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************ UNIVERSITÉ DE YAOUNDÉ I**
************ FACULTÉ DES SCIENCES**
****
CENTRE DE RECHERCHE ET DE FORMATION DOCTORALE EN SCIENCES TECHNOLOGIE ET GÉOSCIENCES
****
UNITÉ DE RECHERCHE ET DE FORMATION DOCTORALE EN PHYSIQUE ET APPLICATIONS
************ DÉPARTEMENT DE PHYSIQUE BP: 812 Yaoundé**
Email: crfd@uy1.uninet.cm

REPUBLIC OF CAMEROON
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************ UNIVERSITY OF YAOUNDE I**
************ FACULTY OF SCIENCE**
************ POSTGRADUATE SCHOOL OF SCIENCE TECHNOLOGY AND GEOSCIENCES**

****
RESEARCH AND POSTGRADUATE TRAINING UNIT FOR PHYSICS AND APPLICATIONS
************ DEPARTMENT OF PHYSICS P.O. Box: 812 Yaoundé**
Web Site: www.uy1researchstg.cm

Laboratoire de Physique de l'Environnement Terrestre
Laboratory of Earth's Environment Physics

Evaluating Water Resources for Sustainable Urban Supply in Kribi Town: A Combined Hydrogeological, Hydrogeochemical, Surface Water, and GIS-Based Assessment

Thesis submitted and defended publicly in fulfillment of the requirements for the Award of the Degree of Doctorate/PhD in Physics.

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By

GAH-MUTI Salvanus YEVALLA

Registration Number: 04Q351

"DEA es Géophysique Interne"

Supervisor

TABOD Charles TABOD
Professor, University of Yaounde I

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DEPARTMENT OF PHYSICS

ATTESTATION DE CORRECTION DE LA THESE DE DOCTORAT/Ph.D

Nous, Professeur **HONA Jacques** et Professeur **NOUAYOU Robert**, respectivement Examinateur et Président du jury de la thèse de Doctorat/Ph.D de Monsieur **GAH-MUTI Salvanus YEVALLA**, Matricule **04Q351**, préparée sous la direction de Professeur **TABOD Charles TABOD**, intitulée « **Evaluating Water Resources for Sustainable Urban Supply in Kribi Town: A Combined Hydrogeological, Hydrogeochemical, Surface Water, and GIS-Based Assessment**», soutenue le **Lundi 21 Avril 2025**, en vue de l'obtention du grade de Docteur/Ph.D en Physique, spécialité Physique de L'environnement Terrestre, option Géophysique et Géoexploration, attestons que toutes les corrections demandées par le Jury de soutenance ont été effectuées.

En foi de quoi, la présente attestation lui est délivrée pour servir et valoir ce que de droit.

Fait à Yaoundé le 29 AVR 2025

Examinateur

Pr HONA Jacques

Le Président du Jury

Pr NOUAYOU Robert

Le Chef de Département de Physique

Le Chef de Département

Ndjaka Jean-Marie Bienvenu
Professeur

DEDICATION

To my loving and caring Mother, Nah Gloria NAH-KUM

And

In loving memory of my Father, Doh GAH-MUTI John MULAH

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ABSTRACT

Kribi Town, a rapidly growing coastal community in Cameroon, faces mounting water scarcity challenges driven by population growth, industry, tourism, and climate change. This research provides a comprehensive assessment of Kribi's water resources using an integrated approach combining hydrogeological, hydrogeochemical, surface water, and GIS-based analyses, aiming to propose sustainable supply strategies.

Advanced geophysical investigations (electroseismic, VES) delineated a heterogeneous aquifer system: a shallow unconfined aquifer (sand/gravel, ~50 million m^3 static volume) and a deeper confined aquifer (fractured/weathered granite). Hydrogeochemical analysis revealed concerning salinity, with 75% of samples exceeding WHO chloride limits (250 mg/L), indicating significant saltwater intrusion, primarily centrally and southward. Localized heavy metal contamination (As, Pb, Hg) exceeding WHO guidelines, likely linked to industrial/waste disposal activities, was also detected. Kribi's northern part shows promise for more sustainable groundwater development.

The Kienke River's potential was evaluated using HEC-HMS modeling, considering rainfall and land use. Results showed remarkably high average discharge. The river's estimated runoff volume is approximately 75 times greater than Kribi's projected 2030 needs, confirming its viability as a primary source despite seasonal variability.

Optimal potential reservoir locations were identified using GIS-based Multi-Criteria Evaluation (MCE), considering environmental and social factors like land use, settlement proximity, and slope to ensure sustainability. MCE analysis successfully identified suitable locations within the Kienke watershed, notably one site near the SOCAPALM plantation boundary.

This research offers a holistic understanding of Kribi's water resources, providing a crucial foundation for informed decision-making and sustainable management. The integrated approach serves as a valuable, adaptable framework for water resource assessment, particularly in data-scarce regions, guiding communities towards a water-secure future.

Key Words: Electroseismic (ES), Vertical Electrical Sounding (VES), Sustainable Water Supply, Hydrological Modeling, Water Resources Management

RESUME

La ville de Kribi, communauté côtière en pleine expansion au Cameroun, est confrontée à des défis croissants de pénurie d'eau, exacerbés par la croissance démographique, l'industrie, le tourisme et le changement climatique. Cette recherche fournit une évaluation exhaustive des ressources en eau de Kribi en utilisant une approche intégrée combinant des analyses hydrogéologiques, hydrogéochimiques, des eaux de surface et basées sur SIG, visant à proposer des stratégies d'approvisionnement durables.

Des investigations géophysiques avancées (électrosismiques, SEV) ont délimité un système aquifère hétérogène : un aquifère libre peu profond (sable/gravier, ~50 millions m^3 volume statique) et un aquifère captif plus profond (granite fracturé/altéré). L'analyse hydrogéochimique a révélé une salinité préoccupante, avec 75% des échantillons dépassant la valeur guide de l'OMS pour les chlorures (250 mg/L), indiquant une intrusion d'eau salée significative, principalement au centre et au sud. Une contamination localisée par les métaux lourds (As, Pb, Hg) dépassant les directives OMS, probablement liée aux activités industrielles ou à l'élimination inadéquate des déchets, a également été détectée. La partie nord de Kribi s'avère prometteuse pour un développement plus durable des eaux souterraines.

Le potentiel du fleuve Kienke a été évalué par modélisation HEC-HMS, en tenant compte des précipitations et de l'utilisation des terres. Les résultats ont montré un débit moyen remarquablement élevé. Le volume d'écoulement estimé du fleuve est environ 75 fois supérieur aux besoins projetés de Kribi pour 2030, confirmant sa viabilité comme source principale malgré sa variabilité saisonnière.

Des emplacements potentiels optimaux pour des réservoirs ont été identifiés par Évaluation Multicritère (EMC) basée sur SIG, considérant des facteurs environnementaux et sociaux tels que l'utilisation des terres, la proximité des habitations et la pente pour assurer la durabilité. L'analyse EMC a identifié avec succès des sites appropriés dans le bassin versant du Kienke, notamment un près de la limite de la plantation SOCAPALM.

Cette recherche offre une compréhension globale des ressources en eau de Kribi, fournissant une base cruciale pour la prise de décision éclairée et la gestion durable. L'approche intégrée constitue un cadre précieux et adaptable pour l'évaluation des ressources en eau, en particulier dans les régions pauvres en données, guidant les communautés vers un avenir où l'eau sera sécurisée.

Mots Clés : Électrosismique (ES), Sondage Électrique Vertical (SEV), Gestion des ressources en eau, Modélisation hydrologique, Approvisionnement durable en eau

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LIST OF ACRONYMS AND ABBREVIATIONS

IWRM = Integrated Water Resources Management

CVL = Cameroon Volcanic Line

CARS = Central African Rift System

GIS = Geographic Information Systems

HEC-HMS = Hydrologic Engineering Center's Hydrologic Modeling System

MCE = Multiple Criteria Evaluation

GPR = Ground-Penetrating Radar

TEM = Transient electromagnetic

FDEM = Frequency-domain electromagnetic

ES = Electroseismic

EDL = Electrical Double Layer

FDM = Finite-Difference Method

FEM = Finite-Element Method

SEM = Spectral-Element Method

VES = Vertical Electrical Sounding

ERT = Electrical Resistivity Tomography

TDS = Total Dissolved Solids

EC = Electrical Conductivity

WHO = World Health Organization

USTs = Underground Storage Tanks

BMPs = Best management practices

IPM = Integrated Pest Management

SCS = Soil Conservation Service

CN = Curve Number

HRUs = Hydrological Response Units

DEM = Digital Elevation Model

AHP = Analytical Hierarchy Process

GRDC = Global Runoff Data Centre

WMS = Watershed Modeling System

MDD = Maximum Day Demand

DOI = Depth of Investigation

HSG = Hydrologic Soil Group

NOAA = National Oceanic and Atmospheric Administration

NDS = National Development Strategy

LIST OF SYMBOLS

Greek Letters & Mathematical Symbols:

ΔV : Potential difference or Streaming Potential (Volts)

ΔP : Pressure change induced by seismic wave (Pascals)

ε : Fluid permittivity (Farads/meter)

ε_0 : Vacuum permittivity

ζ : Zeta potential (Volts)

η : Fluid viscosity (Pascal-seconds)

σ : Fluid conductivity (Siemens/meter)

ρ : Fluid density (kg/m ^{3})

ρ_e : Electric charge density (Coulombs/m^3)

ρ_a : Apparent resistivity (?m)

μ : Fluid dynamic viscosity

$\nabla \cdot$: Divergence operator

$\nabla \times$: Curl operator

$\partial / \partial t$: Partial derivative with respect to time (or $\frac{\partial}{\partial t}$)

Σ : Summation symbol

$\delta^2 H$: Deuterium isotope ratio (‰)

$\delta^{18} O$: Oxygen-18 isotope ratio (‰) (Implied, used alongside $\delta^2 H$)

Latin Letters (Variables & Parameters):

u : Fluid velocity field (vector quantity)

p : Fluid pressure

F : External body forces (vector quantity)

E : Electric field (vector quantity, Volts/meter)

B : Magnetic field (vector quantity, Teslas)

J : Total current density (vector quantity)

J_s : Streaming current density (vector quantity, Amperes/m^2)

L : Electrokinetic coupling coefficient

K : Geometric factor (for VES)

I : Injected current (Amperes)

A, B, M, N: Electrode labels in VES (Current A, B; Potential M, N)

K : Muskingum travel time parameter (hours)

X : Muskingum weighting factor parameter

Q_o : Observed discharge (m³/s)

Q_m : Modeled discharge (m³/s)

$\bar{Q}_o$: Mean observed discharge (m³/s)

t : Time or index for time steps

T : Total number of time steps

N_t : Population at time t

N_0 : Initial population

r : Per capita growth rate

GENERAL INTRODUCTION

Water, the essence of life, is a finite resource facing unprecedented strain across the globe. Urban areas, with their concentrated populations and economic activities, are particularly susceptible to water scarcity. This challenge arises from a complex interplay of factors including rapid population growth, industrial expansion, climate change, and inadequate water infrastructure and management practices (Howard et al., 2010; UN-Water, 2021).

The magnitude of the global water crisis is staggering, with an estimated 2 billion people, representing 26% of the world's population, experiencing severe water scarcity for at least one month annually (UN-Water, 2021). The situation is particularly concerning in Sub-Saharan Africa, where water demand is projected to outpace supply by 40% by 2050 due to population growth and economic development (Howard et al., 2010). This region faces unique water challenges, including aridity in areas like the Sahel and widespread infrastructure gaps that limit access to safe drinking water (UN-Water, 2018).

Cameroon reflects these challenges, with only about 58% of the population having access to safe drinking water. The gap continues to widen as the increasingly urban population places further strain on existing service providers (Fonjong and Fokum, 2017). Kribi Town, a coastal town in Cameroon, exemplifies the struggles of many burgeoning urban areas. Its growing population, estimated at 40,000 inhabitants in 2018 (PAK, 2018), coupled with ambitions for tourism development, places immense pressure on its water resources. This research aims to address these challenges by comprehensively evaluating Kribi's water resources and proposing sustainable solutions to ensure the town's future prosperity and the well-being of its residents.

This thesis begins with this general introduction, providing context and highlighting the urgency of the water crisis. Chapter 1 presents a thorough literature review, examining existing research on urban water resource management strategies, hydrogeological assessments, water quality analyses, and integrated approaches like IWRM. The subsequent Chapter 2 details the materials and methods employed in this study, encompassing the specific techniques used for data collection, analysis, and modeling. Chapter 3 presents the results obtained from the field investigations, laboratory analyses, and computer simulations, followed by a comprehensive discussion of their implications for understanding Kribi's water resources and potential solutions. Finally, the thesis concludes by summarizing the key findings, outlining recommendations for sustainable water management in Kribi Town, and highlighting the broader significance of the research for addressing water scarcity challenges in other communities.

1 CHAPTER ONE: LITERATURE REVIEW

1.1 Introduction

The escalating global water crisis, driven by a confluence of factors like rapid population growth, industrial expansion, and the looming threat of climate change, has placed immense pressure on urban areas to adopt sustainable water resource management (WRM) strategies (Howard et al., 2010; UN-Water, 2021). Urban centers, with their concentrated populations and economic activities, are particularly vulnerable to water scarcity, jeopardizing public health, economic development, and environmental sustainability (ICLEI and Habitat, 2009). Coastal towns, like Kribi in Cameroon, face the added complexities of limited freshwater availability and increased susceptibility to contamination and saltwater intrusion (Sendrós et al., 2021). This necessitates a specific focus on integrated and sustainable water management approaches that consider the unique context of coastal environments.

Kribi Town, similar to many burgeoning urban areas, grapples with insufficient water infrastructure and a growing need for innovative solutions to meet its increasing water demands (SNH, 2008). This literature review delves into existing research on urban water resource management strategies, encompassing hydrogeological assessments, water quality analyses, and integrated approaches like IWRM. The aim is to identify methodologies and best practices applicable to Kribi's specific situation while highlighting knowledge gaps that require further investigation. This will allow for the development of tailored and effective water management strategies that ensure a secure and sustainable water future for Kribi Town.

