Master Thesis

Faculty of Technology, Policy and Management

Pwalugu Multipurpose Dam: Beneficial for Local Communities too?

A System Dynamics perspective on the costs and benefits of the construction and operation of the Pwalugu Multipurpose Dam on local and national levels.

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Acknowledgements

Dear reader,

Thank you for showing interest in and taking time to read my thesis. This thesis is conducted as part of my final graduation for the Engineering and Policy Analysis Master Programme at Delft University of Technology. It marks the end of five years of studying at the Technology, Policy and Management department of the TU Delft in which I had the privilege to learn a lot from experts in all different kinds of fields.

From the first course of System Dynamics in the Bachelor Programme I knew that this would be the method most suitable for me. Since I really like modelling, but lack the computer engineering expertise to model in Python. This led me to Jill Slinger. Her enthusiasm from the first meeting onwards made her the perfect first supervisor for me. So did Jill not only help me with finding an interesting project to work on but she also arranged some funding for my trip to Ghana. I will forever be thankful for this and her enthusiasm at our weekly meetings always gave me more energy to continue working on my thesis. Which pushed it to another level.

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Raoul Rademaker Delft, 2022

Executive Summary

Key Findings

- An integrated System Dynamics model of the White Volta River simulates the effects of the construction and operation of the Pwalugu Multipurpose Dam on costs and benefits on both local and national levels, quantifying the associated trade-offs between flood protection, hydropower generation, irrigation and ecosystem-based activities of local communities.
- The optimization of hydropower generation will lead to 20% more water in the PMD reservoir, but it will also triple the number of flood casualties and reduce the irrigated farmland by 40%.
- A higher steady base flow of the river to increase the area of irrigated farmland will lead to a 30% increase in irrigated farmland, but will reduce the amount of fish caught at the riparian ponds by 35%
- Climate change-induced wet conditions are potentially beneficial as they increase the amount of water available in the system. The associated enhanced seasonality is beneficial for riparian pond and flood-recession agriculture.

Figure 0.1: Key findings of conducted research

The development of large dams are designed to bring multiple benefits at national level. However, there are usually many costs associated with them particularly at the local level. Apart from the investment costs, most of the burdens will be carried by the local population directly and indirectly affected by the dam. In flood recession systems, not only their Ecosystem Based Activities (EBA) have to transform, but some could also have to leave their houses and resettle elsewhere. Pwalugu is such an area, where the construction of the Pwalugu Multipurpose Dam (PMD), which aims to bring prosperity to a still underdeveloped Northern Region of Ghana, will substantively change the lives of many people living in the riparian communities along the White Volta River.

This research aims to analyse both the costs and benefits associated with the PMD at local and national levels, by applying a quantitative systems modelling approach. Whereas local communities are usually disregarded when developing big infrastructures, this research constructs a quantitative model to analyse the distribution of cost and benefits between the national priorities, such as hydropower generation, and local costs, such as livestock loss. The main research question is stated as:

"What are the socio-economic effects, at both local and national levels, of the construction and operation of the Pwalugu Multipurpose Dam?"

This research uses a System Dynamics (SD) approach to turn the available, often qualitative, information into a quantitative model, in which the White Volta River system is connected to the EBAs of the riparian communities. SD is an appropriate method for this as it can capture the the interactions between of the river and smaller sub-systems representing the different EBAs of the riparian communities in a connected model structure, which can then be simulated. This makes it possible to see how the dam will affect the behaviour of the different EBAs over time. The majority of the available information is found in literature, while some additional insights are gained during interviews with experts on either hydrology or the Northern Region of Ghana and its communities. This information is necessary for constructing, specifying and validating the quantitative model which when simulated makes it possible to show the effects of the construction and operation of the PMD on both local and national levels under diverse combinations of climate condition scenarios and dam operation strategies.

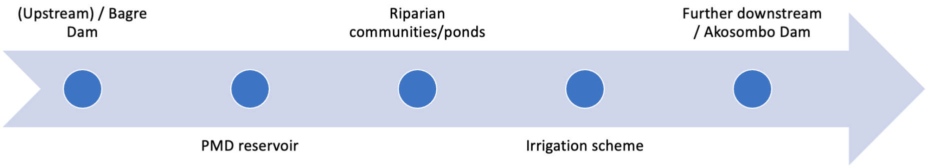


Figure 0.2: Simplified version of White Volta River flow

Figure 0.2 above shows a simplified version of where the White Volta River flows in the model. Water from upstream Burkina Faso flows into the PMD reservoir. High spillage at the Bagre dam can cause flooding in the Northern Region of Ghana which the PMD should be able to mitigate. When water is released or spilled at the PMD, it will flow to the riparian communities, and depending on how high the water level is some flood plains and riparian ponds will be flooded. After the riparian communities the water will reach the irrigation scheme where it will be used for both commercial as well as small household irrigated farming. Once the water has passed the irrigation scheme it flows further downstream and eventually reaches the reservoir of the Akosombo Dam, Lake Volta.

The other smaller sub-models of the quantitative model are all affected by the water flow of the White Volta River, as is common in a recession agriculture and hydropower/irrigation system. There is a sub-model of the electricity generation at the PMD, models of the crocodile and fish populations in the riparian ponds, the livestock and human populations at the riparian communities, and two sub-models of the crops grown and the area of irrigated farmland as well as an indication of damages from flooding. When the full model is simulated, the different sub-models provide a range of indicators of the costs and benefits at local and national scale in response to different dam operation strategies and climate conditions. This is summarised in scorecards indicating the range of behavioural responses and the trade-offs that the White Volta River system and its people will experience following the construction and operation of the PMD.

Following verification and validation of the SD model, more than twenty simulation runs were conducted. The run without a dam shows that without the construction of the dam the system is in a dynamic equilibrium caused by the seasonal flow of the river. The results of runs with the dam indicate that the different dam operating strategies all have different effects on the wide variety of indicators. The policy which aims at a full dam generates the most hydropower, however the lack of outflow will reduce the area of irrigated farmland and the full dam will not be able to mitigate possible floods caused by extreme weather or high spillage at Bagre Dam. Other dam operating strategies which aim for a higher base flow will lead to an increase in irrigated farmland, but will make it less likely that riparian ponds will be filled and less electricity will be generated. Creating artificial floods at the PMD could help with filling the riparian ponds, however it is unsure how effective this policy will be and how much water the PMD would need to spill. These represent the type of trade-offs in costs and benefits at local and national scale that will have to be addressed.

The presence of such trade-offs means that the operators and policy makers of the PMD can't simply implement an operating policy that optimises one of the benefits as this will diminish other benefits. Not a once off choice. Perhaps trade-offs can vary over time. Right now, the modelling study has clarified that trade-offs are inevitable and has quantified the impacts. If national priorities like hydropower generation are preferred, the majority of the cost will be felt by the local communities, who will also under these conditions receive less flood protection. If a more moderate approach is adopted, with a lower hydropower target, results indicate that local communities can derive more benefits. In the long term, the ecosystem-based activities of the local communities will be impacted, but the severity of the impact can be mitigated by appropriate choice of operational strategy. Moreover, climate change could benefit the local communities. Predictions are uncertain, but there appears to be a high probability that the White Volta River flow may increase under cc. This will mitigate effects on the local communities' lifestyle.

Reflecting back on the research it would have been beneficial to do the field trip prior to constructing the model. The field trip brought with it new insights and an improved understanding of the real system. This could have made the model even more realistic. However, since the trip was at the end of the research it was impossible to implement these new insights into the already constructed model. Future students are advised to try and plan a field trip early in a modelling study. Moreover, gaining more concrete quantitative data regarding the input parameters of the model would definitely make the model more accurate. For future research it would also be interesting to examine the construction and operation of the PMD and its effects through a hydrological lens. This research is conducted from an engineering and policy analysis perspective, which means that the focus lay on developing an integrated quantitative model (including the White Volta River flow and associated ecosystem-based activities) and the simulating of policy options and less on accurate hydrological flow simulation. Improving the accuracy of the hydrological simulation would yield more varied and interesting results, making an analysis of inter-annual variability in flow and its effects on operational strategies possible. Moreover, it would be interesting to perform a deeper scenario analysis of the future flow of the White Volta River as it is rather unpredictable. This can be performed with the Exploratory Modelling Analysis workbench in Python which makes it possible to run uncertainty experiments using a range of different policies and climate change and inter-annual variability scenarios.

Contents

1 Introduction

Water is one of the world's most precious resources. Humans cannot live without water, yet too large quantities of water can be harmful as well. Last year's events in Limburg are an example of how extreme precipitation caused by climate change can lead to destructive floods (Welling, 2022). Climate change not only leads to more extreme precipitation, it can also cause longer periods of severe droughts (Amisigo, McCluskey, & Swanson, 2015; Gueneau & Robinson, 2014). These droughts can be very harmful in their own way as they can create conditions conducive to huge forest fires like the ones in Australia and California in recent years (Gibson, Verdon-Kidd, & Hancock, 2022). This increase in extreme weather shows how important water management projects are, and this will only grow over time (Manful & Opoku-Ankomah, 2021).

Regions with a dry climate that only have a few months of precipitation are particularly prone to the effects of climate change (Liersch & Koch, 2022; Tangonyire et al., 2019). The Northern part of Ghana is such a region (Kasei, 2010; Nyarkoa, Eghanb, Essumangc, Amankwahd, & Osaee, 2009). It has a wet season from July till August, in which almost all of their annual precipitation falls (Mul, Pettinotti, Amonoo, Bekoe-Obeng, & Obuobie, 2017). This is followed by a very long dry season with high temperatures. The White Volta River, which originates in Burkina Faso and discharges into the Volta river in central Ghana (Han & Webber, 2020), is also affected by this. While high quantities of water do not flow through the river for most of the year, high precipitation and high spillage at the upstream Bagre Dam, can cause the river to flood (Gonzalez et al., 2021; Zakaria & Matsui, 2021). This leads to substantial damage to local villages in Northern Ghana and sometimes even leads to casualties (figure 1.1). The construction of the Pwalugu Multipurpose Dam (PMD) should pose a solution to this problem (Han & Webber, 2020; Miescher, 2021). The main aim of the PMD is flood mitigation, while it will also generate hydropower and have an irrigation scheme to bring more prosperity to the still underdeveloped Northern part of Ghana (Gonzalez et al., 2021; Mul et al., 2016; Cornille, Bocquet, & Wiafe, 2022). The PMD will cause a more steady base flow of the White Volta River, and should make the river less vulnerable to high precipitation or high spillage at the Bagre Dam (Han & Webber, 2020). However, a steady base flow of the river could disrupt the Ecosystem-Based Activities (EBA) of the riparian communities (Mul et al., 2017). These activities depend on the seasonality of the river. Once the wet season is over the riparian communities start with flood-recession farming. Furthermore, when food becomes scarce at the end of the dry season the main source for food becomes fish from the riparian ponds (Mul & Gao, 2016). Climatic change and changes in the flow of the river could have dramatic effects on these EBA, as occasional floods could damage the crops grown, while a more steady flow could lead to the riparian ponds not filling up and declining fish numbers (Mul et al., 2017; Gueneau & Robinson, 2014; Manful & Opoku-Ankomah, 2021).

This shows that policy makers regarding the construction and operation of the PMD should not only be considering national effects but should also take into account the downstream communities (Mul et al., 2016). Local impacts are factors that seem to be disregarded regularly in strategic decision making on the construction and operation of large dams (Darko et al., 2019). This is due to the fact that effects on local communities tend to be of a lower magnitude than national effects such as guaranteed water and power supply, however this does not mean that they should be disregarded (Darko et al., 2019). Moreover, previous studies regarding the construction and operation of dams tends to be qualitative and do not include the dynamics over time of the effects that the dam will have on the ecosystem based activities of the downstream communities (Bianchi & Gianelli, 2018). This, in combination with taking both the local and national factors into account could aid decision-making regarding the PMD.

Date	Number of Deaths	Affected People	Losses
2007	56	332,600	11,000 houses destroyed 70,500ha of farmland destroyed Thousands of animals killed Production losses of at least 144,000 tons
2010	5	48,000	2,400 houses destroyed 8,000ha of agricultural land damaged
2018	34	31,903	11,959.6 Hectares of farmland have been affected
2019	30	100,000	Between 1,000 and 4,000 buildings were destroyed or severely damaged
2020	19	70,000	12,000ha were affected and 5,000 houses were destroyed in several districts of the Upper East Region and the North-East Region

Figure 1.1: Damage caused by flooding in Northern Ghana in previous years (VRA, 2022)

The scope of this research will be on the White Volta River Basin, with particular focus on the PMD and the riparian communities, as there remains a lack of studies that consider both aspects. The societal impacts of the construction and operation of the PMD will be quantified. However the Bagre Dam will also be considered as spillage at this dam significantly affects the inflow at the PMD (Gonzalez et al., 2021). Apart from that the scope of this research will mainly focus on the features of the PMD and how it affects the local communities. The research will look into the trade-offs associated with the operation of the PMD in order to come up with appropriate policies regarding the construction and operation of the PMD that have benefits at both local and national levels.

The objective of this research is to quantify the effects that the development of the PMD will have on both local as well as national levels. By doing this, the research aims to improve understanding of the trade-offs that need to be considered within the White Volta River basin system and the dynamics these trade-offs have over time. This research also aims to build a System Dynamics model that could be reproduced for evaluating the feasibility of future dam projects without disregarding local communities. A model will be built of the White Volta River Basin in which critical uncertainties, as well as possible dam operation policies will be analyzed to see how these affect the system at both local and national levels. This leads to the following research question:

What are the socio-economic effects, at both local and national levels, of the construction and operation of the Pwalugu Multipurpose Dam.

To try and answer this question this research will construct a System Dynamics (SD) model. SD is a suitable method for this research, as SD modelling can yield insights into how a system behaves over time while bearing in mind uncertainties (Nabavi, Daniell, & Najafi, 2017). The usage of delays and feedback loops within SD also makes it very suitable for modelling dam projects while this will also help with modelling the flood recession agriculture system employed by the riparian communities. The water at different places in the system, for example the PMD reservoir or the riparian communities, will be modelled as stocks or accumulations. These different stocks will be connected with flows, which can be seen as the instream flow or river channel in the actual system. The research will follow the usual

SD modelling cycle which means that first the problem will be defined, the system conceptualised and a dynamic hypothesis will be drafted, after that the system will be modelled, the specified model will be simulated, and ultimately the different policies will be designed and analysed (Bala, Arshad, Noh, et al., 2017).

The next chapter will mainly focus on the research methodology and approach. It will also provide further detail why SD is a suitable approach and how SD has been used in previous studies on dam projects. Once that is clear the third chapter will look closely at the system and what the different dynamics are within the system. Understanding the system is very important in order to be able to construct a realistic model. The constructed model will be discussed in the fourth chapter, this chapter will describe precisely the modelling phase of the research from conceptual model to quantitative model, while also presenting the first base run and run without dam. The constructed model will then have to be validated and verified, which is done in chapter 5. Once the model has been verified we can start looking more closely at the results of the model and these results will be discussed in chapter 6. Then the next chapter will describe the conclusions drawn from the results. The eight and final chapter of this research will reflect on the results of the research and also the research in general and its limitations. Moreover it will recommend policies for operation of the PMD while also discussing what kind of further research might help.

2 Research Methodology

This chapter dives deeper into the method and approach that is used during this research in order to answer the main research question. Additionally this chapter gives insight into which chapter will try and tackle which sub-question. This shows that a mixed methods approach is used in this research. Nevertheless, the main method of the research will be System Dynamics (SD), which is discussed in its subsection 2.2.2. However, for the SD approach to be successful it has to be combined with other approaches like literature study (subsection 2.2.1) and validations interviews (subsection 2.2.3). Ultimately, this chapter talks through the dynamic hypothesis, which is an important feature of the SD modelling cycle (Bala et al., 2017).

2.1 Research Approach

To be able to answer the main research question:

What are the socio-economic effects, at both local and national levels, of the construction and operation of the Pwalugu Multipurpose Dam?

This research will use a combination of different approaches. The main approach is SD, which will be discusses thoroughly in subsection 2.2.2. However, other approaches are needed so that the SD approach can be successful. These approaches are: literature study, case study, and interviews, which means that this research has a mixed methods approach. For a better overview of how these approaches will help in answering the main research questions, the research question has been split into nine smaller sub-questions.

1. How has System Dynamics been used in previous studies regarding the construction and operation of dams?
2. What does the White Volta River system look like and at what scope does it get captured most accurately?
3. What are the ecosystem-based activities of the riparian communities and how much do they depend on water from the White Volta River?
4. How can the dynamics of the White Volta River system be captured realistically in a quantitative model?
5. How suitable is System Dynamics for modelling recession agriculture within the Volta River Basin?
6. What are the different dam operation strategies at the PMD?
7. How will different climate conditions affect the flow of the river and the ecosystem-based activities of the riparian communities?
8. How will the PMD affect the flow of the White Volta River?

Figure 2.1 below shows the process of this research and how every chapter helps in answering the different sub-questions and ultimately the main research question. Literature study is mainly used in the first three chapters of the research in which more data is gathered on the problem situation, as well as on how dams work exactly to be able to construct a realistic model. This literature study will go hand in hand with the case study, as it is important to combine the information found in previous studies with information about the White Volta River basin and the Northern Ghana region. This is mainly discussed in Chapter 3 and will help answering sub-questions 2 and 3. However, not all the information needed is available in literature. Therefore, semi-structured interviews are also conducted with experts on either life in the Northern regions of Ghana or on hydrology in Ghana. This in combination with the literature study provides great insights which helps with constructing the conceptual model. The conceptual model is the bridge between the literature and the eventual qualitative model. The conceptual model shows how the different factors within the system affect each other. Once this information is gathered the quantitative SD model can be build which helps answering sub-questions 4, and 5. The last three sub-questions and ultimately the main research question are answered by analysing the results that the System Dynamics provides. Analysing the results will help to get a better understanding of the effects of construction of the PMD. While also looking at how different dam operating strategies will have different effects and what the trade-offs of these are.

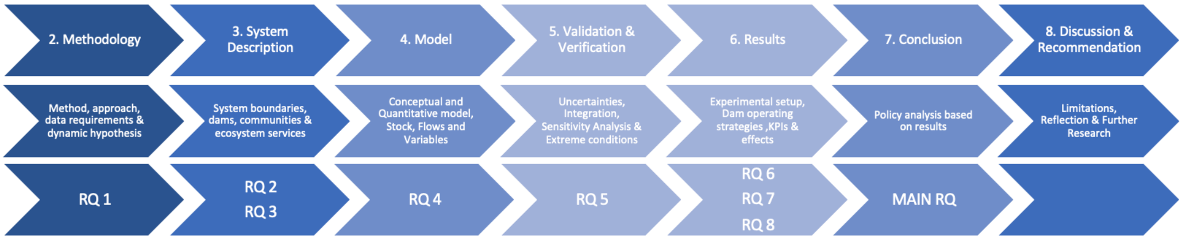


Figure 2.1: Illustration of important sub-steps in the modelling process.

2.2 Mixed Methods

This research uses a mixed methods approach with SD modelling as the main method to get a better understanding of both the socio-technical and environmental systems within Northern Ghana and how the construction of the PMD will affect the different factors within these systems. Previous studies regarding the PMD mainly focus on how it will affect the flow of the river from a hydrology perspective (Gonzalez et al., 2021). However, this research aims to link the river system to other divers effects like ecosystem-based activities of downstream riparian communities as well as irrigation, water supply, power supply and flood mitigation. A System Dynamics approach, in combination with a literature study and validation interviews, is effective in trying to reduce this knowledge gap by constructing a quantitative model that links the river system to the different effects caused by the construction and operation of the PMD (R. G. Coyle, 1997). This does not only give insight into the river system but also into the effects that changes in river flow will have on the EBA of the communities. Where societal cost benefit analysis only show summary indicators, an SD model also gives insight into how the behaviour changes over time. The objective of this research is to get a better overview of how these different factors are affected by the construction and operation of the PMD and to see how different dam operating strategies of the PMD affect each of the factors differently, which will provide insight into possible trade-offs regarding operation.

2.2.1 Literature Study

Before the White Volta River system can be modelled it is first important to review the existing literature. First of all, existing literature regarding the construction and operation of dams and how this could be modelled has to be gathered. This helps with getting a better understanding of how the river system should be modelled and how a dam could affect this system. It helps with determining which case specific data needs to be gathered and how this data should be used to improve the accuracy of the model. Once that has been done it is time to do a more case specific literature study on the Pwalugu Dam and the Northern Region of Ghana. The aim of this case study is to gain more quantitative data that can be used in the model while also gaining more knowledge about the qualitative data of the system which helps with constructing the conceptual system diagram in which the different factors are displayed.

To find appropriate literature on this the following keywords were used: Pwalugu dam, (White) Volta River, riparian communities, Akosombo dam and "dam operation". These keywords were used to search literature databases like Scopus, Google Scholar, and the TU Delft Library. This search led to different types of literature regarding the construction and operation of the PMD published in all different kinds of journals or books. However, the number of relevant literature pieces found was limited, especially at first when the focus was mainly on the Pwalugu Dam, expanding the scope to the whole Volta River Basin, including both the Bagre and Akosombo dam led to a slight increase in number of papers found. This simplified the selection process, the results of the search were evaluated on relevance and number of citations. Furthermore, papers were selected in such a way that both the hydrological aspect and the socio-economic aspect of the PMD are addressed. This provided a good overview of the effects of the PMD, while taking the diverse perspectives of the different stakeholders at both the national and local levels into account.

2.2.2 System Dynamics Modelling

SD is the main method of this research. SD seems like the most appropriate method since there are multiple feedback loops and delays in the socio-technical system (Nabavi et al., 2017). Straightforward examples of this are how spillage at the dam and water level at the dam reservoir will affect each other as well as the dams further downstream in the system. Another feedback loop is regarding the population of the riparian communities, if there is more water available in the riparian communities there will be more crops produced by agriculture which will lead to more food and cause the population to rise more rapidly, which means that the riparian communities will need more water. Moreover, the whole flow of the river and the storage of water in dam reservoirs can be depicted as a stock-flow diagram. Where the different reservoirs and places where water is used can be modelled as stocks while the river is the flow that connects all these stocks.

There have been several previous studies about dam operations which use SD. Lee and Kang (2020) even constructed a SD model which considered both the hydrological aspect of the dam as well as the social. However, there are not many studies that combine flood recession agriculture in a SD model on a dam. Isolated models of flood recession agriculture in response to releases from a dam exist (Slinger, 1988). However, most of the SD studies on dams are on how to manage the water level of the reservoir (eg. Niazi, Prasher, Adamowski, and Gleeson (2014)). The high level of detail of SD allows investigators to assess the impacts of different operation strategies regarding the dam reservoir (Jiang, Simonovic, Yu, & Wang, 2020).

Despite all this, SD has its limitations as well. An SD model can reflect the modellers view of the world and their underlying assumptions. This makes verification and validation of the model very important. This will be undertaken using historical data on water flows, but also by checking the outcomes of the model with experts, and undertaking extensive sensitivity and uncertainty analyses. Moreover, to develop a sound SD model it is important that reliable, local data is available otherwise the model will not represent the real-world system, emphasising the importance of the first two validation methods. The case study will help with setting up a base model on how the system works and the information found in the literature review will help with implementing the PMD into the model in order to be able to answer the remaining sub-questions and eventually the main research question.

2.2.3 Validation Interviews and Field Trip

The third method of the mixed methods approach is the validation interviews and the field trip to Pwalugu. During the research multiple experts on either life or hydrology in Ghana are interviewed to see whether their views of the system where in line with the model. The interviewees are selected mainly on availability as it is difficult to get in touch with experts on the PMD or Northern Ghana, moreover the research aims to interview different stakeholders so that different perspectives can be seen. The first two interviewees were Hammond Antwi Sarpong and Afua Owusu who both are PHD students currently working in Delft. They both grew up in Ghana. Interviewing them gives more insight into what live in Ghana is like and what factors should be taken into account, especially when modelling the EBAs of the communities. During the field trip to Ghana different stakeholders are interviewed as well, people working at the PMD directorate help to get more insight into the goals of the Volta River Authority (VRA) regarding the PMD and how the decision-making process works. While people at the riparian communities tell more about what their life looks like, how they think the construction of the PMD will affect it and what they think about the project in general. Ultimately, during interviews with hydrology experts in Ghana additional knowledge is gained regarding the hydrological situation of Ghana and how other Ghanaian dams are operated. A more elaborate summary of all the conducted interviews can be found in appendices D and E.

2.3 Dynamic Hypothesis

When discussing the dynamic hypothesis it is important to look at two different aspects of the system. The first aspect is how would the system behave over time without the PMD. Just like many other river basins the White Volta river depends a lot on precipitation, which is influenced by to climate change. Climate change will lead to more extreme weather which is in this case can lead to both longer dry periods and higher precipitation during the wet season. Basically more seasonality in a region where seasonality is already very high. This would lead to more floods, which could do damage to crops, riparian communities, and even lead to casualties. It could lead to larger flood plains which could be used for flood-recession farming, however a premature flood or delay in rain could still destroy these crops.

The second aspect that needs to be taken into consideration is how the construction of the PMD will affect the system over time. Just like the Bagre Dam, the PMD will probably lead to a higher base flow of water within the White Volta river basin. This is beneficial for irrigation and would increase the amount of irrigated crops grown. It is also beneficial for water and power supply, moreover the PMD will lead to lower flood peaks which means that riparian ponds might not flow over and the area of floodplains becomes smaller generating less ecosystem-based services for the riparian communities. However, with the construction of the PMD the riparian communities will be less vulnerable to floods caused by emergency spilling at the Bagre Dam.

3 System Description

This chapter looks closely at the White Volta River, which starts in Burkina Faso, where the Volta River Basin originates. The river water gets stored in the Bagre Dam, at 1 in figure 3.1, which focuses on optimizing hydropower generation. From here water passes through to the site of the PMD, at 2 in figure 3.1, which will also store water in the future for electricity generation and irrigation, while the dam will also increase flood mitigation(Cornille et al., 2022). The water will then flow through the irrigation scheme. Around the dam reservoir and irrigation scheme several riparian communities are settled. Ultimately the White Volta River will flow into the huge Volta Lake reservoir created by the Akosombo Dam. This chapter will describe all these different locations the river flows through in more detail from upstream to downstream.

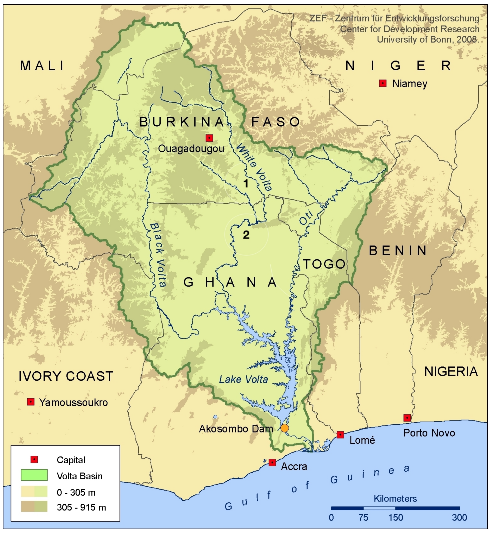


Figure 3.1: Volta River Basin

3.1 Bagre Dam

The White Volta River originates in the North of Burkina Faso, from there it flows all the way South to ultimately culminate in Lake Volta. Burkina Faso has constructed various large dam on the White Volta. The one that affects the inflow into Ghana the most is the Bagre Dam in southern Burkina Faso (M. Mul et al., 2015). Constructed in 1992, the Bagre Dam has a total capacity of 7 billion cubic meters (BCM) (Amuquandoh, 2016). The Bagre Dam is a multipurpose dam with as main purposes food security and electricity generation (Daré et al., 2016). The dam can generate 16 MW of hydropower (Amuquandoh, 2016). Hydropower optimization at the Bagre Dam means that the reservoir will be filled to almost it's maximum capacity (Amuquandoh, 2016). Due to this, operation at the Bagre Dam is sometimes forced to release large emergency spills during the rain season which will lead to floods in Northern Ghana (Musah, Mumuni, Abayomi, & Jibrel, 2013). Moreover, the irrigation scheme which is implemented in combination with the Bagre Dam causes the flow of the White Volta river to change and it is expected that the irrigation scheme will expand over the coming years (Mul et al., 2017). Figure 3.2 shows that before the construction of the Bagre Dam there was hardly any discharge in Pwalugu during the dry season, but since the Bagre Dam has been operational the White Volta river has a more stable base flow and lower flood peaks, which could hurt flood-recession agriculture and other ecosystem-Based activities of the riparian communities.

The Bagre Dam will be considered more as an external factor in the model constructed during this research. As the focus of the research will be more on the PMD as well as the riparian communities near the construction site of the PMD. However, the model can't entirely disregard the Bagre Dam as the dam changes the flow of the river (Amuquandoh, 2016; Mul et al., 2017). It especially is important to get a better view of how the PMD will be able to absorb the emergency releases of the Bagre Dam in order to mitigate floods. Furthermore, an improvement of cooperation between Burkina Faso and Ghana on water management would be an interesting policy to investigate.

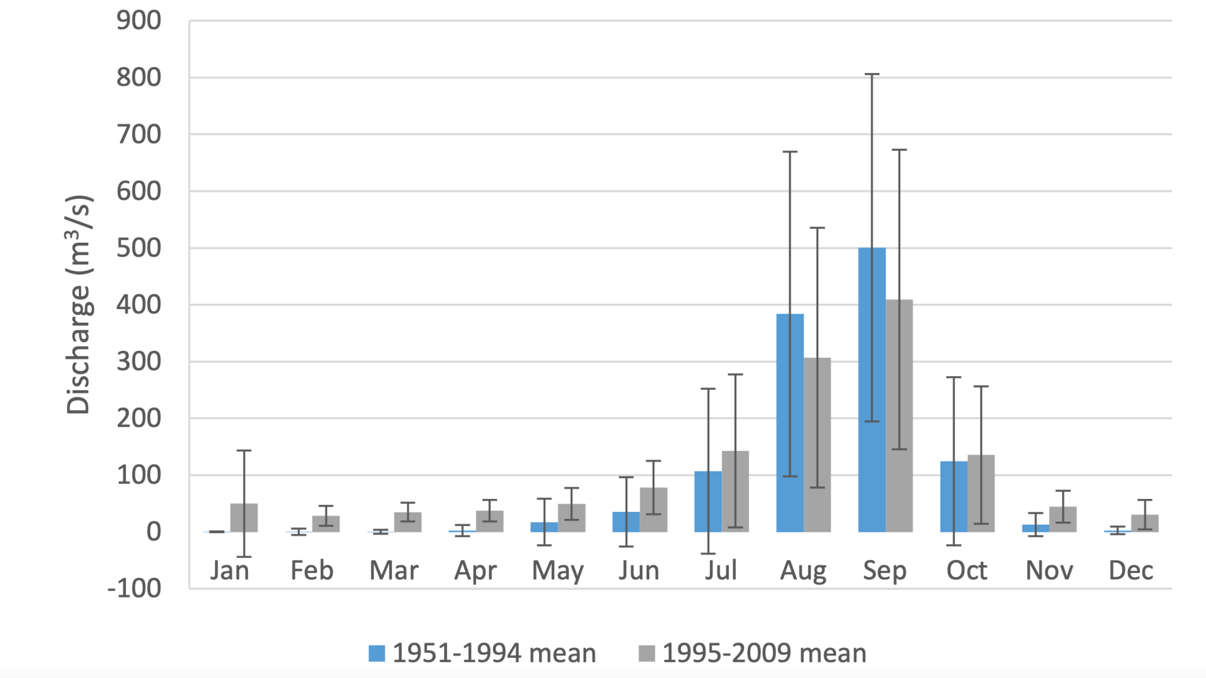


Figure 3.2: Changes in flow in Pwalugu after construction Bagre dam (Mul et al., 2017)

3.2 Pwalugu Dam

Once the water flows out of the Bagre Dam and into Ghana it will come across the town of Pwalugu. This town is just downstream of the site of the PMD which is currently under construction and is due to finish somewhere around 2026 (Tenkorang, Enu-Kwesi, Bendu, & Souvannaseng, 2022). The PMD would provide, hydropower generation, flood mitigation and food security to a still underdeveloped northern region of Ghana (Gonzalez et al., 2021; Mul et al., 2017). The PMD will be able to generate a maximum of 60 MW of hydropower in combination with around 50 MW of solar power (Miescher, 2021), and will have an irrigation scheme of 25,000 hectares (Amisigo et al., 2015; Gonzalez et al., 2021; Gueneau & Robinson, 2014). This could have huge benefits for both Ghana nationally as well as locally. Due to the fact that the PMD is still under construction there is no clear information on how the PMD will affect the flow of the White Volta. However, it can be expected that the PMD will have a similar effect to the flow of the White Volta as the Bagre Dam has. Meaning it will lead to a higher base flow and reduce the flood peaks (Mul et al., 2017). Moreover, it would prevent the local communities from floods caused by emergency spillages at the Bagre Dam.

A more steady base flow could be beneficial for the irrigation scheme of the PMD as well as for the hydropower generation. However, it is not clear if this would be beneficial for the local riparian communities as most of their EBAs depend on the seasonality of the river (Mul et al., 2017). This makes it hard to determine how beneficial different operation strategies of the PMD will be for both Ghana nationally as well as for the local communities. Moreover, as the project is still under construction it is still hard to state where the focus will be when determining the operational policies. VRA (2014) describes in an Environmental Impact Analysis (EIA) that there will have to be a trade-off between hydropower generation on the one end and irrigation and flood mitigation on the other. It will also be important that during the decision-making process all parties involved will be considered in stead of determining the appropriate dam operation based on just national benefits. Which is something that has happened with previous dam constructions in Ghana (Darko et al., 2019; Han & Webber, 2020).

3.3 Riparian Communities

Scattered all around the construction area of the PMD and the irrigation schemes you will find the riparian communities, which still live in rather poor conditions. The main EBA of this riparian communities are farming, fishing and livestock watering and grazing (Mul et al., 2017). These activities are very dependent on the seasonality of the river (Mul et al., 2017). Delays in the flow of the river or flooding of the river can have harmful effects on the crops grown by the riparian communities. Floods do not only destroy farms, but also affect the communities, in 2018 floods lead to 34 deaths (VRA, 2020). However, occasional light flooding is very profitable to the riparian communities as this fills up the riparian ponds and provides them with a very fertile soil around the floodplains which can be used for flood-recession agriculture and livestock grazing.

3.3.1 Agriculture

Agriculture is the most common EBA of the riparian communities, and it is very dependent on water availability. Crops need water to grow, and occasional delays of the wet season or seasonal flooding can destroy a large number of crops (Amisigo et al., 2015). There are three different types of farming at the riparian communities, which will all be discussed in the following three subsections.

Rainfed agriculture Rainfed agriculture is a type of farming that relies heavily on water from rainfall, this makes it very vulnerable to possible delays of the rainy season (Kanchebe Derbile, 2013). Rainfed farming is mostly done on the floodplains and the woodlands of the riparian communities. The crops that are grown at the riparian communities using rainfed farming are mainly cereals and legumes (Mul et al., 2017). These crops are planted at the start of the rainy season which is around April/May and are harvested in September (Mul et al., 2017). Seasonal floods caused by high spillage at the Bagre dam could destroy entire crops, the PMD will make the communities less vulnerable to high spillage at the Bagre Dam. Nevertheless, the PMD will also affect the flow of the White Volta river in its own way.

