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DEVELOPMENT OF A GIS-BASED SUPPORT TOOL FOR INTEGRATED WATER RESOURCES MANAGEMENT: A CASE STUDY OF THE RIVER AGNEBY BASIN, SOUTH OF CÔTE D'IVOIRE.

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Development of a GIS-Based Support Tool for Integrated Water Resources Management: A Case Study of The River Agneby Basin, South of Côte d'Ivoire.

A thesis submitted to the Institute of Water and Energy Sciences (Including Climate Change), in partial fulfillment of the requirements for the degree of Master of Science (MSc) in Water Policy

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DECLARATION AND RECOMMENDATION

DECLARATION

I, Mr. **Christ Herbert KOFFI**, hereby declare that this thesis represents my personal effort, realized to the best of my knowledge. Furthermore, I declare that all information, material, methods, and software from other works presented here, have been fully acknowledged, cited and referenced in accordance with the academic rules and ethics.

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DEDICATION

To my beloved Father ***KOFFI Yao Martin***, gone prematurely in January 2020, two months after my admission to PAUWES, I dedicate this thesis.

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ABBREVIATIONS AND ACRONYMS

AUC	**:**	African Union Commission
CIGN	**:**	Centre de Cartographie et de Télédétection
CDM	**:**	Conceptual Data Model
CSS	**:**	Cascading Style Sheets
DGRE	**:**	Direction Générale des Ressources en Eau
DSS	**:**	Decision Support System
GDP	**:**	Gross Domestic Product
GEE	**:**	Google Earth Engine
GIS	**:**	Geographic Information System
GWP	**:**	Global Water Partnership
HTML	**:**	Hypertext Markup Language
IWRM	**:**	Integrated Water Resources Management
LDM	**:**	Logical Data Model
MINEF	**:**	Ministère des Eaux et Forets
OGC	**:**	Open Geospatial Consortium
OSM	:	Open Street Map
PAR-GIRE/AO	**:**	Plan Régional De Gestion Intégrée des Ressources En Eau
PAUWES	**:**	Pan-African University Institute for Water And Energy Sciences
PDM	**:**	Physical Data Model
PHP	**:**	Hypertext Preprocessor
PNAECI	**:**	National Environmental Action Plan Programme
RDBMS	**:**	Relational Database Management System
SDBMS	**:**	Spatial Database Management System
SDSS	**:**	Spatial Decision Support System
SODEXAM	**:**	Société d'Exploitation Et De Développement Aéroportuaire Aéronautique Et Météorologique
SQL	**:**	Structured Query Language
UN	**:**	United Nations
UNICEF	**:**	United Nations Children's Fund
USACE	**:**	U.S. Army Corps of Engineers
USAID	**:**	U.S. Agency for International Development
WCS	**:**	Web Coverage Service
WFS	**:**	Web Feature Service
WHO	**:**	World Health Organisation
WMS	:	Web Map Services
WPS	**:**	Web Process Service
WWAP	:	World Water Assessment Programme

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ABSTRACT

Climate change, rapid population growth, anthropogenic land use changes, can be classified among global phenomena that put enormous pressure on water resources. Côte d'Ivoire, like most West African countries, has adopted the Integrated Water Resources Management (IWRM) framework in order to manage its water resources sustainably. This notwithstanding, water resource managers of Agneby River Basin do not have technical tools to enhance effective and sustainable management of water resources within the basin. To address this problem, we proposed to develop a GIS tool to support IWRM and decision making in the Agneby River Basin. This coastal basin, with a surface area 8525.84 km², is located in the southern part of Cote d'Ivoire. By utilizing Geographic Information Systems (GIS), a relevant tool for water resources management, we first set up a spatial database which is administered through PostgreSQL relational database management software. Subsequently, we added the PostGIS extension to PostgreSQL to enable the spatial dimension of the database. The objective of this database is to fill the data gaps in the catchment area. We then carried out thematic mapping of spatial entities covering relevant thematic areas (i.e., administrative, water, infrastructure, etc.) which are necessary for managing the water resources of the basin. In order to provide improved access of the information to relevant stakeholders, partners, and the community, we also developed a Web GIS platform that provides web-based maps and GIS functionality. It is anticipated that this will improve organisational productivity, communicate vital information and engage decision-makers. Although the current version of the Web GIS platform we developed is a prototype based on free and open-source tools and software, it can be further developed to achieve the long-term objective of being a water information system for the Agneby River Basin.

Keywords: Integrated Water Resources Management, Decision Support Tool, GIS, Web-GIS, Spatial Database.

RESUME

Le changement climatique, la croissance rapide de la population, les modifications anthropiques de l'utilisation des terres, peuvent être classés parmi les phénomènes mondiaux qui exercent une pression énorme sur les ressources en eau. La Côte d'Ivoire, comme la plupart des pays d'Afrique de l'Ouest, a adopté le cadre de la gestion intégrée des ressources en eau (GIRE) afin de gérer durablement ses ressources en eau. Malgré cela, les gestionnaires des ressources en eau du bassin de la rivière Agneby ne disposent pas d'outils techniques pour améliorer la gestion efficace et durable des ressources en eau dans le bassin. Pour résoudre ce problème, nous avons proposé de développer un outil SIG pour soutenir la GIRE et la prise de décision dans le bassin de la rivière Agneby. Ce bassin, d'une superficie de 8525,84 km^2, est situé dans la partie sud de la Côte d'Ivoire. En utilisant les Systèmes d'Information Géographique (SIG), un outil pertinent pour la gestion des ressources en eau, nous avons d'abord mis en place une base de données spatiale qui est administrée par le logiciel de gestion de base de données relationnelle PostgreSQL. Par la suite, nous avons ajouté l'extension PostGIS à PostgreSQL pour permettre la dimension spatiale de la base de données. L'objectif de cette base de données est de combler les lacunes de données dans le bassin versant. Nous avons ensuite réalisé une cartographie thématique des entités spatiales couvrant les domaines thématiques pertinents (c'est-à-dire, administratif, eau, infrastructure, etc.) qui sont nécessaires pour la gestion des ressources en eau du bassin. Afin d'améliorer l'accès aux informations pour les parties prenantes, les partenaires et la communauté, nous avons également développé une plateforme SIG Web qui fournit des cartes et des fonctionnalités SIG sur le Web. On s'attend à ce que cela améliore la productivité organisationnelle, la communication d'informations vitales et l'engagement des décideurs. Bien que la version actuelle de la plateforme SIG Web que nous avons développée soit un prototype basé sur des outils et des logiciels libres et gratuits, elle peut être développée davantage pour atteindre l'objectif à long terme d'un système d'information sur l'eau pour le bassin de la rivière Agneby.

Mots-clés : Gestion intégrée des ressources en eau, outil d'aide à la décision, SIG, Web-SIG, base de données spatiales.

CHAPTER 1: INTRODUCTION

1.1 Chapter Introduction

This chapter presents the necessary information to understand the aim of this dissertation. It presents the current situation of IWRM of the case study, states the core of the problem, and defines the main objectives as well as the scope of the research. Besides that, the importance of the study and the limitations encountered through the process are also presented.

1.2 Background Information

Climate change, exponential population growth, and land-use change are recognized as global natural and socio-economic changes that put enormous pressure on water resources. From a social, economic, and physical point of view, these phenomena limit access to sufficient and adequate water for human needs. The natural environment is not immune either (Nikolic & Simonovic, 2015). One widely used approach to this problem is Integrated Water Resource Management (IWRM). By definition, IWRM is a step-by-step approach to managing water resources in a harmonious and environmentally sustainable way by bringing together stakeholders and involving them in planning and decision-making processes (GWP, 2009). The main goals of IWRM are to meet human and ecological needs and to provide protection against water-related hazards. Therefore, it addresses the issues of planning, development and operation of complex water resource systems to assess the quantity, quality, temporal and spatial distribution of water. Consequently, the pursuit of "*ensuring availability and sustainable management of water* … (SDG 6)" has been adopted as part of the United Nations Sustainable Development Goals (Ferri, 2010; Malaza & Irene Mabuda, 2019).

Information technology and data play a key role in diverse aspects of IWRM. They provide essential information to support effective decision-making. The sustainable use, control and management of water resources at the river basin level has made data an indispensable element. Data is therefore crucial to the effective implementation of any water resource management paradigm, whether it is integrated water resource management or adaptive management. (Adeoti, 2020).

One of the main challenges to the effective implementation of IWRM is data availability. Unavailability of data leads to a lack of information since the information is derived from processing or analyzing data. The development of a database is a prerequisite for the availability of information, which is the basis of IWRM. These data, collected over time and space, help to understand the environmental, social, cultural, and economic dynamics of a given area. (McDonnell, 2008). A second challenge relates to the development of tools and dynamic coupling of physical and socio-economic components of water resources systems. Numerous scientific literature, such as the Dublin Principles of 1992 (Cap-Net, 2008), (Kluge, Thomas; Liehr, Stefan; Lux, Alexandra; Niemann, Steffen; Brunner, 2006), stated that there are usually missing elements (i.e., problems including relevant datasets, rational charging policies, water conservation, water management, and the use of computer models in decision-models) at the technical level in IWRM.

Most of these problems are typical to the implementation of IWRM in the River Agneby Basin (RAB) in Côte d'Ivoire where the main problems identified are water supply and availability, protection of water resources, and non-effective policies. To address these problems, a Geographical Information System (GIS) based spatial decision support tool is developed within the IWRM framework to support technical decision making across the Agneby River Basin in Côte d'Ivoire.

1.3 Statement of the problem

Côte d'Ivoire, like most West African countries, faces several types of water resource management problems that become more pronounced over time and lead to situations that are detrimental to social development such as water shortages, water-borne diseases, and floods. These water-related problems have multiple causes, including the physical constraints of an unfavorable environment for the hydrosphere (factors related to climate, vegetation, and subsoil conditions) and human factors (e.g., poverty, social, economic, and cultural constraints, demography, and low technical capacity). Increased demand for water due to population growth and economic development has led to high pressure on the resource in a country where water plays a key role in food production and economic, agricultural, and industrial development (PAR-GIRE/A0, 2003). The need to balance water needs, resources, and environmental functions requires a holistic approach that takes into consideration all relevant factors and stakeholders for a balanced, environmentally sound, and sustainable use of water resources. This led to the adoption of the IWRM concept – an approach that was developed by many theorists, policymakers and international bodies – in the country.

For more than two decades (as can be referenced from the Water Law of 1998), the country has implemented the IWRM scheme in its attempt to respond to the joint national action towards sustainable management of water resources (Touré, 2017). Practically, however, the concept is poorly implemented. There are no coordinated and synchronized decisions among stakeholders. Water-related activities are allocated to a number of ministries (Ministry of Water and Forests, Ministry of Agriculture, Ministry of Hydraulics, etc.) and national agencies whose responsibilities are sectoral and often competitive. This fragmentation hinders attempts to coordinate and integrate water resource management activities. Yet, according to GWP (2009), the appropriate unit for implementing of IWRM in a given country is the river basin scale. The application of IWRM is quasi non-existent at the river basin scale even though the concept is part of national development objectives.

The lack of basin-wide perspectives, defined by geographical and hydrological characteristics, makes it difficult to practically integrate basin-wide issues, downstream as well as upstream, and to consider the quantitative and qualitative aspects of available surface and groundwater resources. Lack of information on the cumulative land uses in a river basin, such as urban development, agriculture, and forest conservation, can have a profound impact on the management of water resources of the basin. This problem limits water managers' ability to address the linkages between water resource management and the management of land and other related resources.

As regards the IWRM of Agneby River Basin in particular, some technical elements are missing. For example, the IWRM does not have any GIS-based spatial decision support tool. So far, attempts have been made to develop GIS tools through pilot projects, notably in Bandaman, the largest watershed in the country. Although these projects did not end with effective implementation, it shows the interest of the authorities in spatial decision support tool. Another problem is that water resource spatial data are scattered in different organizations where, due to poor planning and lack of understanding of water resources management by decision makers, no provision is made to analyze and make them useful for (and understandable to) non-GIS users.

This project contributes to the technical component of River Agneby Basin's IWRM by developing spatial decision support system to guide decision makers on how to harmoniously use and conserve water resources in the basin using available spatial data. There has never been a greater need for such a GIS-based tool to help in evaluating the applicability of complex environmental models to Agneby basin.

1.4 Goals and Objectives

The main goal of this study is to develop a GIS – based support system as a contribution to the IWRM in the River Agneby Basin, Ivory Coast. The objectives are investigated in the context of improvement of water resources management.

1.5 Specific Objectives

The specific objectives of this study are:

- To set up a spatial database of all water-related components.
- To produce maps, graphs, tables, pictures from available spatial data and incorporate them into an interactive GIS-tool.
- To deploy and make the GIS-tool and the information derived available to all the stakeholders and organizations that make decisions about water within the Agneby River Basin.

1.6 Research Questions

The research questions that arise from the specific objectives above are the following:

- How can spatial (and ancillary) data about the water-related components of Agneby River Basin be effectively integrated?
- How can maps provide information for a better management of the River Agneby Basin?
- How to make information and knowledge available for all the stakeholders in the River Agneby Basin?

1.7 Significances of the study

This study and its results are important for different beneficiary stakeholders including the Ministry of Waters and Forests, private startups and NGOs, researchers and students. Specifically, the spatial decision support system/tool developed in this study will enable the integration of spatial data and related information to generate knowledge about the water resource capacity and quality of the basin and the extent to which they benefit the populations that live in the basin's catchment. This knowledge will be useful to the Ministries stakeholders in water resources management when assessing the nations progress toward achieving SDG 6. In the same way, the system/tool will significantly enhance the work of the water resources managers of the basin. Private startups and NGOs which deliver water-related services will also benefit directly by integrating the tools into their operations. Moreover, the tools can used to generate information that can be used directly by researchers and students or fed as inputs to socio-economic and scientific models to generate additional knowledge for the benefit of society.

1.8 Scope of the work

Following the important role of information, this study is conducted to address issues of lack of information and support the decision-making processes in IWRM using GIS. The scope of this study is limited to provide basic data collected in space and time to understand the environmental, social and economic dynamics of the Agneby River Basin. Due to time and financial constraints, the tool developed in the framework of this thesis will be just a prototype which can, of course, be improved. It will be proposed to the national authorities in charge of water resources management as technical tool supporting decision-making in IWRM. All the software used in this study are free and open source.

1.9 Outline of the study

The structure of this thesis consists of five chapters which are organized as described in the subsequent sentence. Chapter 1 presents the context or background of the study, the definition of the problem in the study area, the study objectives and research questions, the study significance, as well as the scope of the work.

Chapter 2 deals with the review of the literature on key concepts and studies related to IWRM and decision support tools. Chapter 3 broadly deals the methods used in this study including a detailed description of the study area, methods of data collection, processing and analyses, as well as a summarized description of the database creation procedure. Chapter 4 presents the applied methodology. Here, the methods and materials used for the development of the spatial decision support tool are described. Chapter 5 presents the results and discussions. Finally, Chapter 6 presents the strategic guidelines for good water resource management at the study area level followed by the conclusions.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Introduction

This Chapter presents a brief review of the literature on Integrated Water Resources Management It discusses the strengths, limitations, and, most importantly, the gaps identified in previous studies in IWRM. The literature reviewed the challenges of IWRM implementation in Cote d'Ivoire, existing Decision-Making tool and application of GIS as a decision-making support tool. Upon completion of the review, conclusions were drawn that preceded the choice for the methodology applied for a better understanding of the remaining parts of this document.

2.2 Water, an indispensable resource

Amongst the physical elements of the Earth, water is unique in the role it plays. It provides an important supply of drinking water and is present in most socio-economic activities such as food production, industry, transportation and recreation, hydropower, mining, etc. Water is also an integral part of aquatic ecosystems, providing habitat for fish and other aquatic life (Statistics Canada, 2017).

In recent years, the development of technology and industrialization have brought enormous pressure on water resources. The United Nations (UN) warns that the world's natural resources (water, food and energy) are under significant pressure and this will continue to increase over time (C. Cosgrove & W. Cosgrove, 2012). The increasing pressure on water resources is linked to climate change, rapid human population growth, urbanisation and the resulting increase in consumption. With the explosion in population and consumption, humanity is beginning to realise the limits of this resource that was once considered infinite. While 70% of our planet is covered by water - hence the name Blue Planet - the concern is about available freshwater, and its spatial and temporal distribution in different regions of the world (Hunt, 2004). Only 2.5% of the total volume of water is freshwater, the rest being salty. Of this 2.5%, about 70% is trapped in the Antarctic and Greenland ice sheets. Some of the rest exists as soil moisture, or in deep underground aquifers that are difficult for humans to access, leaving less than one percent directly accessible for use. This freshwater is found in rivers, reservoirs, lakes and upper aquifers. (USGS Phamphet & NASA Earth Observation, 1984).