1.2 Evaluating Water Resources within Cameroon

Cameroon, located in Central Africa, possesses abundant water resources with diverse sources including rivers, lakes, and groundwater aquifers. However, the distribution of these resources is uneven, with some regions experiencing water scarcity while others face challenges related to water quality and access (Ako et al., 2010). Evaluating water resources in Cameroon requires a comprehensive approach that considers both the national context and the specific circumstances of local areas like Kribi Town.

Evaluating water resources in Kribi requires a detailed understanding of the local hydrogeological context, including the characteristics of the aquifer system, recharge potential, and vulnerabilities to contamination and saltwater intrusion. Additionally, assessing the potential of alternative water sources, such as the Kienke River is crucial for developing a sustainable and resilient water supply for the town. This thesis aims to address these knowledge gaps and provide a comprehensive evaluation of Kribi's water resources, laying the foundation for effective and sustainable water management strategies.

1.3 Water Resources Management Context in Cameroon

National Policies: Cameroon's water sector operates under the framework of the 1998 Water Law (Law No. 98/005), emphasizing principles of IWRM, sustainable use, conservation, and equitable access (Tamasang, 2007). A recent revision in 2023 aims to strengthen the law's implementation and address emerging challenges (GWP, 2023).

Institutional Framework: Despite ongoing decentralization efforts in Cameroon, water governance remains largely centralized, raising questions about the extent to which regional and municipal authorities have the capacity and resources to effectively manage water resources (Ndonko and MFOUABON, 2021).

Existing Studies: While research on water resources in Cameroon exists, it has primarily focused on national or regional water balances, agricultural water demand, and the impacts of climate change (Ako et al., 2010; Lienou et al., 2008). Specific studies addressing the complexities of urban water management, particularly within the unique context of coastal towns like Kribi, remain limited (Fonjong and Fokum, 2017).

1.4 Study Area Description

1.4.1 Geography

The study area centers on the coastal town of Kribi, located within the Ocean Division of Cameroon's South Region. Kribi comprises two subdivisions (Kribi 1 and Kribi 2) and borders the Atlantic Ocean to the west (Figure 1). Situated approximately 150 km southwest of Douala, Cameroon's economic capital, Kribi lies within the Gulf of Guinea's coastal zone. The town's geography is characterized by relatively flat coastal plains that gradually transition into undulating hills further inland. This topographic variation influences both surface water drainage patterns and the characteristics of the local aquifer systems. The town's coastal location also raises the potential for interactions between groundwater and saltwater, an important consideration when assessing water resources in the region.

1.4.2 Climate

Kribi Town experiences a tropical monsoon climate (classified as "Am" according to the Köppen climate classification system), characterized by consistently warm temperatures and distinct wet and dry seasons (Weatherbase, 2021). Average high temperatures throughout the year range from 29-32 °C, creating a warm and humid environment. The region receives significant annual rainfall, exceeding 2500 mm (100 inches), concentrated in two distinct wet seasons: a long wet season from March to June and a shorter wet season from September to November (Lienou et al., 2008).

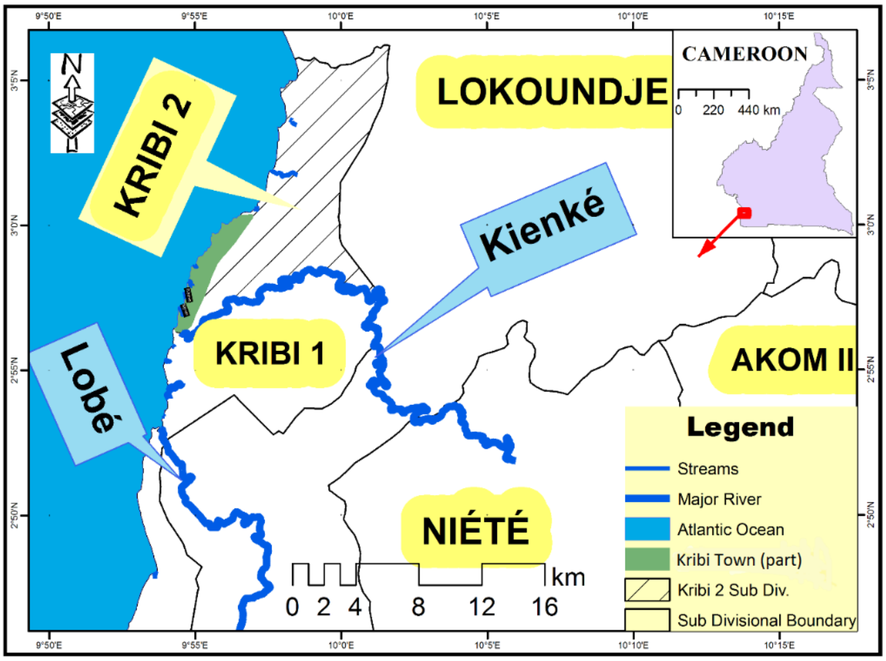


Figure 1: Location of Kribi town at the lower end of the Kienke River.

This high precipitation plays a crucial role in replenishing groundwater resources, as rainfall infiltrates the soil and percolates down to recharge aquifers. However, the intense rainfall events typical of a monsoon climate can also lead to rapid runoff and increased risk of flooding, necessitating careful management of surface water resources.

The consistently warm temperatures and high humidity levels throughout the year contribute to significant evapotranspiration rates. Evapotranspiration, the combined process of evaporation from the land surface and transpiration from plants, removes water from the hydrological system and can impact water availability, especially during the dry season (GWP, 2010).

Understanding these climatic patterns is essential for comprehending the dynamics of Kribi's water resources. Rainfall patterns influence groundwater recharge rates and surface water availability, while temperature and humidity impact evapotranspiration rates, affecting the overall water balance of the region.

1.4.3 Geomorphology and Hydrography

Kribi Town occupies a relatively flat coastal plain, characterized by gentle slopes extending across the catchment area. This low-relief topography suggests limited surface runoff during precipitation events, potentially favoring significant infiltration of rainwater into the subsurface and contributing to groundwater recharge. The Kienke River, skirting the edge of the town, serves as the primary drainage feature, collecting runoff from the surrounding area and discharging it into the Atlantic Ocean.

However, due to the river's peripheral location, direct recharge of Kribi's aquifers from the Kienke River may be limited. Therefore, the primary source of groundwater recharge within the town is likely the infiltration of precipitation through the soil. The overall river network within the study area appears sparse, with the Kienke River dominating the drainage system and no major tributaries observed.

1.4.4 Hydrogeology and Aquifer System

Similar to many coastal regions in Cameroon, Kribi Town's groundwater resources are characterized by relatively shallow aquifers. Investigations conducted by AES/Sonel at the Mpolongwe site reveal the presence of unconfined aquifers occurring at depths ranging from 3 to 11 meters, while confined aquifers are typically found at greater depths, between 40 and 70 meters (Paterne et al., 2021). These findings are corroborated by (Lordon et al., 2012), who identified the unconfined aquifer system within coarse, reddish sands at depths of 3 to 6 meters. Further along the Edea-Kribi corridor, José et al. (2021) confirmed the shallow nature of the aquifers, with unconfined systems ranging from 2 to 10 meters deep and confined aquifers found between 19 and 40 meters.

The lack of a specific and detailed hydrogeological model for the urban center of Kribi underscores the significance of this research. This study aims to establish a crucial baseline for understanding, managing, and sustainably utilizing the town's valuable groundwater resources. By characterizing the aquifer system, assessing water quality, and developing a comprehensive hydrogeological model, this research will provide essential information for ensuring the long-term availability and sustainability of Kribi's water supply.

1.4.5 Tectono-geological Settings

Kribi Town's geological setting as seen in Figure *2* reflects its position within Cameroon's diverse and dynamic landscape, creating a complex tapestry that significantly influences groundwater occurrence and flow patterns. The foundation of the region is composed of ancient Precambrian basement rocks, primarily metamorphic gneisses and schists, forming a stable and resistant base upon which younger geological formations have been deposited (Ngako et al., 2003).

Overlying this basement complex are younger sedimentary formations, potentially including sandstones, limestones, and shales, deposited during periods of marine transgression and regression throughout geological history. These sedimentary layers introduce variability in porosity and permeability, creating potential aquifers within the subsurface (Ntamak-Nida et al., 2010).

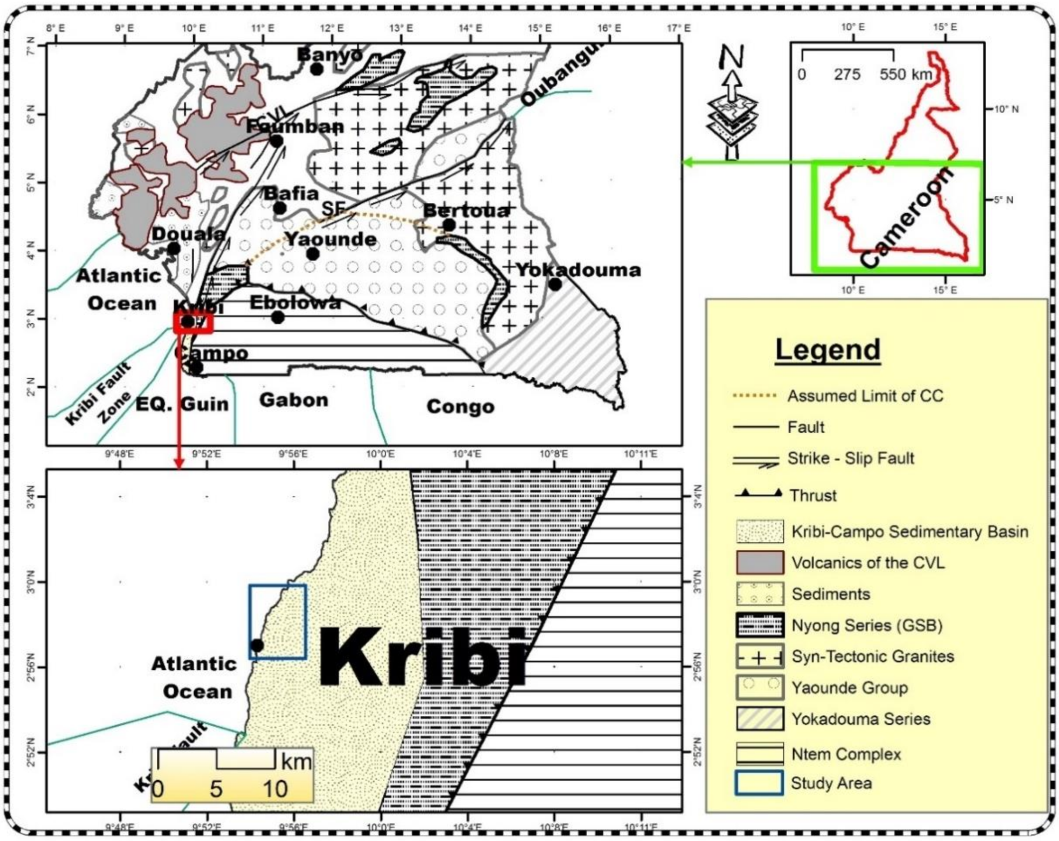


Figure 2: Geologic map of the area of interest, modified from (Owona et al., 2011)

Further shaping Kribi's geology is its proximity to two major tectonic features: the Cameroon Volcanic Line (CVL) to the west and the southern extent of the Central African Rift System (CARS). The CVL, a chain of volcanic massifs and volcanic centers extending from the Gulf of Guinea into the interior of Cameroon, introduces the possibility of localized igneous intrusions and volcanic deposits within the Kribi area. These volcanic rocks can create complex hydrogeological conditions, with both porous and fractured aquifers potentially present (Nfomou et al., 2004).

The influence of the CARS, a zone of crustal extension and rifting, suggests the presence of faults and fracture systems within the region. These structural features can act as conduits for groundwater flow, creating preferential pathways and influencing the connectivity of different aquifer units (Kissaaka et al., 2011).

The Kribi Basin itself, nestled between the CVL to the west and the Ntem Complex to the east, exemplifies this geological complexity. The Ntem Complex, composed mainly of gneisses and granites, provides a stable eastern boundary to the basin (ResearchKey, 2021). Within the basin, a sequence of Cenozoic sedimentary rocks, including sandstones, shales, and limestones, fills the depression created by tectonic activity and provides the primary target for groundwater exploration (Ntamak-Nida et al., 2010; Owona et al., 2011).

Understanding the hydrogeological characteristics of the Edea-Kribi corridor is crucial for comprehending groundwater flow dynamics in the Kribi area. José et al. (2021) highlight the importance of recognizing the different rock types present, with foliated rocks like gneisses and intrusive complexes like granites exhibiting varying degrees of fracturing and permeability. The tectonic history of the region has resulted in a complex network of fractures oriented in various directions (N10, N45, N50, E-W, etc.), which exert a significant control on groundwater flow paths and aquifer connectivity.

1.5 Problem Statement

Kribi Town faces a critical water crisis stemming from the limitations of its current water supply, the potential for groundwater contamination, and the urgent need for sustainable water management strategies. The town's heavy reliance on a limited number of groundwater boreholes makes it vulnerable to water shortages, particularly during the dry season. Additionally, the lack of proper wastewater treatment and the presence of potential pollution sources, including industrial activities and agricultural runoff, pose significant risks of groundwater contamination. This situation necessitates a shift towards sustainable water management solutions that ensure a secure and reliable water supply for Kribi's growing population and economic activities while safeguarding public health and environmental sustainability.

1.6 Research Objectives

The main objective of the study is to conduct a comprehensive assessment of water resources in Kribi Town, integrating hydrogeological, hydrogeochemical, surface water, and GIS-based analyses, with the aim of developing sustainable strategies for ensuring a secure and reliable water supply for the town's future. In order for this to be attained, the specific objectives are to:

- ✓ Develop hydrogeological models using geophysical methods, geological datasets, and 3D implicit geological modelling in order to quantify the groundwater resource;
- ✓ Evaluate the hydrogeochemical parameters of groundwater within Kribi as well as their suitability for various uses;
- ✓ Develop a precipitation-runoff model of the Kienke River using HEC-HMS to evaluate its potential as a water source;
- ✓ Propose sustainable municipal water supply alternatives that integrate groundwater resources, surface water resources (Kienke River), and utilize GIS-based reservoir siting with the Multiple Criteria Evaluation (MCE) method for optimal location selection.

