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Faculté de génie
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**A SWAT-BASED DECISION SUPPORT SYSTEM FOR MULTIPURPOSE
RESERVOIR OPERATION AND FOOD-WATER-ENERGY-
ENVIRONMENT TRADE-OFF ANALYSIS: CASE STUDY OF SELINGUE
RESERVOIR**

A thesis presented by: Edgard Tisson Sia

Master of Applied Science: Civil Engineering

Department of Civil Engineering
Engineering
University of Ottawa

Thesis supervisor: Dr. Ousmane Seidou

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Abstract

The world's water resources face unsustainable pressure from population growth, changes in consumption patterns, pollution, and overexploitation. Water resources managers have developed holistic approaches such as IWRM (Integrated Water Resources Management) and, more recently, the WEEF (Water-Energy-Environment-Food) nexus to address the situation. However, their application in day-to-day water resources management is still challenging due to the of little knowledge, data, and tools. One area where that challenge needs practical solutions is reservoir operation.

The current study aims to improve the reservoir module in the Soil and Water Assessment Tool (SWAT) so that operation rules that aim to meet various water, food, and electricity objectives can be simulated. The improved SWAT model is used to simulate the management of the Sélingué reservoir in Mali, West Africa

The reservoir operation was simulated under three different operation rules: 1) priority to monthly hydropower production (HPP) target (rule 1); 2) respect of predefined monthly target storage (rule 2); 3) priority to downstream environmental flow, irrigation, and municipal water demands (rule 3).

Results show that when priority is given to the HPP target (rule 1), 98.3% of the electricity demand is met. At the same time, the dam can supply 81.72% of the water demand to maintain environmental flow and sustain irrigation and municipal water consumption. It also ensures water availability with an annual target storage deviation estimated at 1.8%. When rule 2 is implemented, a gap of 8.5% between electricity production and electricity demand is observed. Rule 2 also failed to sustain environmental flow and supply flow for irrigation and municipal consumption as a gap of 15.39% between the supply and the demand was observed. Similarly to rule 1, It ensures water availability with an annual target storage deviation estimated at 1.25%.

When rule 3 is enforced (i.e., the priority is given to environmental flow, irrigation, and municipal water demands) the reservoir can maintain the environmental flow and maintain irrigation, and municipal water requirements with a gap of 17.7% between the supply and the demands. However, HPP production decreases with a gap of 12.56% between the electricity supply and demand. Its capacity to supply water in the long term is low as it has the highest target storage deviation with a value of 18%. These results indicate that rule 1 offers more guarantees considering the food and electricity security and environmental challenges.

Note that the simulations are done assuming that these rules are systematically followed. In practice, decision-makers can deviate from a rule in exceptional circumstances to maximize benefits or avert unwanted consequences. Finally, a decision support system (DSS) was developed to assist decision-makers in selecting efficient reservoir operation policies for multipurpose reservoirs combining HPP and irrigation.

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LIST OF ABBREVIATIONS

SWAT	Soil and Water Assessment Tool
DSS	Decision Support System
IWRM	Integrated Water Resources Management
HPP	Hydropower production
ROC	Rule of Curves
WEEF	Water-Energy-Environment-Food
IHA	International Hydropower Association
EPAUS	United States Environmental Protection Agency
IND	Inner Niger Delta
UNB	Upper Niger Basin
WFDEI	WATCH forcing Data methodology applied to ERA-interim reanalysis
MATLAB	Matrix Laboratory
FAO	Food and Agriculture Organization
GNAFC	Global Report on Food Crises
IWA	International Water Association
GWP	Global Water Partnership
SIWI	Stockholm International Water Institute
GDP	Gross Domestic Product
ODN	Office du Niger
AWPS	Alberta Water portal Society
MRC	Mekong River Commission
UN	United Nations
WEFE	Water Energy Food Environment
LP	Linear Programming
NLP	Nonlinear Programming
DP	Dynamic Programming
QP	Quadratic Programming (QP)
SLOP	Standard Linear operating policy
CGA	Conditional Genetic Algorithm
CTSA	Conditional Tabu Search algorithms
WEAP	Water Evaluation and Planning
MHA	metaheuristics algorithms
IRBM	Integrated River Basin Management
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
IMS	Information Management System
CSDSS	climate-smart Decision support system
ENV	Environment
IRR	Irrigation
MNP	Municipal
CIESIN	Center for International Earth Science Information Network

GUI Graphical User Interface
DFCRCs Dynamic Flood Control Rule Curves

Chapter 1: GENERAL INTRODUCTION

This chapter provides the background of the research and its justification.

1.1 Background

Water is an essential natural resource that plays a vital role in all countries economic and social development. Unfortunately, water is not equally distributed in all regions of the world. Access to water in adequate quantity and quality has become a global problem because of several factors, including population growth and climate change. Experts from the world bank have predicted a water scarcity crisis by 2030, with a gap of 40% between the demand and the available water supply (Worldbank, 2022). The main contributors to this situation are the fast growth of the global population and the persistence of some bad practices. The demand for food and energy is expected to increase as the population does. Knowing that water, food, and energy are interconnected, water scarcity can lead to a social and economic crisis that includes food and energy insecurity.

Another contributor to the water scarcity crisis is the poor management of water resources. Dams and Reservoirs are typically used to store water during wet periods and release it during dry periods so that water availability at and downstream the dam becomes more predictable. The stored water can be used for various purposes, including drinking water, irrigation, hydropower, and flood control. The goals of the first artificial reservoirs were to control flooding to avoid crops damages in agricultural areas and store water to prevent water shortage in dryer seasons (AMERICANDAMS, 2023). Dams evolved during the industrial revolution: in response to the increasing demand for electricity for large machinery, engineers have improved dam efficiency to support industrial activities (Viollet, 2017).

Over the last century, reservoirs have been mainly used for HPP (Tigrek & Aras, 2012). Hydropower has become one of the principal sources of electricity in the world. According to the International Hydropower Association IHA (2018), hydropower represents one of the world's most important renewable electricity generation sources.

Reservoirs and dams are essential in water resources management because they can be used to meet multiple demands. However, the operation of multi-objectives reservoirs can become very complex. The complexity of reservoir operation increases as the number of objectives increases. One of the challenges of reservoir operation is intra and inter-annual variability in streamflow and rainfall, which leads to uncertainty on the outcome of any given operation decision. That uncertainty is getting larger and larger because of climate change, making the tasks of water resources managers even more complicated.

The application of appropriate reservoir operation rules can minimize these issues. The best way they evaluate reservoir operation policies is through reservoir modeling and simulation. The simulations may include different scenarios, such as wet and dry years, changing demand patterns, and climate change.

Over the years, progress in mathematics and computing has allowed software development for many fields, such as economy, agriculture, and water resources. The Soil and Water Assessment Tool (SWAT) is a software widely applied in water resources to address hydrologic and environmental issues (Tan et al.,2019).

(SWAT) includes reservoir operation routines (Arnold et al., 1998). It can simulate reservoir inflow and outflow under various climatic conditions (Shrestha,2021). It can also help predict the environmental impacts of land use, land management practices, and climate change (EPAUS, 2017). Although SWAT has many tools to complete water resources simulation, it has some limitations considering reservoir operations. According to Shrestha (2021), the WAT model cannot carry realistic reservoir operation methods. The available options target storages and uncontrolled outflow with no options to modulate the release based on internal or external events. Therefore, SWAT needs to be upgraded to handle reservoir simulation and optimization. An upgraded version of SWAT should be able to:

- ❖ Optimize reservoir operation.
- ❖ Optimize the management of hydropower schemes.
- ❖ Manage large-scale reservoir with HPP capacity.
- ❖ Determine the effects of flow on reservoir operation and HPP.
- ❖ Determine the effects of various purposes on HPP.
- ❖ Quantify the impact of climate change on reservoir operation.
- ❖ Determine the effects of sediment deposition on reservoir operation.

Adding more realistic reservoir operation options and a new HPP capability to SWAT will make it more useful for operational hydrology, as various rules can be tested. The impacts of these rules on water security, energy security, and environmental sustainability can then be assessed.

Water, food, energy security, and environmental sustainability are the challenges facing the Mali government. The country does not have enough hydraulic infrastructure to ensure the spatial distribution of water in all regions. In addition, most of the rivers are concentrated in the East-south and center. The population in the north is the most exposed to water shortage. Rural populations live in difficult conditions and are forced to use precarious methods to collect rainwater. They are exposed to all kinds of water-related diseases. The situation of food security is also alarming. The reduction of rainfall due to climate change and the socio-economic crisis in the country has increased food insecurity. The country is living through its worst food and nutrition crisis in a decade (reliefweb, 2022). The number of people affected by the crisis was approximately 1.2 million at the end of 2021 (reliefweb, 2022). The northern regions are the most affected areas due to poor rain distribution and insecurity (reliefweb, 2022).

Regarding energy security, the country is not self-sufficient despite the construction of hydropower and thermal plants. Electricity plays an important role in the mining industry which is one of the foundations of its economy. This forced the Mali government to import energy from neighboring countries such as Ivory Coast. The availability of water is fundamental to

hydroelectricity production. Unfortunately, climate change can affect water availability which can lead to a decrease in hydroelectricity production of the power plant. Nevertheless, the hydropower potential of the country is still under-exploited. Also, the country has other renewable energies such as solar energy that could be exploited in addition to hydroelectricity.

All the food and energy issues of the country are related to water. Mali government must develop some strategies for the sustainable management of water resources. This includes the management of existing and future water resources infrastructures and will require the assistance and support of engineers in the decision-making process.

An improved version of SWAT could help assess Mali's water-related challenges and elaborate a few strategies to address the issues.

1.2 Objectives

The objectives of this research are listed as follows:

- Establish a reservoir hydropower routine in the SWAT model.
- Evaluate the relationship between water, food, energy.
- Create reservoir operation policies based on water, food, and energy nexus.
- Determine the adequate reservoir operation rule for a tradeoff between water, food, energy.
- Develop a decision support system (DSS) to support various users with no engineering background in the decision-making process on multi-reservoir operating policies.
- Provide recommendations for sustainable management of water resources to the Mali government, particularly on the Sélingué reservoir.

1.3 Methodology

The research aims to investigate the relationship between water, food, energy, and the environment in multipurpose reservoir operations. The approach used for the investigation is the simulation of reservoir operation under three different purposes listed as follows:

- monthly HPP target
- predefined monthly target storage
- environmental flow, irrigation, and municipal water demands.

The simulations will be completed on SWAT because it has an integrated reservoir routine and its wide use in past hydrological research. However, SWAT does not have a hydropower routine. Also, it does not have the tools to operate under environmental flow, irrigation, and municipal water demands. Therefore, the SWAT code source will undergo a few modifications to integrate the tools required for the research. A new reservoir hydropower routine will be integrated into SWAT.

A case study on the Sélingué dam in Mali will be completed for the experiment. The data need for this study were reservoir data and subbasins data. Climate data such as temperature and daily

precipitation were collected from the WFDEI meteorological forcing data set (WATCH forcing Data methodology applied to ERA-interim reanalysis). Sélingué data were collected from a previous study completed in the upper Niger (UNB) and the Inner Niger Delta (IND) (Maiga, 2019). Sélingué is in the UNB. The subbasin data comes from local authorities and previous studies (Maiga, 2019).

SWAT has already classified the data into different categories. Thus, the reservoir data are inserted in the reservoir input file, the subbasin data are inserted in the subbasin input file, and the same thing for climate data. SWAT also classifies into different categories the results of a simulation. Thus, the results are collected from a reservoir output file. The results are collected in MATLAB to generate graphs and curves for analysis.

MATLAB is used to display the data because the second purpose of the study which is to develop a decision support system. Thus, a graphic user interface is built in MATLAB to allow users to simulate multipurpose reservoir operations involving water, food, energy, and environmental challenges. This approach enables to clearly understand the impact of the purposes on each other. MATLAB allows to visualize the results and compare them.

1.4 Novelty

This study has 2 novelties. The first one is the integration into SWAT code source of new functions that allow to simulate hydropower production, evaluate irrigation, municipal water demand as well as the impact of water uses on the environmental flow. The second one is the development of a decision support system to determine how different management decisions affect water, food, and energy security so that the decision-maker can make informed decisions.

The novelty of this study is summarized as follows:

- A new HPP module has been developed for the SWAT models.
- A new option is now available in SWAT to give priority to HPP, or predefined downstream water demands.
- A new option is now available in SWAT to give priority to environmental flow, irrigation, or municipal water demands.
- New information on the ability of the Sélingué dam to satisfy conflicting needs for electricity, food security, and environmental flows has been generated.
- A DSS was developed to assist the decision-makers of underdeveloped countries in the elaboration of water management strategies, particularly on multipurpose reservoirs.

1.5 Organization of the thesis

The first chapter of this report presents the background of the topic studied and provides the justification of the research. The second chapter describes two approaches of water management which are IWRM and WEEF. It also explains the meaning of hydrological modeling and multiple-purpose reservoir modeling. The chapter three explain the importance of reservoir operation rules in water management. It also presents 4 techniques of reservoir operation.

Chapter four describes the concept of decision support system and explains its importance in the selection of appropriate decisions on water management. Chapter five explains the methodology of this study and provides additional information on the modification of SWAT and the development of the DSS. Chapter six presents the study area and the context of the research. The chapter seven presents the results of the numerical experiment. Chapter eight discusses the results and chapter nine concludes the research with few recommendations. The flowchart below summarizes the organization of the thesis.

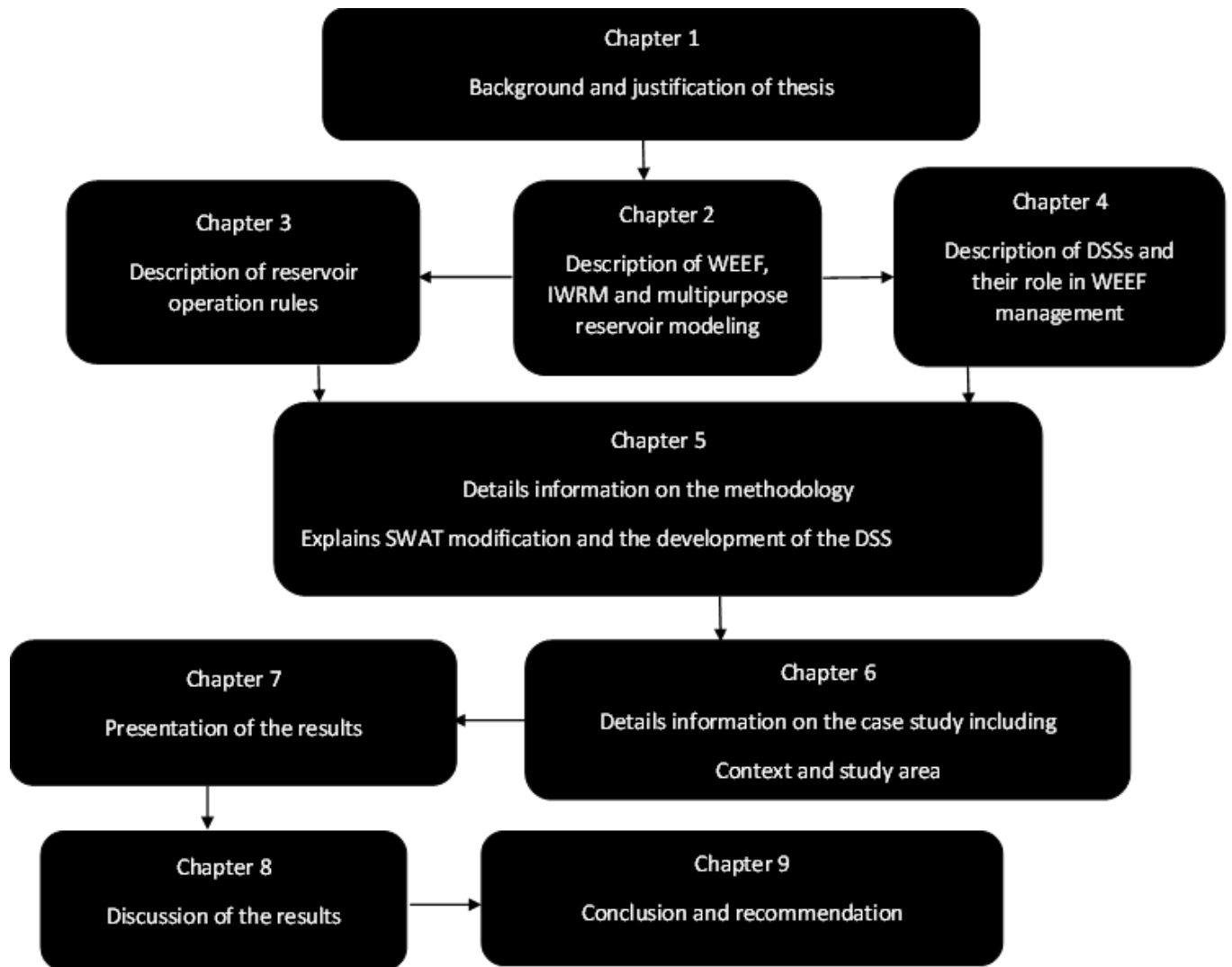


Figure 1 : Research flow chart

Chapter 2: Literature review

This chapter describes the concepts of water, food, energy security, and environmental sustainability. It also describes the modeling of multipurpose reservoirs.

2.1 Water Security

Water is necessary for the survival of human beings as well as for the functioning of all forms of life on earth. It covers 70% of the planet, but only 3% is fresh water that can be used. Water security is a concept promoting sustainable access to water quantity and quality to everyone on every human on earth. The United Nations Agency on water (2013) describes water security as “The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.” The concept has evolved with the will of worldwide governments to provide safe water to their population and prevent them from the negative effects that may cause excess or scarcity of water.

Water security is critical to the socioeconomic development of countries. According to Mishra et al., (2021), the increase in water security will have the following effects:

- 1) Ensure the availability of appropriate water resources and the sustainable distribution of water for all social and economic activity.
- 2) Mitigate water-related risks such as floods, droughts, and pollution.
- 3) Address the conflicts arising from disputes over shared water.

Water security has a wide scope. It encompasses resilience to water disasters, environmental issues, transboundary issues, economics, water safety issues, etc. The following image describes the scope of water security.

Unfortunately, the achievement of water security is threatened by many factors including climatic and hydrological conditions, population growth, rural-urban migration, increase per capita water use, pollution, and over-abstraction of groundwater (Kujinga et al.,2014). As a result, there is a problem with water's spatial and temporal distribution, leading to the so-called “water scarcity crisis.” The World Bank (2021) summarized the water crisis with these numbers:

- 2.2 billion people around the world do not have safely managed drinking water services.
- 4.2 billion people do not have safely managed sanitation services.
- 3 billion lack basic handwashing facilities.”

World leaders are working on the development of several strategies such as integrated water resources management (IWRM) to promote the sustainable management of water resources.

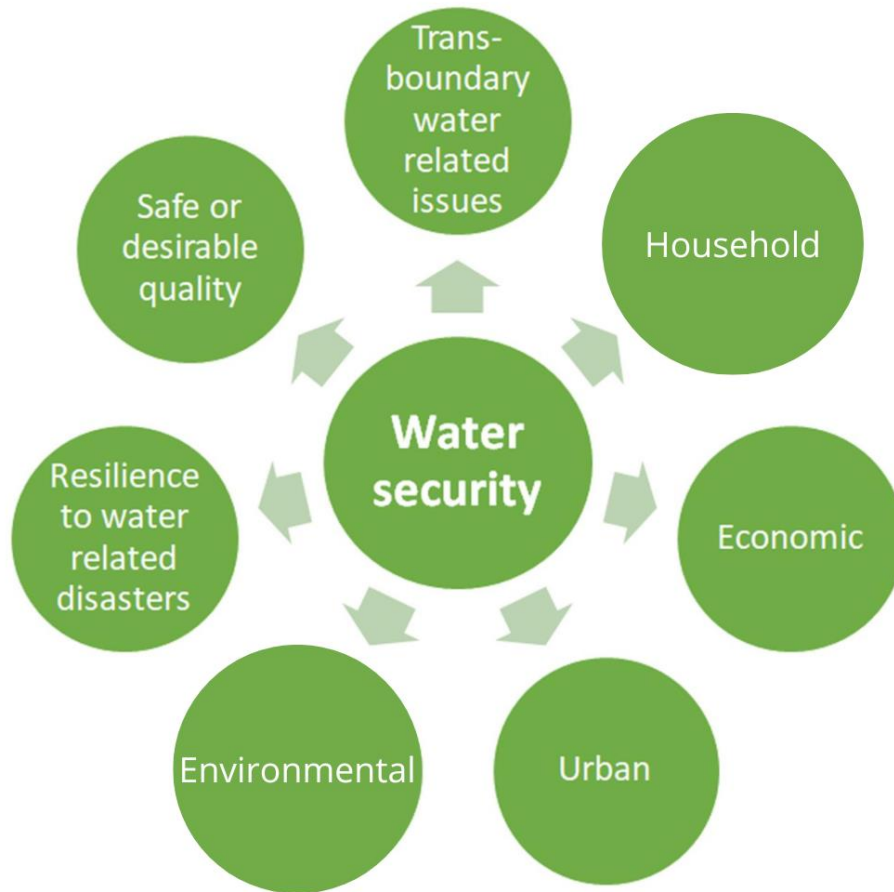


Figure 2 : Water security dimensions (Mishra et al., 2021)

2.2 Energy security

Energy security is affordable and sustainable access to energy sources. The United Nations describes energy security as “the continuous availability of energy in varied forms, in sufficient quantities and at affordable prices” (Miller, 2017). The concept was born from the oil crisis of the 1970s (Energyeducation, 2023). This led to global awareness of energy security. The International Energy Agency (IEA) has been created to ensure the promotion of a stable global energy supply (Energyeducation, 2023). Energy security is critical to food security as it is involved in the production, transportation, and conservation of food. It is essential to households and industry’s functioning. Energy security can be explained into four components named the four AS. It includes availability, accessibility, acceptability, and affordability.

Energy availability is affected by many factors. Firstly, physical factors. The availability of fossil fuels is affected by Geology. The formation of fossil fuels is a geological process. Climate and relief can be a constraint to the extraction of fossil fuels.

The second factor is the cost of exploitation and production of energy resources. The cost of production generally influences the price of energy. High energy production will drive the price of energy up and reduce its affordability. The third factor is the emerging technologies that can increase the environmental threats of energy sources. Finally, political conflicts can affect energy distribution.

Energy insecurity is increasing with the growth of energy demand in developing countries. Also, global conflicts reduce affordability as it drives the price of energy up. However, the issues can be reduced with the following strategies:

- Diversification of energy sources
- Quality and timing of the flow information
- Collaboration of consumers, producers, and governments
- Investment in the development of renewable energy
- Research and development of low-carbon energy
- Technology advancement

(Energyeducation, 2023)

Some energy sources such as fossil fuels are criticized due to their negative effects on the environment. In the future, energy security will be supported by renewable energies and low-carbon technologies. According to Dahlan et al., (2022), the growth of renewable energy will shape energy security with the support of effective policy and regulatory frameworks and innovative business models. Some countries adopted regulations to mitigate carbon emissions. As an example, Canada has established a plan to eradicate fossil fuels car from its territory. It has introduced regulations requiring that at least 20 percent of new vehicles sold in the country must be zero emission by 2026, at least 60 percent by 2030, and 100 percent by 2035 (Canada, 2023). In the long term, electrical cars will replace fossil fuel cars. According to Dahlan et al., (2022), solar electricity on rooftops or electric vehicles will be widely used in the future.

Hydroelectricity is one of the world's most critical renewable electricity generation sources. According to the International Hydropower Association (2018), the worldwide total installed hydropower capacity was approximately 1267 GW (Gigawatt) in 2018, generating 4185 TWh (Terawatt-hour). This represents 16% of the total electricity generated. The potential capacity of Hydropower could increase over the next years. According to the International Energy Agency (2021), around half of hydropower's economically viable potential is not harnessed. Emerging economies and developing countries have a huge potential, with almost 60% of hydropower resources.

However, the sector of hydropower is facing a few challenges. The main challenge is the impact of climate change on electricity production.

HPP is based on the volume of water stored in dams. Hot temperatures in some regions increase evaporation, reducing the volume of water stored. An augmentation of evaporation will influence

the reservoir operation system and reduce HPP. In these conditions, it may become challenging to meet the electricity demand of the growing population.

Countries that mainly depend on hydropower are vulnerable to climate change as they can experience electricity shortages in case of drought. Such a situation can significantly affect the economy of countries. This context encourages the development of DSSs considering climate change to determine adequate reservoir and dam operation rules.

The current study contributes to the water security with the implementation of a DSS to determine the appropriate reservoir operation rule for hydropower production.

2.3. Food security

Food is essential to human survival. The World Food Summit (1996) describes food security as a context “when all people, at all times, have physical and economic access to a reasonable safe and nutritious food that meets their dietary need and food preferences for an active and healthy life.”

From this definition, FAO (2006) deducted the four main dimensions of food security listed as follows:

- Food availability: It controls the supply side of food security and is based on the level of food production, stocks levels, and net trade.
- Food access: The accessibility of food is based on income, expenditure, markets, and prices.
- Food utilization: Appropriate diet and health care enable to meet physiological needs. This determines the state of nutritional well-being.
- Stability of the other three dimensions over time: It refers to the availability and accessibility dimensions of food security. This means people must always have access to food.

Food insecurity has severe consequences such as hunger, malnutrition, and death. Poverty and unemployment, disease are often the sources of people’s food insecurity.

The global report on Food crises (GNAFC) in 2020 shows that:

- 135 million people experienced acute food insecurity.
- 183 million people were under stressed conditions, at the cusp of acute hunger.
- 17 million children suffered from wasting due to acute malnutrition.
- 55 countries and territories in food crises

(GNAFC, 2020)

The main causes of global food insecurity are climate change and conflicts. Climate change influences water availability which affects crop yields. Conflicts disrupt the production and distribution of food. Underdeveloped countries and countries located in conflict areas are the

most affected by food insecurity. Underdeveloped countries lack the infrastructure to optimize, conserve and distribute food production. The rate of unemployment in underdeveloped countries increases poverty which leads to food insecurity. The biggest challenge of food security in the coming years will be to meet the growing demand for food due to the rapid growth of the global population.

To address the global food crisis, governments, international organizations, and other stakeholders worked on response plans. The World Bank (2022) announced its strategies to address the food crisis. It includes the following actions:

- Support production and producers
- Facilitate increased trade.
- Support vulnerable households
- Invest in sustainable food and nutrition security.

The development of agriculture can help to enhance food security. Irrigation which consists of supplying water to the plants is one of the most important steps of agriculture. The contribution of the current study to food security is the implementation of a DSS allowing the evaluation of water demands under different management policies. The DSS incorporates indicators of water demand required for irrigation. It will help to determine the feasibility of agricultural forecasts and ensure adequate planification.

2.4 Environmental sustainability

Environmental sustainability is described as responsible actions toward the environment to avoid the degradation of natural resources and ensure sustainable environmental quality (Study, 2023). Its practice helps to secure the needs of today's population by thinking about that future generations. The concept was born in 1987 in the Brundtland report produced by several countries. The United Nations Brundtland commission described sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs".

The achievement of environmental sustainability is affected by many issues named climate change, water pollution, Air pollution, deforestation, ocean acidification, waste production, natural resource overuse, etc. The main causes of these issues are global production and consumption due to rapid modernization and population growth.

In 2015, United Nations published its plan to restore sustainability and it includes: 1) ending poverty, 2) protecting the planet, and 3) ensuring prosperity for all. They have established an action plan called the seventeen Sustainable Development Goals. UN undertakes to support Nation's members with science-based policymaking, innovation, global advocacy, and partnership building.

To achieve the transition to environmental sustainability, Cohen (2021) from Columbia Climate School recommends the following steps:

- Research, measure, and understand the current state of environmental degradation.
- Understand the *causes* of environmental degradation.
- Develop a strategy for reducing pollution and growing a renewable-resource-based economy.
- Build public sector infrastructure to support environmental sustainability.
- Change the politics, advocacy, and communication of environmental sustainability.

The implementation of the DSS contributes to a sustainable environment by indicating an environmental deficit each time the flow in the subbasin is lower than the environmental flow.

2.5. Holistic approaches to resource management

The interlinkages between different components of water resources systems have been recognized early and led to the development of (theoretically) holistic approaches to water resources management – be best known being integrated water resources management (IWRM), which is water-centric. More recently, the WEF nexus started gaining traction in the international community as a more general resource management option where water has the same weight as energy, environment, and food security. These two approaches are described in the sections below:

2.5.1 Integrated Water Resource Management (IWRM)

Water resources management (WRM) consists of planning, developing, and managing water resources based on water quantity and quality across all uses (Worldbank, 2022). It involves the support of institutions, the construction of infrastructures, and the use of information systems. The goal of WRM is to ensure the availability of quality water for drinking and sanitation services, food production, energy generation, inland water transport, and water-based recreational activities, as well as to sustain healthy water-dependent ecosystems. It also includes, the management of water-related risks cited, such as floods, contamination, etc. Nevertheless, the economies, households, and industrialization make the WRM very complex.

In this context, an integrated management accounting for these factors is required. Integrated water resource management (IWRM) is defined by the Global Water Partnership (GWP) as “a process which promotes the coordinated development and management of water, land, and related resources to maximize economic and social welfare equitably without compromising the sustainability of vital ecosystems and the environment.” It was first introduced at the World Summit on Sustainable Development in 1992 in Rio, where it was the object of an extensive discussion about its practice. The experts recommended it the same year during the international Water and Environment conference in Dublin.

The Dublin conference can be summarized in these principles: the recognition of the vulnerability and economic value of water, and the involvement of users, planners, policymakers, and women in its process of development, management, and safeguarding (GWP, 2018). The key components of IWRM are listed as follows:

- The Management of water resources at the lowest possible level
- The supply optimization
- The management of water demand
- The provision of equitable access to water resources through participatory and transparent governance and management
- The establishment of improved and integrated policy, regulatory and institutional frameworks
- The use of an inter-sectoral approach to decision making
- Integrated management means that a single intervention has multiple benefits (GWP, 2018).

IWRM has three main principles: Social equity, economic efficiency, and environmental sustainability (IWA, 2018). Before the implementation of any strategies, IWRM encourages country leaders to evaluate their decisions through the following questions: “will my decision result in the most efficient use of resources?”, “how will my decision affect other water users?”, etc. The IWRM process requires the involvement of decision-makers through the creation of policies and their efficient implementation, as well as the development of equitable and sustainable solutions to water problems. The following picture is an illustration of the IWRM approach to water governance.