2.3 Water resources and human activities

Water resources have played an essential role in human evolution. Water remains irreplaceable and is used in almost every sector of activity. (Nikolic & Simonovic, 2015). In addition to providing drinking water for households, water extracted from rivers supports economic uses including agriculture, mining and oil and gas extraction, thermoelectric power generation, manufacturing, and more. There are also so-called "non-water use" activities such as navigation, fishing and recreation, not to mention the importance of water in maintaining ecosystem functions, vegetation, fish and wildlife. (Statistics Canada, 2017).

Agriculture uses large quantities of water for irrigation and food production, making the world's biggest consumer of freshwater (source). The UN World Water Assessment Programme (WWAP) has estimated that groundwater extraction worldwide has increased threefold over the past 50 years, which has "fundamentally changed the role of groundwater in human society and the irrigation sector."(WWAP, 2012). About 3.1 trillion cubic meters of fresh water, or 70 percent of global water withdrawals, is used for agricultural activities (FAO, 2017). For some countries with high economic growth, the figure is closer to 90%. The global population is projected to grow by 2 to 3 billion over the next 40 years, and food demand is expected to increase by 70 percent by 2050. This could increase water use to 4.5 trillion cubic meters by 2030 (Snellen & Schrevel, 2004).

According to population forecasting studies, the world's urban population will grow from 3.4 billion in 2009 to 6.3 billion in 2050 (C. Cosgrove & W. Cosgrove, 2012) . It can be assumed that problems related to adequate water supply, sanitation and drainage will follow this trend, making large megacities in developing countries particularly vulnerable. Recent estimates suggest that 1.2 billion people have no sanitation facilities, while 2.5 billion people do not have access to developed sanitation facilities (WHO & UNICEF, 2017).

Water resources are essential in today's energy sector, whether for generating electricity to cool power plants, extracting fossil fuels, refining oil or irrigating crops for biofuel production (source). About 20% of the world's electricity is produced by hydroelectric dams. It is a key source of renewable energy worldwide (C. Cosgrove & W.Cosgrove, 2012).

For example, in Canada, the main users of water in 2013 were electricity generation and distribution, manufacturing, households, agriculture, mining and natural gas distribution, water supply, sewage systems and others (Figure 1). These industries, which are important consumers of water, contributed 22% of total GDP and 14% of employment in 2013. All other industries together accounted for only 3% of water use in 2013.

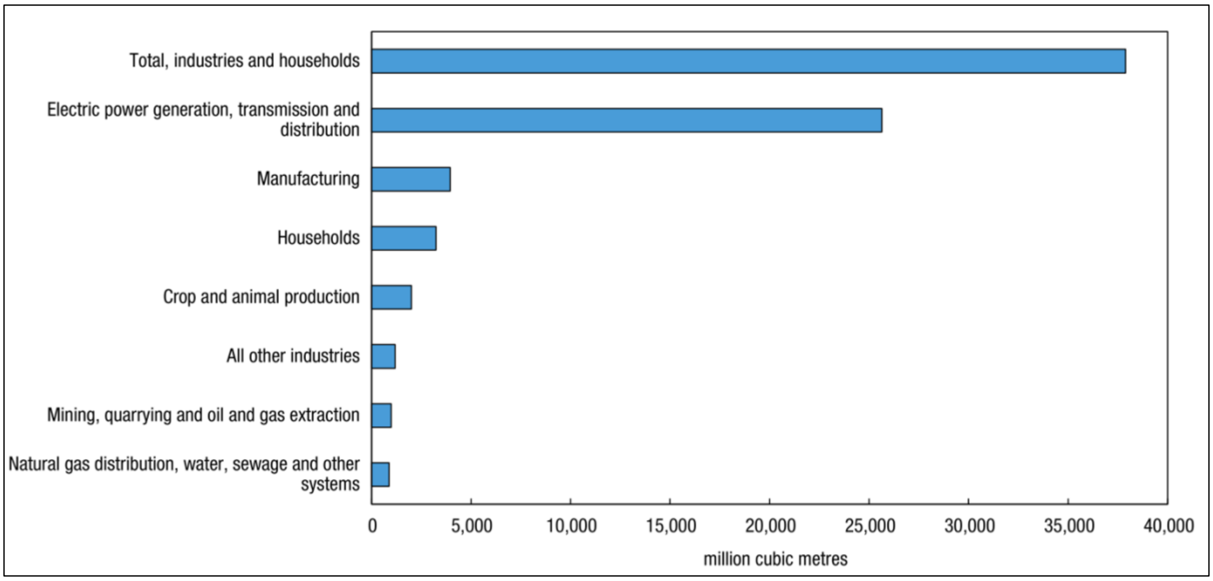

Figure 1: Water Use in Canada, 2013

Source: Statistics Canada, CANSIM Table 153-0116.

2.4 Integrated Water Resources Management

The concept of IWRM recognizes the technical and social complexity of water management issues and acknowledges the increased competition, conflict, environmental impacts and resource degradation or depletion that have characterized the water sector over the past 25 years, to varying degrees in different regions (although in sub-Saharan Africa low water mobilization often remains a problem in itself) (Molle, 2012). Based on the definitions in Table 1, the concept of IWRM therefore encompasses the three main collective values associated with sustainable development, namely the values of social equity, environmental sustainability and economic efficiency and rationality. These values are further referred to as the 3 “E” of IWRM” (Molle, 2012) as shown in Figure 2.

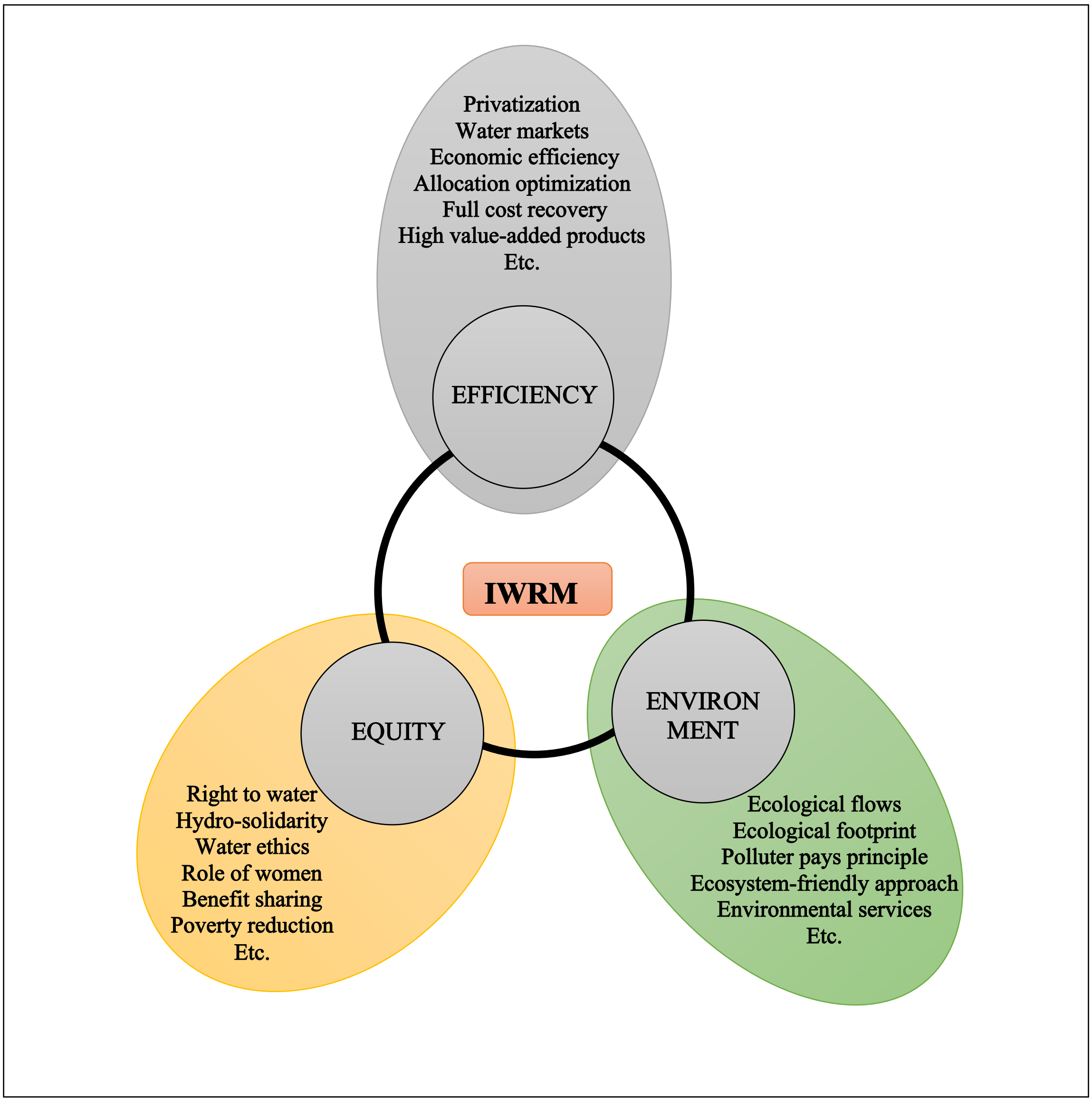

Figure 2: IWRM and its 3 "E"

As a concept, IWRM has evolved over time and has developed on the basis of the experience of practitioners and policy makers. This evolution of IWRM starts from the first United Nations World Water Conference in Mar del Plata in 1977 (introducing the initial principles related to water resources) to the International Conference on Water and the Environment in Dublin, Ireland in 1992. The main outcome of this meeting was the development of the Dublin Four Principles, which provide a solid foundation for the freshwater management component of the United Nations Freshwater Conservation Agenda also known as Agenda 21(Nikolic & Simonovic, 2015). The four Dublin Principles are (Frone, 2012):

- Principle *1: "Freshwater is a finite and vulnerable resource, essential for sustaining life, development and the environment"*.

- Principle 2*:* "*Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels*".
- Principle 3*:* "*Women play a central part in the provision, management and safeguarding of water"*.
- Principle 4*:* "*Water has an economic value in all its competing uses and should be recognized as an economic good"*.

IWRM has been defined by different organizations according to their view of the concept. A selection of definitions by key institutions (or major actors) in the IWRM domain is provided in Table 1 below:

Organisation	**"Integration Water Resources Management…"**
Global Water Partnership (GWP 2000; p.7) **https://www.gwp.org/en/GWP-CEE/about/why/what-is-iwrm/**	*"…is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".*
U.S. Agency for International Development (USAID, 2002 p.1)	*"…is a participatory planning and implementation process, based on sound science, which brings together stakeholders to determine how to meet societies long-term needs for water and coastal resources while maintaining essential ecological services and economic benefits"*
U.S. Army Corps of Engineers (USACE) (Cardwell et al., 2009; p.9)	*"…is a goal-directed process for controlling the development and use of river, lake, ocean, wetland, and other water assets in ways that integrate and balance stakeholder interests, objectives, and desired outcomes across levels of governance and water sectors for the sustainable use of the earth's resources"*
World Bank (World Bank, 2006)	*"…aims to establish a framework for coordination whereby all administrations and stakeholders involved in river basin planning and management can come together to develop an agreed set of policies and strategies such that a balanced and acceptable approach to land, water, and natural resource management can be achieved"*

Table 1: Selection of definitions used by some major actors in the IWRM domain.

2.4.1 Application of IWRM at the river basin level

Watersheds are suitable units for integrated management. The application of IWRM principles at the catchment scale is increasingly being applied worldwide as a means of addressing the major challenges facing the water resources sector.

According to GWP (2009), A basin-level perspective, defined by geographic and hydrological characteristics, facilitates the practical integration of downstream and upstream and basin-wide issues, and the incorporation of quantitative and qualitative aspects of surface and groundwater resources and land use. Assigning management tasks to basin units or authorities allows priority environmental and socio-economic issues to be integrated into evolving management plans and supplementary regulatory decisions.

2.4.2 IWRM, disasters and environmental issues

Water-related extreme events can have very severe impacts on the social and economic well-being of our societies. These include floods, droughts, erosions, etc. The management of these hazards and their risks should be an integral part of IWRM and should not be considered in isolation (Cap-Net UNDP, 2008). Water resources are closely dependent on the climate. High rainfall can lead to flooding and its inevitable consequence of erosion. On the other hand, low rainfall can lead to drought, and the drying up of rivers and the non-renewal of groundwater. Proper management of water resources provides more options for promoting and supporting the resilience and robustness of natural ecosystems and human activities to climate change (Nohara et al., 2018). Through monitoring, analysis and assessment, seasonal and annual changes in water quality and quantity can be estimated and then incorporated into planning and operations. For example, the operation of dams for flood control, water supply and hydropower can be regulated to maximize their effectiveness while ensuring environmental emissions. In this way, IWRM applied at the basin level can appropriately include water-related hazard and risk management and mitigate potential environmental impacts.

2.4.3 Why participate in an IWRM process?

The promotion of IWRM is partly a result of the awareness, even today in some countries, of the poor interaction between sectoral activities, such as agriculture, flood control, hydropower, etc., which has led to ineffective coordination among sectors. Another disadvantage of this decentralized approach is the lack of focus on national sustainable development and integrated water resources management. The first step in integration requires each sector to have access to all data compiled in the watershed, up-to-date information, and the ability to avoid unanticipated risks due to uncoordinated activities within and/or outside sectors. What's moreIn addition, the processes involved in achieving watershed sustainability require a combination of flexible measures and mutual coordination, as well as stakeholder engagement, through a series of urgent actions (GWP, 2009).

2.4.4 IWRM in Côte d'Ivoire

The Dublin and Rio conferences in 1992, which placed water at the heart of sustainable development issues, marked the beginning of the implementation of the IWRM approach in Côte d'Ivoire. The National Environmental Action Plan Programme 6 (PNAECI, 1996-2010), which aims at coordinated water management, both nationally and transnationally, considers three closely related dimensions: (i) water availability; (ii) water quality; and (iii) management of available resources. To prevent crucial problems of water availability in the medium term, the programme envisaged three (3) interventions as follows.

- The establishment of a national system for observing the hydrological cycle;
- The establishment of a national water quality observation network
- The development and implementation of a master plan for integrated water resources management.

Also, new legal instruments (i.e., decrees) were to be issued to strengthen the water management framework. Accordingly, the following nine (9) decrees, summarize in Table … below were made.

Decree No.	Date	Purpose
2012-239	07 March 2012	Declared the public utility of close perimeters and secured immediate perimeters of catchment areas of the Autonomous District of Abidjan.
2012-1047	24 October 2012	Fixed the modalities of application of the polluter-pays principle as defined by law No. 96-766 of 3 October 1996 in the Environment Code
2013-44	30 January 2013	Established the National Water Week in Côte d'Ivoire
2013-440	13 June 2013	Determined the legal regime of water resources protection perimeters, hydraulic developments and works
2013-441	13 June 2013	Determined the conditions and modalities of classification and downgrading of water resources,

		hydraulic works and facilities as well as granting the public utility regime to water resources, hydraulic works and facilities
2013-507	25 July 2013	Determined the periodicity of the inventory of water resources, facilities and hydraulic works
2015-346	13 May 2015	Determined the list of infringements of the Water Code that may give rise to a transaction and infringements that exclude any transaction
2019-591	03 July 2019	Related to filling, diking, and riprapping of sea shores and inland waterways.

Table 2: Summary of decrees related to water management in Côte d'Ivoire

2.4.4.1 Institutional framework

The review of the institutional framework will focus on the ministries, state institutions and services as well as private organizations involved in the water sector in Côte d'Ivoire. The government of the country has recently, on 6 April 2021, appointed (under the Decree No. 2021-181) ministries and institutions of state along with definitions of the responsibilities of each body, in accordance with the new nomenclature of the government as proposed by the Prime Minister. In all, 25 ministries and 39 state institutions and services have been tasked to contribute to the water sector. A summary of responsibilities of seven (7) ministries are presented in Table 3 as an illustration.

