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DYNAMICS OF WATER SUPPLY AND DEMAND IN THE BANDAMA RIVER WATERSHED OF COTE D'IVOIRE

A Thesis Presented

By

SARAH A. TRAORE

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2022

Environmental Conservation
DYNAMICS OF WATER SUPPLY AND DEMAND IN THE BANDAMA RIVER WATERSHED OF COTE D’IVOIRE

A Thesis Presented

by

SARAH ALIMA TRAORE

Approved as to style and content by:

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Timothy O. Randhir, Chair

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Kaline De Mello, Member

____________________________________
Paige Warren, Department Head,
Environmental Conservation
DEDICATION

To my loving and supportive husband

To my parents
ACKNOWLEDGEMENTS

I would like to express my gratitude to my adviser, Dr. Timothy Randhir, for his patience, wisdom, and support over the last two years. I am quite appreciative of his efforts to assist me in completing this dissertation. I would also like to thank Kaline de Mello, a member of my committee, for her helpful remarks and suggestions throughout this project's development.

I wish to express my gratitude to Fulbright and the Institute of International Education for funding my master's degree and enabling me to conduct this research. I'd want to offer my gratitude to everyone who volunteered for this project.

I would like to extend my thanks to Mrs. Saramatou Bahire, Mr. Ibrahima Berte, Prof. Goula Tie Bi, and Dr. Soro for patiently addressing my queries and providing me with data for this work.

A particular thank you to my husband, my parents, my in-laws, and everyone else whose encouragement and support helped me stay focused on this project and encouraged me to continue when the going got difficult.
ABSTRACT

DYNAMICS OF WATER SUPPLY AND DEMAND IN THE BANDAMA RIVER WATERSHED OF COTE D'IVOIRE

MAY 2022

SARAH A. TRAORE, B.S., NATIONAL POLYTECHNIC INSTITUTE FELIX HOUPHOUET BOIGNY

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Water is a fundamental human right supporting life, health, and livelihoods. Yet water-related issues are ranked among the top five global economic risks (WEF, 2020). About two-thirds (4 billion) of the world's population live with severe water scarcity for at least one month, of which about 48% live in both India and China (Mekonnen et al., 2016). In Côte d'Ivoire, the Bandama River, one of the largest in the country, has struggled to meet expected demand, causing recurrent water and electricity shortages. The city of Bouaké in Côte d'Ivoire and neighboring towns experienced a severe water shortage in 2018 with the drying up of the water supply reservoir (Loka along the Bandama River), affecting 70% of the population causing difficult economic and social conditions. To fully understand this dimension of water scarcity in the Bandama watershed, this study models current water availability using SWAT and assesses the current watershed system in Cote d'Ivoire. Model calibration and validation performances were suboptimal. However, the model gave important information
about the dominant process and the critical areas of the watershed. This information guided the development of strategies to build resilience in the water supply system through institutional and stakeholder-driven approaches.

**Keywords:** water scarcity, dynamic watershed management, integrated watershed management, GIS, SWAT.
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CHAPTER 1
INTRODUCTION

1.1 Background

Humans need water for survival, health, and livelihoods. Yet water shortages are among the top five global economic threats (WEF, 2020). According to UNICEF (2019), 2.2 billion people lack access to safe drinking water, and over half lack sufficient sanitation. 2/3 of the world's population (4 billion people) suffer severe water scarcity for at least a month, with 48% living in both India and China (Mekonnen et al., 2016). Water concerns cause diarrhea, which kills 297,000 children under five every year (WHO, 2019). They also impact energy, agriculture, ecosystems, and conservation - vital sectors for economic, social, and environmental growth (Cosgrove et al., 2015, Fitton et al., 2019 Rosa et al. 2020; Liao et al., 2020). Although these statistics apply globally, the impact on underdeveloped countries can be more severe due to larger populations and limited resources (Mekonnen et al., 2016; Liu et al., 2017). Every year, numerous African and Asian countries face high to extremely high water risks, according to the WRI's Aqueduct tool (2019). Climate change, rapid urbanization and population increase, economic development, dietary shifts towards more animal products, and inadequate water management have all exacerbated water scarcity (Liu et al., 2017; Faramazi et al., 2017).

Due to a severe drought in 2018, municipal water agencies in Cape Town, South Africa, predicted a complete water shortage on “Day Zero” where residents were required to reduce their water consumption by half to only 50 liters per day (Rodina, 2019). The Bandama River in Côte d'Ivoire has also struggled to satisfy
demand, causing water and electrical shortages. In 2018, Bouaké, Côte d'Ivoire, and other cities in the north (Niakaramandougou, Ferkessedougou, Tortiya, Odienne) and center (Diabo, Botro, Sakassou, etc.) faced severe water shortages. The water supply reservoir (Loka along the Bandama river) dried up, affecting 70% of the population (Niasse et al., 2020; Konan, 2018). In May 2021, the country of Côte d'Ivoire had water and electricity shortages due to a lack of water to recharge dams that produce electricity and supply water to some localities (Le Point Afrique, 2021; Comodafrica, 2021).

Understanding the dynamic relationship between demand and supply in the context of integrated watershed management (IWM) is required to properly appreciate this dimension of water scarcity in the Bandama watershed for which relatively few studies can be found in the literature.

This study models current water availability using SWAT and assesses the current watershed system in Côte d’Ivoire. It is expected to assess the spatial distribution of deficits and temporal trends that can be used in integrated watershed management that will be applied at multiple scales in the Bandama watershed.

This information will be used in developing strategies to improve the sustainability of water supply and demand infrastructure through systems and stakeholder-driven approaches.

1.2 Research objectives

1.2.1 General Objectives

The general objective of this research is to contribute to the development of sustainable solutions to water scarcity challenges at many scales in Côte d’Ivoire through the application of IWM and modeling techniques.
1.2.2 Specific Objectives

The specific objectives are:

i) To study the baseline water conditions at multiple scales

ii) to assess trends in water demand and supply in the study area

iii) to develop strategies and policies to manage water at multiple scales

1.3 Hypotheses

i) To study the baseline water conditions at multiple scales

   HA1.1- Precipitation-runoff relationship is different between scales

   HA1.2- Infiltration-withdrawal relationship is different between scales

ii) to assess trends in water demand and supply in the study area

   HA2- Risk of shortage is increasing over time in the study area

iii) to develop strategies and policies to manage water at multiple scales

   HA3.- The IWM principle can be enhanced to include multiple scales to achieve water sustainability

1.4 Thesis plan

   The thesis is divided into five sections. The first chapter contains an introduction and bibliographical references. The second chapter explores the watershed's baseline water conditions. Chapter 3 discusses the patterns and trends in water demand and supply in the research area. Chapter 4 discusses strategies and policies for water management at several scales, while Chapter 5 discusses ideas for improving the model in the Bandama watershed's data-scarce context.
1.5 Literature review

1.5.1 Water budget

Water availability is an increasing challenge, necessitating the quantification and management of water resources. The water budget is a critical tool that water managers use to analyze the historical and future water circumstances of an area. Water budgets quantify the movement of water between inflows and outflows within a watershed (Ghale et al., 2018; Kansoh et al., 2020). Precipitation, direct runoff, groundwater, and surface water discharges into the lake or river are considered inflows, whereas evaporation, groundwater, and surface water discharges from the lake or river are considered outflows. Certain components of the water budget, such as precipitation, evaporation, and runoff, are determined by meteorological conditions and can be approximated using ground-based monitoring stations, satellite data, or modeling (Kansoh et al., 2020; Kushwaha et al., 2021). Whether they are Land Surface Models, such as the SAC-Sacramento Soil Moisture Accounting Model and Mosaic (Xia et al., 2016), or Global Hydrological Models, such as the Soil Water Assessment Tool (SWAT; Norvanchig et al., 2021) and Variable Infiltration Capacity models (VIC; Kansoh et al., 2020; Shah et al., 2019), models have demonstrated remarkable (Kushwaha et al., 2021; Baroni et al., 2019). However, these estimating approaches are prone to biases and uncertainties as a result of inadequate parameterization or insufficient geographical and temporal scales, which can be overcome using a multi-model approach. For example, recent studies (Srivastava et al., 2020; Kushwaha et al., 2021; Kumar et al., 2017) have demonstrated that by combining numerous independent hydrological models, model errors can be minimized, and more trustworthy findings obtained.
Numerous research (Kansoh et al., 2020; Moknatian et al., 2021; Shah et al., 2019) emphasize the critical nature of evaluating water budget components and modeling water systems for water management and modeling. Land management is inextricably linked to water management in agriculture (Smail et al., 2021); thus, a thorough understanding of the water budget enables the adoption of water and soil conservation techniques and the planning of farmland irrigation systems (Tu et al., 2021). However, a recent study (Shah et al., 2019) demonstrated that irrigation practices might alter the water budget itself, depending on the geographical and meteorological conditions. They discovered that irrigation increases mean annual evapotranspiration (ET) and total runoff in river basins of the Indian subcontinent.

Runoff assessment and an understanding of the elements that influence changes are critical for water management, agricultural conservation, and urban planning. Indeed, runoff influences the transfer of sediments, nutrients, and agricultural chemicals, and in some locations contributes to flooding (Xu et al., 2009). Numerous research (Zhu et al., 2019; Xu et al., 2009; Zhang et al., 2018; Worku et al., 2017) have validated hydrological modeling as a method for estimating runoff. Worku et al. (2017), for example, employed the Soil Water Assessment Tool (SWAT) to simulate rainfall-runoff processes and sediment yields to better understand the impact of land use/land cover changes on runoff changes. Zeraebruk (2017) created an 80 percent reliable water budget model using SWAT to determine the safe yield of water reservoirs in Asmara, Eritrea. Other hydrological models (e.g., HEC-HMS: Hydrologic Engineering Center-Hydrologic Modeling System, HEQM: Hydrological, Ecological, and Water Quality Model, and PREVAH: Precipitation-Runoff-Evapotranspiration Hydrotepe Model) have demonstrated strong
performance in runoff simulations under a variety of land-use scenarios (Zhang et al., 2018; Tassew et al., 2019; Brunner et al., 2019).