1.7 Hydrogeological Investigations for Urban Water Supply

1.7.1 Groundwater Occurrence and Aquifer Systems in Coastal Regions

1.7.1.1 Types of aquifers in coastal regions:

Coastal regions exhibit diverse hydrogeological settings, hosting various types of aquifers with distinct characteristics and vulnerabilities. Understanding these aquifer types is crucial for effective water resource management.

- **Unconfined aquifers (phreatic aquifers):** Unconfined aquifers are characterized by a water table open to the atmosphere, making them highly susceptible to contamination from surface sources. Their shallow depth and direct connection to precipitation make them a primary source of freshwater in many coastal areas. However, their vulnerability requires careful management to prevent pollution and overexploitation (Freeze and Cherry, 1979).
- **Confined aquifers:** Confined aquifers are bounded by impermeable layers, offering protection from surface contamination and potentially higher storage capacity. These aquifers often hold good quality water due to natural filtration processes. However, extraction from confined aquifers can be challenging and may require specialized well designs and pumping strategies (Bear, 2013).
- **Leaky aquifers:** Leaky aquifers are semi-confined, with a partially confining layer allowing limited interaction with adjacent aquifers or surface water bodies. This interaction can influence water quality and availability in the leaky aquifer, depending on the properties of the confining layer and the surrounding hydrogeological setting (Wang and Anderson, 1995).

- **Coastal karst aquifers:** Karst aquifers, formed in soluble rocks like limestone, are characterized by complex networks of conduits and caves. These aquifers are highly vulnerable to saltwater intrusion and contamination due to their rapid flow paths and interconnectedness. Coastal karst systems require specialized management approaches to address these vulnerabilities and ensure sustainable water use (Appelo and Postma, 2004).

1.7.1.2 Geological formations and their influence on aquifer systems:

The geological formations underlying coastal regions play a crucial role in shaping the characteristics and behavior of aquifer systems. Understanding the influence of these formations is essential for assessing groundwater resources and managing them effectively.

- **Sedimentary formations:** Sedimentary deposits, including sand, gravel, and clay, are common in coastal areas and often form important aquifers. The size, shape, and arrangement of sediment grains determine aquifer properties like permeability and porosity. Sandy and gravelly deposits typically exhibit high permeability, allowing for efficient water movement and storage. Clayey deposits, on the other hand, tend to have low permeability, acting as confining layers or aquitards that impede groundwater flow (Freeze and Cherry, 1979).
- **Fractured rock aquifers:** In coastal regions with hard rock formations, groundwater flow primarily occurs through fractures and fissures within the rock. The permeability and storage capacity of fractured rock aquifers depend on the density, orientation, and interconnectedness of these fractures. Factors like tectonic activity, weathering, and stress regimes influence fracture development and can significantly impact groundwater flow patterns (Domenico and Schwartz, 1997).
- **Influence of geological structures:** Geological structures, such as faults and folds, can act as conduits or barriers to groundwater flow in coastal regions. Faults can create zones of high permeability, facilitating groundwater movement and potentially connecting different aquifer systems. Folds can influence the depth and distribution of aquifers, affecting groundwater availability and extraction strategies. Understanding the impact of these structures is essential for accurate hydrogeological modeling and sustainable water resource management (Anderson et al., 1992).

1.7.1.3 Factors influencing groundwater flow and recharge:

Groundwater flow and recharge in coastal areas are influenced by a complex interplay of factors, including topography, climate, and interactions with the ocean. Understanding these factors is crucial for assessing water resources and predicting their response to natural and anthropogenic influences.

- **Topography and elevation:** Topography and elevation gradients play a significant role in determining groundwater flow direction and velocity. Water generally flows from higher to lower elevations, following the slope of the water table. In coastal areas, the presence of hills, valleys, and other topographic features can create complex flow patterns, with groundwater converging in low-lying areas and discharging into the ocean or surface water bodies (Bear, 2013).
- **Climate and precipitation patterns:** Climate and precipitation patterns directly impact groundwater recharge rates and the overall water balance in coastal areas. Rainfall intensity and distribution determine the amount of water available for infiltration and recharge. Areas with high precipitation and permeable soils tend to have higher recharge rates, while arid regions or areas with impermeable surfaces experience limited recharge (Hem, 1985)
- **Seawater intrusion:** Seawater intrusion occurs when the balance between freshwater and saltwater in coastal aquifers is disrupted, leading to the inland movement of saltwater. This can be caused by excessive groundwater pumping, lowering the freshwater head and allowing saltwater to intrude. Sea-level rise due to climate change exacerbates this issue by further increasing the pressure of seawater on coastal aquifers (Werner et al., 2013).
- **Tidal fluctuations:** Tidal fluctuations influence groundwater levels and flow patterns in coastal areas, particularly in close proximity to the shoreline. The rise and fall of tides exert pressure on the aquifer, causing fluctuations in the water table. This can lead to periodic changes in groundwater flow direction and may contribute to saltwater intrusion in vulnerable areas (Barlow and Reichard, 2010).

1.7.1.4 Case studies of coastal aquifer systems:

Examining case studies from diverse coastal regions provides valuable insights into the challenges and opportunities associated with managing coastal aquifers. These examples showcase successful strategies for sustainable groundwater management and offer lessons applicable to Kribi Town's context.

- **Diversity of hydrogeological settings and challenges:** Coastal aquifers exhibit a wide range of hydrogeological settings, each with unique challenges. For instance, the California coast faces significant saltwater intrusion due to over-pumping and urban development. The Netherlands grapples with land subsidence resulting from groundwater extraction. Small island nations contend with limited freshwater resources and vulnerability to climate change impacts (Barlow and Reichard, 2010).
- **Successful approaches to sustainable management:** Numerous coastal regions have implemented successful strategies for sustainable groundwater management. Orange County, California, utilizes a large-scale artificial recharge program to replenish its aquifers and combat saltwater intrusion. Israel employs advanced water treatment technologies and efficient irrigation practices to maximize water use efficiency. The Netherlands has implemented managed aquifer recharge and integrated water management strategies to address land subsidence and ensure long-term water security (Page et al., 2018).
- **Lessons learned and applicability to Kribi Town:** Case studies highlight the importance of comprehensive hydrogeological assessments, stakeholder engagement, and adaptive management strategies in coastal aquifer management. Lessons learned from successful examples can inform the development of effective strategies for Kribi Town, considering its specific hydrogeological setting, water demands, and environmental considerations. For instance, artificial recharge could be explored to enhance freshwater availability, while conjunctive use of surface water and groundwater could improve water security and reduce reliance on a single source (GWP, 2000).

1.7.1.5 Knowledge gaps and research needs:

While existing research provides valuable insights into coastal aquifer systems, knowledge gaps remain in understanding their complexities and responses to various stressors. Addressing these gaps through targeted research is crucial for effective management and protection of coastal groundwater resources, particularly in the context of Kribi Town.

- **Knowledge gaps in understanding coastal aquifer systems:** In Kribi Town, specific knowledge gaps exist regarding the detailed hydrogeological characterization of the aquifer system, including the extent and connectivity of different aquifer units, recharge rates, and vulnerability to saltwater intrusion and contamination. Understanding the impacts of urbanization, land-use changes, and climate variability on groundwater resources also requires further investigation (Lordon et al., 2012)

- **Areas for further research:** Targeted research is needed to improve the understanding of Kribi Town's coastal aquifer system and inform sustainable management strategies. This includes detailed hydrogeological mapping, aquifer characterization studies, investigation of saltwater intrusion dynamics, assessment of contamination risks, and evaluation of potential artificial recharge sites. Research should also focus on understanding the impacts of climate change and sea-level rise on groundwater resources, and developing adaptive management strategies to address these challenges (ResearchKey, 2021)

1.7.2 Geophysical Methods for Groundwater Exploration

1.7.2.1 Introduction to geophysical methods for groundwater exploration:

Geophysical methods play a crucial role in groundwater exploration by providing non-invasive techniques to investigate subsurface hydrogeological conditions. These methods utilize various physical principles to characterize the properties of rocks and sediments and identify potential aquifers.

- **Types of geophysical methods:** Several geophysical methods are commonly employed in groundwater exploration, each relying on different physical properties:
    - **Seismic methods:** Utilize the propagation of seismic waves generated by artificial sources to image subsurface structures and identify different rock types based on their elastic properties (Kearey et al., 2002).
    - **Electrical methods:** Measure the electrical resistivity or conductivity of subsurface materials, which can be used to differentiate between water-bearing formations and dry rocks, as well as identify changes in water quality (Loke and Barker, 1996).
    - **Electromagnetic methods:** Employ electromagnetic fields to induce currents in the subsurface, providing information about the EC and magnetic properties of rocks and sediments. This helps delineate aquifers and identify features like saltwater intrusion (McNeill, 1997).
    - **Potential field methods:** Measure variations in Earth's gravitational or magnetic fields caused by differences in rock density or magnetic susceptibility.

This information can be used to infer geological structures and identify potential water-bearing formations (Reynolds, 2011).

- **General principles and physical properties:** Each geophysical method relies on specific physical principles to investigate subsurface hydrogeological conditions. Seismic methods utilize the principles of elastic wave propagation, while electrical and electromagnetic methods exploit the electrical properties of rocks and fluids. Potential field methods measure variations in Earth's natural force fields. These methods leverage the contrasting physical properties of different geological materials to provide valuable information about the subsurface.
- **Advantages of geophysical methods:** Geophysical methods offer several advantages for groundwater exploration:
    - **Non-invasive:** They do not require drilling or excavation, minimizing environmental disturbance and costs.
    - **Efficient coverage:** They can rapidly cover large areas, providing a broader understanding of the subsurface than point-based drilling data.
    - **Subsurface information:** They offer insights into subsurface geological structures, aquifer properties, and water quality without the need for extensive drilling.

1.7.2.2 Electromagnetic methods:

Electromagnetic methods utilize electromagnetic fields to induce electrical currents in the subsurface and measure the resulting responses, providing valuable information about the EC and magnetic properties of rocks and sediments. These methods are particularly useful for delineating aquifers and identifying features like saltwater intrusion.

- **Principles of electromagnetic methods:** Electromagnetic methods typically involve transmitting an electromagnetic field into the subsurface using a transmitter coil or antenna. This primary field induces secondary currents in conductive materials, which generate their own electromagnetic fields. The receiver coil or antenna measures the combined response of the primary and secondary fields. By analyzing the characteristics of these responses, information about the EC and magnetic properties of the subsurface can be obtained (McNeill, 1997)
- **Types of electromagnetic methods:**

  - **Ground-penetrating radar (GPR):** GPR uses high-frequency electromagnetic waves to image the shallow subsurface. It is particularly effective for identifying subsurface structures, interfaces between different materials, and the presence of water (Reynolds, 2011).
  - **Transient electromagnetic (TEM):** TEM methods induce a time-varying magnetic field in the subsurface and measure the decay of the secondary field over time. This technique is sensitive to changes in EC with depth and is often used to map aquifer geometry and identify conductive features like saltwater intrusion (Zhdanov and Keller, 1994).
  - **Frequency-domain electromagnetic (FDEM):** FDEM methods use continuous-wave electromagnetic fields at different frequencies to measure the subsurface response. By analyzing the phase shift and amplitude attenuation of the received signal, information about the EC distribution can be obtained (Kearey et al., 2002)
- **Advantages:** Electromagnetic methods offer several advantages:
  - **Sensitivity to water and salinity:** They are highly sensitive to the presence of water and changes in salinity, making them ideal for delineating aquifers and mapping saltwater intrusion.
  - **DOI:** Different electromagnetic methods can explore a wide range of depths, from shallow subsurface to deeper aquifers.
- **Limitations:**
  - **Resolution:** Resolution can be limited depending on the specific method and subsurface conditions.
  - **Equipment and expertise:** Often require specialized equipment and expertise for data acquisition and interpretation.
- **Applications in groundwater exploration:** Electromagnetic methods are extensively used for groundwater exploration, particularly in coastal areas where saltwater intrusion is a concern. They have been successfully applied to map aquifer geometry, delineate freshwater-saltwater interfaces, and monitor changes in groundwater salinity over time (Evans et al., 2012).

1.7.2.3 Seismic methods:

Seismic methods utilize the propagation of seismic waves to image subsurface structures and characterize geological formations. These methods are valuable tools for understanding the geological framework of aquifer systems and identifying potential groundwater resources, particularly in complex geological settings.

- **Principles of seismic methods:** Seismic methods involve generating seismic waves using an energy source, such as an explosive or a vibrating plate. These waves travel through the subsurface and are reflected or refracted at boundaries between different rock layers. Geophones record the arrival times and amplitudes of the reflected or refracted waves, which are then processed to create an image of the subsurface structure. The velocity of seismic waves varies depending on the elastic properties of the rocks, allowing for the differentiation of geological formations (Kearey et al., 2002).
- **Types of seismic methods:**
    - **Reflection seismic surveys:** Reflection seismic surveys primarily utilize reflected waves to image subsurface structures. This technique is effective for identifying layers with contrasting acoustic properties and can provide detailed information about aquifer geometry and the presence of geological features like faults and folds (Reynolds, 2011).
    - **Refraction seismic surveys:** Refraction seismic surveys primarily utilize refracted waves that travel along the boundaries between different rock layers. This technique is particularly useful for determining the depth and thickness of subsurface layers and can be used to estimate the depth to bedrock and identify potential aquifers (Zhdanov and Keller, 1994)
- **Advantages:** Seismic methods offer several advantages:
    - **High resolution:** They can provide high-resolution images of the subsurface, allowing for detailed characterization of geological formations.
    - **DOI:** They can penetrate to significant depths, making them suitable for exploring deep aquifer systems.
- **Limitations:**
    - **Cost and logistics:** Seismic surveys can be expensive and logistically challenging, requiring specialized equipment and personnel.
    - **Data interpretation:** Interpretation of seismic data can be complex and requires expertise in geology and geophysics.