Ministry	Responsibilities
Ministry of State, Ministry of Defence	This ministry is responsible for the elaboration, implementation and monitoring of the government's defence policy on land, inland waters (transboundary waters) and marine waters
Ministry of State, Ministry of Agriculture and Rural Development	This ministry is responsible for the implementation and monitoring of the government's policy on agriculture. Among its attributions are the management of rural land, the identification and implementation of rural developments, notably hydro-agricultural developments and agricultural mechanisation, the implementation of the Rural Land Code, in liaison with the Ministry in charge of Water and Forests.

Ministry of Hydraulics	This ministry is responsible for the implementation and monitoring of the government's policy on water. In this respect, and in liaison with the various ministerial departments concerned, it has the initiative and responsibility for the following actions: • Participation in the monitoring and protection of water resources; • Management of drinking water sector infrastructures • Development of drinking water supply infrastructure in urban and rural areas • Elaboration and monitoring of the regulations concerning studies, construction and operation of human hydraulic works.
Ministry of Sanitation and Hygiene	This ministry is responsible for implementing and monitoring the government's policy on sanitation and hygiene. In this capacity, and in liaison with the other ministerial departments concerned, the ministry has the initiative and responsibility for various actions in the field of sanitation and hygiene. Those related to water resources are related to the elaboration, implementation, and control of the application of the policy and legislation on sanitation and drainage. This ministry assists local authorities, supervises the professions in the field and controls the proper functioning of sanitation networks and works. It develops and promotes master plans for sanitation and drainage.
Ministry of Water and Forests	This ministry is in charge of implementing the Water Code, in liaison with the other ministries concerned and all stakeholders in the water sector. As such, according to Decree No. 2018-36 of 17 January 2018 on the organisation of the Ministry of Water and Forests, the Directorate General of Water Resources is responsible for: • Implementation of the water policy;

	• Coordination of the follow-up of integrated water resources management activities, hydraulic developments and works • Ensuring the implementation of the Water Code; • Implementing the National Plan for Integrated Water Resources Management; • Promoting cooperation in water resources development and management • Promoting support and follow-up of water resources development and management projects and programmes in national and international basin organisations; • Monitoring international conventions and agreements on water resources management and protection • Promoting education, research and development activities in the field of water; • Ensuring the protection of water resources against all forms of pollution and the restoration of water and aquatic ecosystems; • Ensuring the establishment and control of basin agencies and structures; • Develop and ensure a sustainable financing mechanism for sustainable water resources management; • Ensuring planning and arbitration of uses at national and river basin level; • Ensuring the control, monitoring and evaluation of the implementation of decisions, plans, programmes and projects; • Studying and organising the setting up of an observatory on water resources.
Ministry of Higher Education and Scientific Research	This Ministry is responsible for the implementation and monitoring of the Government's policy on higher education and scientific research. Its attributions take into account: • Monitoring the organisation and functioning of public and private universities and public and private colleges.

	• The planning and implementation of a policy of training, insertion and promotion of researchers of all disciplines; • The management of research institutes and centres.
Ministry of Environment and Sustainable Development	This Ministry is responsible for the implementation and monitoring of the Government's policy on environmental protection and sustainable development. Its role is to implement the Environmental Code and the legislation on environmental protection, in conjunction with the Ministry in charge of Water and Forests. This ministerial department is also responsible for the development of environmental services in the network of parks and nature reserves, in liaison with the ministers in charge of tourism and Water and Forests. The protection and development of aquatic, fluvial, lagoon and coastal ecosystems and wetlands are also within its jurisdiction.

Table 3: Summary of responsibilities of 7 ministries

2.4.4.2 Strengths and weaknesses of the management framework

The Water Code, which is the legal basis for water policy in Côte d'Ivoire, provides a solid foundation for water management in the country. Thus, the water management framework of the country is strengthened by core components of the Water Code including:

- the principles of Integrated Water Resources Management (IWRM), in particular the polluter-pays and user-pays principles,
- the separation between the manager and the user (Article 58),
- the creation of a planning tool (Master Plan for the Development and Management of Water Resources, Master Plan for the Development of Hydraulic Works),
- sustainable financing of water through the creation of a fund for the management of resources from hydraulic works and developments (Article 105).

On the other hand, water management at the national level has many difficulties (i.e., weakness). These include

- the absence of application decrees for the implementation of the Water Code Law,
- the absence of application decrees for the establishment of management structures
- the institutional framework is not in place,
- the institutional framework is not in place

- the fund for the management of resources has not yet been set up.

2.5 Decisions Support Tools for IWRM

There are several reasons that explain the increasing challenges of managing natural resources, particularly water resources. First, water problems are themselves characterized by their inherent complexity due to the complex spatial and temporal characteristics of the resource and associated ecosystems. Second, environmental issues are subject to multiple and even conflicting economic, social and cultural interests. Thirdly, knowledge about ecosystems is often fragmented and difficult to share among stakeholders. Finally, there is a lack of scientifically robust means and tools to help managers and decision-makers (Aleix et al., 2011). The current situation calls for an innovative and integrated approach, combining concepts from different disciplines in a unified methodological and operational framework (Qi & Altinakar, 2011).

Mcintosh, (2008) states that "*decision and information support tools (DISTs, for example, Decision Support Systems) offer promising opportunities for the integration of different disciplines and methodologies in support of decision-making processes and, in particular, by providing the methodological and operational framework to integrate simulation modelling (SM), participatory planning (PP), and decision analysis (DA)*". DIST is a large class of computer-based tools that simplify the transfer of expertise and methods to frame and explore problems and generate information to analyze and support decision-making.

2.5.1 Components of Decision Support Systems (DSS)

Many authors such as Haag & Kaupenjohann, 2001; Power, 2002; Sprague & Carlson, 1982 Marakas, 2003 have identified the four main components of a DSS as follows: (1) the database and database management system, (2) the model and analysis tools and associated model management system, (3) A graphical interface that allows for an interactive dialogue between decision makers and the DSS, and (4) The user. It is also possible to incorporate a GIS component to analyze spatial data so that the system becomes a spatial decision support system (SDSS) (Batty & Xie, 1994).

2.5.2 The role of Decision Support Systems for IWRM

Broadly speaking, DSS is a set of tools and processes for framing problems and supporting decision-making. In a strict sense, a decision support system is a human-computer interaction decision system that uses data and models to support rather than replace decision makers. It addresses unstructured and semi-structured problems by focusing on the effectiveness of the decision-making process rather than the efficiency (Eom, 2020).

Overall, the literature on IWRM DAS is centred on modelling techniques. The most common models are those based on GIS with graphical user interfaces, programming and display consoles, analysis tools and decision trees, at the river basin level allowing managers and decision makers to develop IWRM plans, testing alternative strategies and/or 'what if' scenarios. DSS tools are widely used to address various analytical and modelling issues in the field of water and the environment, specifically water supply management, water quality and environmental regulation, assessments of the occurrence and severity of natural hazards such as floods and droughts, assessment of the impacts of land use changes and climate change impacts and adaptation schemes (Giupponi et al, 2011).

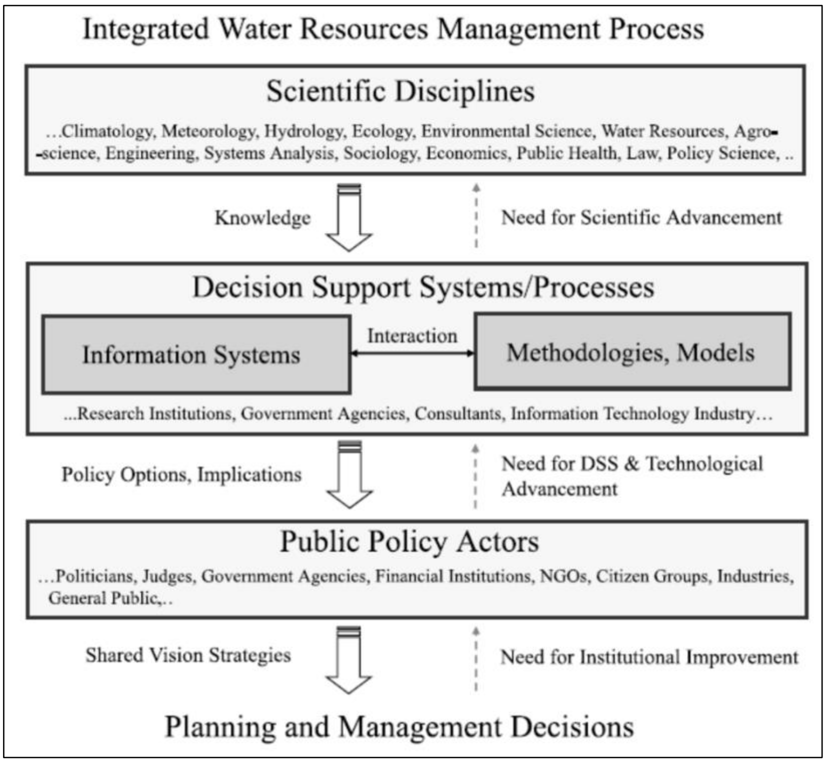

Figure 3:The role of DSS in IWRM. Adapted from Georgakakos (2007)

Several authors have developed different tools, with different functionalities, to help the decision-making process. These tools include mathematical models, GIS and remote sensing techniques, performance evaluation systems, and more. For example:

- Kronaveter et al. (2001) proposed a hydrological micromodel for analysing the effects of urban expansion on infiltration and runoff;
- Zhang et al. (2009) proposed a web-GIS watershed management spatial decision support system called "*Watershed Forest Management Information System (WFMIS)"*. The tool is composed of three sub-models to address nonpoint source pollution mitigation, road system management, and silvicultural operations;
- Purkey et al., (2007) Integrated a Climate Change Assessment Tool into Stakeholder-Driven Water Management Decision-Making Processes in California ranked based on the application of a 3S: Sensitivity, Significance, and Stakeholder support;
- Pearson et al., (2009) developed a decision support framework that assists managers in the urban water industry to analyse a mix of water service options, at the whole-of-city scale.

2.6 Integration of Geographic Information Systems (GIS) and Remote Sensing

GIS and remote sensing are technologies that deal strictly with spatial data and as such are both designed to represent the geographical features of the earth as accurately and realistically as possible and in accordance with cartographic principles. However, these technologies are not identical in every respect. Technically and conceptually, each technique is based on different principles, remote sensing is essentially a data collection technique (i.e., a data production channel), while GIS is mainly devoted to data processing. Remote sensing provides immediate access on a more continuous scale to raw data collected over areas of varying surface area at rapid temporal frequencies based on the spatial characteristics of the sensor or imager. Digital remote sensing data records the radiation of passive (reflected) and active (produced) energy at multiple wavelengths (multispectral) as it interacts with the earth's surface and atmosphere (Mesev, 1990).

In comparison, data processed by GIS are stored as vectors and represent geographic shapes in a structured topology and defined by implicit relationships. Consequently, discrete features are delimited by borders and labelled by unambiguous thematic attributes. However, most digital spatial data stored in a GIS comes from external sources, such as remote sensing, thematic maps, ground surveys using global positioning systems (GPS) (Gao, 2002; Xue et al., 2002).

2.6.1 GIS for water resources management

The constantly increasing need for rational water resources management imposes the necessity of using advanced tools for investigating the application of potential management policies. GIS ranks today among the most prominent tools of this type (Latinopoulos et al., 2004).
Geographic information systems are computer systems that process data, usually with a spatial component. These data can therefore both store and create map products. They also offer the possibility of performing multiple analyses or scenario evaluations such as model simulations. However, the real strength of GIS comes from the use of spatial and statistical analysis methods to process geographic attributes and information (Lyon, 2003). The output of the analysis can be derived information, interpolated information or layered information. GIS maps are then produced to display the information in the form of a cartographical representation of the area.
GIS tools bring a number of benefits to water resources research. For example, GIS can improve the organization and storage of databases on water and related resources. GIS performs tasks such as segmentation of catchments, identification of watersheds and channel networks, characterisation of slope and aspect of terrain, catchment configuration, direction of flow and water accumulation points.
Recently, GIS has been applied to diverse water resource management projects. We can mention the *AMAZON_COOP_H2O*, called "*Project for the Integrated and Sustainable Management of Transboundary Hydric Resources of the Amazon Basin considering Variability and Climate Change*", which aimed to plan and implement activities related to the protection of land, water resources and sustainable management of the Amazon Basin in the context of climate change. This project aimed to implement the *GeoAmazonas GIS* as one of the basin management tools for the identification of conflicts related to the use of water resources and situations of vulnerability (de Deus et al., 2016).
In conclusion, GIS is a powerful tool that can be of great help in water resource management.

2.6.2 The value of maps in IWRM

Maps are an important tool for water management organizations to communicate and share information among stakeholders. The use of maps allows a better understanding and overview of important issues in natural resource management and land use planning (Taylor et al., 2006). Wade & Sommer (2006) defined a map as a graphic representation of the spatial relationship of entities within an aera. Remote sensing and geographic information systems have long been recognized as powerful tools for surface and groundwater mapping. Groundwater survey maps based on satellite imagery, known as hydro-geomorphological maps, are used for the management of drinking water sources and water supply systems. Fracture maps derived from the processing of remote sensing Radar data are used to identify areas of groundwater recharge for the establishment of boreholes for drinking water supply, rainwater harvesting and also to ensure the sustainability of drinking water sources (Sharma, 2019)

2.7 Architecture and functioning of a Web GIS

2.7.1 Components of a web GIS

A web GIS is generally made up of three components: Client, Map Server, Data Server (Laury & Saysanasy, 2011; Trevey, 2016).

- The client is the component represented by a number of tools used to query map servers. There are different clients that allow one or multiple users to view maps online via browsers.
- The map server is the component that allows the creation of maps using geographic data stored on a server. We have two types of map servers: Free map servers such as GeoServer, MapGuide and MapServer, and proprietary map servers such as ArcGIS Server.
- Data server is the spatial database management component. An example of a database is PostgreSQL with the PostGIS extension.

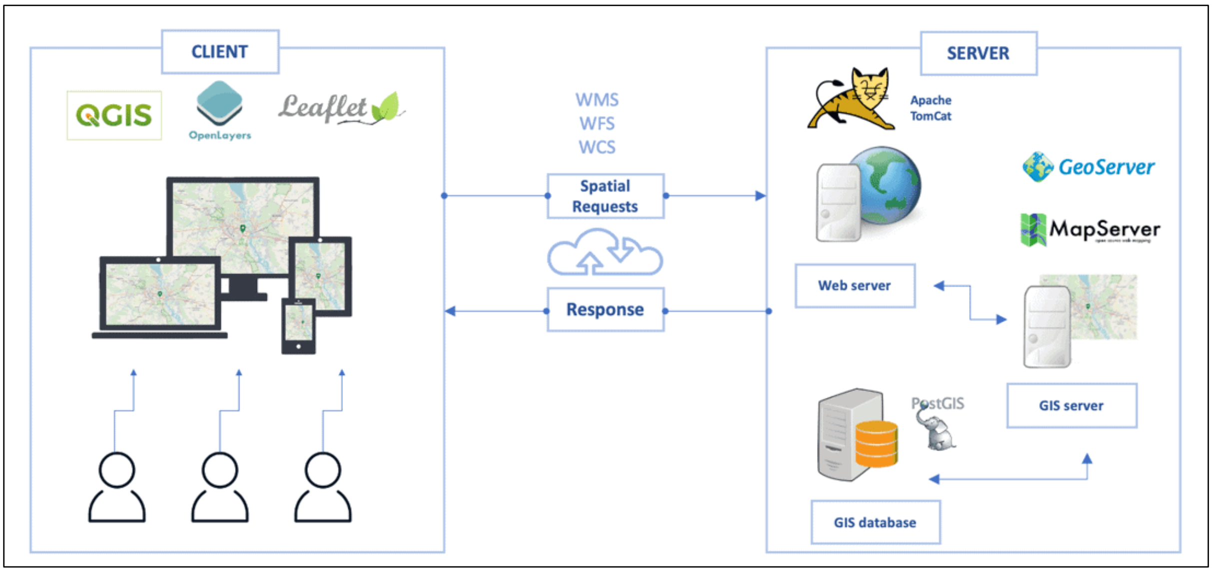

Figure 4:Web-GIS architecture

Source : https://www.gislounge.com/wp-content/uploads/2020/12/web-GIS-architecture-diagram.png

To obtain the desired geospatial data map images, the user calls the client (web application) which sends a request to the map server. The latter processes the geographic request by querying the available spatial data server(s). The response from the map server sends the desired map image(s) back to the client.