Similarly, infiltration is a critical component of the water budget and a fundamental mechanism in the formation of surface runoff. It is the passage of water into the soil that initiates runoff. When sufficient precipitation saturates the soil, the excess water produces runoff; otherwise, the water infiltrates completely. As a result, it affects plant water availability and is influenced by soil structure (Rahmati et al., 2018). Numerous studies (Sihag et al., 2020; Sihag et al., 2019; Babaei et al., 2018) underline the importance of assessing infiltration by simulating infiltration processes using a variety of modeling methodologies. Infiltration models (Sihag et al., 2019; Sihag et al., 2017; Mishra et al., 2003; Shiraki et al., 2019) incorporate artificial intelligence techniques (SWM: support vector machines; GP: Gaussian process; ANN: artificial neural network). They also incorporate physical (Green et Ampt, Philip) and empirical models (Kostiakov, Horton). Water infiltration into the soil is influenced by several elements, including soil moisture prior to precipitation, the amount of precipitation, the soil density and texture, hydraulic conductivity, and vegetation (Angelaki et al. 2021).

To support water management, it is necessary to assess water yield and examine the water supply-demand balance. Recent years have seen the publication of several publications examining worldwide patterns in water supply and demand. The Organization for Economic Co-operation and Development (OECD) projects that global water demand would increase about 55 percent by 2050, owing to rapid increases in manufacturing, power, and home consumption (Piesse, 2020; Mountford, 2011). Wada et al. (2014) assessed worldwide water use from 1960 to 2010 and 2010 to 1999 using the blue water sustainability index (BIWSI). They discovered that water
usage grew by nearly 250 percent between 1960 and 2010, with irrigation being the primary consumer. They projected comparable patterns to the OECD for the period 2010-2099 and predicted a more than 100% growth in home and industrial water consumption in Africa, Asia (South, West, Central), Western USA, Mexico, and Central South America. Reyes et al. (2015) analyzed the water supply situation and demand for water for numerous purposes in Santa Cruz, Galapagos Islands, and discovered that enormous tourism has increased water use, resulting in water concerns. Rai et al. (2018) anticipated a 22 percent rise in water demand between 2021 and 2031 in Varanasi, India, and demonstrated how water consumption increases proportionately with population expansion. Chen et al. (2020) quantified the water balance in Shenzhen, China, and determined the factors driving the area's water consumption. They concluded that Shenzhen's water supply and demand are geographically unbalanced. Zeraebruk (2017) discovered a major mismatch between supply and demand in Asmara, Eritrea, under a scenario of rapid population expansion, forecasting enormous future issues. As a result, it is accurate to assert that an increasing gap exists between water supply capacity and evolution of water demand in different regions of the globe, regardless of their development level. A critical first step toward closing this gap is an assessment of the water supply. Water supply assessments are conducted using a variety of approaches. For example, Chen et al. (2020) quantified the supply capacity of Shenzhen's water resources using the Integrated Valuation of Ecosystem Services and Tradeoffs model (InVEST). Other studies (Faramarzi et al., 2020; Liu et al., 2016; Van Beek et al., 2011; Rouholahnejad et al., 2014; Zeraebruk, 2017) used a variety of hydrological models (SWAT: Soil Water Assessment Tool; PCRaster Global Water Balance; APEX:
Agricultural Policy/Environmental eXtender) to simulate water resource dynamics at multiple scales and resolution.

1.5.2 Water scarcity indicators

The disparity between availability and demand for water results in worldwide water shortage challenges (Beek et al. 2011). Water scarcity is defined as the inability of water supplies to meet demand (Naik, 2017; Damkjaer et al., 2017). Water resources include groundwater, freshwater, and soil moisture, whereas demand includes any activity that uses water and contributes to social, economic, and environmental development. To achieve Target 6.4 of the Sustainable Development Goals (SDGs), which aims to "substantially increase water efficiency across all sectors, ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity" by 2030, it is critical to understand the extent of water scarcity. Water shortage is quantified using indicators developed in the early 1990s. Falkenmark (Falkenmark et al., 1989) created the first metric, called the Water Scarcity Index (WSI). The WSI reflects "the status of water resource availability in terms of vulnerability, stress, and scarcity" (Hasan et al., 2019). Since then, over 150 water scarcity indicators have been developed, the most of which are based on the WSI premise: "water status is a function of the "available water" resource—by demand or consumption" (Hasan et al., 2019; Damkjaer et al., 2017). They range from simple indicators created prior to 2000 to advanced indicators created after 2000. (Liu et al., 2016). The traditional water scarcity indicators include the Water Scarcity Index (WSI), the Withdrawal-to-Availability Ratio (WTA), the Physical and Economic Water Scarcity Index, and the Water Poverty Index; each of these indicators has distinct advantages and disadvantages. While WSI and WTA are both
straightforward to use, they overlook temporal variability and concentrate exclusively on one component of water resources - freshwater - while ignoring groundwater and soil moisture. In terms of water demand, the WSI and WTA focus exclusively on withdrawals, ignoring underlying parameters such as the sources and causes influencing these withdrawals, raising numerous concerns regarding their dependability (Damkjaer et al., 2017; Liu et al., 2016). In the case of Physical and Economic Water Scarcity, it takes into account additional variables, making it more complex and harder to evaluate. The sophisticated water scarcity indicators, on the other hand, include Green-Blue Water Scarcity, Water Footprint-Based Water Scarcity Assessment, Cumulative Abstraction to Demand Ratio, and Life Cycle Assessment-Based Water Stress Indicators. These indicators emphasize the importance of communities being adaptable and flexible to address difficulties linked to water availability and environmentally responsible use. Additionally, indicator 6.4.2 monitors the amount of water stress in the context of SDG Target 6.4 and focuses exclusively on blue water scarcity, neglecting green, green-blue, and economic water scarcity (Vanham et al., 2018). These indicators contribute to our understanding of water sustainability; nonetheless, they quantify water scarcity numerically, with little emphasis on water quality, despite its crucial significance in the availability of water resources. As a result, Liu et al. (2016) proposed that water quality be considered in conjunction with Environmental Flow Requirements across both spatial and temporal scales when assessing water scarcity. Time scale is also crucial in assessing water shortage because it has a substantial effect on the outcomes. Mekonnen et al. (2016) conduct monthly assessments of global blue water shortage in order to account for seasonal variations in water supply and demand that were overlooked in prior research that conducted annual assessments. They
discovered that approximately two-thirds (4 billion) of the global population lives in severe water scarcity for at least a month using high spatial resolution data at the grid cell level of 30 30 arcmins, highlighting the benefit of evaluating water scarcity monthly, which is the involvement of local populations experience that cannot be captured on an annual basis.

1.5.3 Best Management Practices for Land Use Land Cover (LULC)

Change

Climate change is universally acknowledged as aggravating water scarcity problems. However, other causes, such as increased agricultural and urban land use, have disrupted hydrological processes and reduced water quality (Rodriguez-Romero et al., 2018). A firm grasp of the link between land use and water quality is thus critical for watershed management. For instance, Giovanetti et al. (2012) assessed the relationship between water quality and land use land cover (LULC) and found that in Beaver Lake watershed, Arkansas the more developed is the land into pasture or urban land, the more concentrated are nutrients in the watershed. Similarly, more studies (Tong et al., 2002; Bonansea et al., 2021; Nobre et al., 2020; Wei et al., 2020) demonstrated a positive correlation between water quality variables and types of land uses at various spatial scales. Indeed, unsustainable land-use practices cause soil erosion that fosters nonpoint source pollution in watersheds. The relationship between LULC and water quality is sensitive to the spatial scale and seasons (Ding et al., 2016; Xiao et al., 2016). In response to the negative impacts of unsustainable LULC on watersheds, conservation strategies are implemented (Arnillas et al., 2020; Teka et al., 2020).
Best Management Practices (BMPs) are conservation measures that aim to improve water quality in watersheds. They can be structural or non-structural (agricultural) depending on the nature of the problem in the watershed they are meant to address. Many studies (Lopez-Ballesteros et al., 2019; Briak et al., 2019; Liu et al., 2019; Merriman et al., 2019; Jeon et al., 2018; Qi et al., 2017; Uniyal et al., 2020) evaluated the effectiveness of BMPs to sustain agricultural and urban watersheds using SWAT. Model-tested BMPs give an idea of the most effective practice for reducing runoff, nutrients, and sediment loads in the given watershed or subwatershed. For instance, Lopez-Ballesteros et al. (2019) analyzed some agricultural and structural BMPs to reduce sediment and nutrient in Segura Riber Basin, Spain, and concluded that reforestation and check dam restoration were the most effective practices among buffer strips, fertilizer application, and contour planting options. Mtibaa et al. (2018) modeled BMPs under different scenarios in the Joumine watershed, Tunisia, and found that ponds were the most effective BMP to implement at the farm level while contour ridges were to be the most appropriate on gentle slopes. Literature suggests that implementing a combination of BMPs is more efficient and cost-effective at reducing sediment yields than implementing individual BMPs (Uniyal et al., 2020; Merriman et al., 2019; Mtibaa et al., 2018).