- **Applications in groundwater exploration:** Seismic methods are particularly useful for groundwater exploration in complex geological settings where other geophysical techniques may have limited effectiveness. They have been successfully applied to map fractured rock aquifers, identify faults and fracture zones, and characterize the geometry of deep aquifer systems (Comte et al., 2012).

1.7.2.4 Electroseismic (ES) Method

1.7.2.4.1 Introduction

The ES method, rooted in the principles of electrokinetic coupling within porous, water-saturated media, presents a powerful tool for hydrogeological investigations (Pride and Haartsen, 1996). By combining seismic wave propagation with electrical field measurements, this technique allows inferences about aquifer properties and subsurface characteristics. As seismic waves propagate through these media, they generate detectable electrical signals (Figure 3) due to the electrokinetic coupling effect (Mikhailov et al., 1997). Analyzing these signals allows for inferences about aquifer extent, porosity, and potentially even groundwater flow paths.

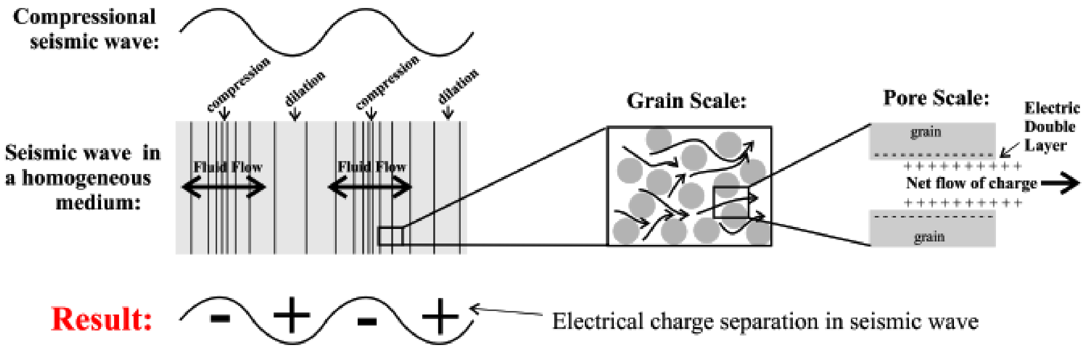
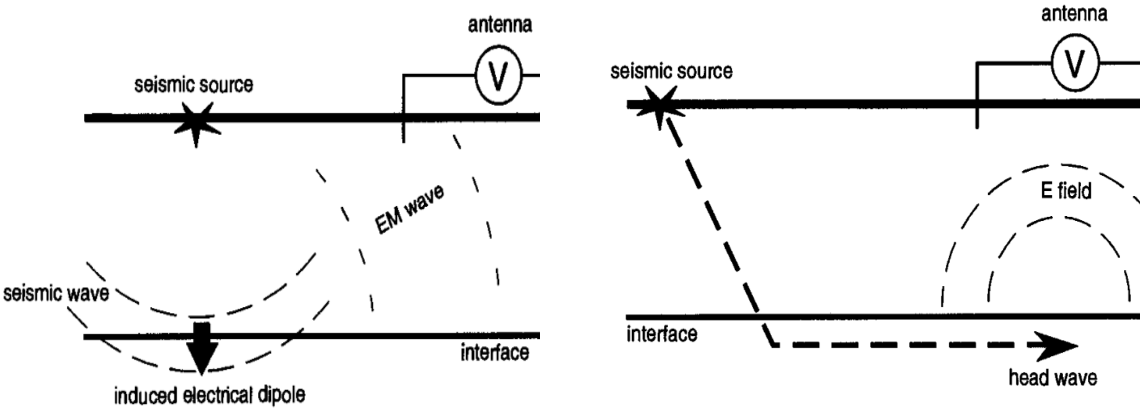


Figure 3: ES phenomena depend on the charge separation created by streaming currents that flow in response to the pressure gradient of a seismic wave. The electric double layer is responsible for streaming currents at the grain scale (Haines et al., 2004).

ES phenomena in porous media have the potential to enable detection of subsurface zones of high fluid mobility and fluid chemistry contrasts, supported by observation, with explicit comparison to full waveform modelling results (Mikhailov et al., 1997) since a seismic wave propagating in a medium can induce an electric field or generate an electromagnetic wave. Therefore, the ES conversion has the potential to become a geophysical tool capable of detecting zones of high permeability, such as fractured zones, and interfaces, such as an oil-water contact (Haartsen and Pride, 1994).

The ES effects employed look at results of a seismic wave crossing or travelling along the interface between two porous media. When a seismic source crosses an interface, there is ES conversion (Figure 4 (a)). When a spherical P-wave crosses an interface, however, the imbalance of the streaming currents induced by the seismic wave on opposite sides of the interface creates a dipole charge separation. The induced dipole radiates an electromagnetic wave, which can be detected by remote antennae (ATSGeoConsultants., 2019; Mikhailov et al., 1997).



(a) (b)

Figure 4: (a) ES conversion at an interface; (b) generation of an electrical field by a head wave crossing an interface (Source: (Mikhailov et al., 1997)).

When a seismic head wave travels along an interface between media (Figure 4 (b)), it causes charge separation across the interface, which induces an electric field that moves along the interface with the head wave and can be detected by ground-dipole antennae when the head wave passes under them (ATSGeoConsultants., 2019; Mikhailov et al., 1997). The electric fields are transformed into a set of time-varying potential differences, which can be captured and processed.

1.7.2.4.2 Electrokinetic Coupling:

The ES effect, a valuable tool for groundwater investigations, finds its basis in electrokinetic coupling phenomena within fluid-saturated porous media (Revil and Jardani, 2013). These electrokinetic effects arise from the unique electrical interactions occurring at the interface between mineral surfaces and the pore fluids within rocks or sediments.

1.7.2.4.2.1 Electrical Double Layer (EDL):

The interface between a mineral surface and the pore fluid is not electrically neutral, as chemical interactions lead to the formation of an EDL (Hunter, 2013). As illustrated in Figure 5, the EDL consists of a fixed layer of charge tightly bound to the mineral surface and a diffuse layer containing an excess of oppositely charged ions that are more mobile within the pore fluid (Hunter, 2013).

1.7.2.4.2.2 Seismic Disturbance & Streaming Potential:

The passage of a seismic compressional wave (P-wave) through a fluid-saturated porous medium induces a minute, temporary displacement between the fixed and diffuse layers of the EDL, disturbing the charge balance (Pride and Morgan, 1991). This displacement results in a flow of ions within the pore fluid, generating a tiny electrical current known as the streaming current. This streaming current generates an accompanying electrical potential difference, termed the streaming potential, which forms the foundation for ES measurements (Revil and Jardani, 2013).

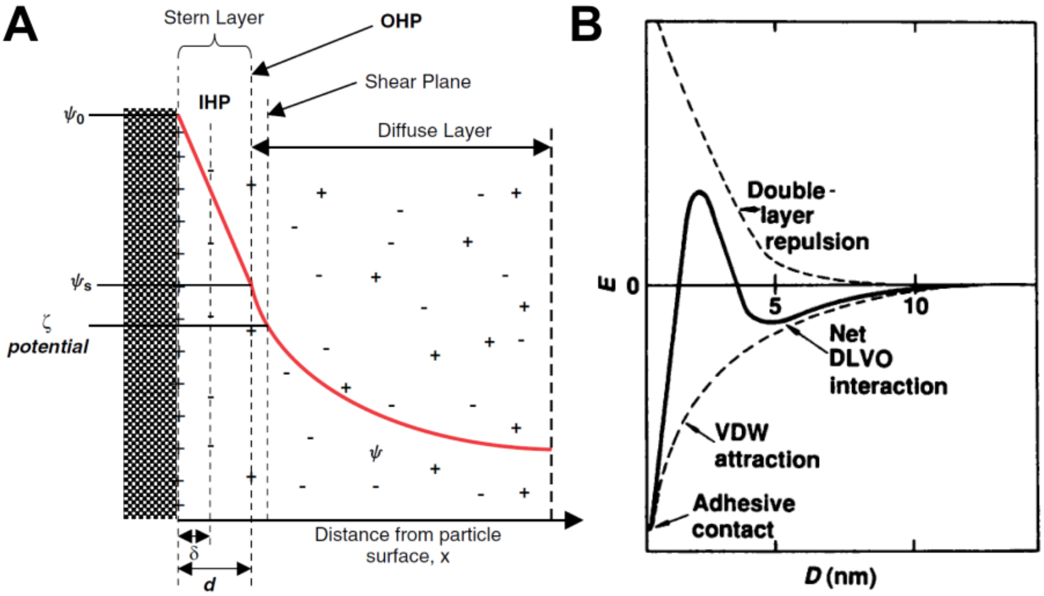


Figure 5: (A) Schematic representation of the electric double-layer (EDL) according to the Guoy-Chapman-Stern model. (B) Classical DLVO potential for two interacting flat surfaces (Tebbe, 2015).

1.7.2.4.2.3 Simplified Streaming Potential Equation:

The magnitude of the streaming potential can be described using a simplified equation that relates it to key properties of the porous medium and the pore fluid (Jackson, 1979). A simplified equation representing this relationship is:

$$\Delta V = -\frac{\epsilon \zeta \Delta P}{\eta \sigma} \tag{1}$$

Where:

$\Delta V =$ Streaming Potential (volts)

$\epsilon =$ Fluid permittivity (farads/meter)

$\zeta =$ Zeta potential (volts) $-$ property of the mineral-fluid interface

$\Delta P =$ Pressure change induced by the seismic wave (pascals)

$\eta =$ Fluid viscosity (pascal-seconds)

$\sigma =$ Fluid conductivity (siemens/meter)

It's important to note that this simplified equation represents an idealized scenario and additional factors, such as surface conductivity and pore geometry, can influence the streaming potential in complex geological settings.

1.7.2.4.2.4 Factors Influencing ES Response:

Several factors influence the strength of the ES signal and our ability to detect it, including properties of the porous medium and the pore fluid itself (Evans et al., 2012):

- **Porosity and Permeability:** Higher porosity and permeability within the porous medium contribute to a stronger ES signal by increasing the volume of mobile ions involved and facilitating fluid flow, ultimately leading to a larger streaming potential (Sattar et al., 2016).
- **Fluid Properties:** The properties of the pore fluid, including its conductivity, viscosity, and particularly salinity, significantly influence the electrokinetic response and the resulting ES signal strength (Cannon, 2015).
- **Mineral Surface Properties:** The zeta potential, a key parameter influenced by the mineral surface charge and fluid chemistry, exerts a strong control on the magnitude of the ES effect (Hunter, 2013).

1.7.2.4.3 Governing Equation:

1.7.2.4.3.1 Introduction

To fully harness the potential of the ES method for groundwater investigations, a solid grasp of the mathematical principles underpinning this technique is essential (Evans et al., 2012; Pride, 1994). Understanding the governing equations allows for moving beyond qualitative observations and making quantitative inferences about subsurface properties from ES survey data. Furthermore, a solid grasp of these equations enables the informed design of field surveys optimized to answer specific hydrogeological questions.

1.7.2.4.3.2 Assumptions

To simplify the mathematical modeling of the ES effect, several assumptions are often invoked, recognizing that real-world geological settings may deviate from these idealized conditions (Jardani et al., 2010). Key common assumptions include:

- **Isotropic and Homogeneous Porous Medium:** This assumes that the rock or sediment has uniform properties (porosity, permeability, mineral composition) in all directions and that these properties do not vary spatially within the area of interest.
- **Laminar (Non-Turbulent) Fluid Flow:** This assumes that fluid movement within the pore spaces follows smooth streamlines and not chaotic, turbulent patterns. Turbulent flow is less common in typical groundwater scenarios.
- **Dilute Electrolyte Solution:** This assumes that the concentration of dissolved ions in the pore fluid is relatively low, simplifying calculations related to EC (Kemper and Quirk, 1970).
- **Seismic Propagation Primarily as Compressional Waves:** While seismic surveys generate other wave types (shear waves, surface waves), ES theory mainly focuses on the interaction of compressional waves (P-waves) with the pore fluid, as they induce the necessary pressure changes.

1.7.2.4.3.3 Derivation Approaches

1) Introduction

The full mathematical description of seismoelectric phenomena can be rigorously derived from various theoretical foundations, such as Biot's theory of poroelasticity (Biot, 1956) or the framework of poroelasticity combined with electrokinetic coupling (Pride et al., 1992), each offering valuable perspectives. However, for this explanation, we'll focus on the derivation starting from the fundamental principles of fluid dynamics (Navier-Stokes equations) and electromagnetism (Maxwell's equations). This approach is particularly well-suited for understanding the core mechanism of electrokinetic coupling, where the movement of ions within the pore fluid, driven by seismic disturbances, acts as the source of the electrical signals. Furthermore, the Navier-Stokes framework allows for flexibility in modeling potential non-linear flow behaviors that might become relevant in certain scenarios.

2) Navier-Stokes Equations

The incompressible Navier-Stokes equation serves as the foundation for describing fluid motion within a porous medium, a critical aspect of modeling the ES effect (Batchelor, 1967). The equation is as follows:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}+\mathbf{F} \qquad (2)$$

Where:

$\mathbf{u}$ (vector quantity): Fluid velocity field within the porous medium.

ρ : Fluid density.

p : Fluid pressure.

μ : Fluid dynamic viscosity (a measure of resistance to flow).

$\mathbf{F}$: External body forces acting on the fluid (can often be neglected in electroseismic modeling).

This equation represents the conservation of momentum for an incompressible fluid, considering factors such as fluid velocity, pressure gradients, and viscous forces.

3) Maxwell's Equations

To account for the electromagnetic aspects of the ES effect, we incorporate Maxwell's equations, which govern the behavior of electric and magnetic fields (Griffiths and Colleger, 1999). For our purposes, the following two equations are most relevant:

- **Faraday's Law of Induction:** Describes how a changing magnetic field induces an electric field. In differential form:

$$\nabla\times\mathbf{E}=-\frac{\partial \mathbf{B}}{\partial t} \qquad (3)$$

- **Gauss's Law for Electricity:** Relates the distribution of electric charge to the resulting electric field. In differential form:

$$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon_0} \tag{4}$$

Where:

$\mathbf{E}$: Electric field (vector quantity, units of volts/meter)

$\mathbf{B}$: Magnetic field (vector quantity, units of teslas). Note that in low-frequency scenarios relevant to ES surveys, magnetic induction effects are often negligible.