2.7.2 Web services: Open Geospatial Consortium (OGC) standards

The diffusion of geospatial data and the interoperability of geographic information systems rely on OGC standards. The latter is an international association, created in 1994, which groups together certain specifications and standards. Table 4 below gives some details on web services.

Web Services	Description	Requests
WMS (Web Map Services)	A protocol that allows data servers to return visual maps with certain features upon client request. There is also a WMS-C, a hidden web service that provides efficient ways to process and obtain tile maps.	*GetCapabilities*, *GetMap*, *GetFeatureInfo*
WFS **(Web Feature Service**)	a protocol that calls for the creation, modification, and deletion of geographic vector features on maps. We distinguish two types of WFS servers (basic and transactional).	***Basic servers*** *(GetCapabilities, DescribeFeatureType, GetFeature)* ***WFS-T transactional servers*** *(GetCapabilities, DescribeFeatureType, LockFeature GetFeature Transaction).*
WCS (Web Coverage Service)	A grid service that provides grid-like geographic data.	*GetCapabilities*, *GetCoverage. DescribeCoverage,*
WPS **(Web Process Service)**	A geoprocessing service for performing geoprocessing	*GetCapabilities*, *DescribeProcess*, *Execute*

Table 4: Web services and the respective descriptions and queries

2.7.3 Web mapping tools

2.7.3.1 GIS software

GIS software performs five main functions:

- **Abstraction** (organizing different geographic data into components and descriptions).
- **Acquisition** (acquiring geographic data for the GIS).
- **Archiving** (storing and managing database systems).
- **Analysis** (querying geographic data to provide answers).
- **Display** (creating and displaying maps with geographic information).

There are two types of GIS software: free GIS, commonly called "open source", and proprietary GIS software. In the frame of this study, we chose to work with only open-source software because it is freely available and accessible and its source code can be modified, adapted and shared by the public.

Open source GIS offers advantages such as transparency, flexibility and quality of the source code, user independence, interoperability according to OGC standards and allows for the dissemination and exchange of data, and reduction of procurement costs (Steiniger & Bocher, 2009). Beyond all the features, open source GIS software has some disadvantages, namely, low revenue sources compared to proprietary software, freedom of competition for similar software, search for additional revenue, and failure to meet all typical user needs (Steiniger & Bocher, 2009). There are many open-source tools, the best known of which are GRASS GIS, Quantum GIS, gvSIG, uDig, SAGA GIS.

2.7.3.2 Map servers

Commercial and open-source solutions are two types of servers that support the publication of data. To ensure interoperability, it is essential to use free servers. Two map servers are used as free solutions: MapServer and GeoServer. However, commercial solutions such as ArcGIS, GeoMedia and MapInfo are also worthy of note.

2.7.3.3 Spatial Database Management Systems (SDBMS)

There are different SDBMS that offer components for storing geospatial data. Examples are MySQL spatial, Oracle spatial, PostgreSQL/PostGIS. In this work, PostgreSQL with the PostGIS extension best meets our needs due to the advantages of being open-source, having a good data management system, being compliant with OGC standards, offering powerful operators, and the possibility to add other systems.

2.7.3.4 Web mapping interfaces

Web Map Interfaces are applications that can be accessed anywhere and at any time. They are executed by users via different web browsers. The Application Programming Interfaces (APIs) of these web map interfaces offer advantages such as the accessibility of applications on different web media (computers, tablets and smart phones), reduced maintenance costs, data interoperability, efficient support and management of multimedia data (text, photos, videos) and accessibility anywhere and everywhere through the internet. Among the new generations of web applications are OpenLayers3, Leaflet, ArcGIS web Mapping, Google maps, and Mappy.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter provides the methods and materials used to obtain the results required by the main objective of this study. Therefore, this chapter begins by providing information on the study area and the data used. The chapter ends by providing the tools and the methodologies employed to generate the results to achieve the specific objectives of this research.

3.2 Presentation of the study area

3.2.1 Geographical location characteristics

The Agneby coastal basin is located in the South-East of Côte d'Ivoire between longitudes 4°45' and 3°43' West and latitudes 5°18' and 6°56' North. It is drained by the River Agneby in the interfluve between the river N'zi and the river Comoé. It is the largest coastal basin in Côte d'Ivoire. The Agneby River rises from a small locality of Angoua in the department of Bongouanou at an altitude of 260 m and flows from north to south. It has a fairly regular longitudinal profile with an average slope of 1.25 m per km and an average altitude of 105 m (Girard et al., 1971). The surface area of the coastal basin of Agneby is 8525.84 km² for 277 km of length (Koudou et al., 2018). The three main left bank tributaries of the Agneby are the M'Pébo, the Kavi and the Séguié. The minor tributaries are the M'borou, Asseubié and Niéké on the right bank.

The relief of the Agneby catchment areas is similar to that of the country. It is monotonous on the whole, with some singularities in places that make the difference between the catchments. The Agneby basin is dominated by two types of relief. From downstream to upstream of the basin, the altitudes range from 0 to 100 m on the one hand, and from 100 to 200 m on the other. The extreme west of the upstream part of the basin more or less hilly with altitudes of between 200 and 300 m (Avenard et al., 1971; Kouadio, 2011; Kouakou, 2018). The overall slopes are always very steep (30 to 40%), which gives to these modest reliefs, (which in some places exceed 600 m in altitude) the appearance of real mountains. This feature is further reinforced by the size of the differences in altitude, which are very often greater than 300 m (Bonvallot & Boulangé, 1970).

Administratively, the coastal basin of the river Agneby crosses three regions from north to south: the Moronou region, the Agneby-Tiassa region and the lagoons regions in its lower reaches. It includes the sub-prefectures of Bongouanou, Arrah, M'batto, Akoupé and

Agboville; the extreme east belongs to the department of Adzopé and the district of Abidjan in the South.

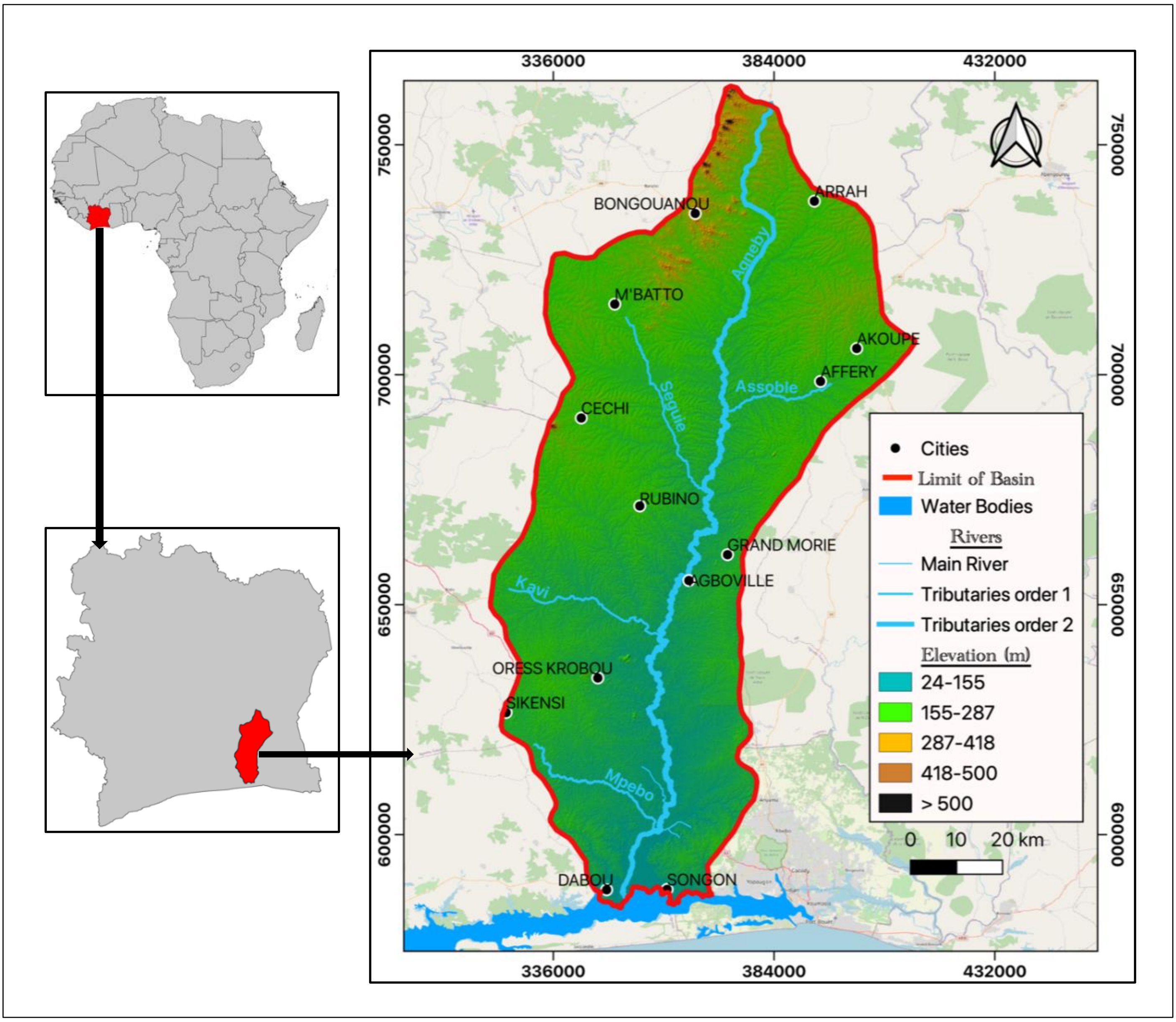

Figure 5: River Agneby Basin

Following the DEM, it is seen that the hydrographic network of the basin is very dense. However, for this work, it was considered only drains containing water throughout the year (permanent waterflow).

3.2.2 Morphometrical characteristics of the basin

The morphometrical characteristics of the Agneby catchment were determined using topographic maps at 1:200,000 and the BDGéo200 database of the *Centre de Cartographie et*

de Télédétection (CCT). The Agneby basin has a compactness index of about 1.60. The high value of this index means that the runoff takes longer to reach the outlet of the basins.
A summary of some morphometrical characteristics is shown in Table 1.

A (km²)	P(km)	Kc	L(km)	W(km)	Hmin (m)	Hmax (m)	I(m/km)
8525.84	477.31	1.60	224.27	37.87	1	550	1.25

Table 5: Morphometrical characteristics of the basin

S: area, P: Perimeter, Kc: compactness index, L: length of equivalent rectangle, W: Width of equivalent rectangle, Hmin: Minimum altitude, Hmax: Maximum altitude, and I: Longitudinal slope.

3.2.3 Climate

The Agneby basin belongs the equatorial transitional climatic zone. This climate is marked by the four seasons (Kouakou, 2018)

- a long dry season (GSS), from December to March,
- a long rainy season (GSP), from April to July,
- a short dry season (PSS), from August to September, and
- a short rainy season (PSP), from October to November.

There is abundant rainfall (more than 2000 mm per year), high atmospheric humidity and a high temperature with an average ranging between 24 and 33 °C. The assessment of the thermal regime of the Agneby watershed was done using data from the meteorological stations of Abidjan, Adiaké and Gagnoa. The choice of stations is linked firstly to their position in relation to the basin and to the fact that temperature data is available at a limited number of weather stations. Secondly, this parameter varies slightly in the climatic zone. According to the data covering the period 1949-2000, the average monthly temperature values were found to vary from 24 to 27.9°C in Abidjan, from 24.2 to 26.9°C in Gagnoa, and from 24.2 to 27.3°C in Adiaké. The hottest period of the year is from November to May with average monthly temperatures exceeding 27°C. The coldest period of the year is from June to October with temperatures below 24°C. The maximum monthly average temperature sometimes exceeds 28°C during the dry months (February, March, April) (Kouadio, 2011).

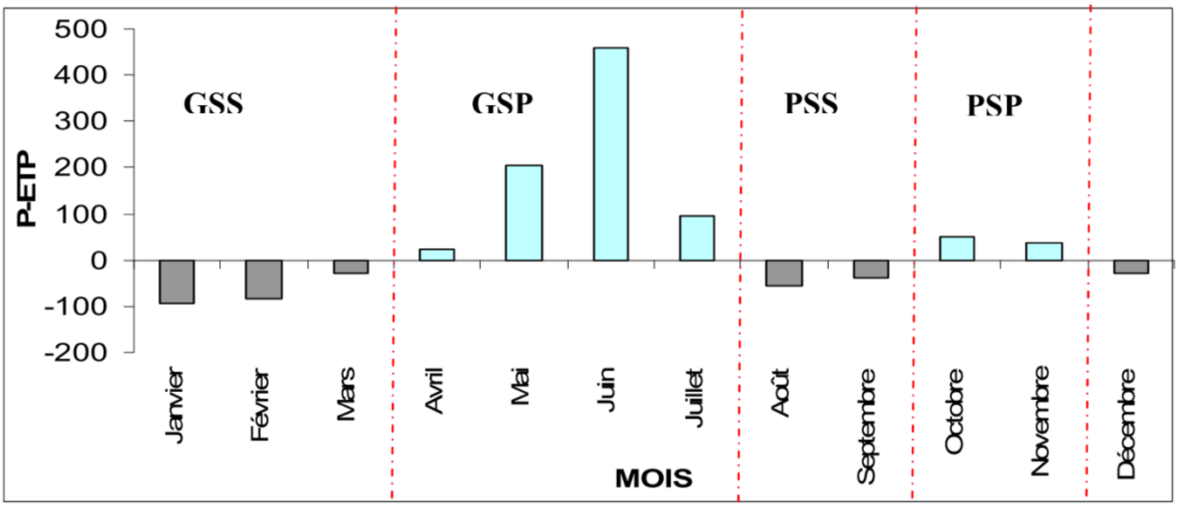

Figure 6:The rainfall pattern of southern Côte d'Ivoire

3.2.4 Soils

The soil types covering the study area can be grouped into 4 main classes – ferralitic soils, ferruginous soils on ferralitic materials, hydromorphic mineral soil complexes, and poorly evolved soils with marine input – described in the following subsections.

3.2.4.1 Ferralitic soils

The dominant soil type in the study area is ferralitic soils, which are highly leached under heavy rainfall (Figure 12) (Perraud, 1971). These soils are grouped into two major groups of soil resulting from the alteration of different bedrocks. The first group includes ferralitic soils on eruptive and metamorphic rocks (granites, schists, and basic rocks). These soils are very deep with a high clay content and good water retention capacity. They are suitable for growing coffee, cocoa, oil palm, banana and food crops. The second group includes ferralitic soils on tertiary sands found in the sedimentary basin. The soils compensate for their poor chemical quality by being sufficiently thick to grow coffee, cocoa, and oil palm. They are also suitable for cultivating pineapple, a plant that requires well aerated soils.

3.2.4.2 Hydromorphic soils

These are the soils whose characteristics are due to an evolution dominated by the effect of excess water as a result of temporary flooding of the surface, or as a result of the presence or rise of a water table. The presence of water is linked to low and flat topographic conditions that lead to:

- areas with difficult drainage (shallows, valley bottoms, lagoon depressions),

- areas flooded by river floodwaters (alluvial terraces), and
- areas where the water table can vary easily (coastal sands).

Excessive water can lead to the accumulation of organic matter, either in a coarse form (peat soils) or in an evolved form (humic soils).

3.2.4.3 Ferruginous soils on ferralitic materials

The ferrugineous soils cover the high ground areas and the valley slopes. They are very poor in Calcium, Potassium, Phosphorus, organic matter and Nitrogen, and their agronomic value is therefore very low.

3.2.4.4 Poorly evolved soils with marine input

These are soils formed on recent or present marine sands and cover only a few hundred meters of the coastline. These soils are poorly differentiated, with a sandy texture and coarse sand that is homogeneous over several meters with a slight enrichment in organic matter over 25 to 30 cm. The water table is very deep. These soils are very poor in mineral elements, but are very well suited to coconut trees if nitrogen and potassium fertilization is applied.

3.2.4.5 Eutrophic brown soils of tropical countries

These soils develop on materials derived from basic rocks and on a generally hilly terrain. The clay fraction is composed not only of kaolinite but also of illite and montmorillonite, resulting in a silica/alumina ratio of >2.