1.5.4 Water conservation approaches

In response to the traditional water management approach that focused on sectorial issues ignoring interconnections between sectors and isolating stakeholders (Biswas, 2004; Steiguer et al., 2003), new approaches to water conservation have emerged. They include systems thinking approaches that aim to increase the resilience of water systems to stress and crisis (Burgess et al., 2018). The vision of
these strategies refers to collaborative frameworks for stakeholder involvement, decentralized water systems, development of alternative water sources, and the integrated management of demand and supply among others (Hipel et al., 2008, Berger et al., 2020). Integrated Water Resources Management (IWRM) is a popular concept that has emerged as a mainstream strategy in solving water problems (Berger et al., 2020; Biswas, 2008). The Global Water Partnership (GWP, 2000) defined IWRM as “a process which promotes the coordinated development and management of water, land and related resources to maximize the resultant economic and social welfare, paving the way towards sustainable development, in an equitable manner without compromising the sustainability of vital ecosystems." The IWRM approach emphasizes key concepts like integration, stakeholders’ involvement, economic instruments, sustainability, monitoring process, and information management (Anderson et al., 2008). Despite its noble purpose, the actual implementation of the IWRM concept is challenging due to the lack of practical details in its well-formulated yet ambiguous original definition (Biswas, 2004). Many authors discussed actions to be incorporated within IWRM policies and principles to overcome this gap between IWRM theory and practice, leading to a divergence of action recommendations in the literature. For example, Shrubsole et al. (2017) collected shared experiences from Canadian water agencies representatives and analyzed the challenges faced by conservation authorities. They identified a successful example of implementation of IWRM that suggests focusing on local water issues, financing the monitoring of programs by developing partnerships and volunteering, determining actions, stakeholders, and funding sources clearly, and sharing the results of the implementation with the public. Other authors (Veale, 2010; Aher et al., 2014, Wang et al., 2016) suggest that the IWRM approach be
spatially narrowed to a single hydrological unit (watershed) to constitute the Integrated Watershed Management (IWM) approach because it presents the benefit of addressing Spatio-temporal variability and variables heterogeneity issues that are less likely to be encountered at a watershed scale.

Additional water management strategies involve digital technologies or “Smart water” resulting from the Internet of Things, Artificial intelligence, the Fourth Industrial revolution, and big data analytics (Sarni et Stinson, 2018; Hays, 2018; Kapelan et al., 2020).

1.5.5 Water governance

The World Economic Forum (WEF) Global Risk Reports have ranked water crises among the top 5 global economic risks in terms of impact since 2012. The latest report in 2020 ranked water problems as the 5th rank among various other risks and consider them the most critical because their impact on society is the greatest. In addition, WEF surveys show that water crises are interconnected with other global risks, the strongest and most direct are food crises and failure of climate action. Therefore, the impacts and consequences of water crises are linked to these interconnected economic sectors. Like Stuckenberg et al. (2018) who argue that water should not be seen as “a peripheral contributor to a region’s economic health, but rather a primary enabler”, water’s economic importance has been discussed in multiple studies. Damania (2020) summarizes recent work on the economic effects of water scarcity and found that there are very few reliable results on the correlation between precipitation and global development growth (GDP) at country levels or larger scales. However, precipitation effects on economic growth are more reliably measurable at subnational levels. By introducing the concept of Virtual Water and
with the use of Computable General Equilibrium (CGE) models, there is evidence that water scarcity impacts economic growth. Water-intensive goods become difficult to produce, causing trade losses. Another perspective of economic impacts of water scarcity given by Dolan et al. (2021) suggests that “water scarcity impacts arise when the difficulty of obtaining water forces a change in consumption.”

Water scarcity is critical for many sectors (energy, agriculture, manufacturing) and can be measured in various ways. Dolan et al. (2021) moved beyond conventional and supply-oriented measures of water scarcity that ignore economic factors to assess the cost of water scarcity and how it affects other sectors. They used the “economic surplus” metric for 235 watersheds in 3,000 global change scenarios and determined the level of physical water scarcity using the conventional withdrawal-to-availability (WTA) metric through a global change analysis model and a discovery approach to avoid any biased or anticipated results. They found that there was no direct correlation between the degree of physical water scarcity and its economic impact. Indeed, one could assume that the physically scarce water areas would imply a negative economic impact, but surprisingly this is not the case. Many basins classified as physically scarce for water have positive economic impacts and vice versa. By capitalizing on their water resources through the exportation of water-consuming goods, some countries have been able to bypass the negative economic trend that was predicted for them. For instance, Damkjaer et al. (2017) compared a country with high freshwater availability such as Congo to a country with low freshwater availability such as Morocco and found that access to drinking water is not correlated with water scarcity; Morocco has a remarkably high percentage of access to drinking water relatively to Congo. Similarly, Naik (2017) argued that water scarcity in Africa is much more economical and managerial than physical and
suggested that creating more water supply infrastructures might not be effective without a maintenance component in the construction contracts because many infrastructures become defective after a few years of utilization. Instead, behavioral changes and wise use of water resources along with good governance are necessary (Naik, 2017; Damkjaer et al., 2017). In the same vein, The UN second World Water Development Report (2006) recognized the key role of governance in developing better water conditions and stated that “the world water crisis is a crisis of governance - not one of scarcity”. The Global Water Partnership (GWP, 2002) defined water governance as “the range of political, social, economic and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society”. In other words, it is a set of institutions and processes essential for water-related decision-making. Jimenez et al. (2020) identified the core functions of water governance which consist of developing laws, policies, and strategies to enforce the water sector, creating mechanisms to facilitate cooperation among stakeholders, developing actionable and resilient plans, gathering financial resources to cover water services expenses, clearly identifying the role of each entity involved, tracking performance to guide decision-making, and developing capacities to sustain the achievements. To be effective, these actions of governance should be participative, transparent, inclusive, communicative, evident-based, accountable, coherent, efficient; equitable, and adaptive (Jimenez et al., 2020; Lautze et al. 2011; Roger and Hall, 2003). The inclusiveness attribute of water governance is linked to the key role of stakeholder engagement in water governance. Referring to a mixture of water users including government agencies, industries, residential water users, public interest groups, aboriginal communities, and commercial shipping and fishing users, Heathcote (1998) highlighted the
importance of stakeholders and stated that “community support is one of the most important elements in the successful implementation of management schemes, and lack of that support can be one of the most formidable obstacles.” Other authors (Megdal et al., 2017; Mott Lacroix et al., 2016) addressed the techniques and processes for a successful stakeholder engagement. Mott Lacroix et al. (2016) studied engagement efforts at national, watershed, and town scales in Arizona, USA. They developed the Stakeholder Engagement Wheel that consists of four major steps with multiple iterations in between as well as four challenges likely to be experienced during the stakeholder engagement process such as paucity of time; the complexity of water resources management; the difficulty of engaging diverse stakeholders; and the lack of advice for an engagement process centered on empowerment, equity, trust, and learning.

Many water issues are a result of governance failure, leading to the emergence of multiple policy reforms in many countries (Choi et al., 2017). Challenges in water governance in developing countries highlighted by the UNDP-SIWI Water Governance Facility (2016) are numerous. Very often governments have multiple agencies with overlapping responsibilities due to unclear identification of formal and informal tasks. Aboniyo et al. (2017) pointed out this issue among agencies and ministries in Rwanda as an undermining factor of the water sector. Added to this are corruption, bureaucracy, lack of investment, and insufficient human capacity.
CHAPTER 2

BASELINE WATER CONDITIONS AT MULTIPLE SCALES IN COTE D’IVOIRE

This section describes the study area and the current water management system in Cote d’Ivoire.

2.1 Study area

The Republic of Cote d'Ivoire (West Africa) covers an area of 322,463 km², including 318,003 km² of land and 4,460 km² of water. The Bandama watershed is named after the river which drains it and is the only watershed entirely national (African Development Bank, 2017). The watershed is located between 3°50' and 7°W and 5° and 10°20'N and covers a surface area of 96,840 km² with a perimeter of 2175 km.

The Bandama watershed (Figure 1) is of low to medium elevation ranging from 3 to 714 m. Its hydrographic network presents many meanders. It first flows from West to East getting around Korhogo city, then takes a North-South direction into the lagoon of Grand-Lahou. In the upstream part, the Bandama river also called "White Bandama" receives successively the Solomogou and the Bou (tributaries of the right bank), the Badenou, and the Lokpoho. The Marahoué, the main tributary of the right bank (550 km long; catchment area of 24,300 km²) is fed mainly by the Yani (200 km), and flows into the Bandama, just upstream of the current lake of the Kossou dam. The N'Zi, the most important tributary of the left bank (725 km; catchment area of 35,500 km²) takes its source at an altitude of 400 m East of Ferkéssédougou and merges with the Bandama a little upstream from Tiassalé.
The Bandama watershed hosts more than 185 dams including the Kossou dam and the Taabo dam which are the largest. They are in the mainstream and have hydroelectric stations (PFO, 2019; JICA, 2001). The Kossou hydropower dam was established in 1971 with a storage capacity of 30 billion cubic meters and an installed capacity of 174 Mega Watt (Kouamé et al. 2019). Beside the production of electricity, this dam is also used for fish farming. Located 120 km downstream of Kossou Lake, the Taabo Lake covers an area of 69 km² at nearly 124 m elevation, stocks a water volume of 630 million cubic meters in which 0.05% is located in Mali, and has a power generating capacity of 210 megawatts (Mortey et al., 2019). The Loka dam used for fish farming and water supply is the main water source for Bouake city and neighboring town. It has a storage capacity estimated to 22.3 million cubic meters. The other smaller dams are used for agriculture, fishery, livestock, and water supply.

Previous studies (Kouakou et al., 2014; Soro et al., 2017) on the geology of the Bandama watershed reported that the watershed is composed of Birimian formations including sedimentary and volcanic rocks and granitoid Eburnean composed of several generations of granites. The sedimentary formations include a variety of schists and mica schists associated with greywackes to form flysch. The volcanic rocks are represented by the foottrace of amphibolite, albite, chlorite, and epidote.

The soil type in the Bandama watershed is dominated by soils with a subsurface accumulation of low activity clays and low base saturation also known as Acrisols according to major soils groups established by the FAO (2001). This soil type correlates with highly desaturated ferritic soils in the French soil taxonomy as previous studies on the watershed (Soro et al., 2014; Kouame et al., 2011) have concluded. On the Bandama watershed, Acrisols are associated with plinthosols and lixisols and are characterized
by a brown, thin surface horizon, a massive macrostructure, and a low natural regeneration. Their lack of plants nutrients coupled with the high composition in aluminum and phosphorous sorption make acrisols favorable for acidity-tolerant crops (FAO, 2001).