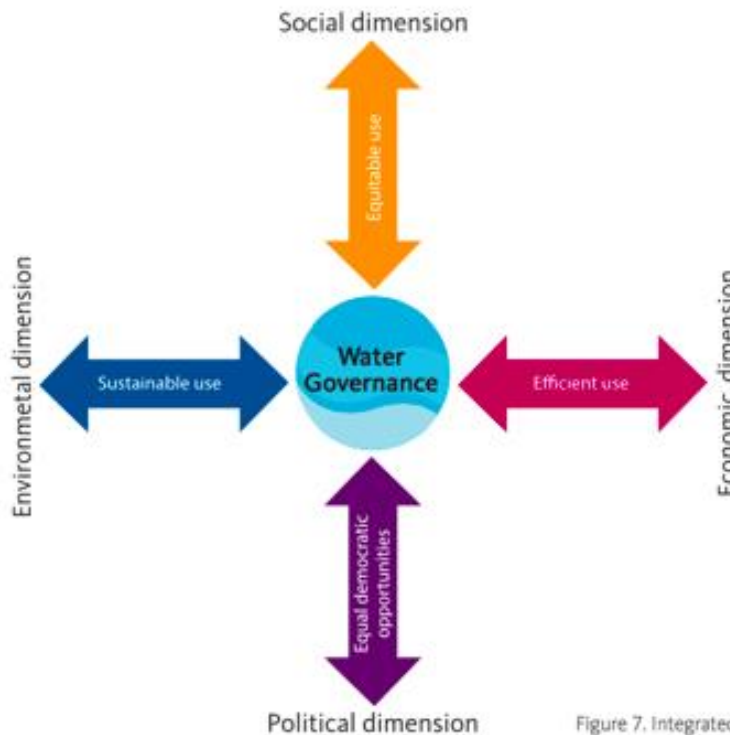


Figure 7. Integrated approach to water governance.

Figure 3 : Integrated approach to water governance (SIWI, 2020)

It is crucial to mention that IWRM is a flexible approach. Countries can implement IWRM based on their reality. However, there are a few conditions to respect for implementing IWRM. These conditions are listed as follows:

- Political will and commitment
- Basin management plan and clear vision
- Participation and coordination mechanisms fostering information sharing and exchange.
- Capacity development
- Well-defined flexible and enforceable legal frameworks and regulation
- Water allocation plans
- Adequate investment, financial stability, and sustainable cost recovery
- Good knowledge of the existing natural resources in the basin
- Comprehensive monitoring and evaluation

(IWA, .Integrated Water Resources Management: Basic concepts, 2021).

The success of IWRM depends on the planning, implementation, and continuous monitoring of the process (SIWI, 2020). The Mekong River Commission in Asia is an example of successful IWRM implementation. Their council has adopted a formal IWRM-Basin development strategy to improve water management. The dialogues between stakeholders were a key component in the decision-making process. This led to actions that contributed to better management of water resources in this zone (Smith & Claussen, 2015).

There are multiple cases of unsuccessful IWRM. It occurs when key components such as stakeholder participation and ecosystem sustainability are poorly implemented (SIWI, 2020). An ongoing process, it is complex to qualify a particular application as a failure. However, the theoretical principles underpinning IWRM are hard to apply in operational contexts: challenges to IWRM include insufficient funding, insufficient and aging monitoring systems, insufficient knowledge of the system behavior, insufficient data, imperfect (or absent) modeling tools, lack of skilled professionals, etc.

2.5.2 The Water, Energy, Environment, Food nexus

Rapid urbanization, population, and economic growth are the signs of a world in constant progress. The demand for basic needs such as food, water, and energy are also increasing. There is an intensive production of food and energy to meet the demand, which requires a high-water quantity. A recent report from the UN-Water (2021) shows that agriculture uses 72% of withdrawals water, municipalities use 16%, and industries use 12%. The poor management of water resources and the lack of control over human consumption is leading to a water scarcity crisis.

Rapid population growth, urbanization, and climate change are the factors encouraging the increase in global demand for water, energy, and food which is expected to increase by more than 50% by 2050 (Ferroukhi, et al., 2015).

Water, food, and Energy are tightly interconnected as illustrated in Figure 2. Any attempt to solve these issues independently can backfire. A better approach is to approach these interactions using a nexus approach ('nexus' is a term that means 'link').

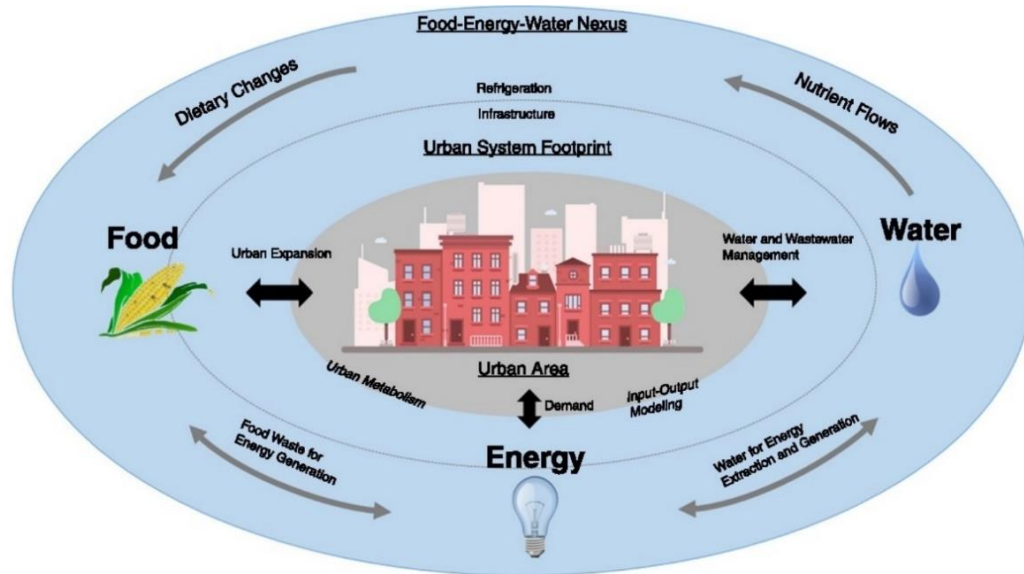


Figure 4 : Interactions between Water, Energy, and Food (Heard et al.,2017).

The nexus formed by Water, food, and Energy is currently one of the main topics of worldwide negotiations. The application of nexus has multiple benefits that can be categorized into three sectors listed as follows by the Global Water Partnership (2020):

Firstly, the economic benefit. It increases the sustainable viability of economic activities and improves their resilience against the effect of climate change. It helps to reduce the risks and associated costs of water-related hazards such as floods and droughts. It sustains the development of the agriculture and tourism sectors. It optimizes the consumption of resources and use of infrastructures as well as trade and innovation.

Secondly, the social and environmental benefits. It supports the sustainable development goals promoted by the United Nations. It improves public health and employment creation. It also supports water security by promoting access to adequate water and sanitation services. It encourages the conservation and the very of ecosystems and habitats.

Thirdly, regional cooperation and geopolitical benefits. It addresses the conflicts on shared resources by improving the cooperation in the management. It participates in the adoption of new cross-border agreements, regulations, and protocols. It also supports the development of regional markets for goods, services, and labor. Finally, it encourages cross-border investments.

The nexus also be used in the management of transboundary water bodies to reduce conflicts and trade-offs. In addition, the nexus can be used as an instrument in the promotion of social cross-cutting issues such as stakeholder engagement, human rights, and combatting poverty (GWP,2020).

However, like IWRM, while the principles are clear, the practical implementation of the nexus faces many challenges:

- Data availability
- Knowledge gap in the understanding of the WEF linkages (Liu J. , et al., 2017)
- Lack of tolls to address the trade-offs in the nexus (Liu J. , et al., 2017)
- Policy challenges
- Communication issues
- Geospatial variety
- Changing traditional attitudes
- Lack of training on WEF in underdeveloped countries
- Population growth

The following table summarizes the potential future challenges of WFEN.

Challenges	Solutions
Lack of integrated policy and legislation for the system	Integrated policy-making such as integrated pricing in water and energy fields, developing a model of agricultural complex and industry proper allocation
Data uncertainty	Implementing the appropriate uncertainty modeling such as stochastic programming, scenario generation, and so on.
Large numbers of data for subsystems	Applying data-mining techniques
System boundary	Accurate detection of cases using precise and rapid identification of subsystems
Lack of sufficient standards and laws	Forming committees comprising subdiscipline specialists to address this gap
Lack of efficient software platforms	Presenting multi-domain software

Table 1: Some of the challenges and solutions for implementing nexus systems (Abdi, Shahbazitabar, & Mohammadi-Ivatloo, 2020)

2.6 Dams as key infrastructures in IWRM and the WEF nexus: benefits and drawbacks

Infrastructures play an essential role in the social and economic development of countries. They are involved in many activities. Reservoirs and Dams are hydraulic infrastructures that can generate hydroelectric power, produce food through irrigation, and supply domestic and industrial water. With the potential growth of the worldwide population, the construction of dams is seen by many governments as the best way to meet food, electricity, and water demand.

Shi et al. (2019) studied the role of large dams in economic development under the pressure of population growth based on the gross domestic product (GDP). Their results show that large

dams significantly impact economic development, especially in developed countries. Also, they found that the construction of additional dams will increase by 67.56% worldwide from 2010 to 2050. They consider large dam construction as a solution to manage the economic development problems in the foreseeable future.

According to the World Bank (2022), constructing Dams and Reservoirs will help approximately 330 000 people in the Niger River Basin benefit from better access to Energy, water, and Livelihoods. Dams can also improve water storage. Liersch et al. (2018) demonstrated that the Upper Niger basin (UNB) without any dam would only store enough water in extraordinarily wet years for dry season cropping, with a gap of 23% on the average flow (1961-2000).

Dams can also help to control floods a recurring threat amplified by climate change. MEI et al. (2016) studied the impact of dams on the flood occurrence of 38 rivers in the United States. One of their conclusions was that dams significantly reduce the flood magnitude nationally. However, they regret the lack of information on how dams and reservoirs can alter the hydrology system. A study of the international Wetland shows that the Sélingué reservoir and the Office du Niger irrigation (ODN) have decreased the Inner Niger Delta (IND) level by 20-25 cm, and inundated area by 900Km^2 . Zwarts et al. (2005) analyzed the effects of Sélingué combined with Fomi dams on the Niger River's average monthly flow (from 1980 to 2001) at the Ké-Macina hydrological station. They completed four numerical experiments to compare the natural flow of the river and the presence or addition of dams. The following figure shows the results of their research. On one side, it shows an increase in flow during the dry months due to the presence of dams. On the other side, it shows a decrease in the flow during the wet months.

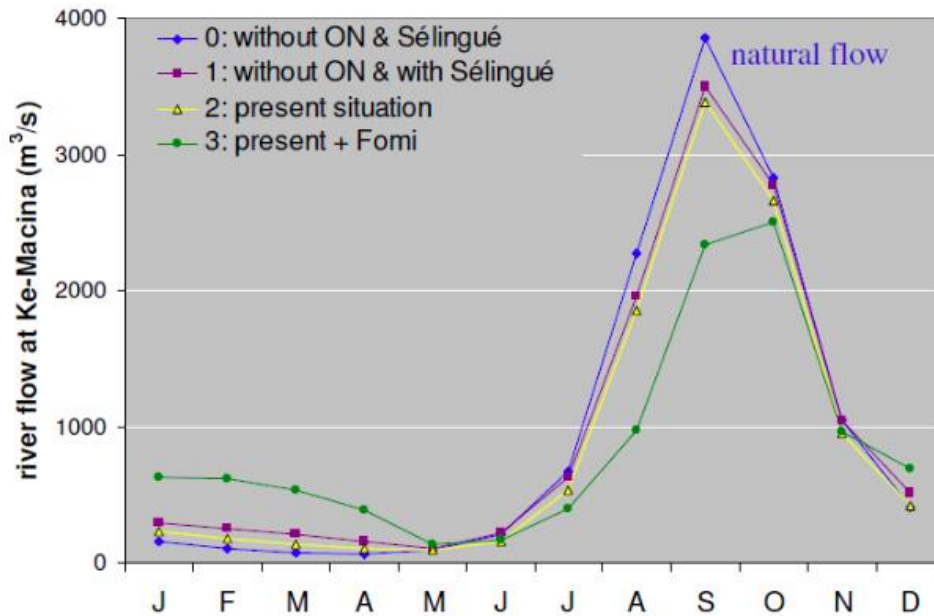


Figure 5 : The average monthly flow of the Niger at Ké-Macina, calculated over the period 1980-2001. Reprinted from (Zwarts et al.,2005).

Liersch et al. (2018) obtained similar results in their study. They observed a decrease of discharges in the high flow season by up to 10% and an increased discharge in the low flow season by 10% or more.

Despite their various advantages, dams can have harmful effects when poorly designed and managed. They alter the hydrological regime of rivers and can cause upstream flooding. As dams block the natural path of water, they affect life downstream, especially ecosystems and populations.

Dams also have a significant impact on sediment transportation which can lead to the infertility of downstream lands and the erosion of riverbeds. A professor of geography and environment at Michigan State University in the US argued that dams are responsible for 30 to 49% of sediment loss (Diehn, 2020). As the construction of a dam usually requires a lot of space, it causes the displacement of human communities and destroys wildlife and aquatic life. Alberta Water portal Society (2015) has criticized the impact of Dams and reservoirs regarding the BC hydroelectric Site C dam on the Peace River. According to AWPS, this project may induce the relocation of people, the flooding of the area required for construction, the displacement of wildlife habitat, and the loss of important cultural sites. This shows that it can lead to the destruction of biodiversity and the extension of species. A study completed by the Mekong River Commission MRC (2018) on the impacts of dams shows that dam projects will reduce the fish stocks of the Mekong River by 40%. This will potentially impact the lives and livelihoods of people that rely on fishing in this region.

As forests are known to maintain Earth's carbon balance, dams contribute to climate change because they flood upstream vegetation in the design processes. The decomposition of the flooded vegetation releases a powerful greenhouse gas called methane. Greenhouse gas emissions caused by dams can be estimated to be approximately a billion tons annually (Deemer, et al., 2016).

Dams do not affect the ecosystem and environment of some rivers because their flow patterns, landscapes, and species are suitable for the changes. The impact of a dam on the flow depends on its size and operating rules. A bigger dam greatly alters the river flow more than a smaller dam. Also, the features of the river are very important. A study published in the International Rivers reported that no one has yet to accurately determine the global extent of the fragmentation of river ecosystems by dams and water diversions (McCully, 2001).

Nilsson et al. (2005) studied large river system's fragmentations and flow regulations. The results of their study indicate that 172 out of 292 rivers have their water discharge affected the dam's operations. Their findings help to identify environmental risks associated with the dam's operations.

Another negative impact of reservoirs is the degradation of water quality. Dissolved oxygen is an important component of river water. Unfortunately, many factors in the reservoir tend to affect the quantity of oxygen available. These factors are the organic material, the depth of water, its

temperature, and its flow in the reservoir. The type of land inundated by the reservoir can pollute water. Streams and rivers flowing into the reservoir may contain pollutants.

Various studies completed on dams and reservoirs reported many advantages and disadvantages. That's why it is essential to complete a preliminary study that includes environmental impact before building a dam. Regulations and policies on dam management are solutions to mitigate or reduce the negative effects of dam operation.

2.7 Climate change and its impacts on WEFE objectives

Climate change is the expected outcome of increased atmospheric concentrations of "greenhouse" gases due to human activities. Generating power, manufacturing goods, deforestation, using transportation, producing food, and overexploiting natural resources are a few human actions that increase climate change. According to the UN (2023), fossil fuels are the main contributor to global climate change. They are responsible for 75% of global greenhouse gas emissions and around 90% of all carbon dioxide emissions (UN,2023).

Climate change has negative effects on WEFE objectives. Firstly, it drives the temperature up and affects precipitation. The variation of precipitation can lead to drought or flooding in some regions and reduce the water supply. It impacts the life cycle of water and increases water insecurity. Water is fundamental in the energy cycle to generate hydropower, biofuels, and another form of energy. Energy is used in all human activities such as transportation, industries, and food production. The lack of water will lead to global economic chaos. The role of water in energy generation shows que water insecurity leads to energy insecurity.

Similarly, water is involved in the food production channel through irrigation, harvesting, and processing. The lack of food can conduct to hunger and the death of people. This shows the importance of water in food security.

As demonstrated above, water is involved in all human activities. Unfortunately, climate change attacks the availability of water. It represents an important threat as the lack of water will lead to the death of vegetation, animals, and humans (due to the lack of drinking water and food), economic crisis, loss of diversity, depopulation, electricity shortage, and more (Maiga, 2019).

2.8 Hydrological modeling

According to Allaby & Allaby (1999), Hydrological modeling is the characterization of real hydrologic features and systems using small-scale physical models, mathematical analogs, and computer simulations. They are used to analyze, understand, and explore solutions to water-related challenges. According to Burges (1986), they answer environmental transport questions where water excess, scarcity, or dissolved or solid content is of primary importance.

More precisely, a hydrological model is a set of equations or a computer algorithm capable of replicating a system with its behaviors. It can estimate non-observed variables such as evaporation, infiltration, and surface runoff. It can also simulate a system under different climate change scenarios. Hydrological models are widely used for water resources projects as a design

and management tool. Results obtained from hydrological models can be used to assist decision-support processes for drought/flooding-hazard assessment, monitoring, and management as well as aid groundwater management (Kuwayama et al., 2017).

They can serve as an evaluation tool for the social, economic, and environmental risks of water's spatial and temporal distribution (Seidou O., 2018). Nevertheless, the outputs of hydrological modeling might have a few uncertainties related to errors in input data, model structure, and model parameters (Emam, Kappas, Fassnacht, & Linh, 2018).

There are three hydrological models: rainfall-runoff models, time series models, and statistical extreme events models. The current study uses the model developed by (Maiga, 2019), which is a rainfall-runoff model. There are several tools available for hydrological modeling.

SWAT for example is a small-scale model used to simulate the quality and the quantity of surface and groundwater and can provide (Thokchom, 2020). The US Department of Agriculture developed SWAT in the early 1990s (Gassman, Reyes, Green, & Arnold, 2007). It has been improved over the years and has become a referenced water resource management software. According to the food and Agriculture Organization of the United Nations FAO (2022), SWAT can quantify the impact of land management practices in large, complex watersheds. The SWAT model divides river basins into sub-basins, further subdivided into hydrologic response units (HRUs). HRUs are the smallest SWAT unit to calculate a catchment's hydrological properties (Gassman et al., 2007). The parameters used in SWAT are weather, hydrology, sedimentation, soil temperature, crop growth, nutrients, pesticides, bacteria, and algae land management practices. Hydrologic processes and soil erosion and sediment yield at each HRU are calculated on SWAT based on the following water balance and Modified Universal Soil Loss Equations (MUSLE) from (Williams, 1975):

$$SW_t = SW_0 + \sum_{i=1}^n (R_{day} - Q_{surf} - E_a - W_{seep}) \quad (1)$$

$$SY_t = 11.8 * (Q_{surf} * q_p * A)^{0.56} * K * LS * C * P \quad (2)$$

Where SW_t is soil water content (mm), SW_0 is initial soil water content (mm), R_{day} is daily precipitation (mm), Q_{surf} is surface runoff (mm), E_a is evapotranspiration (mm), W_{seep} is percolation (mm), and Q_{gw} is groundwater flow (mm) and; SY_t is sediment yield (metric ton/ha), q_p is the peak flow rate (m^3/s), A is the area of HRU (ha), K is the soil erodibility factor (0.013 metric ton m^2 hr / (m^3 metric ton cm)), LS is the slope length and gradient factor, C is the cropping management factor, P is the erosion control practice factor.

To calculate the flow routing in the stream channels, SWAT uses the variable storage coefficient method (Williams 1969) or the Muskingum method (Chow 1959).

SWAT has functions to calculate the water balance for a reservoir on a daily scale. A regular reservoir is designed with two types of spillways to control floods: an emergency spillway to

control large floods and a principal spillway to control frequent floods. The reservoir water balance enables to determine the reservoir outflow with the following equation:

$$V = V_{stored} + V_{flowin} - V_{outflow} + V_{pcp} - V_{evap} - V_{seep} \quad (3)$$

where V represents the volume of water in the reservoir at the end of the simulation step (m^3), V_{stored} is the volume of water stored in the reservoir at the beginning of the simulation step (m^3), V_{flowin} is the volume of water entering the reservoir (m^3), $V_{outflow}$ is the volume of water flowing out of the reservoir (m^3), V_{pcp} is the volume of precipitation falling on the reservoir (m^3), V_{evap} is the volume of evaporated water from the reservoir (m^3) and V_{seep} indicates the water lost from the reservoir by seepage (m^3).

SWAT handles hydrological calculations such as evaporation, precipitation and seepage through several formulas integrated in its programming. Additional changes on the hydrological model of SWAT were made by (Maiga ,2019).

The outflow ($V_{outflow}$) can be managed in SWAT with these four different methods: measured daily outflow, measured monthly outflow, average annual release rate for an uncontrolled reservoir, and controlled outflow with target release:

- The measured daily and monthly outflow method uses the time series data of daily or monthly outflow rate provided by the user to determine the reservoir outflow ($V_{outflow}$).
- In the average annual release rate method, the volume of water released from the reservoir depends on the principal spillway volume. Whenever the volume of the spillway is exceeded, the reservoir releases water automatically.
- In the target release method, the volume of water to release depends on the target storage and defined non-flood season (Jalowska & Yuan., 2019).

With these methods, SWAT is appropriate for reservoirs with adequate measured outflow data, but not those where the outflow has to be estimated during the simulation based on internal variables or operation rules. According to Shrestha et al.(2020), SWAT lacks capabilities for modeling highly regulated, large-scale reservoirs with HPP capacity.

2.9 Multiple purpose reservoirs modeling

The complexity of multipurpose reservoirs depends on the number of purposes attributed to the reservoir. Conflicts can arise in multipurpose reservoirs due to the number of demands. Reservoir operation rules enable addressing the tradeoffs between the purposes. According to Lin and Rutten (2016), optimization and simulation models are critical to the optimal operation of a multipurpose reservoir system because they provide the quantitative information essential to the improvement of water management.

There are many approaches to the optimization of reservoir operations. The traditional methods used for optimization were linear programming (LP), nonlinear programming (NLP), Dynamic

programming (DP), and Quadratic programming (QP). The reservoir simulation was completed with hydrological and hydraulic models.

Linear programming was suitable for reservoirs with linear objectives. However, it is limited because the management of multiple-purpose reservoirs can include nonlinear objectives. DP can solve complex optimization problems through the decomposition of the problems into sub-problems. DP is widely used in reservoir optimization due to its ability to handle nonlinearity and stochastic features of water systems (Li et al., 2014). According to Lin and Rutten (2016), DP applies to multi-objective problems with its approach based on a multiple-stage decision process.

The progress of mathematical research and computing has caused the emergence of new algorithms for reservoir optimization. The emerging methods are evolutionary algorithms, artificial neural networks, and genetic algorithms.

Evolutionary algorithms are a form of stochastic search algorithms highly praised by many experts for complex reservoir operation. According to Sharifi et al. (2021), its high capabilities to find optimal solutions attracted the attention of researchers and water resources managers. In their study, Sharifi et al. (2021) completed a comparative analysis of some evolutionary-based models in optimizing dam reservoir operation. The research results suggest to water resources managers and decision-makers the application of the moth swarm algorithm (MSA) to improve multi-reservoir operation policies. Adeyemo (2011) published a detailed discussion and formulation of reservoir simulation models and optimization techniques using evolutionary algorithms. The results of his study confirmed that evolutionary algorithms are suitable to solve complex, non-linear convex, and multidimensional reservoir problems.

Anand et al. (2018) have associated SWAT and genetic algorithms to optimize multipurpose reservoir operation. The objective of their experiment was to reduce the yearly sum of squared deviation from preferred storage capacity and required release for irrigation purposes. The result of the study indicates that the association of SWAT and GA is efficient for the derivation of the operation of the reservoir. They concluded that the association is competitive and promising.

2.10 Identified gaps and justification of the study

Water, food, and electricity are basic needs of human beings. Rural communities still live in precarious situations because of the poor distribution of these resources. Even worse, the abundance of these resources is likely to decline due to the consequences of climate change.

The rapid growth of the global population represents another challenge facing governments. Water, food, and energy are commonly at the center of international debates to determine management strategies and ensure a better distribution of these resources. Agriculture and hydropower both require water for their production. As water is the most important resource for humans, international organizations such as the UN promote its sustainable use.

Several studies and conferences were conducted on the water, food, and energy nexus. They have led to the development of modeling tools, DSSs, reservoir operation systems, and most

importantly the creation of holistic approaches for sustainable water management. IWRM is an example of an approach that aims to unite government, communities, and stakeholders to develop water management strategies.

Underdeveloped countries are the most vulnerable to the water crisis because of their poor water management and lack of infrastructure. Some countries have a relief and a hydrographic network that does not favor equitable water distribution.

The construction of reservoirs and dams is an approach to reducing unequal water distribution. However, it is essential to determine the appropriate reservoir operation policies through experiments. Reservoir modeling is the best way to evaluate operation policies under different scenarios.

The open-source SWAT model is one of the most used hydro-ecological models in the world. It has been applied to nearly every significant watershed worldwide. Unfortunately, its reservoir routine can only handle simplified operation rules and does not simulate HPP.

Shrestha (2021) proposed a new reservoir operation routine integrated into SWAT to quantify changes to river flow and sediment regime in a river system due to the operation of a hydropower system. His system includes two subroutines:

- 1) hydropower reservoir operations without considering sedimentation (HydROR)
- 2) accumulation and removal of sediment under hydropower reservoir operations and sediment management techniques (ResSMan)

The study's objective is to develop a new hydropower reservoir routine in SWAT to simulate various operation policies. The improved SWAT model will then be used to assess the impacts of the reservoir operation rules on water security, energy security, food security, and environmental sustainability. Unlike (Shrestha, 2021), the current study allows the reservoir to operate under multiple objectives: hydropower, irrigation, municipal water, and environmental flow. Unfortunately, the current study does not consider sediment deposition in the model. However, its main contribution is developing a friendly use decision support system (DSS) to assist decision-makers in developing multipurpose reservoir operating policies.

Based on the results of the experiments and past studies, the current paper provides few recommendations on the sustainable management of water resources are given.

Chapter 3: reservoir operation

Reservoirs are one of the most important infrastructures in water resources systems. A reservoir is an artificial lake created by building a dam across a stream to store water. In general, its primary function is to regulate streamflow. The water surplus in the stream can be stored in the wet season and released in the dry season to offset some of the streamflow reduction. The water stored can be distributed in many places through pipes or canals or even kept for later use. The inflows and demands are two parameters that influence reservoir-related decisions, whether to keep or distribute.

Reservoir operations play an essential role in the planning and management of water resources. To ensure efficient reservoir management after construction, the designated operator must receive detailed guidelines and training to avoid poor management decisions. Reservoir operation policies provide information on the amount of water to release or store, considering the state of the reservoir, level of demand, inflows, etc. Single and multipurpose reservoirs have different operation problems. Single-purpose reservoirs manage water released to maximize the benefits for the purpose. Multipurpose must maximize the benefits and optimize the allocation of water released for all objectives.

The number of objectives of a reservoir influence the complexity of its operation. The operation of a multipurpose reservoir is more complex than a single-purpose reservoir. When the purposes are compatible, the coordination requires less effort. The objectives are often antagonistic, so difficult trade-offs are necessary.

3.1. Reservoir purposes

Below are several reservoir purposes and their functional requirements related to these purposes:

3.1.1. Hydroelectric power

The electricity demand comes from many sectors, such as households, transportation, industries, etc. Hydroelectric power production, as well as the demand, vary seasonally. During the wet season, the abundance of water favors a high production, considering the turbines' capacity. In the dry season, the production of hydropower is low. However, proper reservoir management can address this issue by planning the water storage for the dry season. The water head is a parameter related to water storage used for HPP. The Head of water provides space to store water in case of floods (Jain & Roorkee, 2022). The volume of water and the effective head affect the amount of power generated. After its passage through turbines, water can be reused for consumptive uses downstream (Jain & Roorkee, 2022). The hydroelectric power demand is classified as non-consumptive water use.

3.1.2. Irrigation

Irrigation usually depends on precipitation in the cropped area. Therefore, its water requirements are seasonal. The cropping pattern impact also the water demand. The irrigation

demand is classified as consumptive. In drought, an appropriate management system may allow reservoir storage to support cropping.

3.1.3. Flood control

Reservoirs are very helpful in case of flooding. To reduce flooding, the reservoir stores the upstream floodwater and reduces the flood peaks and intensity downstream. The empty storage space in the reservoir determines the degree of flood moderation.

Multipurpose reservoirs face different conflicts regarding the number of demands related to the various purposes. The conflicts can be classified into three groups: in space, in time, and discharge.

The reservoir's operating rules are the heart of the water resources management system as they define the storage and release of water for reservoir purposes. The operating policies of a multipurpose reservoir are a set of rules which specifies either individual reservoir desired (target) storage volumes or desired (target) releases based on the time of year and the existing total storage volume in all reservoirs (Oliveira R. , 1997). The design purpose of the reservoir shapes its operation policies.

The operating policy depends on the yearly operation of reservoirs designed and operated for seasonal storage. The operation policy of reservoirs designed for multi-annual storage depends on long-term targets (Jain & Roorkee, 2022) . In this case, long-term data are used to estimate water availability. The projection of demand figures is used to determine the demand for conservation use such as irrigation or hydropower. When hydropower is one of the reservoir purposes, the releases related to consumptive uses are firstly driven to the powerhouse to produce the target energy.

3.2. Reservoir Operation Rules

There are various reservoir operation techniques. Here is the description of 3 common reservoir operation techniques.

3.2.1. Standard Linear Operating Policy

The Standard Linear operating policy (SLOP) is the simplest reservoir operation policy (Jagadeesha, Brema, & James, 2016). The most important parameters in SLOP are the volume of water stored and the target demand. The idea of that method is to release the total volume of water stored anytime the target demand exceeds the available stored water. If the water stored exceeds the target demand, the excess water is stored, and the rest is released to meet the demand. If the reservoir cannot store the excess water after the release, then the amount of water over the maximum storage capacity is released. The objective is to meet the water demand in each period considering the water available in that period. This method is suitable for reservoir operation with predefined target demand. The major advantage of SLOP is its operating efficiency during periods of plentiful inflow (Jagadeesha, Brema, & James, 2016). Its

weakness is its vulnerability to potential water shortage, as its operation does not consider this factor. The following picture is a graphical representation of SLOP.