CLASS 1 : FERRALITIC SOILS	
Sub-Classes	**Soils groups**
Medium and/or low desaturated	- Typical (or rejuvenated) soils - Reworked soils - Weakly indurated and depleted reworked soils
Highly desaturated	- Reworked or typical soils with induration and tropical eutrophic brown soils.
Highly desaturated alternating with medium and/or low desaturated soils.	- Reworked and indurated soils + Reworked soils - Reworked soils
CLASS 2 : FERRUGINOUS SOILS	
Indurated reworked soils	
CLASS 3 : HYDROMORPHIC SOILS	
Hydromorphic soils with gley and pseudogley	
CLASS 4: POORLY EVOLVED SOILS WITH MARINE INPUT	
- Northern limit of the sedimentary basin (Tertiary sands) - Bauxite or old ferruginous summit clays	

Table 6: Soils classification

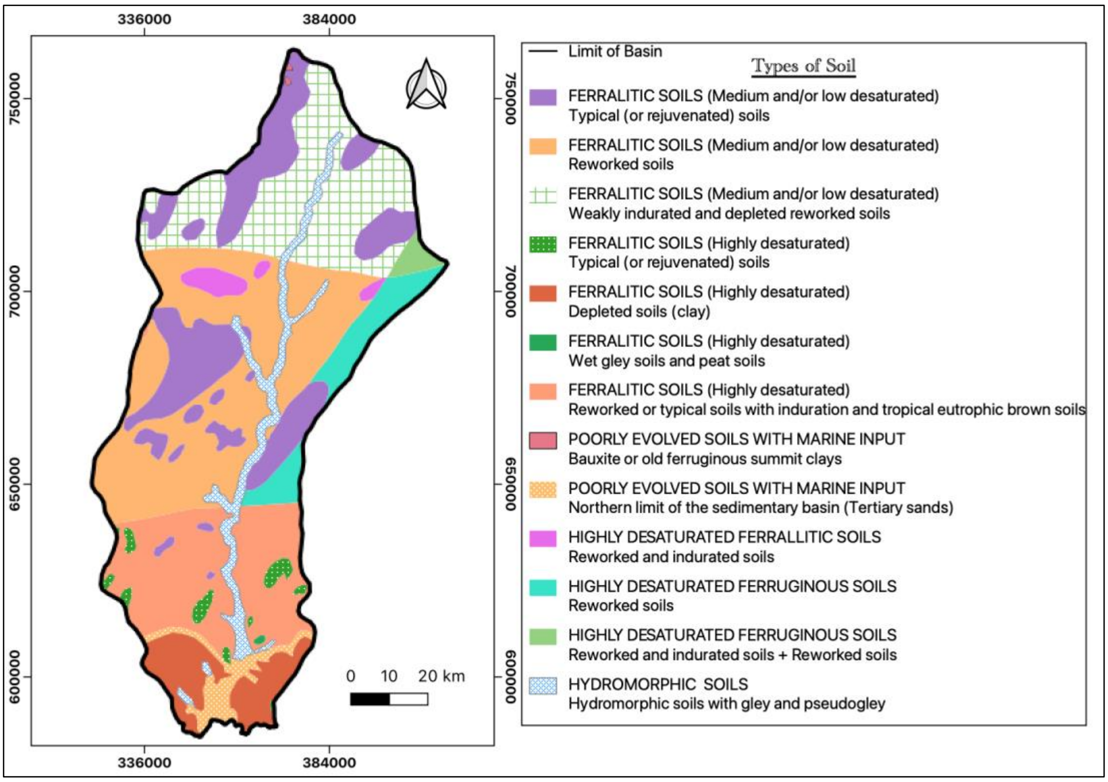

Figure 7: Map of soils

3.2.5 Geology

The geology of the basin is made up of two main formations. the Precambrian crystalline basement (92%) and the sedimentary part (8%). Dominated in large part by the Precambrian crystalline basement (92%) in its upper part, the Agneby coastal basin belongs to the Proterozoic domain (middle and lower) which was structured during the Eburnean orogenic megacycles (2,500 to 1,550 M.y.). The lower sedimentary part (8%), of Tertiary and Secondary formation, is made up of sandy and clayey sediments as well as coastal sediments from the Quaternary period occupying the downstream bed. The induration phenomena in this region result in the formation of armoured surfaces (Assoma, 2013).

The coastal sedimentary basin of Côte d'Ivoire is partly influenced by the tide and the movements of the lagoon. It is crossed from west to east by the lagoon rift. This rift separates two distinct zones:

- to the north, a zone where the very weak cover to the north and the very thin cover rarely reaches 300 m in thickness (very thin continental Mio-Pliocene sediments) and
- to the south, a deep basin (known only from boreholes) where the basement, vertically to the coast, reaches 4,000 to 5,000 m in depth (Martin, 1974).

The Agneby basin lies above the lagoon rift.

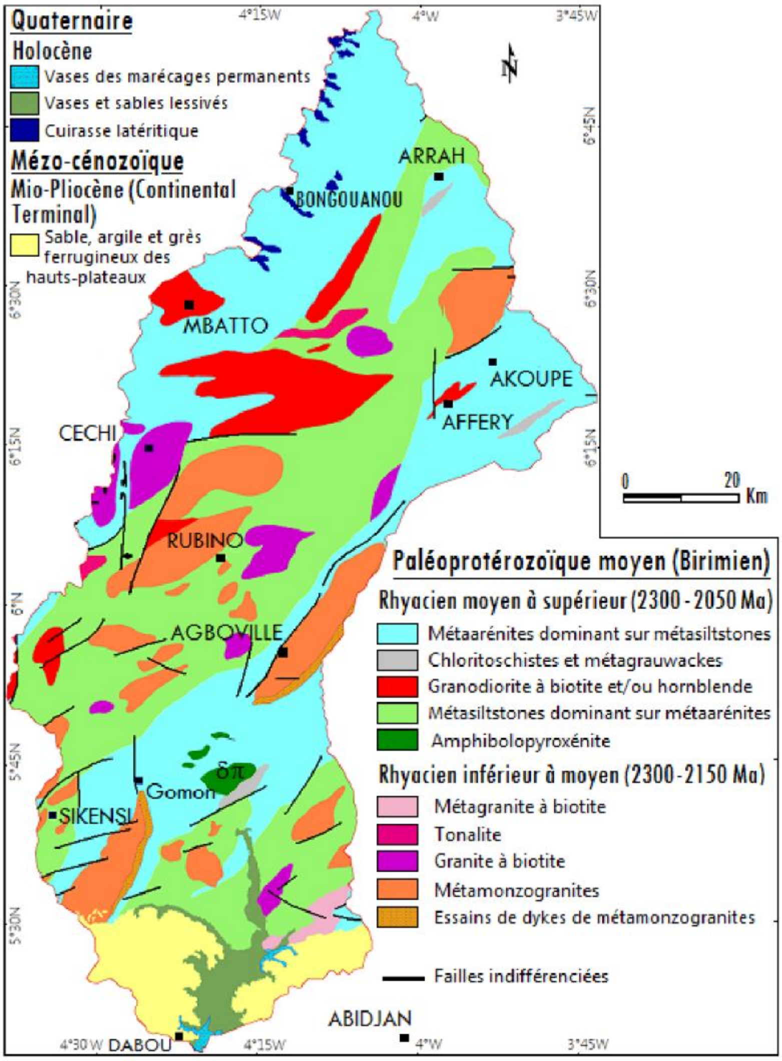

Figure 8: Geology of the Agneby basin. From (Assoma, 2013; Délor et al., 1992)

3.3 Data and Methods

3.3.1 Data collection

This step consists of collecting the data necessary to the work. First, we reviewed the literature. Previous studies carried out in our study area provided some data and interesting information. Libraries, university archives, and websites are the means by which we have consulted these past studies. Secondly, we consulted available data banks. The data bank of the National Office of Drinking Water and that of the Directorate of Water Resources of the Ministry of Water and Forestry, where we obtained data of hydraulic equipment and the location of the stations (rain gauges, streamflow gauges, etc.). Thirdly, cartographic data were obtained from the National Centre for Remote Sensing and Geographic Information. As for climatic data, they were acquired from SODEXAM, the National Meteorological Agency. Finally, we carried out field missions to have an overview of the large farms present in our catchment area. In addition, this mission also had the objective of identifying industries and possible pollution points in the watercourses. The table below summarizes the data obtained along with related information during the data collection phase.

Data classes	Category	Format	Sources
Basin's boundaries	Map	pdf	DGRE
Administrative	- Villages - Cities - Sub-prefectures	Shapefile (.shp)	CNTIG
Surface waters	- Rivers - Water bodies - (Lakes, reservoirs, ponds, lagoons)	Shapefile (.shp)	DEM-12.5m (from Alos Polsar) Open Street Map CNTIG
Hydraulic Equipments	- Boreholes - Reservoirs - Water Intake installations	xlsx	ONEP
Topographic	- DEM - Isolines	Tiff Shapefile (.shp)	DEM-12.5m (from Alos Polsar)
Climatic	- Rainfall - Temperature - ETP - Stations	Xlsx	SODEXAM
Environmental	- Soils - Geology - Protected forests - Land cover	Pdf Shapefile (.shp) Tiff	CIGN REDD+
Infrastructural	- Roads - Health facilities	Shapefile (.shp)	Ministry of public health Open Street Map

Table 7: Summary of data collected

3.3.2 Material

The work for this study was performed with the help of a software package and tools. The table below presents this software.

Software / Tool	Tasks
QGIS 3.16	Realisation of Cartographic tasks
PostgreSQL 12	Database management
PgAdmin 4	Database management
Geoserver	Cartographic server
Apache Tomcat	Webserver
Excel 2019	Data classification and computation
Word 2019	Redaction
GPS	Field activities

Table 8: Software and tools used and their related activities

3.3.3 Data processing

The data processing was about bringing the data into conformity. It consisted essentially in the manipulation of layers and their attribute tables. Georeferencing, digitization, merging of layers, joining of tables and importing of data collected on the field via the GPS were carried out. These operations, for the most part has been done with QGIS to verify and organize our data and to make them suitable for integration into our database. It should be noted that given the importance of our study, it was essential to have a clean and quality database.

3.3.4 Creation of the database

For the structuring and linking of data, we opted for a Relational Database Management System (RDBMS). Thus, the modeling of the database was strongly based on the MERISE formalism. Thereafter, the taking into account of the spatial and geometrical dimensions of the objects, required another modeling specific to the GIS.

The database design process is built in several stages, namely

- The creation of the conceptual data model (CDM);
- Creation of the logical data model (LDM);

- Creation of the physical data model (PDM).

Since most of the data used in our database are shapefiles, we did not necessarily have to follow the three steps mentioned above. In fact, these steps are already done in the design of a "*shapefile*". A shapefile is a file with two main dimensions (generally, there are 5 dimensions, but focus is hereby given on two), a spatial dimension (.shp) and an attribute dimension (.dbf). The spatial dimension is the main (i.e., mandatory) file, which is a direct access, variable-record-length file in which each record describes a shape with a list of its vertices. The attribute dimension is a table containing all the descriptive information of the spatial dimension. It is actually a database, a relational database (dbf means **d**ata**b**ase **f**ile).

3.3.4.1 Preparation of the Relational DataBase Management System (RDBMS)

We created the RDBMS to receive our spatial data previously edited in QGIS in a sequence of steps listed below.

- Creation of a server in " localhost " (Port: 5432)
- Creation of a database following the "postgres" model
- Creation of group roles (to manage access rights to the databases and their objects)
- Creation of a connection role (to connect to the servers). This role is considered as the user and has different rights allowing him to manage the database.
- Creation of schemas
- Addition of the "Postgis" extension for the spatial dimension.

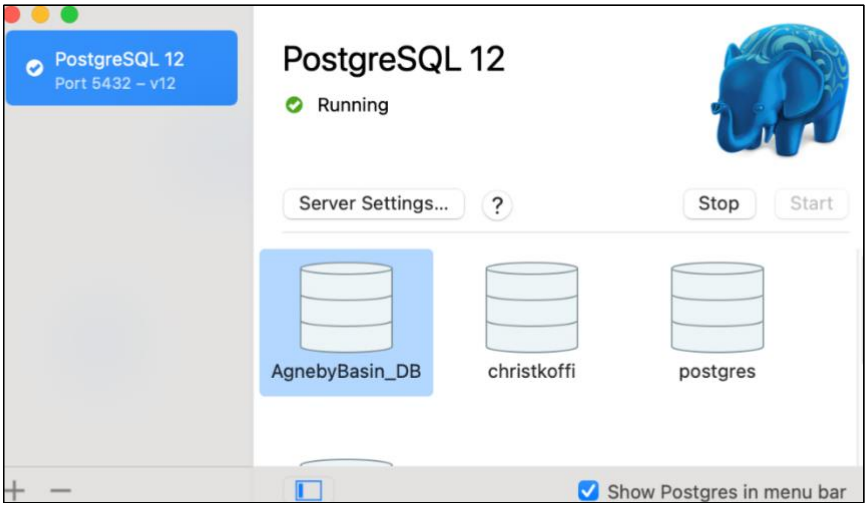

Figure 9: PostgreSQL server in localhost hosted on port 5432

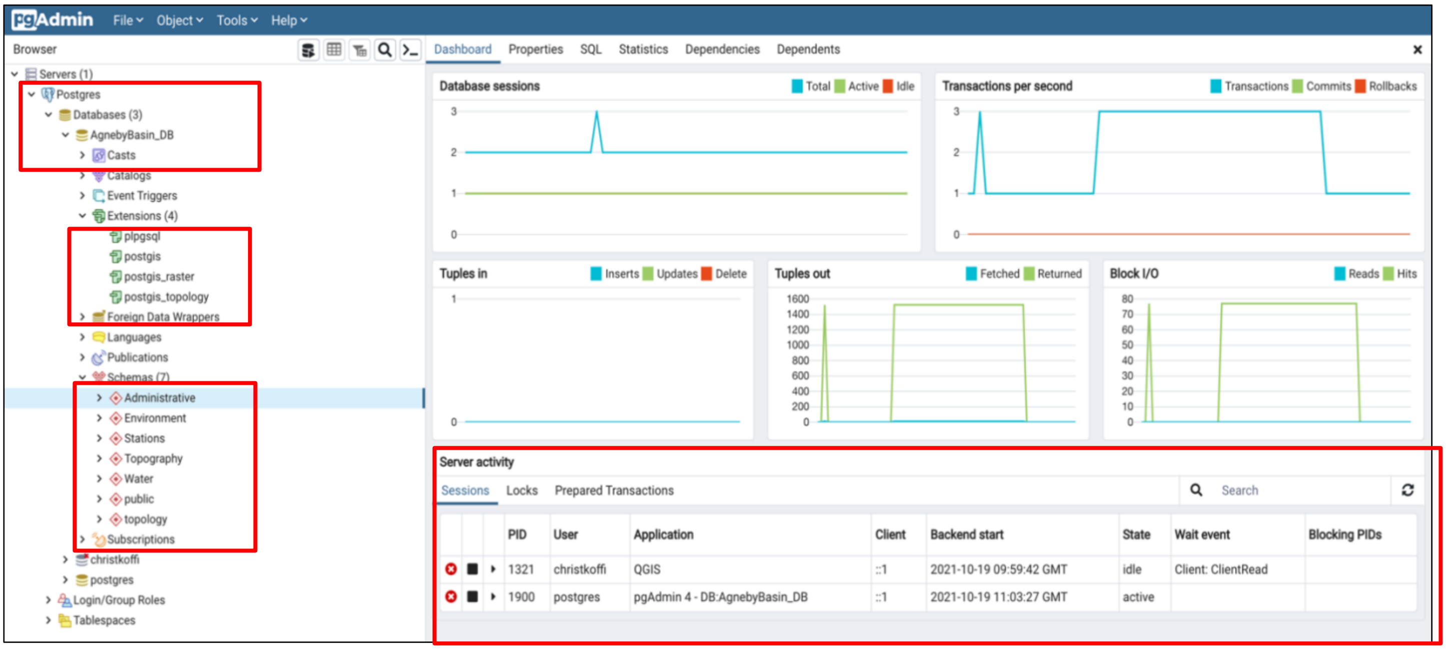

Figure 10: Graphical User Interface PgAdmin for Postgresql Database management

3.3.4.2 Implementation of the Web and cartographic servers

GeoServer is an open-source map server based on Open Geospatial Consortium (OGC) standards. It makes available vector or raster spatial data stored in a database or directly by downloading the raw data. The data dissemination protocols are numerous: Web Map Service (WMS), Web Map Tile Service (WMTS), Web Coverage Service (WCS), Web Feature Service (WFS) and Transactional (WFS-T).