![Map of Bandama watershed](image)

**Figure 1:** Location of the Bandama watershed

### 2.1.1 Precipitation

The average annual precipitation in the watershed is within a range of 1,100 mm to 1,800 mm depending on the climatic regime. The climatic regime of the watershed in 2010 extends over three different climates which follow the rainy season. Its northern part is characterized by a dry subtropical climate while the central and southern parts are characterized by an equatorial climate and a humid equatorial climate respectively (Soro et al., 2017). From 2010 to 2018, there is a decrease in
rainfall, especially in the central and northern parts of the watershed. Although the rainfall range remains the same, its distribution changed in 2018. The average annual precipitation between 1,200 mm and 1,350 mm has become predominant in 2018 resulting in less rainfall of more than 1,500 mm and the dry subtropical climate is dominant all over the watershed (Figure 2).

**2.1.2 Land use - land cover**

The Bandama watershed is shared between different land covers (Figure 3). Its southern part is dominated by a mosaic of native vegetation and cultivate land (crops, sugar cane, rubber tree, cocoa, etc.). Its northern and central parts present more evergreen and deciduous forests. The population living in the Bandama watershed is predominantly rural, and the main activity is
agriculture (Anoh et al., 2018). This practice in the watershed leads to significant deforestation responsible for soil erosion. The study by Kouame et al. (2019) on the analysis of the evolution of cropland between 1988 and 2016 in the Bandama watershed shows that agricultural land has increased over savannah, and forest (deciduous and evergreen) which have decreased over time. Besides agriculture, the watershed is occupied by urban areas, fish farming, pasture, mining, and textile industries.

![Figure 3: Land use land cover of the Bandama watershed](image)

**2.1.3 Dams in the watershed**
Water supply, hydropower generation, agriculture, and other activities in the Bandama watershed are supported by 184 dams which accounts for nearly 32% of the country’s available dams. They are distributed as follows. 176 hydro-agricultural dams existing in the upstream basin (PFO, 2019), 2 hydro-electric dams, and 6 dams for drinking water supply (Figure 4).

Figure 4: Dams in the Bandama watershed

2.2 Institutional framework

The water supply sector in Cote d'Ivoire was managed along with the road network by the Ministry of Economic Infrastructure until 2018 after the creation of the Ministry of Hydraulics which took over this mandate. The Ministry of Hydraulics has the responsibility of establishing the government's policies regarding water
supply and monitoring their implementation all over the country. It is assisted in its mission by the National Water Agency (Office Nationale de l'Eau Potable, ONEP), a public agency created in 2006 whose objective is to ensure access to drinking water for the entire population and the management of public and private assets in the territory. ONEP works hand to hand with the Water Distribution Company (Société de Distribution d'Eau de Côte d'Ivoire, SODECI) to ensure the water supply in urban and semi-urban areas. SODECI is a private company of public services that operated from 1960 to 1987 under a drinking water and sanitation concession contract and switched to a leasing (affermage) contract until today. SODECI is under the supervision of both the Ministry of Hydraulics and the Ministry of Sanitation and Health for drinking water supply and sanitation services respectively. According to the World Bank (2019), this is the longest-running public-private partnership (PPP) for urban water in West Africa. The drinking water supply in rural areas is managed by local communities after the construction of infrastructures.

Water resources used for drinking water supply, agriculture, electricity, industry, recreation, and other activities are managed by the Ministry of Waters and Forests. The Ministry of Waters and Forests is the nodal agency of the government for the implementation and monitoring of the Ivorian forests, wildlife, and water protection policies and programs. The Ministry includes several directorates including the General Directorate of Water Resources set up in January 2018. This Directorate is the main entity responsible for ensuring the implementation of the Government’s water policies and programs in terms of water resources protection. Specifically, it is responsible for the development and protection of hydraulics infrastructures, the inventory and mobilization of water resources, and the coordination of the hydrological, hydrogeological, and quality monitoring of water
resources among others. The General Directorate of Water Resources is also the one in charge of the implementation of the country’s National Action Plan for Integrated Water Resources Management plan (PLANGIRE).

With the aim to reform the water sector, the Government of Cote d’Ivoire created the High Commission for Hydraulics in 1996. Upon creation of this commission, the country has known some institutional and regulatory evolution with the creation of the Water Code in 1998, the IWRM Master Plan in 2001, and the PLANGIRE in 2012. However, creating laws and plans without enforcement institutions to implement them is not sufficient to get improvements. The government fails to acknowledge the critical need to manage water resources and to take further actions beyond the above code and plans. Even the PLANGIRE, established in 2012 has not been adopted by the government yet. No policy or financing for its implementation has been considered.

**National Action Plan for Integrated Water Resources Management (PLANGIRE)**

The PLANGIRE was developed in 2009 and validated by scientific stakeholders in June 2012 to map out the national water strategy regarding IWRM. It consists of 42 actions referring to the enabling environment, the institutional roles, and the management tools, all three pillars of the IWRM approach. The PLANGIRE (Kouame, 2019) implementation is estimated to 20 billion F CFA (approximatively 33 million USD) and is still in its early stages as of today (2022). It suggests the creation of several institutions which do not yet exist. These include the National Water Agency, the Basin Agencies, the Interministerial Water Committee, the National Water Committee, the Basin Committees, and National Water Resources Management Fund (Bloomfield Investment, 2019; MINEF, 2018).
management agencies which are supposed to be the entities that gather all the stakeholders of the water sector at the watershed level are still waiting to be created. This prevents the water management system to be integrative as required by the IWRM approach (MINEF, 2018).

The IWRM approach also emphasizes the crucial importance of public participation in the decision-making process and the clear identification of stakeholders ‘responsibilities. However, in Côte d'Ivoire, there is no mechanism for the systematic inclusion of the public in decision-making. Public participation is generally on a case-by-case basis and very often does not involve all stages of projects. It is even less so in rural areas where the social and economic conditions of the populations often constitute an obstacle (MINEF, 2018). Very often, the role of the institutions is not clearly identified, the responsibilities either overlap or are not assumed because whether they are not officially attributed to any institution, or some institutions fail to achieve their mission. That was the case during the severe drought that happened in Bouake city in 2018 where the Ministry of Waters and Forests, responsible for protecting water resources and ensuring that water is available for the needs did not notice the water level decrease in the Loka dam by lacking monitoring system and warning the dam’s users. This affected other institutions like the Ministry of Hydraulics now forced to pay more attention to the water resources it exploits for supplying drinking water while that was not initially part of its mission.

Despite the obstacles and delays to implementing the PLANGIRE, several programs and activities that align with the goal of the PLANGIRE have been implemented such as the Mano River Ecosystem Conservation and International Water Resources Management Project. This project executed by the International Union for Conservation of Nature (IUCN) aims to improve the management of
transboundary watersheds through an integrated and participatory approach (IUCN, 2016). Other projects are intentionally being implemented for IWRM. The “Support Project for Integrated Water Resources Management (IWRM) in Côte d’Ivoire, Bandama pilot watershed (upstream of Lake Kossou) - Phase 1” was initiated by the Directorate for the Protection and Development of Water Resources of the Ministry of Water and Forests (MINEF) in 2020. Expected to be completed by June 2022, the first phase of the project aims to the development of a participatory water management plan document elaborated at a subwatershed level based on ad hoc governance and ensure that relevant feedback and conclusions will be drawn from the project for a potential extension at the national level (International Office for Water, 2022).

2.3 Regulatory framework

The water sector in Cote d’Ivoire is governed by three documents which are the Environmental Code of Law No. 96-766 of 3 October 1996, the Water Code of Law 98-755 of 23 December 1998, and the National Water Policy. The National Water Policy document was established in 2010 by ONEP to define the strategies and guidelines to improve the national water sector. However, the plan has not yet been validated or adopted by the government.

The Water Code is the legal regime governing water, development, and hydraulic works. Supported by several application decrees, it deals with the protection of water, hydraulic facilities, and structures and describes various types of offenses and sanctions related to water resources. The Water Code has not been updated since its creation in 1998 and is the subject of criticism about its relevance in the current context of growing water scarcity and the urgent need for effective water
management. The report on Sectoral Risks (2019) prepared for the Ministry of Water and Forests denounces the focus of the Water Code on the use of water more than on its management. The Code establishes the creation of a water resources management fund but fails to detail the operating rules of this fund as well as the definition of taxes to finance the proposed activities (Bloomfield Investment, 2019). The Code is based on implementing decrees, some of which have been issued and several are still awaiting adoption.

2.4 Major problems facing communities

In the early 2000s, 81% of the Ivorian population had access to safe drinking water. However, the political crisis has strongly affected access to water services and the portion of the population supplied dropped by 15 % between 2000 and 2011. This was due to the lack of regular maintenance and repair of water infrastructures, especially in rural areas in the North of the country (USAID, 2013; World Bank, 2019). Moreover, population growth and urban sprawl have put additional pressure on the water and sanitation infrastructures. The Joint Monitoring Programme (JMP) noted improvements in the access to water estimated at 80% nationwide in 2015 due to the large investment programs in Abidjan; however, there are disparities between the capital Abidjan (90%) and other urban centers (45 %) (World Bank, 2019).

A survey conducted by Kone et al. (2018) reported that water issues represent the 3rd major problems for populations after unemployment and poverty. They showed that 68% of the respondents acknowledged that they experienced water shortages in 2017 of which 52% live in rural areas against 30% in urban areas. This aligns with the report from SODECI, according to which 468 water shortage episodes were recorded in 2017 (Claon et al., 2020).
In terms of water quality, there is no systematic monitoring in Cote d'Ivoire, but a continued degradation of the water quality is observed, caused by point and nonpoint sources pollution. Indeed, the increase of the population in urban centers has led to more pressure on sanitation facilities with sewage being discharged into waterways without treatment. Economic development efforts have increased the number of industrial effluents, and the use of chemical fertilizers is increasing chemical runoff. Illegal mining also constitutes a major source of pollution of freshwater and groundwater in Cote d’Ivoire, especially with the use of prohibited chemicals such as mercury and cyanide. As of 2019, more than 241 illegal mining sites were active across the country (Kouao, 2019). Most of the surface water resources, particularly in peri-urban areas like most of the areas in the Bandama watershed, are under these pollution sources, which causes them to experience episodes of eutrophication, due to nutrient inputs from domestic waste and agriculture. These issues are exacerbated by the political crisis during which wastewater treatment facilities lacked maintenance and upgrading investment (USAID, 2016; World Bank, 2019).