Flood-recession agriculture Flood-recession agriculture is a type of farming which is common in areas that are prone to floods and have a high poverty level (Sidibe, Williams, & Kolavalli, 2016). The Northern Region of Ghana can be considered such an area. Flood-recession crops are grown on the floodplains which are flooded during the wet season, once the water recedes again the soil of these plains tends to be highly fertile. This makes flood-recession farming highly dependent on the seasonal flooding (Gonzalez et al., 2021). Which means that the higher the flood peak is during the wet season the more area will be available for flood-recession farming. Crops that are mainly grown during flood-recession farming are peas, maize, and rice (Mul et al., 2017). As the PMD will probably lead to less high peaks of floods, this could probably lead to a loss of arable land for flood-recession farming.

Irrigation farming The last type of farming at the riparian communities is irrigation. This type of farming needs more materials and needs water all year round. This is why it is not done a lot at the riparian communities as a large part of the riparian population can't afford the resources, such as pumps to pump the water from the river onto the farmland. One of the benefits of the PMD will be that it will provide an irrigation scheme somewhere between 20,000 and 25,000 hectares (VRA, 2014). Moreover, the higher base flow caused by both the PMD and the Bagre Dam will make it easier for irrigation farming to expand as there will be more water available during the dry season as well (Mul et al., 2017). However, this would lead to a possible trade-off at the PMD between electricity generation and irrigation (Gonzalez et al., 2021). The irrigation scheme for the PMD is located further downstream than some of the riparian communities, meaning that water will first flow through the communities before it reaches the irrigation scheme. This makes it hard to determine how beneficial this irrigation scheme will actually be for the riparian communities. It should also be taken into considered how far the irrigation scheme will be from the affected communities and whether it will be open to smallholders or if it will mainly be used by big commercial farmers.

3.3.2 Riparian Ponds

When the White Volta river overflows water will flow into the riparian ponds (Mul et al., 2016). Once the wet season is over the river will subside which means that the riparian ponds will get disconnected from the main river. This disconnection means that the fishes in the riparian ponds are trapped. The riparian communities have strict regulations on fishing at the riparian ponds. This allows the fish to grow so they will provide the communities with more food once the fishing season start, which is usually at the end of the dry season (Mul et al., 2017). The water at the riparian ponds is also used for livestock watering and grazing. Different crops are grown in and around the riparian ponds once the wet season is over in September too. These crops will be harvested during the dry season in order to provide the riparian communities with some food during the long dry season in which food starts getting more scarce (Cornille et al., 2022). The riparian ponds do not only have economic value but also have a spiritual value (Insoll & Kankpeyeng, 2014), as inhabitants of the riparian communities believe that the crocodiles that live in the ponds are considered friendly. As they believe that one of the communities female ancestors transformed into a crocodile after her death (Mul et al., 2017). Additionally, the riparian ponds are sometimes used to perform rain dances at the end of the dry season (Mul et al., 2017).

3.4 Akosombo Dam

Finally the water flows into the massive Lake Volta, which has a total capacity of 148 BCM. This is significantly larger than the reservoirs of the previously discussed dams. The 60 MW of hydropower that can be generated by the PMD can almost disregarded when being compared to the 1040 MW that is generated at the Akosombo dam. Ever since operation of the Akosombo Dam started in 1965 the dam has boosted the Ghana economy. However there has also been a lot of discussion about whether the Akosombo Dam can be considered a success as it forced 80,000 people to be displaced (Han & Webber, 2020). Which is something that occurs more often with dam constructions (Price & Singer, 2019) and could happen with the construction of the PMD as well.

The construction of the PMD will not have too big of an effect on Lake Volta, since there is such high volume of water at the reservoir. Ampomah (2017) conclude that water management at the Bagre Dam has no statistically significant effect on the water levels at Lake Volta. This suggests that the PMD also won't have much effect on the water levels at Lake Volta, as the capacity of the PMD can be disregarded compared to the capacity of Lake Volta and Lake Volta also has other tributaries like the Black Volta and Oti rivers. This is why the Akosombo dam itself is not included in the model that is constructed during the research.

3.5 System Diagram

Now that the path that the water in the White Volta river follows is described in more detail, all the different aspects of the system can be put together in a diagram, which can be seen in figure 3.3. The diagram shows policies in red, criteria in green, external factors in blue and internal factors in orange. The diagram depicts how all the different factors within the system are connected to each other via causal loops.

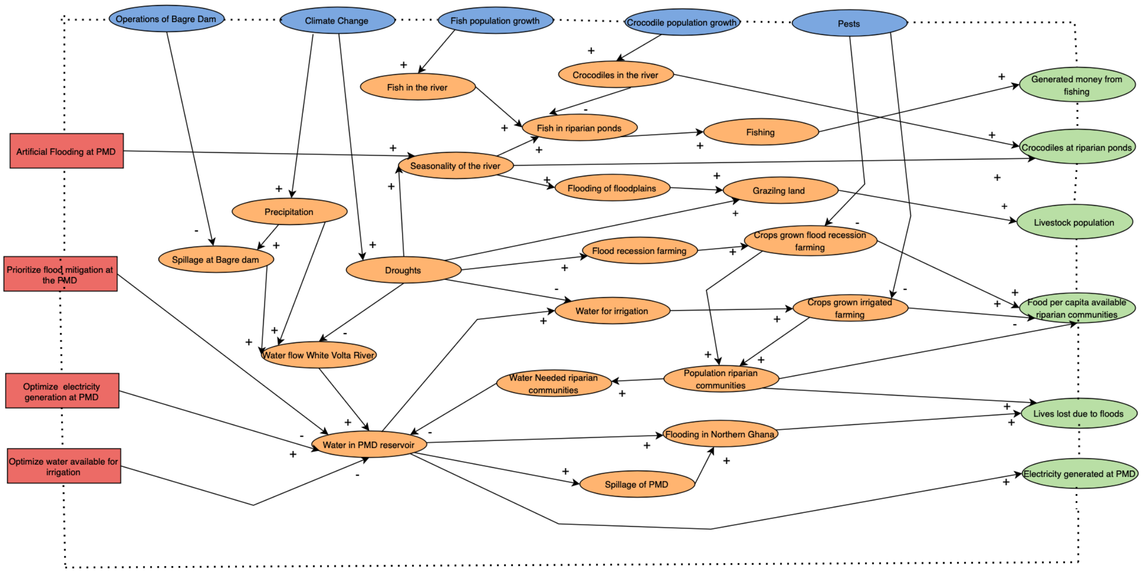


Figure 3.3: System Diagram White Volta River

The system diagram above shows how all the previously discussed aspects of the system are connected with each other. Certain causal relations between two different factors were difficult to specify as either positive or negative. Take for example droughts and flood recession farming. Droughts cause the flood plains to dry up more quickly or remain dry. Which makes it accessible for flood recession farming and grazing, so it would seem positive. However, if the drought period lasts too long the crops grown during flood recession farming won't survive and the grazing will be poor. So as for most relations between factors in the system diagram they can be considered either positive or negative until a certain threshold and once this threshold is passed the relation can change from positive to negative and vice versa. Similarly the dependence of crocodiles on fish as food supply is not modelled in detail. Instead only the major connections are included.

4 Model

This chapter will examine the conceptual model of the White Volta River basin more closely. The different sub-models will feature all the different system aspects that have been discussed in the previous chapter. First a sub-model regarding the river system and the water flow will be discussed. This will be the water resource sub-model that all the other sub-models will revolve around as they depend on the water provided by the river. Then sub-models concerning the riparian ponds will be discussed, these contain a sub-model of the fish population as well as one of the crocodile population. Ultimately, the riparian communities will be discussed, this will include sub-models regarding the population of the riparian communities as well as the farmland, the crops grown on it and the livestock population.

4.1 White Volta River basin

The first system that will be modelled is the White Volta River basin, which is of course the system around which everything revolves. The river provides the water that can be stored in the different dam reservoirs and provides water for the different EBA of the riparian communities (Mul et al., 2017).

4.1.1 River flow

The most important sub-model of this system is of course the one of the White Volta River, as all the other sub-models are dependent on this sub-model in some way. The sub-model, as can be seen in figure 4.1, shows how the water flows from the upstream Bagre Dam to the irrigation scheme downstream of the riparian communities. As the scope of this research is on the PMD, both the Akosombo and Bagre dam are not added to the sub-model. However, the upstream Bagre dam will affect the inflow at the Pwalugu dam and the amount of water used throughout the system will affect the water level at the Akosombo Dam. Even though it is expected that this effect will be negligible (Miescher, 2021).

The model starts with the inflow into the PMD reservoir, this inflow is affected by operating policies of the Bagre Dam and the seasonality of the river (Adomah Bempah & Olav Øyhus, 2017; Amuquandoh, 2016; Ampomah, 2017). Once the water is in the PMD reservoir it can either evaporate or be released. In case of a flood it is also possible that the dam will generate some spillage. This spillage and outflow of the PMD will enter the riparian communities through the river. Here water can be used for domestic use and if the water level is high enough the riparian ponds will also fill up (Mul et al., 2017). At the riparian ponds the water can evaporate or also be used for livestock watering (Lawson, 1966). The water from both the riparian communities and the riparian ponds will flow to the farmland where the water can be used for irrigation or other types of agriculture (Ampadu, Sackey, & Kyeremeh, 2017). Once these farmlands are passed the river will flow further downstream were it will eventually culminate into the Volta river which flows into Lake Volta (Baah-Kumi & Ward, 2020; Gonzalez et al., 2021).

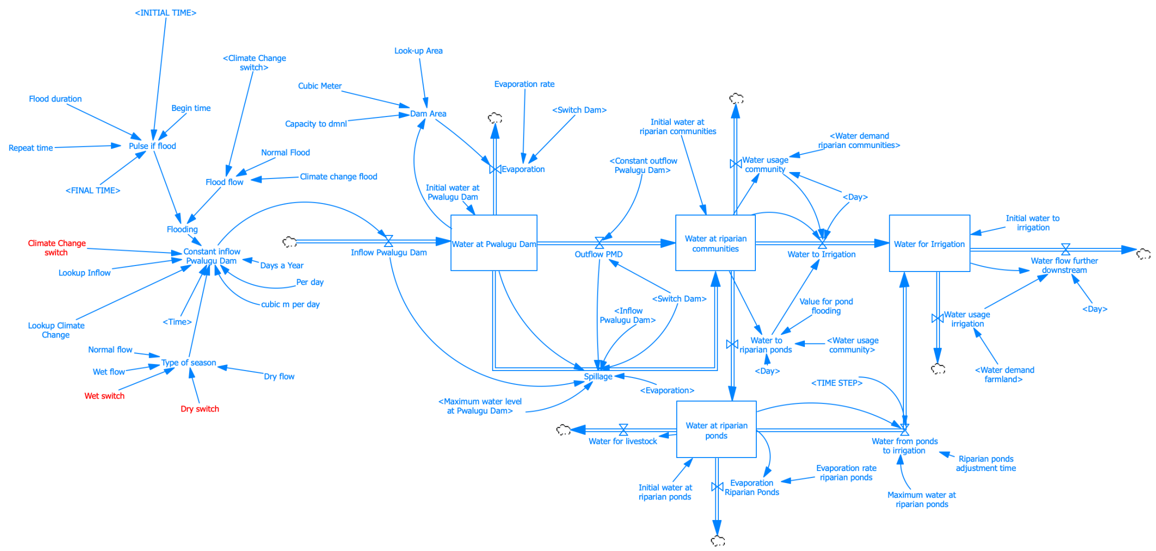


Figure 4.1: Sub-model: White Volta River

4.1.2 Electricity Generation

One of benefits of the PMD is that it will generate hydropower, which should help with providing electricity to a rather poor rural Northern Region of Ghana (Cornille et al., 2022). Dams generate hydropower by letting the water flow out of the reservoir, meaning the water will fall from a high altitude. This will cause the dams turbines to rotate which generates hydropower (Quaranta & Davies, 2022). This means that the amount of hydropower generated at the PMD is dependent on the outflow of the dam, the height of the dam, the efficiency of the turbines, the water level, and the density of water, as can be seen in figure 4.2. Demand for electricity generation is also one of the factors that influences the outflow of the PMD, if the demand is high the outflow could be higher in order to generate more hydropower (Gyamfi et al., 2020). Moreover, water needed for downstream activities like irrigation or domestic water use can also lead to a higher outflow (Liersch & Koch, 2022; Gonzalez et al., 2021).

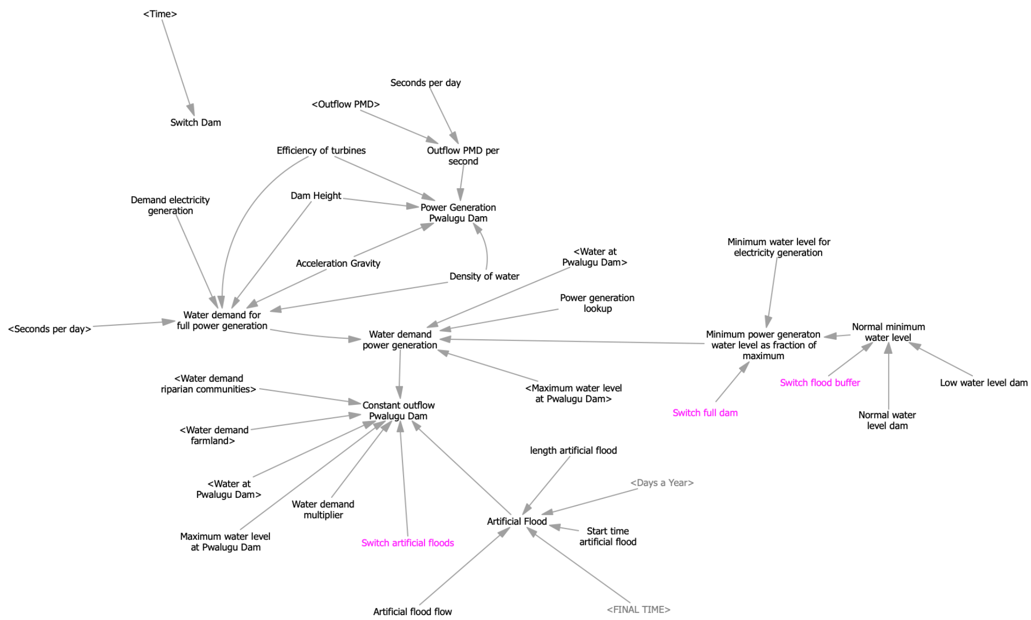


Figure 4.2: Sub-model: Electricity Generation

4.1.3 Damage

Water has a lot of beneficial effects on the local communities, as most of their EBA depend on water (Mul et al., 2017). However, too much water can have harmful effects on the riparian communities. Over the last few years floods have lead to dozens of casualties (Miescher, 2021; VRA, 2022), while also leading to huge costs (Almoradie et al., 2020). That is why damage needs to be taken into account in the model as well and this lead to the construction of the damage sub-model shown in figure 4.3. This is a rather simple model as the level of water is compared to a beneficial water level, once the level of water goes above this beneficial level there will be damage. This damage can be in the form of casualties, loss of crops, livestock drowning, or simply damage to buildings. This damage function will be used throughout multiple other sub-models as well.

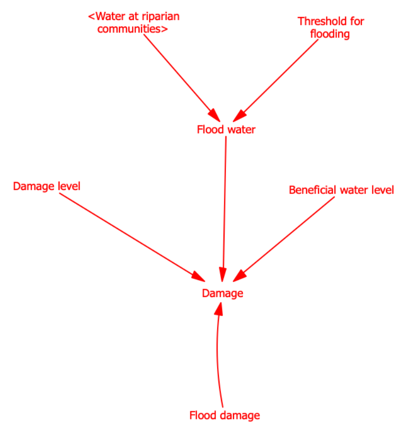


Figure 4.3: Sub-model: Damage

4.2 Riparian Ponds

Now that the sub-models regarding the White Volta River system have been discussed it is time to narrow down the scope further and examine the riparian ponds and communities more closely. First the riparian ponds will be discussed. These ponds are on the outer banks of the river and will fill up with water during the wet season, as the water recedes the ponds will be closed off from the river (Johnston & McCartney, 2010). The riparian ponds play a role in certain EBA of the riparian communities like fishing and livestock (Mul et al., 2017; Miescher, 2021), while also having a spiritual value to animists as the crocodiles at the riparian ponds are believed to be the riparian communities ancestors (Mul & Gao, 2016; Insoll & Kankpeyeng, 2014).

4.2.1 Fish

The riparian ponds are important for fishing (Gonzalez et al., 2021), as fishing in a pond is easier than fishing in the river. Fish will swim or be transported into the riparian ponds during the wet season when the river flows over the outer banks onto the flood plains and riparian ponds. Here some fish species breed and the ponds act as nursery habitats. However once the water recedes and the ponds get closed off there is no way for the fish from the pond to the river. This means the fish stock provides an easy catch for the riparian communities. The riparian communities have specific regulations regarding the fishing in the riparian ponds. Fishing at the riparian ponds is only allowed at the end of the dry season as other food sources are getting more and more scarce (Mul et al., 2017). This also gives the fish the time to grow bigger, which means there is more fish protein for consumption. Ultimately, fish can also be eaten by crocodiles that also swim in the riparian ponds, or lie on the outer banks. This whole system can be seen in figure 4.4 below. Another aspect that should be borne in mind when considering fish is that the construction of the dam will affect the population. As the dam will of course change the flow of the river, but also because the dam will make it impossible to swim further upstream (Wu et al., 2019).

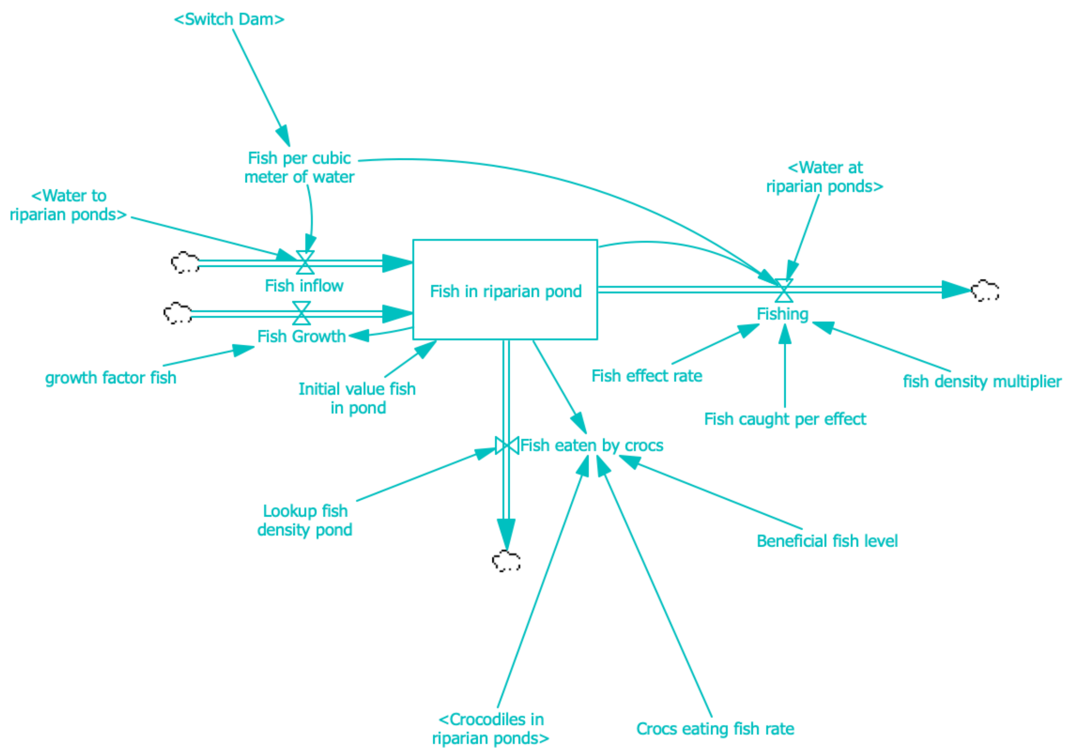


Figure 4.4: Sub-model: Fish

4.2.2 Crocodiles

Fish are not the only species that can move from river to ponds during a flood. Crocodiles can also do this, however a big contrast is that crocodiles can move back on land which means that they will never get stuck at a pond. This can also be seen in figure 4.5 below, where there are flows from both the river and the ponds stock going into the other stock. These movements are dependent on the amount of water, since crocodiles prefer to be in water, or at least close to water. This means that when the water level at the ponds is declining it is reasonable to suggest that the crocodile population at the ponds will decline as well. The EBA of the riparian communities are not dependent on the crocodiles at the ponds, crocodiles might only eat some of the fish. Nevertheless, the crocodiles do have a big spiritual value to the riparian community. This has to do with the fact that it is widely believed that one of the community's late ancestors has been reincarnated into a crocodile living at the riparian pond (Mul et al., 2017). This means that the crocodiles that live at the riparian ponds are considered as their ancestors and people and the crocodiles live peacefully side by side (Insoll & Kankpeyeng, 2014). Crocodiles in the river however, are considered dangerous.

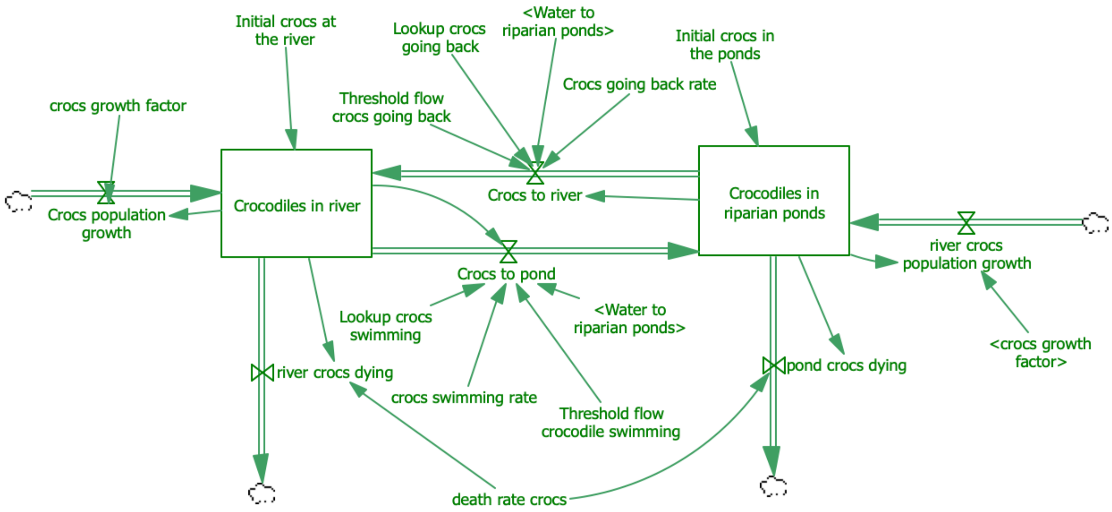


Figure 4.5: Sub-model: Crocodiles

4.3 Riparian Communities

Ultimately, it is time to look more closely at the riparian communities, with special regard to the EBAs that are dependent on the water provided by the river (Mul et al., 2017). First it is important to look more closely at the population of the riparian communities. Once there is a better view of this it is time to look at their EBA which are mainly concerned with farming, fishing, and keeping livestock.

4.3.1 Population

The sub-model of the population of the riparian communities, figure 4.6, is not much different from any other population model. The population can decline and grow by a death and growth rate respectively. These rates are dependent on the amount of food and water that is available to the population, meaning that if these resources are scarce, the death rate will increase and the growth rate will drop. One more aspect that needed to be added to the sub-model about the population is the casualties that can be caused by a flood (Baah-Kumi & Ward, 2020; Asare-Kyei, Forkuor, & Venus, 2015). In order to calculate the number of casualties a function similar to the damage in figure 4.3 was used. This means that the higher a flood the higher the flood death rate will be, this number is then multiplied by the population to estimate the number of flood casualties during a certain flood.

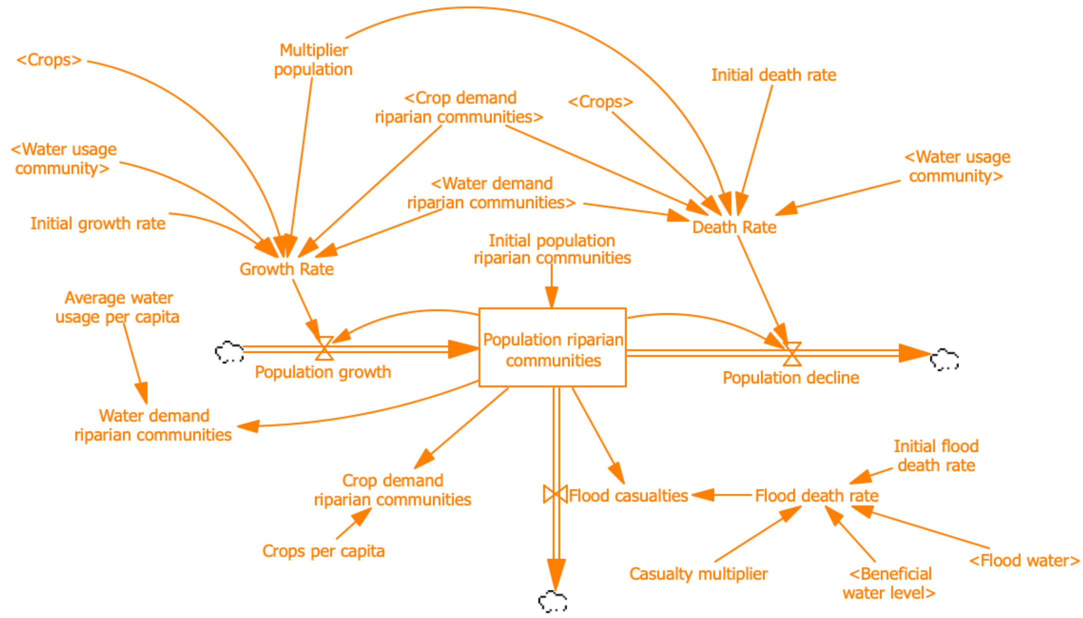


Figure 4.6: Sub-model: Population Riparian Communities

4.3.2 Farmland

Farming is one of the most important EBA at the riparian communities, agriculture is the main source of food and most of the community works in the agricultural sector (Ampadu et al., 2017; Cornille et al., 2022). Farming can be divided into three different types: Flood-recession, rainfed and irrigation (Balana, Sanfo, Barbier, Williams, & Kolavalli, 2019). In the farmland sub-model in figure 4.7 the trade-off between irrigation and rainfed farming can be seen. This trade-off depends on the amount of water available for agriculture. If there is insufficient water for irrigation the farmland will be used for rainfed agriculture which needs less water (Fontaine et al., 2019; Abungba Ayiiwe, 2013). A bigger area of farmland will of course lead to a higher number of crops, which can be seen in the next section. Moreover, the construction of the PMD would lead to a higher base flow of the river while also reducing the severity of floods which could be optimal for irrigation farming (Mul & Gao, 2016).

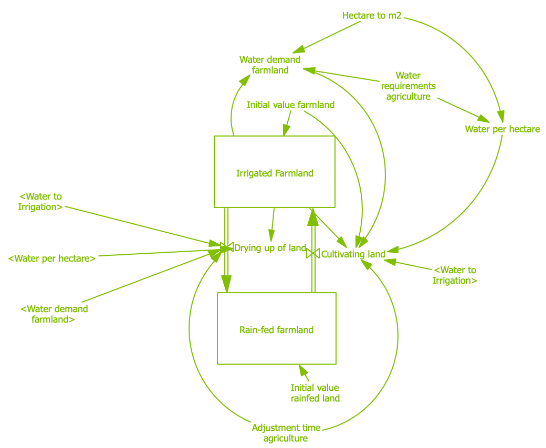


Figure 4.7: Sub-model: Farmland

4.3.3 Crops

Now that the sub-model regarding the farmland has been discussed it is time to look more closely at the sub-model of the crops grown on the farmland. Which can be seen in figure 4.8. Rainfed, flood-recession and irrigated farmland are all within this sub-model as the system of crops growing on a certain area of farmland is the same for all three types of agriculture (Balana et al., 2019). In Vensim subscripting can be used for this. In the sub-model it can be seen that the the model of crops looks quite similar to the sub-model of the population. Crops can be planted and harvested, the amount of crops planted is dependent on the area of the farmland which is dependent on the amount of available water. Then after a certain time the planted crops will be harvested. Another aspect of this sub-model is the loss of crops due to floods. This function is similar to the casualties function in figure 4.6, meaning that if a flood reaches a certain height some crops will be lost and the higher floods get the more crops will be lost. It can be expected that the construction of the PMD will decrease the severity of floods (Miescher, 2021; Gonzalez et al., 2021).

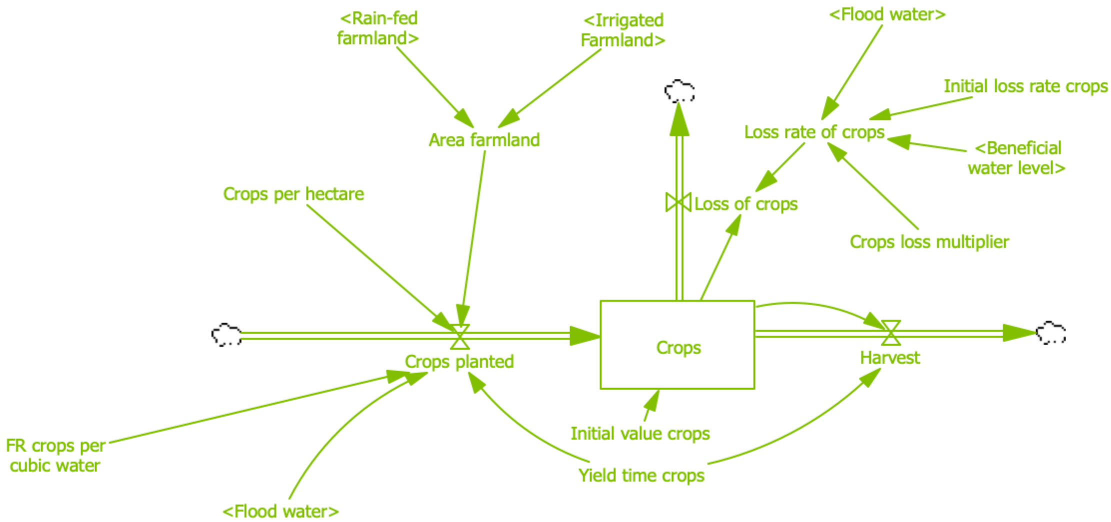


Figure 4.8: Sub-model: Crops

4.3.4 Livestock

The final sub-model is about the livestock that is kept by the people at the riparian communities. Keeping livestock is one of the main EBAs of the people at the riparian communities besides farming (Abungba Ayiiwe, 2013). Livestock can provide food and can be sold at the local market for money (Mul et al., 2017). The sub-model of livestock, which can be seen in figure 4.9 underneath, is again just like a population sub-model. The livestock population can either grow or decline based on the growth and death rates of the livestock. Livestock will do a lot of grazing on the floodplains as these are very fertile once the floodwater recedes (Slinger, 1988). This increase in fertility will improve the health of the livestock greatly and will lead to higher growth rate and lower death rate of the livestock (Ampadu et al., 2017). Additionally, the livestock can decline in two other ways as well, as livestock can either be sold or livestock can drown during a flood. Livestock selling depends on the livestock population. It can be assumed that if the livestock population rises more livestock will be sold and that when the population is low the people at the riparian communities will not be too keen on selling their livestock. Additionally, livestock can also drown, which is similar to the flood casualties and the loss of crops discussed previously. This means that when a flood reaches a certain level it will cause livestock to drown which would reduce the livestock population as well. Again the construction of the PMD will probably reduce the number of livestock drownings (Cornille et al., 2022; Baah-Kumi & Ward, 2020).

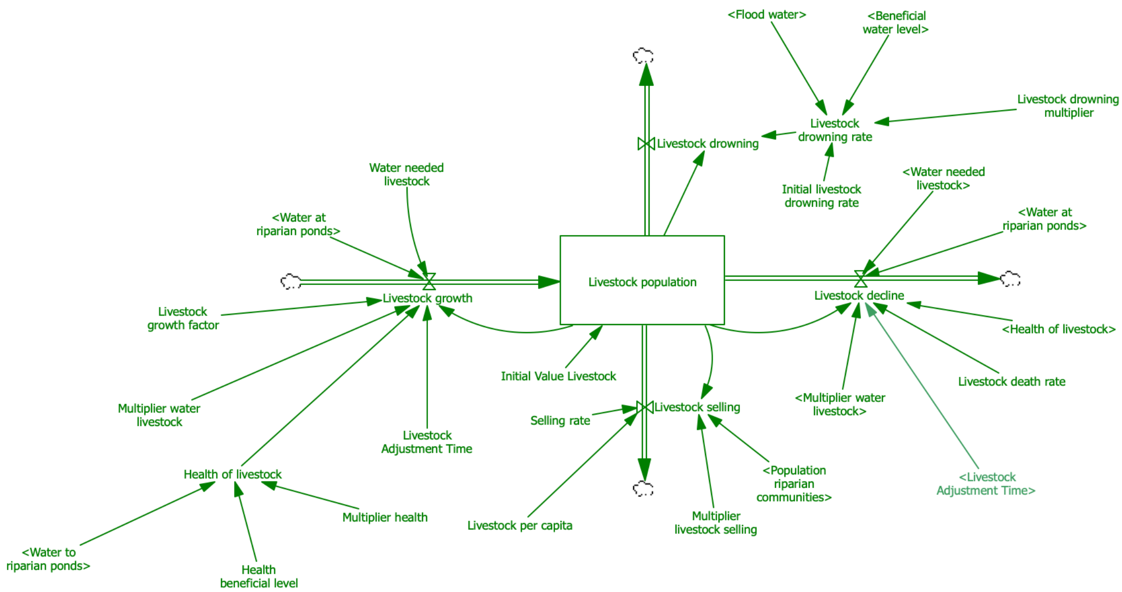


Figure 4.9: Sub-model: Livestock

4.4 Model Specification

Each element of the stock-flow diagram is specified either as a parameter value or in the form of an equation. The flows, specified in the form of rate equations, act upon the system accumulations, the stocks, to increase or decrease them. These effects are captured in difference equations, first order differential equations. System Dynamics modelling software is usually used for the specification of the model. In this case the modelling package Vensim PRO 9.1.1 was used.

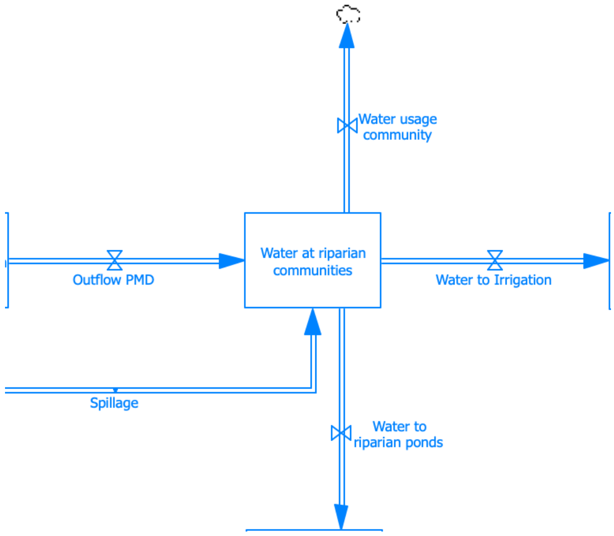


Figure 4.10: Stock Flow Diagram of Water at Riparian Communities

The stock-flow diagram represents the underlying difference equation, which is then solved numerically to obtain a pattern of response over time for each variable (see section 5.1 on integration, and the simulation run in section 4.5). For example, the stock "Water at riparian communities",represented in figure 4.10 above, the underlying equation of that stock can be formulated as:

$\frac{d}{dt}$(Water at riparian communities) = Outflow PMD + Spillage - Water usage Community - Water to riparian ponds - Water to irrigation

This shows that the value of the different stocks are mainly calculated by the difference between the inflows and the outflows over time, representing a convenient way to model river systems.

