research should be done on the benefits of energy storage on energy production and reliability when more turbines are added. Currently, the system misses energy production during high flows in the environmental flow policies since these high flows are spilled.

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A
Synthetic hydrology

This appendix explains the steps taken to go from historical data to the inflows that are used in the 50 simulations of 20 years each. First, the historic inflow data is analysed to estimate the contributions of each catchment of the chosen flow station. Then the Kirsch-Nowak method is used to generate flows that include more extreme situations. Lastly, the tailwater, evaporation and Kpong head data is extended towards the future.

A.1. Historic Flows

It is first needed to select and analyse previous historical data sets to look at future data sets. The data set chosen for this part of the thesis is that of the GRDC (2022). The GRDC has a collection runoff data in m^3/s for a range of stations in the Volta basin. In this thesis, the runoff data of the Senchi location has been chosen before 1964. The set before 1964 is selected because this gives an idea about pre-dam conditions since, after 1964, the flows at Senchi are controlled by the decisions of the VRA. Senchi is situated before the Kpong and after Akosombo, giving a good indication of flows in the river at Akosombo.

A.1.1. GRDC data editing

To use the inflow data of GRDC in section 3.2.6, a few edits to the set are made. First, data after 1964 and before 1937 is discarded. This is because after 1964, the dam interrupted the flow of water, and in 1936 the measurements started but not at the beginning of the year. Secondly, the years where monthly data are missing were removed from the set. This resulted in a final data set of 24 complete years out of the remaining 28 years. These monthly averages of m^3/s were then used to fill in the daily values of m^3/s. The same daily value occurs every day in a single month. This is argued to suffice since a single day of peak inflow will not change the reservoir levels a lot due to the large size of the lake and the buffering ability that comes with that.

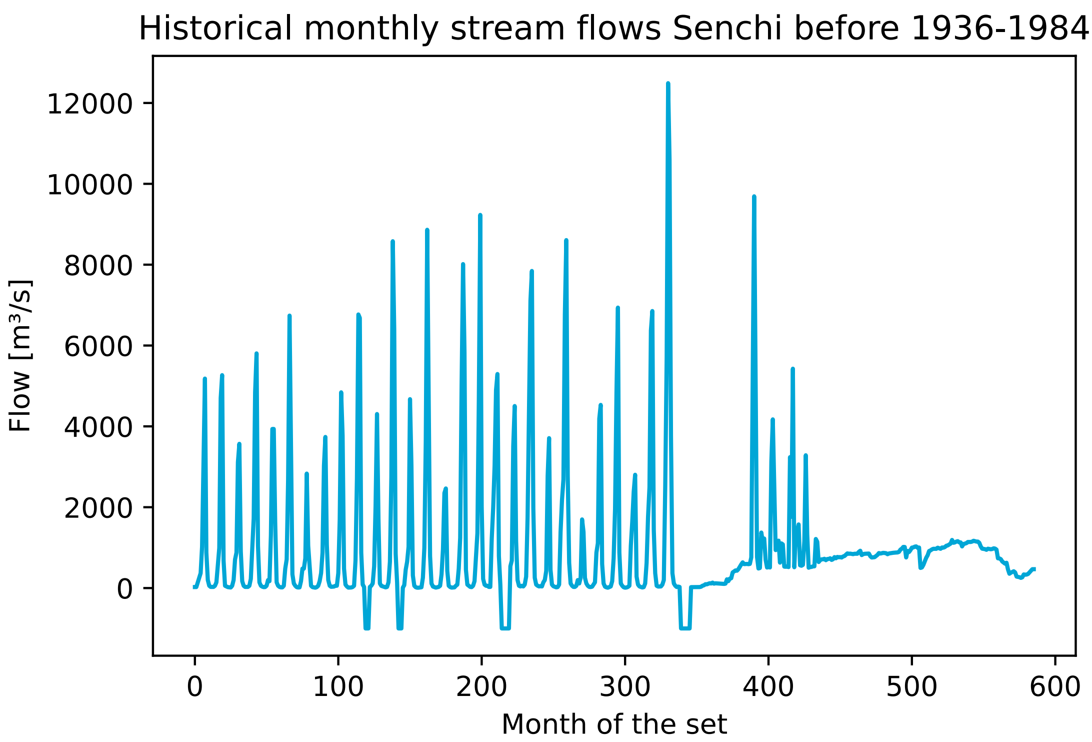

Figure A.1: Complete historical dataset of the GRDC (2022). The data is plotted from 1936 until 1984 showing both pre and post dam conditions of the flows.

A.2. Kirsch-Nowak streamflow generation

Using the Kirsch-Nowak techniques as used in Salazar et al. (2017); Quinn et al. (2017); Giuliani et al. (2017) and Github repository of Giuliani et al. (2022), one can take a historical data set of flows and transform that into datasets that are longer and include more extremes. These data sets are called synthetic hydrology. In this thesis, the historical inflow dataset of the GRDC (2022) as described in Section A.1 is taken as an input to generate multiple inflow sets. This is done to include more extremes as it has been said that historical datasets do not always contain measurements of extreme droughts or extreme inflows (Salazar et al., 2017).

In this thesis, it has been decided that 50 sets of 20 years would be suitable. The 20 consecutive years and 50 sets provide an appropriate variation throughout the years.

The Kirsch-Nowak method resulted in the following streamflows seen in Figure A.2 and can be described by the flow exceedance probability curve in Figure A.3. The Flow exceedance curve has an edgy nature since the daily data is consistent throughout the month. This means that many values reoccur while some values are never included within the dataset, creating jumps in the probabilities.

A.2.1. Validation

To verify the resulting synthetic flows and that they are similar to the historical distribution, the sets are compared to see if they are statistically similar or different. This was done in the same way as in Giuliani et al. (2022). The medians and variance of the sets are tested in Figure A.6. Since the flows are not normally distributed, a Wilcoxon rank-sum test and Levene's test is used to compare the two sets. It can be seen that none of the months in the synthetic set is statistically different from the historical set at a significance level set at 0.05.

Next to this test, it is also tested if the autocorrelation between both monthly and daily data is similar to that of the historical record. In A.4, one can see that the synthetic autocorrelation is close to that of the historical data.

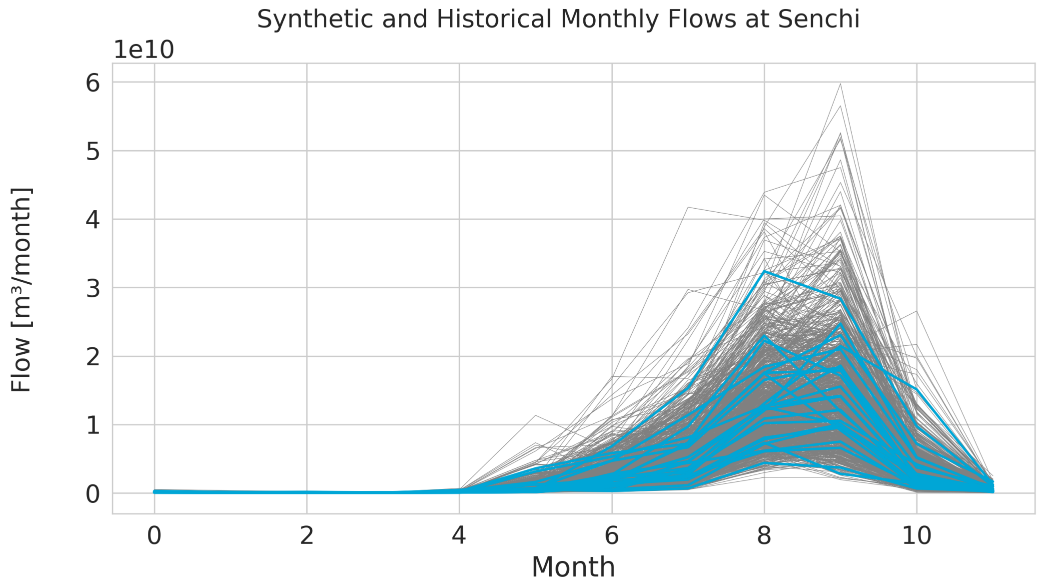

Figure A.2: A 1000 years of used synthetic streamflows (grey) plotted compared to historical flows at Senchi before 1964 (blue). Average monthly flows are plotted per month. Month 0 is January and 11 is December.

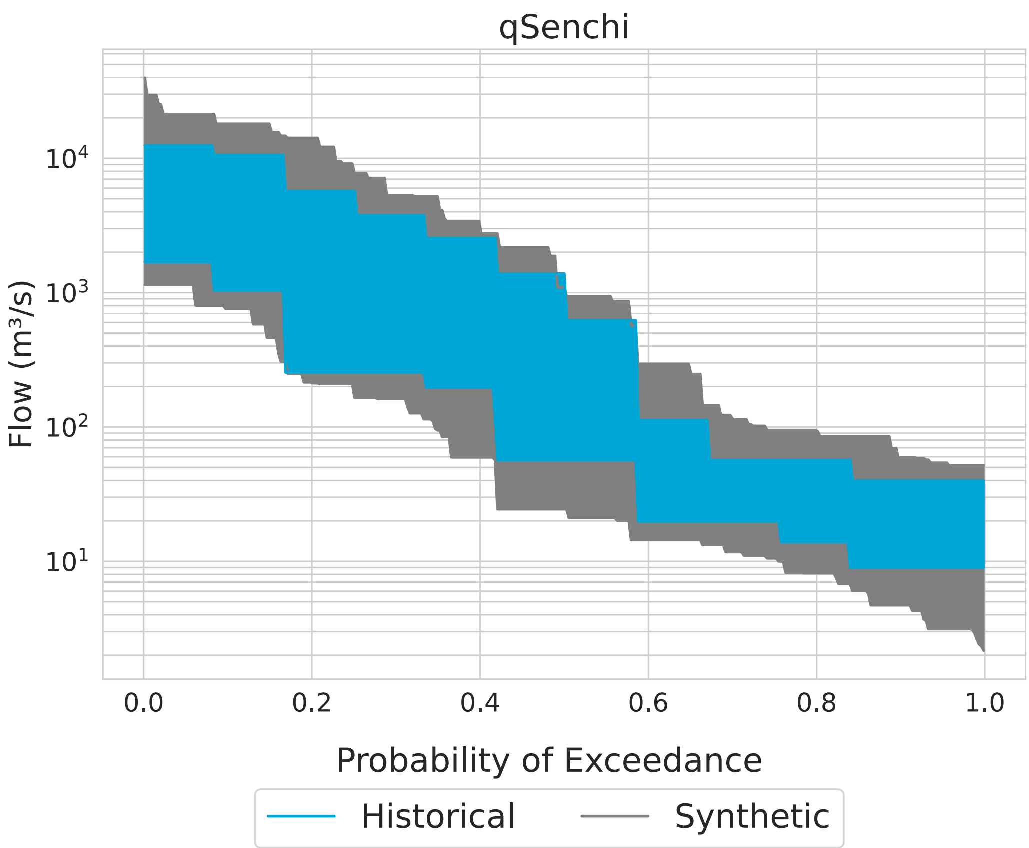

Figure A.3: Inflow exceedance probability curves of both historical (blue) and synthetic (grey) data for the Akosombo system.

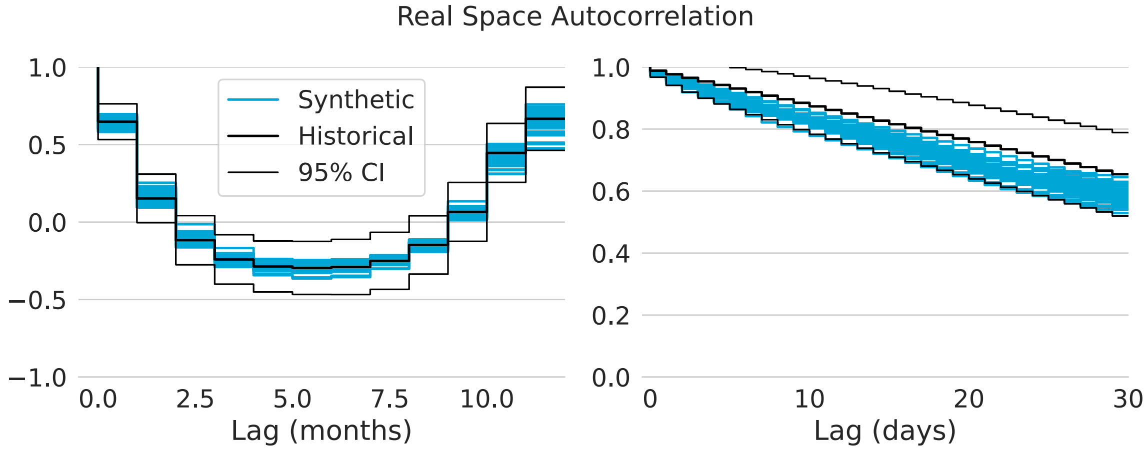

Figure A.4: Real space autocorrelation plots for both historic and synthetic streamflows for the flows at Senchi. The black lines indicate the historic mean and 95% confidence intervals in the set.

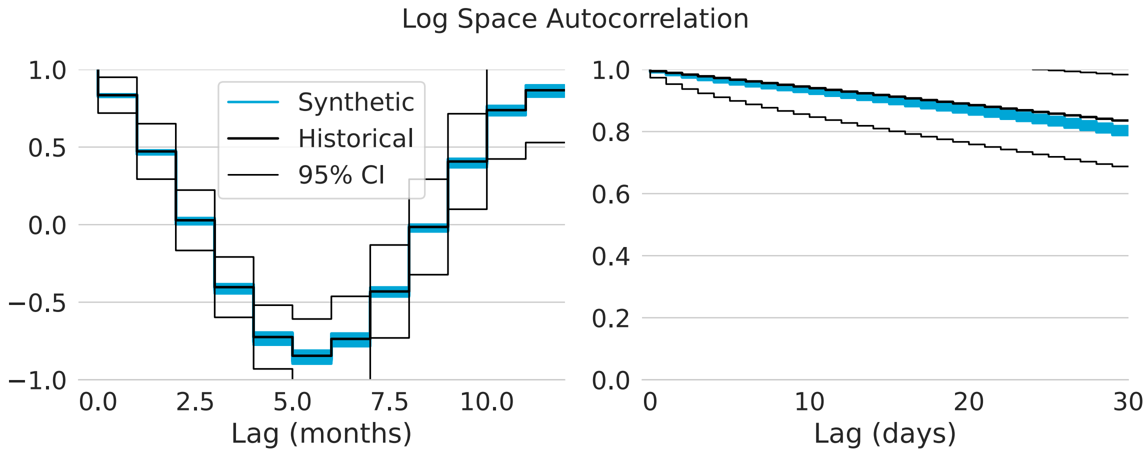

Figure A.5: Log space autocorrelation plots for both historic and synthetic streamflows for the flows at Senchi. The black lines indicate the historic mean and 95% confidence intervals in the set.

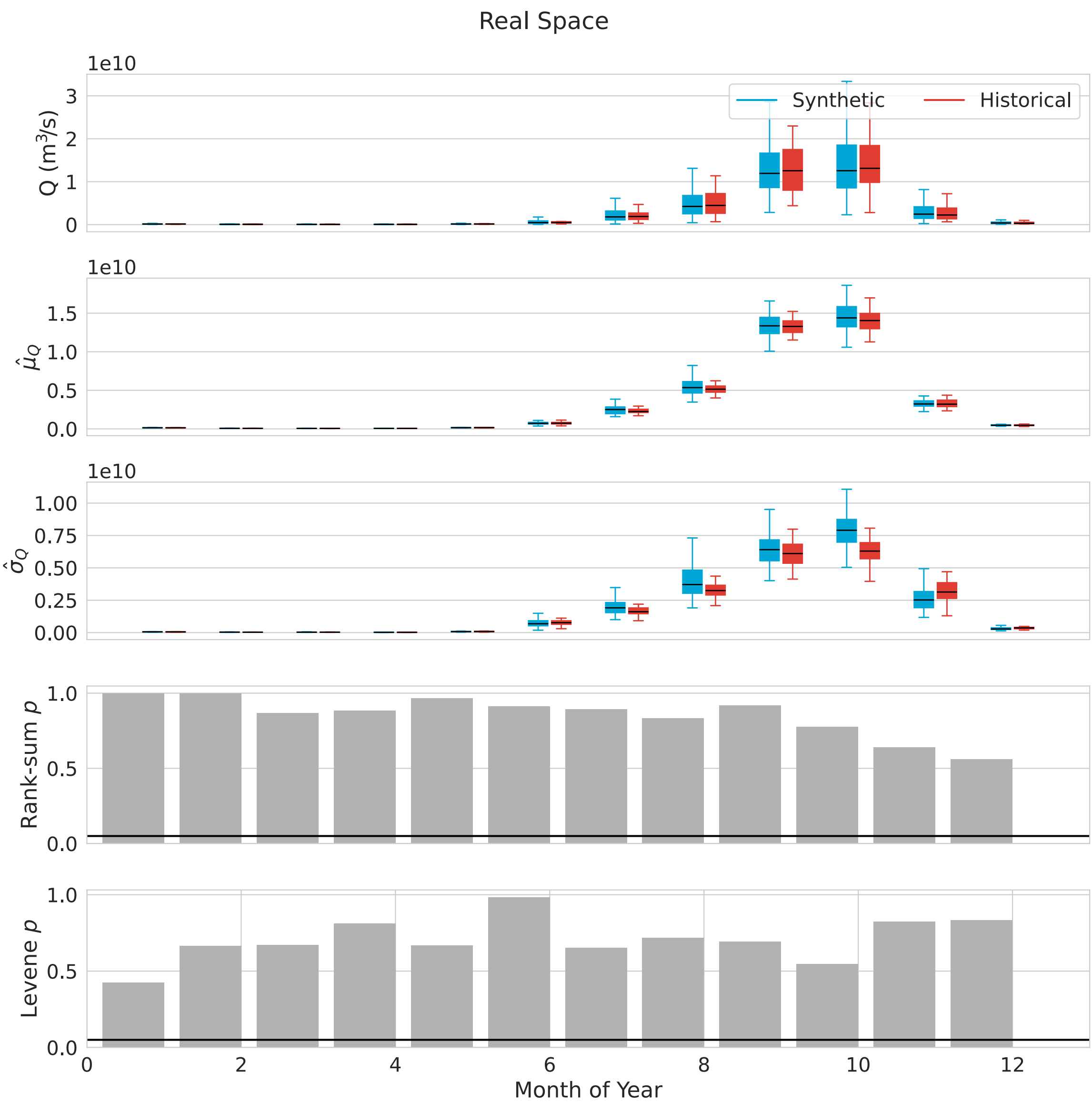

Figure A.6: Boxplot comparison between the historic and synthetic flows, means, and standard deviation. The bottom two panels show the Wilcoxon rank-sum and Levene test outcomes are shown together with a horizontal black line indicating the 0.05 threshold.