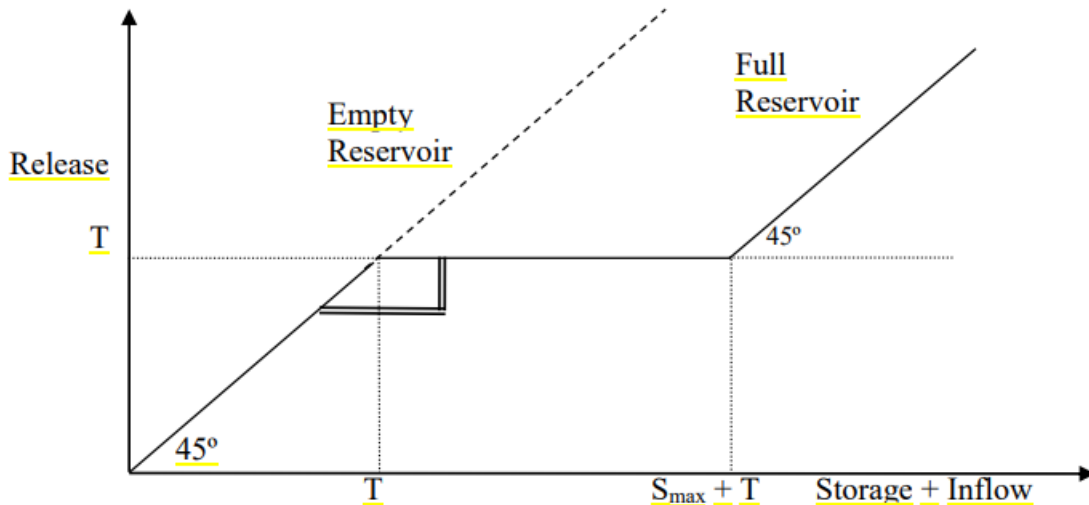


Figure 6 : Graphical Representation of Standard Linear Operation Policy (Jagadeesha, Brema, & James, 2016)

SLOP operates as a one-time step. This means that a release is associated with only a one-time step. The rigidity of this approach made it unpopular. In day-to-day operations, governments are looking for flexible solutions. According to Jain & Roorkee (2022), it is extensively used in planning studies.

3.2.2 Rule Of curves (ROC)

Some reservoir operation policies use controlled release to maintain reservoir water levels within established bounds that depend on the time of year (Howard & ASCE, 2004). The time-dependent bounds are also called rules of curves. They specify the water storage or the space to be maintained in the reservoir during different periods (Jain & Roorkee, 2022). This concept aims to define the storage levels at different times with the rules of curves and ensure the reservoir operation respects these water levels. The rules of curves are determined using data from previous studies (flows, dams). Unlike other methods, ROC does not provide the quantity of water to release from the reservoir. According to Jain & Roorkee (2022), the volume of water to be released is based on the inflows or additional rules of curves. This technique is practical for controlling high inflows events. Bravo et al. (2006) believe that ROC can be used to control floods or conserve water in drought periods. According to Howard & ASCE(2004), this approach may not be resilient to climate change as ROC does not consider weather and watershed conditions. However, ROC has evolved over the years, integrating some concepts related to modern challenges such as climate change, negotiation of conflicts between users (Chang, Ho, & Chen, 2010), and advanced systems analysis methods.

Another disadvantage is that ROC policy has not a clearly defined function that is due to the variation of water levels at different times of the year Howard & ASCE(2004). ROC can create a link between multi-objective reservoir purposes and sustain it for a long period. According to Jain & Roorkee (2022), ROC finds a trade-off between various project objectives. A reservoir operation policy that only sticks to ROCs can easily develop rigid behavior. ROC is generally associated with different methods or rules of curves to bring flexibility to the system.

Many studies focused on optimizing reservoir operation to determine the optimal set of ROC. Optimization models depend on the hydrological cycle. Considering the objectives, these models resolve the problem of inflow, outflow, and water demand. Ara & Yasar (2022) , studied the optimization of rules of curve operation for cascade reservoirs using the Cuckoo Search Algorithm. They found that the optimized ROC has allowed it to satisfy the irrigation and flood constraints and maximize the total energy production. Many studies of reservoir optimization involve advanced mathematical algorithms. Kangrang, Prasanchum, & Hormwichian (2018) worked on developing optimal rule curves for Multipurpose reservoir operation using Conditional Genetic Algorithm (CGA) and Tabu Search algorithms (CTSA). After different simulations, they found that the new rule curves from CGA and CTSA associated with a simulation model provide better responses to drought and flood situations than existing rule curves.

In cases where ROC is not fully efficient, it is appropriate to guide the reservoir operator. A decision support System that includes recommendations on releases based on computer modeling and observed data will be ideal.

In water scarcity conditions where various demands must be met in an entire year, the rule of the curve is calculated using different approaches. Rule levels for conservation demands like irrigation and hydroelectric power are calculated assuming the following conditions (Jain & Roorkee, 2022):

- i) The reservoir level reaches dead storage level by the end of the water year (end of May).
- ii) 75% reliable inflow is entering the reservoir.
- iii) The demand under consideration and other higher-priority demands are met in full

The rule of curves is the technique used at Sélingué dam.

3.2.3 Storage Zoning

This method divides the entire reservoir storage into multiple zones or pools with imaginary horizontal planes at different elevations. Their sizes are variable with time. The idea of this concept is to provide at any time an ideal storage to supply water for a goal. This approach is expected to maximize the benefits of the reservoir. The strength of this approach is the freedom and flexibility it offers to the decision-makers, as they can modify the storage level of a specific zone. Managing the reservoir level in a particular zone depends on the hydrologic system. The following figure is an illustration of storage zoning.

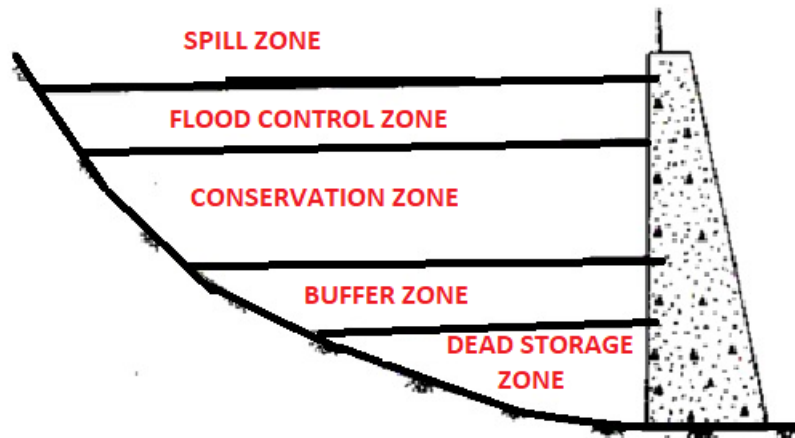


Figure 7 : Reservoir zones for various purposes (Jain & Roorkee, 2022).

The majority of reservoir operation policy releases water when the spill zone is reached to avoid flood damage downstream. The risk of flood increases as soon as the volume of water reaches the flood control zone. In these conditions, the operation intends to bring water to the conservation zone. In the conservation zone, the water is released based on the various purposes that must be met. Sometimes, the releases may be adjusted considering the inflows and operations forecasting. If the amount of water is expected to be shorter than demand, the releases might be stopped (Jain & Roorkee, 2022). The Water Evaluation and Planning (WEAP) model is a water management software that allows for performing storage zoning.

3.2.4 Hedging rules

In finance, the concept of the hedging rule is used to avoid risk through purchasing (You & Cai, 2008). The same principle is applied to reservoir operation. It consists of managing the water supply appropriately to prevent water shortage risks. According to Bower et al. (1962), the hedging rule aims to improve the resilience of the reservoir in low inflows conditions. Thus, the water is supplied considering some deficits to avoid important water or energy shortage in the future. Hedging rules are widely used in drinking and irrigation water supply (Neelakantan & Sasireka, 2015).

3.3 Simulation and Optimization of reservoir operation

Reservoirs are one of the most important components of water resources systems. Their primary function is the regulation of natural streamflow by storing the extra water in the wet season and releasing the stored water in the next dry season. The improvement of a reservoir operation must follow a process involving design and testing phases. Simulation and optimization are two engineering techniques commonly used to obtain the best version of a system.

3.3.1. Reservoir simulation

Simulation is a process that consists of designing a model of a real-world system and conducting experiments with it. The objectives are understanding the system's behaviors and determining appropriate strategies for its operation (Jain & Roorkee, 2022). The results of a simulation do not provide an immediate and optimal solution. It may take multiple trials before to end up with an adequate solution. There are three types of simulation models in engineering: physical models (built in a laboratory), analog models (electrical components systems), and mathematical models (using mathematical equations and algorithms). Mathematical models are performed using a computer. Computer modeling is commonly used in water resources management (Jain & Roorkee, 2022). They are very appreciated because they are not expensive, require fewer logistics, and can execute multiple tests quickly.

The main contribution of simulation in water resources management is the capability to evaluate the existing or designed system under expected or unexpected conditions. The simulation analysis allows for comparing the different systems tested and determining the most adequate for the future or existing project, helping develop resilient operation policies.

According to Loucks & Beek (2017), mathematical simulation and optimization models performed with computer programs enable planners and managers to predict the behavior of any proposed water resources system design or management policy before it is implemented.

Optimization is a method that consists of finding the optimal solution among multiple alternatives.

3.3.2. Reservoir optimization

Lai et al. (2022) defined reservoir optimization as a set of rules that maximizes or minimizes the reservoir benefits without compromising its objective functions and constraints. The optimization process can be complex when several complex factors are involved in selecting the alternatives.

Traditional models of reservoir optimization were based on: Linear programming (LP), non-linear programming (NLP), dynamic programming, Lagrange relaxation, and network optimization. Linear Programming (LP) uses graphical or algebraical methods to determine the optimal solution. The objective function and constraints are resumed to a linear function of decision variables (Jain & Roorkee, 2022). According to Britannica (2022), LP is useful as a guide to quantitative decisions in business planning, industrial engineering, etc.

Dynamic programming is an approach that consists of dividing the problem into simpler sub-problems and determining the solution for each sub-problem. The sum of all the sub-solution will represent the solution to the problem. It is a multi-stage technique. It is optimal for multipurpose reservoir operation.

Traditional methods were able to simulate and optimize reservoir operation with mathematical models. Unfortunately, these approaches have difficulties in handling complex reservoir systems

such as multipurpose reservoirs (IM, et al., 1963). A reservoir with multi objectives operates under various operational constraints and design restrictions such as hydro power, municipal, industrial, and irrigation demands, flood control and navigation, and environmental flows for fish and aquatic lives, recreational needs, and downstream flow regulation (Shrestha et al. 1996).

The failures of these old methods encourage the emergence of new algorithms that are more flexible. These new approaches include metaheuristics algorithms and other meta-heuristic algorithms (MHAs).

MHAs are categorized by Nguyen et al. (2020) as follows:

- evolutionary based (e.g., coral reefs optimization)
- swarm-based (e.g., particle swarm optimization)
- physics-based (e.g., simulated annealing)
- human-based (e.g., teaching-learning optimization)
- bio-based (e.g., invasive weed optimization)
- system-based (e.g., water cycle algorithm)
- math-based (e.g., Sine Cosine Algorithm)
- music-based (e.g., Harmony search)
- probabilistic-based (e.g., cross-entropy method)

MHAs are used to address the following problems: algorithms' premature convergence issues (Lei et al.,2018); shortcomings in complex optimization problems like dimensionality (Jiang, Ji, Qin, & Feng, 2018) ; huge computation burden (Wang, et al., 2020) and parameter tuning (Niu & Feng, 2021).

The management of reservoirs is usually based on predefined operation rules set with agreements between stakeholders (J.P. Shrestha ,2021). Optimization models are used to determine predefined rules that are adequate to various operational constraints, reduce spills, increase energy production, or minimize expected future undesired deviations from various water release, storage capacity, and/or energy production targets (Oliveira & Loucks, 1997). The following figure shows the summary of all reservoir optimization techniques.

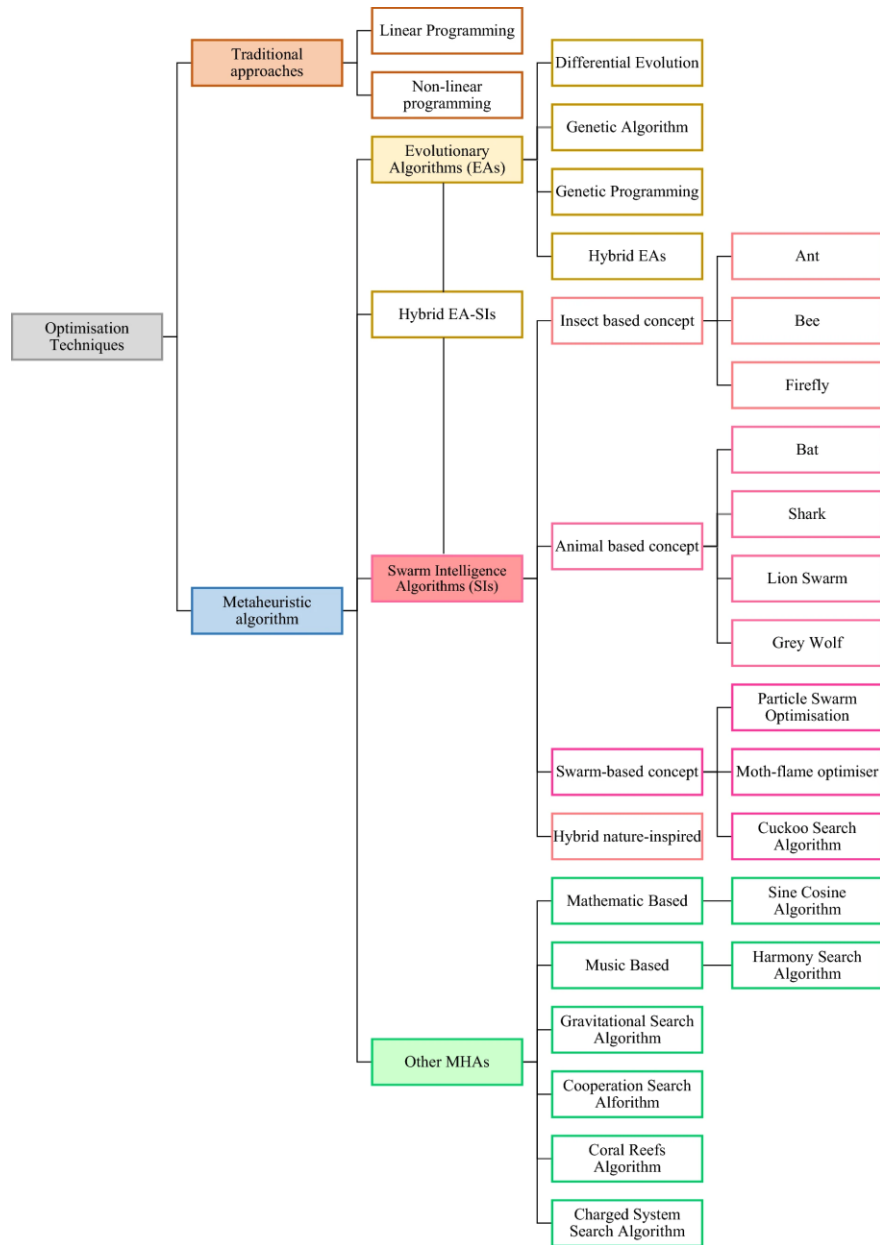


Figure 8 : Classification of the optimization techniques reviewed (Lai et al.,2022)

Chapter 4: Technology and Decision support systems Tools in water resources

This chapter describes the DSSs and their role in the development and application of sustainable water management approaches.

4.1 Background

Water is a central resource used in many human activities. Unfortunately, its availability depends on many factors that can be controlled or uncontrolled. The timing, the manner of its arrival, and the physical setting of regions are uncontrolled parameters while governments can control engineering infrastructures and legal regulatory and institutional policies. All these parameters make the management of water complex. As water availability is increasingly threatened by climate change, the need for water decision support systems has increased (Wardropper & Brookfield, 2022). , information and support systems on water and climate change have been created at global, regional, and local scales to provide adaptive decision-making and reduce vulnerability (, Hewitson et al.,2017; Kirchhoff, 2013, Kirchhoff et al., 2013).

Decision support systems (DSS) are computational systems integrating data and models on water and relevant drivers of change to help in decision management (adapted from (Fitch et al.,2026)). DSSs intervene to clarify the solutions to a problem and another outcome (Lautenbach et al.,2009, McIntosh, et al., 2011). DSS are developed in different forms regarding the goal, the context, and the type of end-user, usually decision-makers and stakeholders. DSSs include spreadsheet tools (Brookfield, 2016) , visualizations (e.g., Srinivas et al.,2020), and conceptual frameworks (e.g., (Tomer et al.,2013)).

The concept of DSS was born in the 1970s by Keen and Scott Morton (Kumar, Kumar, & Chauhan, 2011). Keen & Morton (1978) developed the first DSS to address issues in the context of theoretical studies of organizational decision-Making. Previously, in 1971, a researcher named Gorry worked on the strength of computers and analytical models that allow the user to decide. In 1974, Gordon Davis studied the relationship between management information systems and decision-making functions in the organization (Janz & Wetherbe, 2022). He designed an integrated system that provides information to support operations and management of the decision-making process of organizations.

Later, engineers started to focus on the internal technical parameters of DSSs. Many studies focused on the DSS framework of database, model base, dialog generation, and management software (Sprague, 1980, Sprague and Watson 1986, Sharda et al.,1988).

In 1980, more progress was observed with the development of Executive Information Systems (EIS), Group Decision Support Systems (GDSS), and Organizational Decision Support Systems (ODSS) for the single-user and model-oriented DSS (Kumar, Kumar, & Chauhan, 2011).

In the 1990s, new functions of DSSs were discovered. Data warehousing and On-Line Analytical Processing (OLAP) were integrated into DSS. In 1994, Kroenke and Hatch designed a new (EIS)

that contributes to the interaction of several elements such as people, procedures, information, and technology. All the improvements made in the 90s began to increase the value of DSS. DSS was considered a technical tool to enhance the decision-making process (Kumar, Kumar, & Chauhan, 2011). This encourages DSS developers to improve DSS with research based on decision analysis tools, technique development, integrated systems, and applications. The following table summarizes the evolution of DSS over the years.

Year	Studies
1950 & 1960	Theoretical studies laid out and technical work as computing carried out in two decades
1970s	Decision Support System
1980s	Expert Information System, Group Decision Support System, Organizational Decision Support Systems (ODSS)
1990s	Data warehousing and On-Line Analytical Processing (OLAP)
2000s	Web-based DSS

Table 2: Landmark in DSS Development (Kumar, Kumar, & Chauhan, 2011)

The performance of DSS in data management and analysis has increased its use in various sectors such as agriculture, economy, water resources, etc. Maiga (2019) has developed a DSS to facilitate decision-making related to the planning and management of the Fomi dam for various users (engineers, hydrologists, or other decision-makers, with or without a coding background). Ahmad & Hossain (2019) have developed a web-based open-source DSS to improve stakeholder engagement in the decision-making process involving atmospheric modeling, hydrologic modeling, and web technology. Pelkola (2018) has developed a DSS for hydropower planning under inflow uncertainty.

4.2 DSS in Water Resources Management

DSS was introduced in the water resources field in the mid-1970s. Several studies explain the introduction of DSS in water resources problems (Georgakakos and Martin, 1996; Labadie and Sullivan, 1986; Loucks, 1985a and 1985b). In the 1990s, the emergence of DSS applications related to natural resources was observed. These applications included a user interface, model base alternatives, and a database. They can perform simulation models to evaluate the characteristics of multiple decision and their effects. Huang (1996) introduced a DSS to find reservoir releases in an uncertain environment during the dry season. The system was composed of 3 components: a hydrologic model, an optimization model, and a fuzzy decision model. Water supply, irrigation, and hydropower were considered within the operation process. After different simulations, Huang (1996) finds that DSS can successfully support government officials in defining operating policy for the Tech reservoir during the dry season. Also, the system was simplified to facilitate the transition from theoretical knowledge to practice. Lilburne, Watt, & Vincent (1998) have designed a prototype DSS to evaluate the irrigation management plan. This DSS consisted of a simulation model and framework data. In that study, Lilburne et al. (1998) introduced the

idea of integrating crop yield, and simulation models in agricultural decision support to improve the outcomes. In the past, DSSs were applied intensively in the agricultural field to estimate irrigation demand (Heinemann et al., 2002; Mateos et al., 2002; Silva et al. 2001).

DSS can contribute to the development of policies and regulations on water management aiming to promote responsible agriculture Arumugam & Mohan (1997) studied a DSS that helps the operation of a tank (small-scale reservoir) irrigation system in south India. The DSS consisted of a data subsystem, a model subsystem, a knowledge base, and a user interface. The evaluation of this system shows that Shortages in irrigation water supply simulated from the DSS were less than those in the actual operation practiced by water authorities.

The operation of reservoirs with multipurpose is usually challenging with the number of conflicts related to the demands. Several studies have analyzed that issue and suggested some solutions. DSS appeared as one of the solutions to address the problem. Rajasekaram & Nandalal (2005) have developed a DSS for reservoir water management conflict resolution (RWM-CRSS) in a multipurpose single reservoir system. The system included a communication system, a database management system, and a model-based management system.

Traditional DSSs developed in water management had limited decision-making scope (Serrat-Capdevila, Valdes, & Gupta, 2011). The DSS design of DSSs was inspired by black-box optimization models and focused on specific purposes like dams and infrastructures. They were used to support decision-making as follows (Serrat-Capdevila, Valdes, & Gupta, 2011):

- Read and understand GIS and visualization tools.
- Understand costs and effects of construction alternatives regarding design specifications.
- Operating tables or models based on actions to perform regarding different constraints.
- Simulate and evaluate the impacts of different operating policies or management alternatives.

However, their outputs were only understandable by technical people. Although they have been optimized, DSSs were not flexible enough to integrate important factors such as societal preferences and environment into their calculations. Traditional approaches were hermetic and not transparent to the public. Therefore, questions have arisen on how to improve DSSs to make them useful for users with various backgrounds. What is the best approach to address the complexity of water management? The evaluation of DSS logistics, including the interface, showed it is one potential barrier to the decision-making process but not the primary issue (Inwood & Dale, 2019) . The more significant barrier is when the DSS does not integrate environmental, sociocultural, and institutional factors (Wardropper, et al., 2021).

Miser and Quade (1985) proposed a general methodology to design a DSS by considering the following steps:

- ❖ Problem formulation
- ❖ Identification, design, and screening of management alternatives

- ❖ Forecasting future contexts
- ❖ Building of models to predict consequences
- ❖ Ranking and comparing alternatives

This methodology needs to be improved, as decision-makers and analysts were looking for holistic approaches and cross-disciplinary teams that could address complex interactions at the basin scale and evaluate alternative futures (Serrat-Capdevila, Valdes, & Gupta, 2011). Integrated water resources management (IWRM) appeared as a reliable solution for the decision-making process in water management.

4.3 DSS for IWRM

The practice of Integrated River Basin Management (IRBM) promoted by the European Union (EU) is very challenging because it involves many actors and factors. It requires determining a balance between the interests of different stakeholders and the effects of combined measures on multiple river functions (Teodosiu, Ardeleanu, & Lupu, 2009). Many water management parameters such as climate change, political priorities, economic development, and water security influence IWRM in the river basin.

Decisions on operating strategies are generally political because they depend on the objectives to be achieved using reservoirs. However, the need for scientific assistance in the decision-making process has increased, given the technical limits of the authorities. Due to their characteristics, DSSs represented a solid alternative to assist different users with no engineering background, especially stakeholders in developing water resources management policies.

DSS for IWRM allows for comparing different strategies under several scenarios by considering multiple purposes. A typical DSS includes data and information management tools, socioeconomic evaluation tools, and an (interactive) communication framework for sharing and disseminating information to the public (GWP, UNEP-DHI, 2022). The Global Water Partnership (GWP) describes DSS as an interactive software developed to assist the use of data and information and provide solutions to decision maker on complex issues (GWP, UNEP-DHI, 2022). Over the years, DSSs operated in several disciplines including water resources management. DSS has multiple purposes for IRBM, such as analysis of different management alternatives, communication, education, and knowledge management (De Kok and Wind, 2003; Giupponi, 2007; De Kok et al., 2008). Many projects that include DSS were developed to simulate and optimize water management policies. These projects deal with various topics related to river basins, like water resource system configurations, institutional conditions, and management issues (Giupponi, 2007; De Kok et al., 2008).

A combination of IWRM and DSS has emerged as a specific category of DSS named “IWRM-DSS” (Integrated Water Resources Management Decision Support System) (Giupponi & A., 2013). (UNESCO, 2014) supported this approach as they believe it will resolve the conflicting demands between stakeholders, economies, and the environment. UNESCO(2014) completed a full study on IWRM and DSS aiming the following points: establish IWRM methodologies for

securing water efficiency; identify the potential method for climate change adaptation in river basins by considering stakeholders' business process; identify room for improvement in water efficiency concealed in business processes; to support communication, negotiation and mutual understanding among stakeholders; clarify what kind of information is required by whom, when, where and how, by assessing the requirements of stakeholders' business processes and providing information on them. The following picture shows a framework that includes common components in many DSSs.

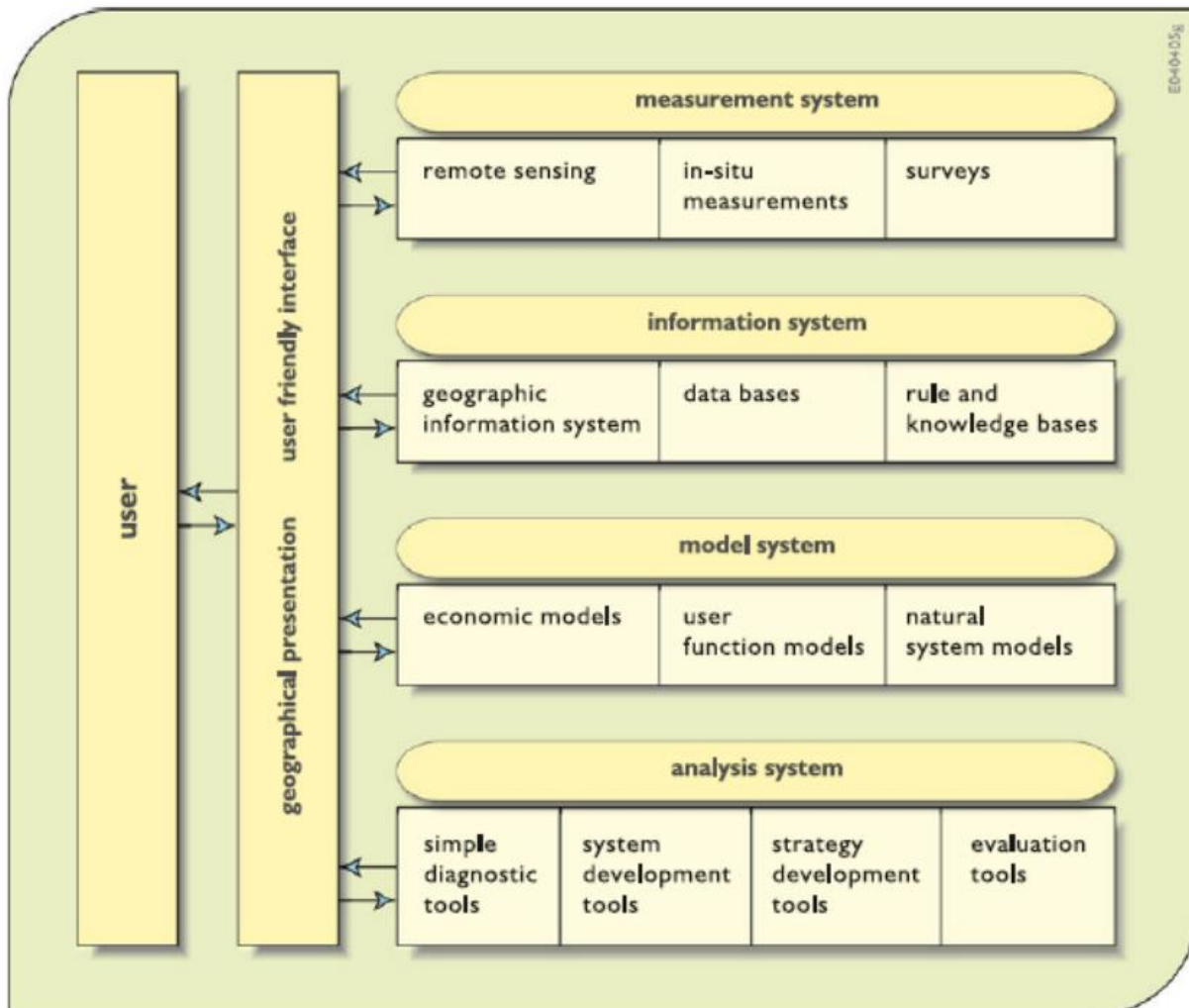


Figure 9 : Common components of many decision support systems. Reprinted from: Loucks et al. (2017)

The IWRM process at the river basin level faces a few issues and challenges. DSSs are among the reliable analytical tools that can be used to address these problems.

GWP (2013) suggests carrying out water resources assessments where two major components are compared: water availability and water demands in time and space. These assessments provide a large overview, including water resources status, problems, and conflicts. The lack of data can affect the quality of the assessments. A DSS is adequate in these conditions because it

can provide a framework for an information management system (IMS). IMS allows the collecting, storing, displaying, analyzing, and processing of relevant data. Once that step is completed, analytical tools such as water resources management and hydrological models use the information to develop a comprehensive overview of the current and future situations. That approach is relevant, especially in developing countries where the authorities struggle to define the needs and monitor the networks. They will be able to develop an appropriate monitoring system tailored to the country's capabilities (GWP, UNEP-DHI, 2022).

Communication is a key component in the success of IWRM. A DSS improves interactive communication between stakeholders and the public by sharing data, information, studies, and decisions. DSS for IWRM represents a strategic planning resource and a tool to predict future impacts of different factors such as climate change, population growth, energy supply, etc. According to GWP (2013), the combination of appropriate models in DSS with the development of indicators and multi-criteria ranking, and cost-benefit analysis represents an effective tool for identifying adequate solutions.

DSS can also play an essential role in the development of resilient infrastructure in the context of uncertainties related to climate change. Urban DSSs an innovative concept that gives alerts and instructions for the opening and closing of gates, operation of pumps, and use of retention basins, for instance (GWP, UNEP-DHI, 2022).

As the main goal of DSS is to support decision-makers, they should be developed in collaboration with all the stakeholders, including the decision-makers. A DSS in the middle Rio Grande and Upper San Pedro River was built in partnership with stakeholder groups. They aimed to fix management challenges in the basin and reduce the gap between demand, natural availability, and environmental needs (Serrat-Capdevila et al.,2011). The implementation of DSS must include a training section to facilitate the use of the tools (Maiga, 2019).

Giupponi et al. (2013) conducted a study on DSS for water resources management in developing countries, especially in Africa. In their exchange with field Experts, it emerges that the biggest challenge is not developing tools but rather a) ensuring the execution and effectiveness of IWRM legislative and planning frameworks, b) training and capacity building, networking and cooperation, c) harmonization of transnational data infrastructures and d) mostly learning from past experiences and adopting enhanced protocols for DSS development.

The following tables, adapted from the Global Water Partnership (2013) show the issues and challenges in IWRM where a DSS can help manage processes.

