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Water for Energy and Food: A System Modelling Approach for Blue Nile River Basin

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Abstract: The world is facing a more water constrained future as a result of urbanisation, population growth, industrialisation and the emergence of climate change. This has direct impacts on the resilience and performance of the energy and food industries, as water plays a key role in electricity generation processes and agriculture production. Water, energy and food dependencies are more evident in transboundary river basins where several countries share the same source of water for irrigation demand and energy production. From the perspective of the upstream users, it would be ideal to store the water for hydropower generation and the agriculture sector while protecting the environment, whereas the downstream users need the supply of water for their agricultural growth and municipal requirements. We aim to develop a system thinking study by focusing on the transboundary Blue Nile River basin where the Ethiopian government investment in the Grand Renaissance dam has led to opposition by downstream users due to potential reduction of water resource availability downstream. We propose a system thinking approach for analysing different water management practices that considers all the available resources and the requirements set by all the users. To simulate this interaction, we use system dynamics to model the linkage between food production, water abstraction and energy generation. We link the simulation model to an optimisation engine to achieve effective management of the reservoir's operation. The study provides a platform to investigate how the reservoir operating policies can improve an understanding of the value of water in its alternative uses, and shows how different optimal reservoir release rules generate different optimal solutions inherently involved in upstream and downstream users' requirements. The proposed methodology is an attempt to enable Nile riparian countries to make more informed decisions on water resources policy and management.

Keywords: environmental system thinking; system dynamics; optimisation; Nile River; Grand Ethiopian Renaissance Dam

1. Introduction

Growing demand for water increases pressure on water resources in terms of quality and quantity [1,2], especially in transboundary rivers water basins where several countries depend on the same source of water for social well-being, economic growth and environmental preservation [3–6]. The allocation of water and its management are complicated, as over 40% of the world's population lives within transboundary basins [4]. Cooperative management of a transboundary river basin, while being beneficiary, is usually a source of conflict [7–10]. It is a long-term and resource intensive process to promote cooperation involving an internationally shared river basin; the examples are the studies around the Tigris and Euphrates [11–15] and Nile River [16–22] basins. The major challenge is to realise an understanding of how water, energy, and food resources are managed together and operate on their own. Energy, water and food are dependent in many complex ways and cannot be managed effectively without integration [23–26]. In North Africa, this is evident for Nile riparian, as there is a high degree of dependency on water for energy production and irrigation needs [25] while often the upstream–downstream relationship has also been neglected [18,25,27,28]. In this paper, we provide a framework for modelling and simulation of water, energy and food production through reservoir operating policies within transboundary Blue Nile river. We propose a simulation model and link it to an optimisation engine to show how the reservoir storage can be optimally managed under different policies to benefit the upstream and downstream users. This will serve as a platform to be later refined and elaborated to fit to the purpose of helping Blue Nile riparian countries to make more informed decisions for common water resources considering their requirements. The framework can be developed further if it is intended for future prescriptive policy planning.

2. Case Study Description: Grand Ethiopian Renaissance Dam

Ethiopia, the Blue Nile River upstream country in North Africa, faces an increasing population, undeveloped energy sources and insufficient agricultural production [29,30], which increase pressure on water and energy resources. In reply to this, the Ethiopian government has launched the Grand Ethiopian Renaissance Dam (GERD) in 2011 over the Blue Nile river, which is set to be complete by 2017. The reservoir is capable of storing over 60 cubic kilometres of water. This project will be able to generate more than 5000 MW of electricity with an estimated annual energy production of 15,130 GWH/year [31]. The reservoir has a natural water system from Ethiopian Highlands upstream feeding the Blue Nile, which offers significant hydropower potential. The Blue Nile stretches nearly 850 km in length with a drop of 1300 m in elevation. The annual average precipitation is nearly 1000 mm and evaporation rates are at 1150 mm per year in Ethiopia [29]. GERD is a multi-purpose infrastructure that can help transform the Ethiopia's economy through sustainable provision of cheap power, irrigation systems and storage capacities to protect from floods and droughts while maintaining the environment regulation. The dam, however, faces opposition from Egypt and Sudan as they are located downstream of Ethiopia and are highly dependent on the flows that originate from the Blue Nile for agricultural purposes and municipal supply. Figure 1 shows the location of the reservoir and the catchment area of the Blue Nile River basin.

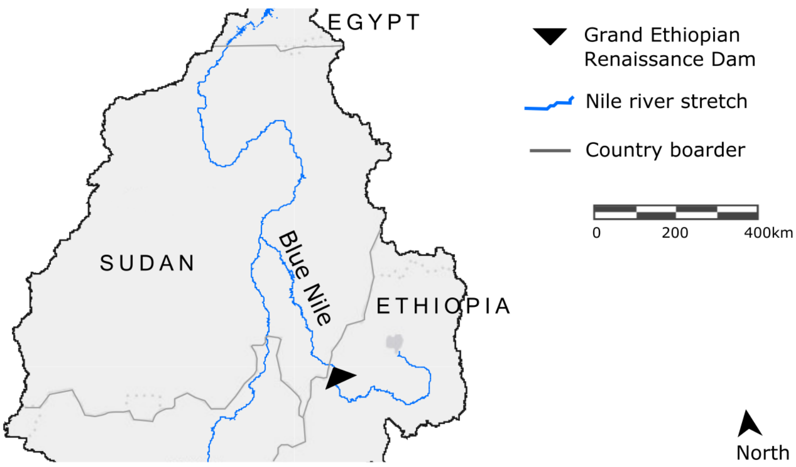

Figure 1. The Blue Nile catchment and the location of the Grand Ethiopian Renaissance Dam.