ρ_e: Electric charge density (coulombs per cubic meter)

ϵ_0 : Vacuum permittivity (a fundamental constant)

Faraday's Law of Induction describes how a time-varying magnetic field induces a circulating electric field. Gauss's Law for Electricity relates the distribution of electric charge to the resulting electric field.

4) Electrokinetic Coupling Term

The Need for Coupling: The Navier-Stokes equations, while governing fluid flow, do not inherently account for the generation of electrical fields, and conversely, Maxwell's equations describe electromagnetism but lack a direct connection to fluid-induced charge transport (Pride, 1994). To bridge these domains and accurately model the ES effect, a coupling term is introduced, linking the mechanical disturbances caused by seismic waves to the generation of electrical fields (Revil and Jardani, 2013).

Excess Charge Density in the EDL: The EDL at the mineral-fluid interface is crucial. The diffuse layer of the EDL contains a net excess of mobile ions (often positive), creating a local imbalance of charge. We define this as the excess charge density: ρ_e

Seismic Disturbance & Current Flow: A seismic wave passing through the porous medium displaces the mobile ions of the diffuse layer relative to the fixed layer of the EDL. This movement of excess charge constitutes an electric current density, known as the streaming current density (Revil and Leroy, 2004).

$$\mathbf{J}_s = \sigma \mathbf{E} + L \nabla p \tag{5}$$

Where:

$\mathbf{J}_s$: Streaming current density (amperes per square meter)

σ : Fluid electrical conductivity (siemens per meter)

$\mathbf{E}$: Electric field (volts per meter)

L : Electrokinetic coupling coefficient

∇p : Pressure gradient (pascals per meter)

The Coupling Term

The electrokinetic coupling term is incorporated by modifying Maxwell's equations. Specifically, the streaming current density becomes a source term in the equation for current conservation:

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho_e}{\partial t} \tag{6}$$

Where:

- $\mathbf{J}$ Total current density, including contributions from conduction and streaming currents.

This modified equation now includes the contribution of fluid-induced charge transport (streaming current) to the total current density, capturing the essence of the ES effect.

5) Modified Equations

Modified Navier-Stokes Equation:

The Navier-Stokes equation is augmented to account for the electrical forces that can act on the ions within the pore fluid. A typical modification includes an electrokinetic body force term (Evans et al., 2012):

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F} + \rho_e \mathbf{E} \tag{7}$$

- **New Term:** $\rho_e \mathbf{E}$ represents the electrical force per unit volume acting on the excess charge within the fluid.

Modified Maxwell's Equations:

The electrokinetic coupling primarily influences Maxwell's equations through the introduction of the streaming current density as a source term (Pride, 1994). For example, the modified equation for current conservation becomes:

$$\nabla \cdot \mathbf{J} = \nabla \cdot (\mathbf{J}_s + \sigma \mathbf{E}) = -\frac{\partial \rho_e}{\partial t} \tag{8}$$

- **Streaming Current:** The inclusion of $\mathbf{J}_s$ explicitly links fluid movement induced by the seismic wave to the generation of electromagnetic fields.

The Coupled System

The modified Navier-Stokes and Maxwell's equations, along with the relationships defining the streaming current density and excess charge density, form a fully coupled system of seismoelectric governing equations. Key points:

- **Two-Way Interaction:** Fluid flow influences electrical fields, and conversely, electrical forces can feed back and modify the fluid flow patterns.
- **Emergence of the Seismoelectric Effect:** This coupled system mathematically predicts the generation of electrical potentials in response to seismic wave-induced pressure variations, the phenomenon we measure in ES surveys.

This coupled system of equations forms the basis for understanding and modeling seismoelectric phenomena in porous media (Haartsen and Pride, 1997)

6) Emergence of Streaming Potential

The coupled system of equations we've derived provides the mathematical foundation for understanding how the streaming potential, the core of ES measurements, arises. Here's the key sequence:

1. **Seismic Pressure Disturbance:** A seismic wave passing through a fluid-saturated porous medium induces localized pressure variations (∇p) within the pore fluid.
2. **Fluid and Ion Movement:** These pressure variations, as described by the modified Navier-Stokes equation, drive fluid flow. Critically, the excess ions within the Edl is transported along with this bulk fluid movement.
3. **Charge Transport = Streaming Current:** The movement of the excess charge density (ρ_e) constitutes the streaming current density ($\mathbf{J}_s$). This current acts as a source term in the modified Maxwell's equations.
4. **Generation of Electric Field:** Through Maxwell's equations, we see that a spatial variation or a change over time in the streaming current directly induces a corresponding electric field ($\mathbf{E}$).

5. **The Streaming Potential:** This electrically generated field, intimately linked to the seismic wave-induced fluid flow, is what we term the streaming potential. It's the signal we seek to measure in ES surveys.

This sequence of events, driven by the coupled seismoelectric equations, elucidates the generation of the streaming potential, the fundamental signal measured in ES surveys (Evans et al., 2012).

1.7.2.4.4 Obtaining Solutions

Limitations of Analytical Solutions: To study realistic subsurface conditions and effectively interpret ES field data, numerical modeling techniques offer a powerful approach (Carcione, 2007). These methods allow for approximating solutions to the governing equations in complex scenarios, enabling the exploration of heterogeneities, intricate geometries, and varied seismic sources.

The Power of Numerical Modeling: To study realistic subsurface conditions and interpret ES field data effectively, we turn to numerical modeling techniques. These methods allow us to approximate solutions to the governing equations in complex scenarios, enabling us to explore the influence of:

- **Heterogeneous Porous Media:** Variations in porosity, permeability, and mineral composition across different geological layers.
- **Complex Geometries:** Realistic aquifer shapes, the presence of faults, or other structural features.
- **Varied Seismic Sources:** Modeling different seismic source types and frequency ranges.

1.7.2.4.4.1 Common Numerical Methods

Several numerical methods are commonly employed for solving seismoelectric problems, each with its own advantages and limitations (Wang et al., 2016).

- **Finite-Difference Method (FDM):** Discretizes the subsurface into a grid of points. Derivatives in the governing equations are approximated using differences between values at neighboring grid points.
- **Finite-Element Method (FEM):** Divides the domain into elements of flexible shapes. The solution is approximated within each element using basis functions. FEM is well-suited for complex geometries.

- **Spectral-Element Method (SEM):** Combines the accuracy of spectral methods with the geometric flexibility of FEM. Increasingly used in geophysics due to its advantages for wave propagation problems.

1.7.2.4.5 Applications to Groundwater Exploration

The ES method excels at delineating aquifer boundaries due to its sensitivity to contrasts in electrokinetic properties between different geological units (Thompson and Gist, 1993). These contrasts often arise from variations in porosity, permeability, and mineral composition, leading to measurable changes in the ES response that allow for effective mapping of aquifer extents.

ES surveys prove highly valuable for detecting freshwater-saline water interfaces, a critical aspect of coastal aquifer management (Evans et al., 2012). Fluid salinity significantly impacts EC, which in turn strongly influences the ES effect, enabling these surveys to pinpoint transitions between fresh and saline groundwater.

While directly extracting permeability values from ES data can be challenging, the method offers potential insights into permeability distributions within an aquifer (Sattar et al., 2016). Permeability, a key hydrogeological parameter, is related to the electrokinetic coupling coefficient, and under favorable conditions, ES surveys, often in conjunction with other geophysical data, can provide valuable information about permeability variations.

1.7.2.4.6 Considerations & Limitations

Despite its potential for providing valuable insights into aquifer characteristics, the ES method presents certain limitations that warrant careful consideration(Haines et al., 2004). The ES signal is often relatively weak, requiring sensitive equipment and meticulous data processing to distinguish it from background noise. This inherent weakness can limit the method's ability to detect subtle electrokinetic contrasts or effectively map deeper targets (Evans et al., 2012). Furthermore, the Depth Of Investigation achievable with the ES method is dependent on the seismic source used, with these surveys often better suited for shallower aquifers compared to traditional seismic methods that can probe greater depths (Mikhailov et al., 2000). Data interpretation within ES surveys requires careful consideration of potential non-uniqueness, often necessitating the integration of complementary geophysical methods, such as electrical resistivity or electromagnetic surveys, for improved reliability and a more robust understanding of the subsurface (Jardani et al., 2010). Careful survey design, including electrode spacing and source placement, is crucial to optimize sensitivity to the specific subsurface targets of interest.

1.7.2.5 Electrical Resistivity Methods

Electrical resistivity techniques are a cornerstone of geophysical surveying used to investigate subsurface properties. Here's a breakdown of what they are, how they work, and their applications:

1.7.2.5.1 Principles

The fundamental principle behind electrical resistivity methods lies in the varying degrees of resistance to electrical current flow, known as resistivity, exhibited by different geological materials (Keller and Frischknecht, 1966). By injecting current into the ground through electrodes and measuring the resulting voltage differences at other electrodes, these methods provide insights into the subsurface resistivity distribution. Interpreting the subsurface resistivity distribution can reveal valuable information about the presence of distinct layers of rock or soil, variations in water content, the potential presence of contaminants, and even the location of buried archaeological features (Loke, 2004).

1.7.2.5.2 Common Techniques

Vertical Electrical Sounding (VES) is a commonly employed electrical resistivity technique used to investigate changes in resistivity with depth at a specific location (Zhdanov and Keller, 1994). By progressively expanding the spacing between electrodes, VES allows for probing deeper subsurface layers, revealing information about the vertical distribution of geological materials and potential aquifers. This technique is particularly useful for characterizing layered earth structures and identifying the presence of water-bearing formations.

Electrical Resistivity Tomography (ERT) is a more advanced technique that generates 2D or 3D images of subsurface resistivity variations (Loke and Barker, 1996). By utilizing multiple electrodes along a survey line, ERT provides a more comprehensive view of the subsurface, allowing for the identification of lateral changes in resistivity and the mapping of complex geological structures. This technique is valuable for delineating aquifer boundaries, detecting zones of contamination, and investigating geological features such as faults or fractures.

1.7.2.5.3 Applications

Electrical resistivity methods find applications across diverse fields due to their ability to characterize subsurface properties and provide valuable insights into geological structures and hydrogeological conditions (Kearey et al., 2002; Reynolds, 2011). In groundwater exploration, these techniques are crucial for detecting aquifers, assessing water quality, and identifying zones of saltwater intrusion (Loke, 2004). Geotechnical engineers utilize these methods to map soil and bedrock properties, aiding in the identification of weak zones or potential landslide areas. Environmental investigations employ resistivity techniques to delineate pollution plumes, locate buried waste, and assess leaks from USTs. Archaeologists use these methods to discover buried structures, foundations, or artifacts without invasive excavation. Additionally, resistivity methods can indirectly map certain types of mineral deposits, contributing to mineral exploration efforts.

1.7.2.5.4 Limitations

Despite their versatility and wide range of applications, electrical resistivity methods are not without limitations (Binley and Kemna, 2005). The interpretation of resistivity data can be ambiguous, as different geological scenarios may produce similar resistivity patterns, necessitating careful consideration of other geological and hydrological information to constrain interpretations. Furthermore, measurements can be affected by nearby infrastructure, such as buried pipes or power lines, introducing potential sources of noise and interference, particularly in urban environments (Loke, 2004). The effectiveness of resistivity methods also diminishes with increasing investigation depth, as the electrical signal weakens and becomes more susceptible to interference from various sources (Reynolds, 2011).

1.7.2.5.5 VES

1.7.2.5.5.1 How It Works

VES typically employs either the Schlumberger or Wenner array configuration, each with specific advantages and limitations depending on the survey objectives and subsurface conditions (Zhdanov and Keller, 1994). The Schlumberger array utilizes two outer current electrodes (A and B) to inject direct current into the ground, while two inner potential electrodes (M and N) measure the resulting voltage difference, as shown in Figure 6. In contrast, the Wenner array consists of four equally spaced electrodes, with current introduced through the outer pair and voltage measured across the inner pair.

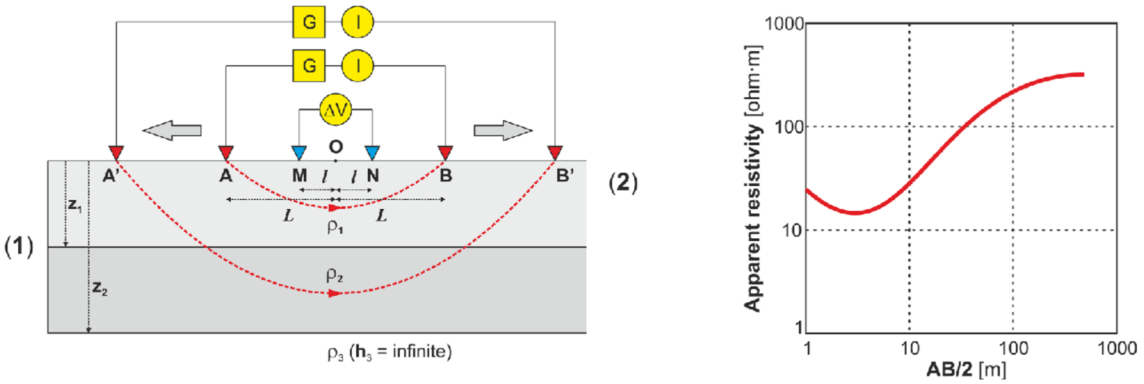


Figure 6: Principle of VES– (1) Data collection (2) Inversion (Source: (Hamzah et al., 2007))

The VES method involves progressively expanding the electrode array to investigate the subsurface at increasing depths. Starting with a small electrode spacing for shallow investigation, the array is symmetrically expanded around the center point, allowing the electrical current to penetrate deeper and probe different subsurface layers. This expansion enables the characterization of the vertical resistivity structure of the ground.