Moreover, dams located in the Bandama watershed are affected by sediments siltation which reduces their available storage volume, and rainfall decrease caused by climate change, preventing them to be filled as expected (Maillard, 2019).

On the economic side, the country is burdened by debts with external funds. This weakens the investments made in the water sector which affects the functioning budget of institutions that become unable to fully achieve their missions (MINEF, 2018). Moreover, the water pricing system has been the same for a long time. According to the World Bank Report (2019) for Additional Financing for the Urban Water Supply and Sanitation Project in Cote d’Ivoire, there has not been a customer tariff adjustment since 2004 nor an explicit improvement strategy of the water
distribution performance in the affermage contract with SODECI. Also, there is a gap between the cost of water production and the recovery of these costs which constitutes a barrier to the autonomy of the water sector.

2.5 Demography

Following the administrative division of Côte d’Ivoire, the Bandama watershed covers 11 regions subdivided into 51 sub-prefectures including Bouake, Korhogo, and Yamoussoukro which represent the major cities (Figure 5). The General Population and Housing Census conducted in 2014 estimated its population (major cities and surrounding localities) to be around 9.2 million people with an average annual growth rate of 2.6% (National Statistics Institute, 2015). Assuming a constant average annual growth rate of 2.6%, the Bandama watershed population is projected to increase to 12 million people by 2025.

As for Bouake city, the United Nations 2019 Revision of World Population Prospects estimates its population to increase about 640,000 people with an average annual growth rate of 1.83%.

Table 1 Bouake city and Bandama watershed population projection (source: National Statistics Institute, 2015; United Nations, 2019)

<table>
<thead>
<tr>
<th>Population / Year</th>
<th>2014</th>
<th>2025</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bouake city</td>
<td>537,392</td>
<td>635,556</td>
<td>873,326</td>
</tr>
<tr>
<td>Bandama watershed</td>
<td>9,158,972</td>
<td>12,146,963</td>
<td>15,701,506</td>
</tr>
</tbody>
</table>
2.6 Water demand

Water demand in Cote d’Ivoire is dominated by agricultural, industrial, and community (households, schools, markets, etc.) uses. According to the Ministry of Waters and Forests of Cote d’Ivoire (2019), agriculture ranks first and accounts for 65% of the water resources, then come industrial (23%) and communities (12%) uses. In Bouake, major city in the Bandama watershed, water demand is estimated at 60,000 m$^3$/day (Novo, 2020).
CHAPTER 3
TRENDS IN WATER DEMAND AND SUPPLY IN THE BANDAMA WATERSHED

Addressing water issues implies a good understanding of the needs and the available resources. The Bandama watershed constitutes one of the most important watersheds in Cote d’Ivoire because of its density of activities and population. This chapter presents the steps to simulate the hydrological processes of the watershed that impact water resources availability in the watershed.

3.1 Conceptual model

The conceptual model for this study (Figure 6Error! Reference source not found.) consists of three parts that present the parameters considered to develop a dynamic watershed management system and the interactions between them. The first section is the watershed system which combines biotic, abiotic, and socioeconomic factors that influence each other. Abiotic factors group together non-living elements and conditions that are part of the ecosystem such as landform, geology, water, topography, soil, etc. On the other hand, biotic factors are living organisms in ecosystems, including Fauna and flora. The third component of the watershed is the socio-economic factor which can exceed the physical limits; it considers the demography and lifestyle of the population of the study area, their culture, and the type of investment and infrastructure made in the watershed. The second section of this model represents the climatic conditions of the study area. Elements like humidity, temperature, wind, and precipitation are essential to the functioning of a watershed system. They play an important role in the balance of the water budget. The state of the watershed system is a guiding factor in decision-making regarding
water supply and demand management, policy development, and water pricing, and is the subject of the third part which is the institutional system.

3.2 Empirical model

The empirical model (Figure 7) shows the data flow in the system. The water supply block represents the hydrologic components of the water balance used in this study. To understand the behavior of the watershed system, the hydrological parameters are estimated through modeling. SWAT (Arnold et al., 2012) is a dynamic semi-distributed hydrological model capable of simulating continuous data.
over long periods. SWAT is appropriate for this study as it has the major advantage of being applicable to ungauged basins (Gosain et al., 2004).

The water demand block shows the parameters that influence water consumption in the watershed. This information is needed to support decision-making and establish policies that can ensure an equilibrium between supply and demand and prevent water scarcity in the study area.

![Watershed System Diagram](image)

**Figure 7: Empirical model**

### 3.3 Empirical methods

The Soil Water Assessment Tool integrated to ArcGIS (ArcSWAT 2012) is used to simulate the behavior of the study area. SWAT (Arnold et al., 2012) is a comprehensive watershed-scale and continuous model developed by the USDA
Agricultural Research Service (ARS) to assess and predict the effect of land management on the behavior of a watershed. The model requires information such as soil types, weather conditions, topography, and land use and cover. It divides the watershed into subbasins and each subbasin is grouped by unique land cover, soil, slope, and management characteristics called hydrological response units (HRUs). SWAT simulates processes such as surface runoff, infiltration, evapotranspiration, canopy storage, lateral flow, impoundments, management scenarios, crop growth, and tributary channels for each HRU (Arnold et al., 2012). The water, nutrients, and sediments fluxes simulated for each HRU are collected and routed through streams and reservoirs to the watershed outlet (Randhir and Tsvetkova, 2009). As the water balance is crucial in the functioning of a watershed, it is the basic concept on which SWAT processes are based and is represented by the following Equation 1:

\[
SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})
\]

where \( SW_t \) and \( SW_0 \) are respectively the final and initial quantity of water contained in the soil (soil water content in mm), \( R_{day} \) is the amount of precipitation (mm), \( t \) is the time (days), \( Q_{surf} \) is the amount of surface runoff (mm), \( E_a \) is evapotranspiration (mm), \( W_{seep} \) is the amount of water that percolates from the soil profile (mm), and \( Q_{gw} \) is the baseflow (mm). SWAT model offers three methods to calculate evapotranspiration: Hargreaves (1985), Priestley-Taylor (1972), and Penman-Monteith (1965). Among these, the Penman-Monteith approach is used for this study as it has demonstrated accuracy and effectiveness in the estimation of potential evapotranspiration under different conditions (Zhao et al., 2021; Sane et al., 2020;
Surface runoff is predicted using the Soil Conservation Service (SCS) Curve Number (CN) represented by Equation 2 shown below:

\[
Q_{surf} = \frac{(R-0.2S)^2}{(R+0.8S)}
\]  

(2)

where R (mm) is rainfall and S is the retention parameter dependent on soil types and land use, management and slope, and variability of the soil water content.

3.4 Input data

Data used for developing the SWAT model include topography, land use and cover, soil type, weather, and flow discharge. They are a set of satellite raster, shapefiles, and on-the-ground measurements collected from multiple sources (Table 2). On-the-ground measurements are streamflow data from five gauging stations within the watershed from 1979 to 2020 with significant gaps in between.

Table 2: Input data for SWAT

<table>
<thead>
<tr>
<th>Data type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Elevation Model (DEM)</td>
<td>30 arc-second DEM of Africa from U.S. Geological Survey's EROS</td>
</tr>
<tr>
<td>Soil type</td>
<td>Digital World Soil database from FAO</td>
</tr>
<tr>
<td>Land use and land cover</td>
<td>300 m Fine Resolution Global Land Cover database (GlobCover) from ESA</td>
</tr>
<tr>
<td>Rainfall, temperature, relative humidity, solar</td>
<td>38 km (T382) Climate Forecast System Reanalysis (CFSR)</td>
</tr>
<tr>
<td>Daily discharge</td>
<td>5 monitoring stations: N’Zianoa, Kimoukro, Bouafle, Bada, N’Zuenoula from the Hydrology Directorate</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>radiation, wind speed at daily scale</td>
<td></td>
</tr>
</tbody>
</table>
Figure 8: Input data (a) DEM, (b) LULC SWAT code, (c) soil types, (d) slope
3.5 Modeling process

3.5.1 Base model setup

The hydrological model of the Bandama watershed was set up using the ArcSWAT 2012 interface. The watershed delineation was the first step. Based on DEM, a threshold area of 2000 ha was defined for the formation of the stream network. Subbasin outlets were selected, and the watershed was delineated and
subdivided automatically by SWAT into 25 subbasins (Error! Reference source not found.).

Land use types were added and reclassified following the SWAT nomenclature into eight types: agricultural land (AGRL), bare areas (BARR), deciduous forest (FRSD), evergreen forest (FRSE), pasture (PAST), range brush (RNGB), urban (URBN), and water (WATR) among which deciduous forests are the dominant land use (Table 3). Five slope classes were defined based on the watershed topography (Figure 8 Error! Reference source not found.d) and 35 soil types were obtained following the FAO nomenclature (Figure 8 Error! Reference source not found.c). Each soil type is identified by its texture, water content, nutrient content, etc. Regarding the texture, the soils are distributed between sand, loam, and clay (APPENDIX). The 25 subbasins were further subdivided into 242 HRUs after applying threshold values of 20% for land use, 10% for soil, and 5% for slope.

Table 3 Land use distribution

<table>
<thead>
<tr>
<th>Land Use</th>
<th>% of Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural land (AGRL)</td>
<td>21</td>
</tr>
<tr>
<td>Deciduous forest (FRSD)</td>
<td>47</td>
</tr>
<tr>
<td>Evergreen forest (FRSE)</td>
<td>5</td>
</tr>
<tr>
<td>Pasture (PAST)</td>
<td>1</td>
</tr>
<tr>
<td>Range brush land (RNGB)</td>
<td>27</td>
</tr>
</tbody>
</table>
The watershed contains many reservoirs; however, due to a lack of information, not all of them were included in the model. Only the two major dams, Kossou and Taabo, were included in the expansion. The Kossou dam, which was built for hydroelectric reasons in 1972 and is located upstream in subbasin 15, is the largest and most complex. Also constructed for hydroelectric reasons in 1979, the Taabo Dam is located downstream on subbasin 23 and is the dam that is the closest to the watershed outlet. It receives water that has been released from the Kossou reservoir. During the first day of simulation in 1979, the Kossou dam's beginning volume was assessed to be 50 percent of its typical volume, while the Taabo dam's initial volume was estimated to be completely empty. Table 4 shows the characteristics of the reservoirs in more detail.