Apache Tomcat or simply Tomcat is an application server, more precisely a free web container of servlets and java server pages (JSP). The Apache web server and the PHP programming language are used to develop web interfaces.

The methodology consists by installing first the web container and host the server locally on localhost:8080, then add Geoserver as a web-application inside the web container. Finally, the layers contained in the database were uploaded in Geoserver via the Postgis extension added previously to the database.

3.3.5 Development of the interactive interface

The interface of our Web GIS of the Agneby basin was designed using common languages of Web programming (HTML, CSS, JAVASCRIPT), PHP and SQL, organized within the Bootstrap Framework. The GeoJSON format is the format in which data are presented. It is a format lighter than shapefile format and completely independent of programming languages and network protocols. The User Interface of the web system was designed in such a way that it provides a very simple and interactive way of visualizing the layers along with related information. GIS functionalities like panning, zooming, on/off layers, print map, measure distance (or area) were incorporated.

3.3.5 Summary

The data used in this research came from literature review, data catalogues, and field missions. The processing of these data required several software (QGIS, Excel, Web Server, PostgreSQL, PostGIS, Brackets), languages (HTML, CSS, JavaScript, PHP, SQL). The methodology is based on several operations including data collection and processing, the creation of the spatial database, the manipulation of the data in the QGIS software and the implementation in the RDBMS. The final operation was the design of the webmapping platform. This operation requires the programming of the different interfaces, the realization and integration of the interactive maps to the interfaces and the deployment of the platform on the web.

Figure 11: Methodological chart

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Setting up of the catchment database

4.1.1 Implementation of the database

The database named "*AgnebyBasin_DB*" (Figure 9) consists of several data schemas which we have called "Dimensions". In the frame of this thesis, we had decided from the start to develop ten (10) main dimensions. However, time and budget constraints allowed us to develop only seven 7) dimensions. It should also be noted that some of the dimensions developed are incomplete. The dimensions of the database are listed in the table below:

DIMENSIONS	COMPONENT	STATUS IN THE DATABASE	
		Done	Missing
Administrative	Basin's Limit Regions Sub-prefectures Main Cities Villages	✓	
Water	Surface water	✓	
	Undergrounds water		✓
Infrastructures	Roads	✓	
	Hospitals	✓	
	Schools		✓
Climate	Rainfall	✓	
	Temperature	✓	
	ETP	✓	
	Stations	✓	
Hydraulic Assets	Water supply and Sewerage networks		✓
	Reservoirs	✓	
	Boreholes, pumps Wells	✓	
	Dams		✓

Environment	**Protected forests**	✓	
	Land use	✓	
	Geology- Pedology- Topography	✓	
	- Flood zones		✓
	- Pollution zone		✓
Socio Economic	Demography	✓	
	Economic activities (Agriculture, Industries, Livestock)		✓
	Incomes		✓

Table 9:Different dimensions of the Database

The basin database developed in this way offers the possibility of grouping the various data by linking them through relationships. This makes it easier to add new data. Similarly, using SQL language, it is possible to query the database to extract specific information.

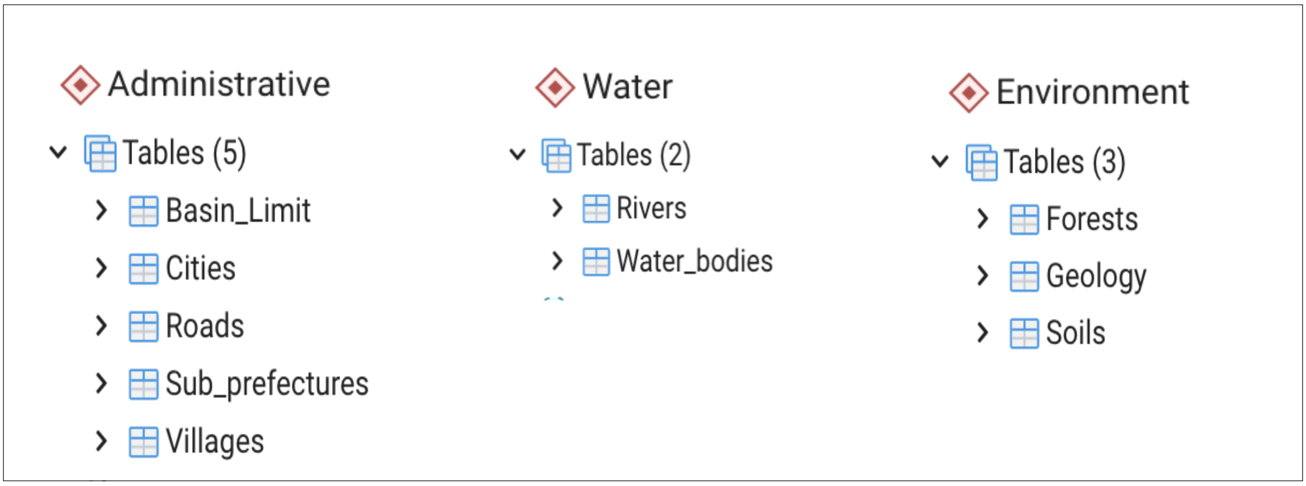

Figure 12: Some components of the schemas (Dimensions)

4.2 Thematic maps

The GIS-based support tool contains layers of graphics information and their relational database that are transformed into maps. The tool allows the user to visualise information of a specific area.

4.2.1 Administrative map of the River Agneby Basin

The administrative map allows us to know the location of the basin on the national territory. It also gives us information about the spatial extent of the basin, the different geographical and administrative entities (regions, departments, sub-prefectures and villages) that are in the basin space and also information on the number of inhabitants and population density. The administrative dimension is very important for coordinating IWRM activities. Indeed, water projects such as drinking water supply are always oriented towards the populations and require information on the people concerned**.**

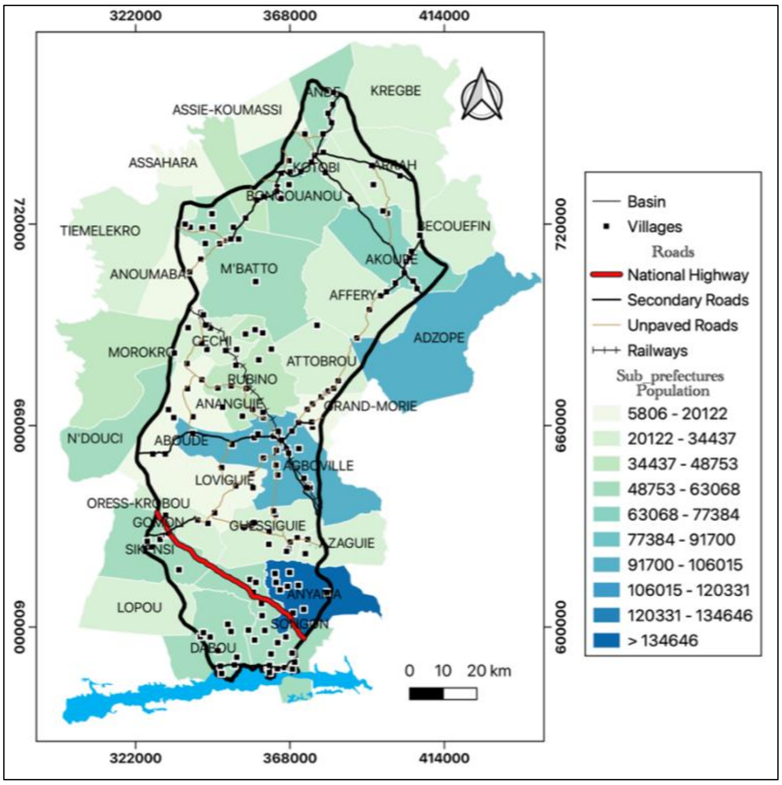

Figure 13: Administrative map of the River Agneby Basin

4.2.2 Water resources of River Agneby Basin

The water resources of the basin are composed of surface water, groundwater and atmospheric water. Regarding surface water, the Basin is drained by the River Agneby, a costal river that takes its source in a small locality at Angoua in the department of Bongouanou flowing from the North-South direction towards the Atlantic Ocean. It has six permanent tributaries that flow all year round. Surface water in the basin is used for many purposes. Many dams are built on the river and its tributaries for drinking water supply, domestic use, crop irrigation, animal feed, etc.

It is also worth noting the presence of the *Ebrié* lagoon in the southern limit of the basin in which the river flows before reaching the sea.

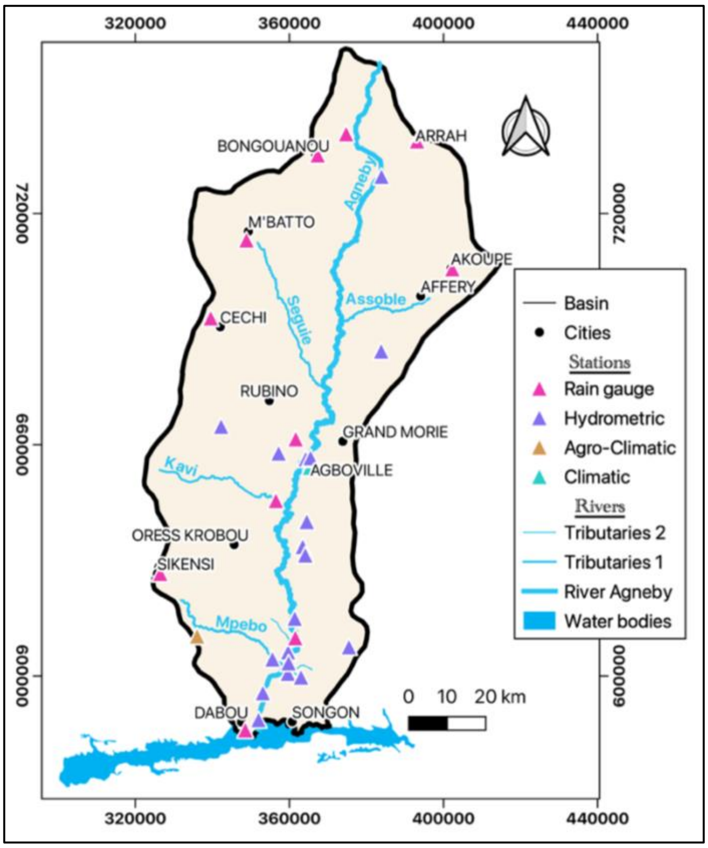

Figure 14: Surface water of the river Agneby Basin

Concerning atmospheric waters, we noted that 95% of the Agneby basin belongs to the transitional equatorial climate zone, while the remaining belongs to the mild transitional equatorial climate. This climatic zone is known for its abundant rainfall (more than 2000 mm per year), high atmospheric humidity and high temperature with an average ranging between 24 and 30 °C. This quantity of annual rainfall is one of the main reasons of abundance of groundwater in this basin. However, we could not obtain the data on groundwater to map its spatial distribution within the basin.

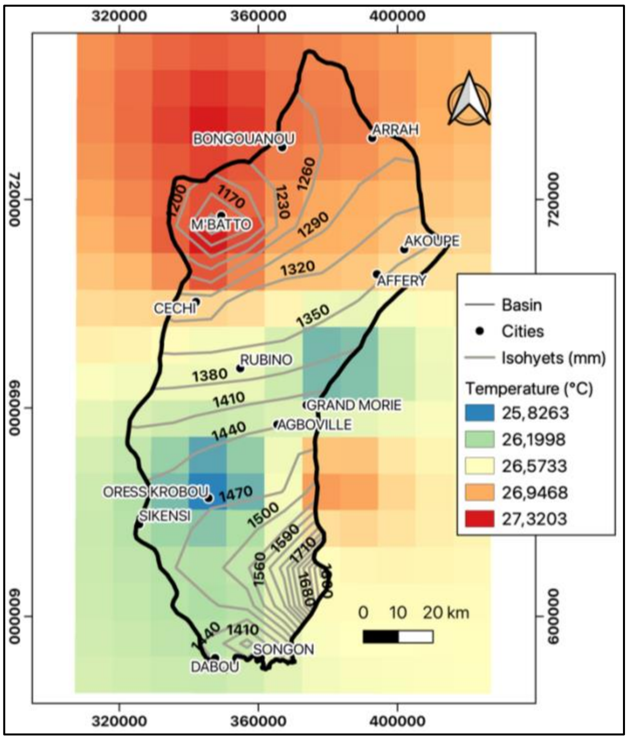

Figure 16: Rainfall and Temperature

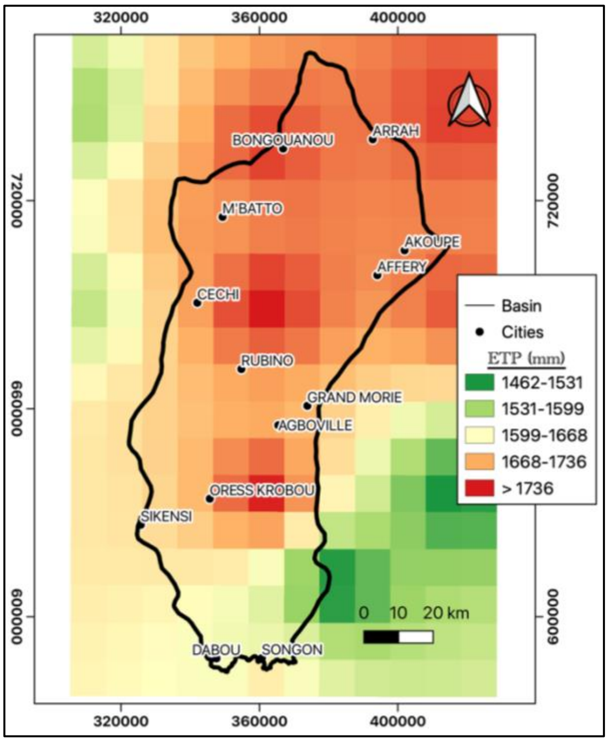

Figure 15: Evapotranspiration

4.2.3 Infrastructural aspect

Another aspect that we considered in the establishment of our database is the infrastructures. In this regard, we intended to collect data on hydraulic infrastructures, schools, roads, health facilities, markets, leisure and recreation centres, etc. However, we could only obtain data on hydraulic infrastructure, health facilities and roads. The hydraulic infrastructure available are mainly composed of boreholes, reservoirs and surface water intake installations. The figures 17 and 18 show an overview of these sets of infrastructure.