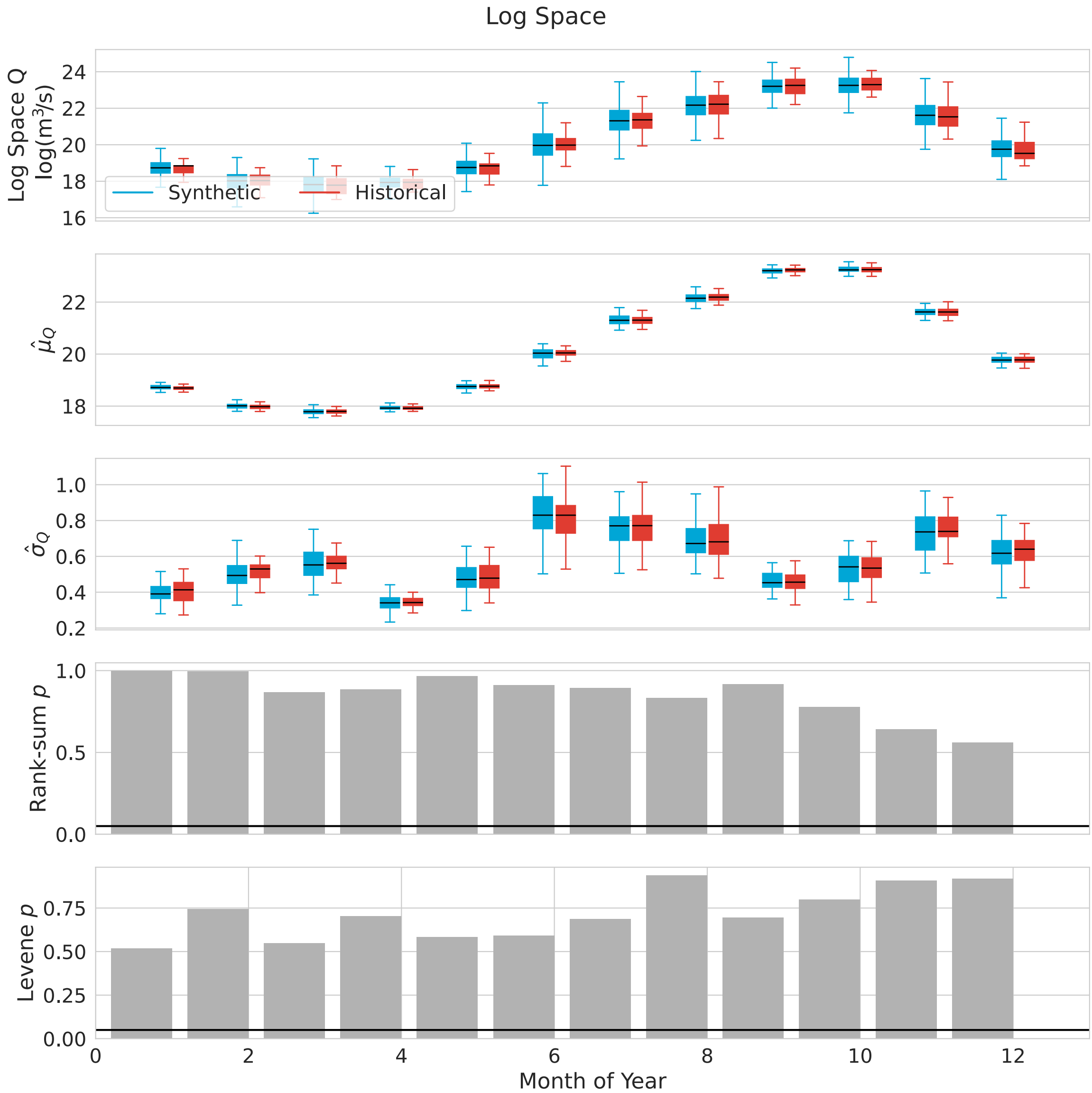

Figure A.7: Boxplot comparison between the historic and synthetic flows, means, and standard deviation. The bottom two panels show the Wilcoxon rank-sum and Levene test outcomes are shown together with a horizontal black line indication the 0.05 threshold.

A.3. Tailwater, evaporation, Kpong head

In the used model, no real relationship is defined for the tailwater, evaporation or Kpong head from the inflows. That is why daily averages of the historical record were used in the synthetic data. This means that from the historical record of 29 years, there will be 29 values for each day. The averages of this were taken. This creates a set of one year. This set is then repeated for 20 years for each simulation.

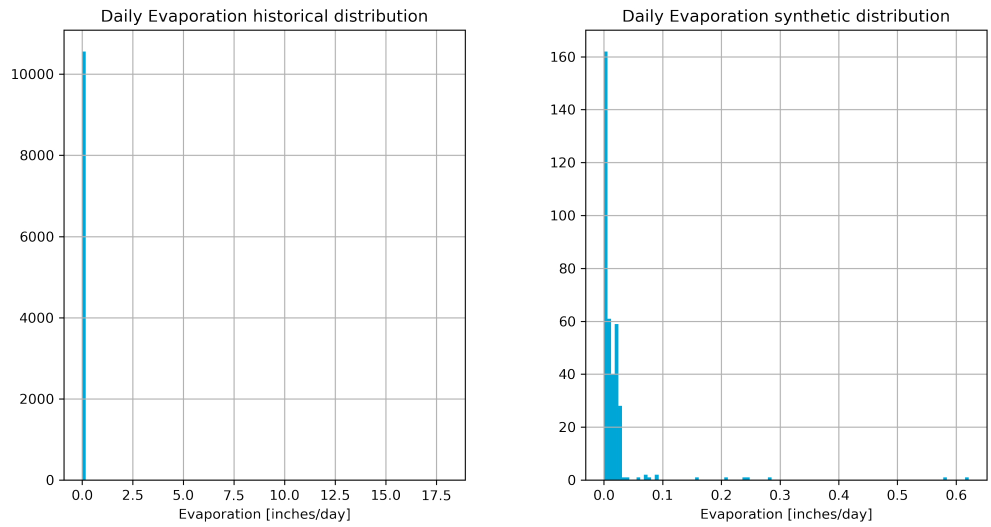

Figure A.8: Histograms of historical (left) and synthetic (right) evaporation.

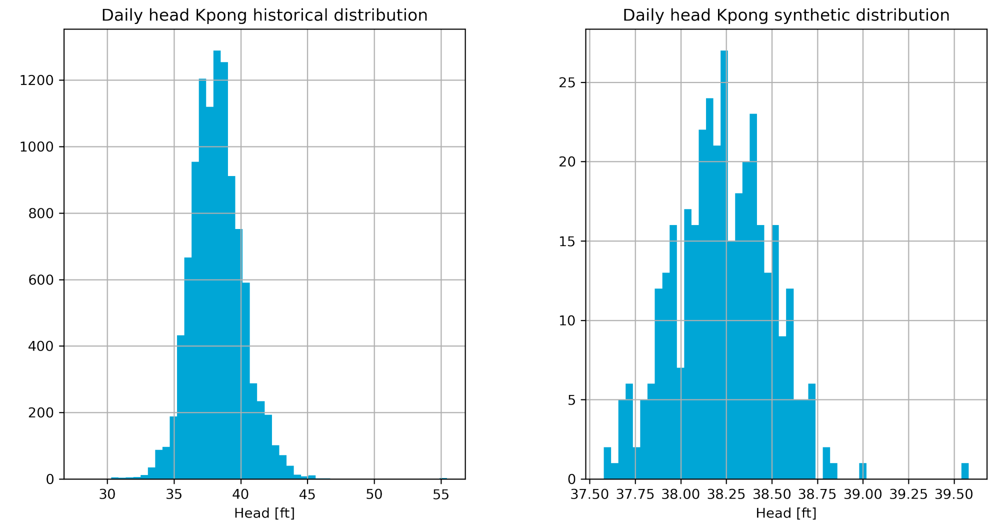

Figure A.9: Histograms of historical (left) and synthetic (right) head at Kpong

A.3.1. Validation

To check whether this choice in simplification can be made, the synthetic data described above were used with historically optimised policies and historical inflow data. This allowed comparison between the results with the historical data and the results with the synthetic data. Three policies that came out of the optimisation were tested. Policy 0 (Best Hydropower), Policy 1 (Best Environment), and Policy 8 (Balanced) were run twice. The results are in Table A.1 and Table A.2.

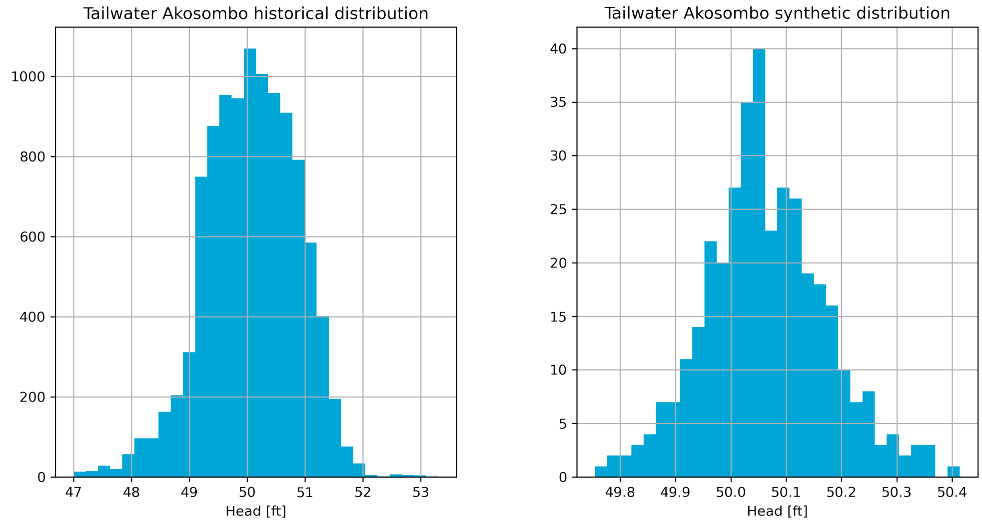

Figure A.10: Histograms of historical (left) and synthetic (right) tailwater levels at Akosombo

$$PercentualDifference = 1 - J_{synthetic} \,/\, J_{historical} \tag{A.1}$$

Table A.1 shows that all the objectives have a mean difference of smaller than 2.5% with most under 1%. The Flood objective is a NaN value since the outcomes of the historical data, and the synthetic data are zero. Dividing by zero gives the NaN value. Using the mean, the synthetic inputs seem to be justifiable.

The results of Table A.2 shows more information. It shows that the maximum deviation for most of the objectives is quite small, below or around 5%. However, the Hydropower production at Kpong is quite different, around -10% difference from the historical data. This means that the new synthetic data results in more hydropower than what can be found with historical data. The year in which this happens is not particularly dry or wet. The data does show that there has been a slight change in tailwater and head levels within the year. This change from the average is presumed to cause the large difference. These situations are not considered in the model, and the difference is therefore not deemed to be a problem in this research.

Table A.1: Mean percentual deviation of the synthetic evaporation, tailwater, and Kpong head data from the real input data. A low number is preferred. A negative number means that the synthetic data gives higher outcomes than the historical data. A positive number means that the synthetic data returns lower outcomes than the historical data.

	HP_ak	HP_kp	Energy_shortage	Irrigation	Environment	Flood
Pol 0 (Best HP)	0.383589	0.204396	-0.003378	0.226846	-0.022686	NaN
Pol 1 (Best Environment)	0.273786	0.108733	-1.023084	0.405445	0.000000	NaN
Pol 8 (Balanced)	0.379312	0.178123	-2.437304	0.753483	0.000000	NaN

Table A.2: Maximal percentual deviation of the synthetic evaporation, tailwater, and Kpong head data from the real input data. A low number is preferred. A negative number means that the synthetic data gives higher outcomes than the historical data. A positive number means that the synthetic data returns lower outcomes than the historical data.

	HP_ak	HP_kp	Energy_shortage	Irrigation	Environment	Flood
Pol 0 (Best HP)	1.873194	-9.875183	-0.869212	1.020256	-0.022686	NaN
Pol 1 (Best Environment)	0.897321	-10.160974	-3.631029	0.555965	0.000000	NaN
Pol 8 (Balanced)	1.065561	-10.239726	-5.610980	0.872509	0.000000	NaN

B

Interview reports

To gain more insight into the Akosombo and Kpong dam system, interviews were conducted near the end of the research. The interviews were done under the approval of the Delft University of Technology Human Research Ethics Committee for the PhD research of A. Owusu.

B.1. Water Resources Commission

From the interview with someone from the Water Resources Commission, we gathered that it is essential to stay in close contact with the dam operators, VRA. They have important and relevant data, but potential solutions also need to fit in with their requirements and mandate. Hydropower needs to be produced for VRA to fulfil their mandate.

The interviewee recalled the 2010 dam spilling and the flood that occurred. The event gave people in the downstream areas a look into the life of what a pre-dam situation would look like in the Lower Volta. Many people did not perceive this as a good situation due to the flooding reaching their homes for the first time since the dam was built in the 1960s. However, people also look negatively upon the dam implementation and blame VRA. The communities expect the VRA to support them, even with unrelated events such as the COVID-19 outbreak.

Back in the day, the Akosombo provided all the electricity in the region and exported it to other countries in the basin. The role of the Akosombo in Ghanaian life was enormous. Mr. Boateng-Gyimah, however, sees the role of the dam declining due to increased focus on other sources of power, such as solar and thermal. The hydropower generation will be more of a buffer. The dam is said to stay in existence, but it will also be less relevant for power generation.

When asked about the impacts of upstream countries, the interviewee responded that that could be a big problem. Especially Togo, since the Oti river brings in most of the water volume into Ghana. However, the VBA created a new Water Charter that is to be ratified this year by a required four of the six countries in the VBA. This new Water Charter addresses this issue of water sharing. The interviewee said this document would benefit Ghana by obtaining a set portion of water. Some exchanges in benefits were mentioned, such as the energy provision to other states and a plan to supply Lomé, Togo, with water from Ghanaian soil. Currently, electricity is collaborated upon in the West African Power Pool.

Other effects on the water resources of Ghana could be a decline in runoff due to increasing temperature and, therefore, evaporation rates. The interviewee argued that land use does not play a significant role since upstream land is primarily rural, except for two big cities: Tamale and Ouagadougou. It was noted that maybe in the future, this could change, and perhaps this could play a factor in the runoff. However, research would need to be done on this.

B.2. Volta River Authority

The interview started with a short explanation of the VRA's position within Ghana's energy sector. The VRA generates electricity through hydro, thermal, or since lately, solar plants. This energy is then supplied to the Ghana Grid Company (GRIDCo) for further transmission. From there, electricity is distributed to its paying customers by the Electricity Company of Ghana and the Northern Electricity Distribution Company (NEDCo), a subsidiary of the VRA.

The interviewee mentioned that the objective is to use as much hydropower in the energy mix as possible, as this is the cheapest form of energy (2.5-3 cents GHS/kwh). At the opening of the Akosombo, the electricity supply was 100% of the total demand in Ghana. Nowadays, it is about 35-40% of the demand. The VRA forwards the energy production requirement to each of the plants. These plants will do their best to adhere to this but can deviate due to the actual situation in the grid. GRIDCo determines this. The VRA creates ten-year demand forecasts for the future by looking at historical records and talking to their customers. When they see the system cannot handle the demand, the VRA has to start planning new plants if needed.

The Akosombo hydropower generation is supposed to be a minimum of two turbines to keep the electricity system of Ghana up and running. This is called the FIRM power demand and serves to keep the system stable. The interviewee was not worried this FIRM power demand cannot be reached. This is because the Volta Lake can handle three years without inflow and still be able to run on the two turbine minimum for FIRM power. Next to that, in the history of Akosombo, the plant never needed to shut down due to limited water in the reservoir.

Using models built together with a Dutch company, the VRA can find releases that they are confident will use the storage well. However, the political climate does offer its challenges due to an increase in pressure to produce more hydropower to keep the energy mix cheap since gas and oil are expensive.

When asked about the return times of certain flooding events, there came an answer they had flood action plans for different intensities of floods. However, after multiple requests, the interviewer could not get an indication of how often they expected to need these plans in terms of return times of floods. The interview also touched upon the irrigation made possible by the Kpong. Even though this task is outside of the responsibilities of VRA, the interviewee knew it had an irrigation potential of about 100 000 hectares. This is potential, currently it is a lot less than that. Environmental flows were also discussed, but the way the interviewee saw it, the flows were more than enough to serve the ecosystems. On the interviewer's remark that too much water was being let downstream to some ecosystems, the interviewee talked around it.

The interviewee does not see large risks for the future. Climate change will shift the inflow peaks, but the storage reservoir acts as a buffer to counter this. Also, an increase in power demand due to industrial activities and population growth is not a stressor on the Akosombo-Kpong system. The market will have to jump in to supply the demand. The Akosombo-Kpong system will not produce more than it currently does. There could be limits to the inflow due to upstream infrastructure in other riparian states. This is deemed a small risk since Ghana exports power to other countries, and they are also dependent on the inflows the Akosombo receives. On the question if their own dam can solve that, the interviewee responded by saying a dam also brings many difficulties, such as costs and space. Next to that, the Volta Basin Authority is in place to ensure equitable water distribution among the countries. The interviewee said that Ghana currently benefits greatly from the inflow of other countries, and it is important to try and keep the benefits. The interviewee also gave some insight into the cooperation in the VBA. When the interviewee last attended a VBA meeting, member countries' contributions were not paid by all countries. It was not disclosed which ones. For the VBA to operate, it needs people employed to review and develop projects. This becomes difficult when financially challenged.

The interviewee said that Burkina Faso would be the most significant challenge when it would decide to use more water. This was argued with the fact that it had such a large basin area. However, when asked the percentage of water flows coming from Burkina Faso, there was no clear answer.

The Kpong has a maximum head of 15m and a minimum of 7.79 m. The deviation comes from what Akosombo supplies. The Kpong usually cannot convert everything that Akosombo releases due to its smaller power capacity and needs to be spilled often.

When asked about the relevance of the dams in the future when the Akosombo provides relatively less and less power due to increased demand filled by other sources, the interviewee mentions it will always remain important. The importance is due to the critical services the system supplies. It can provide a black start in the system, which is needed to start the whole electricity system again after a shutdown. It also provides voltage regulation to help the power grid. Even though the Akosombo had an initial design life, the interviewee argues that this is already and will be extended by servicing and upgrades.

B.3. Pwalugu Multipurpose Dam

The meeting started with a presentation in which general details of the dams were given. The dam is near the Nngo community, a few kilometres east of Pwalugu. The access road to the location is located south of Pwalugu. Within this area live six communities that will have to be resettled due to complete flooding of their land to create the basin. However, based on a map shown in the presentation, there were more communities further upstream of the river and downstream of the river that seemed to be affected. According to the interviewees, these communities are only partly affected or not affected. Due to national laws, only fully affected communities will have to be resettled by the government. Partly affected communities will receive cash compensation to buy new lands. Cash is given because the government finds finding land nearby too hard since the VRA would have to take land from a neighbouring community and find new land of a neighbouring community and so on. That is why these communities have to buy land themselves, as this is deemed easier.