Components of the IWRM cycle	Issues and challenges	DSS role and contribution to water resources management
Water resource status and Issues	<ul style="list-style-type: none"> • Poor knowledge of water resources availability and scarcity • Water resources data scattered and difficult to access • Data processing is uneven and made in an ad hoc manner • Poor knowledge of geographically distributed water surpluses/deficits • Impact estimates predominantly qualitative 	<ul style="list-style-type: none"> • A comprehensive structure to review the water resources of a basin • A repository for water resources and water use data • A tool for data processing • A tool to compare water availability and demand • A tool to assess environmental and socioeconomic impacts
Commitment to reform and actions at the political and stakeholder levels	<ul style="list-style-type: none"> • Low awareness of water resources management at the stakeholder level • Reform objectives are unsupported statements • Reform measures and objectives are not coherent • Political dialogue has little or no evidence base • Information is not sufficiently available nor understood 	<ul style="list-style-type: none"> • A platform for communication and stakeholder interaction • Structured evidence to underpin reform objectives • A tool to evaluate reform measures against objectives • A tool to underpin political dialogue • Increases transparency of information

<p>Management framework and functions</p>	<ul style="list-style-type: none"> • Scenarios, climate change risks, and environmental risks are not systematically analyzed • Strategic planning is done using a poor evidence base • Investment planning is done on a precarious basis • Operational planning and management are done in a static fashion 	<ul style="list-style-type: none"> • A tool for scenario and risk management planning • A tool for strategic planning • A tool for investment planning • A tool for operational planning and management
<p>Strategy and action plans</p>	<ul style="list-style-type: none"> • Multi-criteria analysis is lacking in the set of management instruments • Allocation is done in a haphazard manner and without environmental flow considerations 	<ul style="list-style-type: none"> • A tool for options, scenarios, trends, forecasts, and multi-criteria analysis • A tool for allocation management and environmental sustainability planning
<p>Implement management frameworks</p>	<ul style="list-style-type: none"> • Regulations, rules, and instruments applied without solid evidence of the consequences • Economic instruments are applied without thorough impact estimates 	<ul style="list-style-type: none"> • A tool to design and test reform of management rules and instruments (regulations, social or informal rules, market-based instruments, property rights) • A tool to incorporate economic incentives to address inefficiency and externality issues

<p>Implement Infrastructure development under the management framework</p>	<ul style="list-style-type: none"> • Impact of infrastructure not known in sufficient detail • Irrigation systems impact not known in sufficient detail • Hydropower systems impact not known in sufficient detail • Environmental flow requirements not taken sufficiently into account • Flood protection and drought emergency plans not sufficiently evidence-based • Optimal design of urban water systems not achieved 	<ul style="list-style-type: none"> • A tool to determine the location, scale, and cost-effectiveness of infrastructure • A tool to assist the conceptual design of irrigation systems • A tool to assist the conceptual design of hydropower infrastructure • A tool to determine environmental flow requirements • A tool for the conceptual design of flood protection and drought emergency plans • A tool for the conceptual design of urban water systems
<p>Monitor and evaluate progress within the management framework and infrastructure development</p>	<ul style="list-style-type: none"> • Monitoring of development objectives indicators is deficient • Management is not sufficiently informed about issues and lack of progress 	<ul style="list-style-type: none"> • A tool to benchmark and assess progress against development objectives • A tool to provide feedback to management on progress and to facilitate management responses
<p>Operate water resources management infrastructure</p>	<ul style="list-style-type: none"> • Operation of infrastructure is done in a static and haphazard manner • Real-time operations lacking • Disaster risks and emergency responses are insufficiently assessed 	<ul style="list-style-type: none"> • A tool for optimization analysis • A tool to manage real-time operations • A tool to manage disaster risks and emergency response

Table 3: the issues and challenges in IWRM where a DSS can contribute to management processes (GWP, 2022)

4.4 Optimization of DSS

The optimization of DSS is in continuous progress. Much research involving multiple optimization algorithms was completed to quantify the decision variables (Kumar et al., 2011). One of the most important challenges of DSS is to perform modeling in uncertain scenarios. Soncini-Sessa et al., (2003) and Koutsoyiannis et al. (2003) have developed a DSS for integrated planning and management of water resource systems with a focus on water reservoir systems. Their system includes models that perform simulation and optimization of the hydro system. Their studies show and that deterministic models are inadequate to represent uncertainty and that scenario analysis can replace stochastic optimization when no probabilistic rules can be adopted.

Optimization can be used to perform automatic model calibrations and identify optimal strategies for reservoir operation (GWP, UNEP-DHI, 2022).

The optimization of DSS intends to provide accurate and robust decision insights to stakeholders. Therefore, the optimization process must consider multi-criteria analyses. This means it must include pieces of information such as measured or forecasted flow time series to compute a set of indicators for a range of possible strategies (GWP, UNEP-DHI, 2022).

As the water, food, and energy nexus is becoming a global topic of interest, how DSSs have been developed to improve the management of these resources. Given that Climate change influences crop yields, many experts have focused on the development of DSS considering this factor.

Rowshon et al. (2019) developed a water management tool called a climate-smart Decision support system or CSDSS. It can produce water demand models for rice irrigation schemes under climate change impacts. Rowshon et al. (2019) aimed to evaluate the impacts of climate change on irrigation water demand and other key hydro-climatic parameters in the Tathe njung Karang rice irrigation scheme in Malaysia for the period 2010–2099 concerning the baseline period of 1976–2005.

Jaiswala et al. (2021) developed a DSS framework to classify uncertainties and management options in a basin confronted with problems such as water scarcity, surplus, and non-uniform distribution of surface water. Their system uses a method of participatory scoping for scenarios analysis based on six interrelated modules that are: (i) water balance of reservoirs for computation of runoff (ii) statistical downscaling for climate projection (iii) hydrological modeling (iv) sediment assessment (v) water management and (vi) decision support for the assessment of the performance of multiple management plans designed for three future assessment periods of 2020-35, 2046-64 and 2081-99. Their simulation results show that the developed DSS can contribute to strategic water resources planning and management under projected climate scenarios using the participation of farmers, technocrats, and water resource managers.

4.5 Perspectives in DSS development

The development of DSS is improving over the years due to the significant evolution of in-situ and remotely sensed data (e.g., (Tayyebi, et al., 2016)), computing and mobile accessibility (Car et al., 2012), and real-time data integration (Easton, et al., 2017).

The future DSSs will integrate new parameters, such as recent developments in sensors, data transmission, computational processing, and science communication (Wardropper & Brookfield, 2022). These parameters will address potential incoming challenges related to uncertainty in model development, availability and reliability of data for parameterization and calibration (Merritt et al., 2017, Rissman and Carpenter, 2015), and challenges associated with usability (Walling & Vaneeckhaute, 2020).

Chapter 5: Methodology and Development of SWAT hydropower routine

This chapter describes the methodology of the research including the SWAT code modification and the development of a DSS for the decision-making process of reservoir operation. It presents all the parameters and methods used.

5.1 General methodology

The research is divided into two sections.

The first part consists of integrating SWAT a hydropower reservoir routine and multipurpose reservoir operation policies. It includes the following steps:

- Create the additional parameters of the reservoir and their inputs for the hydropower routine in Fortran.
- Create the additional parameters of the subbasin and their input to simulate multipurpose reservoir scenarios in Fortran.
- Collect data from literature and local authorities.
- Insert the data in the reservoir and subbasin input files.
- Create different methods of reservoir operation for the following policies: 1) priority to monthly HPP target; 2) respect of predefined monthly target storage; 3) priority to environmental flow, irrigation, and municipal water demands.
- compute outflow for the different policies in Fortran
- Compute hydropower based on the conventional formula of hydropower.
- Build the code (compile) in Fortran to generate a SWAT executable.

The second part of the research consists of developing a DSS in MATLAB and it includes the following steps:

- Create a GUI in MATLAB to allow the user to insert the parameters of the selected reservoir.
- Run the SWAT executable from MATLAB and collect the results from the reservoir output file.

- Generate the graph of reservoir volume, outflow, HPP, and supply gap between electricity demand and HPP.
- Conduct a set of scenarios based on the selected policies and compare the results.
- Apply the new SWAT code and the DSS in a case study.
- Determine the policies that provide the best outcomes for hydroelectricity, irrigation, municipalities water, and the environmental flow.
- Give suggestions to improve the sustainable management of water resources.

5.2 Proposed modifications to the SWAT reservoir module

This research will not include the development of a swat model. An existing SWAT model developed by (Maiga, 2019) will be used to integrate the hydropower reservoir routine. The modification of the model is set through Fortran, the programming language used to develop SWAT. All the input data come from (Maiga, 2019).

5.2.1. Addition of new input variables to SWAT

However, for the current research, the reservoir input file and the subbasin input file will be modified. For the subbasin, three parameters will be added: monthly environmental flow (m^3/s), monthly water withdrawal for irrigation, and monthly municipality water use (m^3/s). For the reservoir file the added data are turbine height, maximum turbine outflow, tailwater, monthly HPP target, efficiency, and a list of three subbasins surrounding the reservoir. For testing purposes, temporary values were assigned to the variables. However, to run the model with the additional data created, the user will be requested to provide the real values of the variables.

5.2.2. Addition of HPP

To calculate the energy generation from the HPP plant for every day of a year the following formula is used:

$$E = \frac{Q_{tur} * H_{net} * \gamma * \aleph * \Delta t}{1000}$$

Where E is the energy generation in MWh, Q_{tur} is the flow through the turbine (m^3/s) but $min_flowHPP$ will be used to avoid water wastage, H_{net} in m is the difference between water level and the tailrace level/turbine level (tailwater), γ is the specific gravity of water in KN/m^3 , \aleph is the efficiency, Δt will be 24h for each day. The water level is determined based on a rating curve which converts volume into water height along with the calculated release. The following flowchart describes SWAT reservoir operation when the priority is given to hydropower.

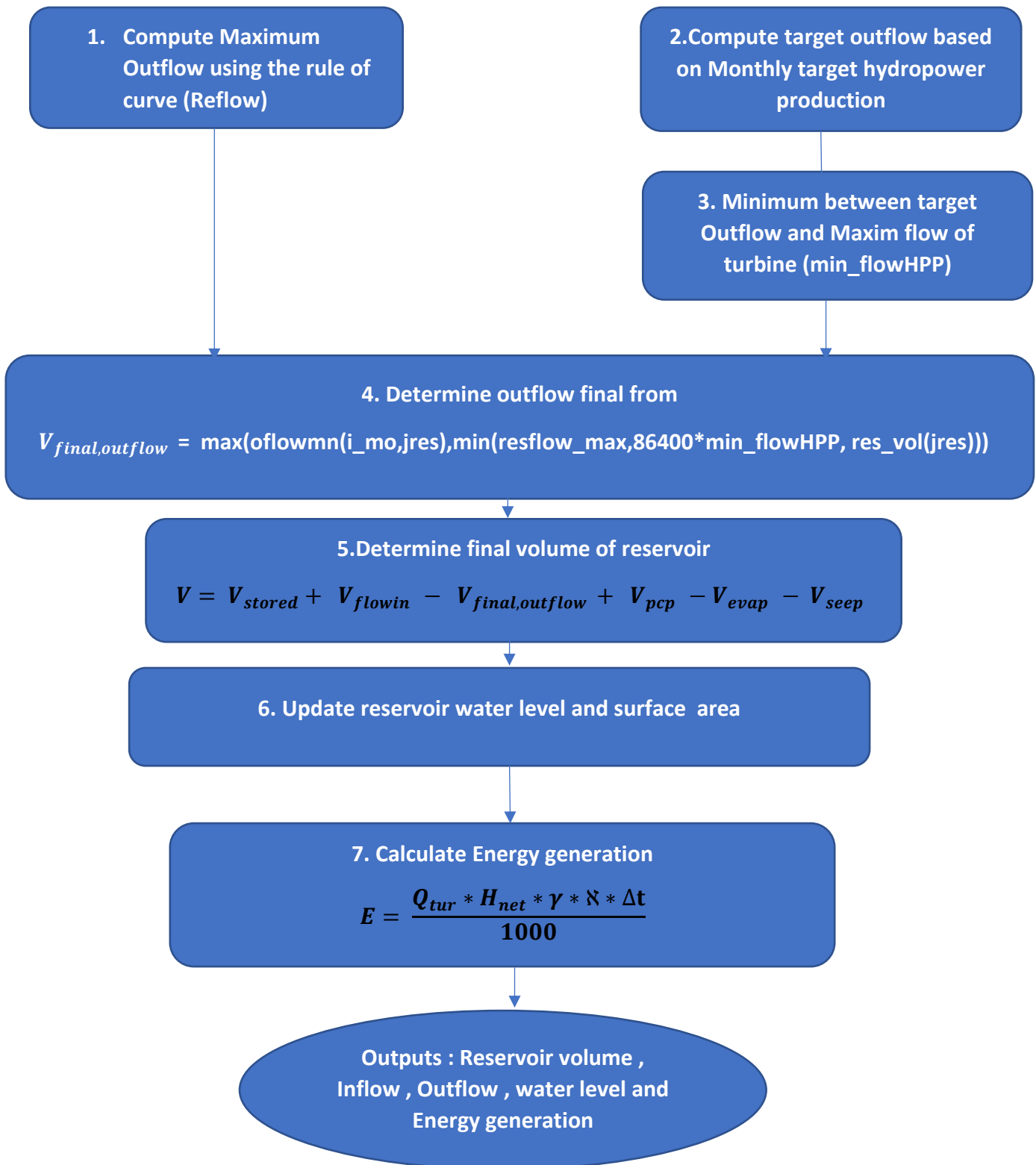


Figure 10 : Framework of the new reservoir operation governed by HPP target.

5.2.3. Inclusion of downstream water requirement for a given reservoir

5.2.3.1- Environmental flow

The environmental flow must be provided by the user. In this study, the values of the environmental flow are determined using 60% of the outflow at downstream of the reservoir. It's a standard value due to the lack of data. The values are converted from daily data to monthly data and are inserted in the subbasin input file. An environmental deficit is when the subbasin outflow is lower than the environmental outflow. In case of environmental deficit, the water stored can be used to regulate the subbasin flow.

5.2.3.2. Agricultural water demand

The agricultural water demand must be provided by the user. In this research, the water demand for irrigation is based on the water demand of office du Niger (ODN). The data were collected from (Maiga, 2019) and were inserted in a subbasin input file. A consumption deficit happens when the outflow of the subbasin does not meet irrigation water demand. The amount of water stored can be used to sustain agriculture.

5.2.3.3. Municipal water demands

The municipal water demands must be provided by the user. In this study, it has been calculated based on Mali's national domestic uses which were estimated to be 590 million m³/year in 2000 (echO2, 2022). Consumption deficit includes the lack of water for irrigation. The water stored can also be used to meet the irrigation demand. The following flow chart describes SWAT reservoir operation when priority is given to environment flow, irrigation, and municipal water demands.

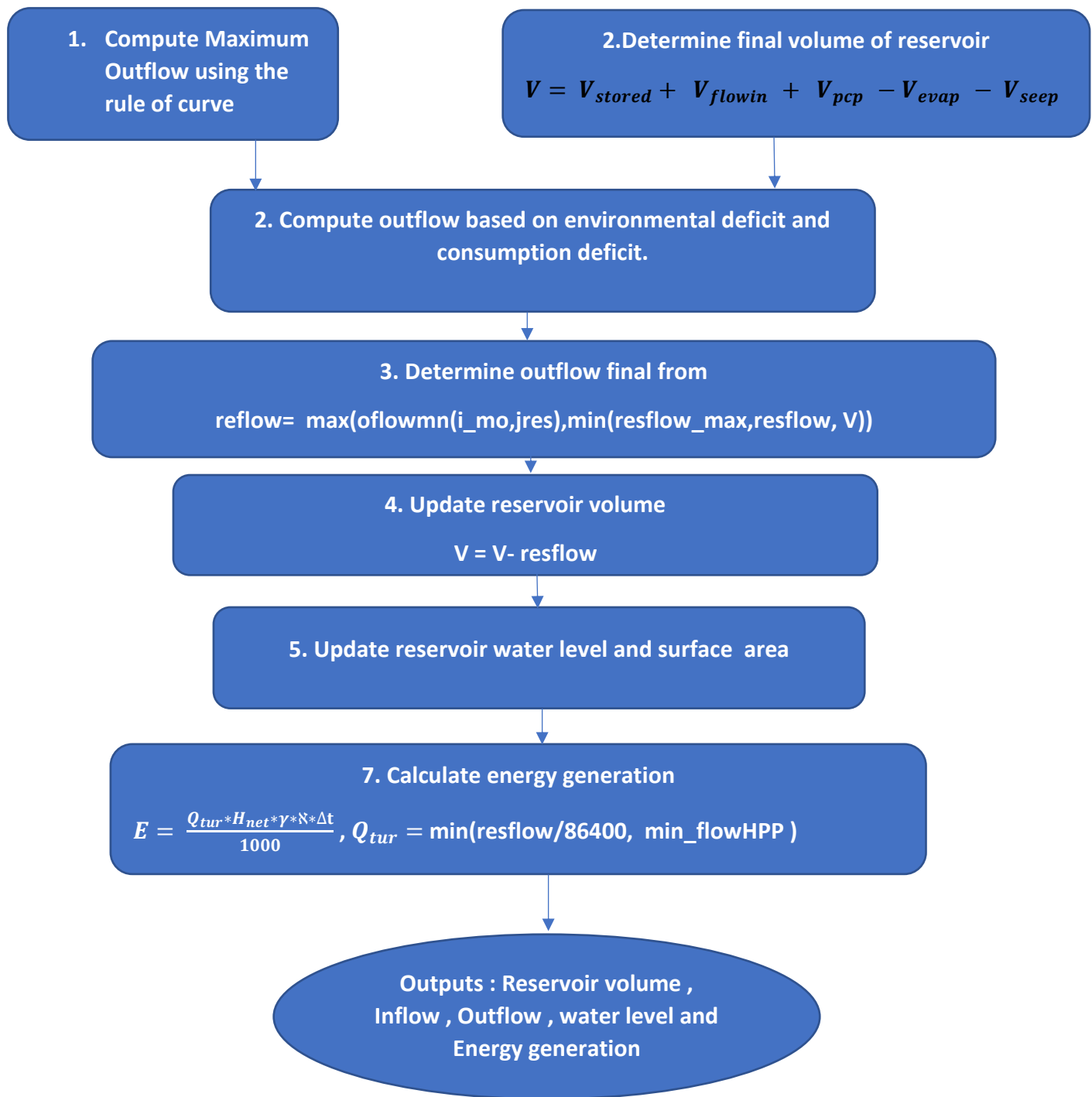


Figure 11 : the reservoir operation policy under environmental flow, irrigation, and municipal water demand.

5.2.4 Reservoir target storage

The reservoir has 12 targets storage. There are two possible cases when the reservoir operates under predefined target storage. The first case is when the volume of water in the reservoir exceeds the target, then the exceedance is released.

The second case is when the volume of the reservoir does not reach the target storage, and the daily minimum outflow of the reservoir is released. The following flow chart presents the

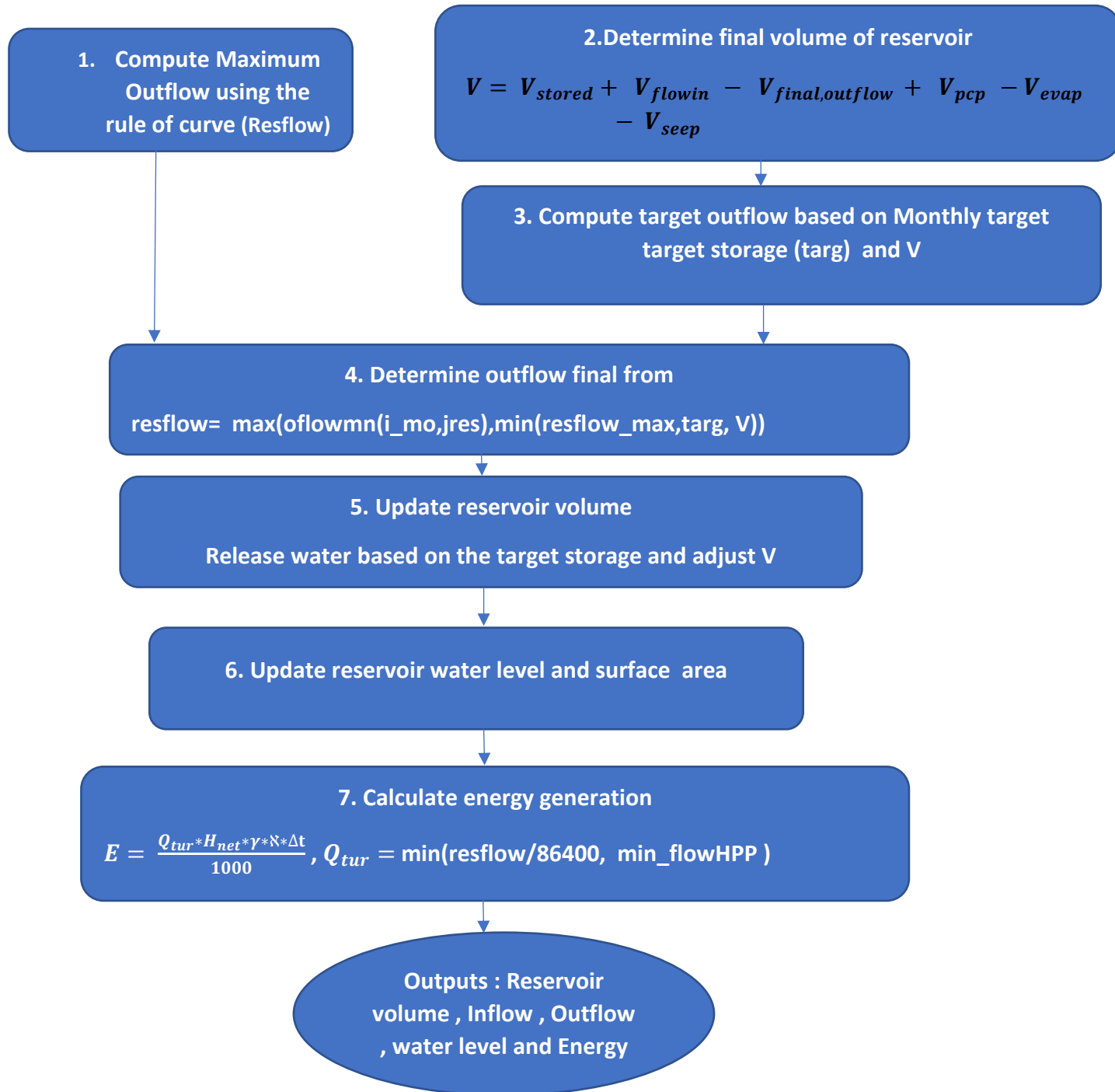


Figure 12 : SWAT code governed by target storage

5.2.4. new SWAT operation rules:

- Rule curve operation without hedging (downstream demand stratified whenever possible)
- Rule curve operation with hedging (only part of downstream demand stratified)
- Operation with priority to environmental flow
- Operation with priority to power generation

5.2.5. Development of the decision support system

The Decision Support System (DSS) aims to support various users, especially decision-makers, and stakeholders, in easily visualizing the impact of a given rule curve on food, water, energy security as well as environmental sustainability. It's a graphical User Interface (GUI), developed in the MATLAB AppDesigner, that serves as a preprocessor and postprocessor for the SWAT model of the Upper Niger Basin. It is a preprocessor in the sense that it allows a user to select one of the three operation rules discussed in this thesis, set monthly HPP targets or monthly reservoir storage, as well as environmental flow requirement as well agricultural water demands in any subbasin of his choice. The DSS then transfers the information into the SWAT input files, more specifically, into the corresponding reservoir (*.res) file and the corresponding subbasin (*.sub) files. The interface then automatically launches SWAT and runs the model for 38 years (1979,2016). The simulation was performed from 1979 to 2016 due to the lack of data for the recent years. The study used the data of a previous research on the Niger river (Maiga ,2019).

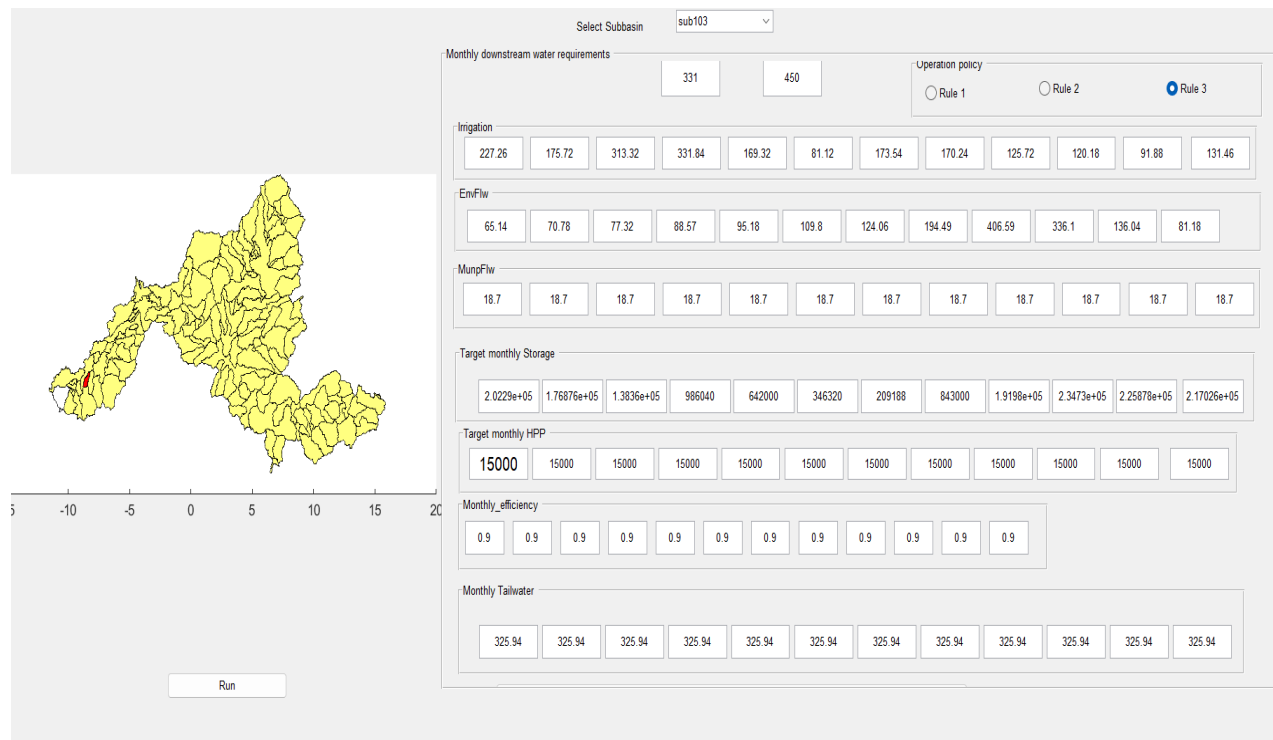


Figure 13 : DSS main interface

Once the execution is finished, it reads the output files then calculates a set of indicators and graphs that are displayed. Figure 13 shows the main window of the interface and the input

variables the user is required to provide. The first decision is the selection of the operation rule among the three options available.

The required inputs depend on the rule selected: for rule 1 (priority to HPP), the user has to provide:

- 12 monthly HPP targets

For rule 2 (priority to predefined target storage), the user must provide:

- 12 monthly target storage

For rule 3 (priority to environmental flow, irrigation and municipal water demands), the user has to provide:

- 12 monthly environmental flow
- 12 monthly irrigation water demands.
- 12 monthly municipal water demands.

Once the execution is finished, the DSS imports reservoir volume, outflow, and HPP time series, along with simulated streamflow in all sub watersheds. These time series are compared with target monthly volumes, energy production, environmental flow, irrigation water requirements and municipal water requirements to generate graphs that are easy to interpret. These graphs represent HPP gap, reservoir volume deviation, irrigation gap, environmental flow gap and municipal water demand gap defined as follows:

The gap between the HPP target (demand) and the production is calculated with the following formula:

$$\%Supply\ gap = \left(\frac{HPP_{target,month} - HPP_{simulated,month}}{HPP_{target,month}} \right) * 100$$

When the %supply is null, it means the demand is fully met. %Supply is a good indicator of the effects of the selected policy on HPP. The HPP gap is represented as a Heatmap with a graphical representation of a 38 by 12 vector where the gap of the 5th month in the 10th year is represented in cell (5,10), as shown in Figure below.

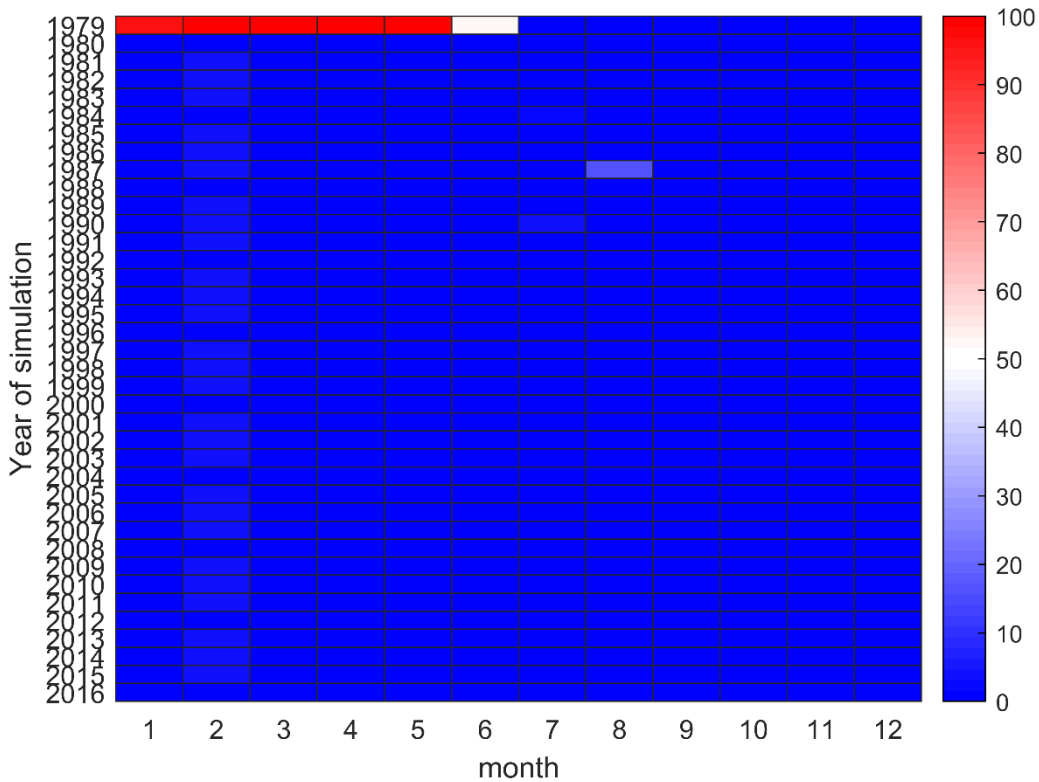


Figure 14 : Monthly HPP gap over 38 years

The gap between the target storage (demand) and the reservoir volume is calculated with the following formula:

$$\% \text{deviation} = \left(\frac{Vol_{target,month} - \min(Vol_{simulated,month}, Vol_{target,month})}{Vol_{target,month}} \right) * 100$$

here $Vol_{target,month}$ represents the monthly target storage, $Vol_{simulated,month}$ is the simulated reservoir volume, min represents the minimum and deviation represents the gap between the target and simulated reservoir volume.