With cooperation from all transboundary parties, it is possible to use the water of the reservoir in its most efficient way. Therefore, it is essential for these countries to develop solutions that would provide a route to future water, energy and food security. This is possible by considering an integrated resource management plan that considers all riparian needs and the resource dependencies.

In this study, we develop an integrated model and link it to an optimisation engine for enabling effective resource management. The main aim of this study is to provide a system thinking approach to minimise the water shortage for energy production and irrigation demand focusing on the GERD management practices. Since no agreeable filling strategy for the reservoir has been established [22], our study proposes a methodological approach to help better inform this process. This helps to understand how dependencies can complicate the process of decision making. Of course, a more detailed model helps a more refined analysis, which is not the intention of our work.

3. Model Development

3.1. System Dynamic Model

With many beneficiaries of water usage, water resource management decisions are relevant if all resource dependencies are considered in integrated modelling. System dynamic models provide a platform to study the interaction between different players and facilitate the understanding of resource linkage in an integrated approach [32]. The models are used to represent the whole problem as a connection between different elements and to help encourage system thinking [33,34]. This would allow better and more transparent understanding of each component of the whole system and the dependencies involved. In this paper, we show the resource relationship using the system dynamic model. We represent the water, irrigation and energy demand of the upstream and downstream countries within the model, and illustrate how they perform under different management policies. Our study is methodological and our developed model fits our purpose of demonstrating how dependencies can make the water management decision making a challenge.

Figure 2 shows the focus of the study. The flow path of the water after the release from the dam consists of a diversion to Sudan along the stream and then towards Egypt for irrigation and municipal use before being diverted into the sea. The model is subject to mass balance equations, dam storage, non-negativity of the variables and transfers, and it is made of different sub-models. Our focal point in this study is on methodology development of modelling and simulation—how dependencies of different factors in water management can lead to different implication. We use Ethiopian management of the GERD dam as the case study that fits our purpose of illustration, and we do not include the data from the downstream Aswan High Dam in Egypt, and the Roseires and Sennar dams located in Sudan. Including these and other factors, while possibly changing the results, does not change the methodology development, which is the main intention of this paper.

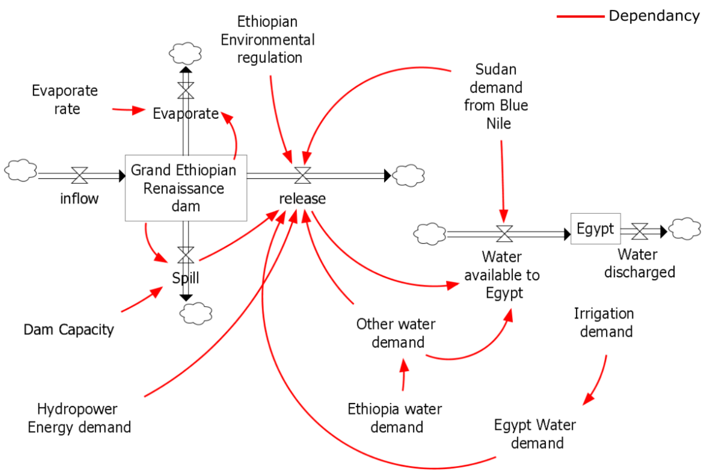

Figure 2. The system dynamic model for the Blue Nile River basin.

Water Submodel. This is comprised of the dam, its hydrological inflow [35–37] and its release rate decision. We have also considered the evaporation and spillage in the mass balance of the reservoir. Sudan downstream demand and Ethiopia urban water requirement are also required for the model [38]. The monthly storage level is allowed under a defined maximum and above dead minimum storage. This will ensure that the environmental regulation policy will preserve the environment as well as protect the city against flooding and drought events. It is also assumed that the total water supply should not exceed the total inflow for the year. This ensures that there will be no under storage scenario when the stored water is used without considering the impact on its future use.

Agricultural Submodel. Egypt's water requirement are mostly subject to agricultural usage [38]. Ethiopia water use for agriculture also accounts for the agricultural usage. For illustration purposes, we have not considered the water loss and crop yield data in this study but have shown the agricultural dependency to water within the model represented as the irrigation demand data.

Energy Submodel. This is mainly about the hydropower energy production and releasing rules in the Ethiopia region. As for hydropower generation, the maximum generation cannot exceed the design capacity respect to actual power generation, which takes into account the efficiency of the turbine and maximum design power generation (MW) in each time period.

3.2. Optimisation Linkage

The following objectives and decision variables are identified to perform optimisation based on the system dynamic model above.

Objective Functions. The main objectives of the reservoir optimisation model are to minimise the irrigation and municipal water supply deficit and maximise hydropower generation. These two objectives are conflicting as maximum hydropower generation requires a high water head in the reservoir to generate more energy, and the water level needs to be kept at the design level. At the same time, downstream countries require the water to be released during the period of high demand that would reduce the water elevation in the reservoir.