For each electrode spacing, an apparent resistivity value is calculated using the measured voltage, current, and a geometric factor specific to the chosen array type. This apparent resistivity represents the average resistivity of the ground beneath the array to the depth of current penetration. By collecting multiple apparent resistivity values at different electrode spacings, a comprehensive profile of the subsurface resistivity distribution can be obtained.

The collected apparent resistivity values are plotted against the corresponding electrode spacing, creating a VES sounding curve. This curve is then analyzed using specialized modeling software to infer the true distribution of resistivities at depth. The interpretation of the VES sounding curve reveals information about the number of subsurface layers, their respective thicknesses, and their individual resistivity values, providing valuable insights into the geological structure and potential presence of aquifers.

1.7.2.5.5.2 Typical VES Field Procedure

The first step in conducting a successful VES survey involves selecting a suitable site that aligns with the investigation objectives and minimizes potential sources of electrical noise, such as power lines or underground utilities (Loke, 2004). These noise sources can interfere with the measurements and affect the accuracy of the results.

Once a suitable site is chosen, the electrode array is deployed in the chosen configuration, either Schlumberger or Wenner. The electrodes are laid out in a straight line, starting with a small spacing between them. It is crucial to ensure good contact between the electrodes and the ground to obtain reliable measurements.

Data acquisition involves injecting a controlled electrical current into the ground through the outer electrodes and measuring the resulting voltage differences between the inner potential electrodes. This process is repeated at each expanded electrode separation, progressively probing deeper into the subsurface.

The acquired data is then processed to calculate the apparent resistivity values for each electrode spacing. These values are plotted against the corresponding electrode spacing, creating a VES sounding curve that represents the variation of resistivity with depth.

Finally, specialized software is used to model and invert the VES data. This process involves finding a layered earth model that best explains the observed resistivity values. The resulting model provides information about the number of subsurface layers, their thicknesses, and their individual resistivities, offering valuable insights into the geological structure and potential presence of aquifers.

1.7.2.5.5.3 Applications of VES

VES is a valuable tool for groundwater investigations, aiding in the identification and characterization of aquifers (Nwankwoala and Kekwaru, 2019). By analyzing resistivity variations with depth, VES can determine the location, thickness, and even water quality, particularly salinity, of potential aquifers, providing crucial information for assessing groundwater resources and planning sustainable water extraction strategies.

In engineering studies, VES is employed to map the depth to bedrock, characterize soil types, and detect weak zones in the subsurface (Di Maio et al., 2020). This information is essential for various engineering applications, such as foundation design, slope stability analysis, and infrastructure development, enabling engineers to make informed decisions to ensure the safety and stability of structures.(Sattar et al., 2016).

Environmental assessments utilize VES to locate and delineate contaminant plumes in groundwater, identify areas with buried waste, and assess the extent of leaks from underground storage tanks (USTs) or landfills (Mepaiyeda et al., 2020). The distinct resistivity signatures of contaminants and waste materials facilitate their detection and mapping, aiding in environmental remediation efforts and protecting groundwater resources.

1.7.2.5.5.4 Developing the Schlumberger Array

The Schlumberger array, a commonly used configuration in VES surveys, is characterized by its electrode arrangement. The two current electrodes (A and B) are positioned further apart than the two potential electrodes (M and N), with the center point of the array remaining fixed as the current electrodes are symmetrically expanded outward during the survey. This configuration allows for efficient investigation of the subsurface at increasing depths.

The geometric factor (K) plays a crucial role in calculating apparent resistivity using the Schlumberger array. It accounts for the specific geometry of the electrode arrangement and its influence on the measured electrical potential. The geometric factor is calculated using the formula:

$$K = \pi \cdot \left[\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2 \right] / MN \tag{9}$$

where AB represents the distance between the current electrodes and MN represents the distance between the potential electrodes.

Apparent resistivity (ρ_a), a measure of the bulk average resistivity of the subsurface to a certain depth, is calculated using the geometric factor, the measured potential difference (ΔV), and the injected current (I). The formula for apparent resistivity is:

$$\rho_a = K \cdot \left(\frac{\Delta V}{I} \right) \tag{10}$$

By calculating apparent resistivity values at different electrode spacings, a VES sounding curve can be constructed, providing insights into the vertical distribution of resistivity in the subsurface (Zhdanov and Keller, 1994).

1.7.2.5.5.5 Schlumberger Array: Suitability for Kribi Town

The Schlumberger array presents several advantages for VES surveys in coastal areas like Kribi Town, particularly due to concerns about saltwater intrusion (Comte et al., 2012). VES is highly sensitive to salinity variations, allowing for the differentiation between seawater intrusion and freshwater aquifers due to the stark contrast in resistivity between saline and fresh water. Additionally, the Schlumberger array provides a practical balance between DOI and field efficiency, making it a suitable choice for exploring both shallow and deeper subsurface layers.

This practicality is particularly advantageous compared to the Wenner array, which may require more extensive electrode movement during data acquisition.

However, conducting VES surveys in Kribi Town also presents challenges. The urban environment introduces electrical noise from power lines and other infrastructure, potentially affecting data quality and requiring careful noise reduction techniques during data processing. Furthermore, the complex geology often found near coastal areas can make the modeling and interpretation of VES data slightly more intricate, necessitating a thorough understanding of the local geological setting and the potential influence of various geological formations on resistivity patterns.

1.7.2.6 Integration of geophysical methods:

Integrating data from multiple geophysical methods is essential for improving the accuracy and reliability of subsurface interpretations in groundwater exploration. Each geophysical method provides unique information about the subsurface, and combining these datasets allows for a more comprehensive understanding of hydrogeological conditions.

- **Importance of data integration:** Integrating data from different geophysical methods offers several benefits:
  - **Reduced uncertainty:** Combining datasets from methods with different sensitivities and depths of investigation helps reduce uncertainty in interpretations.
  - **Enhanced resolution:** Integrating data can improve the overall resolution of subsurface imaging, allowing for more accurate delineation of aquifers and geological structures.
  - **Complementary information:** Different methods provide complementary information about various subsurface properties, leading to a more holistic understanding of the hydrogeological system.
- **Techniques for joint inversion and data fusion:** Several techniques exist for integrating geophysical data:
  - **Joint inversion:** This technique involves simultaneously inverting data from multiple geophysical surveys to obtain a single model that best fits all datasets. Joint inversion can significantly improve the accuracy and reliability of subsurface models (Vilhelmsen, 2012).

  - **Data fusion:** Data fusion techniques combine information from different geophysical surveys using statistical or machine learning methods. This approach can be used to generate maps of specific hydrogeological properties or to identify areas with high potential for groundwater resources (Pace et al., 2021).
- **Case studies of integrated approaches:** Numerous case studies demonstrate the successful application of integrated geophysical approaches for groundwater exploration and characterization. For instance, combining electrical resistivity and seismic methods has been effectively used to map complex aquifer systems and identify fractured zones with high permeability (Andersen et al., 2018). Similarly, integrating electromagnetic and potential field methods has been employed to delineate saltwater intrusion and characterize the geometry of coastal aquifers (Comte et al., 2012).

1.7.2.7 Considerations for geophysical surveys in Kribi Town:

Conducting geophysical surveys in Kribi Town presents both challenges and opportunities due to the urban environment, complex geology, and potential saltwater intrusion. Careful consideration of these factors is crucial for selecting appropriate geophysical methods and designing effective surveys to investigate the town's groundwater resources.

- **Challenges and opportunities:**
  - **Urban environment:** The urban setting of Kribi Town may pose challenges for geophysical surveys, such as limited access to survey areas, interference from infrastructure, and the presence of buried utilities. However, the urban environment also presents opportunities for collaboration with local authorities and communities to gather existing data and gain access to key survey locations.
  - **Complex geology:** The geological complexity of the region, with a mix of sedimentary formations and fractured rock aquifers, requires selecting geophysical methods capable of resolving these features and providing accurate information about aquifer geometry and properties.
  - **Saltwater intrusion:** The potential for saltwater intrusion necessitates the use of geophysical methods sensitive to changes in water quality and capable of delineating freshwater-saltwater interfaces.
- **Recommended geophysical methods:**

  - **VES:** VES offers a cost-effective and efficient method for initial assessment of subsurface layering and identifying potential aquifers. Its ability to estimate aquifer thickness and depth makes it suitable for preliminary investigations in Kribi Town (Chiemela et al., 2019).
  - **ES methods:** Due to the potential complexity of the aquifer system and the concern about saltwater intrusion, ES methods could provide valuable insights into aquifer properties and fluid distribution. Its sensitivity to permeability variations and ability to delineate freshwater-saltwater interfaces make it a promising technique for further characterization of Kribi's groundwater resources (Mikhailov et al., 1997).

1.7.3 Hydrogeological Modeling for Sustainable Water Management

1.7.3.1 Introduction to hydrogeological modeling:

Hydrogeological modeling plays a crucial role in understanding and managing groundwater resources by simulating the behavior of complex aquifer systems and predicting their response to various stressors. These models provide valuable tools for sustainable water management and decision-making.

- **Definition and role of hydrogeological modeling:** Hydrogeological modeling involves the development and application of mathematical representations of aquifer systems to simulate groundwater flow and transport processes. These models integrate data from various sources, including field measurements, geological information, and geophysical surveys, to create a simplified representation of the real-world system. By simulating groundwater flow, models help us understand aquifer behavior, predict future conditions, and evaluate the potential impacts of human activities and environmental changes (Anderson et al., 1992).
- **Importance for sustainable water management:** Hydrogeological models are essential for sustainable water management due to their diverse applications:
  - **Water resource assessment:** Models can be used to estimate groundwater availability, recharge rates, and sustainable yield, providing crucial information for water allocation and planning (Harbaugh, 2005).
  - **Prediction of aquifer responses:** Models can predict how aquifers will respond to stressors such as pumping, climate change, and land-use changes. This

    information is critical for developing adaptive management strategies and mitigating potential negative impacts (Zhou and Li, 2011).
  - **Evaluation of management strategies:** Models can be used to test and compare different management scenarios, such as alternative pumping regimes or artificial recharge options, to identify the most effective and sustainable solutions (Doherty, 2010).
- **Types of hydrogeological models:**
  - **Analytical models:** These models use simplified mathematical equations to represent groundwater flow and transport processes. They are often used for preliminary assessments and idealized scenarios but may have limitations in complex settings.
  - **Numerical models:** Numerical models utilize numerical methods to solve the governing equations of groundwater flow and transport. These models offer greater flexibility and can represent complex aquifer geometries and heterogeneities (Wang and Anderson, 1995).
  - **Physically-based vs. conceptual models:** Physically-based models aim to represent the physical processes governing groundwater flow and transport with high accuracy. Conceptual models are simplified representations of the aquifer system, often based on limited data and conceptual understanding. The choice of model type depends on the specific objectives of the study, data availability, and desired level of detail.

1.7.3.2 3D Implicit Geological Modeling

1.7.3.2.1 What is 3D Implicit Geological Modeling?

- **Going Beyond Grids:** Unlike traditional grid-based methods for representing geology, 3D implicit geological modeling utilizes mathematical functions to define the boundaries between geological units (rock or soil types), offering a more flexible and accurate approach (Lajaunie et al., 1997)
- **Advantages:**
  - Handles complex geometries, faults, and folds with more accuracy than grids.
  - Easily updated as new geological data becomes available by refining the functions (Mallet, 2002)

- **Leapfrog Geo:** Software specialized in implicit modeling, providing a user-friendly interface for geological data visualization and model building (Seequent, 2023)

1.7.3.2.2 How It Supports Groundwater Modeling

1. **Building a More Realistic Framework:** A detailed 3D geological model derived using Leapfrog Geo can be directly imported into MODFLOW, providing a more accurate physical structure for your groundwater flow simulation.
2. **Aquifer Delineation:** Implicit models clearly define aquifer boundaries, thicknesses, and the spatial distribution of different hydrogeological units.
3. **Heterogeneity Matters:** By representing variations in hydraulic conductivity linked to geology, you get a more realistic picture of groundwater flow, preferential pathways, and potential zones of slower recharge.
4. **Visual Communication:** Leapfrog Geo's 3D visualization helps you understand the geological controls influencing your aquifer system and effectively communicate this to stakeholders (Houlding, 2006)

1.7.3.2.3 Example Studies Using Leapfrog Geo

- **Combining implicit geologic modeling, field surveys, and hydrogeological modeling to describe groundwater flow in a karst aquifer (D’Affonseca et al., 2020):**

  This study highlights how Leapfrog Geo, informed by geological mapping and borehole data, formed the basis for a MODFLOW model of a complex karst system.

- **The 3D geological model of the Karavanke Tunnel, using Leapfrog Geo (Živec and Žibert, 2016):**

  This case illustrates the use of Leapfrog for modeling complex faulted geology, relevant if Kribi has similar structural features.

1.7.3.2.4 Integrating with the Kribi Project

1. **Data is Key:** The success of the implicit model hinges on gathering geological data: borehole logs, geological maps, and potentially geophysical survey interpretations.
2. **Conceptual Model First:** Before diving into Leapfrog Geo, we develop a sound understanding of Kribi's geological setting. This will inform how to group data and build relationships between the geological units.
3. **MODFLOW Link:** Consider how the geological layers (and their properties) from Leapfrog can be translated to inform the MODFLOW model's aquifer property zonation.

1.7.3.3 Applications of hydrogeological modeling:

Hydrogeological models serve as valuable tools for various applications in water resource management, aiding in the assessment, prediction, and evaluation of groundwater resources and their response to natural and anthropogenic influences.

- **Water resource assessment:** Hydrogeological models are crucial for assessing groundwater availability and sustainable yield. They allow for the estimation of aquifer recharge rates, water storage capacity, and the potential impacts of pumping on aquifer levels and streamflow. By simulating different pumping scenarios, models can help determine sustainable pumping rates that avoid overexploitation and ensure long-term water security (McDonald and Harbaugh, 1988).
- **Predicting aquifer responses to stressors:** Hydrogeological models can be used to predict how aquifers will respond to various stressors, such as climate change, land-use changes, and contamination events. By incorporating climate projections, models can assess the potential impacts of changing precipitation patterns and sea-level rise on groundwater recharge and saltwater intrusion. Similarly, models can simulate the effects of land-use changes on groundwater recharge and quality. In the event of contamination, models can predict the movement of contaminants and evaluate potential risks to human health and the environment (Zheng and Wang, 1999).
- **Evaluating management strategies:** Hydrogeological models play a critical role in evaluating the effectiveness of different water management strategies. They can be used to assess the potential benefits and drawbacks of artificial recharge projects, including their impact on aquifer levels, water quality, and the surrounding environment. Models can also be used to evaluate the effectiveness of wellhead protection measures and to identify areas where additional protection is needed. By simulating different management scenarios, models provide valuable insights for decision-making and promote sustainable groundwater management practices (Doherty, 2010).