The presentation also gave more insight into the planned irrigation scheme in which a planned 25 000 hectares will be considered. Part of this land will be used for smallholder farmers in the area (not the displaced communities), and part will be used for commercial farming. The main offtake is downstream of the reservoir and splits in two directions. First, the commercial farms pump water out of the canal, after which the remaining water moves on to the smallholder farmers through a gravitational irrigation system. The total irrigation usage is expected to be 423.61 MCM with a return flow of 63.54 MCM. After asking how to prevent the irrigation scheme from stalling as in the Kpong irrigation scheme, the interviewees responded that the Ghana Irrigation Development Authority (GIDA) is in charge of actually developing the irrigation potential. However, they argued that more than just water is needed to make it a success, such as access to markets and labour.

During the presentation, the flood requirements were also discussed. The interviewees stated that there is a trade-off between hydropower production and flood protection. Two flood protection scenarios were discussed. The planned dam construction is supposed to protect communities from a 1 in 15-year flood, which means 550 m^3/s with a starting level at the beginning of the rainy season of 155m or a 1 in 10-year flood with 550 m^3/s and a starting level of 157m.

On the topic of the influence of neighbouring countries on the dam operation, the interviewees did not think Burkina Faso will pose a problem regarding upstream water use. There currently is good collaboration in data sharing of the upstream Bagre dam so spills can be anticipated. They also mentioned the Volta Basin authority and the good collaboration they have between Ghana and Burkina Faso.

C

Simulation model and analyses files

All the used models and analyses are made and done with Python. A complete overview of the used files can be found on the following Github repository.

`https://github.com/ArieTieszoon/Volta_opt_reevaluation`

For the original optimisation model of Owusu et al. (2022) the following Github can be visited:

`https://github.com/Afua-O/Vol_Opt`

D

Result figures

D.1. Uncertainty

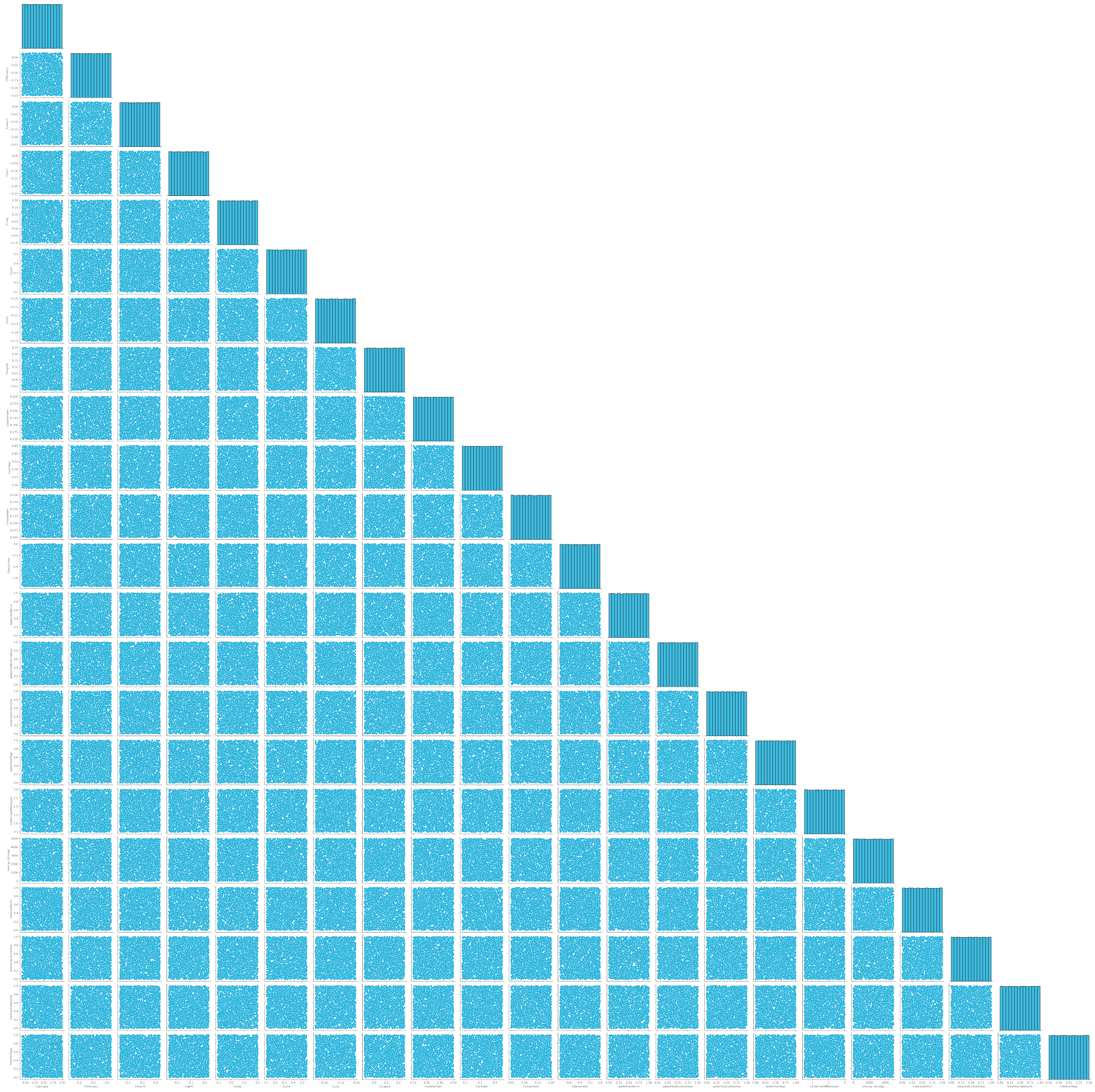

Figure D.1: This image illustrates the experiment space. All uncertainty and lever combinations are plotted to allow for visual inspection of the experiment space and if there are no unexplored scenarios.

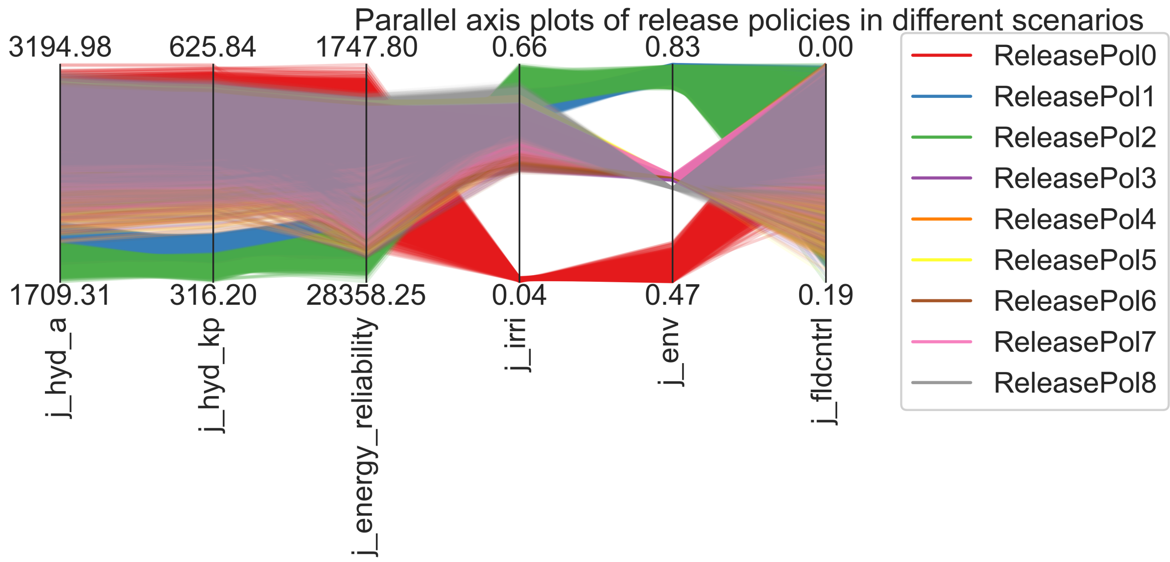

Figure D.2: Policy performance under uncertainty.

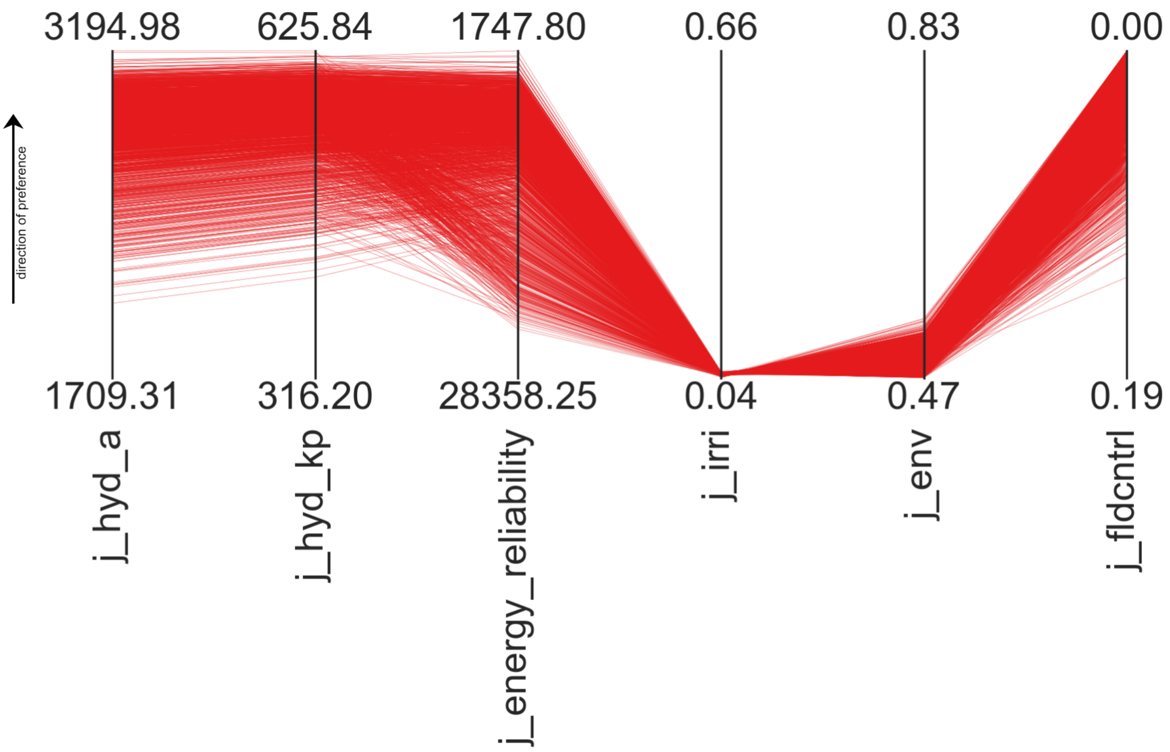

Figure D.3: Performance of policy 0 under uncertainty.

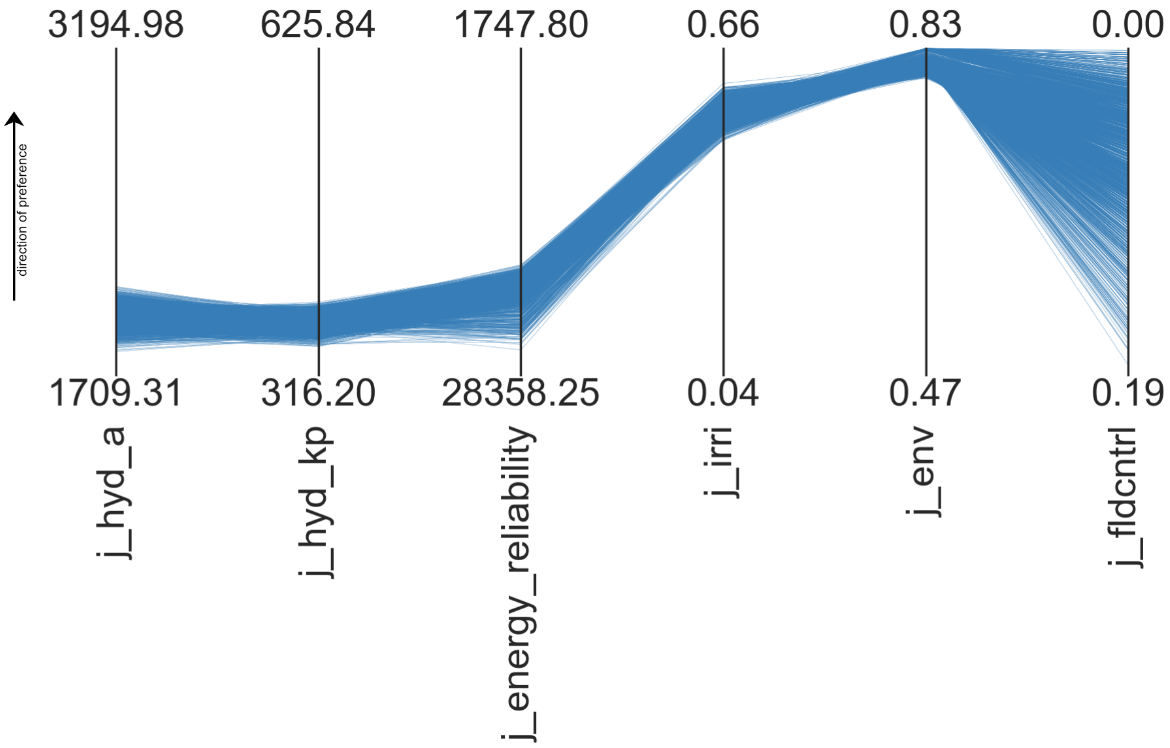

Figure D.4: Performance of policy 1 under uncertainty.

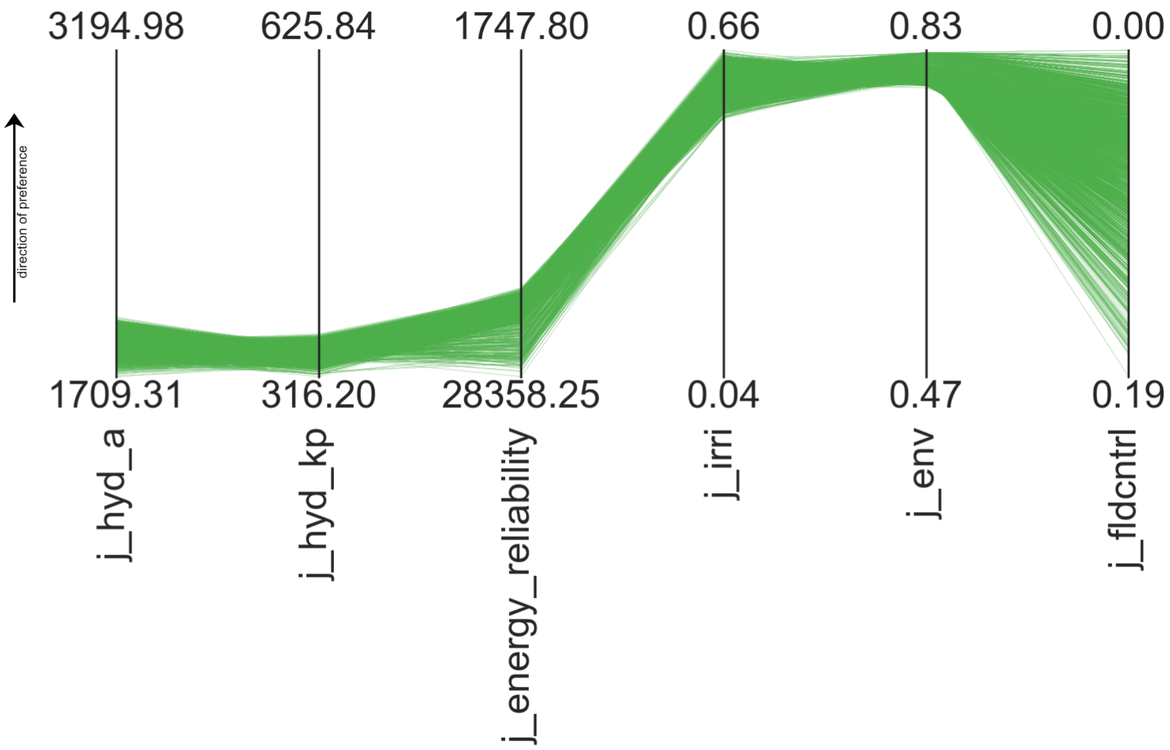

Figure D.5: Performance of policy 2 under uncertainty.

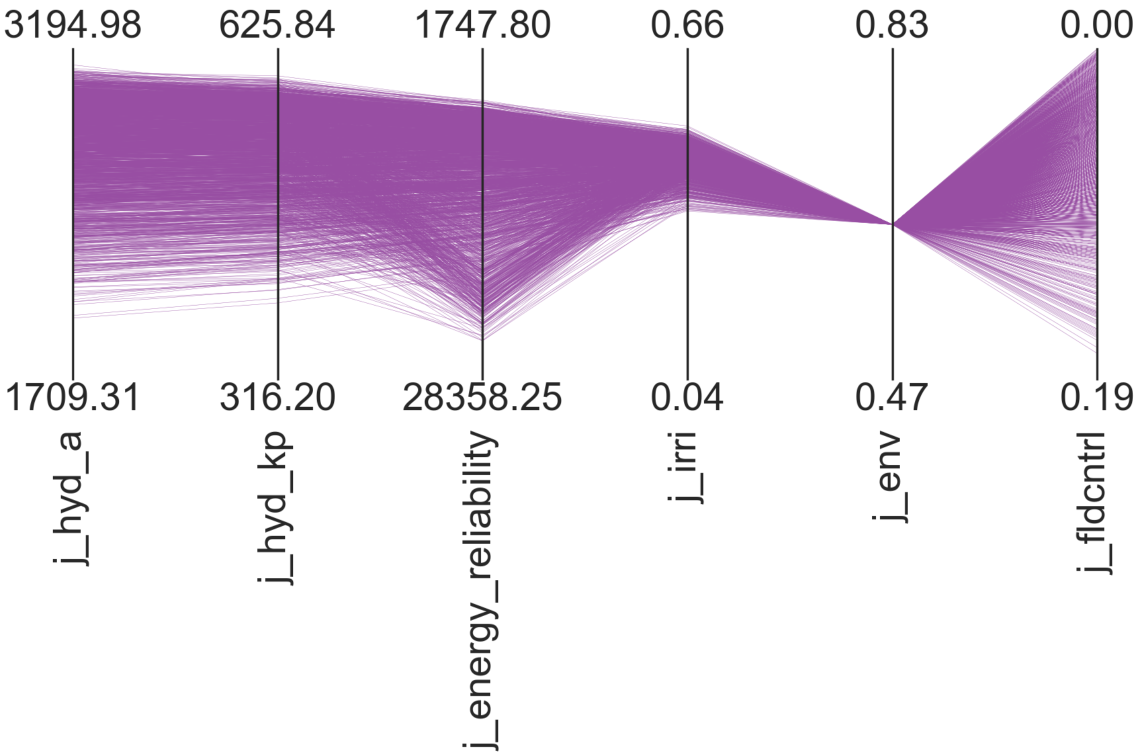

Figure D.6: Performance of policy 3 under uncertainty.