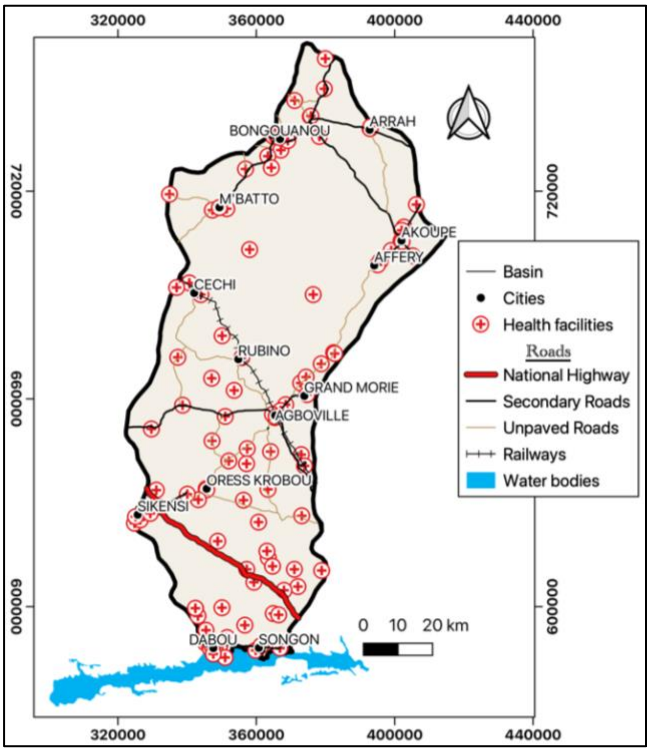

Figure 17: Health facilities

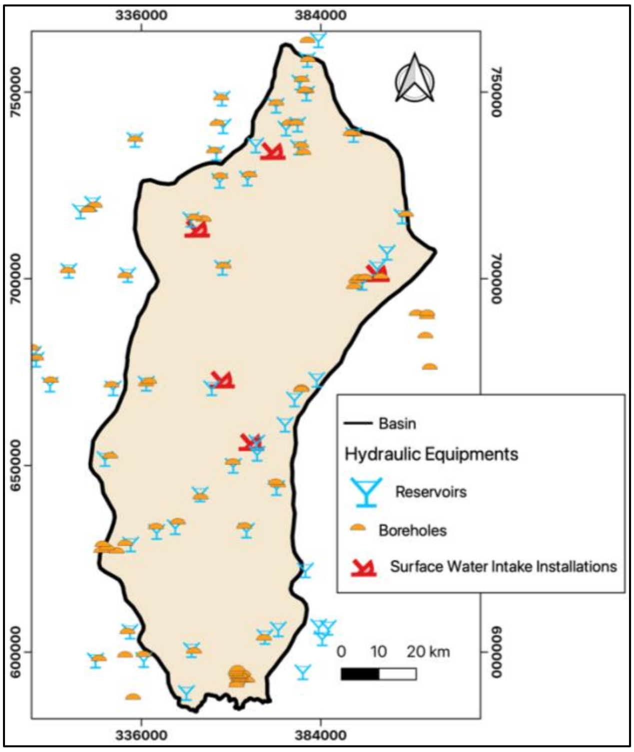

Figure 18: Hydraulic assets

4.2.4 Land use of the River Agneby Basin

Land use is very important in water resources management. In fact, is it now recognized that land use changes have substantial effects not only on key atmospheric processes of the hydrologic cycle, including evapotranspiration and precipitation, and land-surface processes but also on water quality and groundwater recharge (Stonestrom et al., 2009). Because the basin is located in the forest zone of the country, a large part of it is covered by vegetation type land use classes including forest areas, agricultural areas and wetlands. This type of land use, although favourable to groundwater recharge, some of its subclasses (e.g., agricultural areas) are a major consumer of surface water due to irrigation.

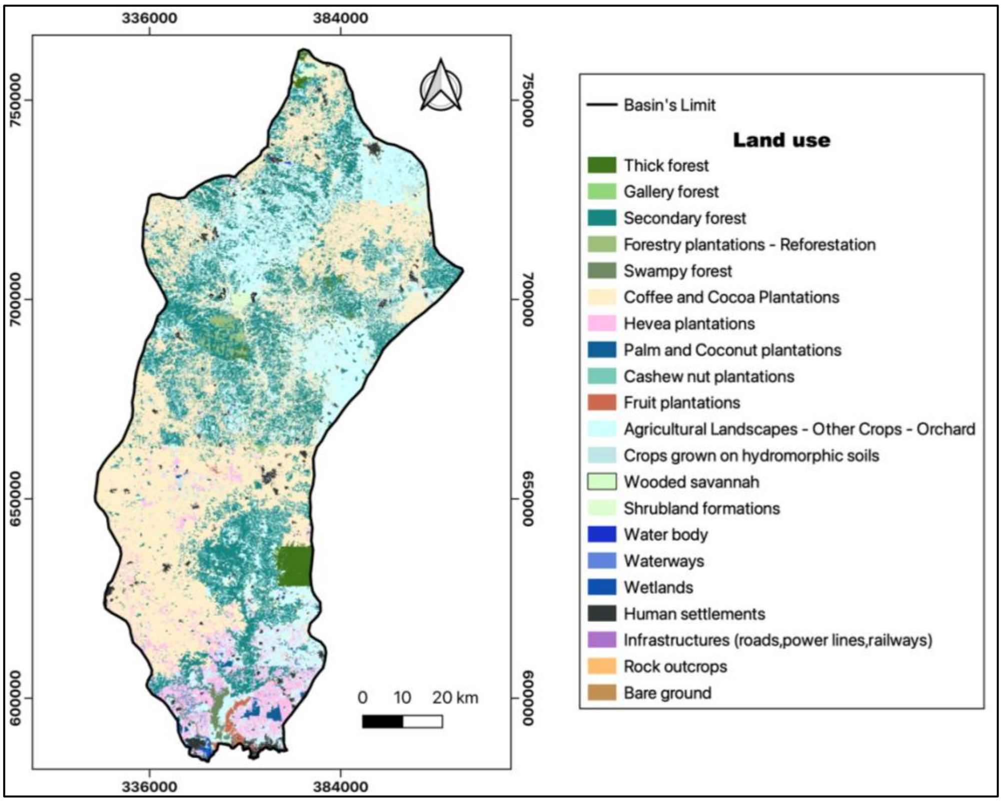

Figure 19: Land use

4.3 The Web-GIS platform

Our web application called "*RIVER AGNEBY BASIN WEB GIS INTERFACE* was designed with simplicity as a major focus because it is intended for an uninformed public. There are, among others, different data layers, a map visualization functionality, as well as tools for the selection of layers, calculation of distances, searching specific information (including coordinates) based on keyworks, navigation (zoom, tooltips, etc.), and drawing.

For improved transparency, we have added a satellite imagery background to the OpenStreetMap background, which allows the entities represented to be viewed directly as if they were on the actual ground.

This webGIS tool is of major importance for integrated water management in the basin. Indeed, it allows stakeholders to have information on the basin at any time and place via the internet. This system solves the problem of scattered data and information between various ministries and offices for effective management of the basin. This allows resource managers to be more efficient and to execute their tasks more quickly by avoiding all the administrative bureaucracy. This developed prototype clearly has the potential to become a water information system for the River Agneby basin and can be used as a benchmark to develop similar water management systems for other basins in the country.

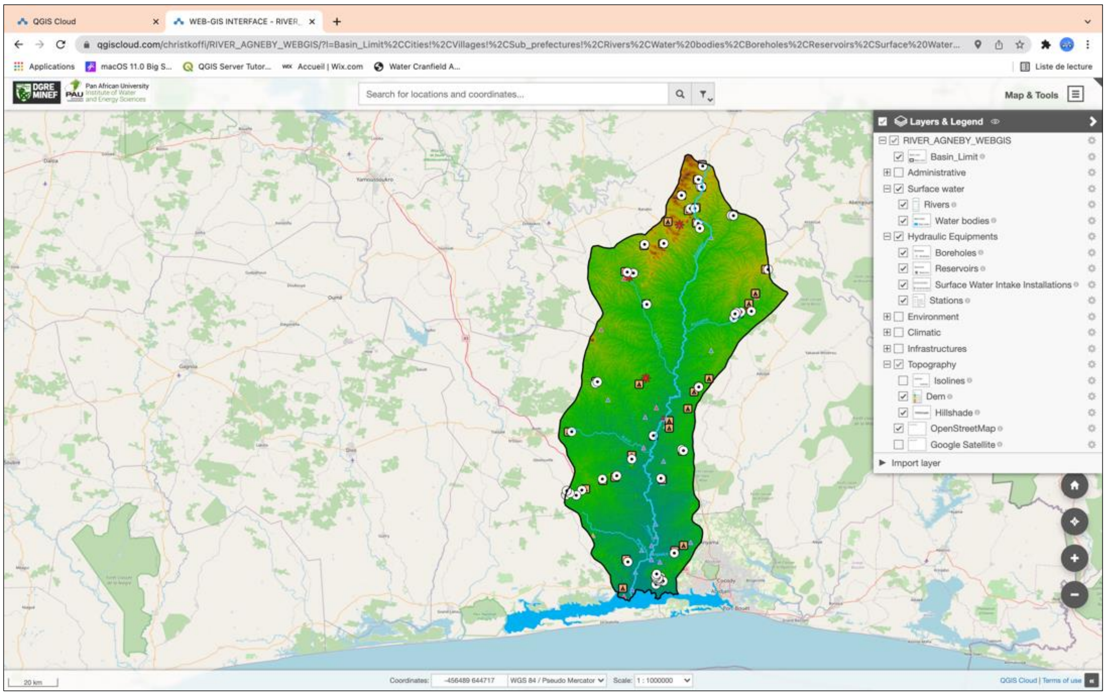

Figure 20: Web-GIS interface

4.4 Discussion

4.4.1 GIS tools and water resources management

In this study, we set up a prototype web-GIS to enhance the management of water resources in the Agneby River Basin in Cote d'Ivoire. In order to improve information awareness, capacity building and access to spatial information in IWRM processes, the project implements GIS tools using several layers and engages with stakeholders in the water and land sectors. The project contributes to a better spatial understanding of IWRM processes and to ensure better decision-making regarding water supply, availability and accessibility.

GIS has become one of the most relevant tools for water resources management in recent decades (Mundia, 2015; Latinopoulos et al., 2004; Jolk et al., 2015). Consequently, many studies in hydrography, (e.g., Deogawanka, 2016), in hydrology (e.g., Stonestrom et al., 2009) and water engineering, (e.g., Teodosiu et al., 2009), have used GIS for the storage, analysis and presentation of water-related data.

Mundia (2015), through his study of development of a GIS-based support tool for IWRM in Zambezi catchment area in Namibia, presents a regional monitoring system that integrates Earth Observations such as satellite imagery and forecast models, with situ and other ancillary information for timely decision-making. As in our study, a database that included general basin information such as the geographical boundary of the basin, administrative divisions of the basin, population, etc. and data directly related to water such as climate, hydraulic and hydrological measurements. Additionally, he included data on the impact of flooding and climate change, as well as mitigation and adaptation measures, all in the context of IWRM. In our study, this last aspect was not taken into account in the scope of this study. Another thing that makes Mundia's study interesting is the integration of the participatory approach in which consultative meetings, focus group discussions, and workshops were held to gather information on people's farming practices. This participatory approach enabled the development of a SWOT (Strengths, Weakness, Opportunities and Threats) analysis of the region. At the end, Mundia (2015) implemented a database has allowed the development of a GIS tool in the form of a software that can be installed on computers, however, our database was used to develop a web-based GIS application that can be utilized via the web.

In the same sense of the application of GIS tools in water resources management, Latinopoulos et al. (2004) presented an application of GIS for the management of water resources in the municipality of Moudania in Chalkidiki (Greece). The study presents the basic components of the GIS and its related computer databases, along with a typical presentation of the management possibilities. In order for the GIS management model to simulate the water resources of the study area satisfactorily, a large collection of data was obtained, adjusted, and integrated into a computer database. Unlike our study, which considered all aspects of water resource management in the basin's catchment area, Latinopoulos et al. (2004) focused on water supply and demand management because the study area was an agricultural landscape in which the water demand for irrigation summed up to 90% of the total water consumption in the area. We could not adopt this simplified approach, but rather a more comprehensive approach, because of the diversity of anthropogenic land use activities in (and the resulting diversified landscape of) the Agneby Basin.

Our study and its approach also compare well with the study of Jolk et al. (2015). In their study, they developed a web-based tool for operational decision making and water management planning of Bogotá River basin in Columbia, including the management and modelling stakeholder's needs.

4.4.2 Relevance of the tool for IWRM in the Agneby Basin

According to Assoma, (2013), mobilizable surface water resources in the Agneby basin have fallen by 50% since 1980 and have remained in deficit. Consequently, it is necessary today to make a quantitative assessment of surface water and groundwater for a sustainable management of the resource. In this sense, the developed GIS tool and its backend database can be of great use for the processing, storage and analysis of quantitative water data. The uses of water in the basin are diverse. We can mention uses for water supply and sanitation, mineral water production, irrigation of agricultural areas, ponds for fish farming, etc. Article 59 of the water code defines the State (through its water management bodies such as MINEF) as the manager of water resources. *The State ensures management by preserving the quality of sources, preventing wastage and guaranteeing availability* (Law N°98-755 of the 23th December Referring to Water Code of the Republic of Cote d'Ivoire, 1998). Despite their status as managers, the state bodies do not have tools for control, monitoring and evaluation. After the allocation of use and abstraction authorizations, no attempt is made to quantify the amount of water withdrawn, which leads to a lack of clarity. That is why it is important to add to our database data of quantification of water withdrawals in order to have figures on the annual volumes directly withdrawn from the water resource, classified by location (spatial distribution of uses in the basin) and by category of water use and to protect the resource. In addition, the tool allows the typology of equipment such as river flow measurement stations, climatic data and hydraulic assets, and to know their characteristics such as the state of functionality, type of material, capacities and their geographical locations (Figure 14).

Figure 17 shows a map of hydraulic assets in the basin. According to the spatial distribution of boreholes, reservoirs and water intake installations, we can say that most part of the River Agneby Basin have access to water for different purposes such as drinking and other domestics needs.

The GIS based tool ensures the modernization of the current management system which consists of the physical archiving of data and information, the disadvantages of which are, among others, the loss of data in the event of a disaster, the problem of access to documents, the risk of loss or leakage of documents, wastage of time, the lack of space for the storage of archives, etc. The digital database ensures modernisation and innovation in services, ease of search through queries, data security, task automation and interoperability.

The tool developed can also be regarded as a stakeholder-oriented integrated water resources management system (IWRMS, an information platform for facilitating communication between stakeholders (including the public) and supporting decision making.

4.4.3 Future dimensions to be developed

The development of a water information system for IWRM requires a very large database. As earlier indicated, there are some dimensions of the database that have not yet been developed due to time constraint. This needs to be done in the future for completeness. The table below provides a non-exhaustive list of data to be added.

Domain	Data Types
Water quality (Ground and Surface waters)	- Chemical composition of water - pollution areas - types of pollution
User's domain	- Irrigated areas. - Industrial areas. - Domestic consumption of drinking water. - Agricultural consumption (irrigation and livestock). - Industrial consumption - Energy-Cooling water in thermal power plants
Groundwater	- Aquifer characteristics (name, identifier, region, direction, transmissivity, - permeability, - Coefficient of storage. - Measured piezometric data. - Aquifer withdrawals. - Hydrochemical data recorded. - Isotope analyses - Hydrochemistry
Socio-economic	- Demographic data - Rural and urban settlements - Agriculture - Irrigated and unirrigated land: major and minor irrigation schemes Livestock resource - Livestock distribution and densities

Table 10: A non-exhaustive list of data for database extension

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, we have set up a prototype web-GIS powered by a database containing spatial data covering the different aspects of water resources management of the Agneby River Basin in Côte d'Ivoire. We consider this to be a preliminary result of our attempt to develop a GIS-based integrated water resources management system for the basin. Several relevant datasets about the basin which were previously scattered in data archives hosted by different institutions, web-based data platforms as well as digital and hard-copy publications have been successfully integrated for effective utilization. Thus, the objectives of this study have been achieved even though the database that underlie our web-GIS can be further improved through further data gathering, processing and integration. For example, the database can be improved by adding data on watershed such as groundwater, flooding, drinking water supply and demand. Our inability to obtain and integrate these datasets is mainly due to limitations in time and finance, coupled with the travel difficulties and delays due to the COVID-19 pandemic.

In summary, our study,

- developed a database made up of several thematic maps of our study area, and
- developed a prototype web GIS which is currently accessible on localhost.

It is envisaged that our GIS-based web tool will provide timely, transparent and easily readable data products, help transform data and information into knowledge, and contribute to decision making in the integrated water resource management of Agneby River Basin.

5.2 Recommendations

The tool that we have developed, will be proposed to MINEF's Water Resources Directorate. Our recommendations are as follows:

- ✓ To continue the development of the database and to integrate more data, especially hydrometric data, data on flood risk areas in the basin and data on water quality with an emphasis on identifying pollution points.
- ✓ The database that has been developed should be used to improve access, exchange and sharing of data and information between different departments and ministries.
- ✓ The database should be continuously and regularly updated to fill in the gaps and add new data to eliminate the existing data gaps and to make the database fully operational and sustainable.

- ✓ Standardization of future data entry is recommended. This will eliminate problems associated with differences in data formats, semantics, as well as missing and erroneous coordinates, etc.
- ✓ To collect, store, archive and retrieve all the data collected, a dedicated GIS and database section be equipped with a GIS software and powerful computers should be set up.
- ✓ The GIS tool presented in this study should be developed so that it transitions from a simple GIS web application to a fully functional Water Information System.