Once the input data had been entered, the model was programmed to run from 1979 to 2014 on a daily time-step, with a 3-year warm-up phase (1979-1981) in between.

### Table 4 Characteristics of Kossou and Taabo dams (source: Groga, 2012; JICA, 2001)

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>RES_ESA/Max reservoir storage area (ha)</th>
<th>RES_EVOL/Ma x storage volume ($10^4$ m$^3$)</th>
<th>RES_PSA/Normal storage area (ha)</th>
<th>RES_PVOL/Norm al volume of the reservoir ($10^4$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kossou</td>
<td>1972</td>
<td>178,000</td>
<td>3,021,100</td>
<td>130,200</td>
<td>2,696,200</td>
</tr>
<tr>
<td>Taabo</td>
<td>1979</td>
<td>6,900</td>
<td>63,000</td>
<td>6,845</td>
<td>62,500</td>
</tr>
</tbody>
</table>

#### 3.5.2 Calibration and validation

Calibration and validation of the model were done with different software. The Sequential Uncertainty Fitting (SUFI-2) algorithm integrated into SWAT-CUP 2012 was used in this study. The SUFI-2 model uses a stochastic approach and accounts
for uncertainties related to model conception, variables (e.g., climate), observed data, and parameters. These uncertainties are calculated at the 2.5% and 97.5% levels of the cumulative distribution of output variables obtained via Latin hypercube sampling and expressed by the 95% prediction uncertainty (95PPU) (Abbaspour, 2015).

**Parametrization and sensitivity analysis**

The model's parametrization is the initial stage in the calibration procedure. The basic parameters were chosen based on the literature (Anoh et al., 2017; Abbaspour et al., 2015; Arnold et al., 2012; Norvanchig and Randhir, 2019, Anoh et al., 2021). To begin, thirteen parameters were picked, and each was calculated using either relative (r) or absolute change (v). Then, these parameters are subjected to a sensitivity analysis. The sensitivity analysis involves altering the model's parameters, either one at a time or in groups, to find which parameter has the greatest impact on the model's output, corresponding to the dominant process in the watershed. To account for potential parameter interdependence in the SUFI2, both one-at-a-time and global sensitivity analysis methods were applied. The t-statistic and p-value of a parameter can be used to determine its sensitivity. A small p-value and a large absolute value of the t-statistic indicate that the model is very sensitive to that parameter. The calibration (Table 5) includes parameters for runoff (CN2, CH K2, CH N2), soil (SOL K, SOL AWC), groundwater (GW DELAY, REVAPMN, RCHRG DP, GWQMNN, ALPHA BF, GW REVAP), and HRU (ESCO, CANMX).

Table 5 Hydrological parameters considered for sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
</table>

41
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN2.mgt</td>
<td>SCS Runoff curve number</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>SOL_AWC().sol</td>
<td>Available water capacity of the soil layer</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SOL_K().sol</td>
<td>Saturated hydraulic conductivity</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>ALPHA_BF.gw</td>
<td>Baseflow alpha factor (day)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>REVAPMN.gw</td>
<td>Threshold depth of water in the shallow aquifer required for “revap” to occur (mm)</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>GWQMN.gw</td>
<td>Threshold depth of water in the shallow aquifer required for return to occur (mm)</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>GW_DELAY.gw</td>
<td>Groundwater delay (day)</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>GW_REVAP.gw</td>
<td>Groundwater “Revap” coefficient</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td>RCHRG_DP.gw</td>
<td>Deep aquifer percolation fraction</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>CANMX.hru</td>
<td>Canopy storage</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>ESCO.hru</td>
<td>Soil evaporation compensator factor</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>CH_N2.rte</td>
<td>Manning's “n” value for the main channel</td>
<td>-0.01</td>
<td>0.3</td>
</tr>
<tr>
<td>CH_K2.rte</td>
<td>Effective hydraulic conductivity in main channel</td>
<td>-0.01</td>
<td>500</td>
</tr>
</tbody>
</table>

**Calibration**

Calibration of the model parameters properly entails determining the parameter values that minimize the modeling error. This phase is important because
the simplification of reality implies that some, if not all, of the model's parameters cannot be directly tied to field data. Thus, using mathematical criteria referred to as the objective function, the model's projected parameters are compared to the observed data under the same conditions. Calibrations were conducted daily and subsequently monthly from 2002 to 2011 at the N'Zianoa gauging station, which is positioned downstream and closest to the watershed outlet.

**Objective function**

Numerous metrics for evaluating a model's performance are available in the literature. SUFI-2 provides eleven distinct objective functions, among which Nash-Sutcliffe (NSE) and R2 are chosen for this investigation. These two performance indicators are frequently used to evaluate the SWAT modeling efficiency (Norvanchig and Randhir, 2019; Briak et al., 2019). They are represented by the following equations 3 & 4:

\[
\text{NSE} = 1 - \frac{\sum_i (Q_{m,i} - Q_{s,i})^2}{\sum_i (Q_{m,i} - \overline{Q_m})^2} \tag{3}
\]

where \(Q_m\) is the measured variable (the discharge in this study), \(Q_s\) the simulated variable, and \(\overline{Q_m}\) is the average. NSE measures how perfectly or not the simulated values match the observed data by comparing the residual variance to the variance of the measured variable. In SUFI-2, NSE ranges from \(-\infty\) to 1, 1 being its ideal value.

\[
R^2 = \frac{\left[\sum_i (Q_{m,i} - \overline{Q_m})(Q_{s,i} - \overline{Q_s})\right]^2}{\sum_i (Q_{m,i} - \overline{Q_m})^2 \sum_i (Q_{s,i} - \overline{Q_s})^2} \tag{4}
\]
where $Q_m$ and $Q_s$ are the measured and simulated variables respectively. $R^2$ measures the relationship between residual and measured variances. Higher values of $R^2$ indicate accurate model simulation. In addition to NSE and $R^2$, the prediction uncertainties were quantified by monitoring the P-factor and R-factor. Abbaspour (2015) suggests a value of the P-factor $>0.7$ and the R-factor closer to 1 for a more realistic prediction of discharge.

Validation

Validation is the process of evaluating the model's performance. It entails simulating the model on an uncalibrated dataset. In this study, internal validation is performed on discharge data from other stations within the watershed from 2002 to 2011.

3.6 Results and Discussion

SWAT Water balance check

Daily and monthly hydrologic simulations of the Bandama watershed using the SWAT model were conducted for each of the 25 subbasins for 36 years (1979–2014). The results were displayed using ArcSWAT 2012's SWAT Error Checker version 1.2.0.10. Automatic analysis of the model output did not reveal any model problems. It did, however, raise certain concerns about watershed hydrology (excessive water yield), land use summary, sediment yield, and plant growth (unusually low phosphorus stress days). These alerts aided in guiding the model's parametrization and identifying processes that could affect the calibration. According to the water balance ratios, baseflow accounts for 60% of total water flow in the watershed, compared to 40% for surface runoff. Numerous research (Hector et al., 2015; Belemtougri et al., 2021; Miguez-Macho et al., 2013) have discovered that
baseflow contributes significantly to total flow in similar climatic settings (tropical humid climates). This percentage of groundwater that flows to streams (baseflow) is consequently critical for the ecosystem's survival and the demands of the Bandama watershed's inhabitants. SWAT determined that 42 percent of rainfall returns to the atmosphere via evapotranspiration, which is significantly less than anticipated. It was anticipated to fall within the 70-80% range attributed to Cote d'Ivoire (JICA, 2001; Kouakou, 2018).

Sensitivity analysis

The sensitivity analysis of the parameters in SUFI2 revealed that CANMX, ALPHA BF, RCHRG DP, SOL AWC, GW DELAY, REVAPMN, and CN2 had the greatest impact on watershed processes (Table 6). Several of these indicators were also identified as sensitive in research conducted by Anoh et al. (2018; 2021) on a part of the Bandama watershed.

Table 6 Sensitivity analysis of parameters after calibration

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Rank</th>
<th>t-Stat</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V__ALPHA_BF.gw</td>
<td>1</td>
<td>-172.60</td>
<td>0.00</td>
</tr>
<tr>
<td>V__CANMX.hru</td>
<td>2</td>
<td>52.32</td>
<td>0.00</td>
</tr>
<tr>
<td>R__SOL_AWC(..).sol</td>
<td>3</td>
<td>19.02</td>
<td>0.00</td>
</tr>
<tr>
<td>V__RCHRG_DP.gw</td>
<td>4</td>
<td>8.48</td>
<td>0.00</td>
</tr>
<tr>
<td>V__CH_N2.rte</td>
<td>5</td>
<td>6.24</td>
<td>0.00</td>
</tr>
<tr>
<td>R__CN2.mgt</td>
<td>6</td>
<td>5.60</td>
<td>0.00</td>
</tr>
<tr>
<td>V__GW_DELAY.gw</td>
<td>7</td>
<td>-3.40</td>
<td>0.00</td>
</tr>
<tr>
<td>R__SOL_K(..).sol</td>
<td>8</td>
<td>-2.32</td>
<td>0.02</td>
</tr>
<tr>
<td>V__GW_REVAP.gw</td>
<td>9</td>
<td>1.85</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Model Calibration and Validation

The SWAT model of the Bandama watershed was calibrated using daily and monthly time increments. The first daily time step calibration trial was conducted during a ten-year period from 2002 to 2011, excluding the three-year warm-up period at N'Zianoa station. The model fails to reproduce the discharge records after two iterations of 500 simulations each. The model performed poorly ($R^2 < 0.1$). Nonetheless, the sensitivity analysis revealed that the most sensitive parameters were ALPHA BF, RCHRG DP, CH N2, and CN2. Between 2007 and 2011, a second calibration trial at daily time steps was done at the same site. Although the model's performance was enhanced ($R^2 = 0.35$), it remained unsatisfactory. This suboptimal outcome could be owing to data gaps and increasing measurement error at daily steps, which is a common occurrence in streamflow simulation (Norvanching and Randhir, 2021; Bo et al., 2020). According to some studies (Pandey et al., 2021, de Mello et al., 2017, Bo et al., 2020), calibrating discharge data at the monthly time step offers the advantage of decreasing errors due to temporal fluctuation, smoothing the data, and resulting in more accurate simulations. The model was calibrated ($R^2 = 0.57$) after four iterations of 500 simulations each using observed discharge data at the N'Zianoa station (subbasin 24) from 2002 to 2011 (10 years); nonetheless, the NSE and PBIAIS values are unsatisfactory (Table 8). The model was next validated.
using discharge data from three more stations during the same period: Zuenoula (subbasin #16), Bouafle (subbasin #16), and Kimoukro (subbasin #21). This method of internal validation has been utilized in numerous studies to establish model confidence (Mello et al., 2017). Let us note that the water discharge record from Bouafle station has a gap of 3 years (2008, 2009, and 2010) which impacts the model validation performance. The fitted values of the parameters are shown in (Table 7).