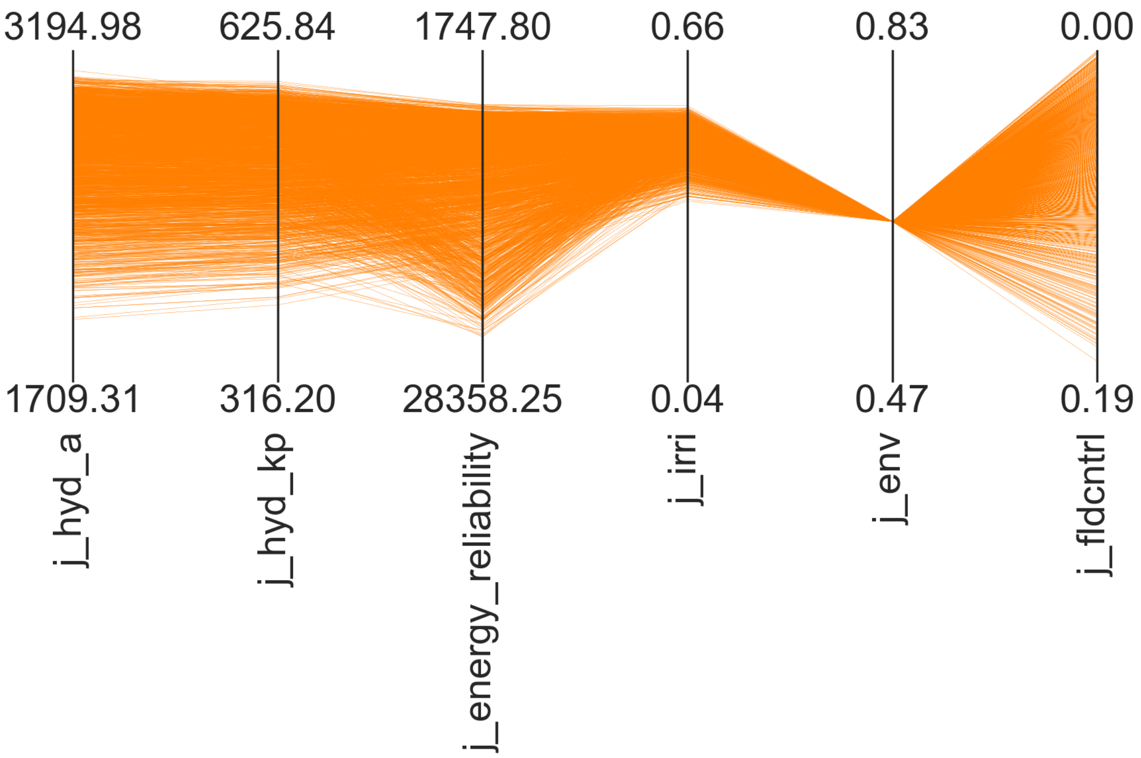

Figure D.7: Performance of policy 4 under uncertainty.

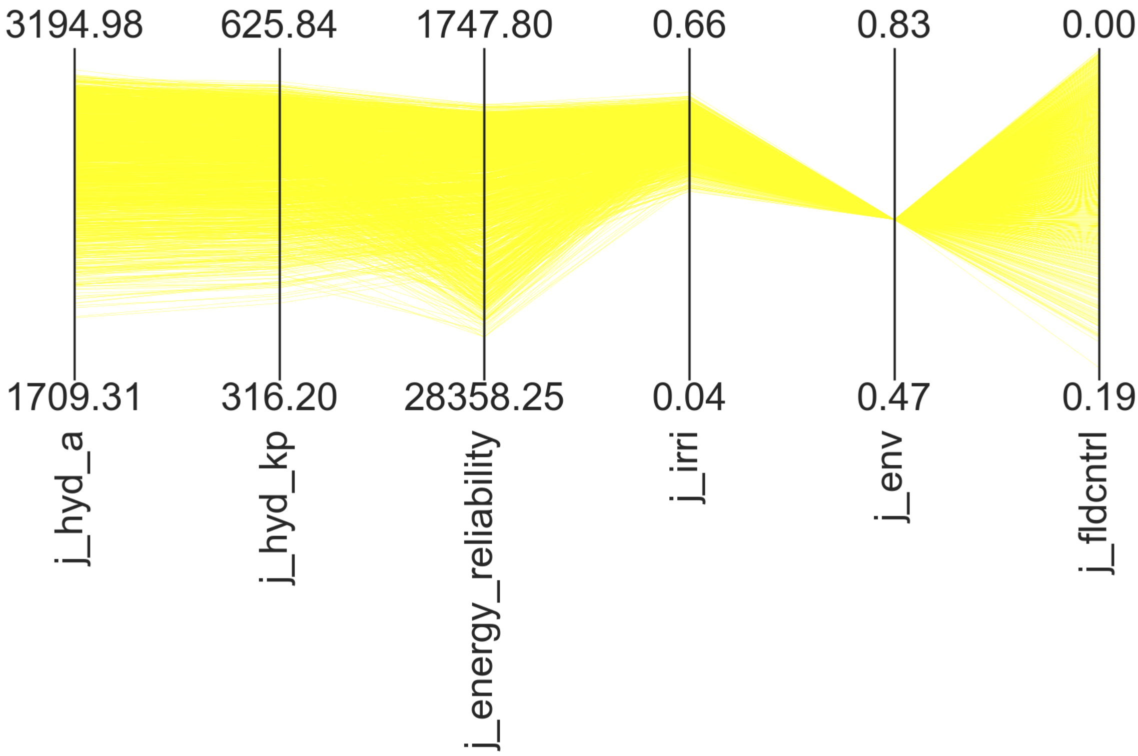

Figure D.8: Performance of policy 5 under uncertainty.

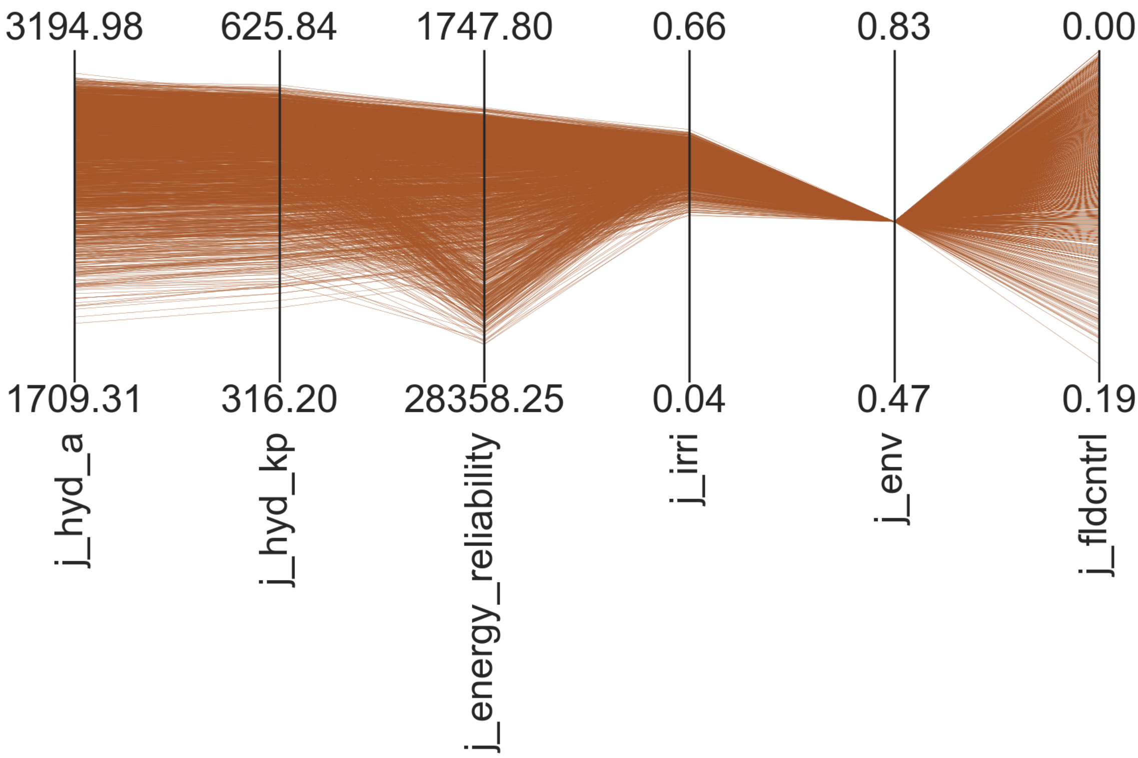

Figure D.9: Performance of policy 6 under uncertainty.

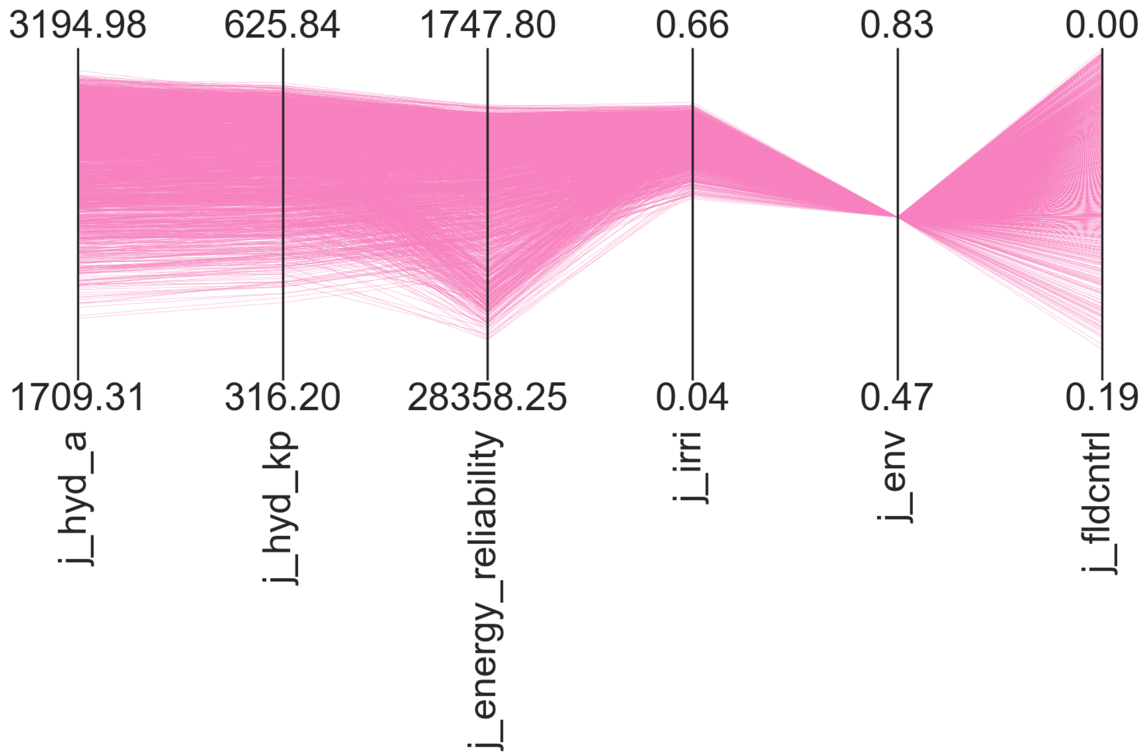

Figure D.10: Performance of policy 7 under uncertainty.

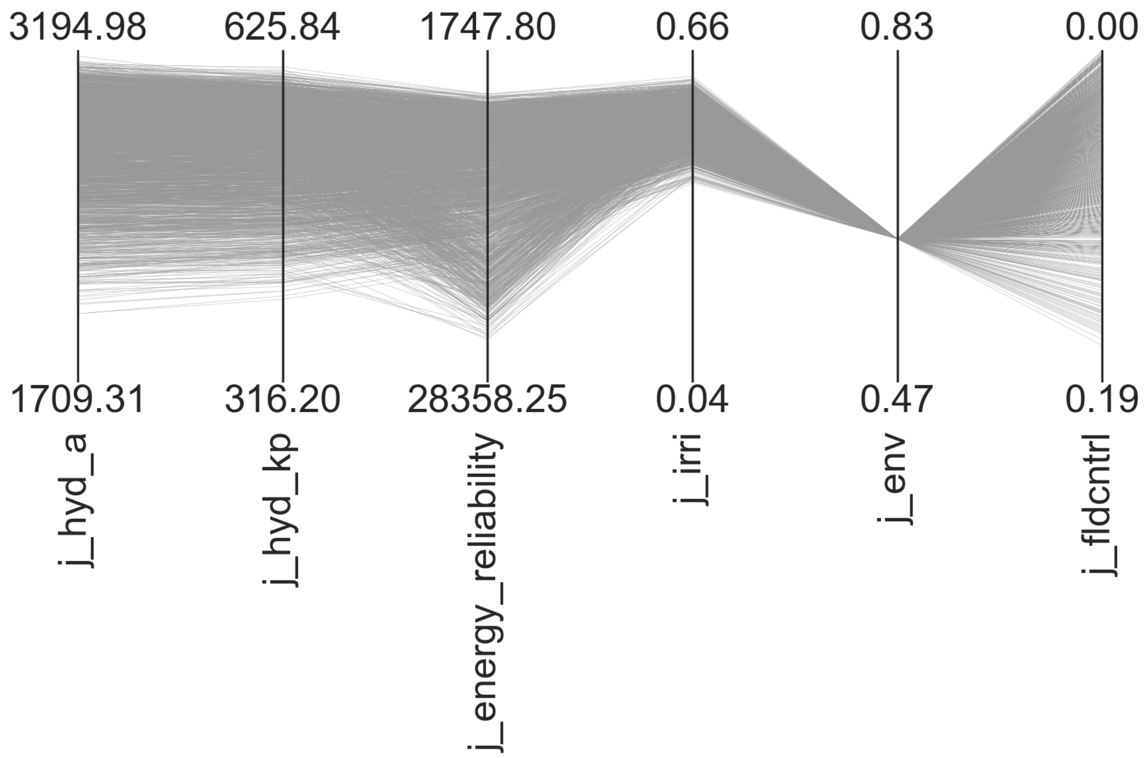

Figure D.11: Performance of policy 8 under uncertainty.

D.2. Robustness

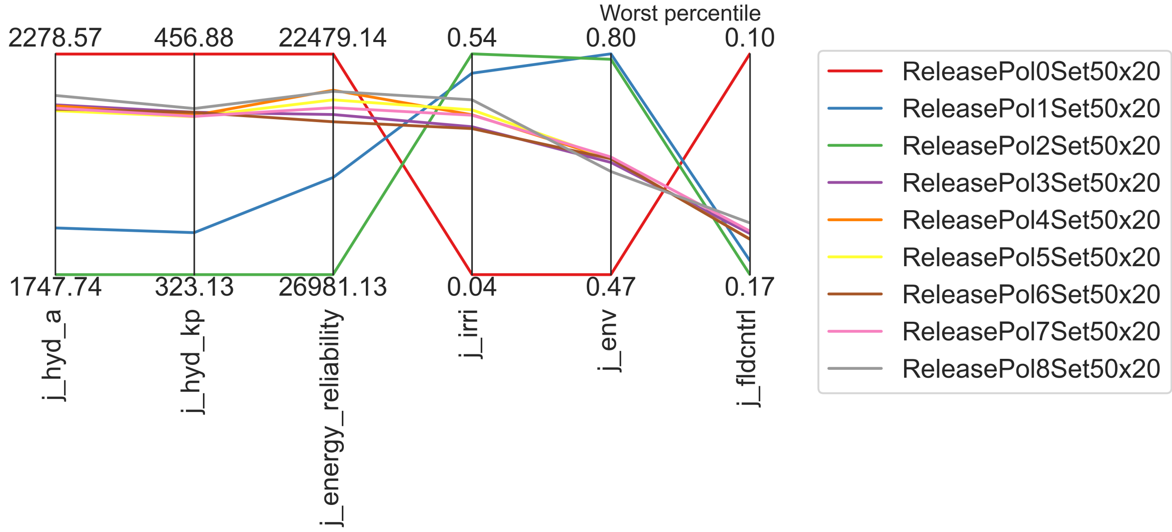

Figure D.12: Worst percentile performance of policies across objectives.

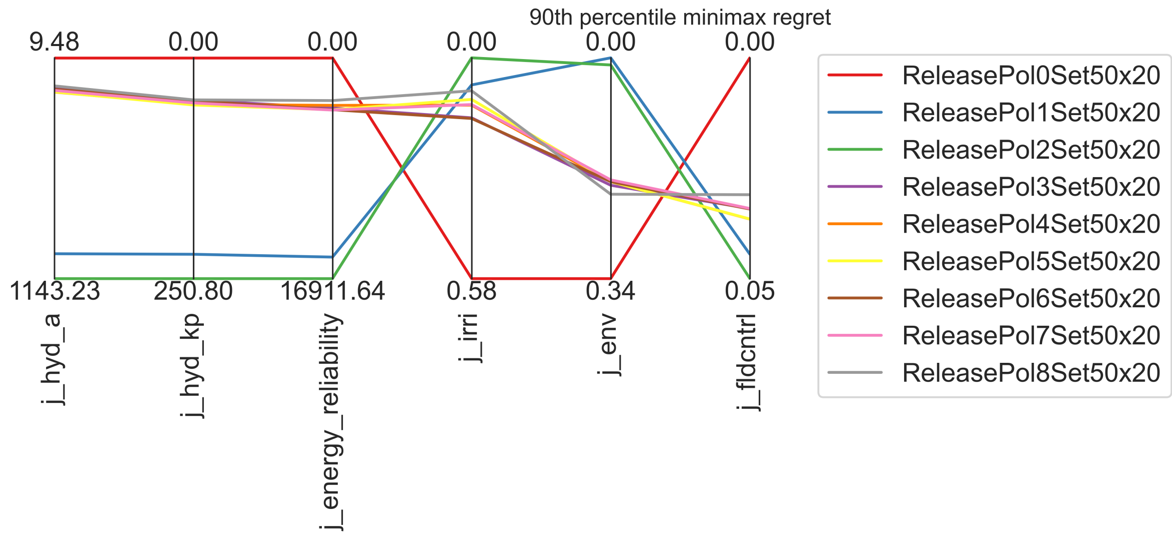

Figure D.13: 90th percentile regret performance of policies across objectives.