Variables and Parameters. The decision variables in this model are the operating rule decisions, which involve storage volume and release rates. Together, they form the release rule that represents the management policy affecting the reservoir's release rate for dry (January–June) and wet (July–December) seasons based on the storage level. The system optimises these variables according to the objective functions and generate the optimal operating rule for the reservoir where optimal target storage as well as the release rate for each month can be identified. There are also two important input parameters in the model—monthly inflow into the reservoir and monthly water demand downstream. These will affect the release rate of the reservoir for every month and the total volume of out-flow from the reservoir as the system generates an optimal release rule. The parameters in this model are the reservoir volume-area-height relationship. These values are used to represent the height and surface area of water in the reservoir for every storage volume at the end of each month. They are used for hydropower purposes and evaporation loss. The storage between 17 cubic kilometres (km^3) and 65 km^3 are used in this study as a constraint to protect against drought and flooding events.

Given the above, the optimisation problem is formulated as follows:

$$Min\ TD = \int_t D_e^t - W_e^t + D_t^t - S_{GERD}^t \tag{1}$$

$$Max\ HG = \int_t P^t \tag{2}$$

which are subject to the following set of constraints,

$$P^t = r^t_{GERD} \times (Ht^t - Tw^t) \times \eta \quad (3)$$

$$W^t_e = r^t_{GERD} - D^t_s - D^t_t \quad (4)$$

$$D^t_e = D^t_i + D^t_m \quad (5)$$

$$r^t_{GERD} = E^t_e + D^t_h + D^t_s + D^t_t + D^t_e \quad (6)$$

$$sp^t = S_{GERD} - C_{GERD}\ if\ S_{GERD} > C_{GERD} \quad (7)$$

$$ev^t = r^t_e \times S^t_{GERD} \quad (8)$$

$$\int_t S^t_{GERD} = in^t - r^t_{GERD} - ev^t - sp^t \quad (9)$$

$$\int_t S^t_e = W^t_e - W_d \quad (10)$$

W_e is water available to Egypt, D_t is Ethiopia water demand, D_s is Sudan water demand from Blue Nile, D_e is Egypt water demand from Blue Nile, D_i is Egypt irrigation demand, D_m is Egypt Municipal demand, E_e is Ethiopian Environmental regulation, D_h is Ethiopia hydropower energy demand, sp is spillage, S_{GERD} is storage level at Grand Ethiopian Renaissance dam, in is inflow to the reservoir, ev is evaporation amount, r_e is reservoir evaporation rate, r_{GERD} is release from the dam, S_e is water discharged to Egypt, W_d is water discharged from Egypt, C_{GERD} is GERD Capacity, HG is total hydropower generation in MW, TD is total water deficit, Ht is GERD column height (head), Tw is GERD tailwater level, and η is hydro to electric conversion efficiency factor. Equations (1) and (2) are deficit due to water shortage and hydropower generation, respectively, to be minimised and maximised through the planning period. Equation (3) is the power that the GERD turbines can produce. The mass balance Equations (4)–(9) accounts for the evaporation, spillage, inflow to GERD, water demand of Sudan and Egypt as well as hydropower and water supply demand of Ethiopia. Equation (10) models the water stream that is being used in Egypt for irrigation and municipal purposes before being discharged into the sea.

The system dynamic model presented above is linked to the optimisation engine for identifying best policy intervention for releasing the water downstream from the dam based on the predicted inflow into the reservoir. The optimisation engine is Differential Evolution (DE) [39] as it provides promising results for many numerical test problems [10]. In DE, a population of individual decision variables vector is randomised and, corresponding to each individual p_k, three individuals p_{s1}, p_{s2} and p_{s3} are randomly chosen. New vector p_c is created by adding the weighted difference of p_{s2} and p_{s3} to the p_{s1} given by

$$p_c = p_{s1} + MR(p_{s2} - p_{s3})$$

where MR is the mutation rate. p_c is accepted as a new vector p_b if the following is satisfied,

$$p_b = \begin{cases} p_c & if\ \ rand(0,1) \leq CR \\ p_k, & o.w. \end{cases}$$

CR is the probability of crossover and $rand$ is a pseudo random number between 0 and 1. In our problem, the population size is 250, the maximum number of generation is 100 and MR and CR values used within DE are equal to 0.7 and 0.5, respectively.

3.3. Management Options

Rather than being a prescriptive approach, we use GERD as a case study to focus on a methodology development. We show how a novel synergy between data modelling, system dynamic and optimisation can help study the implication of finding the best managerial practice for riparian countries. We consider three different scenarios that would likely occur as the result of the development of the dam. Two of the scenarios involve single/independent operation strategy and the third scenario considers the cooperative management between all involved countries. All three scenarios serve different purposes, but they will all take into account the identified constraints such that the system will protect the reservoir from under storage or overflow throughout the year as well as environmental guidelines for flood protection.

Power Priority. The first scenario is to concentrate on the single objective function extreme case that Ethiopia decides to ignore the right of Sudan's and Egypt's demand on water abstraction, and decides to store the water to maximise hydropower generation; this is denoted as power priority. In order to model this, the system requires the water level in the reservoir near its design head at each month, as it is directly proportional to the energy generated from the turbine. The system is set such that the policy will prioritise hydropower production from the dam over the importance of irrigation and municipal supplies. This will generate a power dominated release rule for the single objective function, which would maximise annual hydropower production by operating the system near to the maximum capacity.