In order to evaluate the capacity of the reservoir to provide water for environmental flow, irrigation, and municipal demand, a heatmap was developed using the following formulas:

$$\text{Goal} = \max(Irr_{demand,month} + MNP_{demand,month}, ENV_{month})$$

$$\% \text{Supply gap} = \left(\frac{\text{Goal} - \min(Resflwo_{simulated,month}, \text{Goal})}{\text{Goal}} \right) * 100$$

For the simulation of rule 3, three indicators have been developed.

The first indicator consists of determining the capacity of the reservoir to meet only the demand of the environmental flow. The gap between the environmental flow and the reservoir outflow is calculated with the following formula:

$$\%Supply\ gap = \left(\frac{ENV_{month} - \min(Resflwo_{simulated,month}, ENV_{month})}{ENV_{month}} \right) * 100$$

Where ENV_{month} represents the monthly environmental flow target and $Resflwo_{simulated,month}$ is the outflow obtained from the simulation and min represents the minimum.

The second indicator consists of determining the capacity of the reservoir to meet only the demand of the irrigation. The gap between the irrigation water (demand) and the reservoir outflow is calculated with the following formula:

$$\%Supply\ gap = \left(\frac{Irr_{demand,month} - \min(Resflwo_{simulated,month}, Irr_{demand,month})}{Irr_{demand,month}} \right) * 10$$

here $Irr_{demand,month}$ represents the monthly irrigation water demands.

The third indicator consists of determining the capacity of the reservoir to meet only the demand of the municipality. The gap between the municipal water (demand) and the reservoir outflow is calculated with the following formula:

$$\%Supply\ gap = \left(\frac{MNP_{demand,month} - \min(Resflwo_{simulated,month}, MNP_{demand,month})}{MNP_{demand,month}} \right) * 100$$

Where $MNP_{demand,month}$ represents the monthly municipal water demand.

5.3 SWAT Model input data

Here are the input data and their source used by (Maiga, 2019).

- Climate data (daily precipitation and temperature) comes from WFDEI meteorological forcing data set (WATCH Forcing Data methodology applied to ERA-interim reanalysis).
- Meteorological data from WATCH (Water and Global Change)

Chapter 6: Mali's water, food, energy, and environmental challenges

This chapter described the context of the case study. It explains briefly the challenges related to food, energy, and environment in Mali.

6.1 Republic of Mali

Mali is a landlocked country located in the Saharan and Sahelian regions of West Africa. It is bordered in the north by Algeria, in the south by Ivory Coast and Burkina Faso, in the east by Niger, in the southwest by Guinea, and in the west by Senegal and Mauritania. Its surface area estimated to 1 240 000 Km² makes it the eighth largest country in Africa. Its population was estimated at 21719000 in 2022 (Clark, 2022). Its relief includes plateaus and plains. It is crossed by Niger and Senegal rivers. These two rivers concentrated in the southwest and the center of the countries promote the development of economic activities such as agriculture, fishing, HPP, etc. These are regions with high population densities. It has a hot and dry climate because it is within the tropical zone.

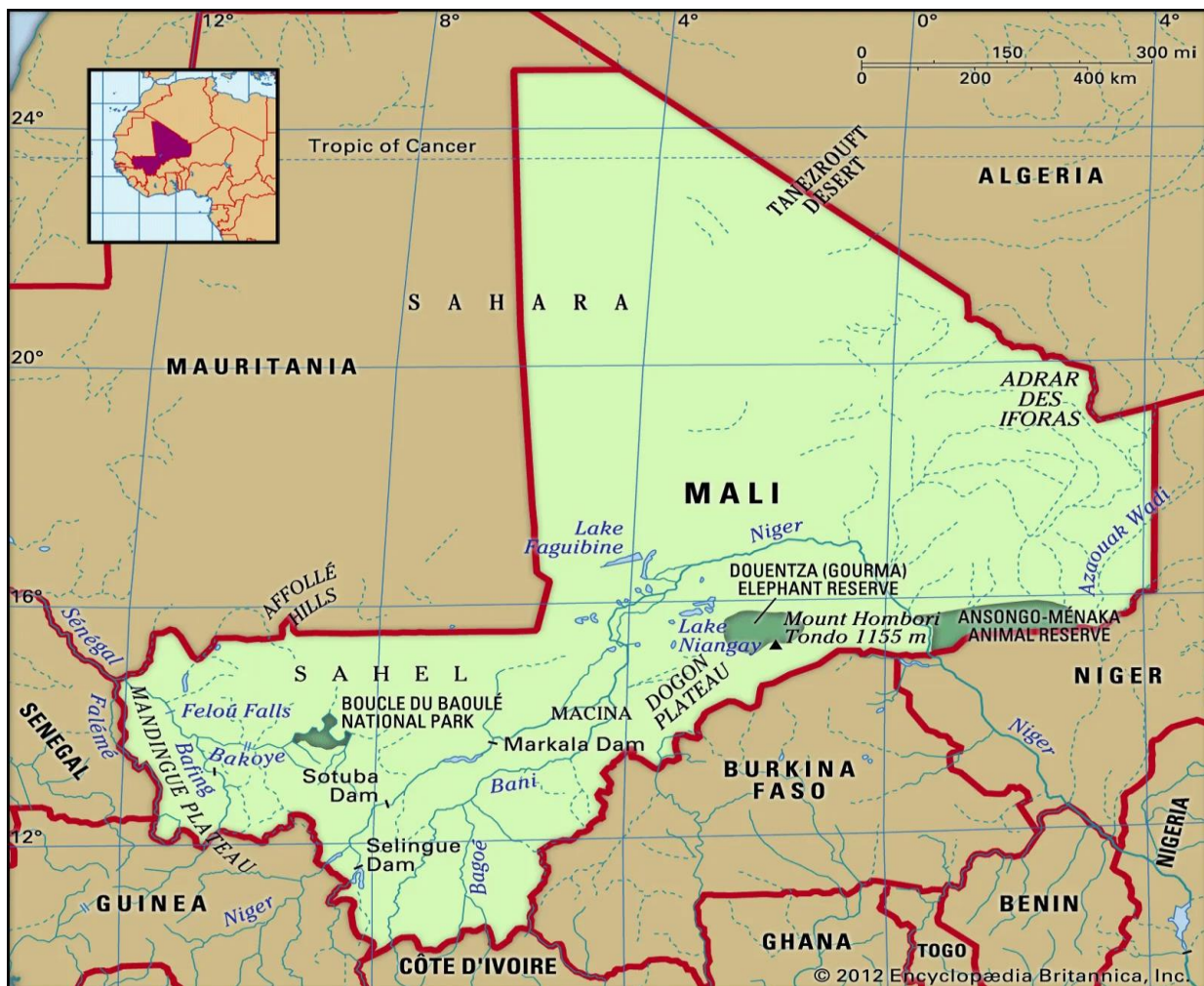


Figure 15 : Map of Mali (Clark, Imperato, & Baker, 2023)

According to World Bank (2021), the Malian climate has three seasons described as follows:

- Dry season: from March to June
- Rainy season from June to September
- Cold season called harmattan from October to February

Its economy is based on the agriculture and mining industries. Agriculture is the main activity of Malians, with 80% of the population working in this sector. It is the cornerstone of Mali's economy, with approximately 33% of the country's gross domestic product (GDP). Agricultural GDP consists of subsistence agriculture excluding rice: 13.6%; rice: 3.1%; industrial agriculture excluding cotton: 1.4%; cotton: 1.0%. The agricultural production depends on rainfall level. Northern regions f, for example, have low production due to water shortage during the dry season and variable rainfall. Its rapid population growth and climate change represent threats to agriculture and food security (WorldBank, 2022). The following image represents the map of Mali.

6.2 The role of Upper Niger Basin and Inner Niger Delta in the food, energy, and ecology of Mali

Niger river basin has a high human density due to the presence of water. A lot of communities live in the IND and the UNB. According to the Center for International Earth Science Information Network (CIESIN, 2016) , the Upper Niger and Bani River basins (UNBB) population was estimated to be 9.8 million people in 2005 and increased by 42% to 13.9 million inhabitants in 2015. This region is one of the fastest-growing populations worldwide, with an annual growth rate of about 4%. (Liersch, et al., 2019). There is a wide cultural heritage with the presence of several ethnic groups, such as the Bambara, Malinke, and Touareg. These groups have developed their activities based on the advantages offered by the river. They are farmers, fishermen, and traders. According to ZWARTS et al. (2006), around one million people in the Inner Niger Delta make a living from arable farming, fisheries, and livestock.

Also, this region's hydraulic network and lands represent an economic asset for the surrounding countries. Over the years, multiple investments have been made in this region. A major part of the economy of Mali depends on the river. (Beukering et al., 2005) define Mali as a classic case of a 'river-dependent economy'. It means that the river plays an important role in Mali's economy.

HPP plants and irrigation dams are infrastructures built to ensure food security and electricity supply. In Mali, the Sélingué Dam is used for electricity production but also irrigation. It supplies water for about 60 000 ha under double cropping (FAO,2021). More than 300 000 people have direct benefits from the irrigation scheme of the Office du Niger and the reservoirs of the Sélingué and Markala dams. It's also a region with high agricultural potential. According to FAO, (2021), the part of IND located in Guinea has an irrigation potential estimated at 185 000 ha of which 100 000 ha are very fertile. Only 6000 ha of these surfaces are used for rice production.

Although the dams have allowed the development of agriculture and hydroelectricity, the country's hydroelectric potential has not yet been fully exploited. At the same time, the energy demand is booming, which stresses energy security. The construction of more HPP plants represents an option to meet the energy demand. The government intends to promote food security by pushing for more irrigated areas. This involves using more water as it is known, agriculture is one of the biggest consumers of water.

The basin is also rich in halieutic resources, which favors fishing. The number of species in the Upper Niger and Central Delta is estimated to be 130 to 140 species (Daget, 1954; Lévêque et al., 1990). The fish catches depend on the water level in the basin. Welcomme (1986) found in its studies that catches are three times higher with high flood than with low flood (Zwarts et al., 2005). Zwarts et al. (2005) compared IND fluctuation in annual fish catch and fluctuation in flood level in the year at Akka station between 1966 and 2003. The following graph shows that fish production is related to flood level.

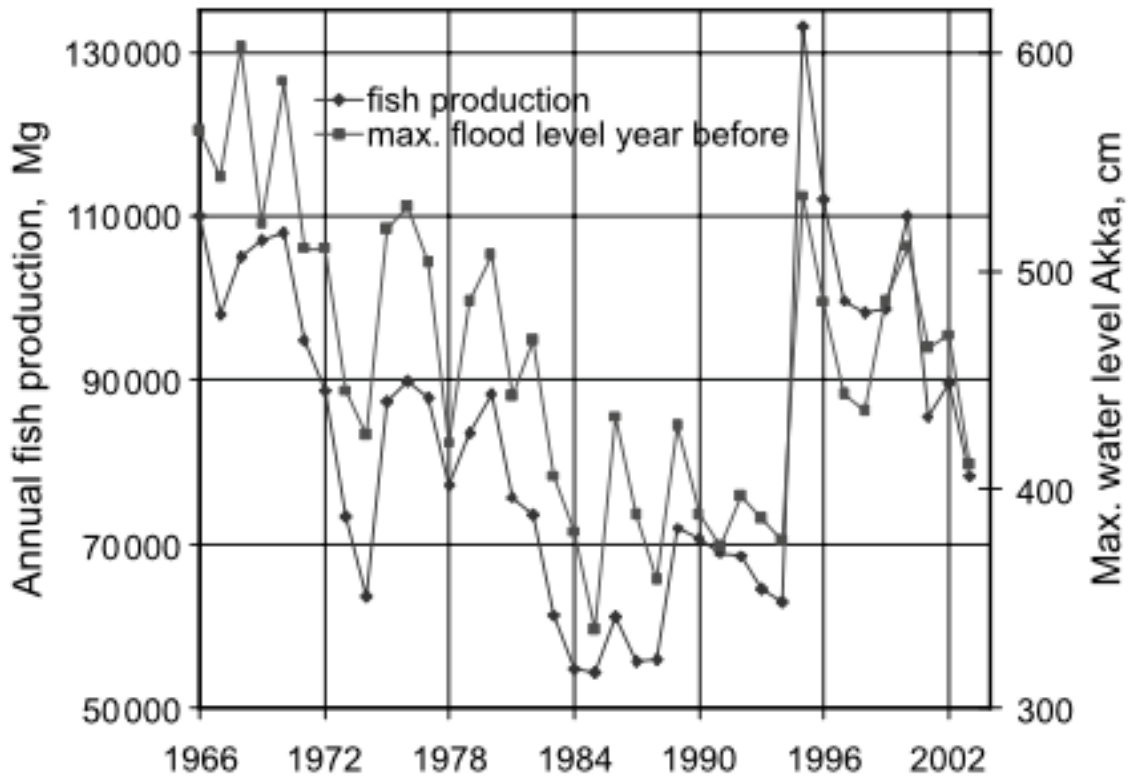


Figure 16 : The fluctuation in annual fish catch in the Inner Delta between 1966 and 2003 compared to the fluctuation in flood level (Akka, cm) in the year before. Reprinted from Zwarts et al. (2005).

Fish is one of the main foods of the inner Niger delta community. According to Zwarts et al., (2005), in 2005, around one-third of the rural population in the IND was living from the fishery. Unfortunately, the practice of extensive fishing has created fish scarcity. Fish scarcity raises a problem of food security in the region.

Despite the abundance of resources, several constraints influence the region's productivity. Climate change is probably the biggest constraint. The variation in rainfall reduces crop yield. The livestock population (cattle, sheep, and goats) is also affected due to the reduction of grass, which is livestock's main food. According to Zwarts et al. (2005), "the maximum sustainable population of livestock is limited by the availability of Bourgou (grass) in the Inner Delta and thus by the flow entering into the Inner Delta."

The ecological importance of the Niger basin is reflected by a rich biodiversity composed of birds, fish, and other terrestrial and aquatic wildlife. The ecosystem of the IND includes freshwater swamp forests, lowland rainforests, and mangroves forest (Izah, 2018). The UNB has some key areas where vulnerable species still live. It is a reason why these areas are protected by international agreements such as Ramsar. The IND is the 3rd biggest Ramsar site in the world with 4 119500 ha. Ramsar represents an international agreement to promote the conservation and wise use of wetlands. IND is a vital part of the eco-regional network, supporting up to 3 to 4 million staging waterbirds, residents, and migrants from all over Europe and western Asia (ZWARTS, et al., 2006). They share these places with other aquatic, mammals, animals, and species.

The construction of dams tends to affect the population downstream of the river. However, according to Beukering et al., (2005), the effects of hydroelectric dams and hydro agricultural dams on downstream are unclear. Dams reduce the flooded areas downstream. This creates a race to survival between the waterbirds, and other species groups like aquatic living mammals and reptiles because they are forced to migrate elsewhere.

In addition, dam construction encourages the destruction of the forest because the vegetation upstream is flooded. The delta forest cover has declined over the years. An extensive forest usually covered this area on the higher grounds and several forests on the lower floodplains. To date, it is an open landscape with grass and rice culture. Human activities have caused the disappearance of forest cover.

A case study on Sélingué dam will be completed to assess the ecological impact of multipurpose dam operation and determine the appropriate reservoir operation policies to meet several purposes. The existing SWAT model was developed for the entire Niger river, but the analysis will be limited to the reservoir of Sélingué. Maiga (2019) used ArcSWAT to set up the project. Figure 17 shows the Niger river with the location of dams including Sélingué and the subbasins.

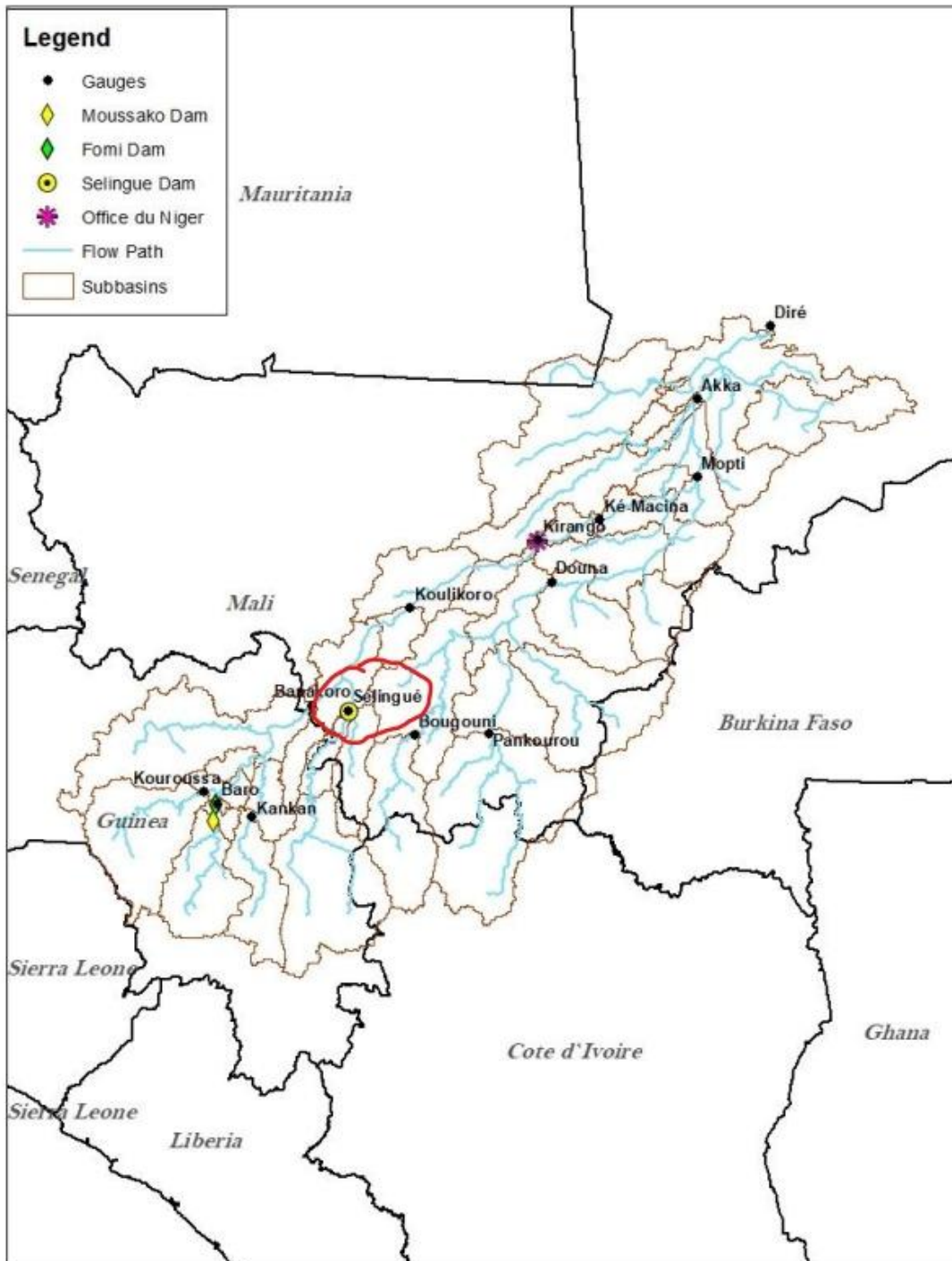


Figure 17 : The Inner Niger Delta and Upper Niger Basins Configuration in SWAT (Maiga, 2019)

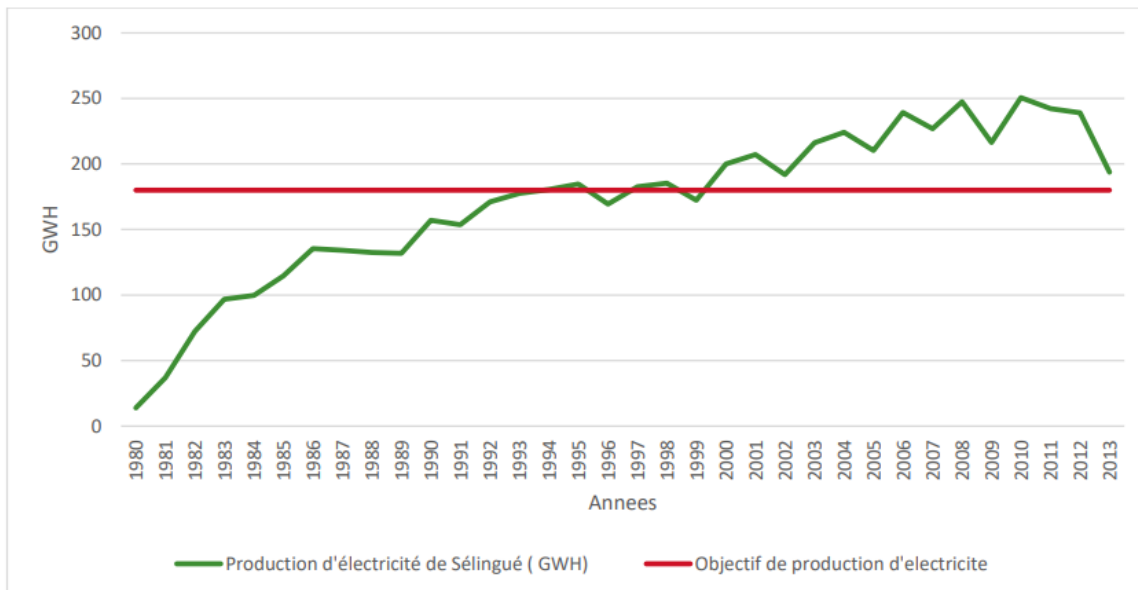
6.3 Sélingué dam

Sélingué dam was constructed in 1996 in the Sankarani river, a tributary of the Niger river. It has four turbines with a hydropower capacity of 47.6 MW. Its volume is estimated to be 1.8 km^3 , a spread surface area of 34.2 km^2 and annual evaporation of 5 km^3 (Maiga, 2019). It is one of the most important infrastructures in Mali. Between 1981 and 2013 its electricity production increased from 36.91 GWh to 193.61 GWh (Hathie, et al., 2017). This represented 55% of the total national electricity production in 2013 against 40.5% in 1981. Although its main function is HPP, it has been also used to supply irrigated areas (Liersch et al, 2018, Kuper, 2002) as food security is a priority for the Mali government. Its HPP is approximately 13 GWh/month of power, a rice production of 9000 tons, and 4000 ton of fish/year (Zwarts, L. et al., 2005). HPP is affected by temperature variation. The volume losses are considerable between the wet and dry seasons. Regarding the impact of climate change on water resources and the growing demand for food and energy due to the rapid growth of the population, Sélingué dam has a critical role to play in Mali's water, food, and energy security.

6.4 Experimental data of Sélingué dam

The following data are related to Sélingué dam and will be used in the different scenarios of reservoir operations.

The table 4 represents the monthly HPP targets selected for the experiment. The annual HPP target of Sélingué from 1980 to 2013 was approximately 180 GWh (Hathie, et al., 2017). This represents a monthly HPP of 15 000 Mwh.



Source : ODRS, 2014; BCEAO, 2015

Figure 18 : Evolution of the HPP of selingue dam (Hathie, et al., 2017)

Month	HPP target 15000 MWH
January	15000
February	15000
March	15000
April	15000
May	15000
June	15000
July	15000
August	15000
September	15000
October	15000
November	15000
December	15000

Table 4: Monthly HPP target

Table 5 represents the monthly target storage of the Sélingué reservoir. They were obtained from (Maiga, 2019).

Month	Target storage 10 ⁴ (m3)
January	202290
February	176876
March	138360
April	98604
May	64200
June	34632
July	20918
August	84300
September	191980
October	234730
November	225878
December	217026

Table 5: target reservoir storage for January - December [10⁴ m3]

Tables 6 represents the irrigation water demand of Office du Niger (ODN) which is Mali largest irrigation scheme (Maiga,2019). The irrigation demand used for the experiment is the monthly average of water demand for the following years: 2005, 2015,2025, 2035, 2045. The data were obtained from (Maiga,2019).

Month	Year (Period)					
	2005	2015	2025	2035	2045	Average
January	48.9	70.5	143	240.6	364.7	173.54

February	47.2	69.5	140.3	236.8	357.6	170.24
March	52.6	72.5	110	165.9	227.6	125.72
April	66	85.5	110.4	149.7	189.3	120.18
May	55.1	71.3	86.4	112.1	134.5	91.88
June	60.9	83.1	123.6	171.5	218.2	131.46
July	112.6	145.6	209.8	287.2	381.1	227.26
August	86.5	113.3	162.3	221.8	294.7	175.72
September	155.9	204.1	293.9	397.1	515.6	313.32
October	157.6	207.6	303.2	423.5	567.3	331.84
November	81.1	110.2	163.4	220.6	271.3	169.32
December	26.7	40.9	72	112.6	153.4	81.2

Table 6: ODN Irrigation withdrawal Scenarios (m³/s) (Maiga,2019)

Table 7 represents respectively the monthly observed downstream outflow of Sélingué, the monthly environmental outflow (ENV), and the average monthly municipal water demand. The observed downstream outflow of Sélingué were obtained from (Maiga,2019). The ENV is calculated considering 60% of the Sélingué outflow downstream as suggested by the Tennant method. The Municipal water demands are determined using Mali's national domestic water consumption which was million m³/year in 2000 according to (echO2, 2022).

Month	Observed Outflow (m ³ /s)	ENV(m ³ /s)	Municipalities water (m ³ /s)
January	108.571952	65.1431714	18.7
February	117.97047	70.7822821	18.7
March	128.862598	77.3175586	18.7
April	147.614369	88.5686212	18.7
May	158.640272	95.184163	18.7
June	183.111	109.8666	18.7
July	206.779677	124.067806	18.7
August	324.148777	194.489266	18.7
September	677.642808	406.585685	18.7
October	560.170458	336.102275	18.7
November	226.729491	136.037695	18.7
December	135.300577	81.1803463	18.7

Table 7: Sélingué observed downstream outflow and estimated monthly environmental outflow.



Figure 20 : Graphical representation of rule 2

- 3) The reservoir is operated following rule 3 (priority to monthly environmental flow, irrigation, and municipal water demands).

It also works as a standard linear policy. The difference between rule 1 and rule 3 is the change of objective. Figure 22 shows a graphical representation of rule 3. For this scenario, three indicators were developed to separately assess the reservoir’s ability to supply water for each of the following purposes: environmental flow balance, irrigation, and municipal needs. Figure 21 is a representation of rule 3.

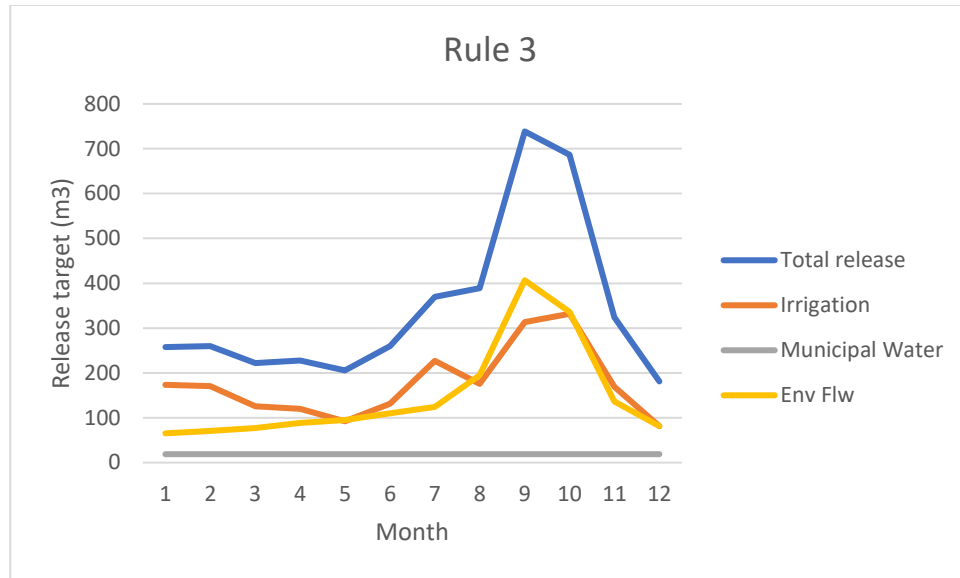


Figure 21 : Graphical representation of rule 3

7.1 Scenario 1

7.1.1 The impact of rule 1 on HPP

The average monthly electricity output is compared to the target electricity output in Figure 22. Electricity output is stable throughout the year, and 98.2% of the demand is satisfied.