Table 7 Fitted values of parameters after monthly calibration at N'Zianoa station

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>r__CN2.mgt</td>
<td>-0.52</td>
</tr>
<tr>
<td>r__SOL__AWC().sol</td>
<td>0.98</td>
</tr>
<tr>
<td>v__ESCO.hru</td>
<td>1.0</td>
</tr>
<tr>
<td>r__REVAPMN.gw</td>
<td>754</td>
</tr>
<tr>
<td>v__RCHRG_DP.gw</td>
<td>0.05</td>
</tr>
<tr>
<td>v__GW_DELAY.gw</td>
<td>358</td>
</tr>
<tr>
<td>v__GW_REVAP.gw</td>
<td>0.03</td>
</tr>
<tr>
<td>v__CH_N2.rte</td>
<td>0.18</td>
</tr>
<tr>
<td>v__CH_K2.rte</td>
<td>432</td>
</tr>
<tr>
<td>r__SOL__K().sol</td>
<td>600</td>
</tr>
<tr>
<td>v__CANMX.hru</td>
<td>98</td>
</tr>
<tr>
<td>River station</td>
<td>R²</td>
</tr>
<tr>
<td>---------------</td>
<td>------</td>
</tr>
<tr>
<td>N’zianoa</td>
<td>0.57</td>
</tr>
<tr>
<td>Kimoukro</td>
<td>0.44</td>
</tr>
<tr>
<td>Bouafle</td>
<td>0.56</td>
</tr>
<tr>
<td>Zuenoula</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 8 Calibration (2002-2011) and validation (2002-2011) performances results of four gauging stations for discharge

The data visualization for calibration at N’Zianoa (Figure 10) and validation at Kimoukro (Figure 11), Zuenoula (Figure 12) and Bouafle (Figure 13) are presented below.
Figure 10: Comparison of observed and simulated data after calibration at N’Zianoa station

Figure 11: Comparison of observed and simulated data for validation at Kimoukro station
Rainfall has a considerable influence on water discharge in the Bandama watershed. At all sites, it is feasible to notice that the wet season (June–October) has the highest peak flows, while the dry season has the lowest (November-May). Moreover, the model has a tendency to overestimate some peaks in streamflow. As a result, we needed to enhance evapotranspiration while decreasing baseflow to match the observed high peaks. The discrepancy between observed and simulated data at the stations was observed, and adjustments were made to improve model accuracy.
N'Zianoa station is due to its geographic position. This station's measuring location is located beneath a large hydroelectric dam on a major river with a complex stream network due to its numerous tributaries. As with N'Zianoa, the Kimoukro station's measuring position lies below the Kossou dam, which has a considerable influence on the recorded discharges. This explains why NSE values were inadequate for all stations except the Zuenoula site (Figure 9), which is positioned above the reservoirs and is not impacted by their releases. This demonstrated that the reservoirs impact significantly the model calibration and that the lack of release data from these reservoirs resulted in an oversimplification of the model, which is frequently the source of modeling mistake (Abbaspour, 2015).

**Water balance components**

Water yield is the parameter often used to quantify water resources (Abbaspour et al., 2015). Thus, it is crucial to evaluate its evolution in the watershed. SWAT model estimated the water yield on monthly and annual basis and other important water balance components such precipitation, evapotranspiration (ET), lateral and baseflow. The average annual values of the water balance components of the watershed on yearly basis (Table 9) and with monthly breakups (Table 10) for the baseline period are shown below.

Table 9 Average annual water balance components on monthly breakup

<table>
<thead>
<tr>
<th>Month</th>
<th>Rain (mm)</th>
<th>Surf Q (mm)</th>
<th>Lat Q (mm)</th>
<th>GWQ (mm)</th>
<th>Percolate (mm)</th>
<th>SW (mm)</th>
<th>ET (mm)</th>
<th>Water Yield (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>6.8</td>
<td>0.000</td>
<td>0.3</td>
<td>1.0</td>
<td>0.2</td>
<td>152.9</td>
<td>15.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Year</td>
<td>Rain (mm)</td>
<td>Surf Q (mm)</td>
<td>Lat Q (mm)</td>
<td>GWQ (mm)</td>
<td>Percolate (mm)</td>
<td>SW (mm)</td>
<td>ET (mm)</td>
<td>PET (mm)</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
<td>-------------</td>
<td>------------</td>
<td>----------</td>
<td>----------------</td>
<td>---------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>2002</td>
<td>890.78</td>
<td>0.3</td>
<td>65.99</td>
<td>0</td>
<td>62.1</td>
<td>146.29</td>
<td>717.31</td>
<td>2193.78</td>
</tr>
<tr>
<td>2003</td>
<td>1169.07</td>
<td>7.03</td>
<td>123.4</td>
<td>0.86</td>
<td>199.68</td>
<td>183.82</td>
<td>801.43</td>
<td>2087.91</td>
</tr>
<tr>
<td>Year</td>
<td>Precip (mm)</td>
<td>Surf Q (mm)</td>
<td>Lat Q (mm)</td>
<td>GW Q (mm)</td>
<td>Percolate (mm)</td>
<td>SW (mm)</td>
<td>ET (mm)</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>-------------</td>
<td>------------</td>
<td>-----------</td>
<td>----------------</td>
<td>---------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>1105.3</td>
<td>2.05</td>
<td>103.94</td>
<td>9.45</td>
<td>142.4</td>
<td>178.5</td>
<td>862.22</td>
<td>2129.37</td>
</tr>
<tr>
<td>2005</td>
<td>763.77</td>
<td>0.27</td>
<td>42.1</td>
<td>14.1</td>
<td>31.71</td>
<td>131.09</td>
<td>737.11</td>
<td>2085.59</td>
</tr>
<tr>
<td>2006</td>
<td>884.44</td>
<td>0.21</td>
<td>67.21</td>
<td>12.68</td>
<td>72.83</td>
<td>152.01</td>
<td>723.28</td>
<td>2133.72</td>
</tr>
<tr>
<td>2007</td>
<td>1068.22</td>
<td>5.3</td>
<td>121.04</td>
<td>14.32</td>
<td>192.27</td>
<td>178.55</td>
<td>723.08</td>
<td>2149.58</td>
</tr>
<tr>
<td>2008</td>
<td>1072.61</td>
<td>3.11</td>
<td>125.76</td>
<td>17.14</td>
<td>188.67</td>
<td>179.83</td>
<td>753.79</td>
<td>2109.46</td>
</tr>
<tr>
<td>2009</td>
<td>1141.96</td>
<td>3.68</td>
<td>115.62</td>
<td>16.83</td>
<td>173.93</td>
<td>185.27</td>
<td>843.28</td>
<td>2009.89</td>
</tr>
<tr>
<td>2010</td>
<td>1306.93</td>
<td>2.71</td>
<td>140.03</td>
<td>20.68</td>
<td>233.98</td>
<td>188.3</td>
<td>927.18</td>
<td>1971.69</td>
</tr>
<tr>
<td>2011</td>
<td>1308.09</td>
<td>8.38</td>
<td>172.51</td>
<td>28.03</td>
<td>310.97</td>
<td>181.85</td>
<td>822.68</td>
<td>1883.23</td>
</tr>
</tbody>
</table>

Figure 14: Temporal distribution of water balance components (2002-2011)
Figure 15: Spatial distribution of water balance components

Figure 16: Spatial distribution of land use land cover

ET (Table 10) is the primary source of water loss in the watershed, accounting for roughly 75% of total rainfall. This high rate of ET could be attributed to the research area’s high temperatures and a land cover dominated by deciduous trees, range brush land, and agriculture (Table 3). The spatial distribution of LULC (Figure 16) demonstrates that water yield is rather constant throughout all subbasins.
regardless of land cover, whether forest, rangeland, or agricultural land, with the exception of subbasins #15 and #25. The large water yields found in these two subbasins can be attributed to their agriculturally dominated land use and mixed slopes with certain sections of high slope classes (5-10%). The nearly consistent water yield in all other subbasins, particularly forested subbasins, may indicate that forests maintain baseflow, which contributes to water yield.

Roughly 74% of the rain recorded in the watershed occurred between June and October (Table 9); the same tendency holds true for streamflow, which reported greater values during these months (Figure 12). According to Soro et al. (2017), rainfall in these months may increase from 5% to 10% in the near future of 2025 and further to 15% in the Bandama watershed by 2050.