4.5 Run without Dam

Now that the model has been formulated and specified, simulations can be performed. Prior to this however, a few validation test are performed which are represented in the first three sections of chapter 5. Before the dam was incorporated into the model, the model was first simulated without the dam to see what the system behaves like now. This will help with validation to check if the behaviour is similar to the current behaviour of the system.

4.5.1 Riparian Communities

Without the dam the riparian communities show a slight increase in population over time. The graph of the flood casualties shows a more interesting behaviour. As it can be seen that every year the number of total flood casualties rises. This comes from the fact that the model simulates an annually recurring flood and without the PMD to mitigate these floods there may be flood casualties every year. The graph shows that every year the total flood casualties increases by approximately twenty. This is realistic as this can also be seen in the figure on flood damages in the Northern Region of Ghana over the last few years in figure 1.1.

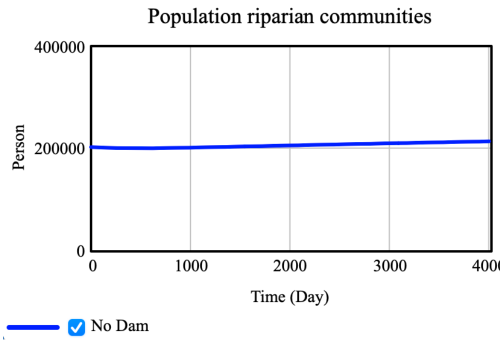


Figure 4.11: No Dam: Riparian Population

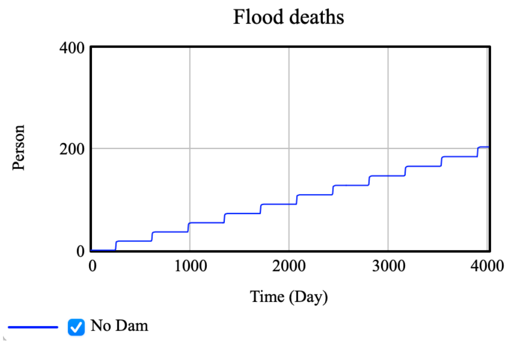


Figure 4.12: No Dam: Flood Casualties

4.5.2 Riparian Ponds

When looking at the riparian ponds it can be seen that without the dam the behaviour of the fish caught and the crocodiles at the riparian ponds is in dynamic equilibrium, with numbers rising in response to the flooding of the ponds every wet season. These graphs show the seasonality of the system. So are all the fish caught at the end of the wet season and after that they have to wait a full year for the next catchment (Mul et al., 2017). The graphs regarding the crocodiles at the riparian ponds shows that in the wet season the percentage of crocodiles at the ponds increases and that once the water recedes again more crocodiles move back to the river and the percentage falls again.

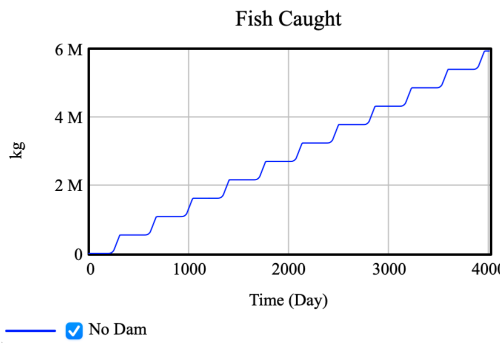


Figure 4.13: No Dam: Fish caught

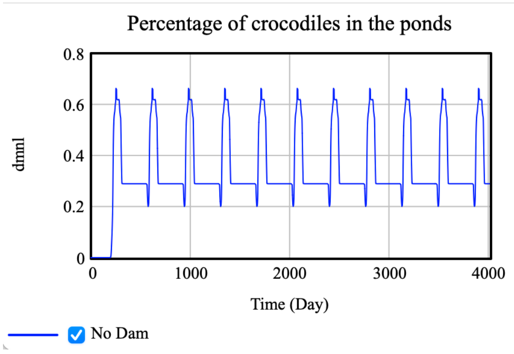


Figure 4.14: No Dam: Crocodiles

4.5.3 Farmland

Just like the riparian communities population, the livestock population behaves rather steady, while there are some fluctuations which are probably caused by livestock drowning due to floods in the wet season as there is no dam to mitigate the floods. As there is no dam, the area for irrigation won't increase either. This means that the percentage of irrigated crops fluctuates somewhere between 10% and 20%. These fluctuations are caused by the seasonality of rainfed and flood-recession farming which can only occur as the flood water recedes. At the start of the graph the number is a little higher as the simulation starts in January, which is the dry season, which means there is not sufficient water available yet for rainfed and flood-recession farming to harvest crops.

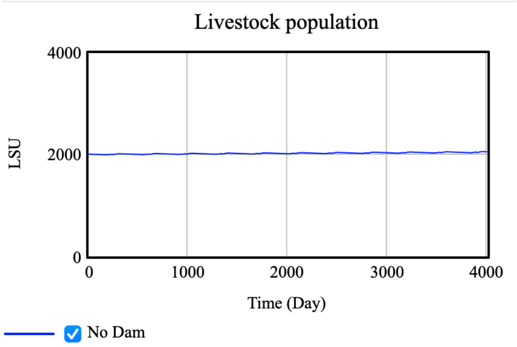


Figure 4.15: No Dam: Livestock Population

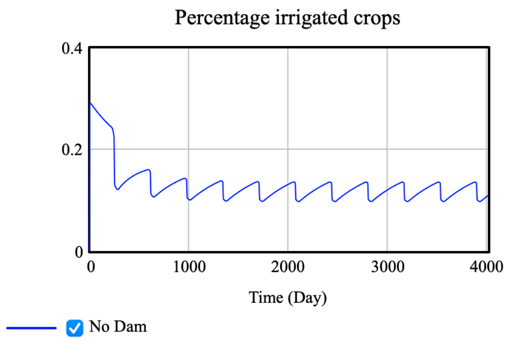


Figure 4.16: No Dam: Crops

4.6 Base Run

At this stage the model has been conceptualised, specified and simulations without the PMD have been conducted. These indicate that the system is in a dynamic equilibrium with annual fluctuations in agriculture, fish caught and crocodile numbers in response to the annual flooding of the floodplain. The population of the riparian communities and their livestock rises slightly over time despite some loss of life owing to floods. Accordingly, a base run that includes the construction and operation of the PMD can now be undertaken. The base run will give insight into how the model behaves under normal conditions and without any dam operating strategies in order to see whether this behaviour is plausible and if the model can be used for further analysis. This section examines the behaviour of the different criteria in the model. Which are derived from the system diagram in figure 3.3.

4.6.1 Dam

The first criteria is the amount of water at the PMD reservoir. This is an interesting variable to look at as this is the factor that affects all the other criteria within the model. Where the water would normally just flow straight through the riparian communities it now is stored in the reservoir of the PMD. As it is expected that the dam will be operational in 2026, it is modelled that the dam starts filling the reservoir after five years. This can be seen in the figure on the right as well. First all the water is stored but once a certain level in reached some water will be passed through further downstream. The graph also shows that after around ten years of filling the water level at the dam will reach and equilibrium, with only some oscillations caused by the rainy season. This filling time is significantly higher than the one year filling time that the VRA aims for (VRA, 2022). This comes from the fact that in the model some water passes through even when the dam is filling to reduce the harmful effects felt by the riparian communities.

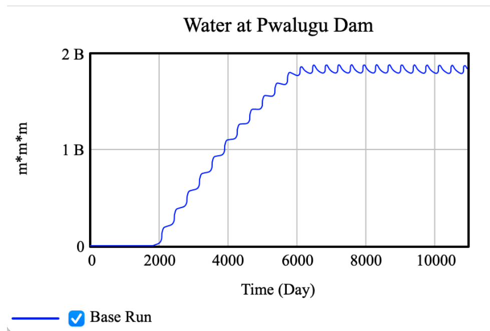
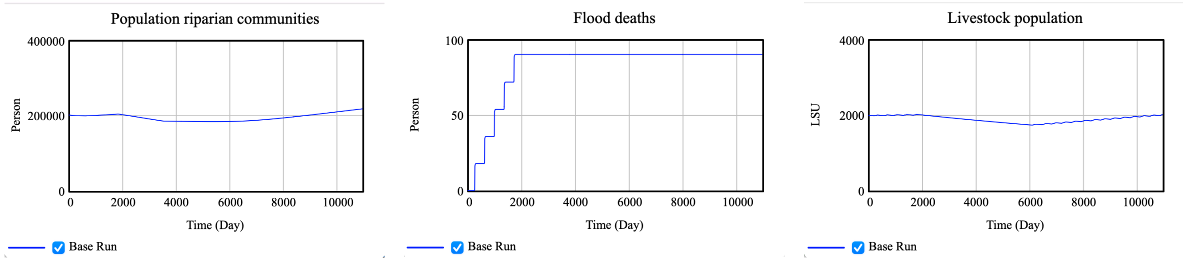


Figure 4.17: Base run: Water at PMD

4.6.2 Riparian Communities

When looking at the riparian communities there actually are three KPIs to taken into close consideration. First, it can be seen that the population is slightly increasing until the dam starts filling and storing the water. This reduction of water available causes the population to drop, once the dam is fully operation the population increases slightly again. Looking at the flood casualties it can be seen that when there is no dam there will be some casualties every year. Which is in line with what happened the last few years (Shown in figure 1.1). Once the dam is constructed there won't be any flood casualties anymore. The livestock population shows a similar pattern to that of the riparian population as it will decrease whilst the dam is being filled and rises again once the dam is fully operation.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure 4.18: Base run: Riparian Communities

4.6.3 Riparian ponds

The construction of the PMD could also affect the filling of the riparian ponds. As the riparian ponds depend on seasonal flooding in order to be filled, the construction of the dam reduces the water level at the ponds. This can also be seen in the number of fish caught at the riparian ponds, whereas before the construction of the PMD a lot of fish were caught, there are less fish caught once the dam is operation. During the filling time there are not even any fish being caught as the riparian ponds will be empty. The number of crocodiles at the ponds also drops due to the construction of the PMD as there is less water at the riparian ponds. Crocodiles are less affected by this however, as they can move more freely between the river and the ponds than fish.

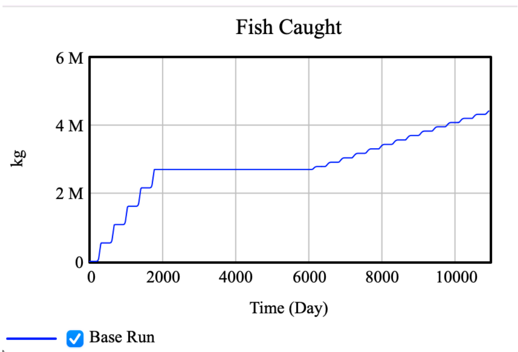


Figure 4.19: Base run: Fish caught

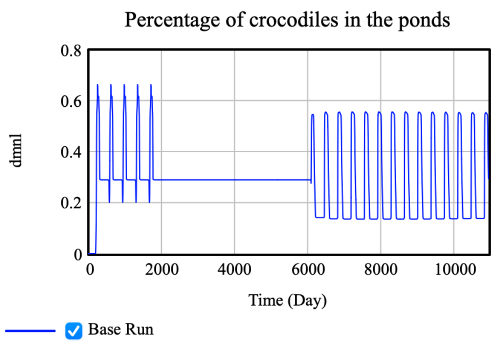


Figure 4.20: Base run: Crocodiles

4.6.4 Farmland

Ultimately, the KPIs regarding the farmland must be considered. Both KPIs show similar behaviour which means that both the percentage of farmland that is used for irrigation as well as the percentage of crops that is grown from irrigated farmland behave in the same manner. Which seems plausible. Both the area of irrigated farmland and the number of irrigated crops will rise drastically once the dam operation. This comes from the fact that the dam increases the base flow of the river. Thus, making it possible to do irrigation farming as there is a year round water supply. The percentage of crops rises more than the percentage of farmland as irrigation is more efficient than rainfed or flood-recession farming. Meaning more crops are grown per area of farmland.

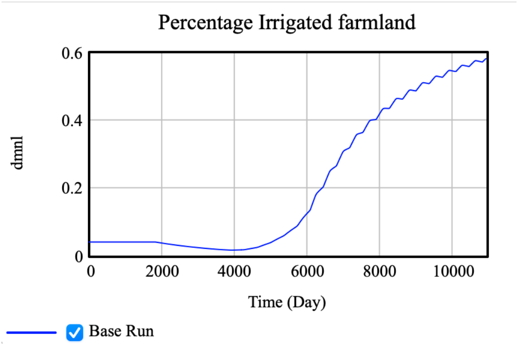


Figure 4.21: Base run: Farmland

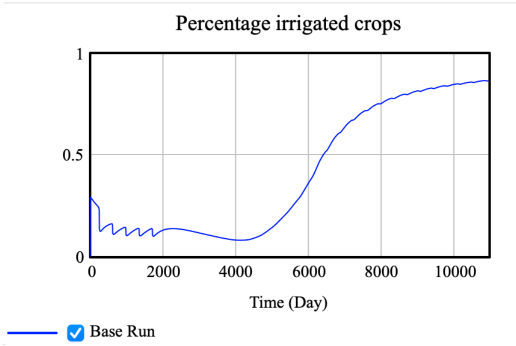


Figure 4.22: Base run: Crops harvested

5 Validation & Verification

Before experiments can be done with the model it is important that the model first is validated and verified. Validation is about checking whether the outputs of the model are in line with real data and that it does not create physically impossible output (G. Coyle & Exelby, 2000). This can be about the structure of the model as well as the behaviour (Barlas, 1989). The base run and the run without the dam, discussed in the previous chapter, will be examined to check if the model is valid. Verification, on the other hand, is mainly about whether the constructed model is in line with the specific modelling rules and that it grasps all the aspects of the conceptual model (Mirchi, Madani, Watkins, & Ahmad, 2012). There are several test that can be performed to validate and verify the model. These tests will be discussed in this chapter.

5.1 Boundary Adequacy

The boundary adequacy analysis investigates whether the concepts that are modeled are actually within the boundaries of the system (Senge & Forrester, 1980; Zhao et al., 2022). In this research the system boundaries are defined from the inflow of the PMD until the river water has passed through the riparian communities and the possible irrigation scheme. This can also be seen by the dashed line in the System Diagram in figure 3.3. This means that the operation of the upstream Bagre Dam can be considered an external factor and that electricity generation at the Akosombo Dam is not taken into account either. Another aspect that is important when regarding the boundary adequacy of the model is that all the KPIs are coming from within the system boundaries (Zhao et al., 2022). The KPIs in this model include the ecosystem-based activities of the people at the riparian communities as well as the hydropower generation at the PMD and the number of casualties and damage caused by flooding. All these KPIs are heavily dependent on the flow of the river and the whole system surrounding it. This means that all the KPIs are well within the system boundaries set at the start of this research. These KPIs can also be found on the right side of the System Diagram in figure 3.3.

5.2 Dimensional Consistency

Another way to verify the model is with a dimensional consistency test (Senge & Forrester, 1980). Dimensional consistency means that all the variables that are used within the model are defined with an appropriate dimension (R. G. Coyle, 1997). For instance, the variable inflow at the PMD has the dimension cubic meter per day (m^3/day). It is important that with all the calculations within the model the right units are still used. Vensim has a built-in function to check whether all the units within the model are correct. However, just running this test is not sufficient to verify as Vensim only checks for consistency between the left and right hand sides of an equation. This makes it important that all the variables also have a physically realistic and suitable unit. Manually checking this did not come up with any dimensional inconsistencies.

5.3 Integration Method and Time Step

When constructing a proper functioning model it is important to check if the integration method and the time step are correct. Regarding integration method, Vensim has two built-in options: Euler and Runge-Kutta4 (RK4). RK4 is considered more precise than Euler, unless Euler uses a very small time step (Islam et al., 2015). Moreover, RK4 is best for models that also have continuous derivatives, while Euler works better when the derivative is not always continuous (Pruyt, 2013). An example of a non continuous derivative is that in the constructed model after five years the dam will start storing water. These discrete derivative functions will lead to accuracy failures when using RK4 (Islam et al., 2015), that is why for this model Euler is a suitable method.

Once the integration method has been chosen it is still of importance to combine this with an appropriate time step. To determine this multiple runs have been done with different time step as can be seen in the figures underneath. Figure 5.1 shows that all the different time steps lead to similar behaviour of the model. However, when zooming in, as is done in figure 5.2, it can be seen that there are actually differences in accuracy between the different time steps. A time step of 0.03125 was considered the most accurate. This means that every 0.03125 day the model calculates all the outcomes and then plots all these different outcomes at the end. Nevertheless a time step this small has an extended simulation time. This is why a time step of 0.0625 days was chosen as it was almost as accurate and had a shorter simulation time.

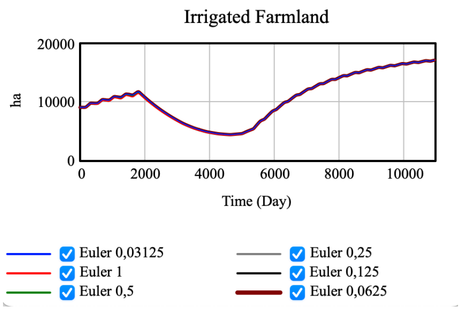


Figure 5.1: Model run with different time steps

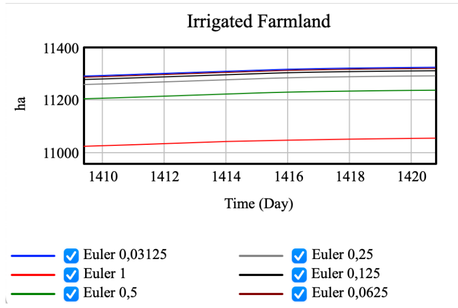


Figure 5.2: Different time steps zoomed in

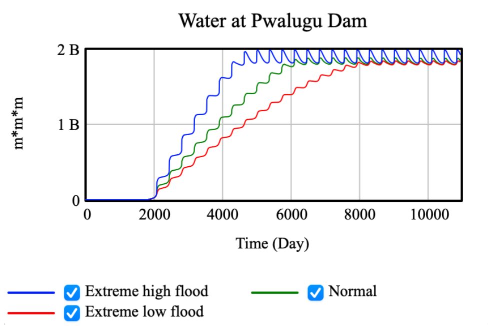
5.4 Extreme Conditions

To validate the model, an extreme conditions test was performed (Schwaninger & Grösser, 2020). During such a test, an extreme value will be chosen for a certain parameter and the model will be ran under these conditions (Senge & Forrester, 1980; Qudrat-Ullah & Seong, 2010). The extreme conditions test is performed for the eight parameters shown in table 5.1 underneath.

Parameter	**Unit**	**Value**	**MIN**	**MAX**
Average Water Usage Per Capita	$(m^3/day)/person$	0,007	0,0002	0,2
Fish caught per effect	kg	300	100	900
FR crops per cubic water	$quintal/m^3$	0,05	0,01	0,5
Livestock growth factor	$dmnl$	0,00225	0,001	0,01
Normal Flood	m^3/day	1,00E+07	0	3,00E+07
Threshold flow crocs going back	m^3/day	300000	10000	800000
Value for Pond Flooding	m^3	400000	10000	800000
Water requirements agriculture	m/day	0,002	0,0009	0,01

Table 5.1: Parameters and their extreme values

The purpose of the extreme conditions test is to investigate how the behaviour of the model changes under extreme conditions (Qudrat-Ullah & Seong, 2010). It is especially important to determine if the model still shows normal behaviour and that no physical laws are broken because of the extreme value. Figure 5.3 on the right shows



an example of an extreme conditions test, the one with the extreme high or low floods. You can see that the behaviour is still plausible, as the dam reservoir still fills up and does not go above the maximum value. The main difference is that with the extremely high inflow the reservoir fills more quickly. To see the results of the extreme conditions test of all the other parameters can be found in Appendix C.

5.5 Sensitivity Analysis

A sensitivity analysis is performed in order to gain insight into how sensitive the outcome variables are to changes in the input variables (Hekimoğlu & Barlas, 2010; Kleijnen, 1995). Sensitivity analysis shows how robust a model is. This is important, as the input variables can never be a 100 percent correctly determined, so you don't want the outcome variables to be affected by small changes in input variables. In a sensitivity test all the input variables are ranged from -/+ 10 percent of their normal values in the model. These values can all be found in the table in Appendix B in which the complete sensitivity analysis will be discussed for all the output variables.

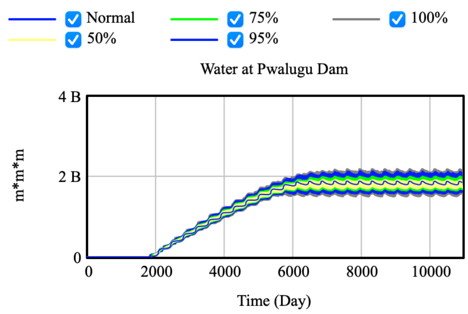


Figure 5.4: Sensitivity: Water at PMD

In figure 5.4 on the right, it can be seen that the water level at the PMD in the model is not affected much by changes in input variables, when the reservoir is filling up there is hardly any effect and once the reservoir is filled the input variables affect the level of the water slightly but not very significant. As the figure shows the range of the water level you can see that the water level at the reservoir is affected, but not too much and the behaviour is still plausible. This is true for all the different outcome variables as none of them are highly sensitive to changes in input variables. That means that the model can be considered robust, which is especially important as there are a number of uncertain input variables in the model.

In addition to the sensitivity analysis, a flow sensitivity analysis has also be conducted. A flow sensitivity analysis aims to depict how sensitive the stocks within the model are to changes in the flows. This analysis also showed that the model is robust and that the stocks are not very sensitive to changes in the flows. How the flow sensitivity analysis has been conducted and how all the different graphs looked can be seen in Appendix B

5.6 Validation Interviews

It is important that the structure of the quantitative model is aligned with the actual White Volta River system. To validate this, different validation interviews, summaries of which can be found in appendix E, were performed with multiple experts regarding either the rivers in Ghana or the construction of the PMD. These validation interviews helped to increase understanding regarding the White Volta River system and it was an effective method to check whether the quantified model does not contradict the working of the actual systems. These interviews showed that each of the sub-systems in the model (livestock, crocodiles, water flow etc.) had a structure and exhibited interactions similar to that understood as part of the real system by the interviewees. However, a model can't reproduce every detail of the system which means that there will be some inconsistencies. One of these inconsistencies is that the riverine communities are located above, below and alongside the dam site in reality, whereas in the model they are depicted as living below the dam. The same can be said about the riparian ponds, which are located straight after the dam in the model. This means that they can be located upstream, at the dam site and downstream of the dam. The drowning of some of the ponds by the filling of the dam is therefore not included in the model. Instead only the impact of the dam on downstream ponds is included. Apart from this the validation interviews showed that most of the quantitative model structure and interactions are consistent with the actual system. This means that the model can potentially give insights into the system behaviour, despite only providing a simplification of reality.

5.7 Historical Data Validation

The last test that is performed to validate the quantitative model is a historical data validation. This means that the data of the output variables in the model will be compared with historical data in order to check whether they are consistent. Unfortunately, due to the PMD not being constructed yet, there is not much historical data to which the model can be compared. However, the interview at the PMD directorate provided interesting information on potential flood casualties when hydropower is optimised (Figure 5.5) which could be compared to the model.

Figure 5.5 shows the calculation of the PMD directorate regarding the flood protection if the electricity generation would be optimised at the PMD. It shows that the dam will almost provide no protection from flooding anymore. This is also what the results of the model showed when hydropower generation was optimised in Figure 5.6. As with the full dam the number of flood casualties will increase significantly. This shows that the constructed model is in line with the analyses performed at the VRA regarding the effect of the construction of the PMD on flood casualties when electricity is optimised.

Protection against N-year flood	Required maximum Initial Water Level	Yearly probability to be protected
2-year flood	159 m asl	30%
5-year flood	Below MOL	0%
10-year flood	Below MOL	0%
15-year flood	Below MOL	0%

Figure 5.5: Flood protection electricity optimization (VRA, 2022)

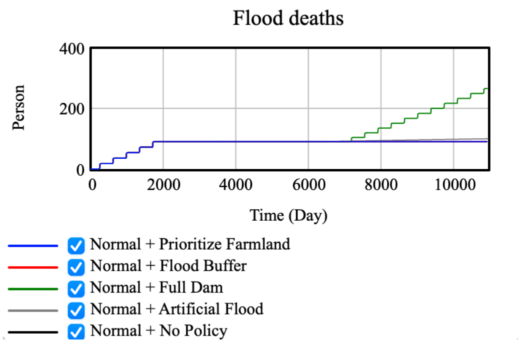


Figure 5.6: Flood casualties in model

Moreover, simulations without the dam were performed to validate the model. As the results of these simulations show in section 4.5, all the key performance indicators exhibit a dynamic equilibrium, where most of the indicators rise during the wet season when more water will be available and then will fall a little during the wet season to then rise again the following wet season. This dynamic behaviour is exactly what you would expect from a region that depends heavily on the seasonality of the river for their ecosystem based activities. The addition of the PMD, as can be seen in section 4.6, shows a disruption of this dynamic equilibrium as the construction and filling of the PMD will change the flow of the river and will store water. As explained in section 4.6 and above, these changes in behaviour can be considered plausible and make the model suitable for further experimenting.

6 Effects of different operation strategies under variable climate scenarios

Now that the model has been validated and verified, it can be used for experiments in order to get a better overview of how different operation strategies will work out under different circumstances. To be able to do these experiments it is first important to construct an experimental design to show what the experiments will look like and which variables will be changed throughout them. For this a list of circumstances has to be established as well as a list with different operation strategies. The combination of a certain operation strategy and a certain circumstance will form an experiment. However, it is also necessary to set up a list of key performance indicators. These are the variables that you are interested in to see how they are affected by different operation strategies or circumstances. The different operation strategies as well as the key performance indicators can be seen in the system diagram which is discussed in section 3.5. Once all these different aspects of experiments have been discussed it is time to analyse the results, first the different dam operating strategies are discussed and after that the different climate change conditions, for both scorecards are generated.

6.1 Climate scenarios

Nothing is as hard to predict as the weather is (Ndamani & Watanabe, 2015). Tomorrows weather is already difficult to predict with 100 percent certainty let alone the weather of the coming thirty years. This high unpredictability of the weather means that it is necessary to come up with different climate scenarios in order to check the effect of the different operation strategies. This lead to the following climate scenarios.

Scenario	Annual Decrease	Annual Increase	Seasonality		
	Decrease (25%)	Increase (25%)	Dry Season decrease (-20%)	Wet season increase (+50%)	Flood increase (200%)
Normal	-	-	-	-	-
Wet	-	x	-	-	-
Dry	x	-	-	-	-
Climate Change	-	-	x	x	x

Figure 6.1: Different climate scenarios

Four different scenarios were chosen for the simulations. The first one is the "normal" scenario, which means that the average water flow over the last few years has been used. This normal scenario has been used for the base run and is also the base on which all the other scenarios have been developed. The wet scenario follows the same pattern as the normal scenario, however the water flow will be increased by 25 percent. The dry scenario, on the other hand, decrease the normal flow by 25 percent. The final scenario is climate change, as it is commonly known that climate change has a huge effect on the weather. Climate change leads to more extreme weather, this means that it won't simply lead to more or less water in the river but it leads to more seasonality (Tangonyire et al., 2019; Miescher, 2021). This has to do with the fact that it will cause more extreme droughts while also causing more prolonged periods of heavy rainfall (Amisigo et al., 2015; Kwakye & Bárdossy, 2021). This can also be seen in the table as in the climate change scenario the river flow will decrease in the dry season while it will increase in the wet season. Additionally, it was chosen to increase the volume of the annual flood during a climate change scenario.

6.2 Dam operation strategies

Now that the different climate scenarios have been discussed it is time to take a closer look into the different dam operation strategies. While determining possible dam operation strategies it must be considered that certain strategies won't be able to be implemented in the model. Take for example a better cooperation with Burkina Faso, this cooperation would lead to less unexpected high spillage at Bagre Dam (Amuquandoh, 2016). However, since this is outside the scope of the model it was not taken into account. The dam operation strategies that could be implemented in the model and that would be interesting to further investigate are shown in figure 6.2 below.

Strategy	Change in model	Description
No strategy	No Change in model	This strategy is added so it can be used as a reference run. This is a run of the base model and will give an idea of how much certain policies affect the outcomes of the model
Full Dam	Maximum dam capacity is 1.1 NOT 0.85	In this strategy the dam reservoir will be filled entirely. The main advantage of this is that it can generate a lot of hydropower, however it makes the dam more prone to flooding.
Flood Buffer	Maximum dam capacity is 0.65 NOT 0.85	This strategy focuses mainly on flood mitigation, a way to mitigate floods would be by filling the reservoir only to a certain level and leaving the rest of the capacity to act as a buffer in case of a flood.
Prioritize Irrigation	Demand water farmland * Maximum farmland NOT farmland	When operating the dam, the focus could also be on optimizing irrigation. This could mean that the dam will make sure enough water will be let through to make irrigation farming possible.
Artificial Flooding	Extra pulse to outflow	This strategy tries to copy the current flow of the river as it is of big importance to the riparian communities. This will mean that once a year the dam has a big outflow for the floodplains to be able to flood and for riparian ponds to fill, which will have beneficial effects on livestock and on flood-recession farming.

Figure 6.2: Dam operation strategies

The table above shows that all the different dam operation strategies have another main focus, and this already gives an idea on what kind of trade-offs there will be when operating the dam.

6.3 Key Performance Indicators

Now that both the different climate scenarios, as well as the different dam operating strategies have been discussed it will be time to look more closely at which output variables would be interesting for further investigation. Where the climate scenarios and the policies can be considered as input, it is now time to have a look at the output. Looking at the different output variables will give an idea of how different conditions and different dam operating strategies affect the outcomes of the model. The most interesting outcomes of the model are considered Key Performance Indicators (KPI) these will be critical indicators to have a look at how they are affected by conditions and or policies. The KPIs for this research can be found in figure 6.3 below. They will be discussed in the following subsections.

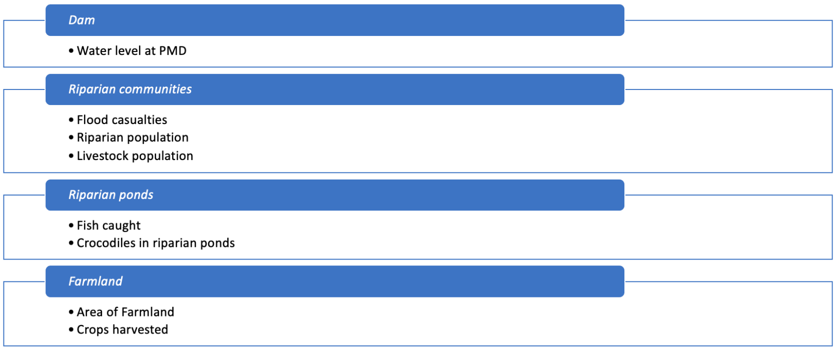


Figure 6.3: Key Performance Indicators (per category)

6.3.1 Water level at PMD

The water level of the PMD reservoir can be considered a KPI as it is a critical value in the model. There are multiple options when filling a dam reservoir and depending on the goal different strategies can be used. For example electricity generation. To generate as much hydropower as possible it would be necessary to keep a high water level at the dam reservoir in order to keep the outflow, which generates the hydropower, high enough (Hunt, Byers, Prenner, & Freitas, 2018). However, if you look at flood mitigation it might be better to keep a flood buffer in the reservoir so it can decrease the severity of floods (Wallington & Cai, 2020). While for the ecosystem surrounding the dam it would be better to recreate the environmental flows (Richter & Thomas, 2007). All these different options make it interesting to see how the water level at the reservoir will be affected by the different dam operation strategies and or the different climate scenarios. This will also provide an interesting outcome variable to compare with other KPIs to see possible trade-offs.

6.3.2 Riparian Population

When looking at the riparian population there are multiple KPIs that should be taken into consideration. First of all it would is interesting to look at the population stock, which will show how the population number will rise or fall over time. It is interesting to see how certain conditions or dam operating strategies affect this and what conclusions can be drawn from this. The second KPI is already taken into consideration in the first one but is also interesting to take into consideration as its own. One of the main goals of the PMD will be flood mitigation (VRA, 2014). This means that the flood casualties outcome variable would be an interesting one to take into account. As the dam should lower the number of flood casualties drastically, however which policy helps reduce the number the most? And could extreme weather caused by climate change lead to an increase of flood casualties? Ultimately, when looking at riparian communities, it would be interesting to look at how the livestock population at the riparian communities will be affected by the construction and operation of the PMD. As the flood plains are an important nutrient resource for the livestock an if these floodplains don't flood anymore this increase in nutrients can get lost which could reduce the quality of the livestock (Karbo & Agyare, 2002; Cornille et al., 2022). So it would be compelling to see how the livestock population behaves in the different experiments.

6.3.3 Riparian ponds

The riparian ponds are of great use to the riparian communities, they don't only hold economic values in the fish that are trapped inside them (Gonzalez et al., 2021), but also have a spiritual value as it is a appealing location for crocodiles to site (Insoll & Kankpeyeng, 2014). These crocodiles have a big spiritual value to the inhabitants of the riparian communities (Mul et al., 2017), and if the flooding of riparian ponds would stop, meaning less crocodiles will come visit, it could have a detrimental effect on the riparian communities. That's why the percentage of crocodiles at the ponds can be considered a KPI. The fish population is also an important food source, especially at the end of the dry season (Gonzalez et al., 2021). However, the fish will need to be able to flow into the riparian ponds. This means that if the dam will drastically reduce flooding of the riparian ponds, fish won't be able to reach the riparian ponds (Johnston & McCartney, 2010). This makes it way harder to local fishers to catch them as catching fish from the river is harder than catching them from the ponds. These two KPIs will give a great insight into the value of the riparian ponds and will also help with showing the trade-offs between having just a higher base rate and the occasional flooding.

6.3.4 Farmland

Finally it is interesting to get an insight into the performance of the farmland under different circumstances. This will be done with two different KPIs first of all it would be compelling to look at the percentage of farmland that is irrigated. As one of the benefits of the construction of the PMD will be to increase the irrigated farmland (Cornille et al., 2022; Miescher, 2021). It would be interesting to see how this hold up under the different operation strategies and conditions. Second reason why this KPI will give great insight has to do with the fact that inside the KPI is already the trade-off between national and local as irrigation will probably benefit the national economy the most while the local communities depend more on rainfed or flood-recession farming (Ampadu et al., 2017; Balana et al., 2019). The other KPI that should be considered is the total crops harvested. As the different types of farmland all have different yielding rates and crops could be lost with floods it would give great insight to see how the total number of crops harvested changes throughout different experiments.