1.7.3.4 Integration with other data and models:

Integrating hydrogeological models with other data sources and models enhances their accuracy, reliability, and ability to represent the complexities of real-world groundwater systems. This integration provides a more holistic understanding of water resources and facilitates better-informed water management decisions.

- **Importance of integrating with other data sources:**

  - **Geophysical surveys:** Integrating geophysical data with hydrogeological models allows for improved characterization of aquifer geometry, identification of geological structures, and estimation of hydrogeological parameters. This information can significantly enhance the accuracy and predictive capabilities of groundwater flow models (Andersen et al., 2018).
  - **Remote sensing data:** Remote sensing data can provide valuable information on land use, vegetation cover, and surface water bodies, which can be incorporated into hydrogeological models to improve estimates of groundwater recharge and evapotranspiration (Elbeih, 2015).
  - **Water quality data:** Integrating water quality data with groundwater flow models allows for the simulation of contaminant transport and the assessment of potential risks to human health and the environment. This information is crucial for developing effective groundwater protection strategies (Yeh and Tripathi, 1989).
- **Coupling groundwater flow models with surface water models:** Groundwater and surface water resources are interconnected, and their interactions can significantly impact water availability and quality. Coupling groundwater flow models with surface water models allows for the simulation of these interactions, including:
  - **Stream-aquifer interactions:** Models can simulate the exchange of water between streams and aquifers, considering factors such as streambed infiltration and groundwater discharge to streams (Anderson et al., 1992).
  - **Lake-aquifer interactions:** Models can simulate the exchange of water between lakes and aquifers, accounting for factors like lake level fluctuations and groundwater seepage.
  - **Wetland-aquifer interactions:** Models can represent the hydrological processes in wetlands and their connection to groundwater systems, including the role of wetlands in groundwater recharge and discharge.

Coupled models provide a more comprehensive understanding of the water balance and facilitate integrated water resource management strategies.

1.8 Hydrogeochemical Assessment of Groundwater Resources

1.8.1 Groundwater Quality Parameters and their Significance

1.8.1.1 Introduction to groundwater quality:

Groundwater quality refers to the chemical, physical, and biological characteristics of groundwater that determine its suitability for various uses. Understanding and managing groundwater quality is essential for protecting human health, ecosystems, and ensuring sustainable use of this vital resource.

- **Importance of groundwater quality:** Groundwater serves as a critical source of water for various purposes:
    - **Drinking water:** Groundwater is a primary source of drinking water for many communities worldwide. Its quality directly impacts human health, and contamination with pathogens or harmful chemicals can pose significant risks (WHO, 2011).
    - **Irrigation:** Groundwater is extensively used for irrigation in agriculture. Water quality parameters, such as salinity and the presence of specific ions, can affect crop yields and soil health (Reddy et al., 2019).
    - **Industrial applications:** Various industries rely on groundwater for processes like cooling, cleaning, and manufacturing. Water quality requirements vary depending on the specific industrial application.
- **Factors influencing groundwater quality:** Groundwater quality is influenced by a complex interplay of factors:
    - **Natural geochemical processes:** The mineral composition of the aquifer matrix, water-rock interactions, and natural organic matter content influence the background water quality and the presence of certain dissolved constituents (Appelo and Postma, 2004).
    - **Anthropogenic activities:** Human activities, such as agriculture, industry, waste disposal, and urbanization, can introduce contaminants into groundwater, impacting its quality and suitability for various uses (UNEP, 2016).
    - **Interactions with surface water:** Groundwater and surface water systems often interact, and the quality of one can influence the other. Surface water contamination can infiltrate into groundwater, while groundwater discharge can impact the quality of surface water bodies.
- **Impacts of poor groundwater quality:** Poor groundwater quality can have severe consequences:

- **Human health impacts:** Contaminated groundwater can cause various health problems, ranging from gastrointestinal illnesses to chronic diseases and even cancer, depending on the type and concentration of contaminants (WHO, 2014).
- **Ecosystem impacts:** Contaminated groundwater discharge can harm aquatic life and disrupt ecosystem functions in rivers, lakes, and wetlands. Excessive nutrient levels can lead to eutrophication and oxygen depletion.
- **Economic impacts:** Poor groundwater quality can increase water treatment costs, reduce agricultural productivity, and limit industrial development, leading to significant economic losses.

1.8.1.2 Physical parameters:

Physical parameters of groundwater, such as temperature, pH, and EC, play a significant role in determining its quality and suitability for various uses. These parameters influence chemical reactions, biological activity, and the overall behavior of contaminants in groundwater systems.

1.8.1.2.1 pH (level of acidity or alkalinity)

Importance: pH influences the solubility of various chemicals and minerals, the effectiveness of water treatment processes, and the potential for corrosion of pipes and infrastructure. It also has implications for aquatic life if groundwater interacts with surface water bodies (Drever, 1988).

Link to Kribi: Coastal towns often have concerns about saltwater intrusion, which can affect groundwater pH. Additionally, identify any potential industrial or waste disposal activities that might release acidic or alkaline substances into the environment.

1.8.1.2.2 Temperature

Importance: Water temperature affects its taste and odor, as well as chemical reaction rates and the solubility of gases. It's also a critical factor in the growth and survival of aquatic microorganisms.

Link to Kribi: Temperature variations could signal seasonal trends in groundwater recharge or potential contamination from warm water discharges (e.g., if there's industry near Kribi).

Monitoring temperature variations can also aid in understanding groundwater flow patterns and identifying potential recharge areas (Appelo and Postma, 2004).

1.8.1.2.3 Total Dissolved Solids (TDS)

Importance: TDS is a measure of dissolved minerals and salts. High TDS can affect taste, contribute to scaling, and have implications for certain industrial processes (Appelo and Postma, 2004).

Link to Kribi: Coastal areas are prone to saltwater intrusion, which significantly increases TDS. Understanding TDS will be crucial for evaluating groundwater as a drinking water source.

1.8.1.2.4 EC

Importance: EC is a related measure of dissolved salts. Changes in EC can signal potential contamination or variations in groundwater sources.

Link to Kribi: EC monitoring helps detect saltwater intrusion and potentially pinpoint other sources of contamination that alter the ionic composition of the water.

1.8.1.3 Chemical Parameters

1.8.1.3.1 Calcium (Ca^{2+}) and Magnesium (Mg^{2+}):

Importance: Major contributors to water hardness, impacting taste, scaling, and soap effectiveness. Also essential for human health.

Link to Kribi: Hardness levels are influenced by the underlying geology of the aquifers. Investigate the predominant rock types in the Kribi area.

1.8.1.3.2 Sodium (Na^{+}):

Importance: High sodium can be a concern for individuals on salt-restricted diets. Elevated levels may indicate saltwater intrusion or certain industrial contamination.

Link to Kribi: Crucial for coastal areas like Kribi to assess the impact of potential saltwater intrusion (Appelo and Postma, 2004).

1.8.1.3.3 Chloride (Cl^{-}):

Importance: High chloride concentrations can impart a salty taste and may indicate saltwater intrusion or sewage contamination.

Link to Kribi: A critical parameter for distinguishing saltwater contamination from other potential sources.

1.8.1.3.4 Sulfate (SO_4^{2-}):

Importance: High sulfate can cause a laxative effect and impart an unpleasant taste. Can also be indicative of industrial pollution or natural mineral dissolution.

Link to Kribi: Identify potential sources of sulfate, such as mining activities or natural geological formations.

1.8.1.3.5 Nitrate (NO_3^-):

Importance: A major health concern, especially for infants, causing methemoglobinemia ("blue baby syndrome"). High nitrate often indicates contamination from fertilizers, sewage, or animal waste.

Link to Kribi: Evaluate the intensity of agricultural practices and wastewater management systems in or near recharge areas (Freeze and Cherry, 1979).

1.8.1.4 Trace Elements /Heavy Metals

1.8.1.4.1 Arsenic (As), Lead (Pb), Mercury (Hg), etc.

Importance: Toxic even in trace amounts, posing serious health risks (WHO, 2011). Their presence often indicates specific industrial pollution or legacy contamination issues.

Link to Kribi: Identify past or present industrial activities in or near Kribi, as well as any known historical contamination issues. Choose relevant heavy metals based on potential sources.

1.8.2 Water Quality Standards and Guidelines

1.8.2.1 Introduction to water quality standards and guidelines:

Water quality standards and guidelines play a critical role in protecting public health, preserving ecosystems, and ensuring the sustainable use of water resources. They provide a framework for assessing water quality, identifying potential risks, and implementing appropriate management strategies.

- **Definitions and differentiation:**
    - **Water quality standards:** These are legally enforceable regulations that set maximum allowable concentrations or limits for specific contaminants in water bodies. They are typically established by government agencies and are designed to protect public health and the environment (EPA, 2012).
    - **Water quality guidelines:** These are non-enforceable recommendations or reference values that provide guidance on water quality for various uses. They are often based on scientific research and risk assessments and are used to inform decision-making and support the development of water quality standards (WHO, 2011).
- **Purpose of standards and guidelines:**
    - **Protecting public health:** Standards and guidelines for drinking water quality ensure that water is safe for human consumption and protect against waterborne diseases and other health risks associated with contaminants.

  - **Preserving ecosystems:** Standards and guidelines for water quality in rivers, lakes, and other water bodies protect aquatic life and ecosystem health by limiting the discharge of pollutants and maintaining suitable water quality conditions for aquatic organisms.
  - **Sustainable use of water resources:** Standards and guidelines promote the sustainable use of water resources by preventing overexploitation, pollution, and degradation of water quality, ensuring that water resources are available for present and future generations.
- **Role of international organizations and national agencies:**
  - **World Health Organization (WHO):** The WHO plays a key role in developing international guidelines for drinking water quality, providing a scientific basis for national standards and regulations.
  - **National agencies:** Government agencies at the national and local levels are responsible for establishing and enforcing water quality standards, monitoring water quality, and implementing measures to prevent and address water pollution.

1.8.2.2 WHO Guidelines for Drinking-water Quality:

The WHO Guidelines for Drinking-water Quality serve as a globally recognized and authoritative source for setting drinking water standards and ensuring safe drinking water for populations worldwide. These guidelines provide a comprehensive framework for assessing and managing drinking water quality.

- **Overview of the WHO Guidelines:** The WHO Guidelines for Drinking-water Quality are based on extensive scientific research and risk assessments, providing evidence-based recommendations for managing drinking water quality. They are periodically updated to reflect the latest scientific findings and technological advancements. The guidelines are intended to be used by countries as a basis for developing their own national standards and regulations for drinking water quality.
- **Categories of drinking water quality parameters:** The WHO guidelines encompass a wide range of parameters to ensure comprehensive assessment of drinking water quality:
  - **Microbiological parameters:** These assess the presence of pathogenic bacteria, viruses, and protozoa that can cause waterborne diseases.

    - **Chemical parameters:** These include inorganic and organic chemicals, such as heavy metals, pesticides, and disinfection byproducts, that may pose health risks at certain concentrations.
    - **Radiological parameters:** These address naturally occurring radioactive substances and those released from human activities, which can have long-term health effects.
    - **Aesthetic parameters:** These relate to the sensory properties of water, such as taste, odor, and appearance, which can affect its acceptability and public confidence in drinking water safety.
- **Rationale behind guideline values:** The guideline values for key parameters are established based on a comprehensive evaluation of health risks, analytical achievability, and treatment feasibility. Health-based targets are derived from toxicological data and epidemiological studies, considering the potential health effects of exposure to contaminants. The guidelines also consider the practical aspects of water quality monitoring and treatment, ensuring that the recommended values are achievable and enforceable.
- **Application in different countries and contexts:** The WHO guidelines are widely adopted by countries worldwide as a basis for developing national drinking water standards and regulations. While some countries directly adopt the WHO guidelines as their national standards, others adapt them to their specific context, considering local environmental conditions, water sources, and treatment technologies. The guidelines serve as a valuable reference point for ensuring safe drinking water and protecting public health globally.

1.8.2.3 Application of water quality standards and guidelines:

Water quality standards and guidelines provide a framework for assessing the suitability of water for various uses and ensuring its safety and quality. They play a crucial role in water resource management, guiding decision-making and promoting sustainable water use practices.

- **Assessing suitability of water for various uses:** Water quality standards and guidelines are used to determine the suitability of water for different purposes:
    - **Drinking water:** Standards for drinking water quality set maximum allowable concentrations for contaminants to protect public health and ensure that water is safe for human consumption.

    - **Irrigation:** Guidelines for irrigation water quality consider factors like salinity, specific ion concentrations, and the presence of potentially harmful elements that could affect crop yields and soil health.
    - **Industrial applications:** Water quality requirements for industrial uses vary depending on the specific application and the sensitivity of industrial processes to different contaminants.
- **Role of monitoring programs:** Monitoring programs play a crucial role in tracking water quality and ensuring compliance with standards and guidelines:
    - **Regular sampling and analysis:** Monitoring programs involve regular collection of water samples from various sources, such as wells, rivers, and lakes, followed by laboratory analysis to determine the concentrations of key contaminants.
    - **Data analysis and reporting:** Monitoring data is analyzed to assess trends, identify potential exceedances of standards or guidelines, and inform decision-making regarding water treatment and management strategies.
    - **Early detection of contamination:** Monitoring programs enable early detection of contamination events, allowing for prompt response and mitigation measures to protect public health and the environment.
- **Use of water quality data:** Water quality data serves various purposes:
    - **Identifying contamination sources:** Analyzing spatial and temporal patterns in water quality data can help identify potential sources of contamination, guiding efforts to prevent further pollution.
    - **Assessing health risks:** Water quality data is used to assess potential health risks associated with exposure to contaminants, informing public health interventions and the development of drinking water treatment strategies.
    - **Developing water treatment and management strategies:** Water quality data is essential for designing and optimizing water treatment processes, ensuring that treated water meets safety standards. It also informs the development of sustainable water management practices, such as source water protection and pollution prevention measures.