Water Priority. In the second scenario, we model the system based on the water rights owned by Sudan and Egypt. This simulation aims to comply with the rights of Egypt and Sudan and supply 28% and 48% of the water needed downstream, respectively. In this simulation, the dam will only release the water according to the demand of downstream users and will not store the water for hydropower benefit. This simulates the case that Sudan and Egypt are the drivers for Ethiopia's development. In this operating system, the objective of the reservoir release rule will aim to minimise water supply deficit downstream as well as reduce the amount of oversupply. The operating system will only supply enough water for irrigation and municipal use to reduce the losses of water to the sea.

Equal Priority. This policy will consider the impacts and benefits of cooperative management between the riparian countries. The optimisation model aims to improve the system by finding an optimal solution that generates the best performance out of the reservoir considering the balance between the water and power priority scenarios. The outcome is a solution that reduces water deficit, and, at the same time, increases power production, which would be in the best interest of all countries in the Blue Nile basin. As all the functions cannot be satisfied at the same time, as they are conflicting in nature, there are inevitable losses in efficiency. This is a solution that optimally trades the water deficit for power supply production. The obtained policy helps to inform the decision making for fair resource allocation of water and for its secondary uses in energy production and irrigation needs.

4. Results and Discussion

Three types of earlier identified possible scenarios are simulated and optimised, and the results are given below. The results presented below should be seen as an indication of how different reservoir management practices lead to different resource allocation schemes, and they should not be seen as prescriptive filling strategy. For the latter to be possible, a more detailed simulation model should be used that incorporates other intervention factors as well as Sudan's and Egypt's downstream dams.

In our model evaluation, the total inflow into the reservoir from the Ethiopian highland is assumed to be 73.8 km^3 per annum based on the annual stream flow data [35–38]. The majority of the flow falls in the summer (July–November) with a peak during September at 16 km^3. It is also assumed that the total outflow per annum should not be more than the total inflow after evaporation loss so that the reservoir will not be depleted at the beginning of the year. The total water demand pattern downstream of the dam is shown in Table 1 with an annual supply of 73.8 km^3 expected from the Blue Nile River.

Table 1. The inflow and water use pattern in the transboundary Blue Nile river.

Period	Inflow into the Reservoir (%)	Irrigation Demand (%)	Municipal Demand (%)	Hydropower Demand (%)
January–March	11	15	20	25
April–June	8	30	30	25
July–August	63	40	25	25
October–December	18	15	25	25

Figure 3 shows the optimal target storage level and the release rate for the reservoir for each operating policy. As indicated in Figure 3a, the optimal target storage for power priority is higher, as this policy needs the water level to be stored to achieve the design head. This will result in the policy's failure to satisfy the water demand for the first seven months of the year. On the other hand, the water priority policy will release the water according to the demand and has a much lower storage target throughout the year. In this policy, a constant amount of water is released to fully satisfy the demand of water downstream. An equal priority scenario takes into account both water and energy uses and the optimal target storage set between the two policies. This equal priority policy satisfies the water demand for the first three months and falls short for the rest of the dry season as it needs to find a balance between these two resources. During the wet season, water demand for irrigation is more important, as it is the summer season where the weather conditions are suitable for agricultural production. In addition, 85% of agricultural production is achieved during this time in the Blue Nile basin and it will have a great impact on the economy. All three of the policies satisfy the water demand during the wet season as shown in Figure 3b, except for power priority during July. Figure 3c shows the hydropower production per month. Both the water and equal priority scenarios have fairly consistent power production. There is a peak during the end of the year for equal priority as the stored water is set to be released to be ready for the beginning of the next year. It is noticeable that the power priority scenario will have lower energy production during the dry season. This is because the system is designed to store the water for higher water elevation and this will cause the operating policy to fall short in terms of firm power demand. The firm power demand in this case study is assumed to be a quarter of the maximum potential, and, if the Ethiopian government decided to achieve this rate at 80% for every month, the power priority scenario will fail to meet the firm power for the first seven months. However, water priority and equal priority will only produce power lower than the firm power for one and two months, respectively. This is due to the fact that water is constantly released instead of being stored but will result in lower annual power production. By showing how the performance of different policies varies, this allows stakeholders to better understand the implications of different reservoir management practices.

Figure 4 shows the monthly irrigation and municipal deficit for the three operating policies. The result of lower flow during the winter months suggests that all the policies will have greater water deficit compared to the summer months. In the water priority scenario, the dam only operates according to demand, and there is no water deficit in this policy. The annual deficit for irrigation and municipal are 25.3 km^3 and 2.7 km^3, respectively. In the balance scenario where the system will operate on a trade-off basis, irrigation and municipal deficits can be reduced to 9.2 km^3 and 2.3 km^3, respectively. This scenario will achieve 85% of water demand as well as producing 15.8 terawatt-hour (TWH) energy for the year and, except for two months, it produces energy above firm power demand.

We note that, if cooperation is encouraged for the balance between water and energy, the hydropower potential can be fully utilised, and, at the same time, the deficit of the downstream uses can be reduced. The introduction of the reservoir will not only bring benefits to Ethiopia but also to the community within the basin. If the dam is operated efficiently, the hydropower potential can be fully utilised to produce cleaner energy and possibly extra power that can be exported to Egypt and Sudan. While the dam will provide a sustainable power resource, it will also act as storage for water, which will benefit the downstream users. The results indicate that the single scenario management options do not provide a viable operation of the dam. That is, the water priority scenario is able to meet all water demands downstream, but the hydropower potential will not be fully utilised. The annual water deficits and hydropower generation for the three policies are shown in Figure 5.