6.4 Runs With Different Dam Operating Strategies

Now that the conditions, policies, and key performance indicators all have been discussed, it is time to start running the model to see how different conditions and policies affect the different indicators. To be able to really see the distinction between the different dam operating policies the policies are ran under the normal conditions so they can be compared to each other. This means that the five different dam operating strategies will be implemented in the model and the model. The effects these different operating strategies have on all the KPIs discussed in the previous section will be examined in this section. All the different operating strategies have also been ran under different climate scenarios, this can be found in appendix F

6.4.1 Dam

The first KPI is the amount of water at the PMD reservoir. The figure on the right shows that the filling of the PMD reservoir, which starts after 5 years, is not affected by different operating strategies. However the water level at the PMD is affected greatly. The full dam policy will lead to the highest water level at the PMD as this is the aim of the policy in order to generate as much hydropower as possible. The flood buffer and prioritise farmland policies lead to a significantly lower water level compared to the run without any policy. This has to do with the fact that the flood buffer policy focuses on keeping the water level below a certain value to mitigate floods while prioritizing farmland will lead to a lot

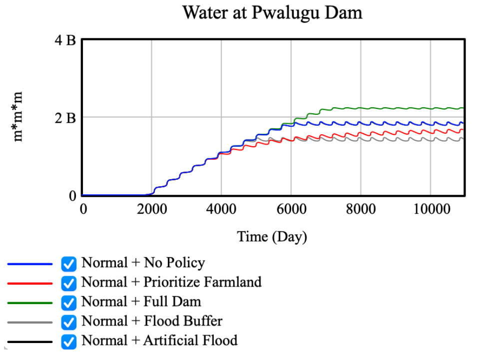
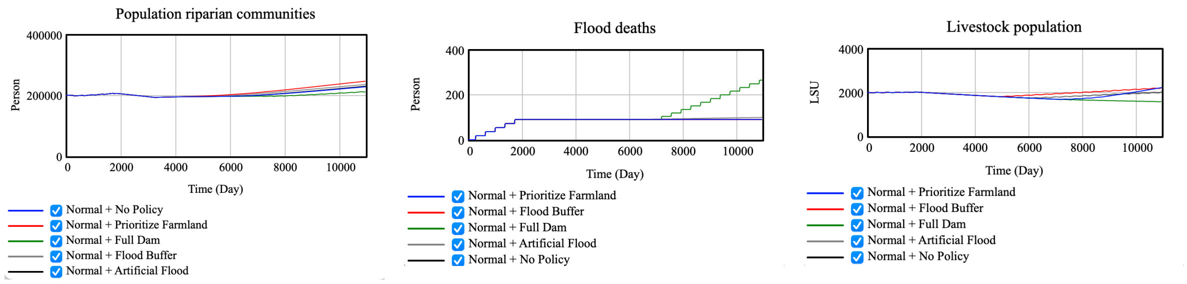


Figure 6.4: Water at PMD

of outflow as more water will be needed to increase the
area of irrigated farmland.

6.4.2 Riparian Communities

When looking at the riparian communities there actually are three KPIs to taken into close consideration. First, the graph of the population at the communities show that all the the prioritizing of the farmland will be the most beneficial for the riparian communities, as this will probably lead to more food security. All the other dam operating strategies also cause the population number to rise slightly, after it decreased during the filling of the reservoir. The full dam policy will lead to the lowest population growth which probably comes from the fact that less water will be available at the riparian ponds while it will also lead to an increase in flood casualties which the second figure shows. While the other dam operating strategies will reduce the number of flood casualties to almost zero once the dam is constructed. The third figure shows that the livestock population also declines with the full dam policy, as less water will be available downstream. On the contrary, all the other dam operating strategies will lead to an increase in the livestock population as it will benefit from the more steady flow of the river, despite the fact that it will be less likely that floodplains will flood which leaves very fertile grazing land.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure 6.5: Riparian Communities

6.4.3 Riparian ponds

Taking a closer look at the riparian ponds shows that none of the dam operating strategies will lead to an increase in neither the annual fish caught nor the percentage of crocodiles at the ponds compared to the the years without the dam. The years of filling tend to hurt the fish caught and crocodiles at the ponds the most as the filling of the reservoir will make it impossible for the riparian ponds to flood. The prioritizing of the farmland policy is the least beneficial for the filling of the riparian ponds, which will lead to lowest number of fish caught and the lowest percentage of crocodiles at the ponds. This comes from the fact that in order for farmland to be optimised the dam will have a high outflow which means that it will be less prone to flooding, so the floodplains and riparian ponds won't flood which means that no crocodiles or fish will be there. The flood buffer policies leads to a lot of fish caught as it will spill more water to keep the water level at the PMD below a certain threshold which means that floodplains and riparian ponds will flood. This also happens with the full dam policy as a full dam reservoir won't be able to mitigate flooding which means that flooding will still occur and floodplains and riparian ponds will flood too.

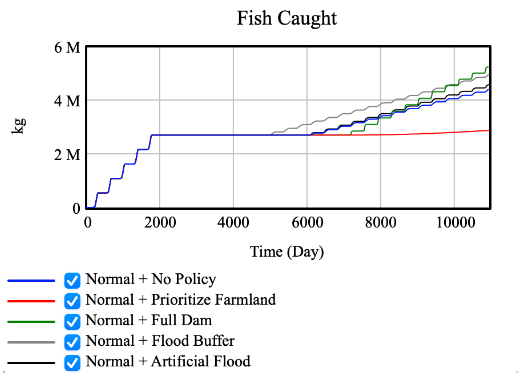


Figure 6.6: Fish caught

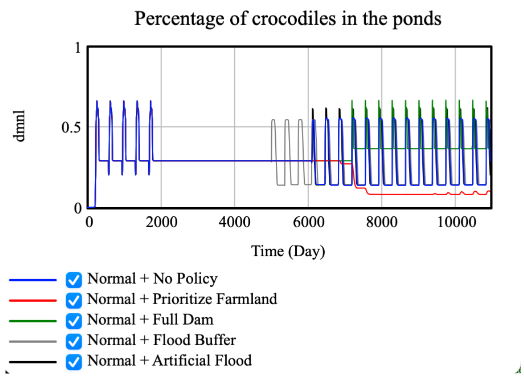


Figure 6.7: Crocodiles

6.4.4 Farmland

Ultimately, the KPIs regarding the farmland must be considered. For both KPIs the construction of the dam will be beneficial as the dam will lead to a higher base flow and will increase both the area of irrigated farmland as well as the number of irrigated crops. This value depends a lot on the outflow at the PMD which means that the policies with high outflow, the flood buffer and prioritizing farmland ones, lead to the highest increase of irrigated farmland and crops. The full dam policy, which will have the lowest outflow, leads to the lowest increase of irrigated farmland and crops as there won't be sufficient water available for a bigger increase.

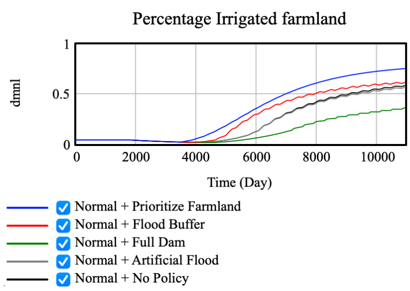


Figure 6.8: Base run: Farmland

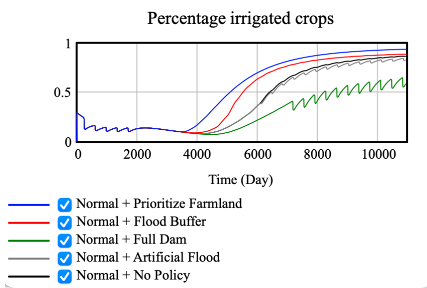


Figure 6.9: Base run: Crops harvested

6.4.5 Conclusion

As the model contains a wide variety of KPIs there is no dam operating strategies which will be beneficial for all indicators. This means that there will be trade-offs when looking at operating strategies. One of the trade-offs can be found in the fact that the irrigated farmland would benefit the most from a high base flow of the river which will mean that more water will be available to be used for agricultural purposes. The riparian ponds on the other hand, would benefit more from seasonal flooding as these are necessary to fill the ponds with water which will also carry fish and crocodiles to the ponds. Reducing the flooding of the riparian ponds completely means that the riparian communities will have less fish for food and will lose the spiritual value that the crocodiles have to them. So will a 30% increase of the irrigated farmland lead to 35% less fish and 65% less crocodiles at the riparian ponds. Another trade-off the operation of the PMD brings along is the one between electricity generation and flood mitigation. To optimise electricity generation the reservoir of the PMD needs to be at or close to the maximum capacity. However, this high water level reduces the ability of the PMD to absorb high inflow and thus won't be able to mitigate floods. It would probably even exacerbate the flood as the PMD will have to spill in order for the dam not to break. So will a 22% increase of the reservoir capacity will increase the number of flood casualties by 191% while also decreasing the irrigated farmland by 40% as there is less outflow.

Figure 6.10 underneath shows the scores of all the different dam operating strategies compared to the run without a policy. As national and local benefits are different, two scorecards are generated. So is it of national interest to generate much electricity, while also increasing the irrigated farmland as much as possible for commercial farming. The local communities would however, benefit more from the flooding of the riparian ponds for fishing, while an increase in commercial farming would be considered a loss to them. Reducing the number of flood casualties is a local as well as a national interest.

NATIONAL	Dam reservoir	Riparian population	Flood casualties	Livestock	Fish	Crocodiles	Farmland	Crops
No policy	100%	100%	100%	100%	100%	100%	100%	100%
Artificial Flood	100%	101%	111%	98%	104%	70%	97%	96%
Flood Buffer	76%	103%	100%	112%	113%	171%	105%	102%
Full Dam	122%	93%	291%	75%	119%	128%	62%	69%
Prioritize Farmland	81%	108%	100%	117%	65%	34%	128%	108%

LOCAL	Dam reservoir	Riparian population	Flood casualties	Livestock	Fish	Crocodiles	Farmland	Crops
No policy	100%	100%	100%	100%	100%	100%	100%	100%
Artificial Flood	100%	101%	111%	98%	104%	70%	97%	96%
Flood Buffer	76%	103%	100%	112%	113%	171%	105%	102%
Full Dam	122%	93%	291%	75%	119%	128%	62%	69%
Prioritize Farmland	81%	108%	100%	117%	65%	34%	128%	108%

Figure 6.10: Scorecard of different dam operating strategies

6.5 Runs Under Different Circumstances

Apart from looking at how the different dam operating strategies affect the KPIs within the model, it is also interesting to see how different climate scenarios affect them. In this section the four different climate scenarios will be discussed. To be able to compare them they were all ran without a dam operating strategy. The runs with both different climate scenarios and dam operating strategies can be found in appendix F.

6.5.1 Dam

The first KPI is the amount of water at the PMD reservoir. When looking at the different climate conditions it can be seen that wet and climate change conditions fill the reservoir significantly faster than the normal conditions and with dry conditions the reservoir fills up even slower. This all seems plausible as it is just dependent on the amount of water that will run through the river. Another interesting aspect is that the reservoir will get to the same water level for every climate scenario, however with the wet and climate change conditions there tend to be bigger fluctuations in the water level than with the dry and normal conditions.

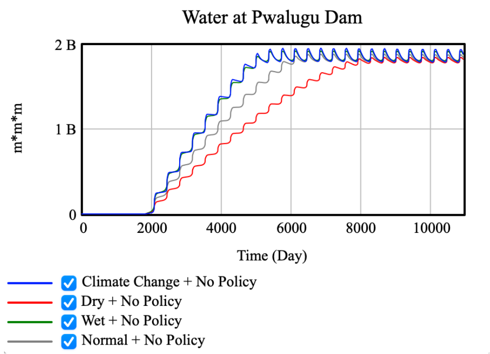
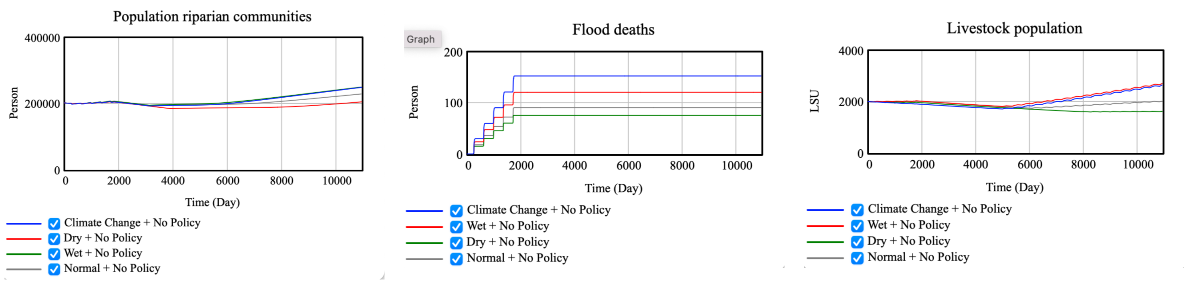


Figure 6.11: Water at PMD

6.5.2 Riparian Communities

When looking at the riparian communities there actually are three KPIs to taken into close consideration. First, it can be seen that the wet and climate change conditions cause the highest increase in population. This probably means that within the model the population number is mostly affected by the amount of water available. The wet and climate change conditions also cause the highest number of flood casualties, as they will lead to bigger floods, however the extra water available for farming and domestic use still causes the population to rise more than in normal and dry circumstances. Another interesting fact is that after construction of the PMD there won't be any flood casualties anymore for any condition. The livestock population shows similar behaviour compared to the riparian population as it first will decrease when the reservoir is filled and afterwards it will rise the most in wet and climate change circumstances, which shows that the population is mainly affected by the amount of water available.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure 6.12: Riparian Communities

6.5.3 Riparian ponds

When looking at the riparian ponds, it shows that the bigger flooding during the wet and climate change conditions are here beneficial too. As the bigger floods will lead to more water in the riparian ponds which will lead to more room for fish and crocodiles in these ponds. The fish stock shows that the number of fish at the riparian ponds also depend heavily on the amount of water available, which means they will benefit a lot from the occasional flooding during the wet and climate change circumstances. The percentage of crocodiles at the riparian ponds is also affected by the water level at the ponds, however it is less sensitive than the fish stock as crocodiles won't be trapped in the ponds as they can move over land. This explain the behaviour of this variables are it fluctuates a lot.

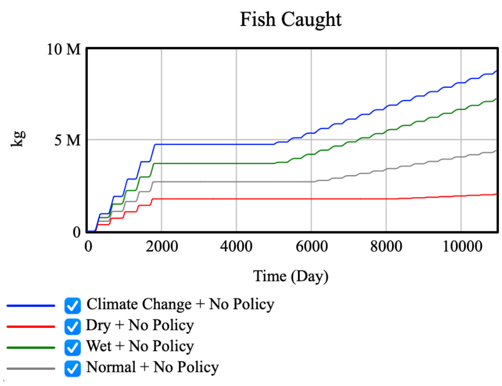


Figure 6.13: Fish caught

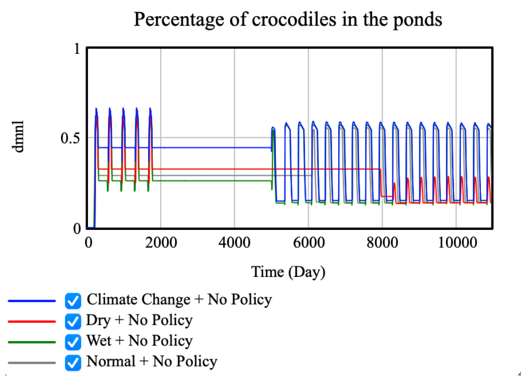


Figure 6.14: Crocodiles

6.5.4 Farmland

Ultimately, the KPIs regarding the farmland must be considered. Both KPIs show similar behaviour which means that both the percentage of farmland that is used for irrigation as well as the percentage of crops that is grown from irrigated farmland behave in the same manner. Irrigation farming is very water dependent so the circumstances in which there is the most water available will have the highest percentage of irrigated farmland. Moreover, during the dry period of the climate change conditions some irrigated farmland will be lost, which causes the fluctuations in percentage of irrigated farmland and crops displayed in the graphs underneath.

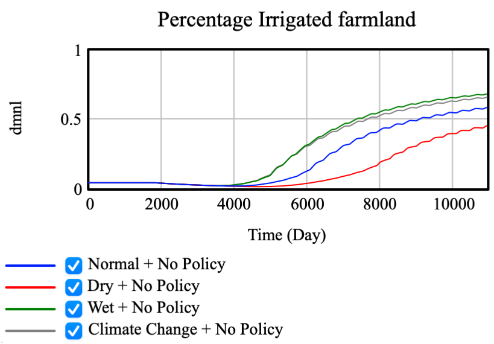


Figure 6.15: Farmland

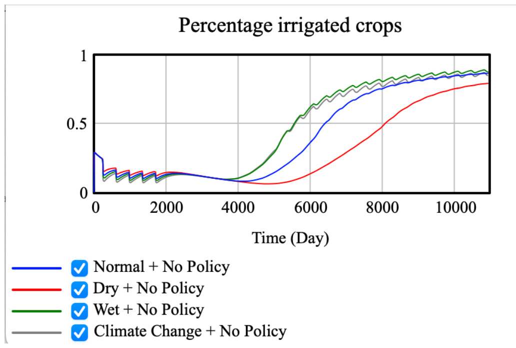


Figure 6.16: Crops harvested

6.5.5 Conclusion

As to be expected, the runs with the different climate conditions show that wet conditions are beneficial for most of the KPIs. As most of the KPIs would benefit from an increase in rainfall, apart from the number of flood casualties. However, as the graph of the flood casualties show the number will not increase once the dam in constructed, so then the wet season will only have benefits. Additionally, figure 6.17 underneath shows that the climate change conditions used within the model would also be beneficial for the system. As the seasonality caused by it will make sure that the riparian ponds will keep flooding, however the farmland does not benefit much from this seasonality. The dry conditions are not very beneficial for the different KPIs it will only lead to the lowest number of flood casualties, but the PMD will prevent most of the flood casualties anyway.

CONDITIONS	Dam reservoir	Riparian population	Flood casualties	Livestock	Fish	Crocodiles	Farmland	Crops
Normal	100%	100%	100%	100%	100%	100%	100%	100%
Climate Change	102%	109%	165%	135%	199%	195%	112%	98%
Dry	99%	90%	84%	78%	46%	48%	77%	92%
Wet	102%	109%	132%	138%	165%	193%	116%	101%

Figure 6.17: Scorecards from model simulations under different climate conditions

6.6 Summary

The PMD is a multipurpose large dam, indicating that trade-offs are inherent in the allocation of water that it stores. However, all the purposes can't all be optimised simultaneously. You can't generate as much electricity as possible, while also optimizing the area of irrigated farmland and making sure that any type of future flood can be mitigated. The model results show this too, as policies that prioritise farmland will generate less electricity and policies that optimise electricity will make the communities more vulnerable to potential flooding. This shows that all the different purposes can benefit from the construction of the PMD, however how much they will benefit depends on the operation of the dam. The riparian communities also can't be completely disregarded as their ecosystem-based activities depend primarily on the seasonal flooding and flow of the river. When looking at the three purposes of the dam, they will probably benefit the most from the flood mitigation, as they don't use much electricity and the irrigated farmland may well belong to big commercial farmers. Another aspect that is very important to the riparian communities are the riparian ponds as they provide them with water for livestock, fishing and the ponds also host crocodiles which are of high spiritual value to the communities. The scorecards provided in figure 6.10 show the different trade-offs associated with choices in the operation of the PMD. The benefits nationally and locally also differ significantly with these choices. When looking at the climate conditions, in figure 6.17, it can be seen that the wet conditions will be very beneficial for most of the KPIs.

7 Conclusion

Now that the results of the different experiments have been analysed, it is time to use the results to answer the main research question. Additionally, the scientific and societal relevance of this research will be examined and ultimately this chapter will provide a recommendation about which dam operation strategy would be most beneficial and how policy makers ca interpret the results provided in chapter 6.

7.1 Answering Research Question

The overarching research question of this thesis is formulated as:

"What are the socio-economic effects, at both local and national levels, of the construction and operation of the Pwalugu Multipurpose Dam?"

The results of the simulation modelling experiments performed in chapter 6 are designed to help answering this question. The model shows that the construction of the dam will change the flow of the river, and this will affect the socio-economic activities of the riparian communities. Primarily the construction of the dam will reduce the flooding of the riparian ponds which means there will be less fish and crocodiles. Moreover, the filling of the PMD will have harmful effects on both the livestock and riparian population as the lack of water available will lead to a drop in both populations, once the dam is operation these numbers will rise again. Flood mitigation and irrigation will benefit from the construction of the PMD, however it is still unknown how much the riparian communities will benefit from this as the irrigated farmland will also be used by commercial farmers.

Different operation strategies of the PMD can either reduce or increase the effects the dam will have on the river. The dam could be operated in such a way that it replicates the flow of the river without the dam. This would be beneficial for the filling of the riparian ponds and would reduce the severity to which the socio-economic activities of the riparian communities will be affected by the dam, but will reduce the other envisaged benefits such as hydropower generation and irrigation. The planned operation of the dam will lead to a higher base flow of the river and reduce the seasonality so as to optimise electricity generation and the area of irrigated farmland. This high base flows means that water will flow through the turbines constantly, which leads to more electricity generation and more outflow means more water available for irrigated farming. This high outflow could disrupt the socio-economic activities of the riparian communities greatly, both economically as well as spiritually (The presence of crocodiles in the ponds has spiritual value). Nevertheless, if these communities are able to adapt, with the help of compensation in the form of resettlement, ownership of a part of the irrigated farmland, or finances, the construction of the dam could be a success for all parties involved. As this would bring more prosperity not only to Ghana on a national level but also to a still underdeveloped northern part of Ghana. However, such success rests on the premise of appropriate compensation and a deep appreciation of the differences in lifestyle that will be occasioned by the construction and development of the PMD, as captured in this research.

7.2 Scientific relevance

This research illustrates a different method of quantifying the cost and benefits of a large infrastructural project. It not only quantifies the effects that the construction and operation of the dam will have on the different indicators, but it also shows how the behaviour of the different indicators will change over time, under changing climatic conditions and diverse dam operating rules. The indicators were chosen to represent both nationally relevant objectives such as hydropower generation and irrigation, as well as objectives relating to the lifestyle of riparian communities. The local indicators include flood casualties, livestock numbers, agricultural yields, fish caught and crocodiles in the ponds. This depiction of dynamic behaviour and the associated trade-offs between local and national objectives is one of the most interesting features of this research compared to commonly used methods like Environmental Impact Assessments and Societal Cost Benefit Analysis (VRA, 2014).

Studies regarding the construction of big infrastructural projects usually just consider the local effects as some side effect as they usually don't outweigh the national benefits. This research aimed to improve insight into the effects the dam will have on the local communities, even spiritual effects like the number of crocodiles in the ponds. This meant that System Dynamics was used to model activities like flood-recession agriculture and crocodiles moving back and forth between the river and the ponds. This really adds to the scientific relevance of this research.

7.3 Societal relevance

Societal impacts have been the focus of this research. With the implementation of a big infrastructure there will always be societal implications and the construction of the PMD will be no exception to this. Not only will certain communities have to be resettled, but also the daily ecosystem-based activities of the inhabitants of the riparian communities will be disrupted which could mean that they will need to change their way of living drastically. These effects the dam will have on the local communities should be considered carefully.

This research is societally relevant as it not only maps the national benefits that can be derived from the construction and operation of the dam, but it also looks at the local benefits and costs of the dam. These local benefits and costs probably won't weigh up to the national benefits when compared one on one. However, this does not mean they should be disregarded. That is why this research tries to narrate the story from both sides and creates scorecards on national and local levels.

7.4 Dam operation strategy recommendation

Construction of the PMD will affect the river. However, the way that the dam will be operated can have an even bigger effect on the river and on the possible costs and benefits that can be derived from the dam. The analyses regarding different dam operation strategies performed in this study indicate that there are specific trade-offs that need to be considered when operating the dam. So is there the trade-off between having a constant base flow of the river or maintaining a flow which is more like the environmental flow of the river. The higher base flow will be good for irrigation and will lead to a big increase in area used for irrigated farming. However, most of the riparian communities use rainfed and flood-recession farming and they depend on the riparian ponds and flooding of the floodplains for their EBA. This means that for them it would be more beneficial to keep seasonality in the flow of the river.

Another trade-off has to do with the water level at the reservoir. For electricity generation it would be beneficial to keep the level at the reservoir as high as possible as this could keep a constant outflow to generate electricity. This strategy increases the risk of flooding. If the reservoir is near maximum capacity, it won't be able to hold large inflow meaning that it will have to do emergency spilling. This spillage could be worse than an eventual flood would be, however they are forced to do it as there would be chances of the dam breaking. This means that the dam won't mitigate floods anymore and the riparian communities remain prone to flooding. Additionally, holding a lot of water at the reservoir means the outflow will be lower and the filling time will be higher meaning there will be less water available for downstream activities. Hence, the optimal dam operation strategy is dependent on from which perspective you look at it. For the VRA it would be optimal to generate as much electricity as possible, while for the national government it would be best to generate a lot of electricity but also to increase the farmland in the Northern Region to bring more prosperity to the country. For the downstream communities it would be important that the riparian ponds still flood occasionally, they would also benefit from more water for the farmland. But only if they can have access to this area and it doesn't get in the hands of a commercial farming company entirely. Thus, it would be best to make compromises regarding the different dam operation strategies in stead of optimizing one of the benefits. However, the main focus should be on flood mitigation as this brings along the biggest costs. Unfortunately, with big infrastructural projects like this one national interest usually prevail. Only if Ghana nationally as well as the riparian communities experience the benefits of the construction of the PMD the project can be considered a true success.

8 Discussion and Recommendations

The last chapter of this research will reflect on the entire process of the research. It will discuss the limitations of the research and how they might affect the results. Once the limitations have been discussed the different parts of this research will be reflected on. After the reflection has been completed it is time to look more closely at possible future research which could improve the research and increase its relevance.

8.1 Limitations

This research aims to model the White Volta River system as accurately as possible, however a model can never depict the exact system. This in combination with the time constrainment and lack in hydrology expertise lead to the occurrence of a number of limitations in this research.

First of all, hydrology is not covered in the curriculum of an Engineering and Policy Analysis study, meaning that modelling the behaviour of the flow of the river accurately in terms of hydraulics can be complex. This meant that the creation of inter-annual flood scenarios was not done in a hydrologically accurate way, but simply by increasing or decreasing the water inflow by a certain percentage. Additionally the generic inflow used in the model is based on historical data of the inflow at Pwalugu. However, the study which covered this only shows averages per month which meant that the water inflow in the model is based on averages and is not susceptible to changes over time. Other hydrology aspects such as sedimentation and morphodynamics are not covered in this research either.

The construction of a big reservoir will also mean that the area will be more prone to disease vectors with one or more life stages in water e.g. malaria. The spreading of such diseases is a study on its own and would increase the size of the model significantly, which due to the time constraint was not possible. Nevertheless, it is a cost that should be considered.

Resettlement is another major societal cost of development of the Pwalugu Multipurpose Dam (PMD). However, it is not incorporated in the model as the research is interested in dynamics over time rather than single events. Nevertheless it is one of the largest costs the riparian communities will have to bear caused by the construction of the PMD and should definitely be covered in a societal cost benefit analysis.

The model also contains some limitations regarding the way in which the communities have been modelled. In the model, all the communities are modelled as one big community. However, in the actual system the communities all live scattered around the entire area, meaning that some live downstream of the future reservoir while other communities live upstream. This means that the available water and the water needed per community could vary significantly. Nevertheless, there was not sufficient information available about the communities on their own to model them all separately.

The limitation of putting all the communities in one big stock before the irrigation in the model will also cause other limitations. When looking at the irrigation scheme, as it is now modelled, it can be seen that all the remaining water in the river just flows there. However in the real system the irrigation scheme could be downstream or upstream of certain communities. Additionally, the accessibility of the farmland is not considered, as certain areas of farmland will be further away from the river than others. The model also does not make a distinction between gravity and pump irrigation and which one will be prioritised at certain times of low water flow. Finally, when looking at the irrigation farmland the model does not distinguish between commercial farming and small farmers, which means that all the irrigated farmland in the model is considered detrimental to the riparian communities.

Another limitation regarding the farmland is that within the model the area of irrigated farmland and rainfed farmland are interchangeable, meaning that when there is not sufficient water available the irrigated farmland will turn into rainfed farmland. In real life this exchange will be hard to realise and will take time. Flood-recession farming though, does not have a maximum area and just looks at the flood water available. Which means that the number of crops could exceed the actual area that is available for flood-recession farming. This can be considered an extreme conditions test failure. As farming is not modelled in too much detail, phenomena like pests, and the type of crops grown, are not taken into account in the model.

As with the riparian communities, the riparian ponds will also be scattered all around the area of the river. This means that some might be filled during a small flood while others need a big flood to get filled. The model disregards this as it is hard to determine the exact location of the riparian ponds and when they exactly flood. This will also affect the fish and crocodile populations within the model as they are dependent on the water at the riparian ponds.

This big dependence of the riparian communities on fish at the riparian ponds is not entirely correct either. As the riparian communities can also fish from the river and in the future even from the reservoir. Nevertheless, fishing in the ponds does play a big role in their lives, for now, as it is easier to fish in a pond than in the river. The reservoir could be a convenient water body to fish in too, which can also be seen in Lake Volta (van Zwieten, Béné, Kolding, Brummett, & Valbo-Jørgensen, 2011). This could be another benefit of the construction of the PMD.

Ultimately, there are also limitations regarding the operation strategies of the PMD. As the model does not take into account height of the spillways of the dam the dam within the model could release unrealistic amounts of water in the model as the maximum release rate is also unknown. This could lead to certain dam operating strategies appearing more beneficial in the model than they actually are in the real system. Additionally, the VRA aims to fill the reservoir within a year (VRA, 2014), whereas in the model the reservoir will be filled in around 5 years. As the annual runoff of the White Volta River is around 3.5 BCM, and the capacity of the reservoir around 2 BCM, it should be possible to fill the dam in one year. However, in the model there is always some outflow, even when filling, which means it will take longer to fill but the ecosystem based activities of the riparian communities will be less disrupted.

8.2 Reflection

Now that the limitations of the research have been discussed, it is time to reflect on the entire research process. This means that the different parts of the research will be reflected upon to see how they added value to the entire research process, but also what could have been done to bring the research to a higher level.

8.2.1 Reflection on the used method

This research used a System Dynamics method to depict the effects the construction and operation of the PMD will have on the flow of the river, and what the effects of this are both locally and nationally. The choice for this method was based on different reasons. First of all, damming a river can excellently be captured in a stock-flow system. As the name already says, the flow of the river can be the flows in the model while the storage of the water at the dam reservoir can be the stock. This leads to every different stage of the river system, for example the communities, riparian ponds, and irrigation, to all become different stocks. Even though some of these stocks are not actually storage locations in the real system. The river is the flow that connects all these stocks to one another. At the start the idea was to also include the Akosombo and Bagre dams as stock into the model, however that would heavily increase the scope of the research and due to lack of time that would only reduce the level of the research as the smaller scope meant that the White Volta River system could be modelled in more detail.

Another reason to use System Dynamics as the main method for this research comes from the fact that System Dynamics will show not just how certain policies affect certain indicators but will also show the behaviour of these indicators over time. As the Northern region has only one wet season, seasonality is an important feature to consider when looking into this system. This is also one of the advantages this approach has over conducting a societal cost benefit analysis which will only show outcomes. Nevertheless, System Dynamics has its flaws too, so it is not suitable for running huge numbers of experiments, which would be helpful knowing the uncertainty there is with river systems affected by climate change. This could be done with the Exploratory Modelling Analysis (EMA) workbench, which could produce thousands of flood scenarios based on historical data, while also being able to implement different policies to illustrate the different trade-offs within the system.

Moreover, when looking at the entire approach, it would probably be beneficial for the model to do the interviews and the field trip to Ghana at an earlier stage of the research as many new insights were gained during the trip, however since the research was already in the final stages it was hard to implement these into the model. A trip to Ghana at the beginning of the research would have improved the insight into the system significantly which means that the constructed model would be a better representation of the actual system.

8.2.2 Reflection on the model

The model aims to depict the White Volta River system as accurately as possible. The most important sub-model of this research is the river and all the different parts it flows through. This stock-flow model shows how the river behaves without the dam and how it changes once the dam is operational. The sub-model of the river is also the main input for all the other sub-models which mostly illustrate the ecosystem based activities of the riparian communities that depend on water. All these different sub-models provide indicators to get a better overview of the effect of both construction and operation of the PMD on both local and national levels.

Even though the model contains a lot of uncertain parameters, the model could be run and provided interesting results as the indicators were not sensitive to changes in the uncertain parameters. The run under different climate circumstances and with different dam operating strategies helped to get a better understanding of how the different indicators would be affected and what kind of trade-offs there would be. This helped with answering the main research question.

Unfortunately, due to lack of time and specific data, the scope of the model had to be narrowed down to only the Northern region of Ghana. This meant that the effect the upstream Bagre Dam was not included in the model, moreover upstream Burkina Faso could also develop more projects around the White Volta River which could affect the flow of the river into the Northern region of Ghana. The downstream Akosombo dam was also not considered in the model as the White Volta River is just one of a number of rivers that culminate in Lake Volta, this means that in order to model the effect the PMD will have on the water level at Lake Volta all these tributaries would have to be taken into account too. Another reason for the exclusion of Lake Volta is that the lake is of such a large volume that the effect the PMD will have on the water level could be almost negligible.

8.2.3 Reflection on the validation of the model

Despite the model containing a large number of uncertain parameters, different validation and verification tests still show that the model can be considered valid. This means that the model can be considered an accurate, though simplified, representation of the White Volta River system. The sensitivity and extreme value tests showed that the different indicators within the model were not very susceptible to changes in parameters. The validation interviews helped to further determine the accuracy of the model while also shedding light on the limitations which inevitably will always be in a model. As the PMD has not been constructed yet, it was difficult to compare the results with historical data. However, the first five years of the model the PMD is not yet constructed, this means that the behaviour of the indicators during that time can be compared to the historical data available. Nevertheless, this was still difficult as there is not a lot of historical data available on the different indicators used throughout the model.

8.2.4 Reflection on the results

The System Dynamics model is run with five different dam operating strategies under four different climate scenarios. This means that there are twenty experiments of which the results can be analysed. There were different indicators that were analysed as the model looks at both national and local effects. This meant that the different policies show that there are trade-offs that have to be considered when looking at dam operating strategies. As most of the benefits for the riparian communities depend on the seasonality of the river while the national benefits would be better off with a steady base flow. When looking at the results the uncertain parameters will have to be borne in mind, as even though the output variables are not very sensitive to changes in uncertain parameters they can still affect the model.

The results show that aiming for a full dam reservoir will completely reduce the ability to mitigate flooding. But it would generate a lot of hydropower. Looking at the farmland it can be seen that a steady base flow will help produce the most growth while the riparian ponds are better off with the creation of artificial floods to fill them up once a year. However, the riparian population could also benefit from the irrigation as they will get ownership over a certain area of farmland, this was not considered in the model as the priority will probably be on commercial farming. The scorecards based on the result of the different experiments help with showing the trade-offs. However, not all costs and benefits were taken into account in the model, for example resettlement. Nevertheless, the model can still help to gain insight into the effects of the construction of the PMD and could also be used for other dam projects with a change in input variables.