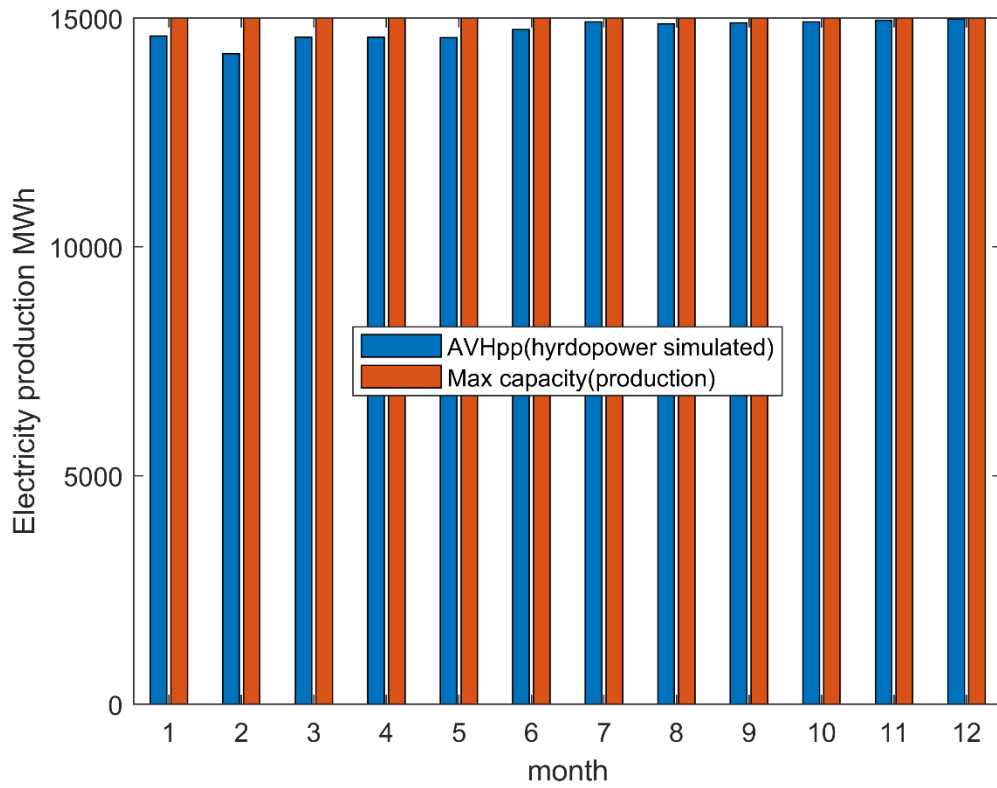


Figure 22 : Monthly HPP target and average monthly HPP simulated for scenario 1

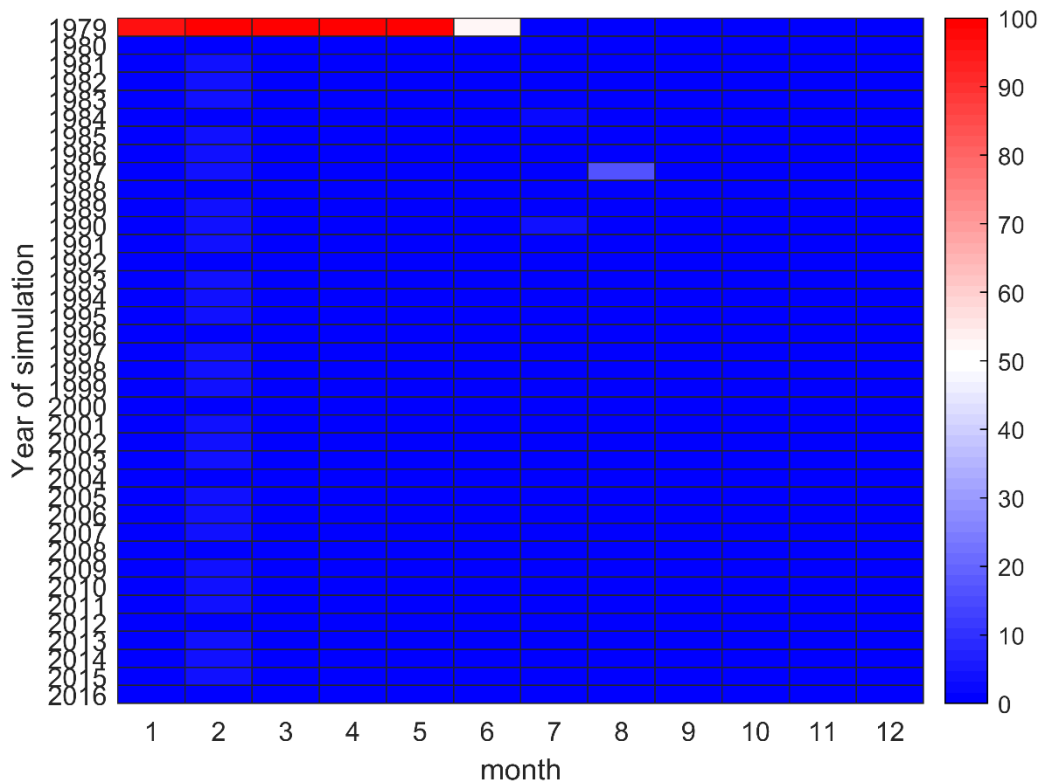


Figure 23 : Average monthly hydropower supply gap for 15000 mwh (Policy 1)

Figure 23 shows that 100% of the electricity demand is fulfilled during the wet months (July to December) while a small gap is observed during the dry period (February to June). The average satisfaction rate of electricity demand for each month is presented in Table 8. The annual supply gap is around 1.7%.

Month	Monthly HPP gap(%)
1	2.5831
2	5.1719
3	2.7825
4	2.7737
5	2.8158
6	1.6491
7	0.5561
8	0.8105
9	0.6649
10	0.5561
11	0.2877
12	0.1211
Average	1.731041667

Table 8: Monthly satisfaction rate of electricity demand (Policy 1)

7.1.2 The impact of rule 1 on reservoir water storage

During the dry season, the decrease in rainfall affects the reservoir inflows while the electricity production continues. This impact the reservoir volume and leads to significant deviations from the current target storage (Figure 24). The monthly average deviation from target storage is presented in Table 9. The annual deviation is approximately 1.8%

Month	Deviation from target storage (%)
1	2.63
2	2.94
3	2.73
4	2.63
5	2.63
6	3.27
7	3.18
8	1.37
9	0.31
10	0.013
11	0
12	0
Average	1.8

Table 9: Average monthly deviation from target storage (%) (Policy 1)

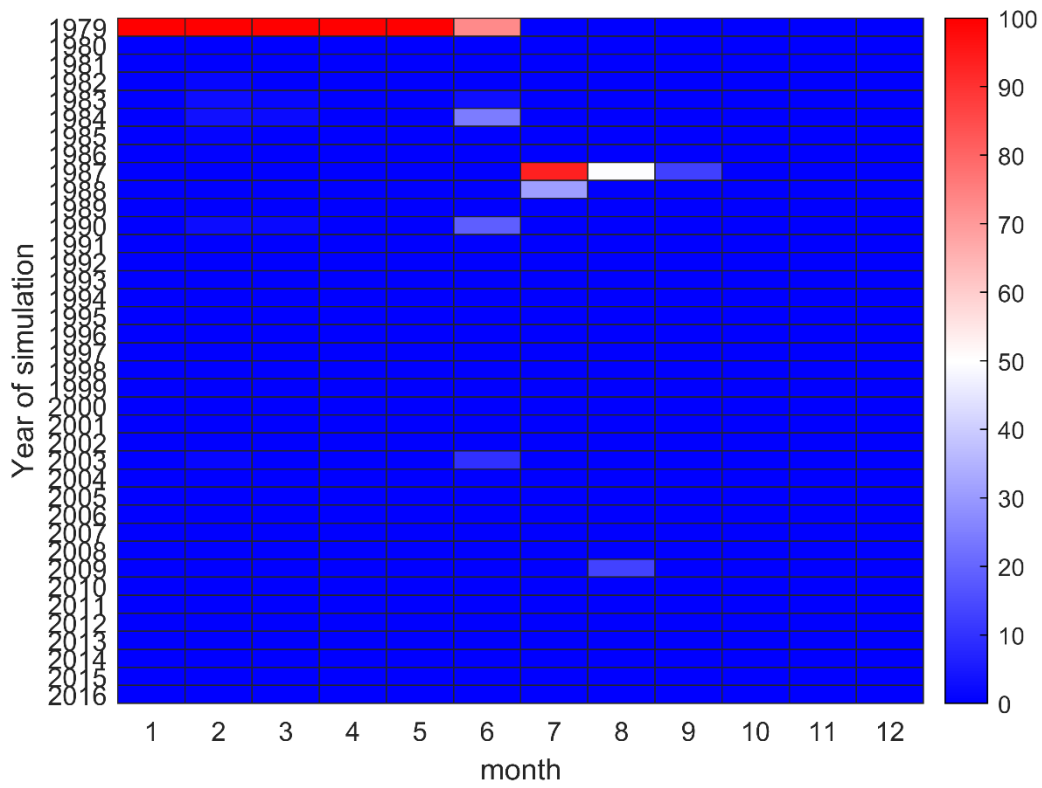


Figure 24 : Target storage deviation (Policy 1)

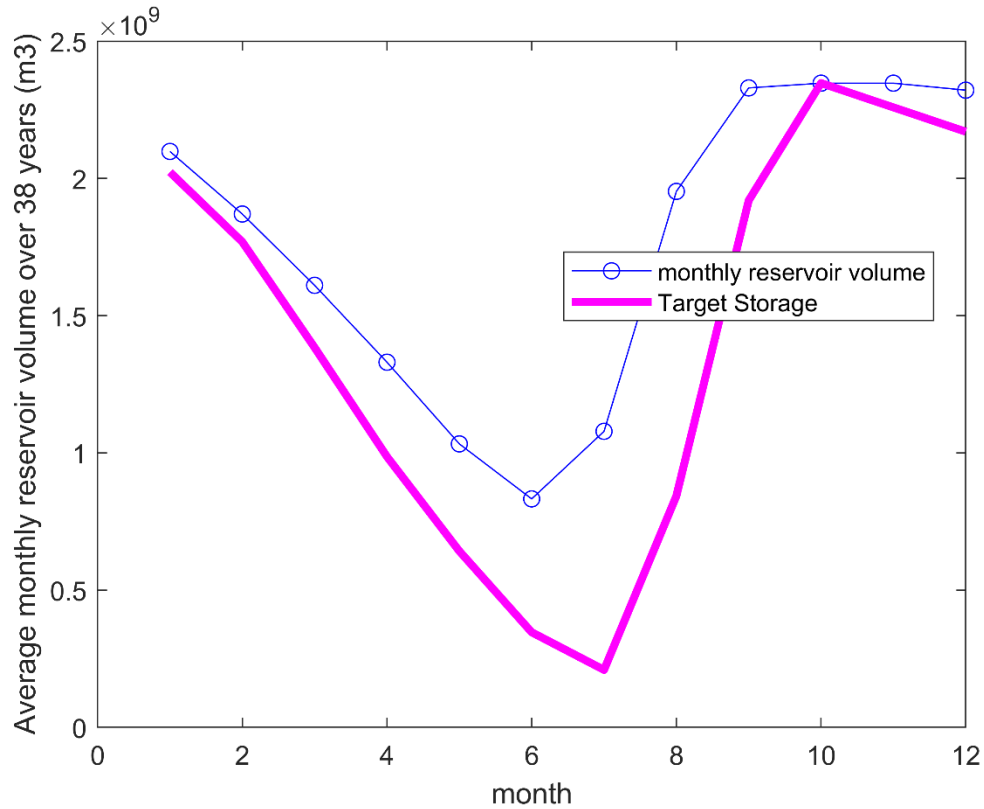


Figure 25 : Average monthly reservoir volume for 15000 mwh (Policy 1)

7.1.3 The impact of rule 1 on water, environment, and food security

Scenario 1 also leads to important deficits in the supply of downstream flow, irrigation, and municipal water requirements during the dry season. Table 10 shows the deficits related to water supply for environmental flow irrigation, and water demand. The annual water supply gap is 18.28%.

Month	Max (irrigation + municipal, environment) gap (%)
1	48.33
2	40.47
3	26.44
4	19.21
5	3.71
6	15.79
7	41.84
8	17.53
9	5.65
10	0.36
11	0
12	0
Average	18.28

Table 10: Monthly satisfaction rate of environmental flow, irrigation, and municipal water demand (Policy 1)

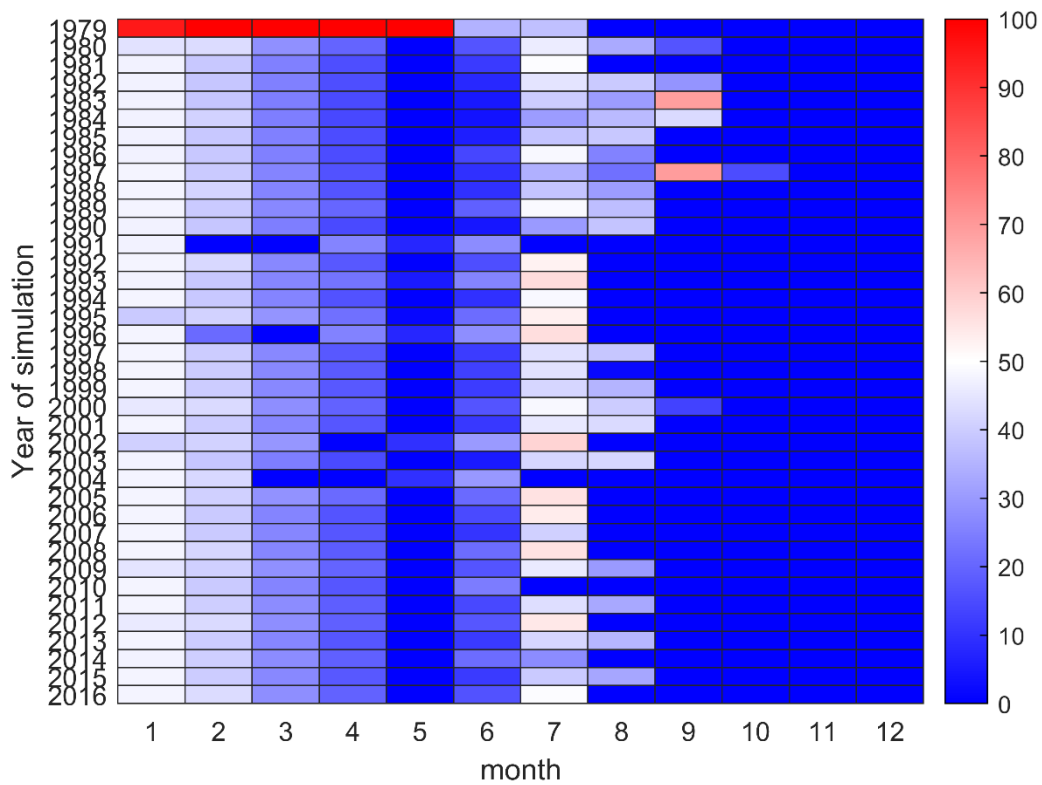


Figure 26 : Gap between the outflow and the environmental flow, the irrigation and municipal demand (Policy 1)

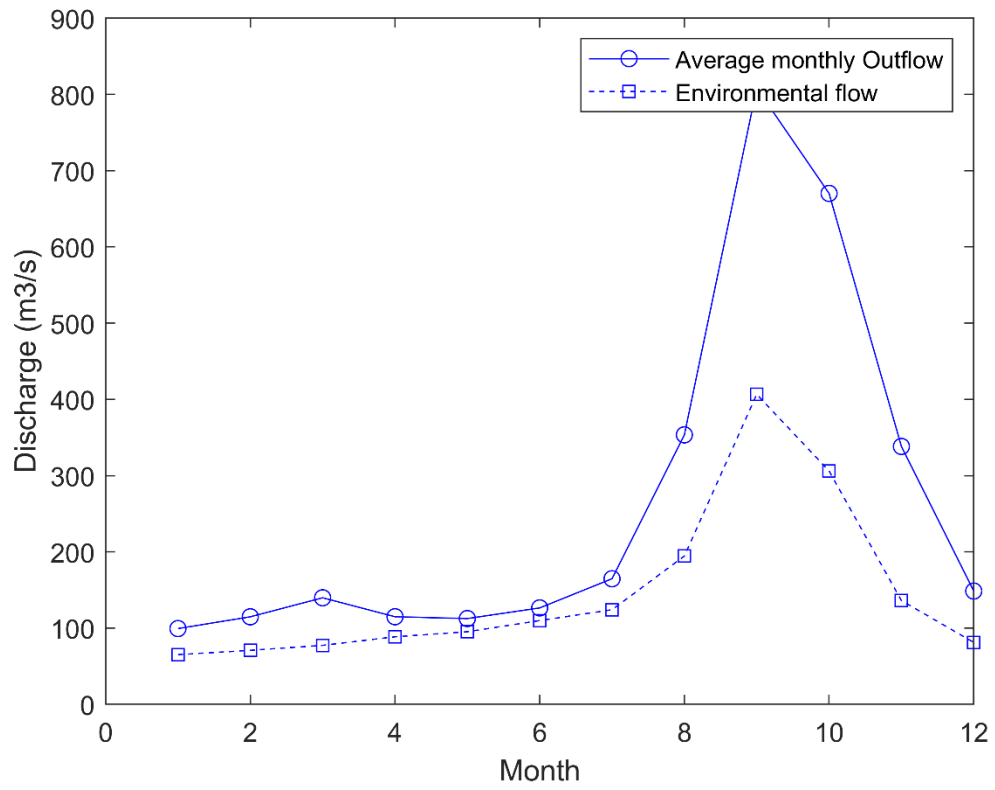


Figure 27 : Average monthly outflow and environmental flow

7.2 Scenario 2

7.2.1 The impact of rule 2 on HPP

The average monthly electricity output is compared to the target electricity output in Figure 28. It can be seen that the electricity supply is less stable than in scenario 1. Only 91.7% of the electricity demand is satisfied.

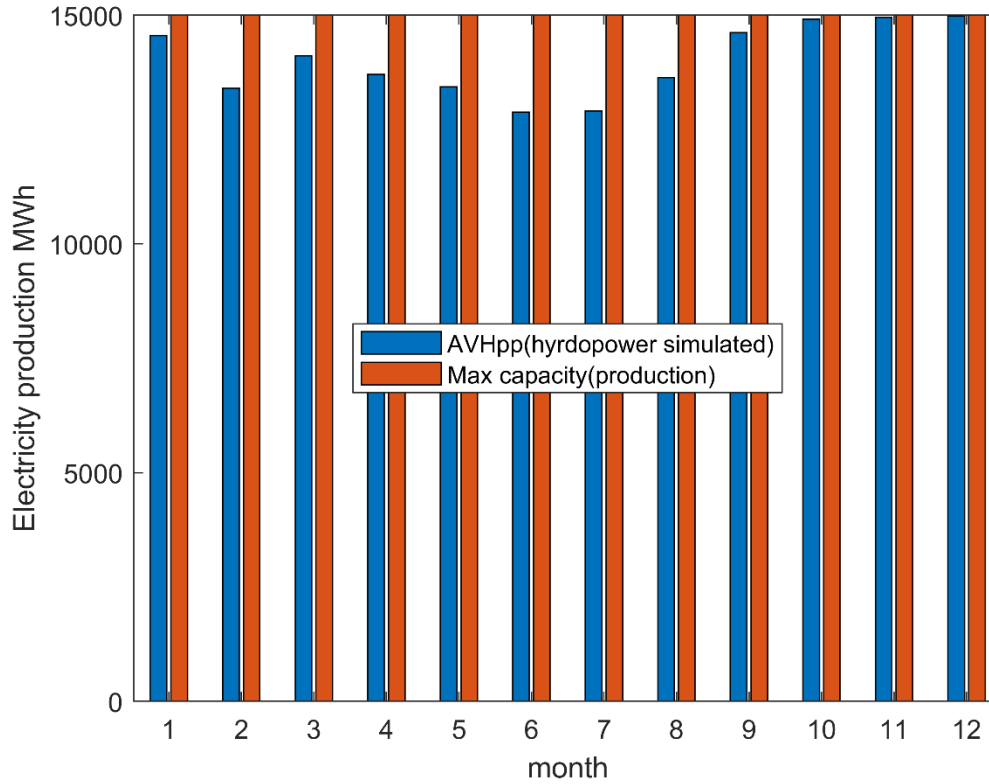


Figure 28 : Monthly HPP target and average monthly HPP simulated (Policy 2)

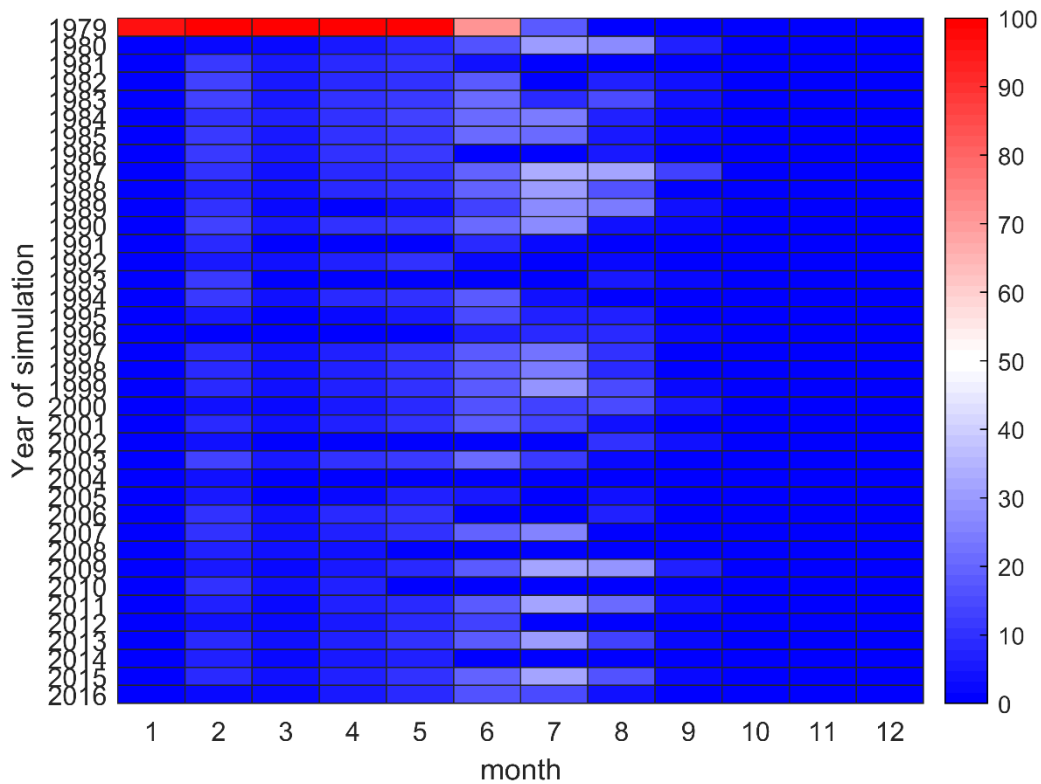


Figure 29 : Average monthly hydropower supply gap (Policy 2)

The average satisfaction rate of electricity demand for each month is presented in Table 11. The annual supply gap is around 8.3%. The maximum gap between the supply and the demand is approximately 21.2% and is observed in June.

Month	Monthly HPP gap(%)
1	2.96
2	10.66
3	5.90
4	14.63
5	15.68
6	21.22
7	17.68
8	8.11
9	1.61
10	0.56
11	0.29
12	0.12
Average	8.3

Table 11: Monthly satisfaction rate of electricity demand (Policy 2)

7.2.2 The impact of rule 2 on reservoir water storage

The high temperatures in the dry season increase the evaporation of the water stored. Also, the decrease in rainfall reduces the inflow. In low inflow conditions, rule 2 continues to operate following the target storage. The monthly average deviation from target storage is presented in Table 12. The annual deviation is approximately 1.25%

Month	Deviation from target storage (%)
1	2.63
2	2.7
3	2.63
4	2.63
5	2.63
6	1.04
7	0.13
8	0.65
9	0
10	0.01
11	0
12	0
Average	1.25

Table 12: Average monthly deviation from target storage (%) (Policy 2)

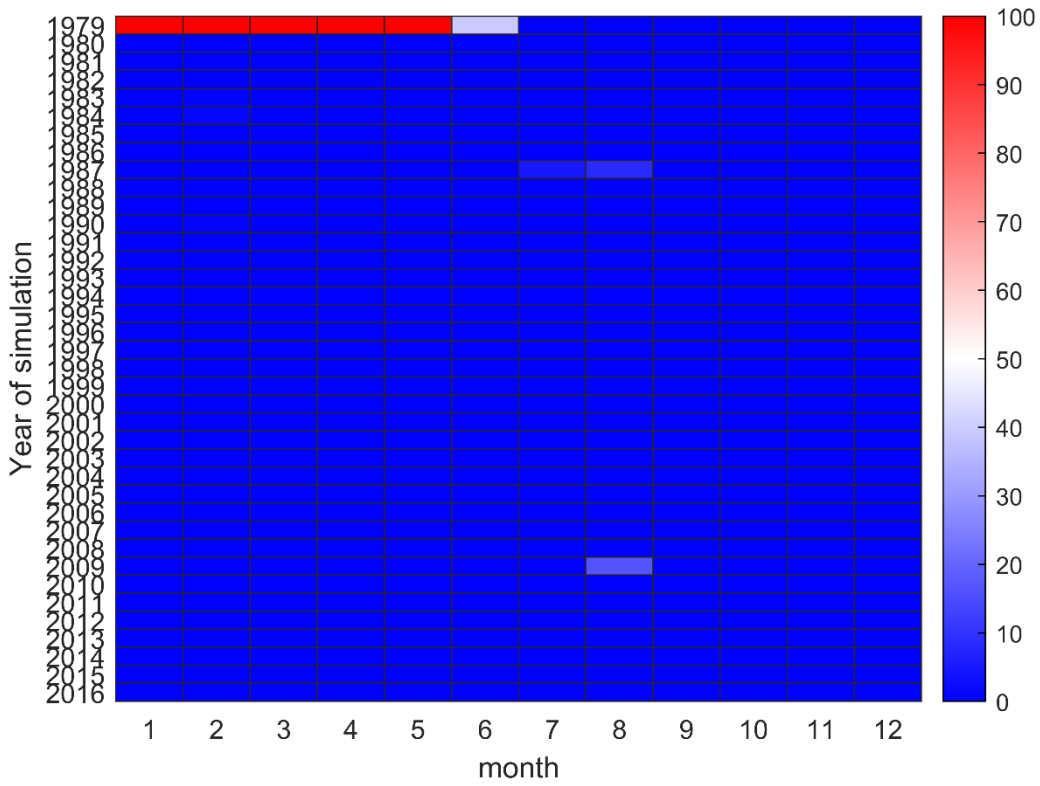


Figure 30 : Target storage deviation (Policy 2)

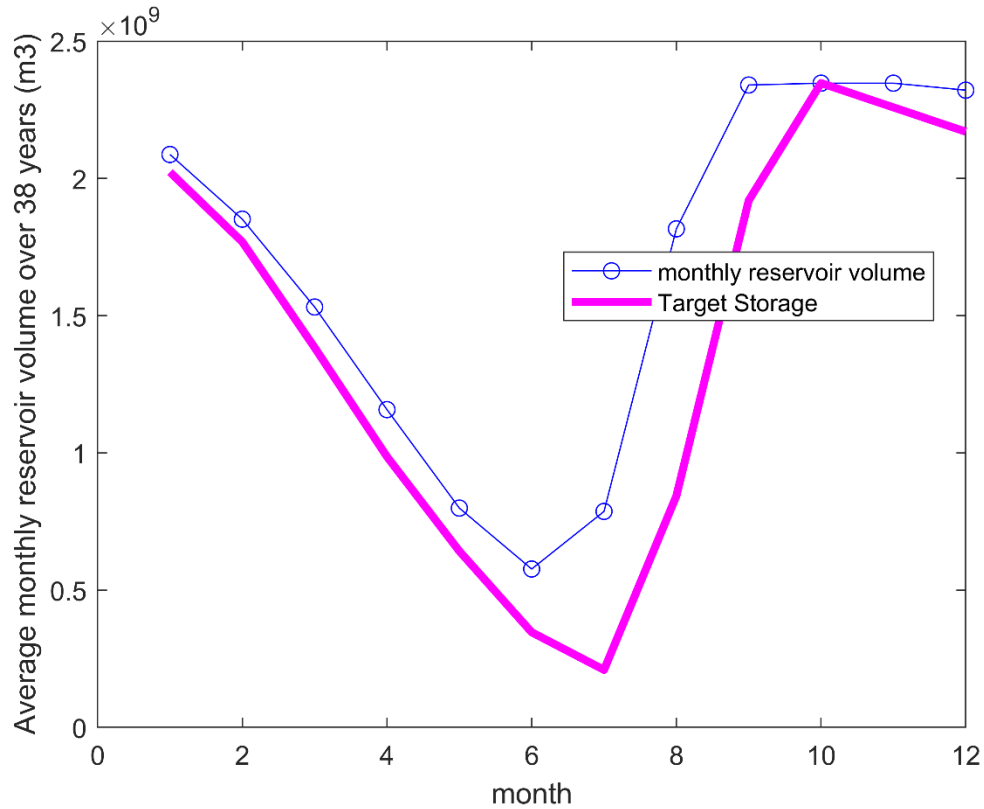


Figure 31 : Average monthly reservoir volume and target storage (Policy 2)

7.2.3 The impact of rule 2 on water, environment, and food security

The potential impact of rule 2 on the downstream flow, irrigation, and municipal water demand was also simulated. Table 13 shows the gap between water supply and environmental flow, irrigation, and municipal water demand. The annual water supply gap is around 15.39%.