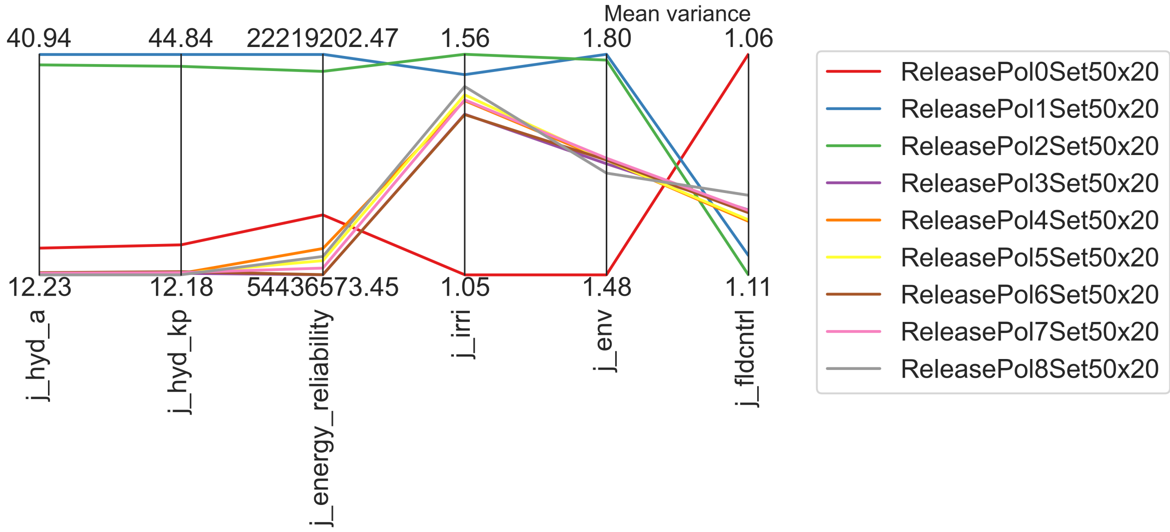

Figure D.14: Mean variance performance of policies across objectives.

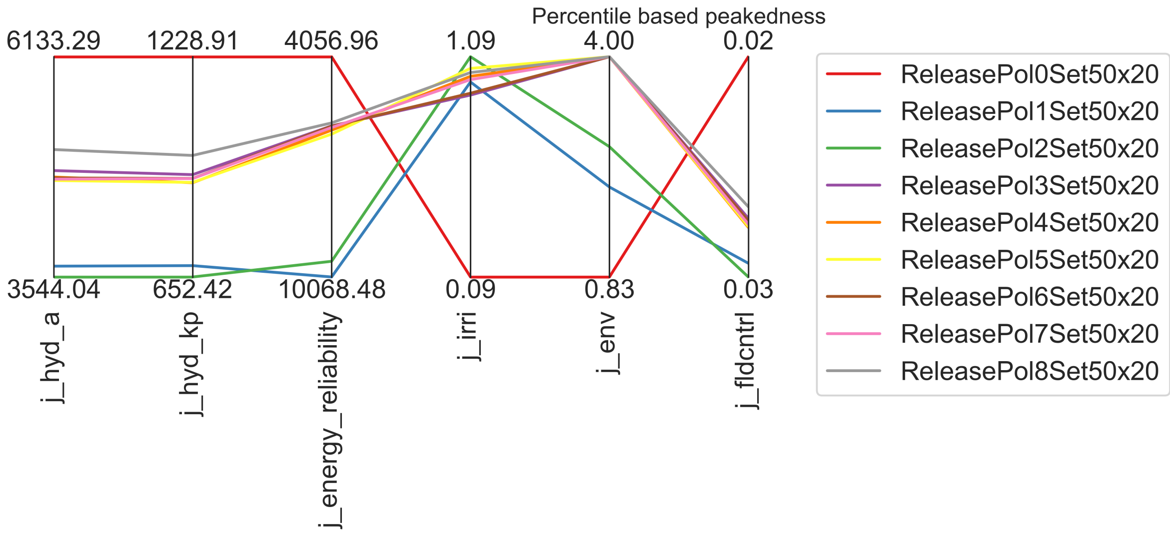

Figure D.15: Percentile base peakedness performance of policies across objectives.

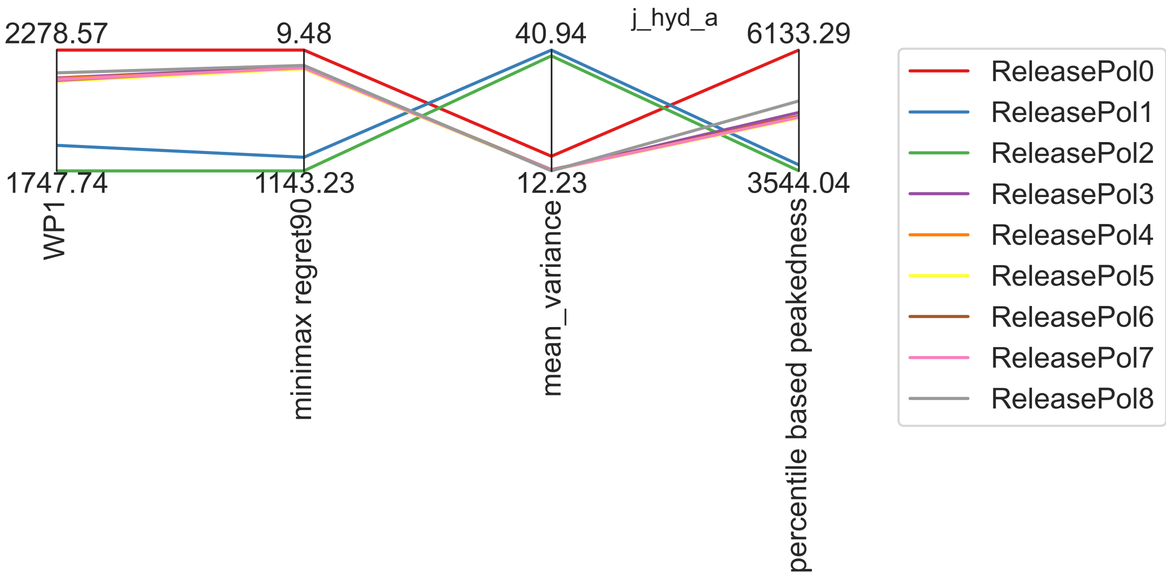

Figure D.16: Performance of policies across robustness metrics for the Akosombo hydropower objective.

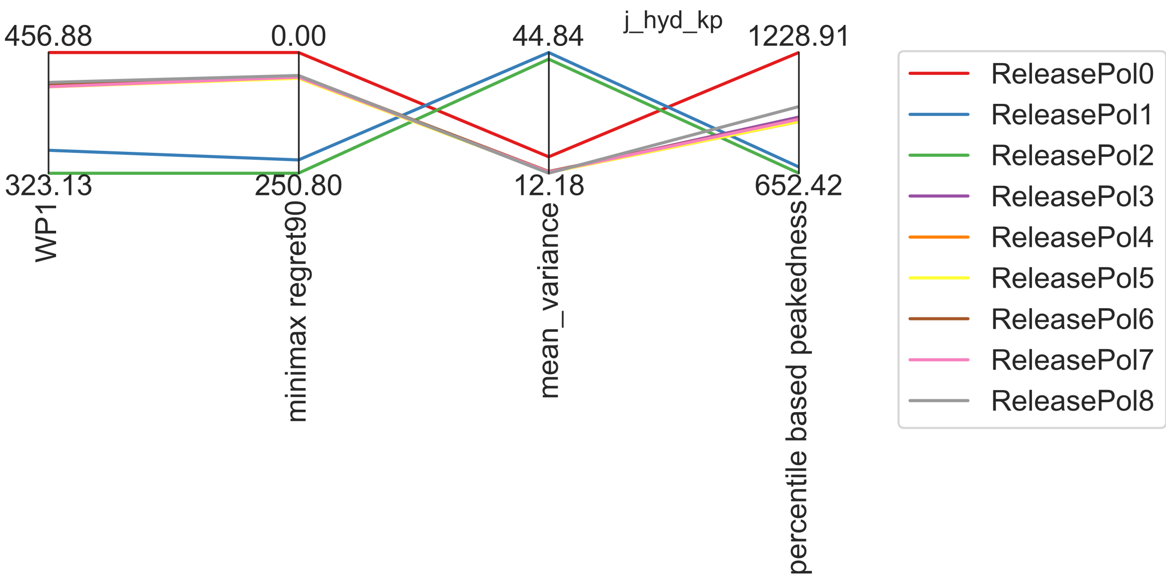

Figure D.17: Performance of policies across robustness metrics for the Kpong hydropower objective.

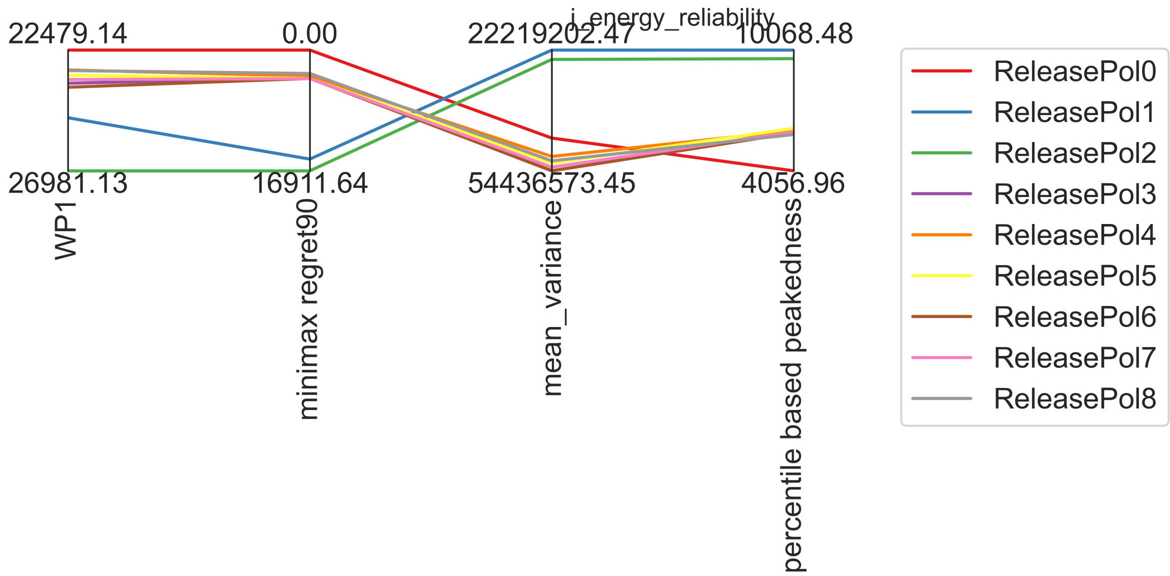

Figure D.18: Performance of policies across robustness metrics for the energy shortage objective.

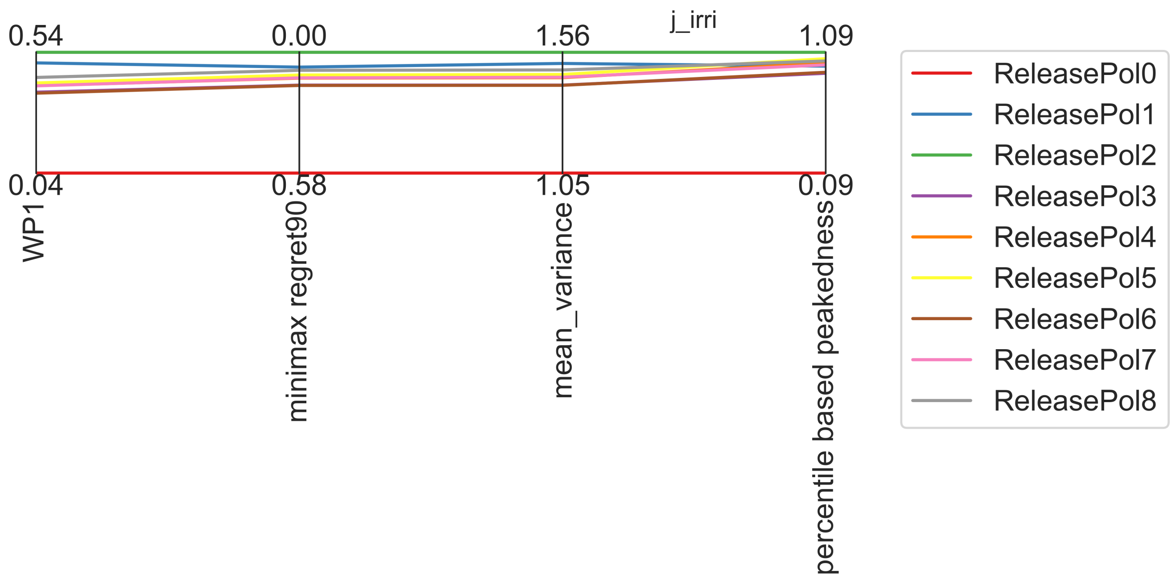

Figure D.19: Performance of policies across robustness metrics for the irrigation objective.

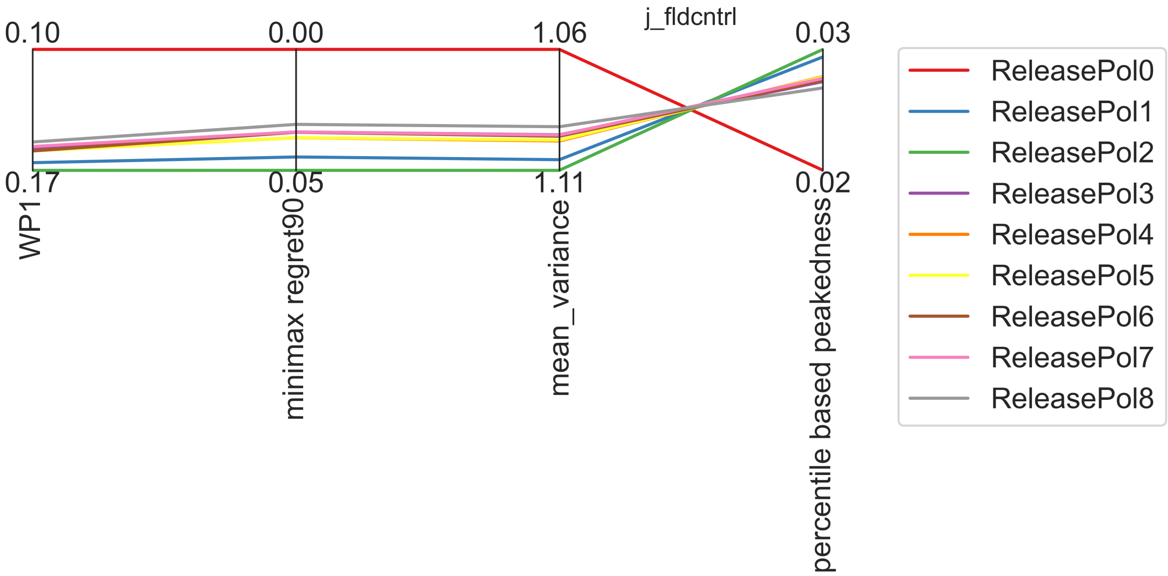

Figure D.20: Performance of policies across robustness metrics for the environment objective.

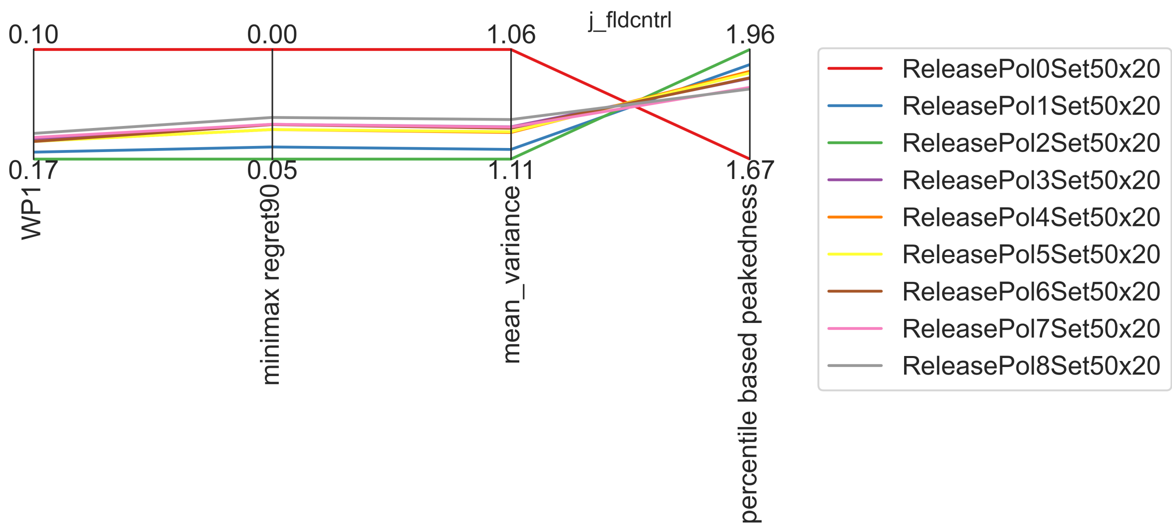

Figure D.21: Performance of policies across robustness metrics for the flooding objective.

D.3. Vulnerability

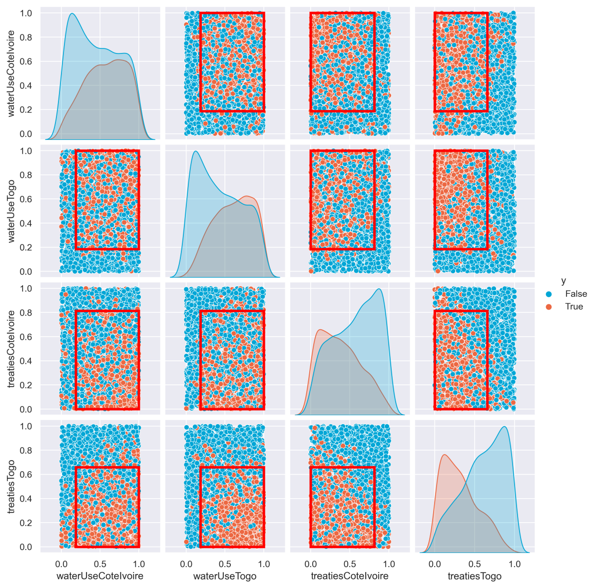

Figure D.22: Scenario discovery of the Akosombo hydrogen production objective worse than the median of policy 0.

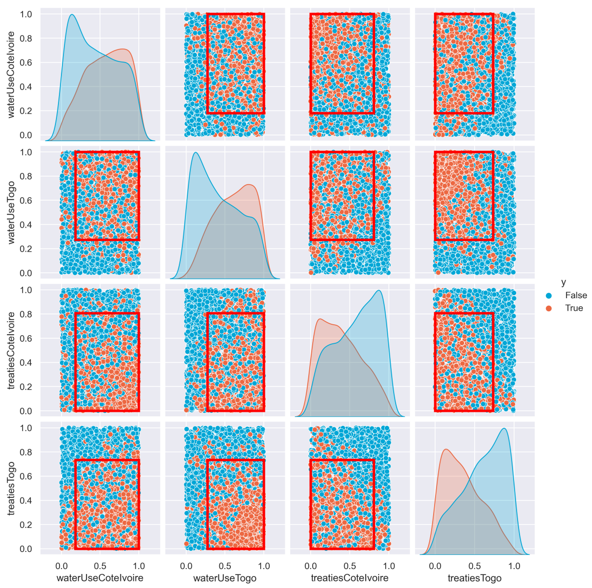

Figure D.23: Scenario discovery of the Akosombo hydrogen production objective worse than the median of policy 8.