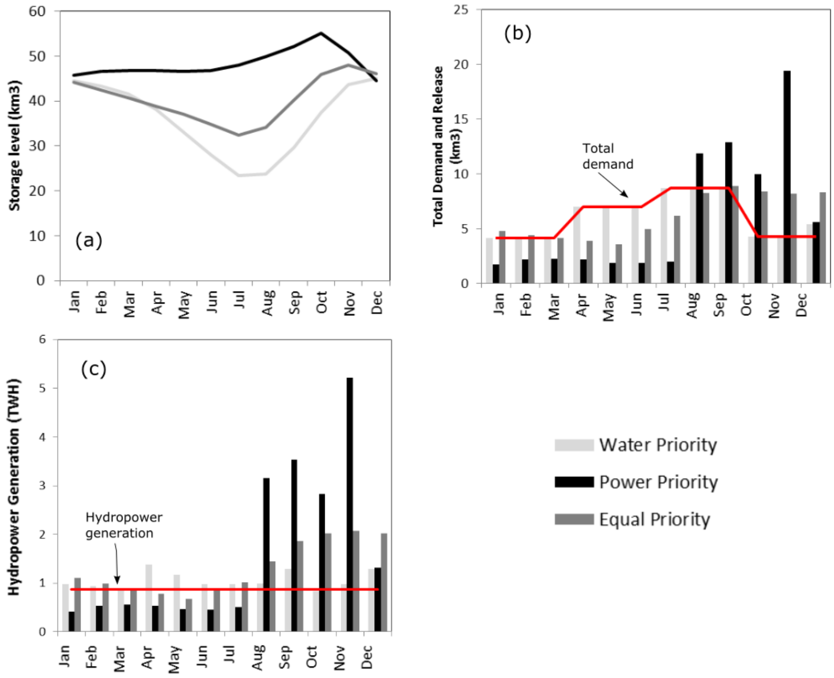

Figure 3. (**a**) monthly optimal storage levels for three different operating policies; (**b**) monthly demands for water downstream and monthly release rates from the dam; and (**c**) monthly hydropower generation and firm power demand.

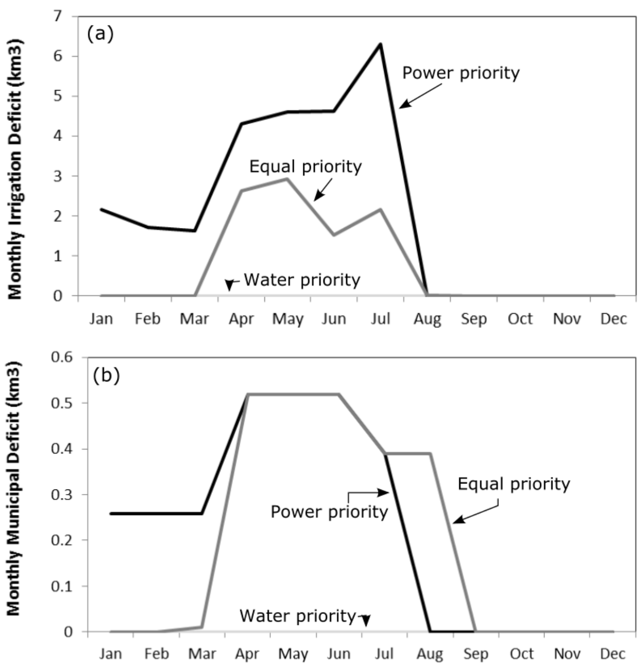

Figure 4. (**a**) monthly irrigation deficit for the operating policies; and (**b**) monthly municipal deficit for the operating policies.

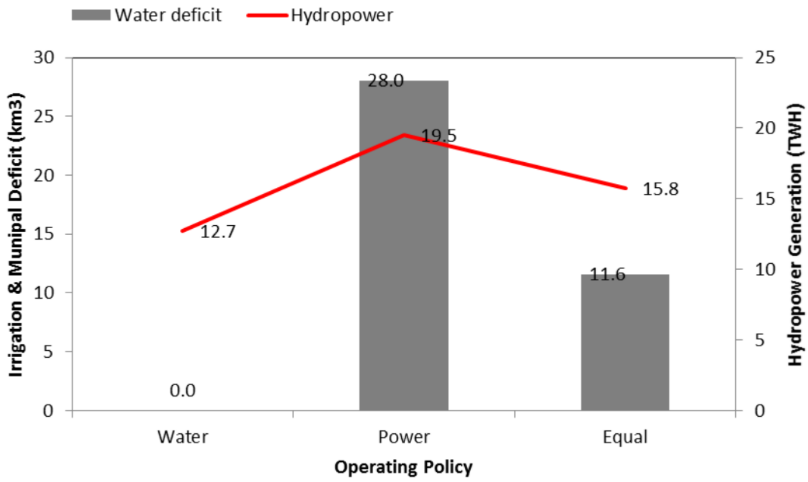

Figure 5. Annual deficits and hydropower generation for three different operating policies.