Month	max(irrigation+municipal, environnement) gap (%)
1	46.19
2	38.65
3	15.2
4	9.7
5	2.63
6	16.93
7	35.77
8	13.91
9	6.92
10	0
11	0
12	0
Average	15.49

Table 13: Monthly satisfaction rate of environmental flow, irrigation, and municipal water demand (Policy 2)

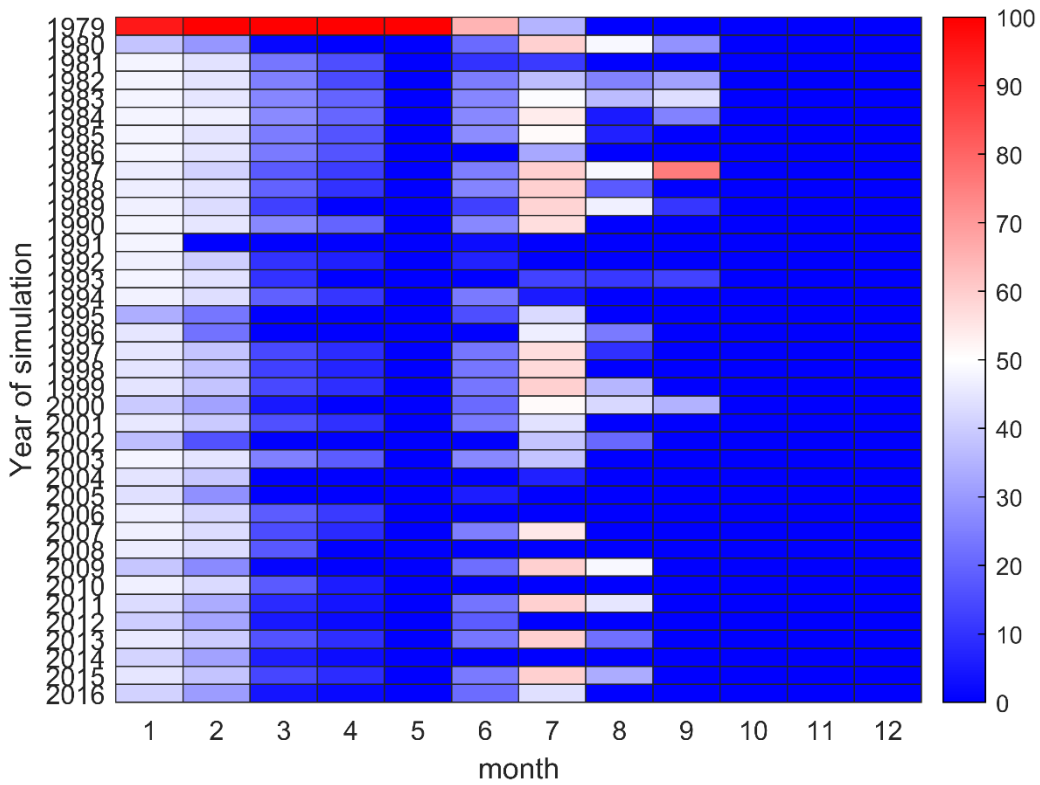


Figure 32 : Gap between the outflow and the environmental flow, the irrigation and municipal demand (Policy 2)

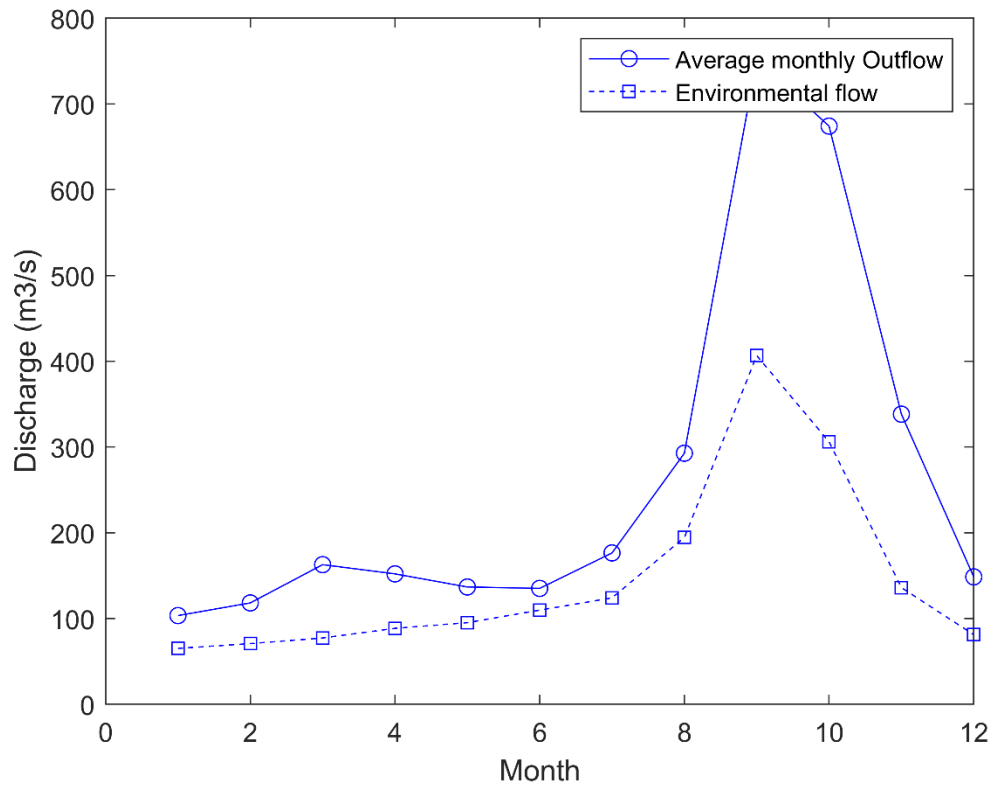


Figure 33 : Average monthly outflow and environmental flow

7.3 Scenario 3

7.3.1 The impact of rule 3 on HPP

The average monthly electricity output is compared to the target electricity output in Figure 34. Electricity output is unstable throughout the year, and 87.4% of the demand is satisfied. HPP varies according to the seasons. In Figure 34, the highest electricity production is observed in the wet season from October to December. During this period, 100% of the demand is met. For the rest of the year, the production decreases especially from May to August.

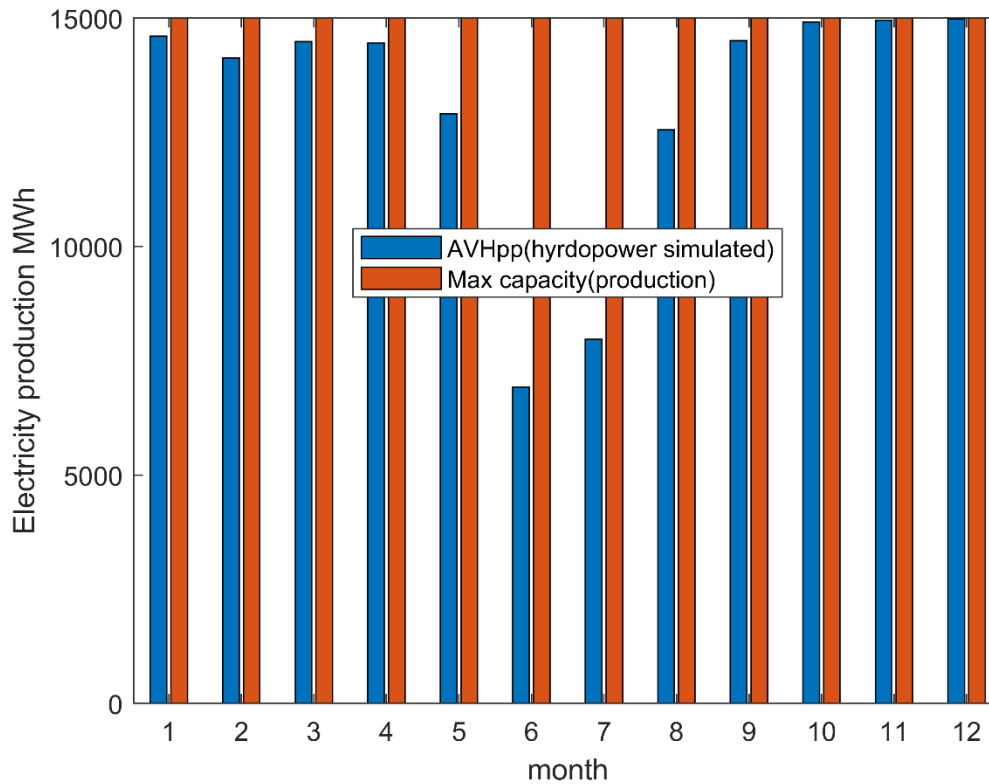


Figure 34 : Monthly HPP target and average monthly HPP simulated (Policy 3)

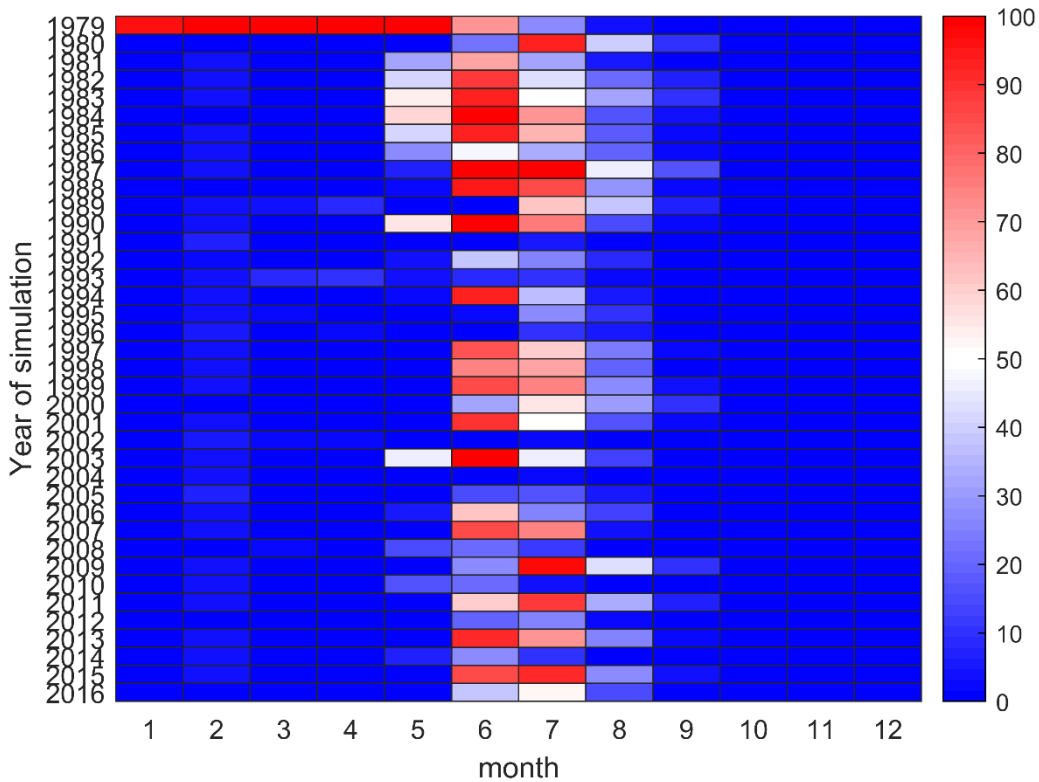


Figure 35 : Average monthly HPP supply gap (Policy 3)

The average non-satisfaction rate of electricity demand for each month is presented in Table 14. The smallest HPP production was observed from May to August with a gap between the supply and the demand estimated respectively at 13.96%, 53.82%, 46.85%, and 16.3%. The annual supply gap is around 12.56%.

Month	Monthly HPP gap (%)
1	2.64
2	5.81
3	3.42
4	3.61
5	13.96
6	53.82
7	46.85
8	16.30
9	3.31
10	0.56
11	0.29
12	0.12
Moyenne	12.56

Table 14: Monthly non-satisfaction rate of electricity demand (Policy 3)

7.3.2 The impact of rule 3 on reservoir water storage

Evaporation and climate change are the factors affecting the inflow and water stored. This affects the productivity of the reservoir. Usually, during the dry season, water shortage can happen. The monthly average is presented in Table 15. The annual deviation is approximately 18%

Month	Deviation from target storage (%)
1	4.12
2	10.76
3	17.57
4	33.59
5	58.44
6	64.49
7	24.94
8	2.46
9	0.01
10	0.01
11	0
12	0
Average	18

Table 15: Average monthly deviation from target storage (%) (Policy 3)

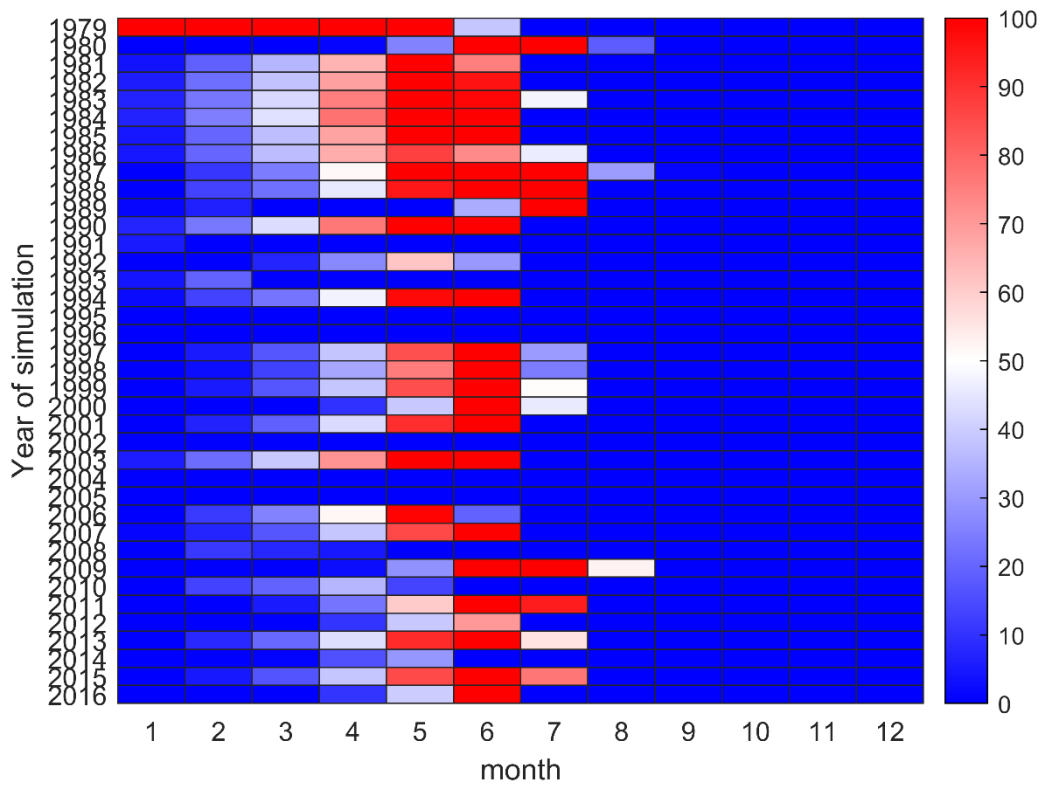


Figure 36 : Target storage deviation (Policy 3) (MATLAB,2022)

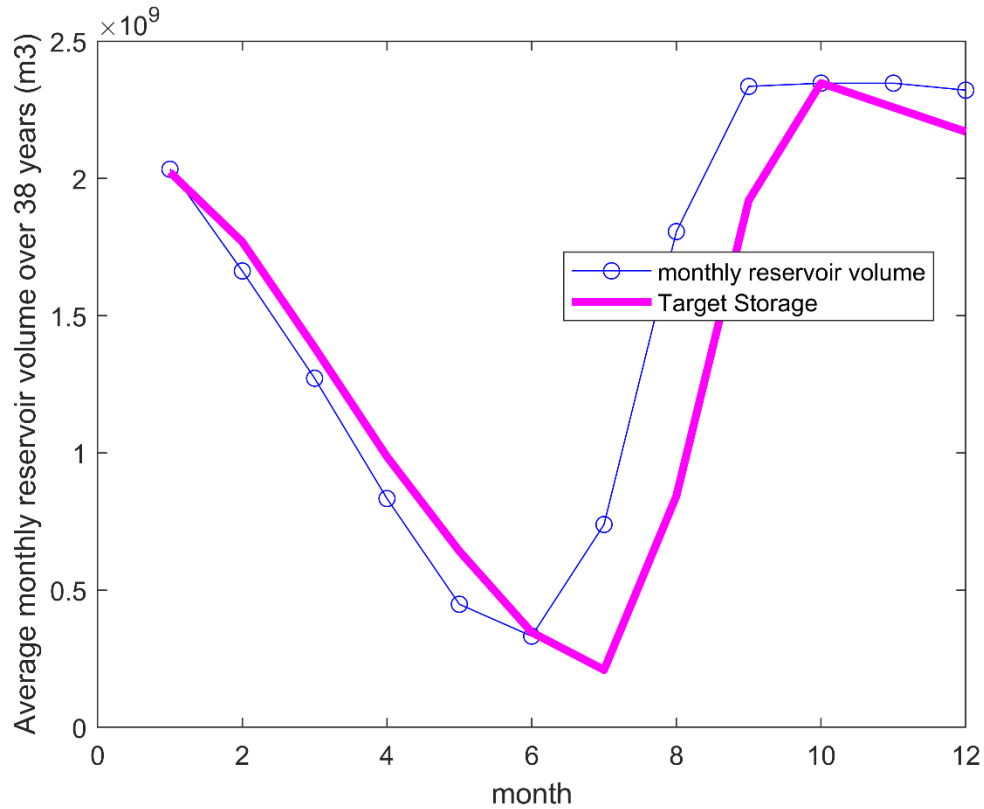


Figure 37: Average monthly reservoir volume (Policy 3)

7.3.3 The impact of rule 3 on water, environment, and food security

As the reservoir operation focus on environmental, irrigation, and municipality needs, HPP is no longer a priority. However, the water supply for the downstream demand for the environment, irrigation, and municipal water demand is not fully met. Table 16 shows the deficit between the water supply and the demand related to the environmental flow, irrigation, and municipal demand. The annual water supply gap is around 17.77%.

Month	Max (irrigation + municipal, environnement) gap (%)
1	35.67
2	10.59
3	6.04
4	5.22
5	4.73
6	45.95
7	63.51
8	30.67
9	10.9
10	0
11	0
12	0
Average	17.77

Table 16: Monthly non-satisfaction rate of environmental flow, irrigation, and municipal water demand (Policy 3)

7.3.3.1 Environmental security

For the same scenario, an indicator was created in order to know the environmental demand that the total outflow would be able to meet annually. It was found that the outflow would be able to meet annually 89.38% of the environmental demand. Table 17 presents the gap between the environmental flow demand and the outflow.

Month	ENV supply gap (%)
1	2.24
2	2.63
3	2.63
4	2.63
5	3.19
6	38.63
7	33.89
8	30.67
9	10.9
10	0
11	0
12	0
Average	10.62

Table 17: Environmental flow supply gap % (indicator 1)

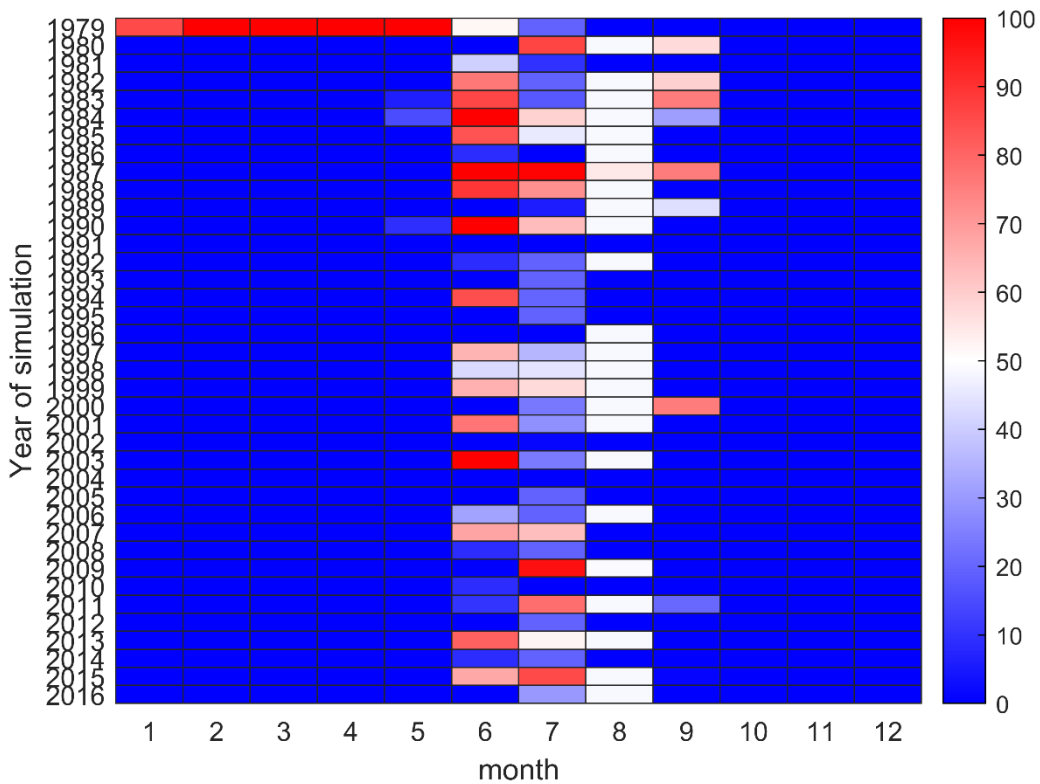


Figure 38 : Gap between ENV flow requirements and the outflow for ENV as the main purpose

7.3.3.1 Food security

For the same scenario, a second indicator was created in order to know the ability of the reservoir to meet irrigation demand. It was found that the outflow would be able to meet annually 84.52% of the irrigation demand. Table 18 presents the gap between the irrigation demand and the outflow.

Month	Irrigation supply gap (%)
1	28.74
2	7.13
3	4.24
4	3.58
5	2.97
6	43.09
7	60.72
8	27.2
9	8.11
10	0
11	0
12	0
Average	15.48

Table 18: Irrigation supply gap % (indicator 2)

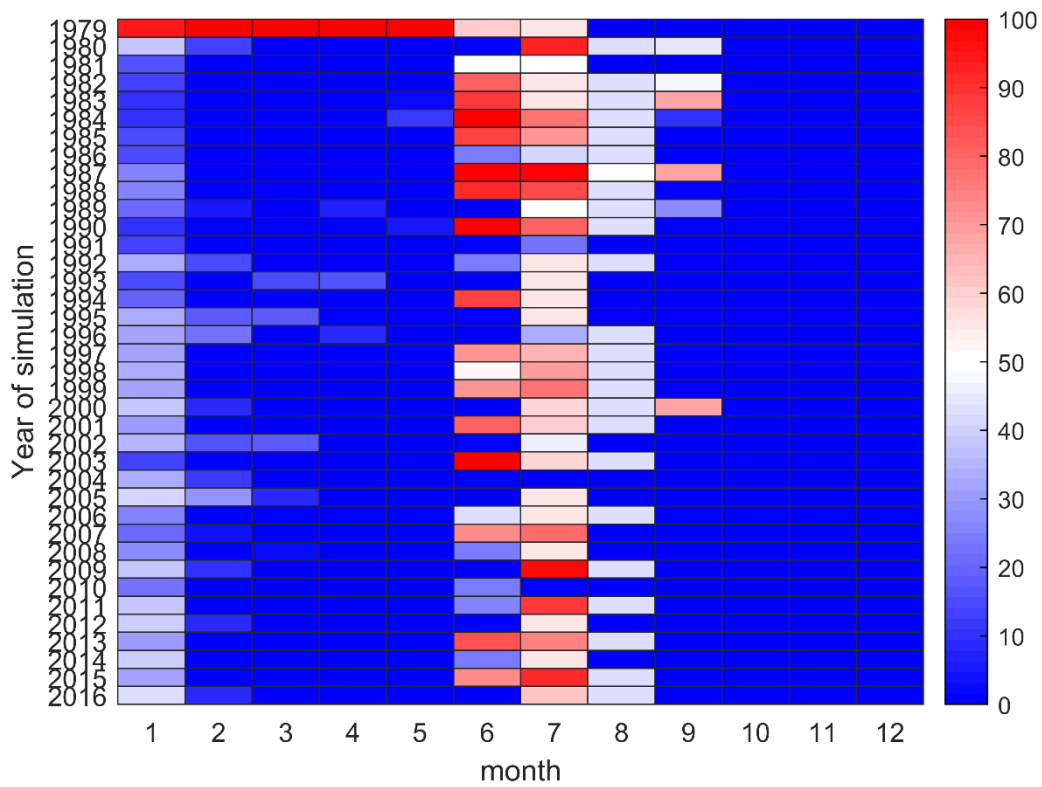


Figure 39 : Gap between irrigation water supply and demand for irrigation as the main purpose

7.3.3.3 Water security

For the same scenario, a third indicator was created in order to know the ability of the reservoir to meet municipal demand. It was found that the outflow would be able to meet annually 98.5% of the environmental demand. Table 19 presents the gap between the municipal demand and the outflow.

Month	Municipal supply gap(%)
1	0
2	2.63
3	2.63
4	2.63
5	2.63
6	7.32
7	0
8	0
9	0
10	0
11	0
12	0
Average	1.5

Table 19: Municipal water demand supply gap % (indicator 3)

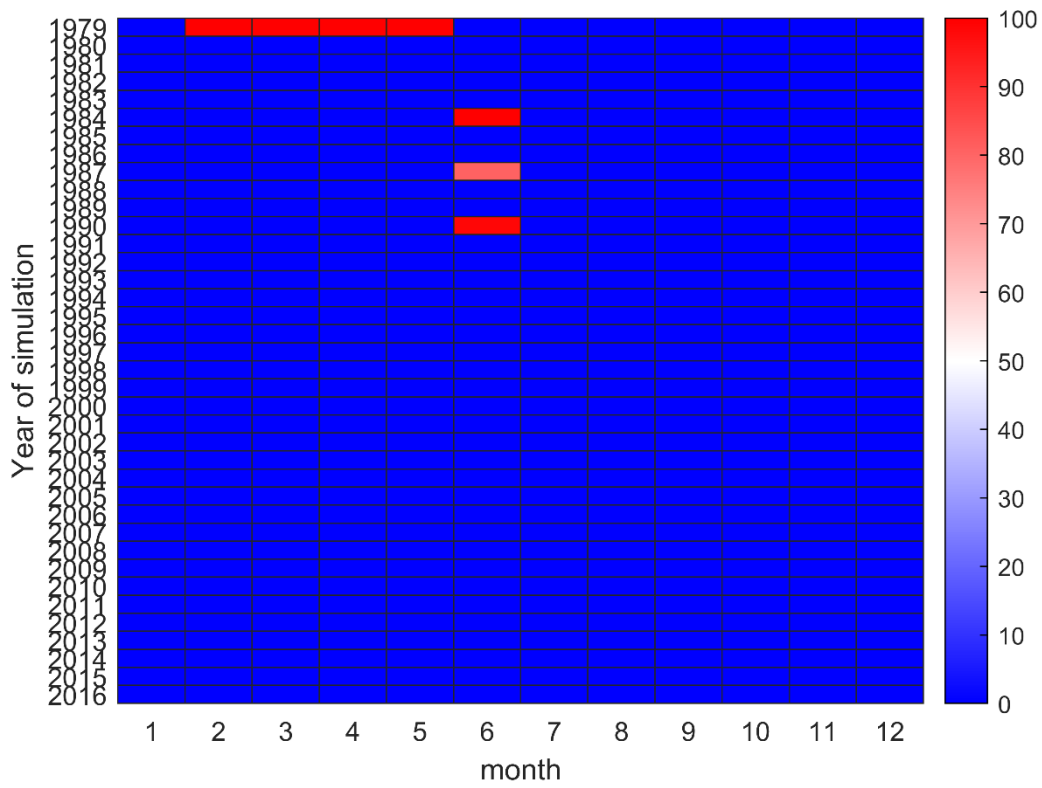


Figure 40 : Gap between supply and municipal water demand for MNP as the main purpose

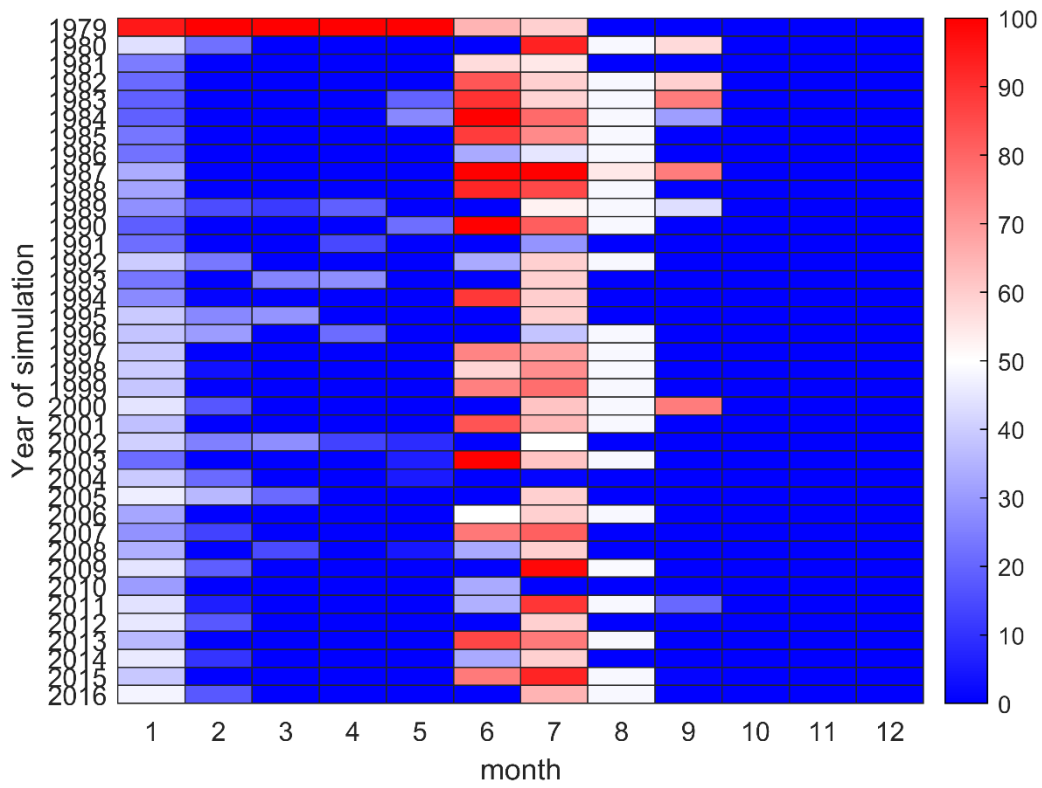


Figure 41 : Gap between the outflow and the environmental flow, the irrigation and municipal demand (Policy 3)

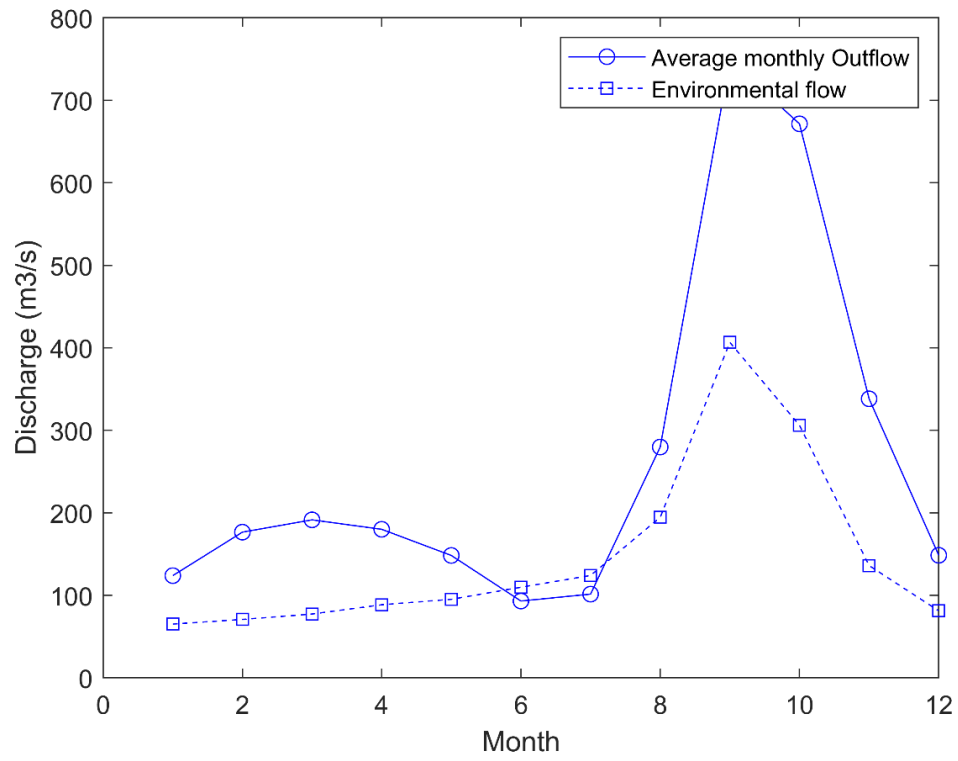


Figure 42 : Average Monthly outflow and environmental flow (Policy 3)

Chapter 8: Discussion

This study aimed to develop a DSS to help decision-makers identify an appropriate reservoir operation policy to account for the tradeoff between water, food, and Energy. SWAT is a well-known model for water-related applications with robust capabilities for hydrologic and water quality applications and flood disaster risk management (Jayakrishnan et al.,2005, Danvi et al., 2016). Another advantage of SWAT is that it can be used as a Decision Support Tool to evaluate the impact of land use changes (Gyamfi, Ndambuki, & Salim, 2016). DSSs have become essential in developing water resource management systems because most decision-makers have no engineering background. Therefore, they need assistance. In extreme cases where the data accessibility is difficult to make a water resources assessment, SWAT can be used to mitigate the issue. According to Lweendo et al. (2017), SWAT can help plan drought and establish mitigation strategies in data-scarce regions.