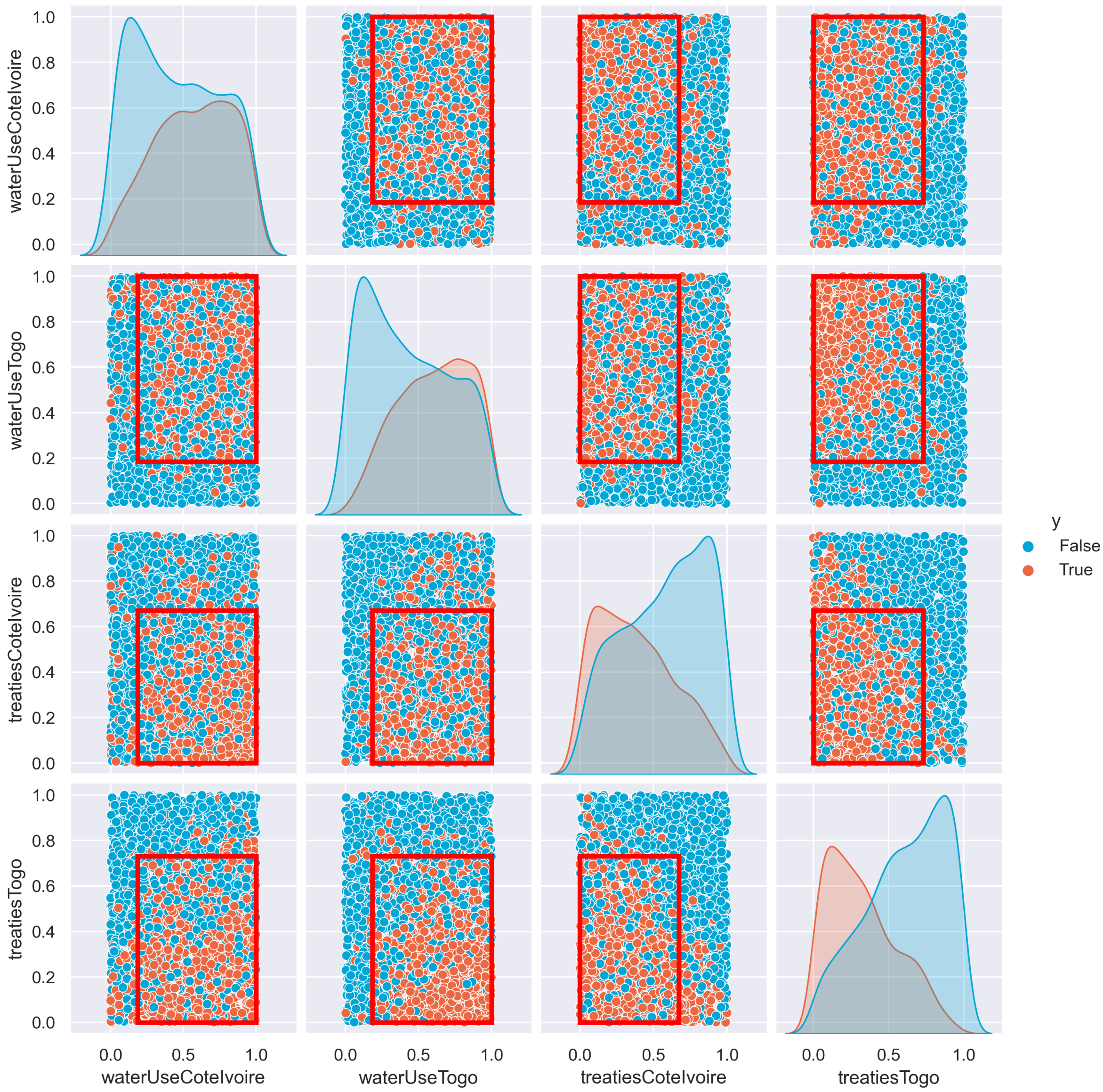

Figure D.24: Scenario discovery of the Kpong hydrogen production objective worse than the median of policy 0.

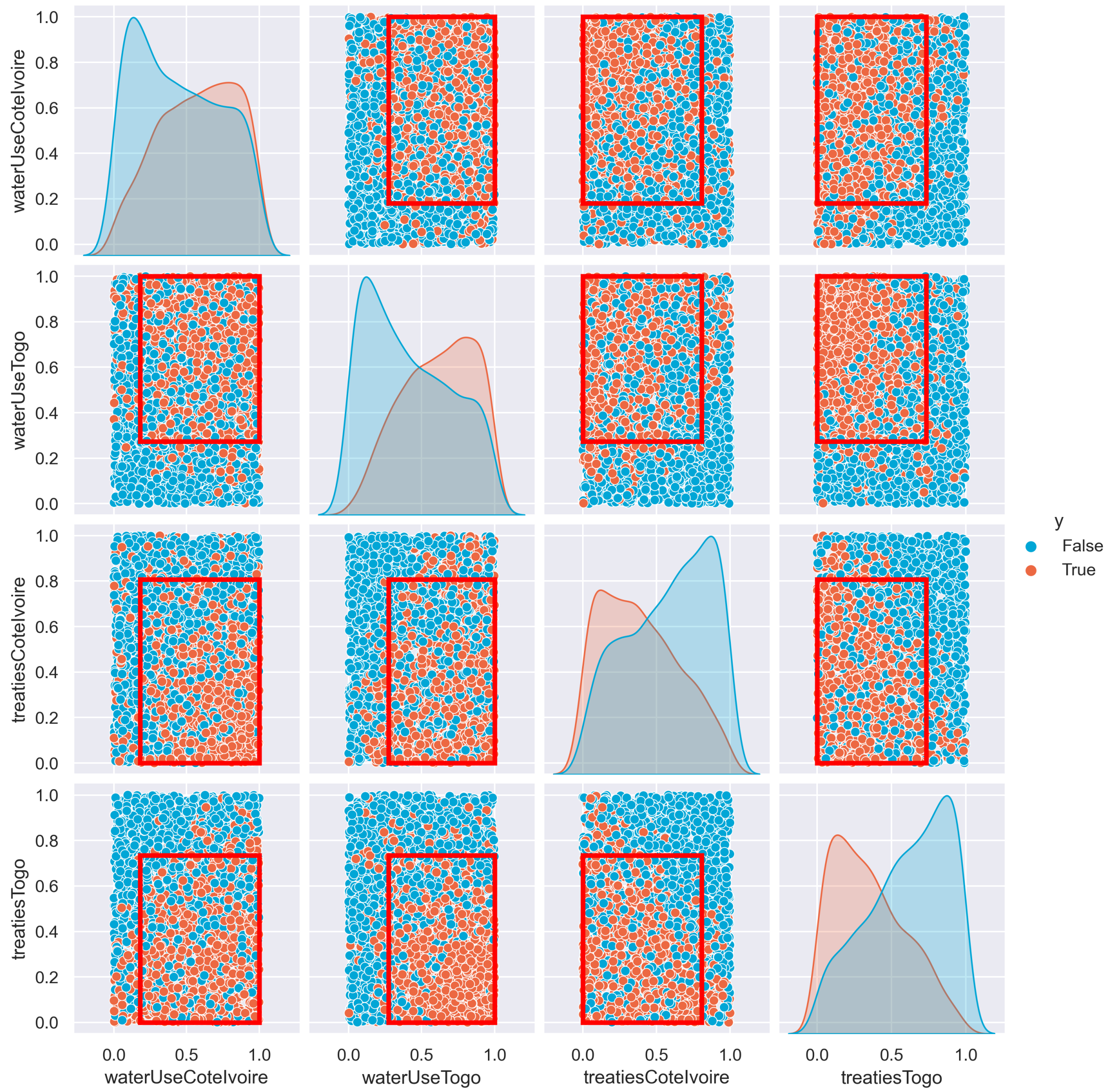

Figure D.25: Scenario discovery of the Kpong hydrogen production objective worse than the median of policy 8.

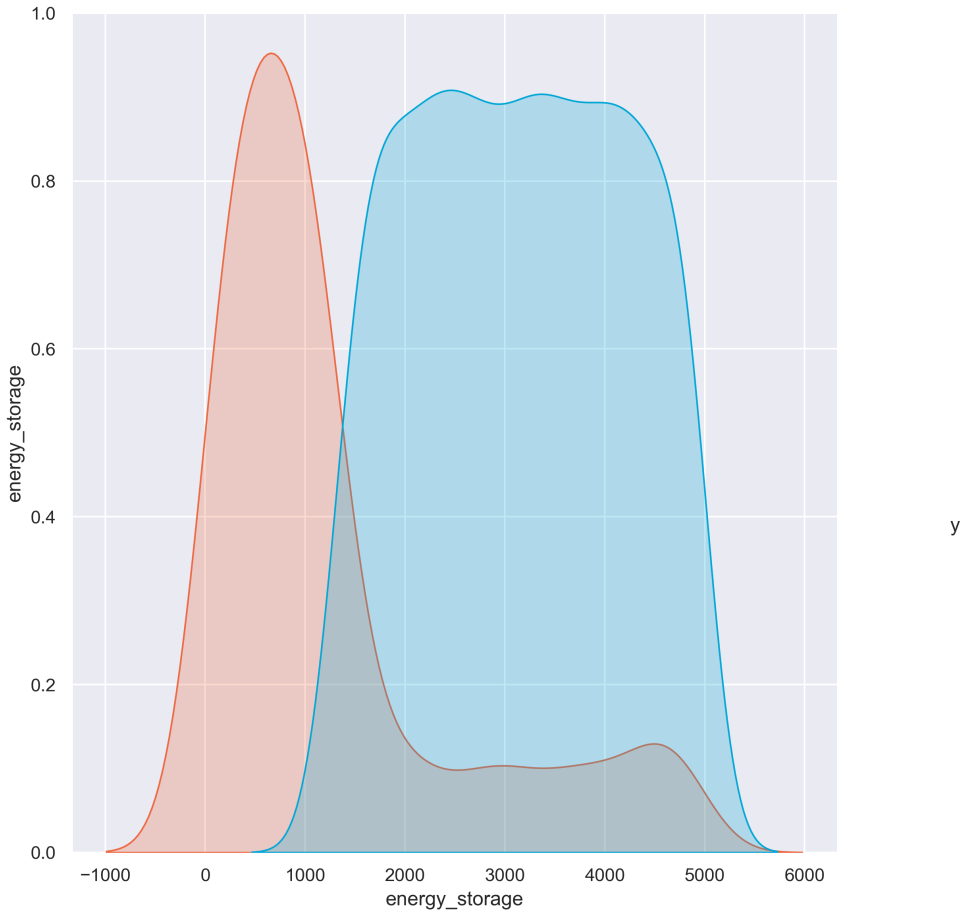

Figure D.26: Scenario discovery of the energy reliability objective worse than the median of policy 0.

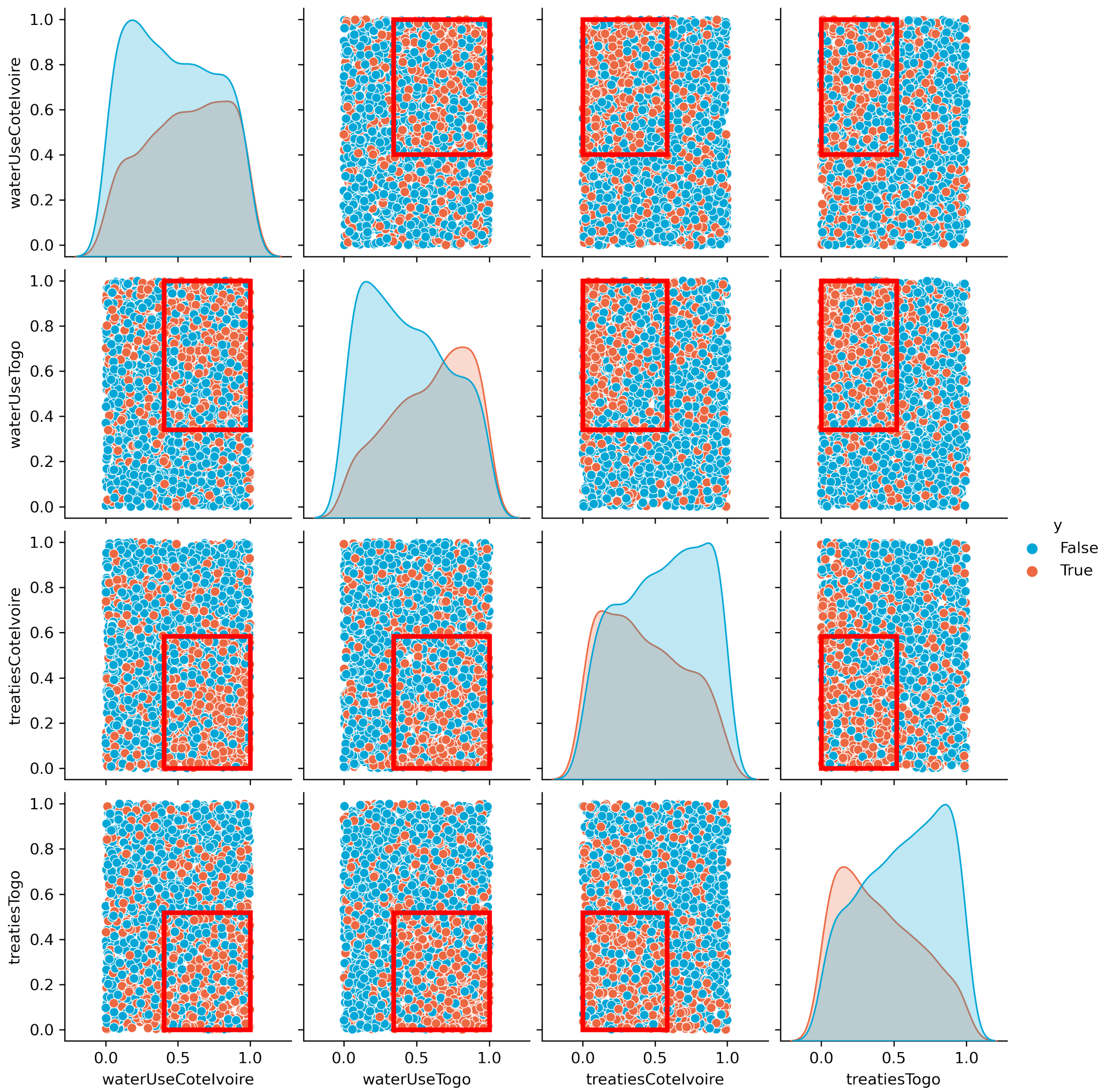

Figure D.27: Scenario discovery of the energy reliability objective worse than the median of policy 8.

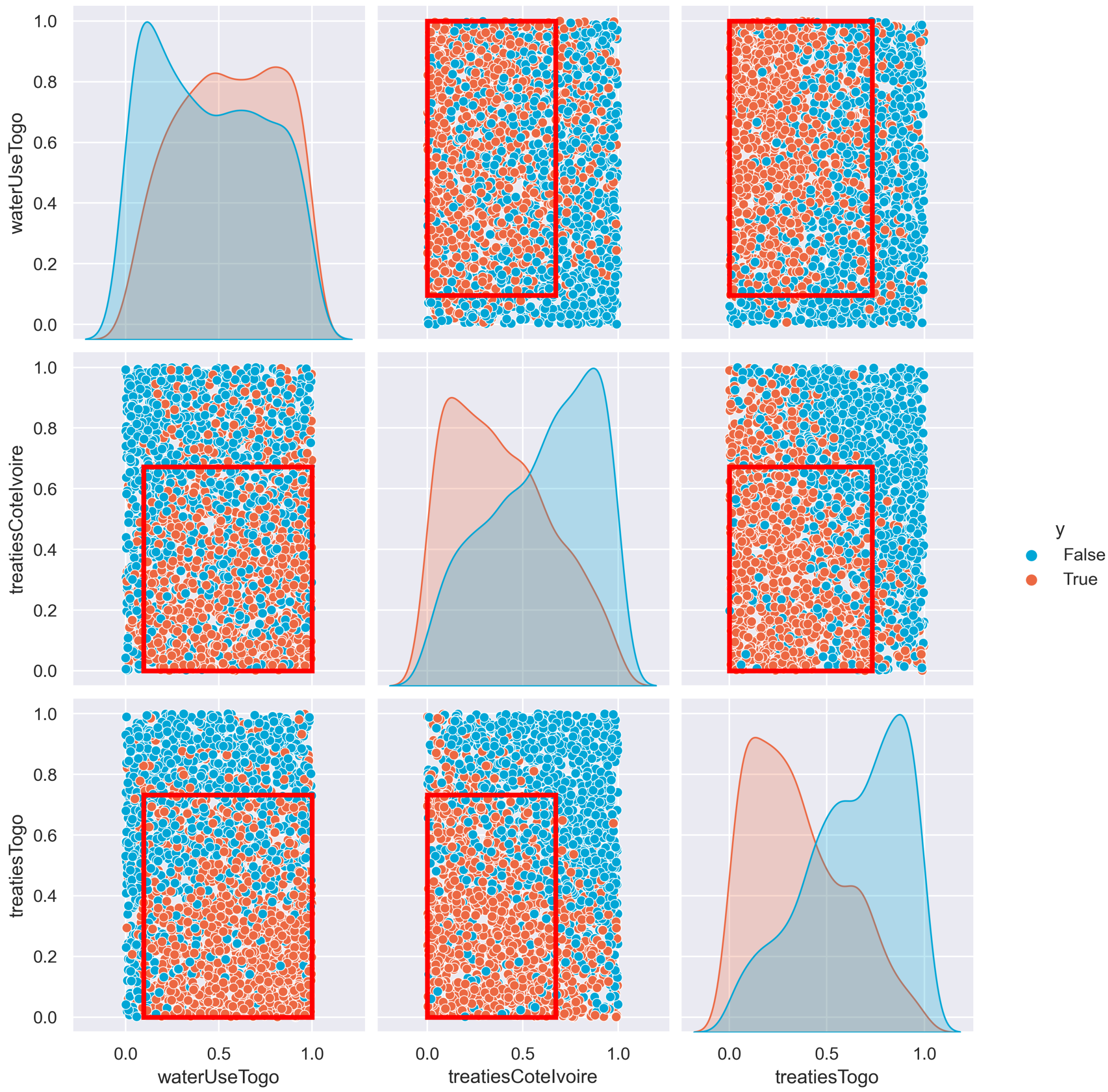

Figure D.28: Scenario discovery of the irrigation objective worse than the median of policy 0.