8.3 Recommendations for future research

Based on the limitations and the reflection discussed in the previous sections this section will come up with recommendations for possible future research that could give more insight into the effects of the construction and operation of the PMD on both local and national levels. First of all, the research and the model could be improved greatly if more accurate real-world data would be available, this would help improve the accuracy of the model and reduce uncertainty. However, setting up a large-scale information gathering project in the Northern region of Ghana would be both time consuming and difficult as the riparian communities are very remote which means they are hard to access and the people living there probably have different perceptions of life. Nevertheless, it would be helpful to do more interviews with people in Ghana who know more about life at the riparian communities as well as with water experts, because the lower the number of uncertain parameters within the model the higher the validity of the model. Which means it can produce more accurate results.

Moreover, it would be interesting to look at the White Volta River system from more of a hydrological perspective. Especially the combination between System Dynamics and hydrology could be a very interesting one. This could add a new level to the model and it would be interesting to see how the model behaves during different flood scenarios based on historical data instead of looking at the same inflow for every experiment, for example the inter-annual flood scenarios constructed by the Volta River Authority in figure 1.1. A more hydrological approach would also help with making the model more realistic, as certain aspects like sedimentation, are not considered in this model. Hydrology could also help significantly with adding climate change into the model, as with the usage of hydrological models it should be possible to generate more accurate run-off forecasts over longer periods of time.

Another way the model could be improved upon is by splitting the water at riparian communities stock into different stocks depending on their location. It would be interesting to look at how the population upstream of the irrigation scheme would be affected by the construction of the dam compared to the population downstream of the irrigation scheme. This distinction between the different locations of the riparian communities will reduce the generalisation of the different communities, meaning it will make the model more accurate and it will give more detailed insight into how the different communities will be affected which would help with coming up with an appropriate compensation based on the type of community.

Ultimately, using a different method to improve understanding of the effects of the construction and operation of the PMD could also provide compelling insights. So would it for example be interesting to construct a model of the PMD into the Exploratory Modelling Analysis workbench in Python. This would not only make it possible to run a lot of different experiments under uncertainty, but the different policies can also be checked to see how they affect the output variables. The big advantage the workbench has over System Dynamics is that it will be able to do a very large number of runs and will provide very clear visualisations of the results and the possible trade-offs there are. System Dynamics is less convenient when aiming to do thousands of different runs, however with System Dynamics you get a better overview of what the system looks like exactly and this will also help with gaining understanding of the system. As with the EMA workbench the model is more of a black box. So, a combination between the two different approaches or combination with a stakeholder-based modelling approach could lead to even more insightful results.

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Appendices

A Model

In this appendix the model will be discussed more thoroughly. This means that all the different aspects of the model will be discussed. First all the parameters will be discussed as the model has to start with those. After that the stocks and different flows will be looked at more closely as they form the main structure of the model. Once those have been covered the look-ups will be covered, which are special graph like functions to add robustness to the model. Ultimately, the remaining variables will be looked at to see how they affect the previously mentioned aspects of the model.

A.1 Parameters

Name	**Unit**	**Value**	**Source**
Accelaration Gravity	9,81	m/s^2	Knowledge
Adjustment time agriculture	182	days	Assumption
Artificial flood flow	500000	m^3/day	Assumption
Average Water Usage Per Capita	0,007	$(m^3/day)/person$	(Badsha, 2016)
Begin time [Floods]	250	Day	(Mul et al., 2017)
Beneficial fish level	100	kg	Assumption
Beneficial water level	500000	m^3	Assumption
Climate change flood	20000000	m^3/day	(Tangonyire et al., 2019)
Crocs eating fish rate	2	$kg/(crocs * Day)$	(Britannica, 2022)
Crocs going back rate	0,1	$1/day$	Assumption
Crocs growth factor	0,045	dmnl	(Britannica, 2022)
Crocs swimming rate	0,2	$1/day$	Assumption
Crops per capita	0,15	$quintal/person$	(Ampadu et al., 2017)
Crops per Hectare	1	$quintal/ha$	(Ampadu et al., 2017)
Dam Height	165	m	(VRA, 2014)
Damage level	100	Euro	Assumption
Days a year	365,00	days	Knowledge
Death rate crocs	0,04	dmnl	(Britannica, 2022)
Demand electricity generation	60	MW	(VRA, 2014)
Density of Water	1	kg/m^3	Knowledge
Dry flow	0,75	dmnl	Assumption
Efficiency of Turbines	0,9	dmnl	Knowledge
Evaporation Rate	2	m/y	(Mul et al., 2017)
Evaporation Rate riparian ponds	0,01	$1/day$	(Lawson, 1966)
Fish caught per effect	300	kg	Mul (2017)
Fish effect rate	1	$1/day$	Assumption
Fish per cubic meter of water	0,0001	kg/m^3	Assumption
Flood duration [Floods]	5	Day	Assumption
Flood flow [Floods]	10000000	m^3/day	Assumption
FR crops per cubic water	1	$quintal/m^3$	Assumption

Growth factor of fish	0,0005	$1/day$	Assumption
Harvest time	30	days	(Mul et al., 2017)
Health beneficial level	400000	m^3/day	Assumption
Incubation period	80	day	(Britannica, 2022)
Initial crocs at the ponds	0	crocs	Assumption
Initial crocs at the river	30	crocs	Assumption
Initial death rate	1.92e-05	$1/day$	(VRA, 2014)
Initial flood death rate	1.23e-05	$1/day$	(VRA, 2020)
Initial Growth Rate	7.67e-05	$1/day$	(VRA, 2014)
Initial livestock drowning rate	3,00E-05	$1/day$	Assumption
Initial loss rate crops	0.001	$1/day$	Assumption
Initial Population Riparian Communities	202.000	person	(Mul et al., 2017))
Initial value farmland	9000	ha	(Mul et al., 2017)
Initial value livestock	2000000	LSU	(VRA, 2014)
Initial value rainfed	16000	ha	(Mul et al., 2017)
Initial water at Pwalugu Dam	0	m^3	Knowledge
Initial Water at Riparian Communities	100000	m^3	Assumption
Initial Water at Riparian Ponds	0	m^3	Empty
Initial Water to Irrigation	0	m^3	Empty
Length artificial flood	24	days	Assumption
Livestock adjustment time	180	days	Assumption
Livestock death rate	0,006	dmnl	(Abungba Ayiiwe, 2013)
Livestock growth factor	0,00225	dmnl	(Abungba Ayiiwe, 2013)
Livestock per capita	0,0003	$LSU/person$	(Abungba Ayiiwe, 2013)
Low water level dam	0.65	dmnl	Assumption
Maximum value irrigated farmland	25000	ha	(VRA, 2014)
Maximum water at riparian ponds	400000	m^3	Assumption
Maximum Water Level at Pwalugu Dam	4237	m^3	(VRA, 2014)
Minimum Water Level at Pwalugu Dam	761	m^3	(VRA, 2014)
Minimum water level for electricity generation	1,1	dmnl	Assumption
Normal Flood	10000000	m^3/day	Assumption
Normal water level dam	0,85	dmnl	(VRA, 2014)
Planting time	30	day	(Mul et al., 2017)
Repeat Time [Floods]	365	Day	(Mul et al., 2017)
Selling rate	1,00E-06	dmnl	Assumption
Threshold flow crocs going back	400000	m^3/day	Assumption
Threshold flow crocs swimming	300000	m^3/day	Assumption
Threshold for flooding	800000	m^3	Assumption
Value for Pond Flooding	400000	m^3	Assumption
Water needed livestock	1,00E-05	m^3/LSU	(Abungba Ayiiwe, 2013)
Water requirements agriculture	0,002	m/day	(Ampadu et al., 2017)
Wet flow	1,25	dmml	Assumption
Yield Time crops[Irrigated]	182,5	days	(Balana et al., 2019)
Yield Time crops[Rainfed/Flood-recession]	365	days	(Balana et al., 2019)

Table A.1: Parameters of the different constants used in the Model.

A model won't be able to run without parameters, that why they will be discussed first. The table above shows the different parameters, their unit, value, and the source for their value. The first thing that catches the eye is that there are a lot of uncertain parameters This comes from the fact that many of the parameters are hard to determine and there is not much information available as the dam will be built in a rather undeveloped part of Ghana. Additionally, it can be seen that most of the other parameters are either provided by the VRA or by a paper written by Marloes Mul.

A.2 Stocks

Name	**Units**	**Initial Value**	**Equation**
Crocodiles in riparian ponds	Crocs	0	Crocs to pond+river crocs population growth-Crocs to river-pond crocs dying
Crocodiles in river	Crocs	30	Crocs population growth+Crocs to river-Crocs to pond-river crocs dying
Crops	Quintal	0	Crops planted[Farmland]-Harvest[Farmland]
Fish in riparian ponds	kg	0	Fish Growth+Fish inflow-Fish eaten by crocs-Fishing
Flood recession crops	Quintal	0	Planting FR crops-Harvesting FR crops
Irrigated farmland	ha	25000	Cultivating land-Drying up of land
Livestock population	LSU	77	Livestock growth-Livestock decline-Livestock drowning-Livestock selling
Population riparian communities	person	202000	Population growth-Flood casualties-Population decline
Rain-fed farmland	ha	3000	Drying up of land-Cultivating land
Water at Pwalugu Dam	m^3	7.61eˆ8	Inflow Pwalugu Dam-Spillage-Evaporation-Outflow PMD
Water at riparian communities	m^3	100000	Outflow PMD+Spillage-Water to Irrigation-Water to riparian ponds-Water usage community
Water at riparian ponds	m^3	0	Water to riparian ponds-Evaporation Riparian Ponds-Water for livestock-Water from ponds to irrigation-Water for livestock
Water for irrigation	m^3	0	Water from ponds to irrigation+Water to Irrigation

Table A.2: Table of the stocks used throughout the model.

The model contains quite a few stocks. Stocks are special variables in Vensim that are able to store certain values. They are mainly used for populations or things that can be stored for example water in a dam reservoir. It can be seen that all the different stocks are determined by an equation that either subtracts or adds values to the stocks. These variables that affect the stocks are called flows and they will be discussed in the following section.

A.3 Flows per sub-model

This subsection will discuss all the different flows that are used within the model. All the different flows will be discussed per sub-model. This was done in order to get a better overview of the different flows that are important for the different stocks is every sub-model. Flows always have the unit of stocks divided by the a time variable as their value gets added or subtracted every time step from the stock. This means if the flows going in the stock combined are bigger than all the flows going out of the stock the value of the stock will increase every time step.

A.3.1 River

Flow	**Unit**	**Equation**
Evaporation	m^3/day	IF THEN ELSE(Switch Dam=1, Evaporation rate * Dam Area,0)
Evaporation riparian ponds	m^3/day	Water at riparian ponds*Evaporation rate riparian ponds
Inflow Pwalugu Dam	m^3/day	MAX(Constant inflow Pwalugu Dam,0)
Outflow PMD	m^3/day	IF THEN ELSE(Switch Dam=1 , Constant outflow Pwalugu Dam,0)
Spillage	m^3/day	IF THEN ELSE(Switch Dam=1 , IF THEN ELSE(Water at Pwalugu Dam+(Inflow Pwalugu Dam-Evaporation-Outflow PMD)*Day > Maximum water level at Pwalugu Dam, Inflow Pwalugu Dam - Evaporation - Outflow PMD,0),Inflow Pwalugu Dam)
Water flow further downstream	m^3/day	(Water for Irrigation/Day)-Water usage irrigation
Water for livestock	m^3/day	IF THEN ELSE(Water at riparian ponds > 0 ,1000,0)
Water from ponds to irrigation	m^3/day	IF THEN ELSE(Water at riparian ponds¿Maximum water at riparian ponds,(Water at riparian ponds-Maximum water at riparian ponds)/TIME STEP ,Water at riparian ponds/Riparian ponds adjustment time)
Water to irrigation	m^3/day	(Water at riparian communities/Day)-Water usage community-Water to riparian ponds
Water to riparian ponds	m^3/day	IF THEN ELSE(Water at riparian communities > Value for pond flooding ,((Water at riparian communities - Value for pond flooding) /Day) - Water usage community,0)

Water usage community	m^3/day	MIN(Water demand riparian communities,Water at riparian communities/Day)
Water usage irrigation	m^3/day	Water demand farmland

Table A.3: Table of the flows in the river sub-model.

The flows of the river system basically show the flow of the river into the different places. So will there be an inflow of the dam reservoir or riparian ponds while water can also be at the irrigation scheme and the riparian communities. This means that basically all the flows in this sub-model are about water flowing from one place to another. This makes it a very good structure to model the White Volta River system as this usually is how rivers work as water will flow past all the different time steps.

A.3.2 Fish

Flow	**Unit**	**Equation**
Fish eaten by crocs	kg/day	Crocodiles in riparian ponds*Crocs eating fish rate * Lookup fish density pond(MAX(Fish in riparian pond,0)/Beneficial fish level)
Fish growth	kg/day	growth factor fish*Fish in riparian pond
Fish inflow	kg/day	Fish per cubic meter of water*Water to riparian ponds
Fishing	kg/day	Fish caught per effect*Fish effect rate*fish density multiplier((MAX(Fish in riparian pond,0)/MAX(Water at riparian ponds,1))/Fish per cubic meter of water)

Table A.4: Table of the flows in the fish sub-model.

The fish population in the riparian pond can either increase via fish growing bigger or fishing being carried into the riparian pond by the current. The fish population can also decline as people will do fishing at the end of the dry season and as crocodiles can eat them.

A.3.3 Crocodiles

Flow	Unit	Equation
Crocs population growth	crocs/day	(crocs growth factor * Crocodiles in river)/Incubation period
Crocs to pond	crocs/day	Crocodiles in river*crocs swimming rate * Lookup crocs swimming(MAX(Water to riparian ponds,0)/Threshold flow crocodile swimming)
Crocs to river	crocs/day	Crocodiles in riparian ponds*Crocs going back rate * Lookup crocs going back(MAX(Water to riparian ponds,0)/Threshold flow crocs going back)
Pond crocs dying	crocs/day	(death rate crocs*Crocodiles in riparian ponds)/Incubation period
River crocs dying	crocs/day	(death rate crocs*Crocodiles in river)/Incubation period
River crocs population growth	crocs/day	(crocs growth factor * Crocodiles in riparian ponds)/Incubation period

Table A.5: Table of the flows in the crocodiles sub-model.

The movement of crocodiles is also modelled with different flows. So is there a population of crocodiles at the river and one at the riparian ponds. As crocodiles can move between the two water bodies there will be flows going from both sides. Moreover, crocodiles can reproduce to increase the population while they can also die which will decrease the number of crocodiles.

A.3.4 Population

Flow	Unit	Equation
Flood casualties	person/day	Flood death rate*Population riparian communities
Population decline	person/day	Death Rate*Population riparian communities
Population growth	person/day	Growth Rate*Population riparian communities

The growth and decline is pretty straightforward as the population can either grow via births and decline via deaths. However flooding can also lead to an additional number of deaths. Migration to and from the different riparian communities has not been taken into account.

A.3.5 Farmland

Flow	Unit	Equation
Cultivating of land	ha/day	IF THEN ELSE(Irrigated Farmland + ((Water to Irrigation- Water demand farmland)/Water per hectare) ¿= Maximum value irrigated farmland,0,IF THEN ELSE(Water demand farmland ¡ Water to Irrigation,(((Water to Irrigation-Water demand farmland)/Water per hectare)/Adjustment time agriculture),0))
Drying up of land	ha/day	IF THEN ELSE(Water demand farmland¿ Water to Irrigation,(Irrigated Farmland-(Water to Irrigation/Water per hectare))/Adjustment time agriculture,0)

The model contains two types of farmland, rain-fed and irrigated farmland. They are dependent on the amount of water that will be available. If there is sufficient water available there will be plenty of irrigated farming and some rain-fed farmland will even be turned into irrigated farmland. However, when there is a lack of water available some of the irrigated farmland can be transformed into rain-fed farmland.

A.3.6 Livestock

Flow	Unit	Equation
Livestock decline	lsu/day	(Livestock death rate*Livestock population*(1/Health of livestock)*Multiplier water livestock(MAX((Livestock population*Water needed livestock),0)/MAX(Water at riparian ponds,1)))/Livestock Adjustment Time
Livestock drowning	lsu/day	Livestock population*Livestock drowning rate
Livestock growth	lsu/day	(Livestock growth factor*Livestock population*Health of livestock*Multiplier water livestock(MAX(Water at riparian ponds,0)/MAX((Livestock population *Water needed livestock),1)))/Livestock Adjustment Time
Livestock selling	lsu/day	Livestock population*Selling rate*Multiplier livestock selling(MAX(Livestock population,0)/MAX((Population riparian communities*Livestock per capita),1))

The population of the livestock can be affected just like all the other population stocks by either births and deaths of livestock. Additionally, the livestock population can just like the population of the communities be decreased by casualties caused by flooding. The livestock can also be decreased due to the fact that some people will sell their livestock for money at the market.

A.3.7 Crops

Flow	Unit	Equation
Crops planted	quintal/Day	(Crops per hectare[Farmland]*Area farmland[Farmland])/ Yield time crops[Farmland]
Harvest	quintal/Day	Crops[Farmland]/Yield time crops[Farmland]
Loss of crops	quintal/Day	Crops[Farmland]*Loss rate of crops

Crops that are on the land can either be planted or be harvested. These two flows usually happen once or twice a year. Nevertheless, floods can also cause the crops that are planted to die, which means they can't be harvested and will be lost.

A.4 Look ups

Lookup	Min	Max	Dependent variables
Casualty multiplier	0	100	Flood water /beneficial water level
Flood damage	0	100	Flood water /beneficial water level
Lookup climate change	0	3650000	Time
Lookup crocs going back	0	5	Water to riparian ponds / threshold flow crocs going back
Lookup crocs swimming	0	5	Water to riparian ponds / threshold flow crocs swimming
Lookup fish pond density	0	2	Fish in riparian ponds / beneficial fish level
Lookup inflow	0	2000000	Time
Multiplier livestock drowning	0	40	Flood water /beneficial water level
Multiplier livestock selling	0	4	Livestock population / (population riparian communities * livestock per capita)
Multiplier population, birth rate	0	2,2	Water usage communities / water demand communities
Multiplier population, birth rate	0	2,2	Crops / Crop demand communities
Multiplier population, death rate	0	2,2	Water demand communities / water usage communities
Multiplier population, death rate	0	2,2	Crop demand communities / Crops
Multiplier water livestock	0	5	Water at riparian ponds / (livestock population * water needed livestock)
Water demand multiplier	0	1,05	Water at pwalugu dam / maximum water level pwalugu dam

The model uses a lot of different types of look-ups. Look-ups are variables that are in the form of a graph and then are dependent on the value of a certain variable. It is important that the dependent variables are dimensionless which means that the variable will be divided by certain threshold variable. These look-ups will add robustness into the model as it will reduce the dependence on certain parameters. The graphs are all shaped in an S form to add more robustness.

A.5 Remaining Variables

Variable	Submodel	Unit	Equation
Pulse if flood	River flow	dmnl	PULSE TRAIN(INITIAL TIME+Begin time[Floods],Flood duration[Floods],Repeat time[Floods],FINAL TIME)
Flood flow	River flow	m^3/day	IF THEN ELSE(Climate Change switch = 1,Climate change flood,Normal Flood)
Flooding	River flow	m^3/day	Flood flow[Floods]*Pulse if flood[Floods]

Constant inflow Pwalugu Dam	River flow	m^3/day	(IF THEN ELSE(Climate Change switch=1,(Lookup Climate Change(MODULO(Time,Days a Year)*Per day)*cubic m per day +Flooding[Annual],(Lookup Inflow(MODULO(Time,Days a Year)*Per day)*cubic m per day) +Flooding[Annual]))*Type of season
Type of season	River flow	dmnl	IF THEN ELSE(Dry switch = 0,IF THEN ELSE(Wet switch= 0,Normal flow,Wet flow),Dry flow)
Dam area	River flow	m^2	Cubic Meter*"Look-up Area"(Water at Pwalugu Dam*Capacity to dmnl)
Outflow PMD per second	Electricity Generation	m^3/second	Outflow PMD/Seconds per day
Power Generation Pwalugu Dam	Electricity Generation	MW	Outflow PMD per second*Acceleration Gravity*Dam Height*Density of water*Efficiency of turbines
Water demand for full power generation	Electricity Generation	m^3/day	(Demand electricity generation/(Acceleration Gravity*Dam Height*Efficiency of turbines*Density of water))*Seconds per day Gravity*Dam Height*Efficiency of turbines*Density of water))*Seconds per day
Water demand power generation	Electricity Generation	m^3/day	Water demand for full power generation*Power generation lookup(Water at Pwalugu Dam/(Maximum water level at Pwalugu Dam*Minimum power generation water level as fraction of maximum)
Minimum power generation water level as fraction of maximum	Electricity Generation	dmnl	IF THEN ELSE(Switch full dam = 0 , Normal minimum water level, Minimum water level for electricity generation)
Normal minimum water level	Electricity Generation	dmnl	IF THEN ELSE(Switch flood buffer = 0,Normal water level dam , Low water level dam)
Artificial flood	Electricity Generation	m^3/day	PULSE TRAIN(Start time artificial flood,length artificial flood , Days a Year,FINAL TIME)*Artificial flood flow
Flood water	Damage	m^3	MAX(Water at riparian communities-Threshold for flooding,0)
Damage	Damage	Euro	Damage level*Flood damage(Flood water/Beneficial water level)
Fish per cubic meter of water	Fish	kg/m^3	IF THEN ELSE(Switch Dam=1,0.003,0.005)

Growth Rate	Population	1/day	Initial growth rate*Multiplier population(MAX(Water usage community,0)/MAX(Water demand riparian communities,1))*Multiplier population ((SUM(Crops[Farmland!]))/MAX(Crop demand riparian communities,1))
Death Rate	Population	1/day	Initial death rate*Multiplier population(Water demand riparian communities/MAX(Water usage community,1))*Multiplier population (Crop demand riparian communities/MAX((SUM(Crops[Farmland!])),1))
Crop demand riparian communities	Population	quintal	Crops per capita*Population riparian communities
Flood death rate	Population	1/day	Initial flood death rate*Casualty multiplier(Flood water/Beneficial water level)
Water demand riparian communities	Population	m^3/day	Average water usage per capita*Population riparian communities
Water per hectare	Farmland	(m^3/ha)/day	Hectare to m^2*Water requirements agriculture
Water demand farmland	Farmland	m^3/day	IF THEN ELSE(Switch farmland policy=0,(Irrigated Farmland*Hectare to m2)*Water requirements agriculture,(Maximum value irrigated farmland*Hectare to m2)*Water requirements agriculture)
Loss rate of crops	Crops	1/day	Initial loss rate crops*Crops loss multiplier(Flood water/Beneficial water level)
Livestock drowning rate	Livestock	1/day	Initial livestock drowning rate*Livestock drowning multiplier(Flood water/Beneficial water level)
Health of livestock	Livestock	dmnl	Multiplier health(MAX(Water to riparian ponds,0)/Health beneficial level)

The remaining variables in the model can be considered some kind of in-between variables between parameters and flows. This are usually variables that use parameters in combinations with look-ups.

B Sensitivity Analysis

This appendix will focus on the sensitivity analysis. Two different sensitivity analyses have been performed during this research. The first is just the ordinary sensitivity analysis in which every parameter will be increased by either positive or negative 10 percent of its value used within the model. The second type of sensitivity test that has been performed is a flow sensitivity analysis. This analyses how sensitive the different stocks within the model are to changes in the flows. For this analysis the flows had been either increased or decreased by 1 percent.

B.1 Parameter Sensitivity Analysis

First the commonly used sensitivity analysis will be discusses. This sensitivity analysis looks at all the different parameters and checks how sensitive the different output variables are to 10 percent changes in the input variables. The value for the different parameters can be found in the table underneath.

Parameter	**Value**	**MIN**	**MAX**
Adjustment time agriculture	2190	1971	2409
Average Water Usage Per Capita	0,007	0,0063	0,0077
Begin time[Annual]	250	225	275
Beneficial fish level	100	90	110
Beneficial water level	500000	450000	550000
Climate Change flood	2,00E+07	18000000	22000000
Crocs eating fish rate	2	1,8	2,2
Crocs going back rate	0,1	0,09	0,11
Crocs growth factor	0,0001	0,00009	0,00011
Crocs swimming rate	0,2	0,18	0,22
Crops per capita	0,15	0,135	0,165
Crops per Hectare [Irrigation]	1,5	1,35	1,65
Crops per Hectare [Rain-fed]	0,6	0,54	0,66
Dam Height	165	148,5	181,5
Damage level	100	90	110
Death rate crocs	0,00006	0,000054	0,000066
demand electricity generation	16500000	14850000	18150000
Efficiency of Turbines	0,9	0,81	0,99
Evaporation Rate	0,00054795	0,000493155	0,000602745
Evaporation Rate riparian ponds	0,01	0,009	0,011
Fish caught per effect	300	270	330
Fish effect rate	5	4,5	5,5
Flood duration [Annual]	5	4,5	5,5
Flood duration [Monthly]	3	2,7	3,3
Flood flow [Annual]	10000000	9000000	11000000
Flood flow [Monthly]	1000000	900000	1100000
FR crops per cubic water	0,05	0,045	0,055
Growth factor of fish	0,0005	0,00045	0,00055
Health beneficial level	400000	360000	440000
Incubation period	80	72	88
Initial crocs	30	27	33

Initial death rate	0,0000192	0,00001728	0,00002112
Initial flood death rate	0,0000123	0,00001107	0,00001353
Initial Growth Rate	0,0000767	0,00006903	0,00008437
Initial livestock drowning rate	0,00003	0,000027	0,000033
Initial loss rate crops	0,001	0,0009	0,0011
Initial Population Riparian Communities	202.000	181800	222200
Initial value farmland	9000	8100	9900
Initial value livestock	200000	180000	220000
Initial value rain fed	16000	14400	17600
Initial Water at Riparian Communities	100000	90000	110000
Livestock Adjustment Time	90	81	99
Livestock death rate	0,006	0,0054	0,0066
Livestock growth factor	0,00225	0,002025	0,002475
Livestock per capita	0,0003	0,00027	0,00033
Maximum value irrigated farmland	25000	22500	27500
Maximum water at riparian ponds	400000	360000	440000
Maximum Water Level at Pwalugu Dam	2237	2013,3	2460,7
Normal Flood	1,00E+07	9000000	11000000
Normal minimum water level	0,85	0,765	0,935
Repeat Time [Annual]	365	328,5	401,5
Riparian ponds adjustment time	1	0,9	1,1
Selling rate	0,000001	0,0000009	0,0000011
Threshold flow crocs going back	300000	270000	330000
Threshold flow crocs swimming	400000	360000	440000
Threshold for flooding	800000	720000	880000
Value for Pond Flooding	400000	360000	440000
Water needed livestock	0,00001	0,000009	0,000011
Water requirements agriculture	0,002	0,0018	0,0022
Yield Time crops [Flood-Recession]	365	328,5	401,5
Yield Time crops [Irrigation]	182,5	164,25	200,75
Yield Time crops [Rain-Fed]	365	328,5	401,5

Now that all the different parameters and how much they are changed are shown it is time to look at the results of the sensitivity analysis.

B.1.1 PMD

The first output variable that will be discussed is it water that will be at the reservoir of the PMD. This is the first stock of the model and can be considered the stock that changes the rest of the model. When looking at the sensitivity graph it can be seen that the variable is not affected that much by changes in parameters. The behaviour of the variable looks the same every time, it can be seen that the reservoir will first be filled and that

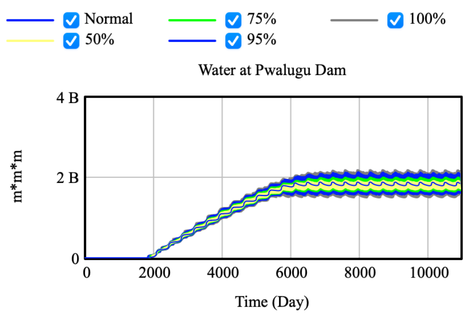


Figure B.1: Sensitivity: Water at PMD

once its filled the reservoir will stay on a certain water level but still oscillate from time to time. It can be seen that the changes in the parameters do affect the water at the reservoir a little, especially the maximum level and the filling time. But, these effects are all considered reasonable.

B.1.2 Riparian communities

When looking at the riparian communities, it can be seen that the water available at the riparian communities is not much affected by changes in the different parameters. This probably has to do with that the water at riparian communities is affected by a lot of different factors already which makes it pretty robust. Looking at the behaviour of the population of the riparian communities it can be seen that the total population can be affected by changes in different parameters. However, the growth tends to remain the same, under some parameters just a bit higher than others. But nothing that seems out of the ordinary.

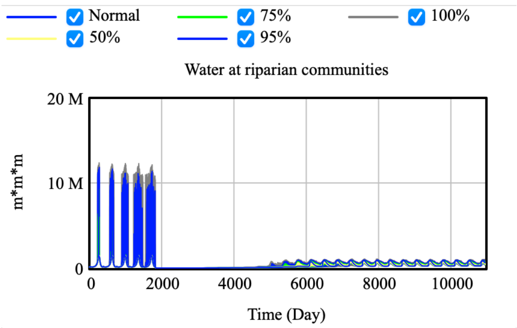


Figure B.2: Sensitivity: Water at riparian communities

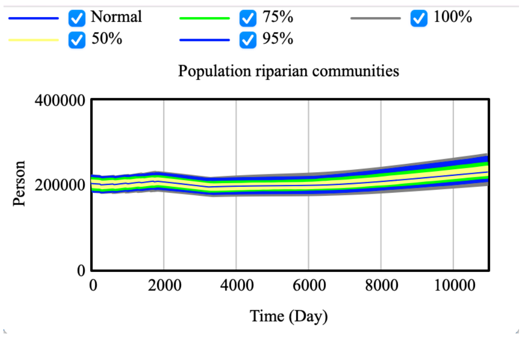
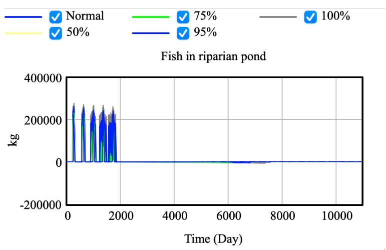


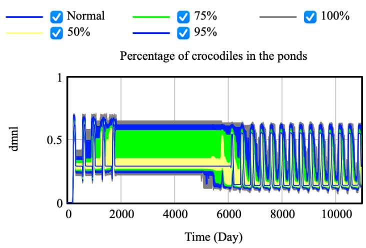
Figure B.3: Sensitivity: Riparian population

B.1.3 Riparian ponds

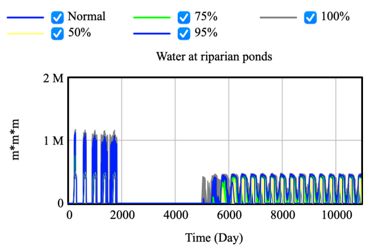
The riparian ponds have three outcome variables that could be affected by changes in parameters. Both the fish and water at riparian ponds variables have rather similar behaviour and both are not very affected by the changes in parameter values. This probably comes from the fact as that these variables are very low most of the time and then spike up at some point to then get back to their original value again. When looking at the crocodiles variable it can be seen that the variable is actually pretty sensitive to changes in parameters. The behaviour of the two crocodiles variables was already very sensitive, which can also be seen in the figure below. This probably comes from the fact that crocodiles will be able to move freely from ponds to the river and that this behaviour is pretty unpredictable.



(a) Fish



(b) Crocodiles



(c) Riparian ponds

Figure B.4: Sensitivity: Riparian ponds

B.1.4 Farmland

The last outcome variables that are considered are those of the farmland. Both the percentage of farmland that is used for irrigation and the total crops harvested variables show similar behaviour throughout the model and also show a similar sensitivity to changes in the parameters. Even though the sensitivity graphs shows that there can be quite some variance in the outcomes of these two variables the behaviour of the two remains the same and this shows that just like most of the other outcome variables the outcome variables regarding the farmland are not very sensitive to any changes in the parameters that are used within the model.

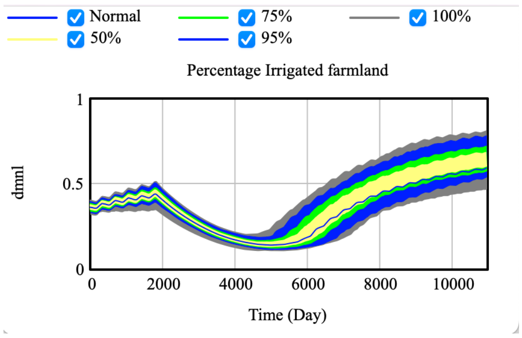


Figure B.5: Sensitivity: Irrigated Farmland

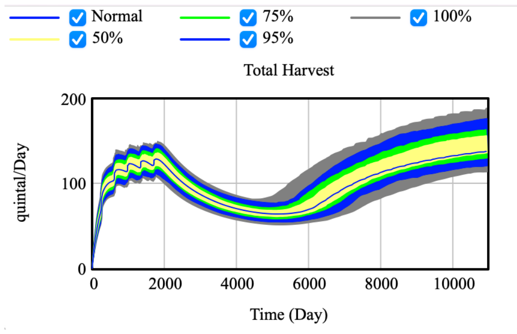


Figure B.6: Sensitivity: Total harvest

B.2 Flow Sensitivity Analysis

Now that the normal sensitivity analysis has been completed it is time to take a closer look into the different flows of the model and check how sensitive the stock are to percentage changes in the flows. The flows were all increased or decreased by 1 percent, the test aims to give an insight into how much this small change affects the stock values in the model.

B.2.1 PMD

First the flow sensitivity of the water at the PMD reservoir will be discussed. The figure shows that the behaviour of this stock will remain the same even with the changes in inflow or outflow. The reservoir will still need some time to fill up and once it's at a certain level the water level will only fluctuate slightly when there is a flood. Due to the fact that it is only a one percent change it can be seen that the variance between the different runs is actually very low.

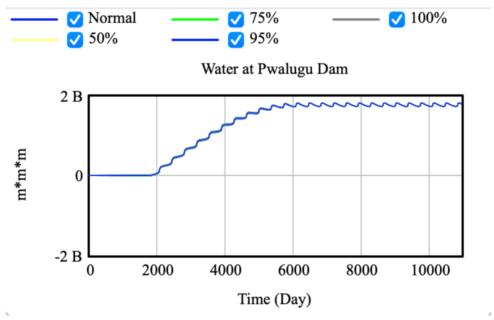


Figure B.7: Flow Sensitivity: Water at PMD

B.2.2 Riparian communities

When looking at the riparian communities it is hard to see any variance between the different run of the flow sensitivity analysis. This shows that both stocks are hardly affect at all by one percent changes in either inflow or outflows. This shows that both stocks can be considered pretty robust, meaning that changes in the flow variables affecting the stock don't lead to any unpredictable behaviour.