**Identification of critical areas of the watershed**

It is critical to identify sections of the watershed that are most impacted by land use and slope before implementing management strategies. This knowledge is critical since implementing management scenarios across the entire watershed can be complex and difficult. The SWAT model estimated soil erosion caused by sediment inputs, which was beneficial for identifying key subbasins. Soil erosion is generally minimal (< 1 T/ha/year) in the Bandama watershed, reaching a high of 0.64 T/ha/year in sub-basin #25. (Figure 17). No comparison to the simulation is available due to a lack of observable data on sediment fluxes into the watershed. Instead, soil erosion was classified into three groups in order to determine the relative contribution of each subbasin to total sediment yield. The greatest erosion rate observed in sub-basin #25 is consistent with its downstream location and land cover. This sub-basin serves as the primary exit for both water flows and sediments in the watershed and is dominated by
agriculture (Figure 16). Additionally, we discovered that sub-basins #17, #20 and #21 immediately below sub-basin #15 and #14 – the sub-basins on which the Kossou and Loka dams are located respectively – have a comparatively low rate of soil erosion. This can be explained by the reservoirs’ action of trapping incoming material, resulting in reported siltation and a reduction in the reservoirs water storage capacity. Due to the critical nature of these dams for water and electricity supply and their support of socioeconomic activities within the watershed, developing land management scenarios for the immediately adjacent subbasin can help avoid the dams being impacted by land use practices, although this is beyond the scope of this study.

Figure 17: Subbasin distribution of the estimated soil erosion rate in the Bandama watershed
CHAPTER 4
DISCUSSIONS ON STRATEGIES AND POLICIES FOR WATER MANAGEMENT AT MULTIPLE SCALES

The examination of Cote d'Ivoire's water management system identified various shortcomings addressed in previous chapters. This chapter makes some proposals for improving water management at the national and watershed levels.

4.1 Institutional framework

In Côte d'Ivoire, water resources management is carried out by several institutions, the major ones are the Ministry of Waters and Forests, the Ministry of Hydraulics, the Ministry of Sanitation and Health, and the SODECI. The management system assessment revealed that collaboration between these entities is not spontaneous. It is determined by the requirements of each project. This exacerbates difficulties of overlapping tasks. We promote close collaboration and coordination between all these entities indicated by the green double arrows in Figure 18, particularly in the design and implementation of their respective policies.
While the legislation and policies governing water resources in Côte d'Ivoire are not often precise, they are pertinent, particularly in light of the necessity to establish executing agencies for water resource management at the national and basin levels. However, the pace of implementation is slow. After interviewing two water managers from the local water agency and the water resources directorate, we found that this slow momentum of policies implementation is because the government has taken little action to prioritize resource management and planning in contrast to the supply side. Government decision-making is centralized, which makes establishing an effective water resources management system difficult without its support. A decentralized system with a strong civil society component might assist focus government attention on water management and strengthen the sector's resilience. Civil society comprises non-profit organizations, water specialists, researchers, women, youth, and children.
farmers, employees, etc. (Bouman-Dentener and Devos, 2015). Several studies (Bouman-Dentener, 2015; Ni Thein, 2015; Maliasili Initiatives and Well-Grounded, 2015) demonstrate the positive impact of civil society organizations on water management through volunteering and public advocacy. In the Ivorian setting, non-profit groups that fight for improved management of water resources, whether for enhancing, protecting, or restoring them, are needed. Naturally, these organizations will require a supportive environment and scientific guidance to operate effectively.

While the SWAT model enables a broad understanding of the Bandama watershed hydrology and management in general, it takes a more targeted approach by identifying unique combinations of soil types and slopes associated with land use and informing on critical areas that require attention to avoid water issues. This is consistent with the study's recommendation of a decentralized and tailored approach to water management via CSOs. SWAT outputs are also beneficial for identifying the appropriate stakeholders for each CSO based on the location and issue.

4.2 Public Participation

The IWRM approach places high value on public engagement as a necessary component of a successful water management system. Beyond a process, public participation is a right of population to have access to information and to participate in making decision that concern them. To enhance public participation in the Bandama watershed's decision-making process, several approaches can be considered. In rural areas of the watershed, radio programs, open houses, public meetings, and group discussions may be accurate methods to get population’s input in the decision-making process. In urban and semiurban areas, methods like surveys, polls using social media, key informant interviews can supplement the methods above listed.
This will result in making decisions that reflect the changing social values and providing alternative solutions to complex water management problems. Moreover, public participation will contribute to establish of a new decentralized data gathering system that will benefit water users, utilities, businesses, and the government, and to build trust between communities and water managers. Examples of positive impacts of public participation in water managements exist in Maputo, Mozambique, Kenya, and Cameroon (Adams, 2018).

4.3 Data Management

In Cote d'Ivoire, access to water data is a major challenge. Occasionally, technical and financial resources are insufficient to develop an effective data collection system. Certain remote, inaccessible places are frequently not covered, and thus lack data. Water data are not publicly available in the regions where they are available. There is no structure in place to assess and publish water statistics for the sake of transparency. Access to data is granted on an individual basis and is consolidated at the level of government entities. This cumbersome procedure of obtaining water data obstructs the potential for reform that could be accomplished through scientific study, public education, advocacy, private sector investment, and so on. Crowdsourcing is one technique to increase data availability, particularly in rural areas of the country. Indeed, crowdsourcing entails citizens providing data in near-real time (Mistry et al., 2016). In the context of water management, information about water quality, water discharge, rainfall intensity, conflicts, etc. can help guide water authorities' actions while also educating and raising awareness among the population. In Singapore and California, creating a database where knowledge is exchanged between water managers, enterprises, and users has been shown to be advantageous
for effective water management (Colin et al., 2018; Sarni, 2016). Several projects (Gebremedin et al., 2020; World Bank, 2016) have used crowdsourcing successfully to forecast flooding or drought in Africa. In Cote d'Ivoire, we feel that establishing a formal process for people to submit concerns about water quality and quantity, disruptions to water services, and unsustainable activities in their areas can be beneficial. By combining social media with emerging technologies such as artificial intelligence and sentiment analysis, population intelligence may be acquired and evaluated to enhance government agencies' institutional monitoring and to aid decision-making through a participatory approach.

4.4 Regulatory framework and policies

A significant lesson learned from the Bouake case study is the absence of readily available alternate water sources in the event of a catastrophe. This also applies to other watersheds. The legislation in Cote d'Ivoire may help close this gap by mandating water supply utilities, specifically the SODECI, to prepare an Emergency Response Plan (ERP) for each water utility under its administration. ERPs are thorough processes outlining the steps to take, agencies to contact, and individuals to contact in the event of a water supply emergency. The ERP specifies the function of each entity (government, local governments, private businesses, and contractors, for example) involved in the operation of a utility and provides main contact information for each organization. This will handle the issue of overlapping obligations at the utility scale, which is a more appropriate and manageable scale than the national one. Additionally, the ERP entails anticipating and preparing for alternate water supply possibilities in the event that the primary source becomes unavailable. Such precise
and proactive planning is critical for strengthening the water management system's resilience and averting unanticipated water crises.

4.5 Capacity development

Developing knowledge and skills of local communities will reduce the emergency structure on which the Ivorian water sector is based. In fact, many improvements in the water sector in Côte d’Ivoire were made during a state of emergency following a crisis. Trained populations will help prevent water crises by monitoring water resources in their environments and taking small actions to maintain and operate their local water systems.
CHAPTER 5
CONCLUSION

The purpose of this study was to gain a better understanding of the Bandama watershed's processes and interactions, as well as its management system in order to develop management strategies to tackle its water scarcity issues. The study demonstrated that there is a decrease of precipitation between 2010 and 2018, year of the water crisis in Bouake. SWAT model was used to assess the baseline conditions of the Bandama watershed to understand the interconnections between processes in the watershed. The model was calibrated for 10 years between 2002 and 2011 not including the 3-year warm-up period at N’Zianoa station; then, it was validated following an internal validation approach on Kimoukro, Bouafle, and Zuenoula stations for the same period from 2002 to 2011. The sensitivity analysis of the 13 parameters used for calibration showed that \( \text{ALPHA}_\text{BF}, \text{SOL}_\text{AWC}, \text{CN2}_\text{CANMX}, \text{RCHRG-} \)DP were the most sensitive. Calibration and validation results indicated that the model overestimated the amount of water discharged. This was explained by the quality of the input data, which contained gaps, and the model's oversimplification due to a lack of reservoir information. The two dams included in the model are quite massive, and consequently have a sizable impact on the model calibration.

The analysis of the water balance revealed that baseflow contributes to the overall streamflow in the watershed and that ET accounts for 75% of total rainfall. This high contribution of ET to water losses was explained by the high temperatures attributed to the research area and to land use land cover dominated by deciduous
forests and agriculture. Streamflow at all the stations follows the trend of rainfall and display high peaks during the wet season and low peaks during the dry season.

The sediment yield analysis showed that the soil erosion rate in the watershed is very low. The highest erosion rate was found in Subbasin #25, which was explained by its downstream location and function as the primary outlet for both streamflow and sediments and its intensive agricultural activities. Additionally, some subbasins have less soil erosion as a result of their proximity to dams that hold sediments.

The assessment of the current water management showed that Cote d'Ivoire's water problems are not solely the result of physical factors such as decreased rainfall or temperature increases. They are also a result of institutional influences. This evaluation uncovered a lack of progress in implementing defined policies and enforcing established norms, as well as a lack of strong collaboration among water management agencies. This weakness can be remedied by decentralizing the water management system through the creation of PLANGIRE-planned institutions on the one hand, and by civil society organizations engaging the public and offering their services on the other.

Throughout the study's development, data availability and accessibility were important concerns. It is necessary to develop tools for data mining and water management enhancement. This study proposes the use of citizen science to collect water data, voluntary water monitoring by CSOs, and the release of water data for the goals of transparency, which benefits research, decision-making, public education, and commercial development.

The research's future development will include the development of management scenarios for the watershed's present and future horizons, as well as an assessment of the future water supply and demand balance.
## APPENDIX

**CHARACTERISTICS OF SOIL TYPES IN THE BANDAMA WATERSHED**

<table>
<thead>
<tr>
<th>SOIL</th>
<th>TEXTURE</th>
<th>HYDROLOGIC GROUP</th>
<th>WORLD REFERENCE BASE CLASS</th>
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