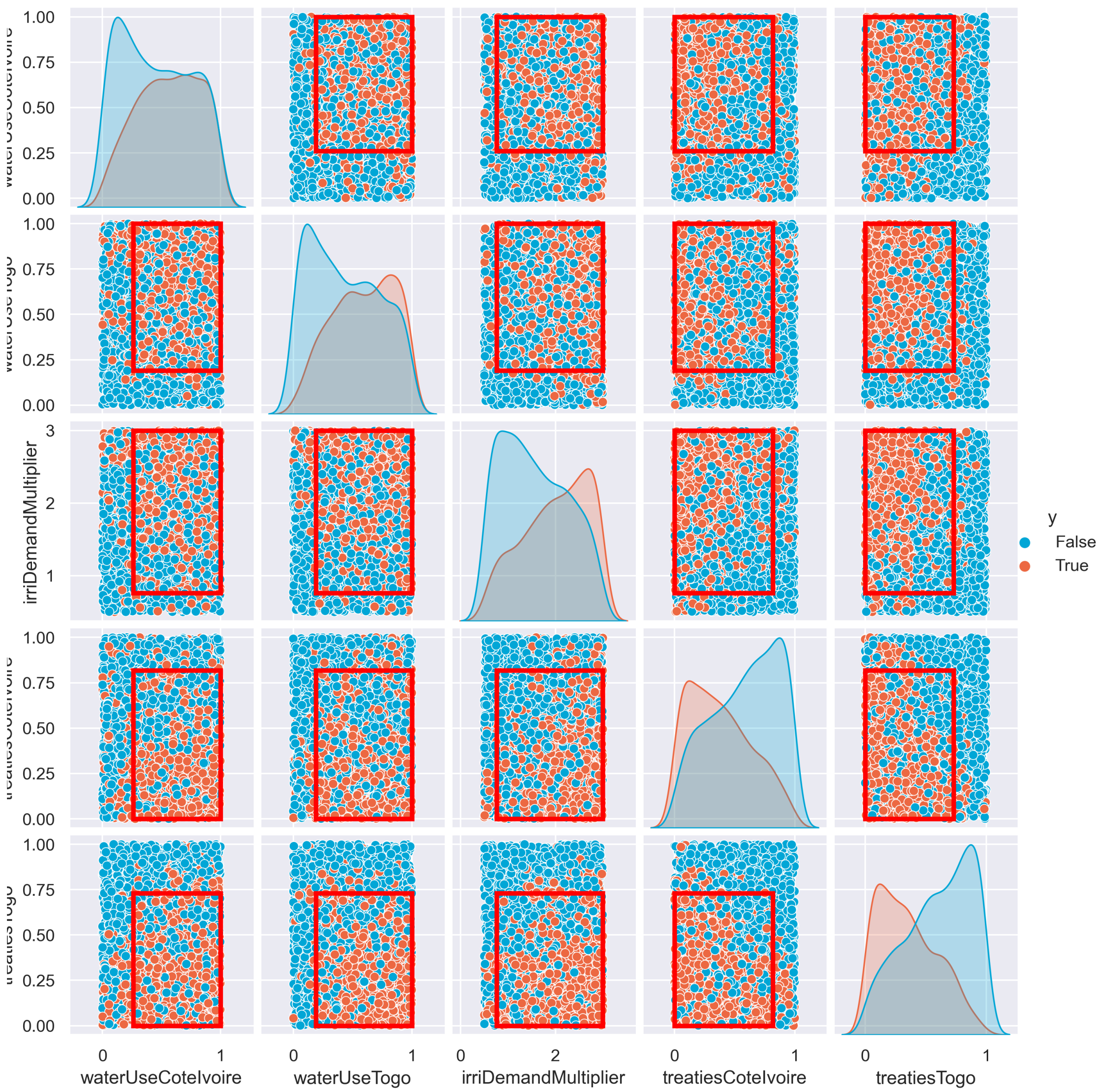

Figure D.29: Scenario discovery of the irrigation objective worse than the median of policy 8.

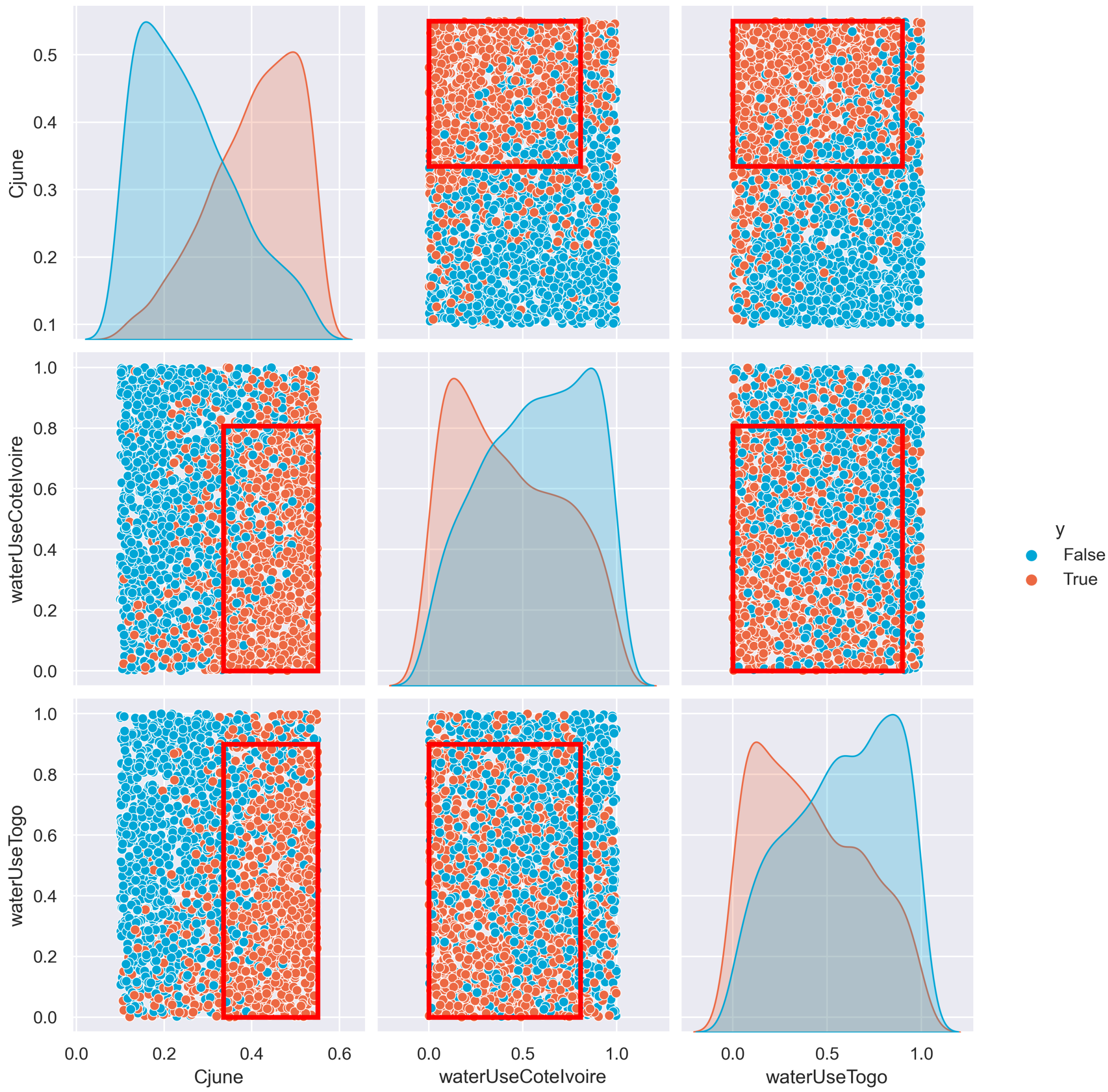

Figure D.30: Scenario discovery of the environmental objective worse than the median of policy 0.

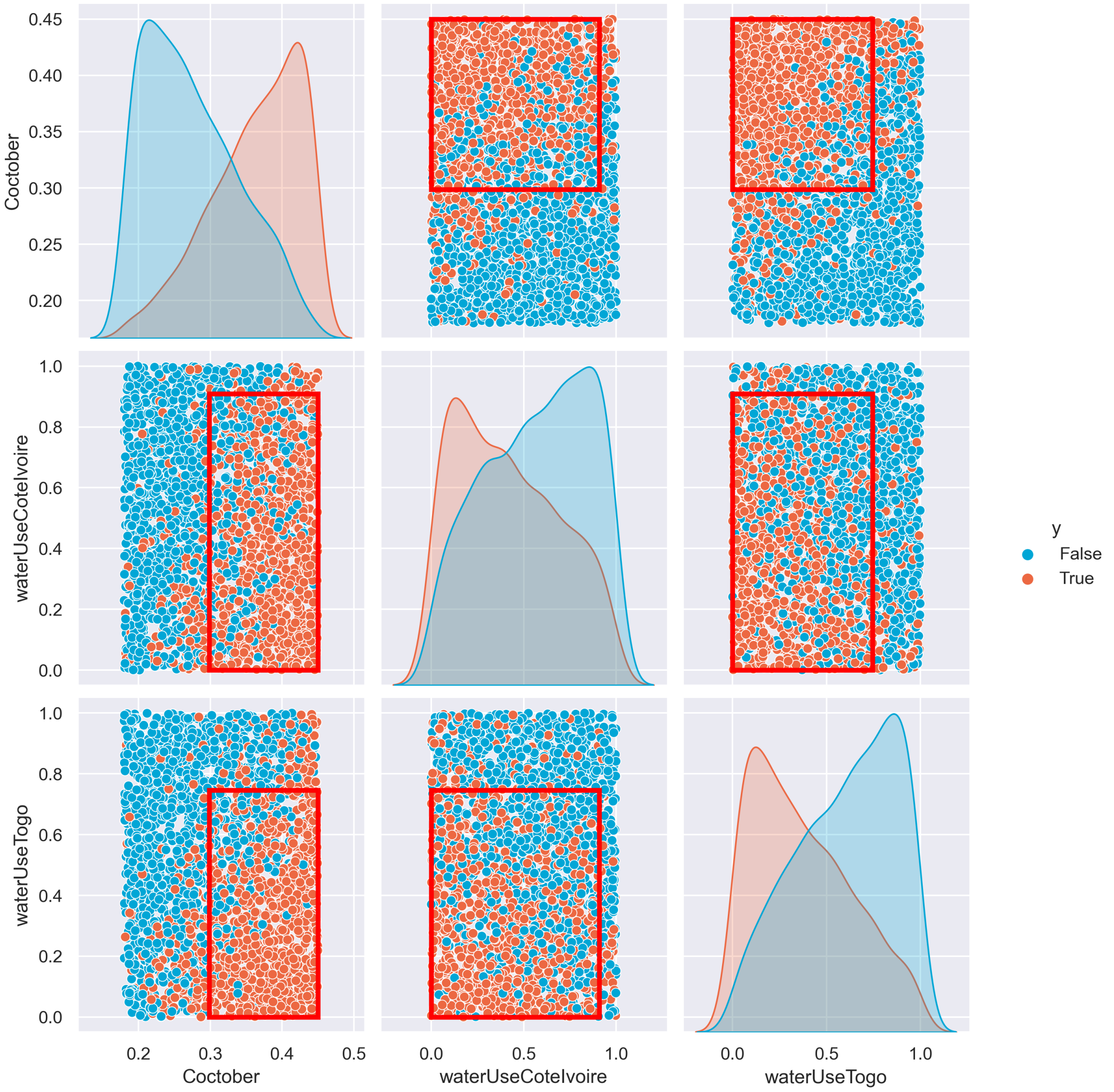

Figure D.31: Scenario discovery of the flooding objective worse than the median of policy 0.

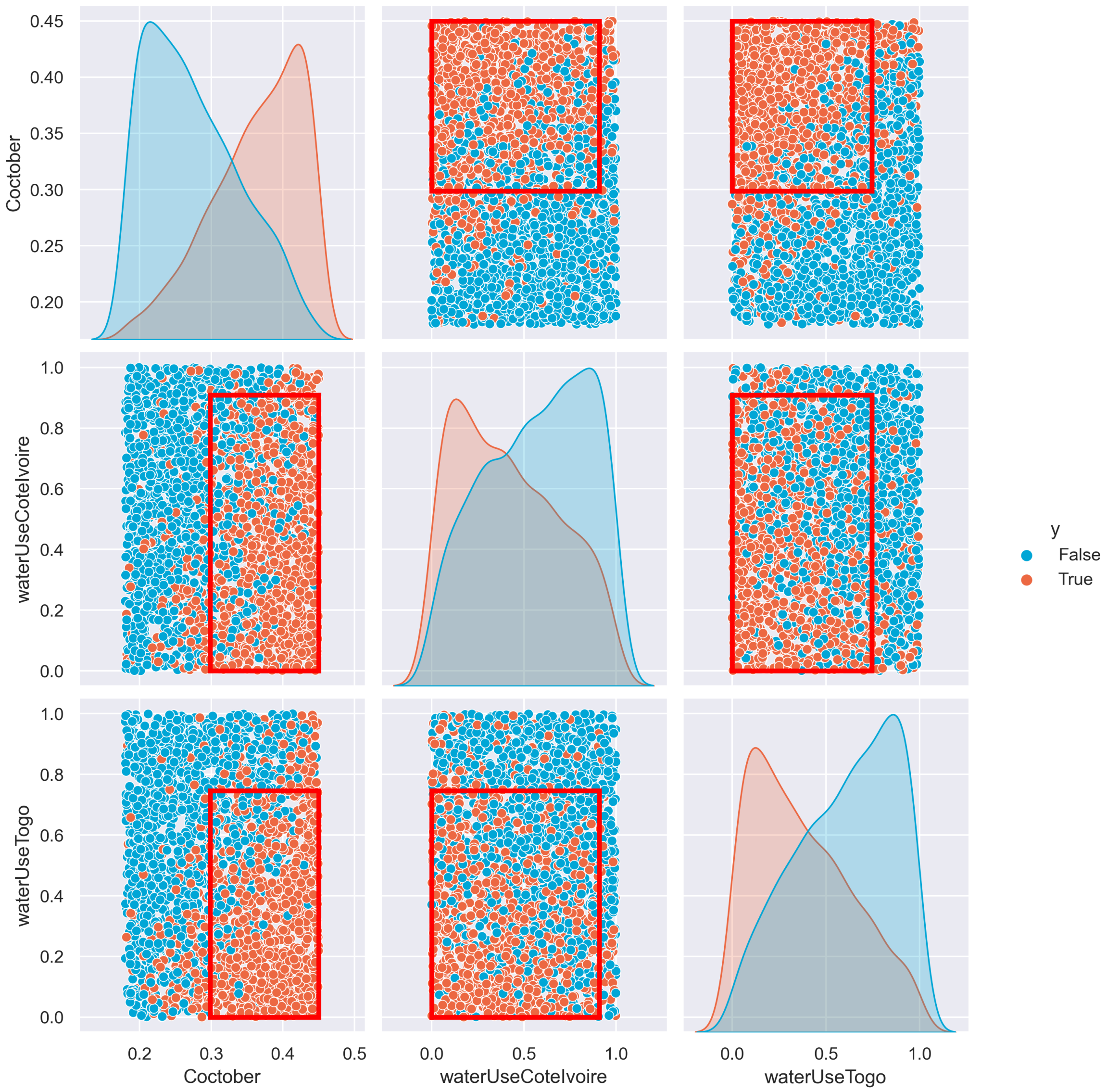

Figure D.32: Scenario discovery of the flooding objective worse than the median of policy 8.

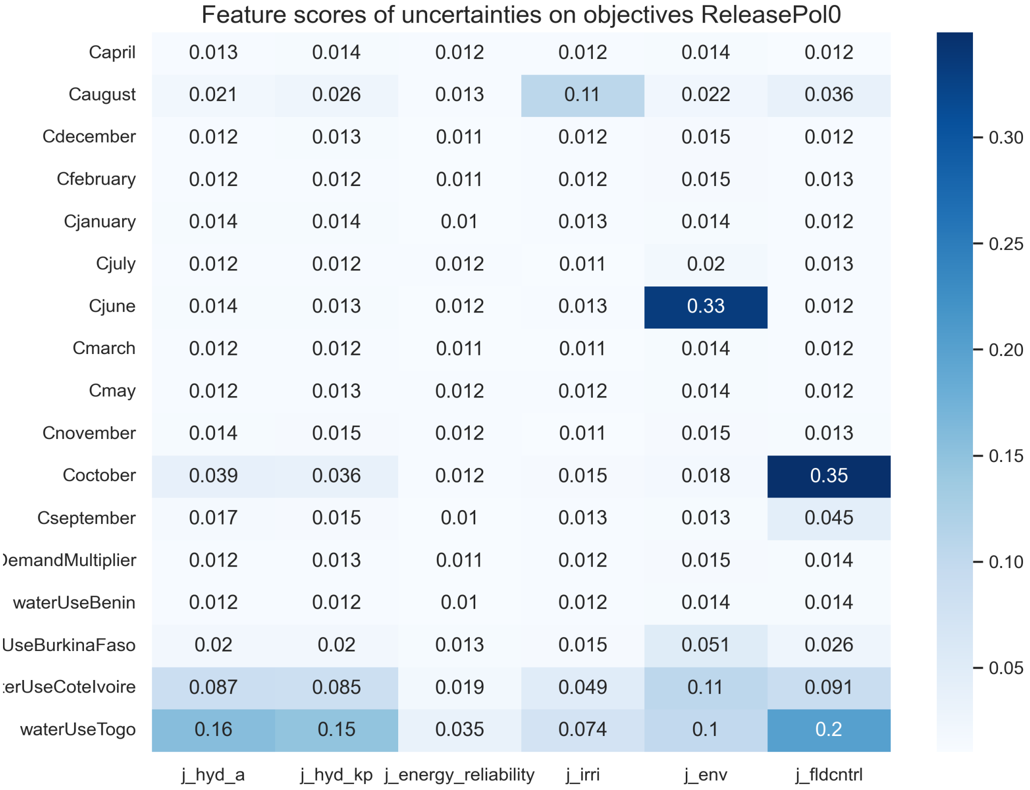

Figure D.33: Extra trees feature scores of uncertainties on the system policy 0.

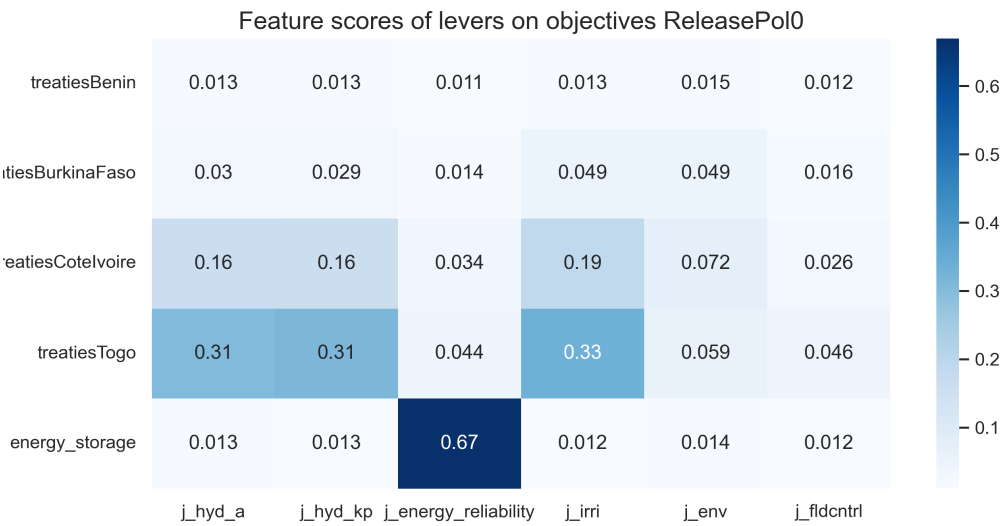

Figure D.34: Extra trees feature scores of levers on the system in policy 0.