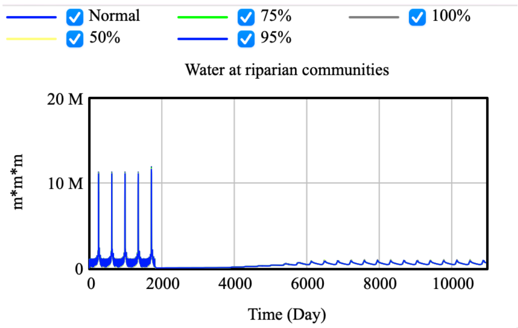


Figure B.8: Flow Sensitivity: Water at communities

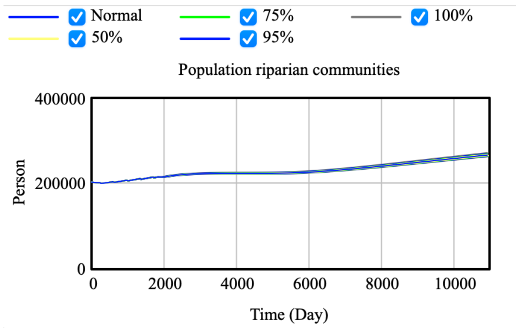
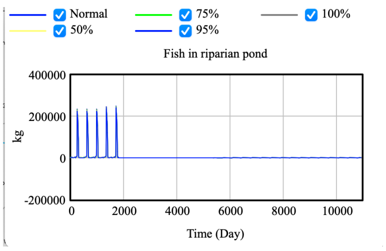


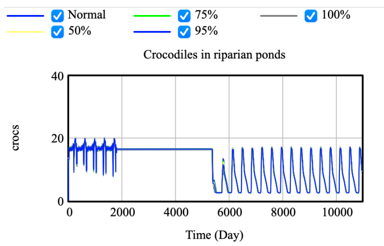
Figure B.9: Flow Sensitivity: Riparian population

B.2.3 Riparian ponds

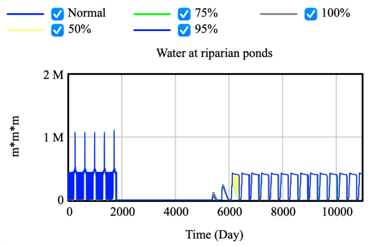
The riparian pond variables actually show similar behaviour during the flow sensitivity analysis as the variables at the riparian communities. As can be seen, all variables fluctuate quite a lot which makes it harder to determine how sensitive the stocks actually are to changes in the flows. Nevertheless, it can be seen that changes in the flows won't lead to entirely new behaviour of the stocks. This shows that the stocks are very robust and not very sensitive to any changes in the flows.



(a) Fish



(b) Crocodiles

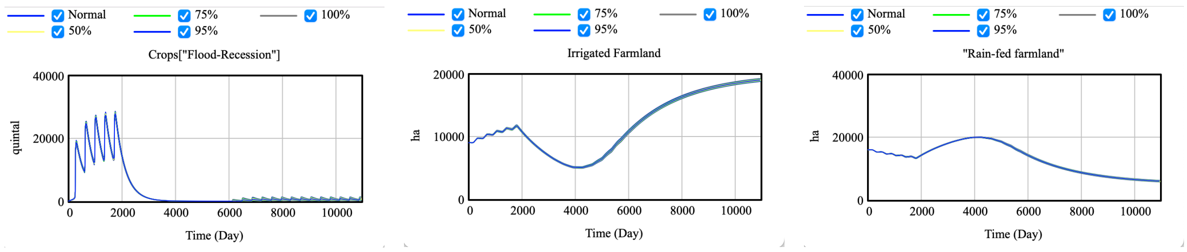


(c) Riparian ponds

Figure B.10: Flow Sensitivity: Riparian ponds

B.2.4 Farmland

Ultimately, the stocks regarding the farmland have been discussed. When look at the flow sensitivity graphs of these stocks it can again be seen that there is not a lot of variance between the different run. Which was also the case with all the previously analysed stocks. This shows that not one of the stocks can be considered sensitive when it comes to changes in the flows affecting the stocks. This is a good way to determine that the model is very robust and that the behaviour the model shows can be validated.



(a) Flood-recession (b) Irrigated (c) Rain-fed

Figure B.11: Flow Sensitivity: Farmland

B.2.5 Summary

So when looking back at the two different sensitivity analyses it can be seen that the outcome variables of the model are not very affected by changes in either the model parameters or the flows within the model. The different graphs show some variance of the output variables but this is always reasonable and never gets to a point where the behaviour of the outcome variable would be significantly different from the behaviour in the original model. This all shows that the outcome variables are actually pretty robust and not easily affected by changes in parameters or flows. This is important to determine as there are many uncertainties within the model. But as the sensitivity analyses show, the model won't be affected much by those uncertainties and thus can still be used as a valid model.

C Extreme value test

This appendix will look more closely into the process of the extreme value test, first the different parameters and their extreme values will be discussed. After that it is time to look into how the extreme values affected the model and if this validates the model.

Since the model contains a large number of parameters it would take up a lot of time to conduct an extreme value test for every parameter within the model. That is why it was determined to just investigate a few parameters in this test. The parameters where chosen in such a way that every sub-model will be affected by them at least once. This lead to the following table of parameters and their minimum and maximum value. These parameters will be discussed one by one.

Parameter	**Value**	**MIN**	**MAX**
Average Water Usage Per Capita	0,007	0,0002	0,2
Fish caught per effect	300	100	900
FR crops per cubic water	0,05	0,01	0,5
Livestock growth factor	0,00225	0,001	0,01
Normal Flood	1,00E+07	0	3,00E+07
Threshold flow crocs going back	300000	10000	800000
Value for Pond Flooding	400000	10000	800000
Water requirements agriculture	0,002	0,0009	0,01

Table C.1: Parameters extreme value test

C.1 Average water usage per capita

The extreme test of average water usage per capita means that the population either needs a very high amount of water per person or a very low. The graph in figure C.1 shows that the population is not affected much by the number of water needed. This can be due to the fact that there usually is sufficient water available. However, it can be seen that the population tend to grow a little less when more water is needed per capita. This is very plausible and the variable still shows reasonable behaviour.

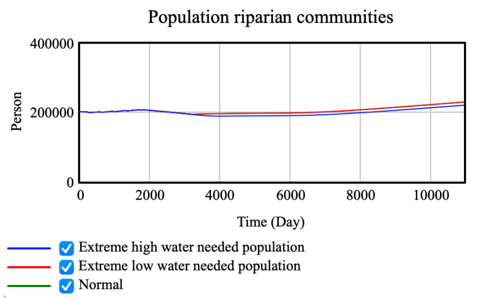


Figure C.1: Extreme water usage per capita

C.2 Fish caught per effect

The extreme values for fish caught per fish effect show a change in the behaviour of the fish population stock in the model. This makes sense since if the fish are not getting caught a lot the fish stock in the riparian pond will increase and it will take more fish effects to empty the pond. When the fish caught per effect is extremely high it will take very short in order to catch all the fish within the riparian pond. Even though the behaviour changes due to the extreme values it is still in line with what you would expect to happen, meaning that there is no problem with it and it can be considered valid.

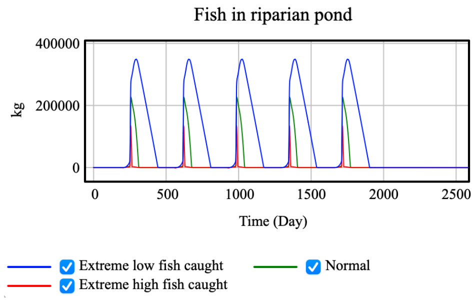


Figure C.2: Extreme fish catchment

C.3 FR crops per cubic water

If more flood-recession crops can be grown with one cubic meter of water there will be more crops for the same amount of water. This will mean that there will be more crops which can be seen in both the total flood-recession crops as well as in the percentage of total crops that are flood-recession. Nevertheless, when at the end of the simulation there is less water at the floodplains there tend to be less crops in all scenarios. Totally plausible behaviour.

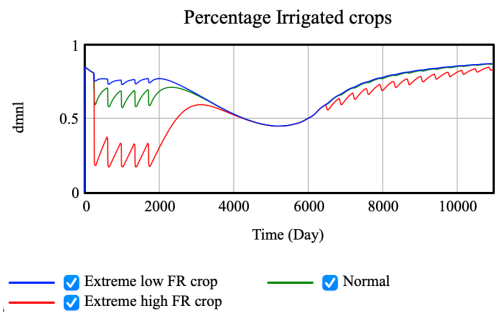


Figure C.3: Extreme FR crops, percentage of crops

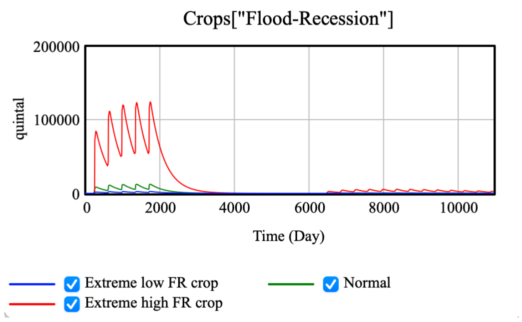


Figure C.4: Extreme FR crops

C.4 Livestock growth factor

When the growth factor of the livestock is extremely high it can be seen that the livestock population will increase drastically. The exact opposite happens when the livestock growth factor is extremely low. Nevertheless, the figure still shows that when there is less water due to the filling of the dam reservoir the livestock population will decline in all scenarios. Moreover, the livestock population seems more affected by a high growth factor than by a low growth factor.

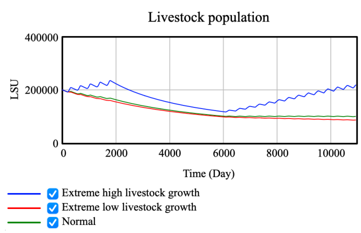


Figure C.5: Extreme livestock growth

C.5 Normal flood

When there are extremely high floods it can be seen that the dam reservoir will fill up more quickly. Additionally, once the reservoir is filled it can be seen that there is a higher fluctuation then there is in the normal or extremely low scenarios. When looking at the riparian ponds, it can be seen that the ponds will fill up way less when there are no floods, which is expectable. The extreme flooding does lead to a lot of water at the riparian ponds.

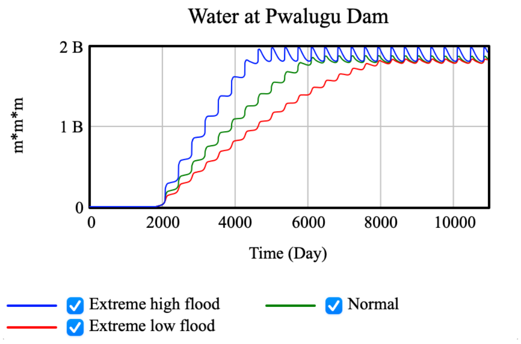


Figure C.6: Extreme floods dam reservoir

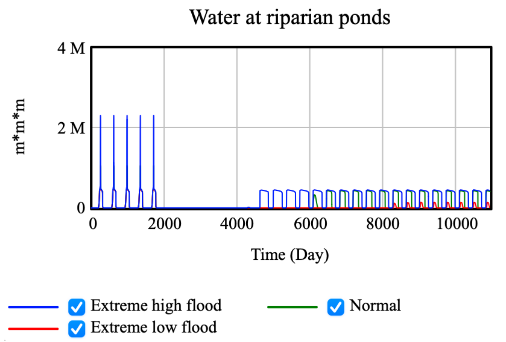


Figure C.7: Extreme Floods riparian ponds

C.6 Threshold flow crocs going back

When the threshold for crocodiles to go back to the river is high it means that more crocodiles will stay in the riparian ponds, this is also what can be seen in the figure. Additionally, it can be seen that when the threshold is lower, more crocodiles will go back to the river, meaning that the number of crocodiles at the riparian ponds will drop. The behaviour of the variable still remains the same, however sometimes its a bit higher or lower. This behaviour is still very dependent on the seasonal flooding as you can see that there tend to be an annual increase during the wet season.

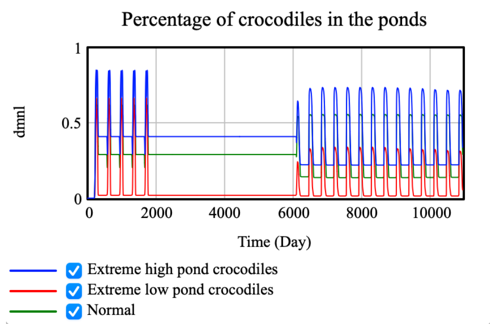


Figure C.8: Extreme crocodiles

C.7 Value for pond flooding

When the threshold for pond flooding is lower, the ponds will flood more often and this can also be seen in the figure where the ponds will not be emptied again. The number of crocodiles is also a bit effected by the threshold for pond flooding, because when the ponds don't flood it won't be attractive for crocodiles to move to the ponds.

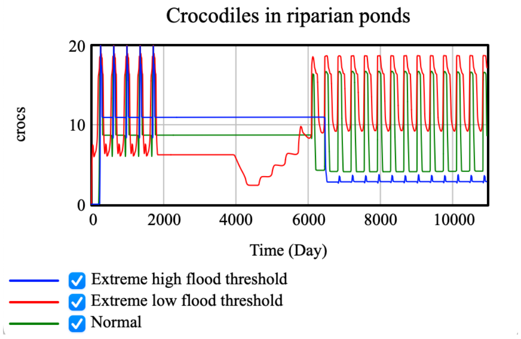


Figure C.9: Extreme water at ponds, crocodiles

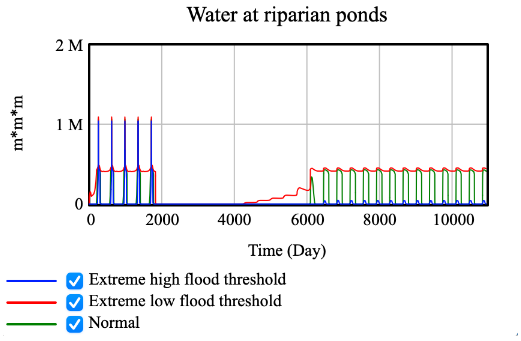


Figure C.10: Extreme water at ponds

C.8 Water requirements agriculture

If growing irrigated crops requires more water, it can be seen that there will be less irrigated crops grown and the farmland area will be smaller as there is not enough water to cover the whole area with irrigated crops. Moreover, when the irrigated crops need less water both the number of crops as well as the area of the farmland will increase. Here it can also be seen that the main behaviour of the variable will remain the same as the number of crops will drops when the reservoir is being filled and once it reservoir is full the number will increase again.

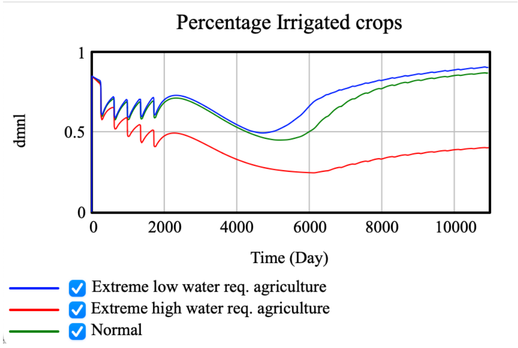


Figure C.11: Extreme water requirements crops

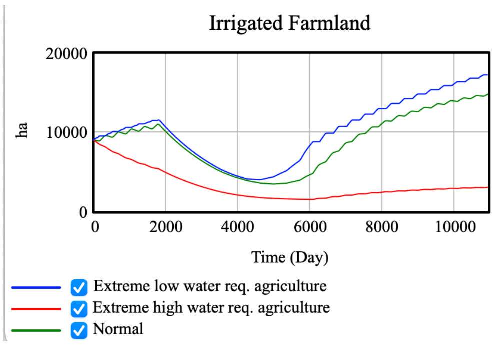


Figure C.12: Extreme water requirements farmland

C.9 Summary

To conclude, it can be seen that all the different extreme value of the different parameters in the different sub-models affect certain output variables. However, as they might increase or decrease, the behaviour remains mostly the same. This shows that the model is robust and that an extreme value won't affect the behaviour of the model too much and won't cause the model to produce wrong outcomes. No output variable shows any outcomes that are contrary to any physical law, for example, there are no stocks which turn negative due to some extreme value. Thus, it can be concluded that the model can be considered valid when it comes to extreme values, bearing in mind that only a number of parameters have been taken into account.

D Interview Questions

D.1 Interview Questions Afua/Hammond

Agriculture

- How much do people in North East Ghana rely on agriculture?
- How much of the water they have available goes to agriculture?
- What will the irrigation system look like? And how much of the irrigation scheme provided by the PMD will be used by residents of the riparian communities?
- How hard will it be for people at the riparian communities to change from rain-fed/flood recession agriculture to irrigation?
- When there is not sufficient water for irrigation will the area be used as rain fed agriculture? Is it possible to switch this up?
- Is flooding a regular issue in north eastern ghana and how much crops are affected by floods?
- Are the crops that are grown all used for own consumption or sometimes also sent to southern parts of Ghana?

Fish

- How big of a role do fish play in the diet of people at the riparian communities?
- Do you have an estimation of how long it takes the people to fish the entire pond?
- Do you have any idea how much fish there is in the river and the ponds?

Crocodiles

- How many crocodiles are there in the White Volta River basin?
- Do crocodiles move a lot between the ponds and the river?
- How many crocodiles are there at the ponds?
- How high must the water level be for crocodiles to move to the riparian ponds?
- Do you know about the spiritual values that crocodiles have in Northern Eastern Ghana?

Livestock

- What is the average lifetime of livestock?
- Are livestock important to the lives of Ghanaian people?
- Do they have any spiritual value?

- How much livestock is sold on the market?
- Do people eat their own livestock or do they just use their products?
- How much livestock is there at the riparian communities compared to people?
- How much water does livestock need daily? From the ponds or holes?

Flooding

- At what water level will the river flood?
- How long do floods last?
- How high must a flood be to cause damage?
- How many casualties have floods caused the last few years?
- Have recent years shown any effects of climate change and in what forms?

Riparian ponds

- Do people use a lot of water from the ponds for domestic use?
- Will riparian ponds dry up totally in the dry season?

Governance

- How were the plans of the construction of the PMD received within the government as well as among the local communities?
- Were local communities taken into account in the decision-making process regarding the PMD?
- How much does the narrative of the government getting things do by putting up something concrete like a dam influence the decision-making regarding the construction of the PMD?

Pwalugu Dam

- What would be the optimal level of water in the reservoir?
- What would different operation strategies of the dam be?
- What are possible flood scenarios?
- What kind of outflow is most beneficial for the irrigation system and does this affect the riparian communities as they are located in between the irrigation system and the dam?

D.2 Interview Questions Mawell Boateng/Kwame Darkwah

- Have you seen any effects of climate change over the last few years when looking at the inflow of the dam reservoir?
- How much could an Early Warning System help with managing the water level at the dam? How many days should it be prior to a flood?
- How does the decision-making process regarding the outflow of the dam happen? Clear rules or discussions?
- How is the contact between you and the other dam operators along the river, both in upstream Burkina Faso as in more downstream Ghana?
- Do you see many similarities between the construction of the Akosombo Dam in the 1960s and the current construction of the PMD?
- Will the energy generated at the PMD be used mainly in the North?
- Will the construction of the PMD have any effects on Akosombo?

D.3 Interview Questions Riparian Communities

Agriculture

- How many days a year do you work on the farmland?
- Do you eat a lot of products that you grow yourself?
- Would you change your rain-fed agriculture to irrigated agriculture if possible?
- Does it happen often that a harvest fails, due to flooding or delays or rain?
- How often do you go to the market to buy food?

Fish

- How often do you eat fish?
- Are there any fish at the end of the dry season in the ponds?
- Do you fish in the riparian ponds? How much do you catch when you do?

Crocodiles

- Do you see a lot of crocodiles in the White Volta River basin?
- Do crocodiles move a lot between the ponds and the river?
- How many crocodiles are there at the ponds?
- How high must the water level be for crocodiles to move to the riparian ponds?
- What value do the crocodiles have to you?

Livestock

- How old is the livestock you have?
- What is the main function of livestock to you? Food?
- Do you ever buy or sell livestock at the market? Does this happen often?
- How often do you consume livestock?
- Do all the people in the Northern communities own livestock?
- Where do you get water for your livestock? From the ponds or holes?

Flooding

- At what water level will the river flood? Can you show me a landmark that the water reaches during a flood?
- How long do floods last?
- How high must a flood be to cause damage?
- How many casualties have floods caused the last few years?
- Have recent years shown any effects of climate change and in what forms?

Riparian ponds

- Where do you get your water for domestic usage?
- Will there be water at the riparian ponds at the end of the dry season?

Governance

- When did the government inform you on the plans of the construction of the PMD?
- Does the construction of the PMD have any effects on your life as it is today?
- Has the government promised you some kind of compensation for the construction of the PMD?
- Do you have any electricity in the town?

Pwalugu Dam

- What would be the optimal level of water in the reservoir?
- What would different operation strategies of the dam be?
- What are possible flood scenarios?
- What kind of outflow is most beneficial for the irrigation system and does this affect the riparian communities as they are located in between the irrigation system and the dam?

D.4 Interview Questions PMD Directorate

- How much will the area of irrigated farmland increase due to the construction of the PMD?
- How much water is needed for irrigated farming and how will the water go there?
- Is the irrigated farmland located upstream or downstream of the local communities?
- Do you have an idea how the construction of the dam could affect the fish population in the white volta river?
- How many casualties have floods caused the last few years?
- How do upstream dams of Burkina Faso affect flooding in Ghana? Are there talks on working together to reduce these risks?
- What would be the optimal level of PMD reservoir in order to prevent flooding?
- With the introduction of the PMD, which will cause a high steady flow and less floods, will the riparian ponds still fill up?
- Do the riparian communities have any electricity and how will the PMD change this?
- What would different operation strategies of the dam be? And what is the main focus when looking at operations?
- Are there more advantages of the dam apart from flood mitigation, irrigation, and electricity generation?
- How will the dam deal with high floods caused by either high precipitation or by high spillage at Bagre dam?
- At what height are the spillway gates of the reservoir?
- What is the minimal level of water at the reservoir in order for the dam to be operational?

E Interview Summaries

E.1 Interview Hammond Antwi Sarpong

Hammond Antwi Sarpong is a PHD researcher at Dundalk Institute of Technology in Ireland currently working at Delft University of Technology. He was born and raised in Ghana which makes him a very interesting person to interview as he can give me better insight into what life is like in the Northern region of Ghana. This will help me massively with validating the quantitative model as it gives me better insight into how the system exactly works.

Regarding the local communities in the Northern Region of Ghana, Hammond told me that most of the people work in agriculture, while the rest of the people work in the more public sectors like education. Most of the crops that are grown are used for own consumption while the remaining crops will be sold on the local market for a certain fee or traded with other goods. As most of the farming is either flood-recession or rain-fed, due to the lack of water in the dry season, the crops are harvested only once a year. The rest of there are not much farming activities. The construction of the PMD will lead to a higher baseflow, which could be beneficial for irrigation farming, and less flooding, which causes loss of crops. If there is more water available the agricultural sector can be expanded which would bring more economic prosperity to the still underdeveloped Northern Region. This economic prosperity will also make it less appealing for people to migrate to the Southern parts of Ghana.

This shows that the construction of the dam and the policymaking behind it has much to do with the policies of the parliament regarding the one district one dam. However, the dam will definitely have advantages and is not only constructed because the government wants to build something concrete. Pwalugu also used to be an economic district as it had a tomato factory which recently closed, so it seems like a logical decision to construct the dam over here. Nevertheless, where the actual dam and the irrigation schemes will be sited depends on the government and also the local chiefs. As the government would probably locate these close to where they got a lot of supporters and the local chiefs also have a big say in this. This can also be seen when looking at the location of the current boreholes that provide the communities with water resources. Sometimes these holes are next to the house of the chief and sometimes they are located a few kilometers away from the town.

When looking at the effects the dam has on the water at the riparian ponds and communities it can be clear that the dam will cause a higher base rate and will make the communities less prone to high spillage at the upstream Bagre Dam. However, some good cooperation between Ghana and Burkina Faso could really help that even more and could make operations at the PMD a lot easier. Even though the dam causes less floods, it does not mean that the riparian ponds won't fill anymore as there will still be enough water during the wet season to fill the ponds. This is important as the communities rely on the fish that live in the riparian ponds as these will provide them food at the end of the dry season. Fish is an important part of the diet of people at the riparian communities as they consume it more than meat and is actually cheaper than fish in the southern part of Ghana which is at the ocean.

Another value the riparian ponds have has to do with the crocodiles that live there occasionally. These crocodiles do of course not have any economic value, however they do have a big spiritual value to the people at the riparian communities. As the local communities believe that the crocodiles in the ponds are their ancestors that passed away. This means that they consider the crocodiles that live in the riparian ponds as good while the ones living in the river are considered dangerous. But as already said before, even after the construction of the PMD the riparian ponds will still be filled which means that crocodiles will still come there.

Other animals that have spiritual value are livestock, especially cows. They are seen as a status symbol which leads to poor people sometimes living in poor conditions but still having a few cows. As they are a symbol of status, people at the riparian communities don't eat them a lot, usually only at special occasions, however they do use their products like dairy. Livestock is sometimes sold on the markets as well, for example when people need the money for example for paying for education of their kids. All this livestock also needs to be watered, and usually the water from the riparian ponds is used for this as well as the water from the boreholes. The PMD will help provide water all year round for this.

E.2 Interview Summary Afua Owusu

Afua Owusu is a joint PHD researcher at Delft University of Technology and IHE Delft Institute for Water Education. She is from the Southern parts of Ghana, but she has done some field research in the Northern Region. This in combination with her expertise in the field of hydrology makes her a very interesting subject to interview. As she can tell me more about the Northern Region in Ghana as well as providing me with a better understanding of how the White Volta River system might be influenced by the construction and operation of the PMD.

Afua told me some interesting facts regarding the governance behind the PMD. So was it already determined in the 1960s that Pwalugu would be a great site for a dam. This was at the time that previous dams like Akosombo and Bui were also discussed. This means that the idea of constructing a dam in Pwalugu has been there for a long time and now it is finally time to realise it. Due to the plans being dated such a long time ago, the construction of the dam will not lead to a lot of displacement as most of the area has already been reserved for the dam. This is a huge relief for the local communities as they don't have to move their entire households which happened when Lake Volta was created.

It is expected that construction of the PMD will create a higher base flow just like the Bagre Dam in Burkina Faso did. The high spillage of the Bagre Dam in the wet season could cause high spillage in Northern Ghana even though they warn the communities nowadays cooperation is still not optimal. The PMD will help mitigate the flood risk in the Northern Region caused by spillage or heavy precipitation. The higher base flow that will be created by the PMD will be beneficial for irrigated farming. This also seems the most important feature of the dam as the Northern Region of Ghana has great conditions to grow crops apart from the lack of water, the PMD could possibly solve this problem. However, it is not clear whether the local communities will actually benefit from this, as they mainly focus on either rainfed or flood-recession farming and if the river loses its seasonality they won't be able to do this. Of course for irrigated farming this is beneficial, however these farms will become commercial farms owned by large corporations. This means that local communities won't benefit much from this.

The local chiefs are taken into consideration during the decision-making process regarding the PMD. However, this does not always mean that local communities will benefit from the PMD as these negotiations don't always lead to good solutions. This has to do with the fact that there is a lot of information asymmetry in these negotiations as the local chiefs lack knowledge of how the flow of the water actually works. Moreover, the benefits for the local communities are usually overestimated, while the costs are underestimated. For locals it must sound appealing that they will have water available the whole year round, however they forget about the fact that their way of farming actually depends on the seasonality of the river.

The introduction of the PMD to the White Volta River system will also lead to the riparian ponds filling up to a lesser extent or maybe not even filling up at all. This depends on how far they are located from the river. These riparian ponds are important to the people at the local communities. Which again is something that they hopefully took into account when deciding about the construction of the PMD, but it's uncertain.

E.3 Interview Maxwell Boateng Gyimah

Maxwell Boateng Gyimah is a project coordinator at Water Resources Commission (WRC) in Ghana. He constructs model that take a closer look into the Volta River Basin, which means that he has a lot of information about how the system works and how dependent Ghana is over certain countries for their water inflow. He especially investigated Lake Volta and how the creation of this enormous lake has changed the lives of many people living in the surrounding areas of it and what kind of flow regimes the Akosombo dam could use to restore the natural conditions around there.

Maxwell looked closely at how dam operation at the Akosombo dam could be changed and re-optimised to restore the natural conditions. As the creation of the Akosombo dam in the 1960 caused the whole environment to change around there, people were first dependent on the seasonal flooding of the river and the construction of the Akosombo dam caused a higher base rate of the river without much seasonal flooding. When the river finally flooded again in 2010, the people had become so accustomed to the steady base rate that they didn't like the occasional flooding since it ruined their crops. When asked if the same thing could happen in Pwalugu, Maxwell says yes, he says that the same could happen around there as well as people depend on the seasonality of the river right now and that it is not sure how much the local communities will benefit from possible irrigation schemes. Additionally, he states that the dam could mean that the costs of living will go up as there will be more economic activity around the community, however the local people will not see an increase in their welfare. A way to slightly tackle this at the Akosombo dam was to provide the local communities with some irrigation schemes, this made it possible for them to keep working I agriculture and to also have some benefit from the construction of the dam. The major benefit in the north would be to go from one harvest per year to a harvest all year round due to irrigation.

Compared to Akosombo the power that will be generated at the Pwalugu dam can almost be disregarded. The Akosombo generates up to 30 percent of the total energy demand of the entire Ghanaian population. Most of this hydropower is used as a buffer when other demand sources can't be used. Moreover, some of the hydropower get exported to neighboring countries. Maxwell also talks about how Ghana is in quite a vulnerable position, as it is located downstream of all the rivers. Which basically means they are the last in line to receive water at if upstream countries decided to dam the rivers Ghana could lose a lot of its water. The development of the Bagre Dam already showed this. However, it only caused a 1 percent drop of the water in Lake Volta. The Bagre dam however does cause huge spillages at the end of the wet season when the rivers in Ghana are already very full which can cause some serious flooding. The construction of the Pwalugu Dam will help prevent this from happening to some extent, as the reservoir will mostly be used to mitigate flooding as the amount of hydropower, they can create there is not even close to the amount at Akosombo.

To tackle this problem, the Western African countries have together formed the Volta Basin Authority which aims to improve the cooperation in the basin and make sure that no country gets left behind. This authority was found in combination with the water charter. This cooperation between the different countries could have benefits for all as Ghana won't be exposed in its weak downstream position, while other countries can benefit from water from Ghana or hydropower which is generated at Akosombo dam which can be send to other countries using the West Africa Power Pool.

E.4 Interview Kwame Darkwah

Kwame Darkwah is a senior system planning engineer at the Volta River Authority (VRA). The VRA is an electricity company and Ghana that is responsible for the construction and operation of the Pwalugu Dam. It also operates the Akosombo and Kpong dams and Kwame contributes to the planning of the Akosombo reservoir, in which he needs to focus on energy demand but also inflow forecasting of the reservoir. Even though the VRA is responsible for the operation of the dams, this does not mean that they can just operate it in the manner that will be most beneficial to them. They must do a lot of stakeholder engagement regarding the operation of the dams. Hence, they meet with the energy commission as well as with the Environmental protection agency (EPA), which must make sure that the construction and operation of the dam does not decrease the natural habitat of certain species. There is also a committee that regularly checks whether the VRA are complying with the regulations.

Kwame explains that the construction of the Akosombo has doubled the e-flows that were around the area before. This comes from the fact that 2 out of 6 turbines are constantly operating. This provides electricity stability for Ghana and its big cities. This means that in the event of a power outage the electricity generated at Akosombo dam can reignite the power in Ghana. As hydropower is considered cheap, there can be political pressure to generate as much hydropower as possible. Nevertheless, the Akosombo dam nowadays only provides 30 percent of the electricity used in Ghana. This has to do with the increasing population of Ghana and the increasing energy demand. However, Kwame does not think the Akosombo dam will vanish any time soon as hydropower is rather cheap compared to other ways to generate power.

When looking at the risk the Akosombo will have to deal with in the future, Kwame says that climate change will influence the operation at the dam. However, the reservoir of the dam is around 144 billion cubic meters, making it the largest in the world. This means that operation at the Akosombo dam will only be marginally affected by changes in inflow. The reservoir is so big that if there is no inflow for three years the dam can still operate at firm capacity. Moreover, the inflow at Lake Volta could be affected by other countries using more water of the river as Ghana is downstream, however Kwame does not believe that other countries will exploit this weak position of Ghana as they depend on Ghana for hydropower and the Volta Basin Authority is there to mediate between the different countries and their priorities.

Ultimately, we discussed the construction of the Pwalugu dam. Pwalugu has been on the agenda ever since the 1960s and now will finally be constructed. The dam will generate both hydropower as well as solar and combined these two should be around 110 MW. When looking at the effect the dam will have on the local communities, Kwame hopes that lessons have been learned from the Akosombo dam and that things will be done better this time, so that people get the compensation they deserve. He also states that the North can't be compared to Akosombo that much as the area in the north is flatter than at Akosombo. Additionally, the dam will help bring more economic prosperity to a still underdeveloped Northern Ghana as it will generate electricity which will be used here instead of generating electricity in the south and then transporting it to the north which loses some of the power. Also ,there will be more irrigation and the PMD will help mitigate flooding caused by spillage at the Bagre dam. However, the dam won't prevent the north from floods entirely as there will still be a flood every 15 years.

E.5 Interview Riparian Communities

During my trip to Ghana, I had some time to look around the different riparian communities that will be affected by the construction of the PMD, some will be having to be relocated while other communities will just be affected by the operation of the dam. When looking around these communities, it is like time has stood still. The people still live in rather primitive houses, and they all work on the farmland. Even compared to other Ghanaian cities like Accra, Bolgatanga and Tamale the difference is very big. Someone at the community told me that the farms at the community mostly use rainwater or water from the boreholes for their farming. However, there are also people living in the community that have a farm closer to the river and thus depend more on the flood-recession farming or even fishing from the river.

When asked if they have heard about the PMD they all say they have. However, they have no clear idea on when the construction of the dam will start, where it will be, how big the reservoir will be exactly and most important of all, if their life will be changed due to the dam and if they will be compensated for this accordingly. They all think the dam could have both benefits and costs. One of the benefits they state is that the dam will provide more water for them and that the dam will prevent flooding from happening. On the other side they are scared that people will fall in the reservoir and die, and that the reservoir that will be created will reduce their area of farmland.

One person also showed me that a few weeks ago there were people that marked all the houses as their community will have to be resettled. This is of course one of the biggest effects of the big reservoir that will be filled. The person tells me that they just came to mark the houses but that they did not inform them much about the resettlement. They all say that the chiefs have been engaged in the policy making however they don't know how exactly this will affected the construction and operation of the dam.

All in all, there are still a lot of unknowns to the people at the riparian communities. Maybe I just spoke with the wrong people, but these people don't seem to know the exact details of the PMD and when it will be built. I also looked around the area of the river myself but could not find anything that could suggest a possible construction site. An interesting finding was a village that was being constructed for people that will be resettled. However, it turned out that the people that will be resettled live in an area where there is gold in the ground so they will start mining there. Maybe the sudden discovery of gold in the area has put the construction of the PMD on hold.

E.6 Interview Pwalugu Multipurpose Dam Directorate

During my trip to Ghana, I had a meeting at the Pwalugu Dam Directorate with Daniel Onny, who is the manager at the office, several other people working at the directorate joined the meeting as well. There was somewhere who focused on the resettlement of the communities, a civil engineer, someone who put special attention towards sustainability and an expert in the field of agriculture. The meeting starting with them presenting the project to us, during this presentation they showed us the details regarding the construction and operation of the PMD, what the benefits would be and what the different impacts would be.