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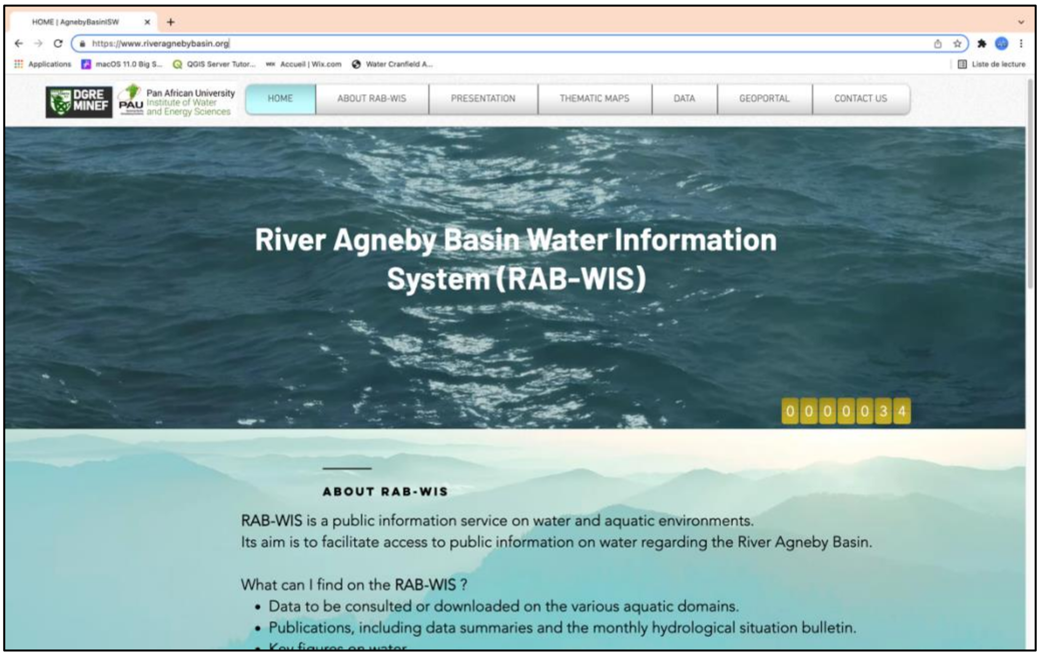
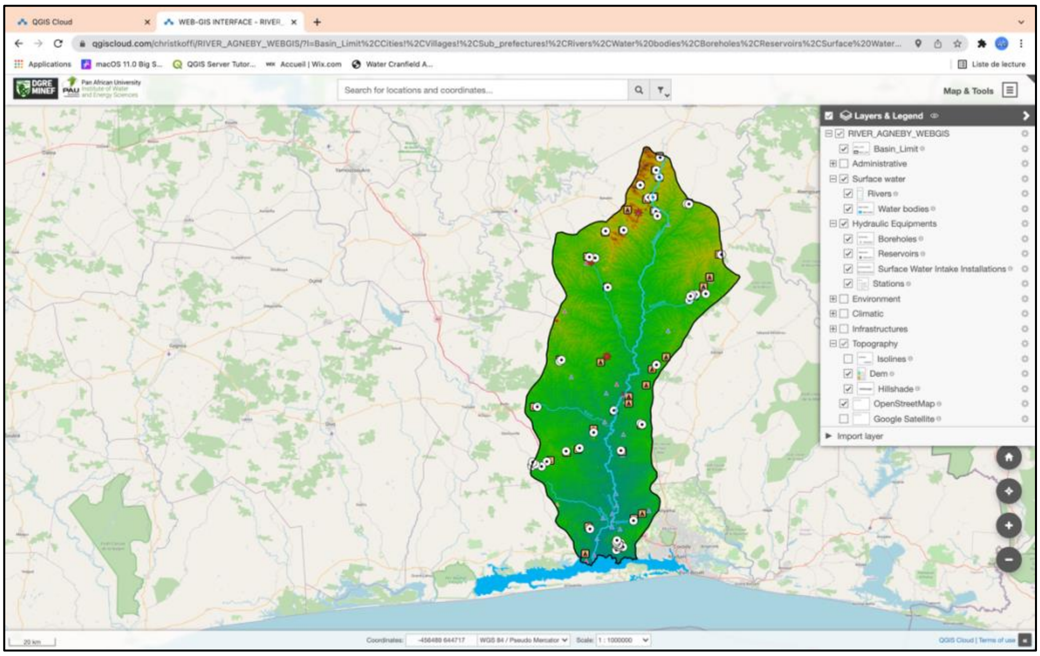
APPENDIX

WEBTOOL LINK: https://www.riveragnebybasin.org/

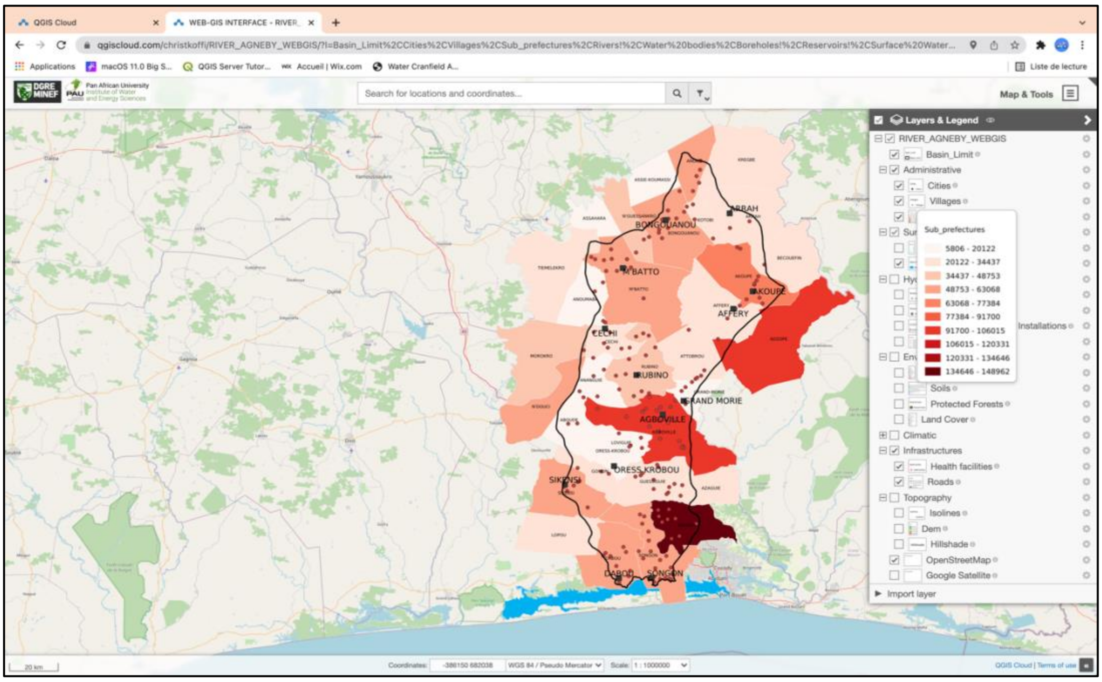
RAB-WIS



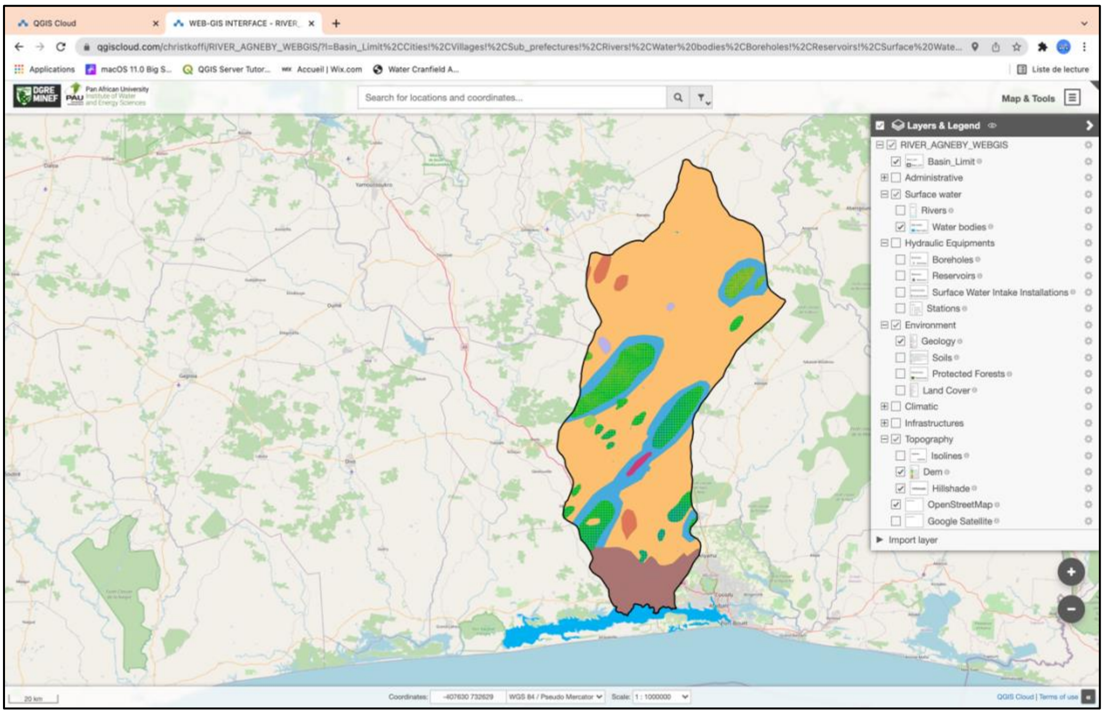
Web-GIS Portal.



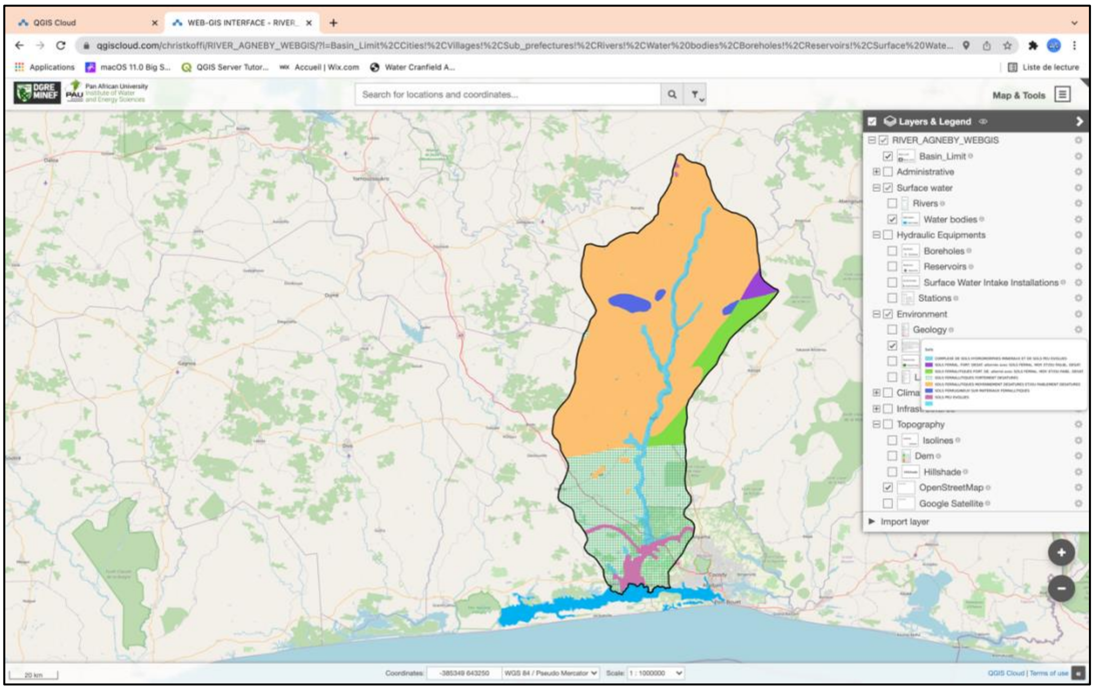
Rivers and hydraulic equipment



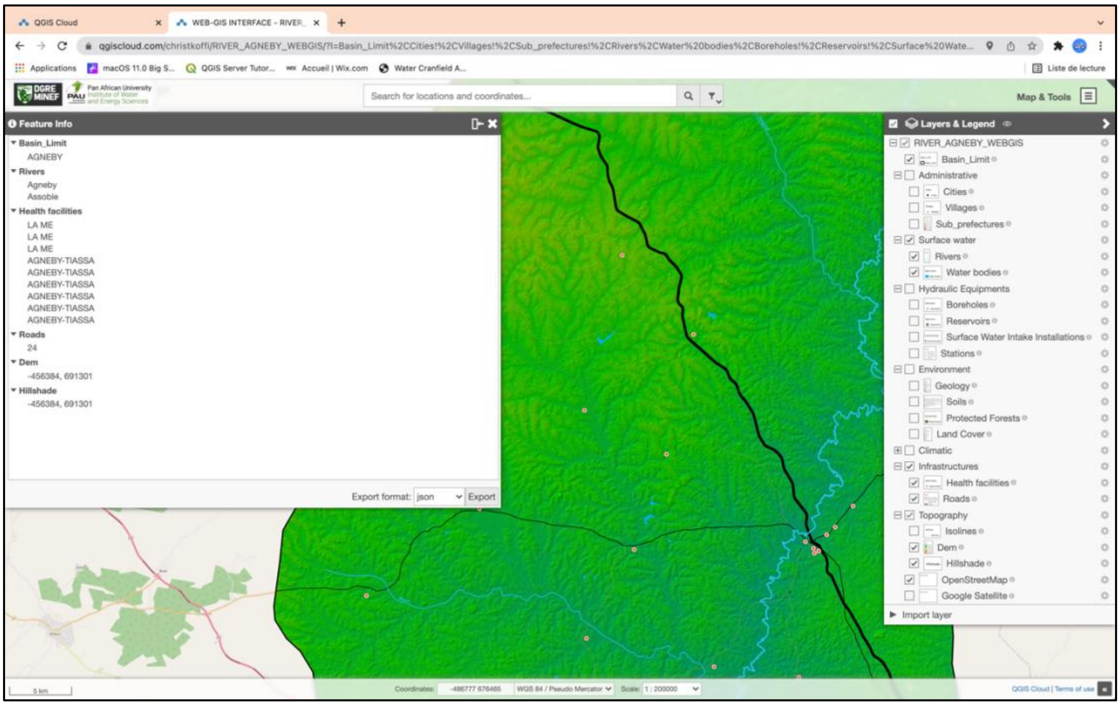
Population and Administrative divisions



Geology



Soils



Query on the Web-Map

Research Budget

S/No.	Item	Unit	Quantity	Rate (Unit price)	Amount*	Link to Research Activity**	Comment*** (For Evaluator Only)	Invoices (in order with PDF version)
(A) Material and Supplies								
1	Internet Service	month	4	25000 FCFA	152,45 €	Online activities		**Invoices_1- 4**
2	Internet Service	-	-	1500 Da	9,40 €	Online activities		**Invoices_16**
	Sub Total				**161,85 €**			
(B) Equipment								
3	Rainfall data				**905,78 €**	Data		**Invoices_6**
4	Web Domain WIX			204 USD	**175,97 €**	WebSite Hosting		**Invoices_5**
5	QGIS Cloud Server				**65,00 €**	WebGIS Hosting		**Invoices_18-19**
	Sub Total				1 146,75 €			
(C) Travel + Visa Costs								
6	Round-Trip	1	1	160599 Da	€ 1 009,61	Research Travel		
7	Visa fee	1	1	19900 Da	€ 125,10	Visa fee		**Invoices_10-12**
8	Field transportation			283000FCFA	€ 431,43	Field study		**invoices_7-9**
9	PCR Test			25000 FCFA	€ 38,11	Covid-19 safety measures		**invoices_13**
10	Test-Covid antigenique			10euro	€ 10,00	Covid-19 safety measures		**invoices_14-15**
11								
	Sub Total				**1 614,25 €**			
(D) Special Activities e.g. course, etc…								
14	Books Purchasing		1	23,56	€23,56	littérature review		**Invoice_17**
15								
	Sub Total				23,56 €			
(E) Contingencies (%) (reserve at least $100 from which eventual bank								
Contingencies						Unexpected cost events that may arise during the		
TOTAL								
A	Personnel							
B	Material & Supplies				161,85 €			
C	Equipment				1 146,75 €			
D	Travel				1 614,25 €			
E	Special Activities				€23,56			
F	Contingencies (%)				0,00 €			
	Grand Total				2 946,41 €			