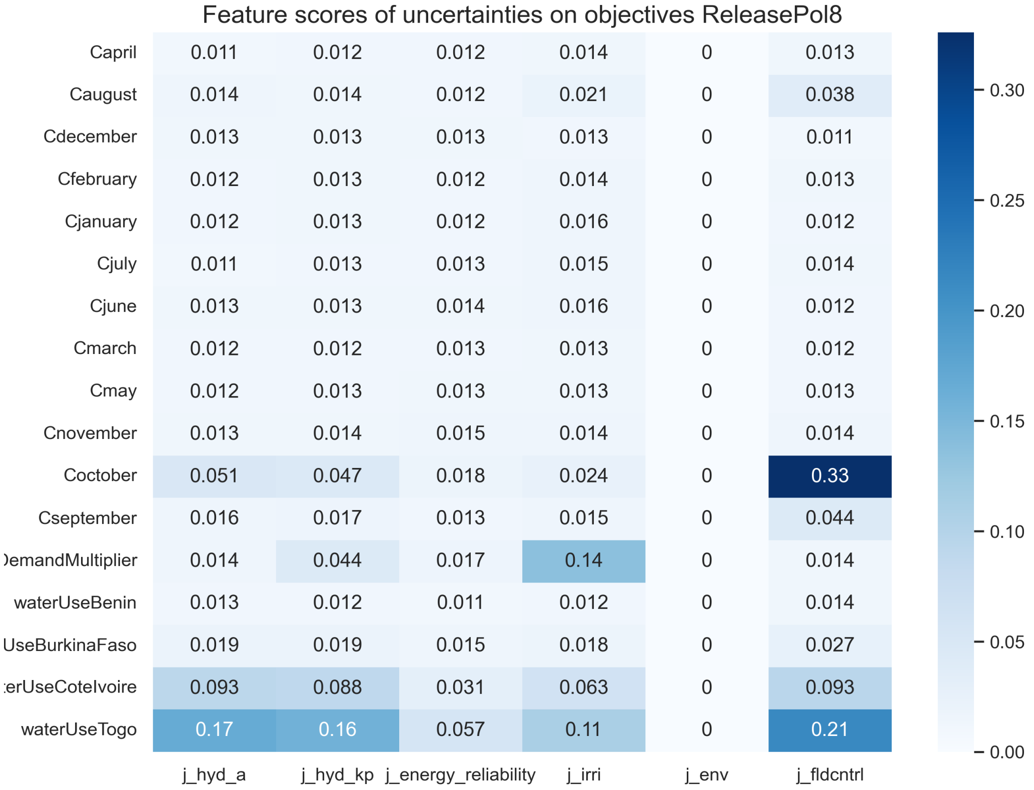

Figure D.35: Extra trees feature scores of uncertainties on the system policy 8.

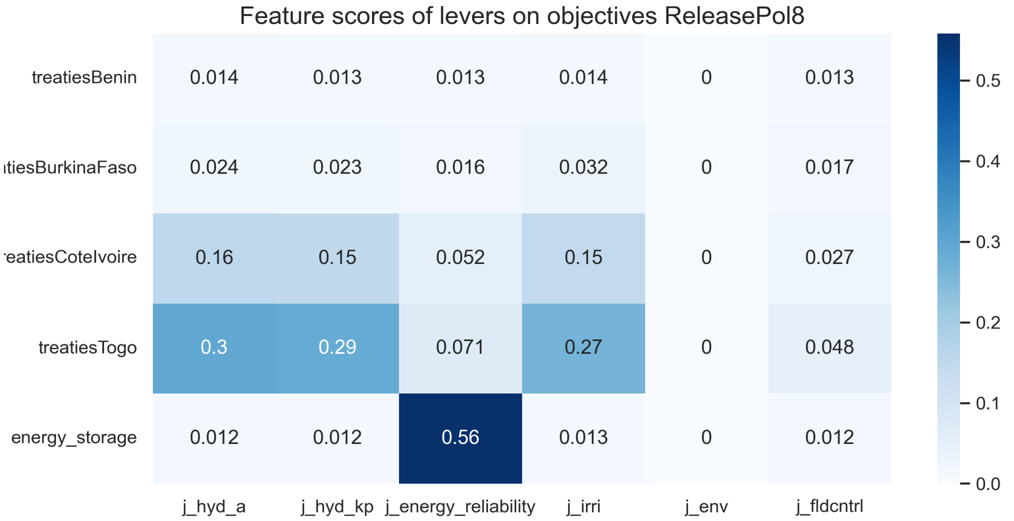

Figure D.36: Extra trees feature scores of levers on the system in policy 8.

E Decision-maker interaction

As discussed in the main text of the thesis, current dam optimisation processes could benefit from decision-maker interaction. The interaction could enhance the decision makers' understanding of the system as well as reveal their preferences towards certain metrics. This thesis argues that that could be done by postponing decisions towards the end of the process (a posteriori) instead of current a priori set decisions and providing 'the' answer for the best release policy. This appendix details the envisioned decision-maker interaction process as depicted in Figure E.1. This process has not been tested but serves as a start for further research.

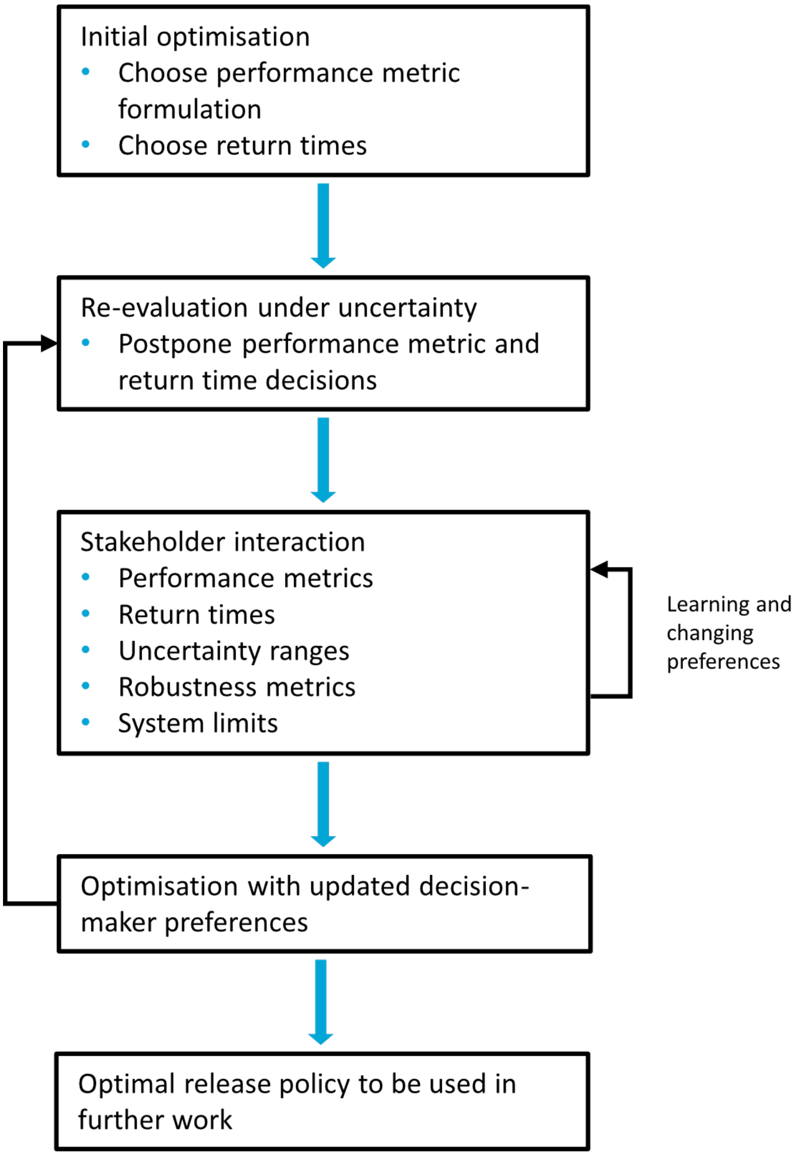

Figure E.1: Steps to be taken to involve decision-maker and come to release policy they can agree on.

E.1. Initial optimisation

Before one can let the decision-maker interact with any results, results need to be formed. This is done in a similar fashion as done in previous EMODPS studies. The first step is to make an initial problem formulation based on interviews, literature, and assumptions of the researcher. For the optimisation process, decisions on return times and performance metrics need to be made in order to be able to optimise. These decisions should be made by the researcher.

From here, the optimisation process can be performed. The optimisation process will lead to a Pareto optimal set of release policies for the reference scenario and set objectives. However, this policy set can be quite large. It is therefore advised to thin the set based on certain criteria. The goal is to get a variety of policies that encompass a range of outcomes.

E.2. Re-evaluation under uncertainty

After this, the chosen policies should be run in uncertainty. However, before that can be done, the simulation needs to be adapted. Where certain initial decisions on return times and performance metric formulations were made in the optimisation phase, these need to be postponed. One suggestion to remain flexible is to store the release flows per objective, as these are the most general form in which metrics can be defined. However, this does create an extensive data set since a value is stored for every release decision for every day for every year for every simulation for every scenario for every policy. To reduce the size of the data set, an aggregation step could be performed as long as enough detail remains available to apply a multitude of performance metrics formulations. The researcher should then decide on different formulations of the performance metrics to capture a range of meanings and preferences. For example, does the total energy production matter or the timing of the electricity production? Having a set of possible metrics allows the decision-makers to choose the one they think fits best and see the result of such a choice. In this phase, the uncertainty ranges are set by the researcher to provide a large overview of things that could happen. This range will be adapted in the interaction phase.

E.3. Interaction

The results of the previous phase are then put into an interactive decision support system (IDSS) which is then presented to the decision-maker. The IDSS should have the ability to perform transformations to the data set. Transformations should be done to go from releases to performance metrics, outcomes for set return times, and calculate a selection of robustness metrics. When these are implemented, the decision-maker can start exploring the performance of the different policies. Within the IDSS, the decision-maker can go back and forth between the choices and recognise what they find important and what they do not. At the end of the session, the final preferences should be recorded for the next step.

E.4. Re-optimise

With these preferences, the researcher can perform the optimisation and the uncertainty analysis once again. Then, the results can be shown to the decision-maker. Once again, an interactive session could be done with decision-makers, or a release policy can be chosen to work with in further planning of the dam system.

E.5. Interactive Decision Support System

Some initial ideas of an IDSS that can be used in the interaction phase are represented here. The IDSS is based on a web browser because it is easily accessible on every computer, and calculations do not have to be done on the computer of the decision-maker.

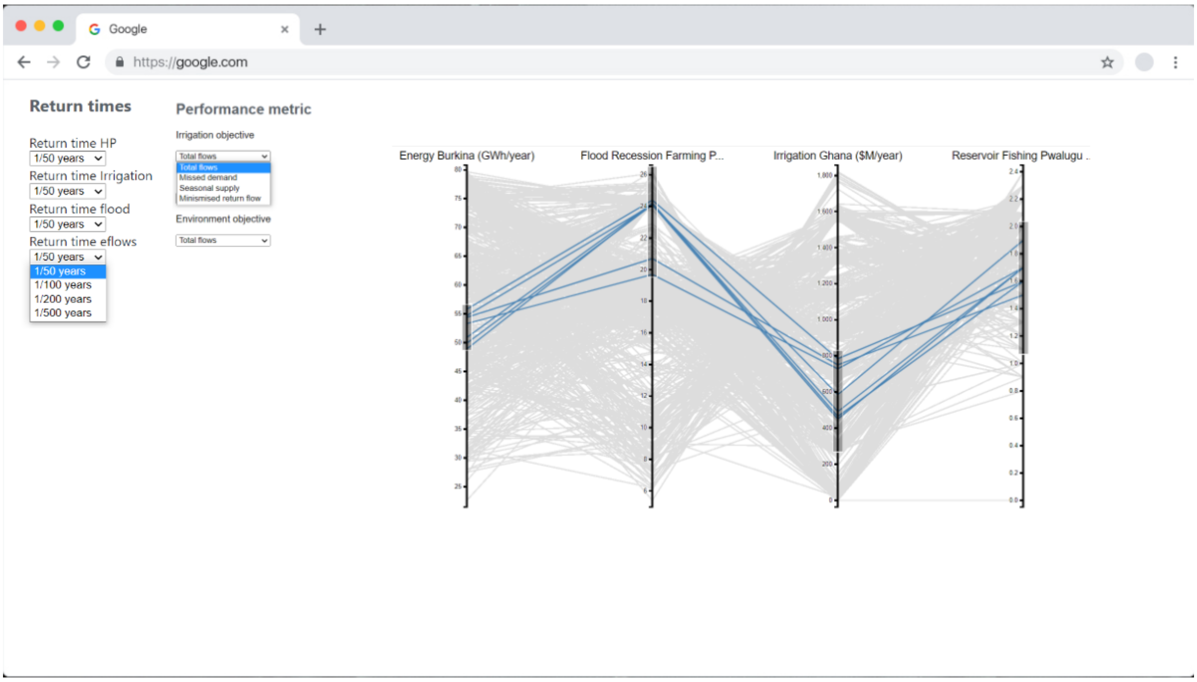

Figure E.2: In the IDSS the decision-maker set the preffered return times and performance metrics. From here the decision-maker can scrub the Pareto optimal set to only show policies that have the outcomes of interest.

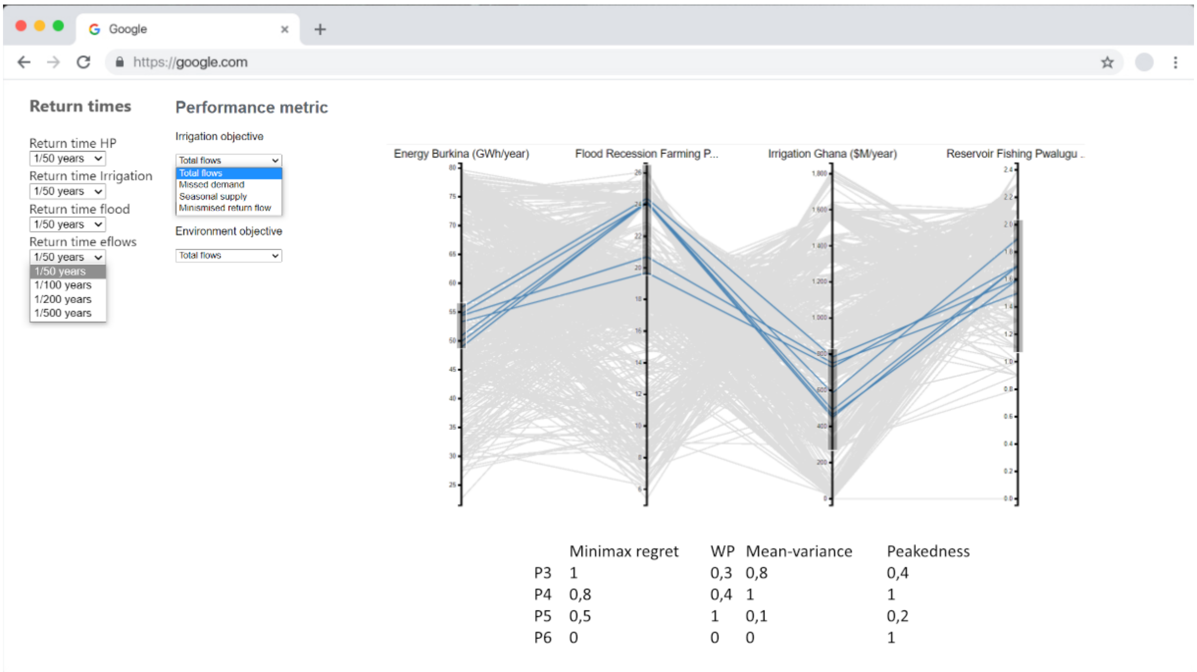

Figure E.3: For the scrubbed policy set the robustness performance can be shown.

Figure E.4: When selecting a policy the decision maker can see the influence of uncertainty on the policy outcomes. They can adjust the uncertainty ranges set by the researcher.

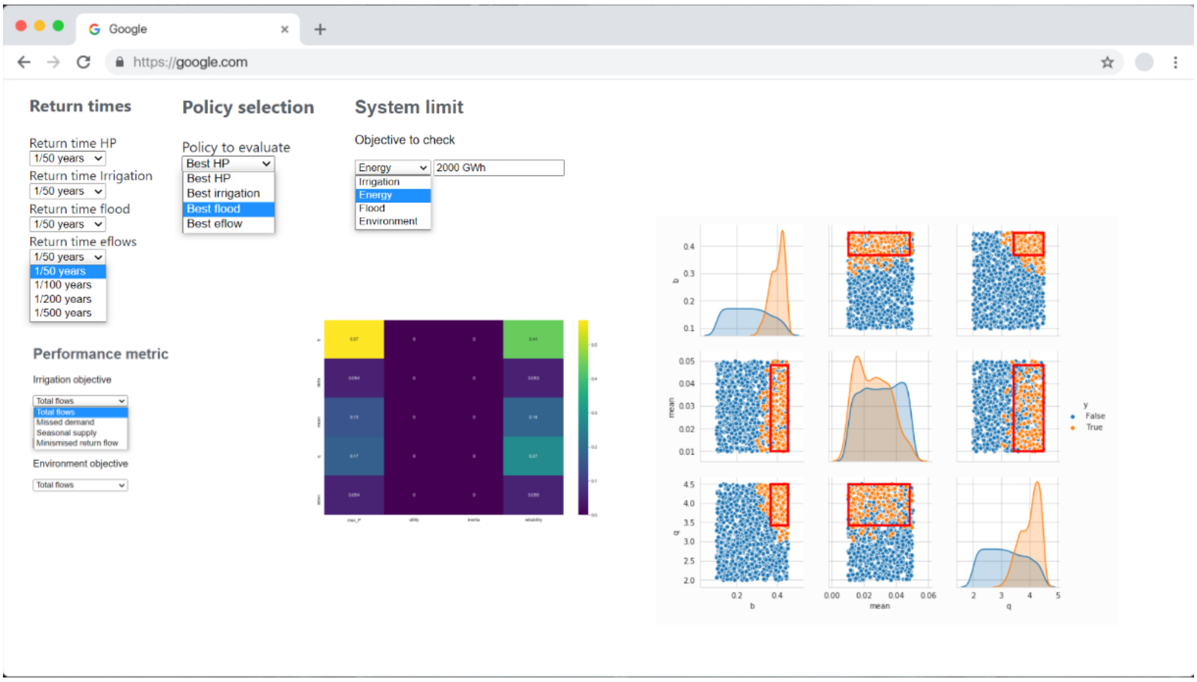

Figure E.5: The decision-maker can set limits for system operation and see the most important factors contributing to that outcome in the vulnerability analysis window.