The benefits discussed during the presentation show that apart from the three main benefits of the dam, flood mitigation, hydropower generation, and irrigation, the VRA believes that the project will also bring more prosperity to the northern region of Ghana in the form of more economic activity and tourism. Figures also showed that the last few years a lot of people in the north were affected by flooding in the area. Meaning every year there would at least be some casualties and a few thousand people affected by floods. When looking at the irrigation scheme for the PMD the VRA showed that some area will be used for commercial farming while other parts will be used for small farmers who lived in the communities affected. The irrigation scheme will use both gravity and pumping. This shows that the irrigation will have both local and national benefits as some will be used for commercial farming and export to the south while other parts of the farmland will be used for livelihood farming of small farmers. However, it is unknown which part will be prioritised once there is not enough water for the entire farmland.

Regarding the resettlement of the communities living in the future reservoir, the presentation shows that there are six communities which must be resettled, and they will be compensated, and financial compensation only is not allowed. The communities can choose where exactly they want to be resettled and the VRA will provide them with land and jobs too. Which would really help them building up a still rather poor Northern region. The power that will be generated at the PMD, 50 MW solar and 60 MW hydropower, will mainly be distributed in the north too.

When looking at potential operation strategies for the PMD the VRA concluded that if they want to optimise hydropower generation at the dam it would not be able to mitigate any floods. Since the amount of hydropower that will be generated is almost negligible compared to other power sources like Akosombo it was decided that the dam operating strategy would first focus on flood mitigation and after that look at hydropower generation. As not all the different benefits can't all be optimised. Regarding the filling of the reservoir the directorate believes that they can fill it within a year. All and all the Pwalugu Multipurpose Dam Directorate really believes that the construction of the dam will be a success both nationally but especially locally as most of the benefits will be for Northern region. However the lives of the local communities will be changed significantly and it's still unknown how well they will adopt to a new situation.

F Results

In this appendix the results of all the experiments will be analysed. Since there are 4 different weather conditions and 4 different dam operating strategies, this appendix will have 8 sub-chapters which all focus of a specific condition or operating strategy. When a condition is taken a closer look at it means that all the different operating strategies will be shown under these circumstances. When one dam operating strategy is analysed it will look at how it behaves under different circumstances.

F.1 Normal Conditions

This sub-chapter will take a closer look at what the effect of different dam operating strategies is on the different KPIs under normal conditions.

F.1.1 Dam

When looking at the water level at the PMD reservoir, the full dam strategy will lead to the highest water level at the reservoir. Which seems plausible as it mostly focuses of getting a high level at the dam to generate more hydropower. It is also interesting to see that the artificial flooding scenario will have the same water level at the PMD as the base run. The prioritization of the farmland and the flood buffer will have a lower water level as they will let more water through to use for irrigation or to keep the water level low to mitigate floods.

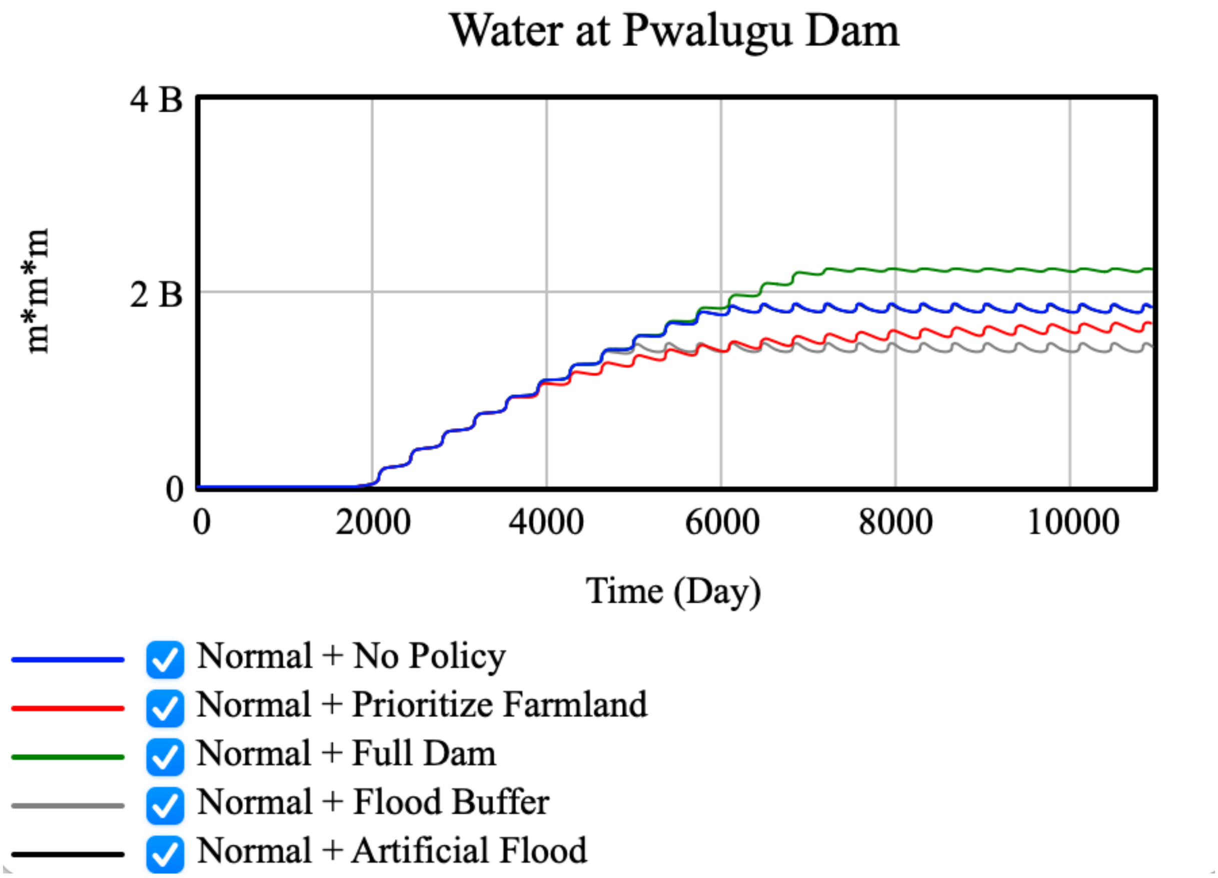
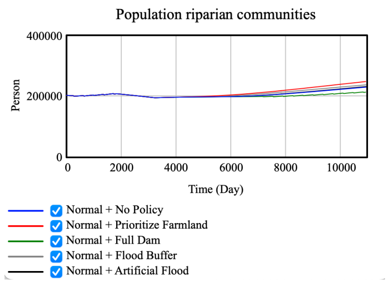


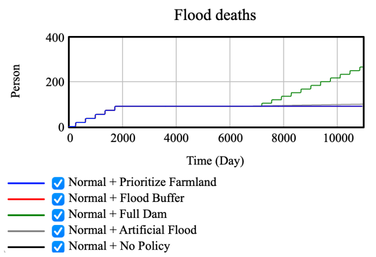
Figure F.1: Normal: Water at PMD

F.1.2 Riparian Communities

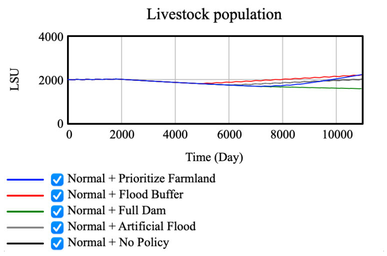
The riparian population increases when the farmland is prioritised, as this will lead to a lot of water downstream and there will be more crops grown. The flood buffer also led to a higher population than the base run as it lets more water pass through for the communities to keep the flood buffer. The full dam strategy leads to a lower population as more water will be stored in the reservoir. When looking at the flood casualties a full dam will be very risky and will cause the most casualties while the other operating strategies barely cause any casualties. Livestock is also affected by water availability downstream, meaning that the prioritization of farmland and the flood buffer will cause the highest growth of the livestock population



(a) Population Communities



(b) Flood Casualties



(c) Livestock population

Figure F.2: Normal: Riparian Communities

F.1.3 Riparian ponds

The riparian ponds benefit from seasonal flooding, this means that the artificial flooding and the full dam will lead to more fish and crocodiles at the ponds as there will be more flooding. The flood buffer and prioritise farmland strategies will spill water more regularly and thus prevent flooding which means there won't be much water at the riparian ponds.

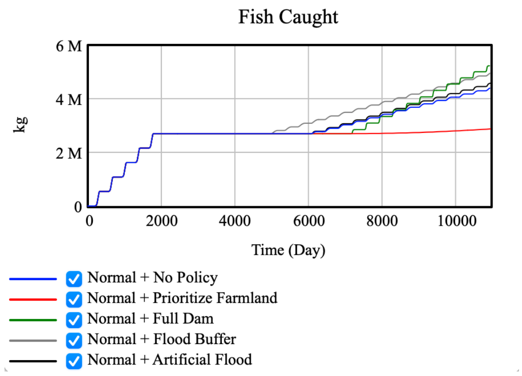


Figure F.3: Normal: Fish caught

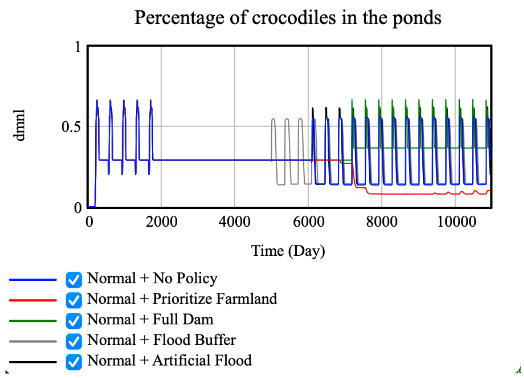


Figure F.4: Normal: Crocodiles

F.1.4 Farmland

The two KPIs regarding the farmland are both increasing the most during the flood buffer and prioritise farmland strategies as these strategies will let more water pass through the dam and this means there will be more water available at the farmland so the percentage of irrigated crops and farmland will grow.

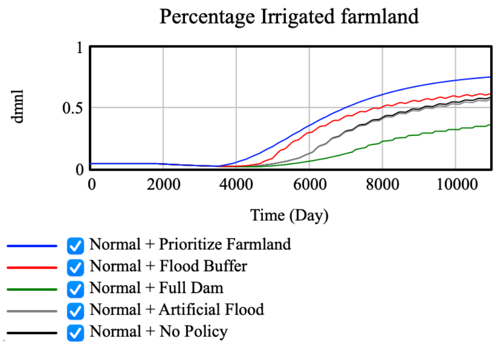


Figure F.5: Normal: Farmland

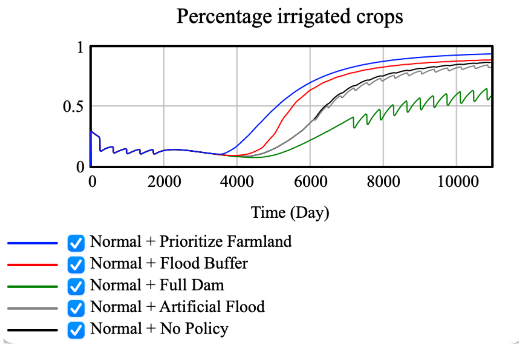


Figure F.6: Normal: Crops harvested

F.2 Dry Conditions

This sub-chapter will take a closer look at what the effect of different dam operating strategies is on the different KPIs under dry conditions.

F.2.1 Dam

The dry conditions show that it will take longer to fill the reservoir and some strategies will lead to a lower water level at the PMD as more water will need to be passed through to serve the downstream needs for either irrigation or to remain the flood buffer of the dam. The full dam strategy will however still fill up the reservoir the most which means it can generate the most hydropower.

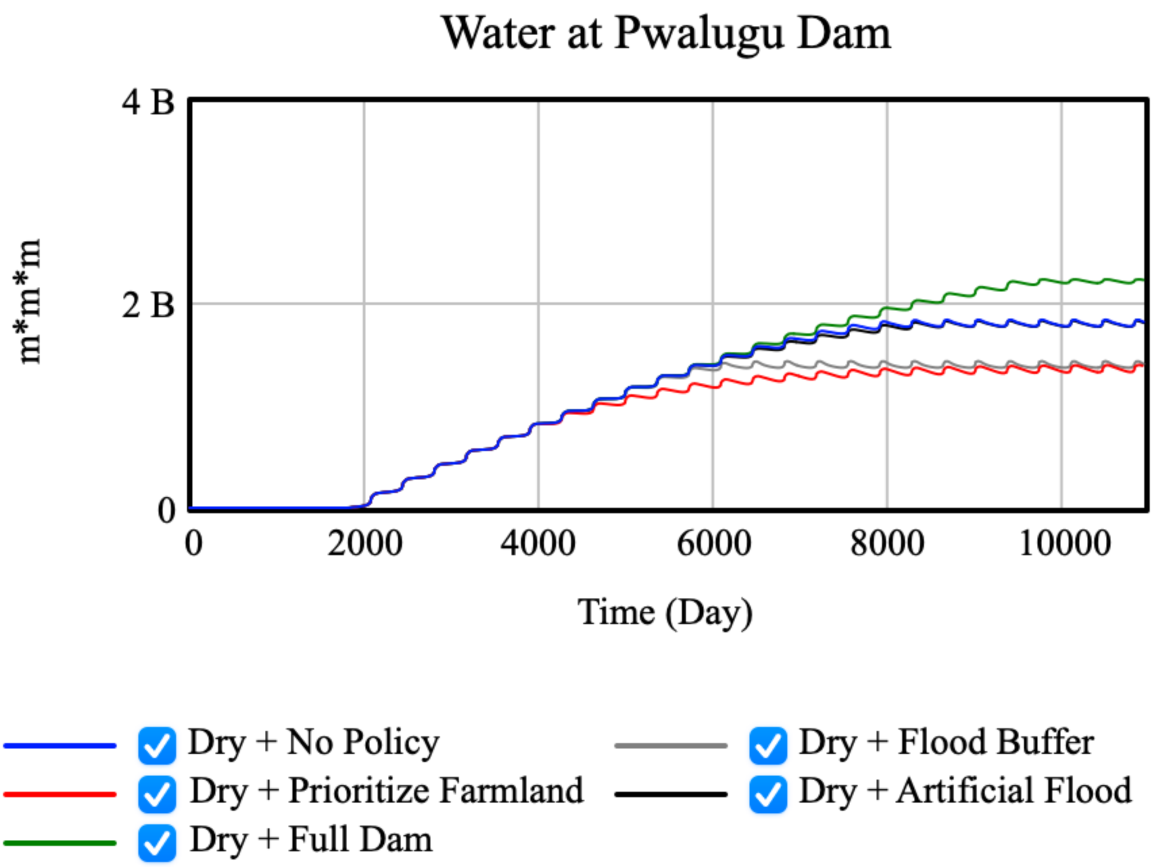
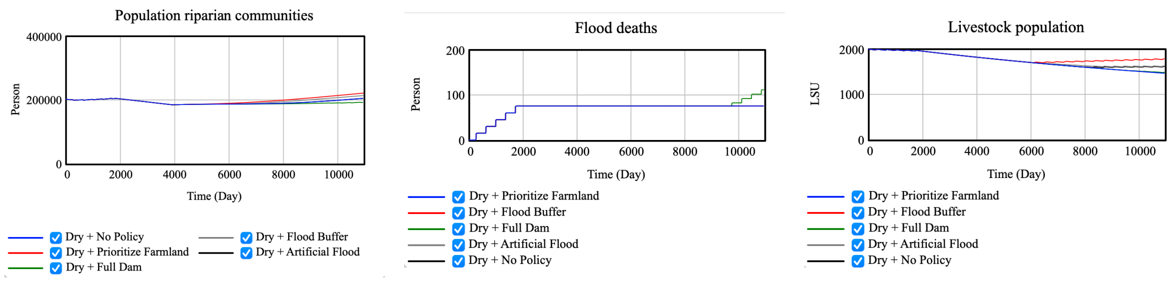


Figure F.7: Dry: Water at PMD

F.2.2 Riparian Communities

The riparian communities won't grow much during dry conditions, which also makes it harder to determine which strategy will benefit the population growth the most. However again the prioritizing of the farmland and the flood buffer will help the communities grow the most. Due to the dry conditions, there barely will be any flood casualties, however the risk of the full dam still leads to some casualties down the line. Livestock is also suffering greatly from the dry conditions, meaning that in with every strategy the population will still decrease. However, the flood buffer will lead to the smallest decrease as it will pass through the most water.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure F.8: Dry: Riparian Communities

F.2.3 Riparian ponds

As the dry conditions will make it harder for the water to reach the riparian ponds, the fish and crocodile population will also decrease. Looking at the fish graph, there won't be many fish caught once the dam is operational under dry circumstances. The flood buffer will lead to the most fish. The number of crocodiles also drops mightily under dry circumstances however some flooding with a full dam reservoir will increase the percentage of crocs at the ponds.

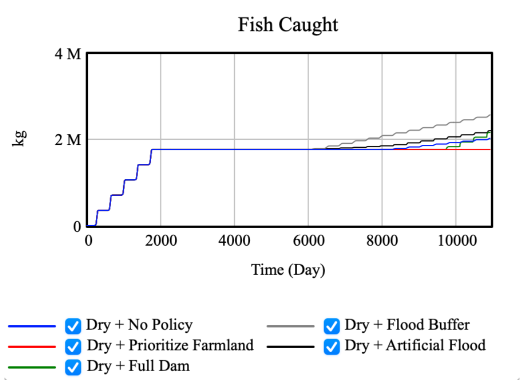


Figure F.9: Dry: Fish caught

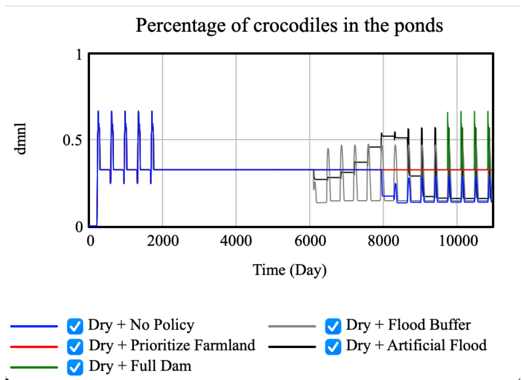


Figure F.10: Dry: Crocodiles

F.2.4 Farmland

Even though there are dry conditions the percentage of irrigated farmland still grows, as the dam will cause a steadier base rate which is necessary for irrigation. The higher this steady base rate is the higher the percentage of irrigated farmland and crops will be.

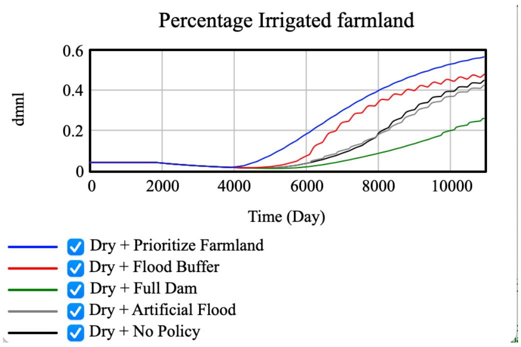


Figure F.11: Dry: Farmland

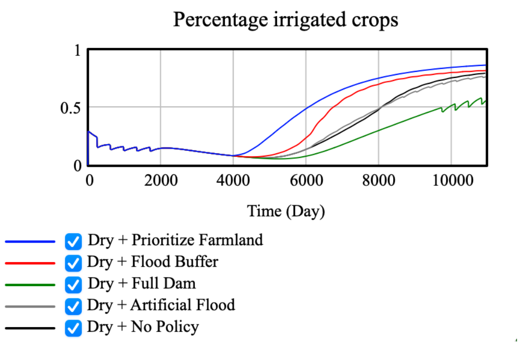


Figure F.12: Dry: Crops harvested

F.3 Wet Conditions

This sub-chapter will take a closer look at what the effect of different dam operating strategies is on the different KPIs under wet conditions.

F.3.1 Dam

Under wet circumstances the dam fills up a lot faster, the graph shows that when the full dam policy is implemented the water level will be at the highest point. All the other strategies have around the same water level. Apart from the flood buffer that strategy purposely keeps the water level at the dam below a certain amount to mitigate floods.

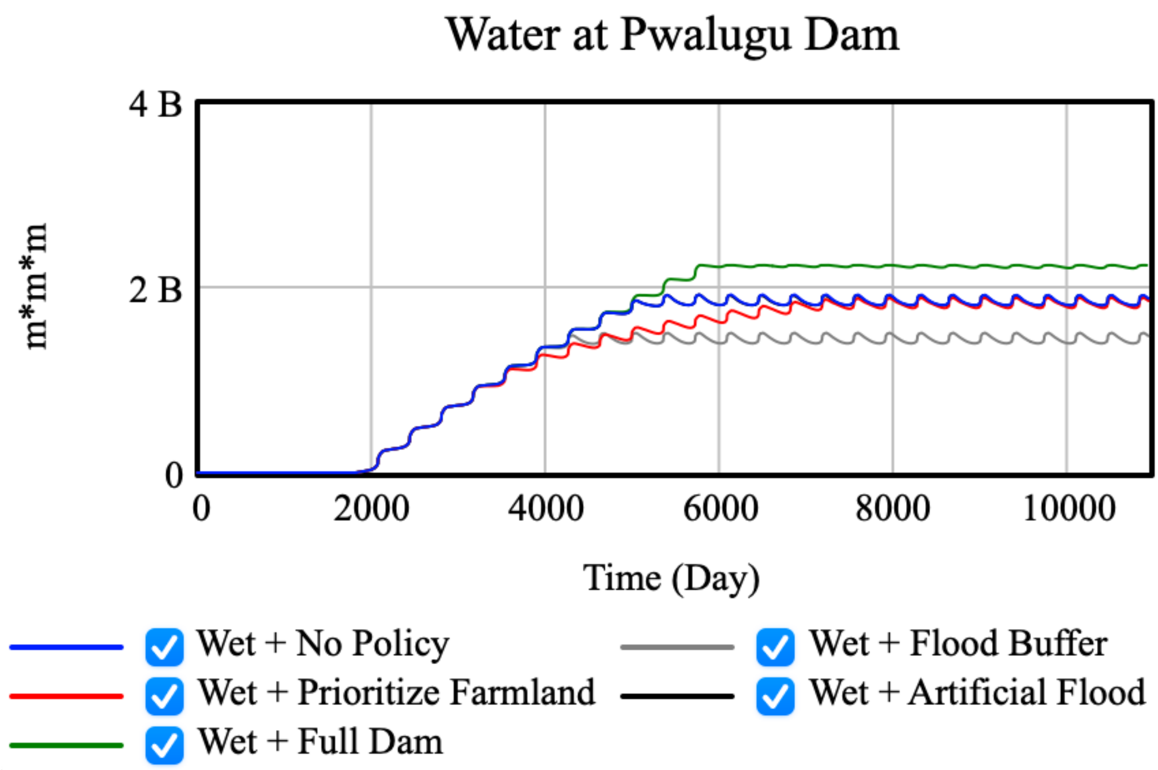
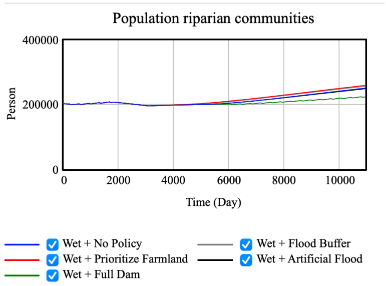


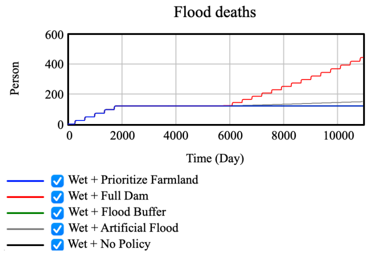
Figure F.13: Wet: Water at PMD

F.3.2 Riparian Communities

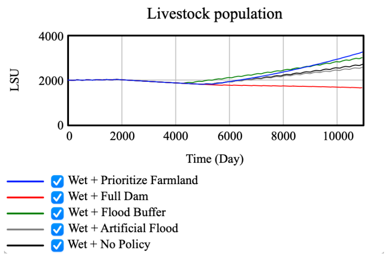
The higher quantities of water lead to a higher population growth at the riparian communities, with every different dam operation strategy the population increases once the dam is finished. However, the full dam policy has the lowest growth as it keeps more water at the reservoir so less water will be available for the communities. The full dam policy also leads to the most flood casualties while the other dam operation strategies mostly prevent them. Livestock shows similar behaviour as the population of the riparian communities. It grows the most when farmland is being prioritised and only when the focus is on a full dam reservoir the livestock population will decrease.



(a) Population Communities



(b) Flood Casualties



(c) Livestock population

Figure F.14: Wet: Riparian Communities

F.3.3 Riparian ponds

The wet conditions also cause the riparian ponds to fill more often which leads to more fish getting caught at the ponds. The prioritizing of farmland leads to the least number of fish getting caught as this scenario will always let through a certain amount of water which prevents flooding. When looking at the crocodiles, all the different dam operation strategies show similar behaviour as they all fluctuate a lot. With the artificial flooding leading to the highest number of crocodiles.

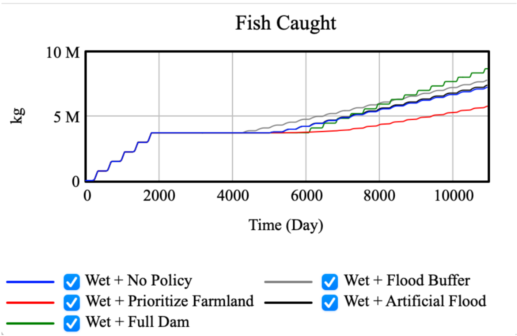


Figure F.15: Wet: Fish caught

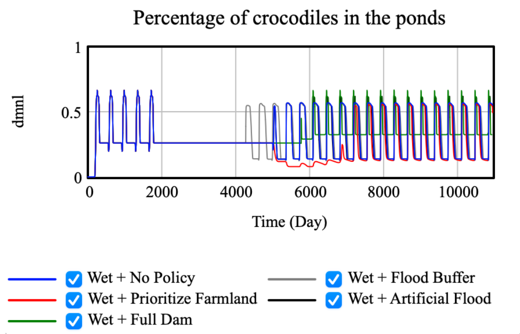


Figure F.16: Wet: Crocodiles

F.3.4 Farmland

The wet conditions are also very good for the farmland as the dam makes sure that a high base rate of water will be passed there the percentage of irrigated crops and farmland will rise greatly once the dam is operation. The full dam policy leads to the smallest grow of irrigated farmland as less water will be passed along and more water will be kept at the reservoir.

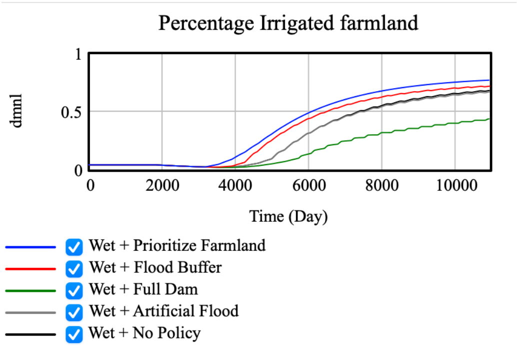


Figure F.17: Wet: Farmland

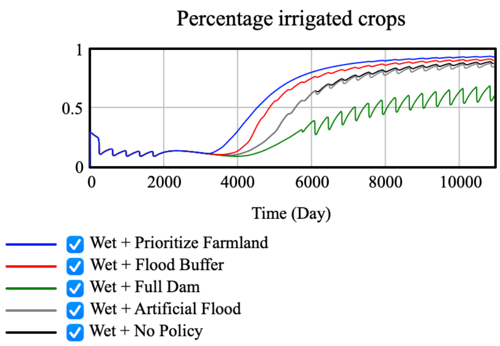


Figure F.18: Wet: Crops harvested

F.4 Climate Change Conditions

This sub-chapter will take a closer look at what the effect of different dam operating strategies is on the different KPIs under climate change conditions.

F.4.1 Dam

The climate change circumstances give slightly similar results to the wet conditions as the dam fills rather quickly. The water will be the highest with the full dam policy and it will be lower than the base run during the flood buffer policy. All other policies are more or less the same as the base run.

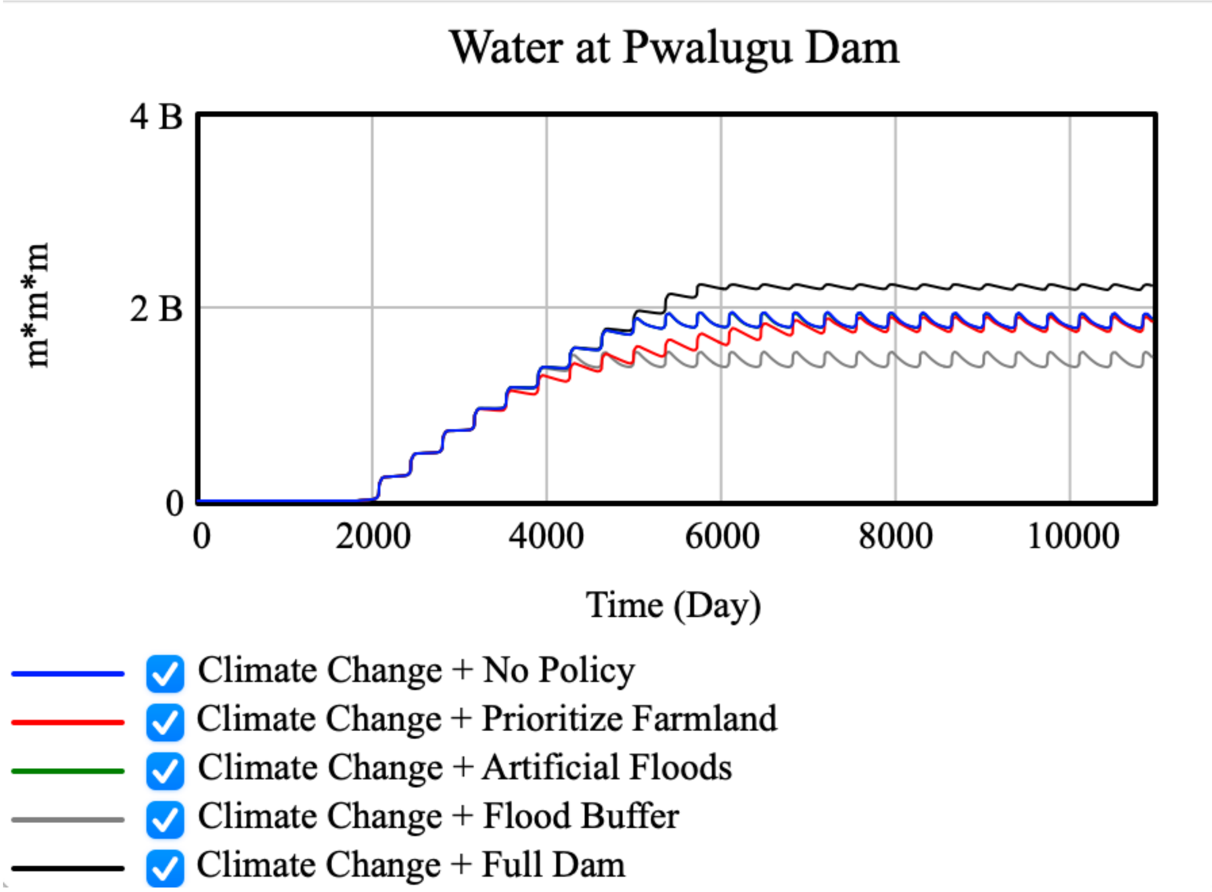
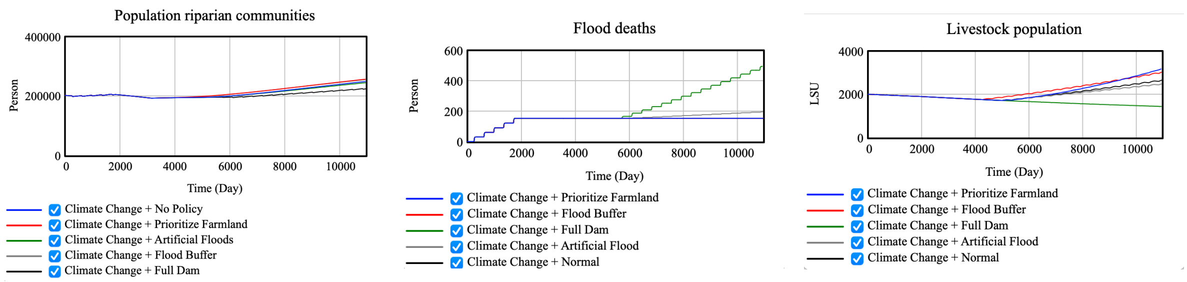


Figure F.19: Climate Change: Water at PMD

F.4.2 Riparian Communities

The riparian communities can grow a lot since there is a lot of water available and apparently, they are not affected by the fact that most of the water comes in the rainy season. The high seasonality does lead to more floods which can be seen in the figure of the flood casualties which shows that with the artificial flooding and the full dam policies there still will be flood casualties. Livestock again shows similar behaviour to the population stock as the full dam policy is the only one where the livestock population will decrease.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure F.20: Climate Change: Riparian Communities

F.4.3 Riparian ponds

The seasonality caused by climate change will have some great benefits for the riparian ponds as these will continue to flood once a year. The graph of the fish caught shows that with every different dam operation strategy there will be fishes caught at the riparian ponds. The number of crocodiles keeps fluctuating and shows similar behaviour for every different dam operation strategy. The number does tend to get lower with the construction of the dam.

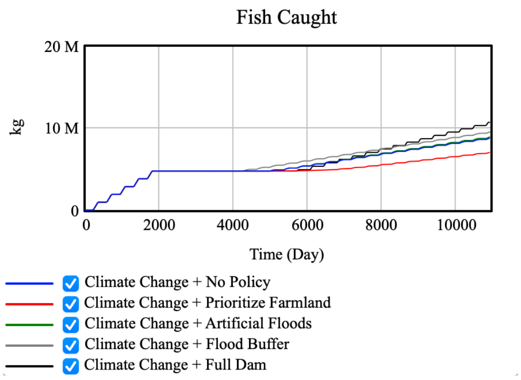


Figure F.21: Climate Change: Fish caught

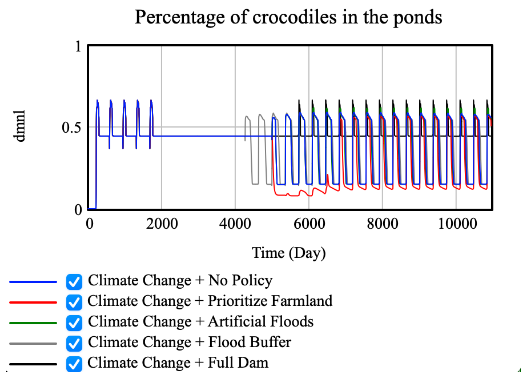


Figure F.22: Climate Change: Crocodiles

F.4.4 Farmland

Farmland increases mightily as the dam will be able to store some of the seasonality of the climate change circumstance to have water for irrigation available all year round. The number of crops tend to fluctuate a lot as climate change would also be great for rain-fed and flood-recession farming as it will keep the seasonality.