5. Perturbation Analysis

5.1. Sensitivity Due to Inflow

As river flows are sensitive to climate change and variability, the sensitivity of the inflow into the reservoir is tested against lower and higher flows. In this study, the multiplier factors of 0.9 and 1.1 are used to generate the lower and higher flow, respectively, to test the sensitivity of the results. By multiplying the factor, the nominal annual inflow into the reservoir is 73.8 km^3, the lower flow scenario is 66.4 km^3, and the higher flow is 81.2 km^3. These values are used in the simulation model with the same demands to generate monthly optimal storage and release rates for the changing flows. Figure 6a shows the release rate for each month. The policies for the three different flows are all optimised to produce an optimal operating system. During the low flow year, there will be insufficient water and most of the water is stored in the reservoir to increase the storage level for hydropower purposes and for the high level of agricultural demand during the wet season. This will cause an increase in the water supply deficit during the dry season. As for the higher flow year, the optimal water storage is lower than the normal and low flow event. This is because there is sufficient water for the demand and the consistent release of water will also increase the hydropower production, which will be closer to the maximum capacity and increase annual production.

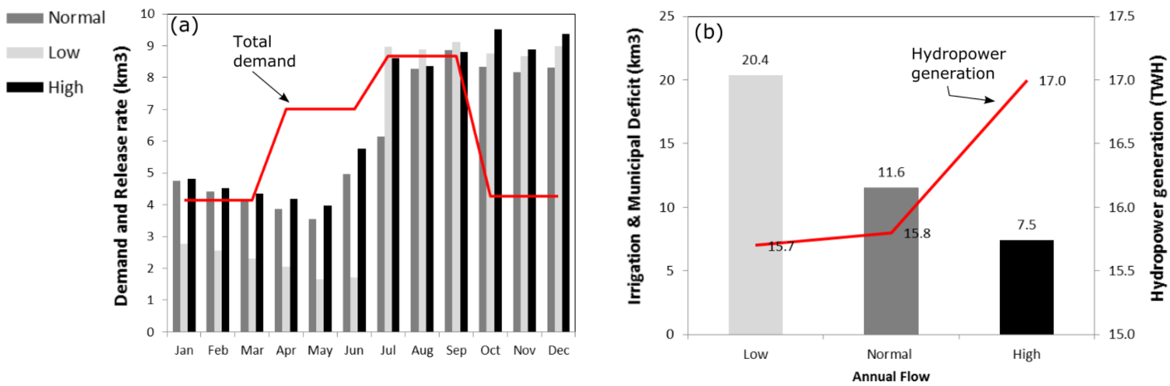

Figure 6. (**a**) monthly release rates for different levels of inflow and the demand for water downstream; and (**b**) the total irrigation and municipal deficit and the hydropower generation for different levels of inflow.

From the results in Figure 6b, it can be seen that the irrigation deficit and municipal deficit are increased by 8.8 km^3 during the lower flow months while the annual hydropower production for both scenarios remains the same. The power production remains nearly the same because of constant storage of water for later release. The stored water will generate greater benefits if it is released during the summer for agricultural use and, at the same time, increases the hydraulic head for power generation. The drawback is that the stored water will cause an increase of water deficit during the dry season when the inflow is low as shown in Figure 6a. In addition, it is evident that water deficit occurs during the high flow events of months April to June as the increase in the inflow of water is not sufficient to meet all the demand without sacrificing hydropower generation. However, the water deficit can be reduced by 4.1 km^3 (37%) from the normal flow while hydropower generation can be increased by 1.2 TWH (8%) during this event.

From these results, it can be seen that when the flow is lower, hydropower production will not be affected, but irrigation and municipal deficits are nearly twice the normal flow. Water deficit will be lower by half during the high flow event, and there will also be an increase in hydropower production. Therefore, irrigation and municipal supplies are more sensitive to the flow variability that mostly affects the downstream users.

5.2. Reliability Analysis

In order to provide a reliable system, we evaluate different policies by changing the irrigation and municipal reliability (r factor) and obtain the total power generated per annum from the optimal system. The reliability is defined as the percentage of water resource demand satisfaction [40]. Table 2 shows the release patterns for different reliability factors, r.

Table 2. Monthly release for irrigation and municipal reliability and the annual power produced.

Month	Rate (km^3)	r = 1	0.9	0.85	0.8	0.7	0.6
January	R1	4.147	4.21	4.755	3.845	2.281	1.736
February	R2	4.152	3.905	4.412	3.456	2.475	2.181
March	R3	4.147	4.168	4.137	3.373	2.408	2.259
April	R4	6.998	4.567	3.86	3.431	2.229	2.168
May	R5	6.998	5.13	3.557	3.513	1.873	1.881
June	R6	6.998	7.393	4.963	3.599	1.88	1.863
July	R7	8.683	8.976	6.143	7.845	10.675	1.996
August	R8	8.683	8.99	8.279	9.02	11.839	11.844
September	R9	8.683	7.738	8.875	9.095	10.616	12.894
October	R10	4.277	5.829	8.347	8.893	9.24	9.97
November	R11	4.277	6.471	8.158	8.775	8.783	19.399
December	R12	5.425	6.423	8.314	8.954	9.501	5.609
Power (TWH)		12.72	14	15.76	16.5	17.5	19.53

It can be seen that as the reliability ratio, r, increases, the amount of hydropower generated will be reduced and the maximum hydropower that can be produced from the system is 19.53 TWH. This is denoted as a power priority scenario and the system only operates at 60% irrigation and municipal reliability. As the result of constant storage of water for the hydraulic head, the amount of water supplied for downstream uses will be affected, as they are not supplied according to their demand pattern. As for the water priority scenario, the reliability ratio is r = 1, where all water demands are fully supplied, and this causes the hydropower production to drop by 35% from 19.53 TWH to 12.72 TWH. This scenario requires constant release of water to satisfy the demand downstream, and the water level in the reservoir target storage will be low throughout the year. The third scenario is to find a balance between water and energy, which is denoted as equal priority where the system will meet 85% of reliability and will also generate 85% of the hydropower potential.