SWAT integrates several tools suitable for reservoir operation. However, reservoir operation rules have a few limitations in SWAT (Jordana et al.,2022). For example, it does not include a hydropower routine in its system. The first task of the current research was to develop a hydropower routine in SWAT. The code source of SWAT was directly modified to allow hydropower computation. The code line added to the SWAT code source in Fortran has enabled the generation of daily and monthly electricity production and displayed it in the reservoir output files.

Another purpose was to develop a decision support system (DSS) to assist stakeholders in selecting appropriate reservoir operation policies for multipurpose reservoirs. The research consisted of designing a user interface with a map of the project area and a few buttons to select the reservoir and perform technical analysis. MATLAB was used to develop the user interface, run the SWAT model, and display the simulation results. Among the tools of MATLAB, there are a graphical user interface (GUI) and several plots and graphs. The DSS was designed to generate monthly HPP, monthly electricity supply gap, volume deviation, monthly irrigation, municipal water, environmental flow gap, monthly reservoir outflow, and volume.

The reservoir of Sélingué was used as a case study to apply the new SWAT code and test the DSS. Sélingué was selected due to the conflicts related to the multi-objectives. The reservoir was built mainly to produce electricity. Then, it was used for agriculture, transportation, etc. Today, the reservoir is challenged by the growing demand for electricity and food. Also, environmental constraints are increasing because it is necessary to protect the region's ecosystem, which is already affected by climate change and reservoir operations.

Adding hydropower simulation capabilities to SWAT enables decision-makers to evaluate HPP under multiple policies. Shrestha (2021) considers its new hydropower routine (Hydror) as a great addition to SWAT because “ it helps users to establish an integrative approach of HPP management in complex reservoir systems under changing conditions such as land use, climate change, and policy.”.

The new SWAT model developed in the current study was evaluated under three different rules: (1) HPP target; (2) predefined target storage; (3) environmental flow, irrigation, and municipal water use.

Results show that rule 1 leads to the highest and most reliable HPP. This rule allows the reservoir to meet the electricity demand. Unfortunately, the water released after electricity production is not enough to meet the irrigation and municipal water demand and the downstream flow requirement. The biggest challenge when using rule 1 is to define a realistic HPP target. The performance is affected by climate change and variability, and the expectations of electricity production should be adapted accordingly. In the wet season, electricity production increases with the high volume of water in the reservoir due to rainfall. In the dry season, the lack of inflow and the will to reach the HPP target reduces the water stored. The advantage of this rule is that it avoids water wastage. All the water leaving the reservoir will generate electricity. The reservoir operates in a way to do not release a volume of water superior to the turbine's maximum flow or the minimum target outflow ($\text{min_flow}_{\text{HPP}}$). Its main disadvantage is that it does not integrate a strategy for water shortage. The obligation to reach the HPP target can lead to emptying the reservoir quickly. It is not adequate in case of drought.

Rule 2 does not allow the dam to meet the full electricity demand. An annual gap of 8.3% was observed between production and demand. The demand and electricity production gap results from the reservoir operation features. During the wet season, the outflow tends to increase due to the frequency of exceedance events. That's why the electricity demand is completely met at certain periods of the wet season. This method can be variable due to the reservoir operation. When the water stored is below the target storage, the outflow depends on decision-makers choices. Political decisions play an important role in reservoir management. Rule 2, associated with other reservoir operation techniques, can be an efficient method in case of drought.

Fan et al. (2022) developed a multi-reservoir operating policy for water supply based on target storage curves with edging rules. The results of their study show that their system is suitable for managing multi-objective reservoir operation problems, especially during drought periods. Target storage is also efficient in case of flooding. It can store the high inflows and delay the releases downstream. The management of reservoirs based on target storage operation has a few inconveniences. The first inconvenience is to release water only when the volume of water exceeds the target storage. This means in case of a water emergency at a site, the reservoir cannot supply water. This feature reduces the flexibility of the system. The concept of target storage consists of retaining water. Therefore, in case of environmental deficit at downstream or water emergency demand, the reservoir will only supply water if an exceedance is observed. The main weakness of target storage is its rigidity. Also, rule 2 fails to meet the irrigation and municipal water demand and environmental flow requirements, with a gap of 15.39% between the supply and the goals. It struggles with multipurpose reservoir operation.

Another disadvantage of rule 2 is water wastage. This means the reservoir can release water without a purpose if the stored water exceeds the target storage. This disadvantage cannot be

controlled. To address all the issues, engineers usually combine several operating policies. For example, Fan et al. (2022) have combined target storage with edging rules to design an efficient management system. Another method to reduce the limits of the target storage policy is to release a percentage of the water stored when there is no exceedance event. In the current study, the reservoir releases the minimum daily outflow (OFLOWMN) when no excess water exists.

The existing reservoir operation policy of Sélingué dam is rule 2 uses a rule of curves. In fact the target storages are established using the rule of curves. ROC has been praised for its capability to operate multipurpose reservoirs. Lin et al. (2005) researched an optimal operating rule curve including hydropower purpose in parallel multipurpose reservoir systems. They have presented an operational model coupled with simulation and genetic algorithms to address issues related to the difficulty with nonlinear and multiple parameters. The results of the study show the highest hydropower benefit. They also indicate that the model simultaneously satisfies the designed firm yield for water supply (Lin, Wu, & Chen, 2005). ROC has also been used for seasonal increasing of water concessions in reservoirs with low regularized discharges (Nunes, Galvão, & Rêgo, 2016). The experiment results indicate that ROC allows the reservoir to manage large inflows periods with no damage and use the excess water to supply during dry periods. ROC is highly rated for flood management. Chaleeraktragoon & Worawiwat (2020) have developed a procedure to apply dynamic flood control rule curves (DFCRCs) for multipurpose reservoir operation under different flood scenarios. The application of the procedure allows for ensuring the reservoir's operation against various floods. However, advanced assessments conducted on the impact of climate change on operational performances have indicated that the system failed for floods at the higher 80th and 95th percentile levels.

The priorities for rule 3 are the environmental flow, irrigation, and municipal water demand. Unfortunately, this rule did not optimize water food a,nd environmental security. In fact this rule aimed to demonstrate the difficulty to pursue three goals simultaneously. When each indicator is used to give the priority to only one purpose , an optimization of the purpose is observed. According to the Pareto optimal solutions , the improvement of one objective involves the degradation of at least one of the other objectives. The rule three was also the worst scenario for HPP , with a gap of 12.56% between electricity production and demand. The reservoir did not release enough water to meet electricity demand for significant periods. In the wet season, the reservoir increases the outflow for probably two reasons: the excess inflow and the high demand for irrigation and municipal water. The performance of the reservoir for hydropower was affected by the will to meet only the environmental deficit, the irrigation, and the municipalities water deficit. Two reasons can explain why the reservoir did not release a lot of water to meet its purposes. The first one is the lack of water in the reservoir. This can be proved by the deviation of 18.03% between the reservoir volume and the target storage. The second reason is that the deficits related to irrigation, municipal water, and the environment were low. The three indicators in scenario 3 showed that the reservoir can meet individual demands but struggles to meet multiple demands simultaneously.

The rule 1 and 3 uses a standard linear policy as they are based on the hydropower demand as well as the environmental, irrigation, and municipal water demand. SLOP is a set of rules that helps to manage the inflow and outflow of water to conserve the target storage level of the reservoir. The SLOP is determined in the reservoir management policy through factors such as the downstream water needs the amount of water available in the river and the weather conditions. Unfortunately SLOP has few limitations such as its linear approach which may not consider complex interactions its rigidity due to its fixed rules and its limited ecological considerations.

Another technique that could have been considered is storage zoning. It can be a good approach in the context of sélingué because it is designed to supply water anytime. Storage zoning has not been evaluated in this project. However, its characteristics suggest that it would suit the Sélingué reservoir. Storage zoning intends to maximize the efficiency of reservoir operations. Its flexibility allows it to adapt reservoir operations to different situations. A study on storage zoning for multipurpose reservoir need to be completed to approve the method.

The reservoir of sélingué plays an important role in Mali's water, food, and energy security. Meeting the demand for different purposes, such as water supply, food, and electricity production, remains challenging. The simulated scenarios have helped demonstrate the difficulty of pursuing hydroelectricity and food demand and satisfying the environmental demand. Each of the scenarios has been efficient for its main objectives. This study recommends the application of rule 1 for the reservoir operation of Selingue. However, it needs to be improved with other reservoir operation techniques, such as the ROC and hedging, to maximize its benefits. The priority can remain HPP, but the reservoir policies' design must also consider the environment, the irrigation, and the municipal water demands.

To increase electricity production, the Mali government can explore other types of natural sources of energy. Mali has a huge potential for solar energy due to its climate. Hydrological models have many uncertainties.

The major uncertainty in this study comes from parameters, especially the seepage. In the experiment, the seepage values depend on the Hydraulic conductivity of the reservoir bottom RES_K [mm/hr]. When RES_K is high, water losses increase, and the volume of water stored decreases. This leads to emptying the reservoir quickly. A low RES_K allows to reduce the reduction of water losses and improves water storage. A 0.1 mm/hr value for RES_K was found to be the most appropriate for the study. Other uncertainties come from the SWAT software. Sediment deposition is an important factor in reservoir operation. It affects the volume of water stored in the reservoir. Unfortunately, it has not been considered in this study. The addition of sediment reservoir operation could have maximized the study's accuracy.

Chapter 9: Conclusion and Recommendations

The rapid growth of the worldwide population has increased the demand for basic needs such as food, transport, and energy. This situation forced governments to adopt new strategies. The construction of multi-objective reservoirs has solved several problems. However, the multi-reservoir operation has many challenges, including the constraints related to the demand for different purposes and the environment. This study aimed to determine optimal reservoir operation for a tradeoff between water supply, agriculture, and energy.

In a case study, three scenarios were simulated where three different reservoir operation rules were applied. The study area selected was the Sélingué reservoir located on the Sankarani river in Mali. The government of Mali was planning to use the Sélingué dam to ensure food security and meet the energy demand. However, previous studies suggested these objectives were unrealistic and that priority must be given to HPP or food production (Maiga,2019). The analysis of the results confirms that the Mali government cannot use the Sélingué reservoir to meet both food and energy demand.

The simulated scenarios were expected to define the best reservoir rule for a tradeoff between water, food, and energy. The scenarios were (1) monthly HPP target; (2) target storage; (3) environmental flow, irrigation water, and municipal water demands.

The result of the study suggests rule 1 for the reservoir operation of Sélingué. In the context of Sélingué, rule 1 can be associated with the rule of curve (ROC) and several operating techniques to optimize water management. The research focused on the optimization of short-term objectives.

The alternatives and mitigation measures section give a few alternatives to improve irrigation, electricity production, and water supply. The DSS developed in this project will assist decision-makers in selecting an appropriate reservoir operation system for better management of water resources.

Study Limitations

This study has many limitations related to multiple factors. Data collection was the major factor limiting this research. A lot of data needed to be estimated to perform the analysis. Those are:

- The flow of the rating curve subset
- Monthly HPP target
- Tailwater
- Turbine elevation
- HPP target

Usually, the missing data were collected from past studies, and others were calculated with a formula. The flow values in the rating curve subset were estimated with an interpolation that comes with an error percentage. Due to the lack of data in the subbasin, the municipality's water

was based on the household's national demand for water in 2000. The parameters required for the simulation were coming from the reservoir and subbasin. Uncertainty on reservoir operation can also come from target release value.

Reservoir operation is usually involving hydrological modeling. Therefore, the hydrological model's uncertainties affect the reservoir management system. According to Maiga (2019), Hydrological model uncertainties come from input and calibration data, model structures and parameters, conceptual simplifications, spatial resolution, and the omission of specific processes occurring in the watershed. Poor data collection affects the quality of the input.

Some uncertainties can come from the reservoir level of complexity. Poulin et al. (2011) strongly believe that the different level of complexity in hydrological models causes uncertainties. Their study shows that model structure is more likely to create uncertainty than parameters. Mogers et al. (2021) summarize the different sources of hydrological model uncertainty and examples of their causes in Appendix A.

There are also some limitations related to the software used for hydrological modeling, which is SWAT. The first limitation of SWAT is its conception of the reservoir. SWAT considers a reservoir as a horizontal water surface with an invariant stage-discharge relationship at the outlet (Maiga, 2019) . Generally, water streams have turbulences that involve the variation of the flow. The original SWAT model has been programmed for linear variation of volume versus elevation in the reservoir (O. Seidou, 2017).

Another limit of SWAT is its rigidity on reservoir flow equations, as the user cannot set a minimum flow for a reservoir in case of low flows. Akoko et al. (2021) reviewed the SWAT model application's performance in Africa. After comparing the SWAT model to other watershed models, they believe SWAT is not the most reliable for predicting hydrologic response. It could not handle the simulation of increasing the runoff ratio from almost zero at the beginning of the rainfall season to over 50% later in the rainy phase and under-predicted the runoff for a vast majority of rainfall events. The software performs poorly because the curve number method in SWAT assumes a relationship between rainfall and discharge (Moges, et al., 2016).

Also, sediment deposition has not been considered in this study. Therefore, its impact on the reservoir water management is unknown.

Finally, the study was completed on the basis of normal conditions. Thus, the developed solutions for multiple purposes reservoir management have not been evaluated under extreme events such as floods, droughts, etc. Usually, governments use emergency protocols in these conditions.

Alternatives and Mitigations Measures

The results of this study suggest that the Malian government should consider easing the pressure on the Sélingué dam. A realistic HPP target must be established, and the development of other sources of energy must be explored to meet the national electricity demand.

Likewise, a realistic target release for irrigation and water use must be established. The planned extension of ODN will require more water. Before executing the extension plan, the Mali government must evaluate the accessibility of water. Sélingué dam could not support the water demand for the project.

Flows regulations are another challenge of the Sélingué dam. Given the negative impact of HPP plants on the river regime, the reservoir must release a minimum flow to ensure the preservation of the hydrological continuity of the river and the consequent conservation of the natural habitat and ecological life (Mussa, Teka, & Ayicho, 2018).

The country is vulnerable to drought in the wet season. The reservoir operations must include a strategy to ensure water supply in case of water scarcity. Drought can affect socioeconomic development considerably, as well as the environment. Drought damages include the death of vegetation, animals, and humans (due to the lack of drinking water and food), economic crisis, loss of diversity, depopulation, electricity shortage, and more (Maiga, 2019).

Mali's government needs to promote sustainable development by encouraging responsible agriculture and renewable energy development. This study proposes mitigations and adaption measures related to the nexus of water -agriculture – energy to support decision-makers. The mitigations come from the literature review and the results of the study. Before their implementations, it is suggested to complete more experiments and analyses. The measures and mitigations are listed as follows:

- Promote other green energy as a complement to hydropower. For example, solar energy is a green, cost-effective method to generate electricity.
- Promote responsible agriculture through techniques minimizing water use, such as pressurized systems and precision agriculture.
- Develop modern water conservation techniques to fight drought.
- Develop a Drought warning system, such as Early Warning System (DEWS) for the regions (Maiga, 2019).
- Develop a flood warning system
- Increase vegetation to mitigate climate change and reduce rivers and reservoirs evaporation due to high temperatures and lack of vegetation cover.
- Develop modern infrastructures to collect and treat precipitations. This will prevent the risk of over-exploiting groundwater and existing water on the surface (IWA,2012).
- Develop and apply efficient recycling methods for water in industrial processes and rainwater harvesting on-site. This can sustain water supply for industry without straining municipal water supplies and reduce the pollution of external water resources (IWA,2012)
- Promote organic farming to limit substances that will pollute water
- Develop the global monitoring information system on the water to provide the information needed for water management
- Promote behavioral change toward the population through a sensibilization campaign

- Train and equip the population on the practice of IWRM.
- Optimize reservoir operation rules
- Develop a system to recycle domestic wastewater for the non-consumptive purpose (Maiga, 2019)

Future studies

The use of rigid policies can prevent the optimal use of a tank. The development of more flexible policies is the way forward. In this study the three rules were based on specific objectives. For rule 3, indicators were used to separate priorities, however, more dynamic rules could have been used by assigning percentages of water distribution to each objective. This could be the topic of further research to determine a better distribution of water.

Water resources management (WRM) is a wide field. IWRM has emerged over the years as an efficient way to manage water resources. However, applying IWRM is very challenging, mostly in underdeveloped countries. Developing appropriate guidelines for applying IWRM is a topic that deserves to be studied.

The reservoir operation system plays an important role in (WRM). The management of multi-reservoir remains complex. More studies on the operating rules of multi-reservoir are needed. They should include optimization techniques and new reservoir operation algorithms.

Considering the number of uncertainties in hydrological models, future studies can focus on a methodology to reduce uncertainties in modeling.

The current studies used SWAT for analysis. Among the four methods used by SWAT to calculate the outflow, only the average annual release rate for uncontrolled reservoirs was used. It is needed to evaluate the behavior of reservoirs under measured daily outflow, measured monthly outflow, and controlled outflow with target release.

Sediment management represents an important challenge in reservoir operation. The current study did not include it in the swat model. SWAT does not have a proper reservoir sediment operation in its framework. The development of reservoir sediment management routines integrated within the framework of the SWAT model is an interesting topic that can be explored.

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Appendices

Appendix A

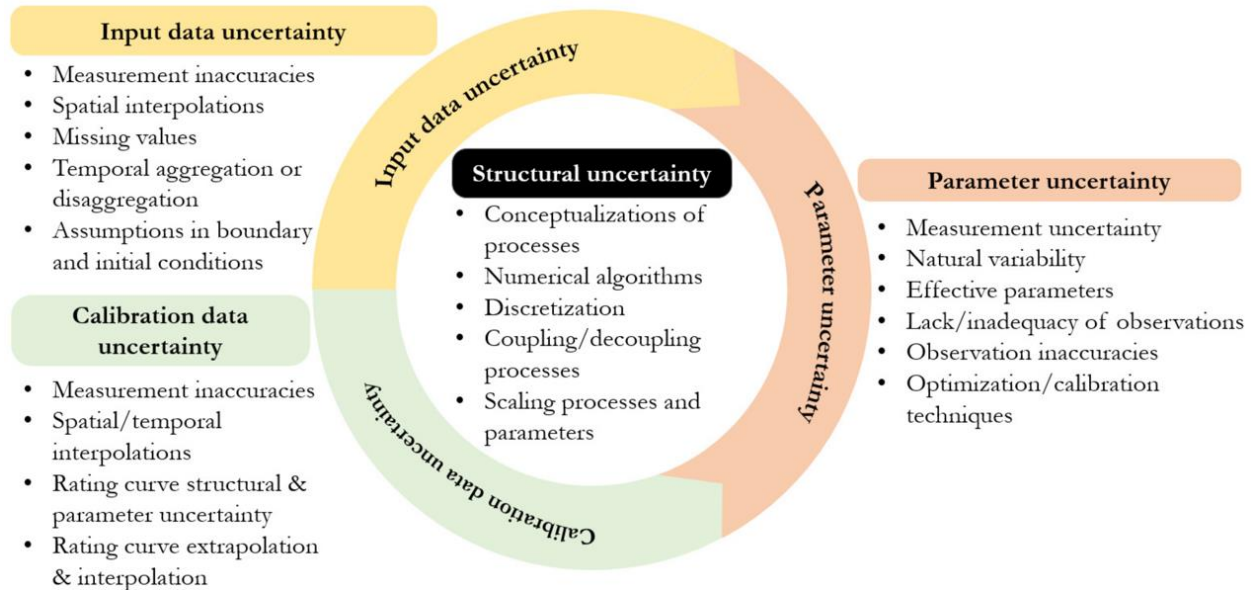


Figure 43 : The different sources of hydrological model uncertainty and examples of their causes (Mogers et al., 2021)

Appendix B: Swat Reservoir Input file (Sélingué)

This appendix provides complementary information on the SWAT reservoir file format used for this study. The parameters are explained in order.

File Name: it includes nine characters. The five first characters represent the sub watershed number. If the sub watershed number is less than three characters, the name is preceded by two zeros. The four last characters are zeros. The name is followed by the file extension (.res). Ex: the file 001030000.res is for reservoir 103.

Reservoir data: The first line provides information about the file and is not used by the program. The next lines provide simulation parameters which are : res_sub, mores, iyres, res_esa, res_evol, res_psa, res_pvol, res_vol, res_sed, res_nsed, res_d50, res_k, iresco, oflowmx, oflowmn, recess_cst. following_res, resmonio, iflod1r, iflod2r, ndtargr, starg, wuresn, wurtnf, evrsv, oflowmn_fps, and starg_fps). Please refer to the SWAT Documentation-2012 for the description of the parameters

```

Reservoir data: .file Subbasin 103 5/24/2018 12:00:00 AM ARCGIS-SWAT - SWAT interface AV
103 | RES_SUB : Number of the subbasin the reservoir is in
0 | MORES : Month the reservoir became operational (1-12)
0 | IYRES : Year of the simulation the reservoir became operational
45500 | RES_ESA : Reservoir surface area when the reservoir is filled to the emergency spillway [ha]
234700 | RES_EVOL : Volume of water needed to fill the reservoir to the emergency spillway [104 m3]
2600 | RES_PSA : Reservoir surface area when the reservoir is filled to the principal spillway [ha]
0 | RES_PVOL : Volume of water needed to fill the reservoir to the principal spillway [104 m3]
2600 | RES_VOL : Initial reservoir volume [104 m3]
4,000.0 | RES_SED : Initial sediment concentration in the reservoir [mg/l]
4,000.0 | RES_NSED : Normal sediment concentration in the reservoir [mg/l]
10.0 | RES_D50 : Median particle diameter of sediment [um]
1.800 | RES_K : Hydraulic conductivity of the reservoir bottom [mm/hr]
0 | IRESKO : Outflow simulation code
OFLOWMX: maximum daily outflow for January - June [m3/s]
3500 3500 3500 3500 3500 3500
OFLOWMX: maximum daily outflow for July - December [m3/s]
3500 3500 3500 3500 3500 3500
OFLOWMN: minimum daily outflow for January - June [m3/s]
100 100 100 100 100 100
OFLOWMN: minimum daily outflow for July - December [m3/s]
100 100 100 100 100 100
0 | RECESS_CST : Name of monthly reservoir outflow file
0 | FOLLOWING_RES : Name of reservoir immediately upstream, if any
| RESMONO : Name of monthly reservoir outflow file
1 | IFLODIR : Beginning month of non-flood season
1 | IFLODIR : Ending month of non-flood season
30 | NDTARGR : Number of days to reach target storage from current reservoir storage
STARG: target reservoir storage for January - June [10^4 m3]
2022900 1768760 1383600 986040 642000 346320
STARG: target reservoir storage for July - December [10^4 m3]
209188 843000 1919800 2347300 2258780 2170260
| RESDAYO : Name of daily reservoir outflow file
WURESIN: consumptive water use for January - June [10^4 m3]
11.2 14.6 21 21.2 11.8 5.5
WURESIN: consumptive water use for July - December [10^4 m3]
4.5 10.3 14.9 18 15.6 5.2
0 | WURTNF : Fraction of water removed from the reservoir via WURESIN that is returned and becomes flow out of reservoir [m3/m3]
0.6 | EVRSV : Lake evaporation coefficient
0 | OFLOWMN_FFS : Minimum reservoir outflow as a fraction of the principal spillway volume
1 | STARG_FFS : Target volume as a fraction of the principal spillway volume

```

Hydrograph rating curve: It includes 50 subsets of 4 elements which are listed in order as follows: the first line corresponds to the volume, the second line to the surface area, the third line is the outflow, and the fourth line is the corresponding water level (stage).

The columns (ten in total) are a series of increasing stages with the corresponding volumes and surface areas (from G1 to G2 in the screenshot below). At the end of the ten columns, the series continues with the next four lines (G11 in the screenshot below (Maiga,2019)). The same data is used for the rising and descending hydrographs.

Rising hydrograph rating curve

G1	0.00	G2	6627.14	13254.29	19881.43	26508.57	33135.71	39762.86	46390.00	53017.14	G10	59644.29
	0.00		4893.00	7005.55	8673.64	10467.60	11783.60	13025.31	14428.84	15938.57		17458.69
	0.00		587.33	836.66	1031.6	1188	1321.73	1444.13	1552.93	1650.4		1741.06
	336.00		338.15	339.25	340.11	340.80	341.39	341.93	342.41	342.84		343.24
G11	66271.43		72898.57	79525.71	86152.86	92780.00	99407.14	106034.29	112661.43	119288.57		125915.71
	18843.45		19942.25	20969.01	22223.50	24095.89	25653.04	26915.83	28119.16	29271.31		30314.29
	1824.93		1902	1974.53	2044.8	2108.26	2169.47	2226.13	2280.53	2334.93		2384.8
	343.61		343.95	344.27	344.58	344.86	345.13	345.38	345.62	345.86		346.08
	132542.86		139170.00	145797.14	152424.29	159051.43	165678.57	172305.71	178932.86	185560.00		192187.14
	31169.40		32023.03	32826.32	33629.61	34506.73	35447.02	36387.30	37272.36	38149.89		39045.21
	2432.4		2482.27	2527.6	2572.93	2616	2659.07	2702.13	2742.93	2781.47		2822.27
	346.29		346.51	346.71	346.91	347.10	347.29	347.48	347.66	347.83		348.01
	198814.29		205441.43	212068.57	218695.71	225322.86	231950.00	238577.14	245204.29	251831.43		258458.57
	40491.48		41937.75	43384.02	43913.18	44362.37	44811.57	45000.00	45000.00	45000.00		45000.00
	2858.53		2894.8	2931.07	2965.07	2999.07	3033.07	3067.07	3098.8	3132.8		3166.8
	348.17		348.33	348.49	348.64	348.79	348.94	349.09	349.23	349.38		349.53
	265085.71		271712.86	278340.00	284967.14	291594.29	298221.43	304848.57	311475.71	318102.86		324730.00
	45000.00		45000.00	45000.00	45000.00	45000.00	45000.00	45000.00	45000.00	45000.00		45000.00
	3200.8		3232.53	3266.53	3300.53	3332.27	3366.27	3400.27	3434.27	3466		3500
	349.68		349.82	349.97	350.12	350.26	350.41	350.56	350.71	350.85		351.00

The next line is the Turbine Height in meters (331 m in this example), followed by the Turbine Max Flow (450). The other values are described in the screenshot below.

331						
450						
325.94	325.94	325.94	325.94	325.94	325.94	Tailwater
325.94	325.94	325.94	325.94	325.94	325.94	
15000	15000	15000	15000	15000	15000	Monthly Hydropower target
15000	15000	15000	15000	15000	15000	
0.9	0.9	0.9	0.9	0.9	0.9	Monthly turbine efficiency
0.9	0.9	0.9	0.9	0.9	0.9	

Appendix C: Swat Subbasin Input file (Sélingué)

File Name: It is like a reservoir file name. The name is followed by the file extension (.sub).

Subbasin data: The file includes the following parameters: the subbasin area, climate in the subbasin, elevation bands, tributary channels, impoundments, and climate change.

```

.sub file Subbasin: 103 5/24/2018 12:00:00 AM ArcSWAT 2012.10_4.19
3263.395053 | SUB_KM : Subbasin area [km2]

Climate in subbasin
11.060885 | LATITUDE : Latitude of subbasin [degrees]
410.00 | ELEV : Elevation of subbasin [m]
100 | IRGAGE: precip gage data used in subbasin
100 | ITGAGE: temp gage data used in subbasin
100 | ISGAGE: solar radiation gage data used in subbasin
100 | IHGAGE: relative humidity gage data used in subbasin
100 | IWGAGE: wind speed gage data used in subbasin
001030000.wgn | WGNFILE: name of weather generator data file
1 | FCST_REG: Region number used to assign forecast data to the subbasin

Elevation Bands
| ELEVB: Elevation at center of elevation bands [m]
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
| ELEVB_FR: Fraction of subbasin area within elevation band
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
| SNOEB: Initial snow water content in elevation band [mm]
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.000 | PLAPS : Precipitation lapse rate [mm/km]
0.000 | TLAPS : Temperature lapse rate [°C/km]
0.000 | SNO_SUB : Initial snow water content [mm]

Tributary Channels
194.757 | CH_L1 : Longest tributary channel length [km]
0.000 | CH_S1 : Average slope of tributary channel [m/m]
165.498 | CH_W1 : Average width of tributary channel [m]
0.000 | CH_K1 : Effective hydraulic conductivity in tributary channel [mm/hr]
0.014 | CH_N1 : Manning's "n" value for the tributary channels

Impoundments
001030000.pnd | PNDFILE: name of subbasin impoundment file
Consumptive Water Use
001030000.wus | WUSFILE: name of subbasin water use file

Climate Change
330.000 | CO2 : Carbon dioxide concentration [ppmv]
| RFINC: Climate change monthly rainfall adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| RFINC: Climate change monthly rainfall adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| TMPINC: Climate change monthly temperature adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| TMPINC: Climate change monthly temperature adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000

```

```

Impoundments
001030000.pnd | PNDFILE: name of subbasin impoundment file
Consumptive Water Use
001030000.wus | WUSFILE: name of subbasin water use file

Climate Change
330.000 | CO2 : Carbon dioxide concentration [ppmv]
| RFINC: Climate change monthly rainfall adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| RFINC: Climate change monthly rainfall adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| TMPINC: Climate change monthly temperature adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| TMPINC: Climate change monthly temperature adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| RADINC: Climate change monthly radiation adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| RADINC: Climate change monthly radiation adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| HUMINC: Climate change monthly humidity adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| HUMINC: Climate change monthly humidity adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| HRU data
1 | HRUTOT : Total number of HRUs modeled in subbasin

```

HRU: Depressional Storage/Pothole

Floodplain

HRU: Riparian

HRU: General

001030007.hru001030007.mgt001030007.sol001030007.chm 001030007.gw

001030007.sep

The last six lines were added to the original files. They represent the in order the monthly environmental flow, the monthly municipality's use, and finally, the irrigation water withdrawn. They are used to determine the environmental deficit and the consumption deficit.

65.14	70.78	77.32	88.57	95.18	109.8] Environmental Flow
124.06	194.49	406.59	336.10	136.04	81.18	
18.7	18.7	18.7	18.7	18.7	18.7] Municipalities water
18.7	18.7	18.7	18.7	18.7	18.7	
173.54	170.24	125.72	120.18	91.88	131.46] Irrigation Water
227.26	175.72	313.32	331.84	169.32	81.120	