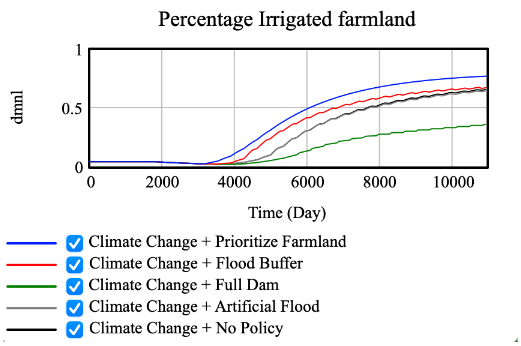


Figure F.23: Climate Change: Farmland

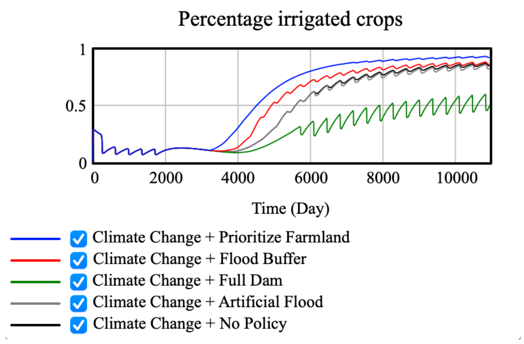


Figure F.24: Climate Change: Crops harvested

F.5 Artificial Flood Policy

This sub-chapter will take a closer look at the effects of the artificial flood policy on the different KPIs under different weather circumstances.

F.5.1 Dam

The dam reservoir reaches the same capacity for every different weather condition, however in with wet conditions the reservoir will be filled quicker as there is more water available. The climate change conditions show the most fluctuations of the water level at the reservoir as this scenario has the most seasonality.

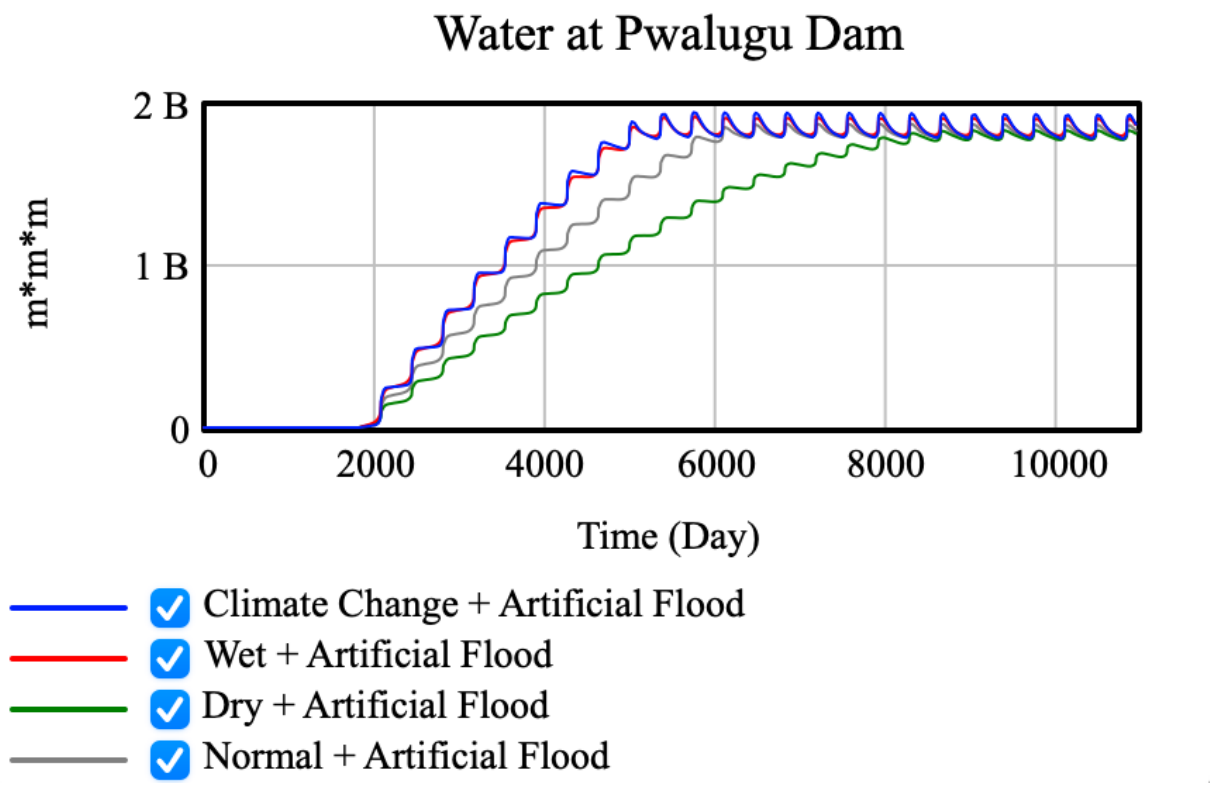
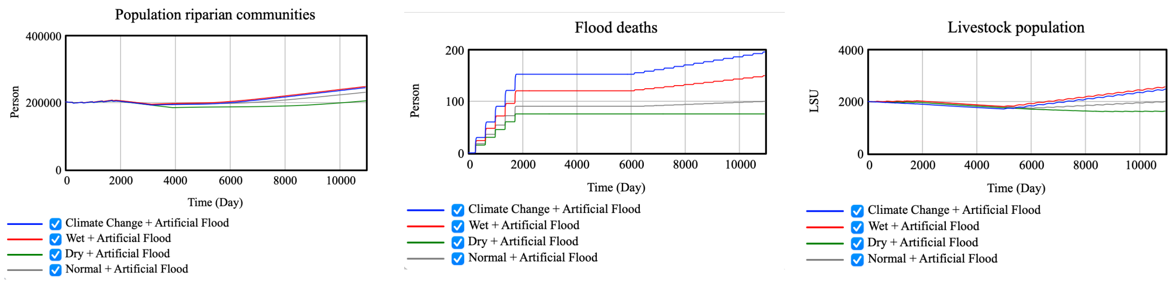


Figure F.25: Artificial Flood: Water at PMD

F.5.2 Riparian Communities

With this policy the riparian communities tend to grow under every circumstance. Since the population depends a lot on water availability, the population grows the least in dry conditions. However, the dry conditions will lead to no more flood casualties once the dam is built. The climate change conditions will lead to the highest number of casualties as this scenario will have the biggest floods. Livestock again shows a pattern like the population of the communities. As the more water available the higher the livestock population will get.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure F.26: Artificial Flood: Riparian Communities

F.5.3 Riparian ponds

Due to artificial flooding the riparian ponds will fill up to some degree once the dam is built under every circumstances. However, as shown in the figure, the dry conditions will just lead to a bare minimum of water at the riparian ponds which leads to some fish but far less than with wet conditions. The percentage of crocodiles in the ponds shows similar behaviour for almost all the different conditions, meaning that they depend less on how much water there will be at the riparian ponds if there is water.

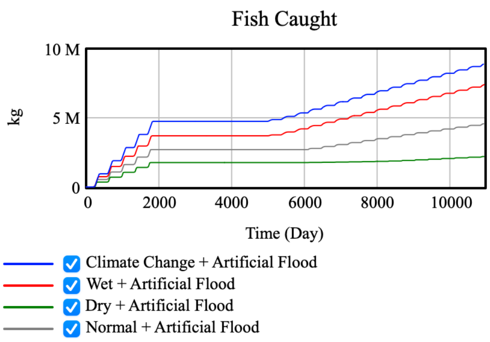


Figure F.27: Artificial Flood: Fish caught

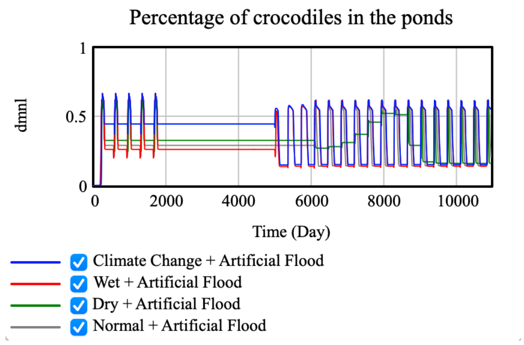


Figure F.28: Artificial Flood: Crocodiles

F.5.4 Farmland

Artificial flooding focusses more on the riparian ponds than it does on irrigation, which means that the percentage of irrigated farmland and crops will grow but it is less than with other policies. The fluctuations in percentage of crops also show that there will be significant harvest of rain-fed and flood-recession crops which may be caused by the artificial floods.

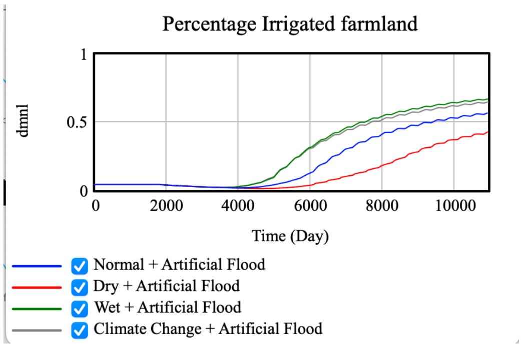


Figure F.29: Artificial Flood: Farmland

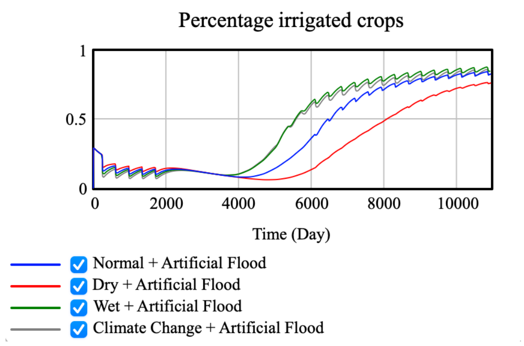


Figure F.30: Artificial Flood: Crops harvested

F.6 Flood Buffer Policy

This sub-chapter will take a closer look at the effects of the flood buffer policy on the different KPIs under different weather circumstances.

F.6.1 Dam

The flood buffer policy focuses on flood mitigation, which means that the dam will be used as a buffer to store floods and to prevent flooding. This can also be seen when looking at the water level of the PMD reservoir. The water level is way lower than with other policies, this means that once there is a flood the water can be stored in the reservoir and be released later.

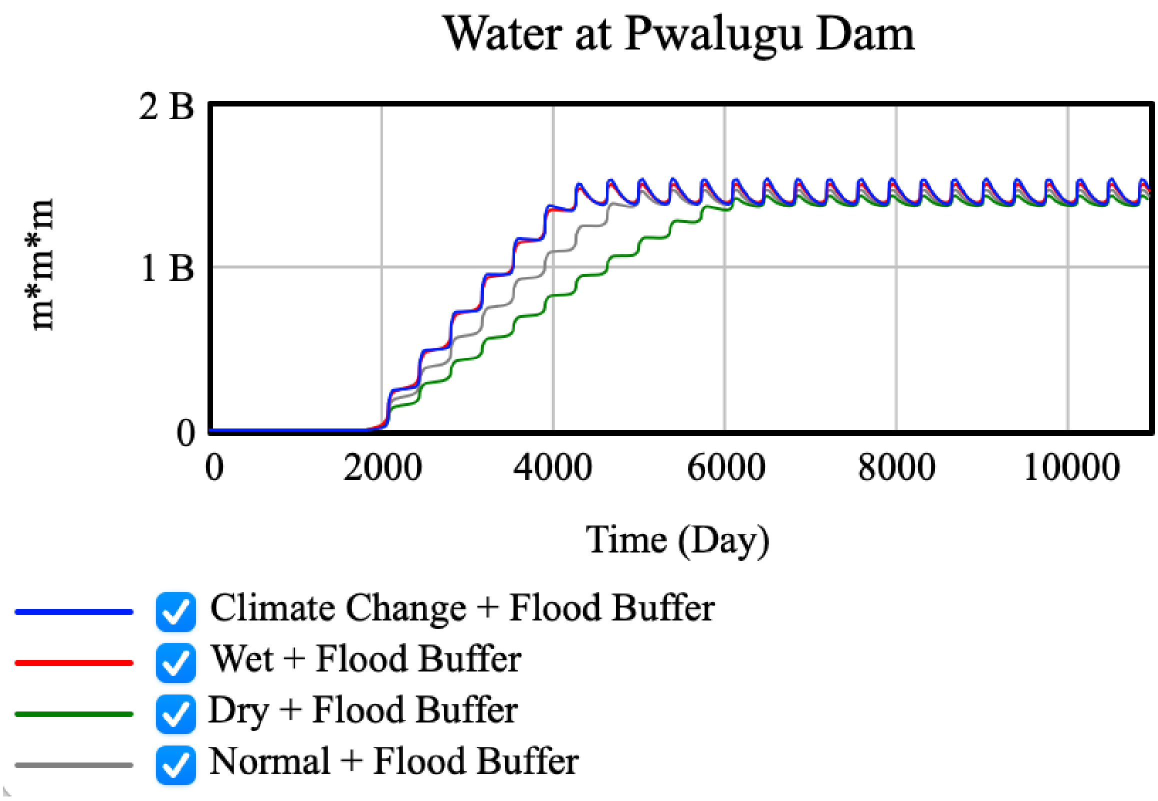
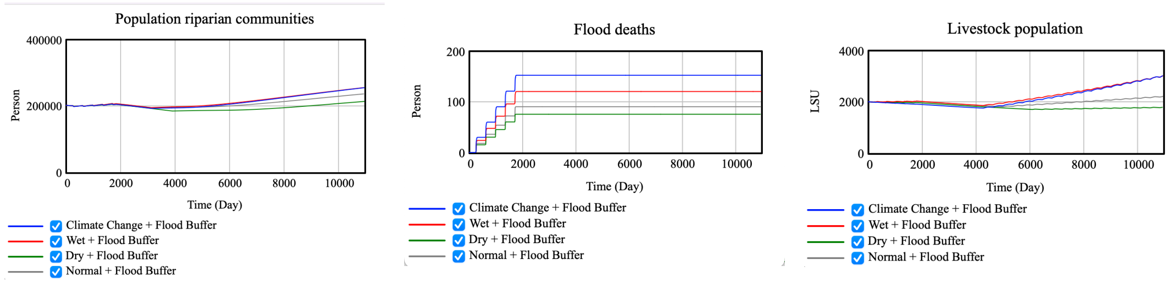


Figure F.31: Flood Buffer: Water at PMD

F.6.2 Riparian Communities

Less storage of water at the reservoir means more water available for the communities, this leads to a high population growth and with some conditions this growth tends to get even higher, especially the conditions that cause larger amounts of water to be available. Due to the buffer the number of flood casualties won't rise anymore after construction of the dam. This shows that the buffer is effective. The livestock population does not benefit much from the construction of the dam, however under wet or climate change conditions the livestock population will rise again. Normal conditions will cause the livestock population to stay at the same level while dry conditions even cause a slight decline.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure F.32: Flood Buffer: Riparian Communities

F.6.3 Riparian ponds

Due to some seasonal flooding and the constant release to keep the water level below a certain point, the riparian ponds will still fill up after construction of the PMD. This means that there will still be fish caught at the riparian ponds, the number of fish getting caught get higher the wetter the conditions are. The percentage of crocodiles in the riparian ponds again shows no clue effect by changes in conditions. However, the percentage of crocodiles tend to decline slightly after construction of the PMD.

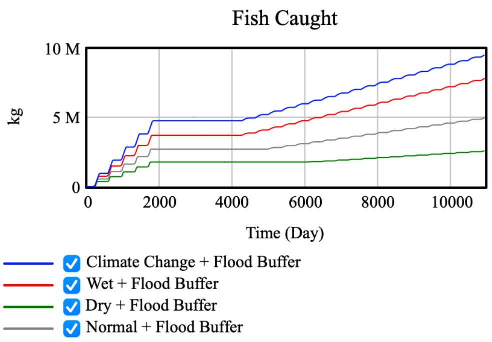


Figure F.33: Flood Buffer: Fish caught

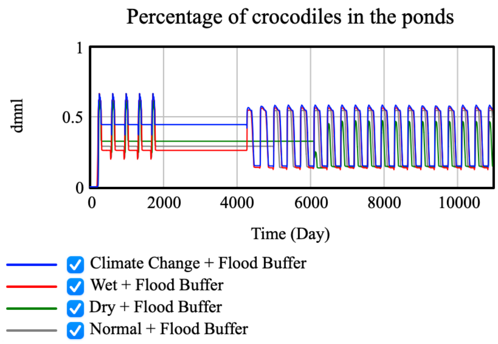


Figure F.34: Flood Buffer: Crocodiles

F.6.4 Farmland

The release of water to keep the water level low also causes the farmland area suitable for irrigation to increase. This will lead to a higher percentage of both irrigated farmland as well as irrigated crops.

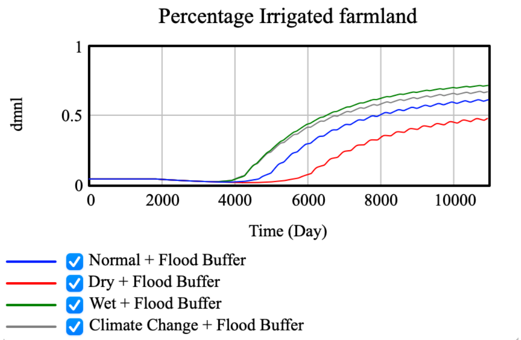


Figure F.35: Flood Buffer: Farmland

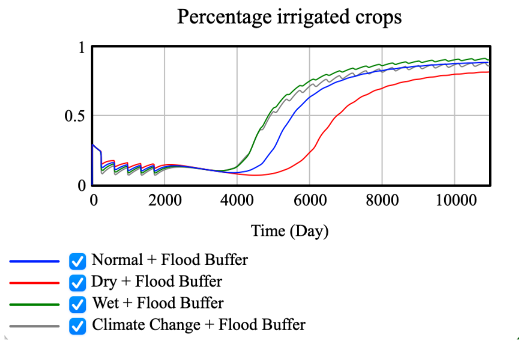


Figure F.36: Flood Buffer: Crops harvested

F.7 Full Dam Policy

This subchapter will take a closer look at the effects of the full dam policy on the different KPIs under different weather circumstances.

F.7.1 Dam

This policy aims to store as much water as possible at the PMD reservoir to be able to generate the highest amount of hydropower. The figure shows that under normal and dry circumstances this will take a very long time to fill the reservoir to that level. Climate change and wet conditions fill the dam more easily.

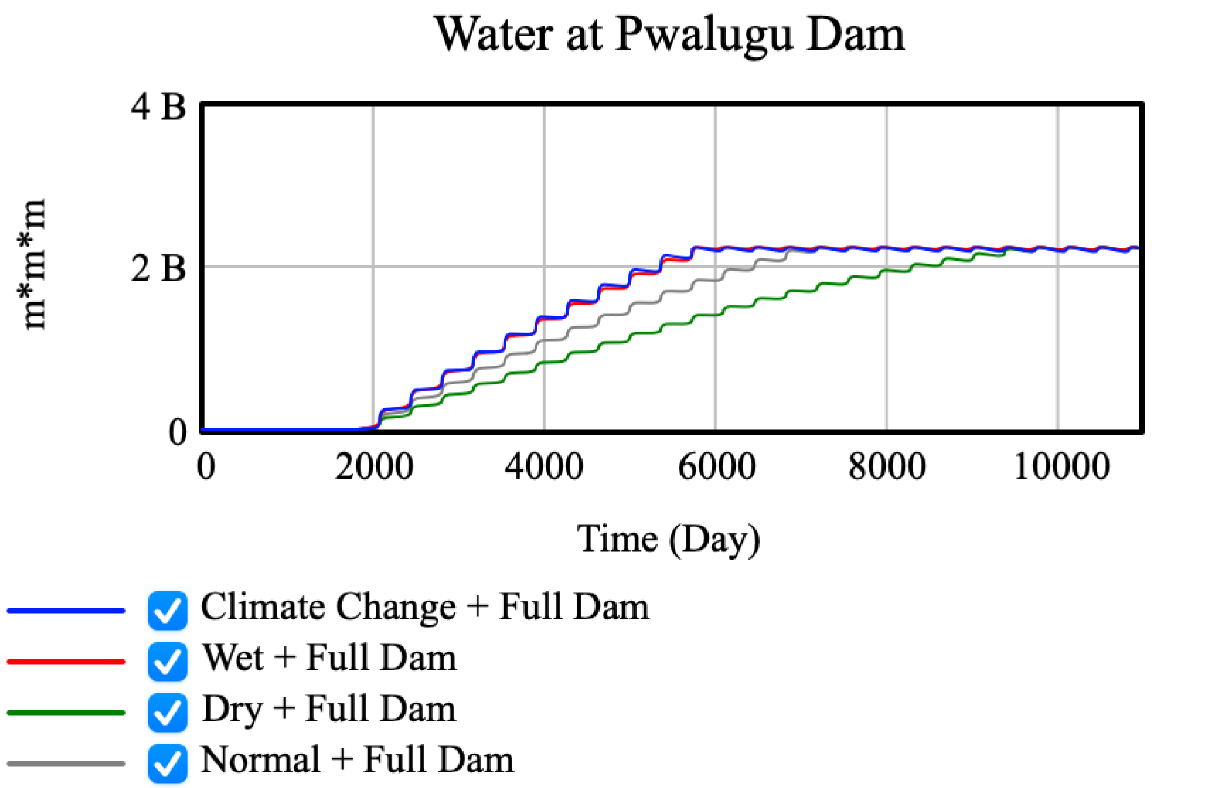
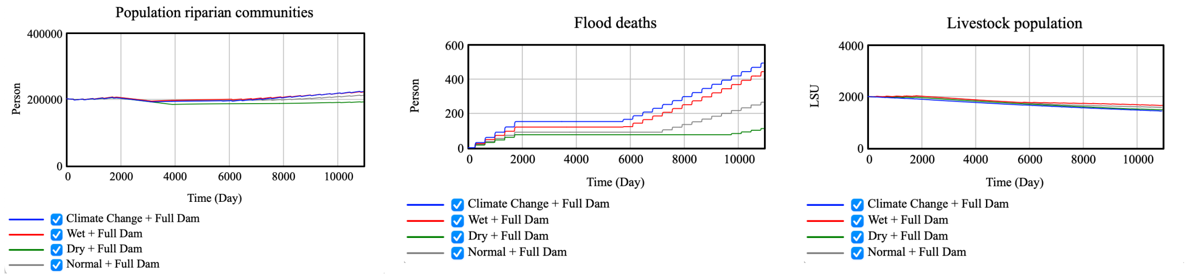


Figure F.37: Full Dam: Water at PMD

F.7.2 Riparian Communities

Due to the large quantities of water being stored at the reservoir there will be less water available for the riparian communities which can be seen in the decline growth of the population. A more critical note of the full dam is that it is a huge risk for floods as a high inflow at the reservoir can't be stored which will lead to high spillage to make sure the dam won't break. The figure shows that even under dry conditions the number of flood casualties will rise after construction of the PMD. Livestock hurts the most from the less water available as the livestock population declines under every condition. The decline is almost similar under all the different conditions.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure F.38: Full Dam: Riparian Communities

F.7.3 Riparian ponds

Once the dam reservoir is completely full there will need to be an emergency spillage at least once a year. This high spillage will cause the riparian ponds to fill which is beneficial for both fish and crocodiles. The fish graph shows that the number of fish being caught from the riparian ponds will rise a lot once the reservoir is filled entirely. The percentage of crocodiles at the riparian ponds also takes on a higher base value while the maximum value remains the same.

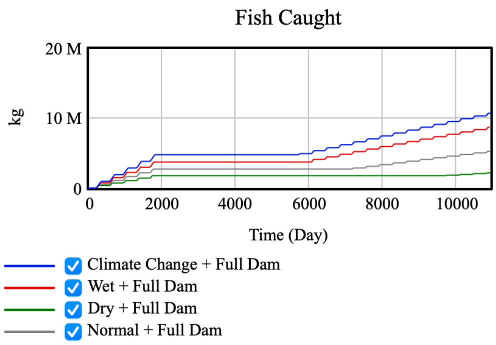


Figure F.39: Full Dam: Fish caught

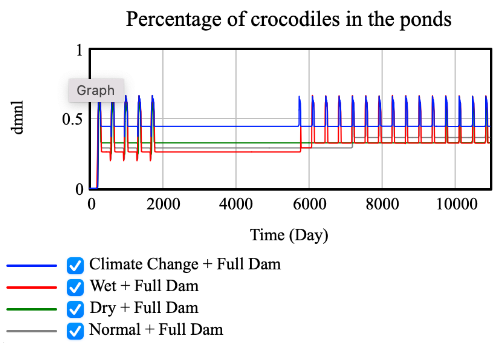


Figure F.40: Full Dam: Crocodiles

F.7.4 Farmland

Just like the riparian population and the livestock, irrigation also gets hurt by the storage of large quantities of water. The percentage of irrigated crops and farmland will rise once the dam reservoir is filled but it won't reach a much higher value than before dam construction. The high fluctuations in crops percentage show that there will still be a significant role for rainfed and flood-recession farming.

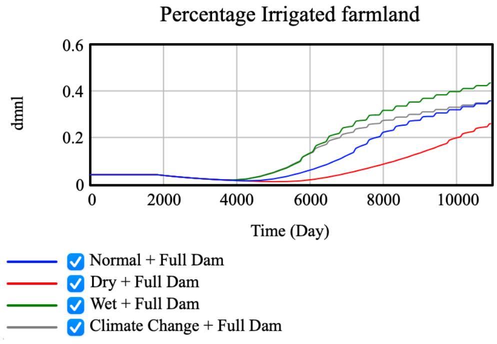


Figure F.41: Full Dam: Farmland

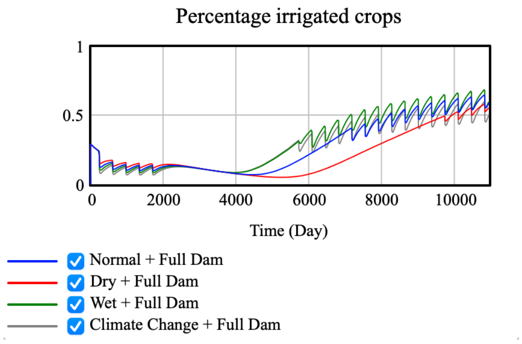


Figure F.42: Full Dam: Crops harvested

F.8 Prioritise Farmland Policy

This sub-chapter will take a closer look at the effects of the prioritise farmland policy on the different KPIs under different weather circumstances.

F.8.1 Dam

The prioritization of farmland shows that under different circumstance different water levels at the dam reservoir will be reached. This has to do with the fact that the outflow of the dam will be constant to make sure that the irrigated farmland can grow enough. This means that under normal and dry conditions the reservoir will be filled to a lesser extent.

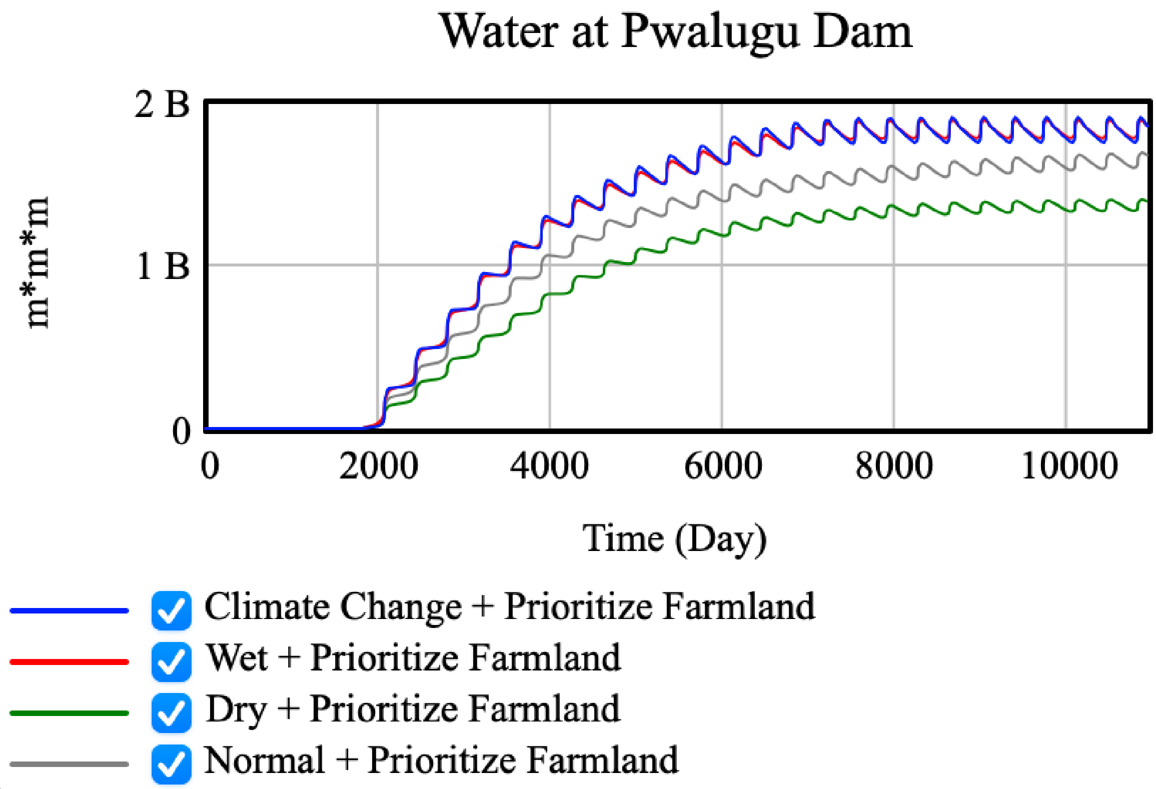
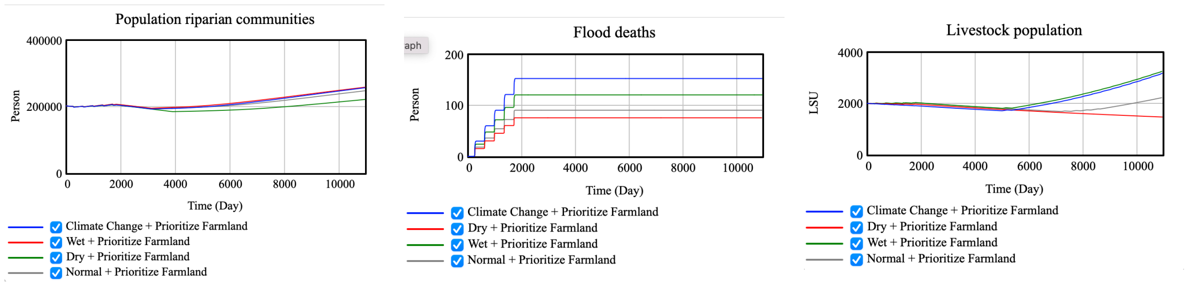


Figure F.43: Prioritise Farmland: Water at PMD

F.8.2 Riparian Communities

The riparian communities benefit from this constant outflow as they will have sufficient water available, while also having sufficient water to grow crops this leads to a high growth rate of the population. The constant outflow causes the reservoir to never be filled completely which means that it will be less prone to floods which is also seen in the number of flood casualties after construction of the dam is finished. Livestock is quite sensitive to the weather conditions, as the population decreases under dry conditions while wet conditions lead to a high increase.



(a) Population Communities (b) Flood Casualties (c) Livestock population

Figure F.44: Prioritise Farmland: Riparian Communities

F.8.3 Riparian ponds

Since there is constant outflow, it means that there will be less flooding of the flood plains and the riparian ponds. The number of fish caught also shows this as this number barely increases once the dam is operational. This decrease in water at the riparian ponds will also lead to a lower percentage of crocodiles at the riparian ponds which could be considered a loss as crocodiles have a high spiritual value in the area.

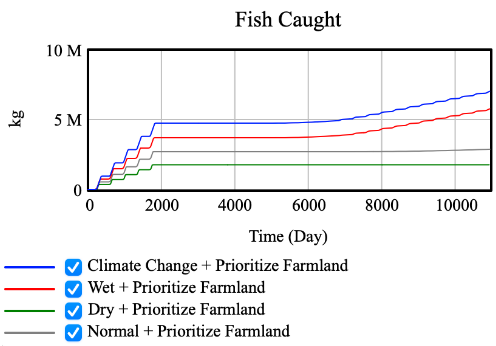


Figure F.45: Prioritise Farmland: Fish caught

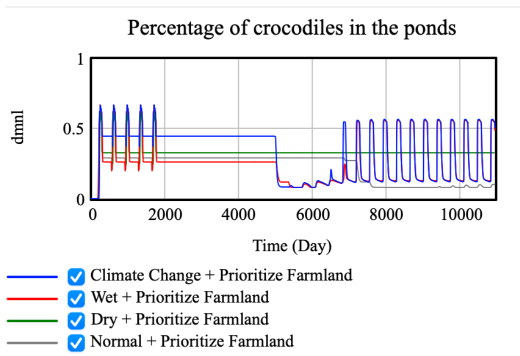


Figure F.46: Prioritise Farmland: Crocodiles

F.8.4 Farmland

This policy prioritises farmland and that can be seen in the graphs. The percentage of irrigated crops and farmland rises significantly and as prioritization is completely on this it can also be seen that it rises regardless of what conditions there are.

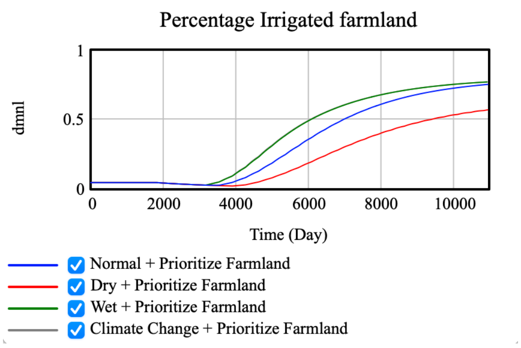


Figure F.47: Prioritise Farmland: Farmland

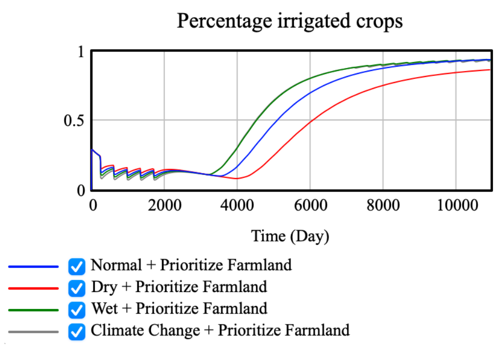


Figure F.48: Prioritise Farmland: Crops harvested

F.9 Summary

To conclude, most of the different KPIs depend on the amount of water that will be available. Especially the population, livestock and farmland depend on a lot of water availability which makes the wet and climate change conditions the most beneficial for them. Additionally, the flood buffer and the prioritization of the farm will release the highest amount of water at the PMD making it the most beneficial for the livestock, riparian population, and the farmland. When look at the riparian ponds it shows that the seasonality of the river will be beneficial for this. This means that conditions where the flood plains can flood, and riparian ponds can fill are beneficial especially in combination with a full dam reservoir or with artificial floods. The full dam can be beneficial for electricity generation; however, it is also the only dam operating strategy that causes flood casualties. The construction of the PMD prevents most flood casualties. Hence, the results show that there is a clear trade-off between different KPIs as being able to generate a lot of electricity will cause a full reservoir which will not benefit the population and farmland and vice versa. This makes it important to determine on what the focus will be, will one of the three benefits be optimised or will there be an operating strategy in which all three benefit to some extent?