6. Conclusions

Balancing water and energy demands while considering the irrigation requirement in the Blue Nile basin is a challenging task, as Ethiopia is developing the Grand Renaissance dam upstream of the river. We have used a system thinking approach to understand the water, energy, and food dependencies and applied system dynamics to understand the value of water in its alternative uses in the basin. The system dynamic model is built to simulate the release from the dam by considering different operating policies according to water, energy and irrigation needs of all countries involved. An optimisation engine is linked to the model to generate a water releasing rule to minimise water supply deficit while maintaining efficient hydropower production. Optimal target storage and release rates for each month are identified for different management operating conditions. As the annual precipitation is not consistent, the sensitivity of the inflow is also tested to establish how the system copes with flow variability. The reliability analysis also indicates how well the system can satisfy water and energy needs under different reliability factors. The evaluation results of this study indicate that the development of the dam provides Ethiopia with a greater control of the water to generate energy. In addition, the dam can be used to store the water which can be later released for use in Egypt and Sudan when demand is high during the summer time for more crops and food production. Although the system dynamic model presented in this study considers the dynamics between water, energy and irrigation demands, it relies on a set of fixed data as parameters and does not consider any crop yield model and alternative electricity usage. Future development can improve the model and bring these components at the system dynamic modelling level. In addition, we have incorporated Egypt's and Sudan's dependencies to GERD by considering their demand and water use data rights from the GERD releasing point and have not included the data from downstream dams. A future fine grained analysis can be done using finer data by considering the above downstream dams and intervening factors. The optimisation engines can be well adapted to consider multi-objective optimisation for proper trade-off studies with different water allocation principles as well as economic and non-monetary analysis. If the GERD model in this study is considered to be used for further policy planning, it must be more elaborated considering the above details and factors. Nevertheless, the methodology developed in this work is a stepping stone to studying any interlinked model such as the GERD water management system.

Author Contributions: Cho Chia Tan produced the first set of results and wrote part of the literature review and background of Nile river. Rasool Erfani conducted the research on system dynamic modelling and wrote part of the literature review as well as the modelling section. Tohid Erfani conducted the research, wrote the main part of the modelling text, coded the model and reviewed the manuscript with added references and background.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Howell, P.P.; Allan, J.A. *The Nile: Sharing a Scarce Resource: A Historical and Technical Review of Water Management and of Economical and Legal Issues*; Cambridge University Press: Cambridge, UK, 1994.
2. Shiklomanov, I.A.; Rodda, J.C. *World Water Resources at the Beginning of the Twenty-First Century*; Cambridge University Press: Cambridge, UK, 2004.
3. Grey, D.; Sadoff, C.W. Sink or swim? Water security for growth and development. *Water Policy* **2007**, *9*, 545–571.
4. Jägerskog, A.; Granit, J.; Risberg, A.; Yu, W. *Transboundary Water Management as a Regional Public Good. Financing Development—An Example from the Nile Basin*; Technical Report; Cambridge University Press: Cambridge, UK, 2007.
5. Speed, R.; Yuanyuan, L.; Zhiwei, Z.; Le Quesne, T.; Pegram, G. *Basin Water Allocation Planning: Principles, Procedures and Approaches for Basin Allocation Planning*; Asian Development Bank: Mandaluyong, Philippines, 2013.

6. Tesfaye, A.; Brouwer, R. Exploring the scope for transboundary collaboration in the Blue Nile river basin: Downstream willingness to pay for upstream land use changes to improve irrigation water supply. *Environ. Dev. Econ.* **2016**, *21*, 180–204.
7. McCartney, M.P.; Menker Girma, M. Evaluating the downstream implications of planned water resource development in the Ethiopian portion of the Blue Nile River. *Water Int.* **2012**, *37*, 362–379.
8. Mirumachi, N.; Allan, J.A. Revisiting transboundary water governance: Power, conflict cooperation and the political economy. In Proceedings of the CAIWA International Conference on Adaptive and Integrated Water Management: Coping with Scarcity, Basel, Switzerland, 12–15 November 2007; Volume 1215.
9. Moller, L.C. *Transboundary Water Conflicts over Hydropower and Irrigation: Can Multilateral Development Banks Help*? Centre for Research in Economic Development and International Trade (CREDIT), University of Nottingham: Nottingham, UK, 2005.
10. Erfani, T.; Erfani, R. An evolutionary approach to solve a system of multiple interrelated agent problems. *Appl. Soft Comput.* **2015**, *37*, 40–47.
11. Kucukmehmetoglu, M. A game theoretic approach to assess the impacts of major investments on transboundary water resources: The case of the Euphrates and Tigris. *Water Resour. Manag.* **2009**, *23*, 3069–3099.
12. Kibaroglu, A.; Ünver, I.O. An institutional framework for facilitating cooperation in the Euphrates-Tigris river basin. *Int. Negot.* **2000**, *5*, 311–330.
13. Kucukmehmetoglu, M.; Guldmann, J.M. Multiobjective allocation of transboundary water resources: Case of the Euphrates and Tigris. *J. Water Resour. Plan. Manag.* **2009**, *136*, 95–105.
14. Daoudy, M. Asymmetric power: Negotiating water in the Euphrates and Tigris. *Int. Negot.* **2009**, *14*, 361–391.
15. Kucukmehmetoglu, M.; Guldmann, J.M. International water resources allocation and conflicts: The case of the Euphrates and Tigris. *Environ. Plan. A* **2004**, *36*, 783–801.
16. Kliot, N.; Shmueli, D.; Shamir, U. Institutions for management of transboundary water resources: Their nature, characteristics and shortcomings. *Water Policy* **2001**, *3*, 229–255.
17. Zeitoun, M.; Mirumachi, N. Transboundary water interaction I: Reconsidering conflict and cooperation. *Int. Environ. Agreem. Politics Law Econ.* **2008**, *8*, 297–316.
18. Ding, N.; Erfani, R.; Mokhtar, H.; Erfani, T. Agent based modelling for water resource allocation in the transboundary Nile River. *Water* **2016**, *8*, 139.
19. Degefu, D.M.; He, W.; Yuan, L.; Zhao, J.H. Water Allocation in Transboundary River Basins under Water Scarcity: A Cooperative Bargaining Approach. *Water Resour. Manag.* **2016**, *30*, 4451–4466.
20. Dinar, A.; Nigatu, G.S. Distributional considerations of international water resources under externality: The case of Ethiopia, Sudan and Egypt on the Blue Nile. *Water Resour. Econ.* **2013**, *2*, 1–16.
21. Zhang, Y.; Block, P.; Hammond, M.; King, A. Ethiopia's Grand Renaissance Dam: Implications for downstream riparian countries. *J. Water Resour. Plan. Manag.* **2015**, *141*, doi:10.1061/(ASCE)WR.1943-5452.0000520.
22. Zhang, Y.; Erkyihum, S.T.; Block, P. Filling the GERD: Evaluating hydroclimatic variability and impoundment strategies for Blue Nile riparian countries. *Water Int.* **2016**, *41*, 593–610.
23. Rahaman, M.M.; Varis, O. Integrated water resources management: Evolution, prospects and future challenges. *Sustain. Sci. Pract. Policy* **2005**, *1*, 15–21.
24. Jaspers, F.G. Institutional arrangements for integrated river basin management. *Water Policy* **2003**, *5*, 77–90.
25. Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.; et al. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* **2011**, *39*, 7896–7906.
26. Lawford, R.; Bogardi, J.; Marx, S.; Jain, S.; Wostl, C.P.; Knüppe, K.; Ringler, C.; Lansigan, F.; Meza, F. Basin perspectives on the water-energy-food security nexus. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 607–616.
27. Endo, A.; Burnett, K.; Orencio, P.M.; Kumazawa, T.; Wada, C.A.; Ishii, A.; Tsurita, I.; Taniguchi, M. Methods of the water-energy-food nexus. *Water* **2015**, *7*, 5806–5830.
28. Erfani, T.; Erfani, R. Fair Resource Allocation Using Multi-population Evolutionary Algorithm. In *Applications of Evolutionary Computation*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 214–224.
29. Block, P.J. *Integrated Management of the Blue Nile Basin in Ethiopia: Hydropower and Irrigation Modeling*; Technical Report; International Food Policy Research Institute (IFPRI): Washington, DC, USA, 2007.

30. Awulachew, S.B.; McCartney, M.; Steenhuis, T.S.; Ahmed, A.A. *A Review of Hydrology, Sediment and Water Resource Use in the Blue Nile Basin*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2009; Volume 131.
31. Hammond, M. *The Grand Ethiopian Renaissance Dam and the Blue Nile: Implications for Transboundary Water Governance*; Global Water Forum Discussion Paper; Global Water Forum: Canberra, Australia, 2013; Volume 1307.
32. Sterman, J.D. *Business Dynamics: Systems Thinking and Modeling for a Complex World*; McGraw-Hill Education: New York, NY, USA, 2000
33. Mirchi, A.; Madani, K.; Watkins, D., Jr.; Ahmad, S. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water Resour. Manag.* **2012**, *26*, 2421–2442.
34. Simonovic, S.P. *Managing Water Resources: Methods and Tools for a Systems Approach*; Routledge: Abingdon-on-Thames, UK, 2012.
35. Initiative, N.B. *Hydrologic Regime in the Nile Basin*; Technical Report; Food and Agriculture Organization: Rome, Italy, 2007.
36. Nile Basin Initiative. *The Water Resources of the Nile Basin—-Nile Information System*; Technical Report; Nile Basin Initiative: Entebbe, Uganda, 2012.
37. Sutcliffe, J.V.; Parks, Y.P. *The Hydrology of the Nile*; International Association of Hydrological Sciences Wallingford: Oxfordshire, UK, 1999.
38. Food and Agriculture Organization. *FAO Statistical Yearbook 2014 Africa Food and Agriculture*; Food and Agriculture Organization of the United Nations Regional Office for Africa: Accra, Ghana, 2014.
39. Price, K.V.; Lampinen, J.A.; Storn, R.M. *Differential Evolution: A Practical Approach to Global Optimization*; Springer: Berlin/Heidelberg, Germany, 2005.
40. Postle-Floyd, H.; Erfani, T. A reliability and robustness analysis of the Masinga dam under uncertainty. *Climate* **2017**, in press.