1.8.3 Potential Sources of Groundwater Contamination

1.8.3.1 Introduction to groundwater contamination:

Groundwater contamination occurs when undesirable substances or contaminants are introduced into groundwater, compromising its quality and potentially impacting human health, ecosystems, and economic activities. Understanding the factors influencing aquifer vulnerability is crucial for preventing and mitigating contamination.

- **Definition and potential impacts:**
    - **Groundwater contamination:** This refers to the presence of anthropogenic or naturally occurring substances in groundwater at concentrations that exceed background levels and pose a risk to human health or the environment (EPA, 2012).
    - **Impacts on water quality:** Contamination can alter the physical, chemical, and biological properties of groundwater, making it unsuitable for drinking, irrigation, or industrial uses.
    - **Human health impacts:** Depending on the type and concentration of contaminants, contaminated groundwater can cause various health problems, ranging from gastrointestinal illnesses to chronic diseases and even cancer (WHO, 2014).
    - **Ecosystem impacts:** Contaminated groundwater discharge can negatively impact aquatic life, disrupt ecosystem functions, and reduce biodiversity in rivers, lakes, and wetlands.
    - **Economic impacts:** Groundwater contamination can lead to increased water treatment costs, loss of agricultural productivity, and limitations on industrial development, resulting in significant economic losses.
- **Factors influencing aquifer vulnerability:**
    - **Aquifer type:** Unconfined aquifers are generally more vulnerable to contamination than confined aquifers due to their direct connection to the surface and lack of a protective confining layer (Freeze and Cherry, 1979).
    - **Geological characteristics:** The permeability and porosity of the aquifer materials influence the rate and extent of contaminant transport. Highly permeable aquifers allow for rapid movement of contaminants, while less permeable formations may retard or attenuate contaminant migration.

  - **Depth to water table:** Shallow water tables increase the vulnerability of aquifers to contamination from surface sources, as contaminants have a shorter distance to travel to reach the groundwater.
  - **Recharge rates:** High recharge rates can dilute contaminants and reduce their concentration in the aquifer, while low recharge rates can exacerbate contamination issues.

Understanding these factors helps identify areas where aquifers are more susceptible to contamination and prioritize efforts for protection and management.

1.8.3.2 Point sources of contamination:

1.8.3.2.1 Industrial activities:

Industrial activities can pose significant risks to groundwater quality due to the potential release of various contaminants, including heavy metals, solvents, and other hazardous chemicals. Proper management and mitigation strategies are crucial for preventing and addressing groundwater contamination from industrial sources.

- **Industrial activities contributing to groundwater contamination:**

Various industrial activities pose a significant threat to groundwater quality due to the potential release of contaminants. Manufacturing facilities utilize chemicals and solvents that can leak or spill, while improper waste disposal further exacerbates the risk. Chemical plants handle large volumes of hazardous materials, increasing the potential for accidental releases and spills. Mining operations generate acid mine drainage with high concentrations of heavy metals, posing a threat to both groundwater and surface water resources. Similarly, oil and gas production involves chemicals and fluids that can leak or spill, contaminating groundwater resources. These activities highlight the importance of stringent regulations, responsible waste management, and effective mitigation strategies to protect groundwater resources.

- **Types of contaminants associated with industrial processes:**
  - **Heavy metals:** Industrial activities can release heavy metals such as lead, mercury, cadmium, and chromium into the environment, posing risks to human health and ecosystems.
  - **Solvents:** Various industrial processes utilize solvents, which can contaminate groundwater if released. Common industrial solvents include trichloroethylene (TCE), tetrachloroethylene (PCE), and benzene.

  - **Other hazardous chemicals:** A wide range of other hazardous chemicals, such as pesticides, herbicides, and polychlorinated biphenyls (PCBs), can be released from industrial activities and contaminate groundwater.
- **Case studies and mitigation/remediation strategies:**
  - **Case studies:** Numerous cases of groundwater contamination from industrial sources have been documented worldwide, highlighting the importance of proper waste management and pollution prevention measures (Mepaiyeda et al., 2020).
  - **Mitigation strategies:** Preventing groundwater contamination from industrial sources requires implementing best management practices, such as proper storage and handling of chemicals, regular inspection and maintenance of equipment, and proper disposal of industrial waste.
  - **Remediation strategies:** If contamination occurs, various remediation techniques can be employed to clean up the affected groundwater, including pump-and-treat systems, bioremediation, and in-situ chemical oxidation.

1.8.3.2.2 Landfills and waste disposal sites:

Landfills and waste disposal sites pose a significant risk to groundwater quality due to the potential for leachate generation and migration. Leachate, a liquid formed as water percolates through waste materials, can contain various contaminants that can pollute groundwater resources.

- **Potential for contamination through leachate:**
  - **Leachate generation:** Leachate is generated as precipitation or other water sources infiltrate through waste materials in landfills and waste disposal sites. As water percolates through the waste, it dissolves and carries various contaminants, forming leachate.
  - **Leachate migration:** If not properly contained, leachate can migrate from the landfill or waste disposal site and infiltrate into the surrounding soil and groundwater, potentially contaminating nearby water resources.
- **Composition of leachate and contaminants:**
  - **Composition:** The composition of leachate varies depending on the type of waste materials, the age of the landfill, and environmental factors. It typically

    contains a mixture of organic and inorganic compounds, including heavy metals, dissolved salts, and organic pollutants.
  - **Contaminants:** Landfill leachate can contain a wide range of contaminants, including heavy metals like lead, mercury, and cadmium, organic compounds such as volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), and pathogens like bacteria and viruses.
- **Regulations and best practices for minimizing contamination risk:**
  - **Regulations:** Regulations governing landfill design and operation aim to minimize the risk of groundwater contamination. These regulations often specify requirements for liners, leachate collection systems, groundwater monitoring, and closure procedures.
  - **Best practices:** Best practices for landfill design and operation include:
    - **Site selection:** Choosing appropriate sites with low permeability soils and hydrogeological conditions that minimize the risk of leachate migration.
    - **Liners and leachate collection systems:** Installing impermeable liners and leachate collection systems to prevent leachate from reaching groundwater.
    - **Groundwater monitoring:** Regularly monitoring groundwater quality to detect any potential contamination and take corrective actions.
    - **Waste minimization and treatment:** Implementing waste minimization and treatment strategies to reduce the amount and toxicity of waste materials disposed of in landfills.

By adhering to regulations and implementing best practices, the risk of groundwater contamination from landfills and waste disposal sites can be significantly reduced.

1.8.3.2.3 USTs:

USTs pose a potential threat to groundwater quality due to the risk of leaks and spills. USTs storing petroleum products or hazardous chemicals are of particular concern, as leaks from these tanks can release contaminants that can migrate through the soil and reach groundwater.

- **Potential for leaks and spills:**

    - **Leaks:** USTs can develop leaks over time due to corrosion, structural failure, or improper installation. Leaks can release contaminants into the surrounding soil and groundwater, potentially impacting nearby water resources and posing health risks.
    - **Spills:** Spills during the filling or emptying of USTs can also release contaminants into the environment. The severity of spills depends on the type and quantity of material released and the effectiveness of containment and cleanup measures.
- **Factors influencing the risk of UST leaks:**
    - **Tank age and material:** Older tanks and those constructed from certain materials, such as bare steel, are more susceptible to corrosion and leaks.
    - **Maintenance practices:** Regular inspection, maintenance, and testing of USTs are crucial for identifying potential problems and preventing leaks. Inadequate maintenance increases the risk of leaks and spills.
    - **Spill and overfill prevention equipment:** Properly installed and functioning spill and overfill prevention equipment can help minimize the risk of accidental releases during tank filling.
- **Regulations and guidelines for UST management and leak prevention:**
    - **Regulations:** Regulations governing USTs aim to prevent leaks and spills and ensure proper management of these potential sources of contamination. These regulations often include requirements for tank registration, leak detection systems, operator training, and financial responsibility for cleanup costs.
    - **Guidelines:** Guidelines provide best practices for UST management and leak prevention, including recommendations for tank installation, operation, maintenance, and closure.

By adhering to regulations and implementing best practices, the risk of groundwater contamination from USTs can be significantly reduced.

1.8.3.2.4 Accidental spills and releases:

Accidental spills and releases of contaminants pose a significant threat to groundwater quality, as these events can rapidly introduce pollutants into the environment and potentially impact nearby water resources. Prompt emergency response and effective cleanup procedures are crucial for mitigating the impact of spills on groundwater.

- **Potential impact of accidental spills:**
    - **Transportation accidents:** Accidents involving trucks, trains, or pipelines transporting hazardous materials can release contaminants into the environment, potentially impacting soil, surface water, and groundwater.
    - **Industrial incidents:** Accidental releases or spills at industrial facilities can release a wide range of contaminants, including chemicals, solvents, and heavy metals, posing risks to groundwater quality.
    - **Severity of impact:** The severity of the impact on groundwater depends on several factors, including the type and quantity of contaminants released, the hydrogeological conditions of the area, and the proximity of the spill to water resources.
- **Emergency response and cleanup procedures:**
    - **Containment and control:** The initial response to an accidental spill focuses on containing the spill and preventing further release of contaminants. This may involve measures such as diking, booming, or using absorbent materials to control the spread of the spill.
    - **Cleanup and remediation:** Once the spill is contained, cleanup and remediation efforts are initiated to remove contaminants from the environment and minimize their impact on groundwater. This may involve techniques such as excavation, soil vapor extraction, or in-situ treatment methods, depending on the specific contaminants and site conditions.
    - **Groundwater monitoring:** Monitoring groundwater quality is essential to assess the extent of contamination and track the effectiveness of cleanup efforts. This information is crucial for making informed decisions about long-term remediation strategies and ensuring the protection of groundwater resources.

Prompt and effective emergency response and cleanup procedures are crucial for minimizing the impact of accidental spills on groundwater and protecting public health and the environment.

1.8.3.3 Non-point sources of contamination:

1.8.3.3.1 Agricultural activities:

Agricultural activities can contribute significantly to groundwater contamination through the use of fertilizers, pesticides, herbicides, and animal manure. These practices can introduce various contaminants into the environment, potentially impacting water quality and human health.

- **Agricultural practices contributing to contamination:**
    - **Fertilizer use:** Excessive or improper application of fertilizers can lead to leaching of nitrates and phosphates into groundwater. Nitrates can pose health risks, particularly for infants, by interfering with oxygen transport in the blood (EPA, 2012). Meanwhile, phosphates contribute to eutrophication in surface water bodies, leading to excessive algal growth and oxygen depletion (Chapman, 2021).
    - **Pesticide and herbicide use:** Pesticides and herbicides can contaminate groundwater if they are not applied according to label instructions or if they are spilled or improperly disposed of. These chemicals can persist in the environment and pose risks to human health and ecosystems, depending on the specific chemical and its concentration (Wotany et al., 2019).
    - **Animal manure management:** Animal manure is a valuable source of nutrients for crops but can also be a source of groundwater contamination if not managed properly. Runoff from manure storage areas or over-application of manure to fields can lead to elevated levels of nitrates, pathogens, and other contaminants in groundwater (Sih et al., 2023).
- **Types of contaminants and their impacts:**
    - **Nitrates:** Nitrate contamination is a common concern in agricultural areas and can pose health risks, especially for infants. High nitrate levels in drinking water can lead to methemoglobinemia, a condition that reduces the blood's ability to carry oxygen (EPA, 2012).
    - **Phosphates:** Phosphates contribute to eutrophication in surface water bodies, leading to excessive algal growth, oxygen depletion, and negative impacts on aquatic life. This can disrupt ecosystem balance and reduce biodiversity (Chapman, 2021).
- **Pesticides:** Pesticides can persist in groundwater and pose risks to human health and ecosystems, depending on the specific pesticide and its concentration. Exposure to certain pesticides has been linked to various health problems, including cancer, reproductive issues, and neurological disorders (Wotany et al., 2019).

- **Best Management Practices (BMPs):** Implementing BMPs can significantly reduce agricultural non-point source pollution:
    - **Nutrient Management Planning:** Developing nutrient management plans ensures that fertilizers and manure are applied at appropriate rates and times to minimize leaching and maximize nutrient uptake by crops (Sih et al., 2023).
    - **Integrated Pest Management (IPM):** Adopting IPM practices minimizes pesticide and herbicide use by combining various control methods, such as biological control, crop rotation, and resistant varieties (Wotany et al., 2019).
    - **Erosion control:** Implementing erosion control measures, such as cover crops and buffer strips, reduces runoff and prevents transport of contaminants to water bodies (Natural Resources Conservation Service, 2019).
    - **Manure management:** Properly storing and handling animal manure through methods like composting or anaerobic digestion helps prevent runoff and leaching of contaminants (Sih et al., 2023).

These BMPs promote sustainable agricultural practices and protect groundwater resources from contamination, safeguarding human health and the environment.

1.8.3.3.2 Septic systems:

Septic systems are common in areas without centralized sewage treatment facilities, but they can pose a risk to groundwater quality if not properly designed, installed, or maintained. Failures or inadequacies in septic systems can lead to the release of contaminants into the surrounding soil and groundwater.

- **Potential for contamination:**
    - **Improper design or installation:** Septic systems that are not designed or installed according to site-specific conditions and regulations can fail to effectively treat wastewater, leading to the release of contaminants.
    - **Lack of maintenance:** Septic systems require regular maintenance, including pumping of the septic tank and inspection of the drainfield, to ensure proper functioning. Neglected systems are more likely to fail and release contaminants.
    - **Soil and site conditions:** The effectiveness of septic systems depends on soil permeability and site characteristics. Poorly draining soils or high-water tables can impede proper wastewater treatment and increase the risk of contamination.
- **Types of contaminants:**

- **Pathogens:** Septic systems can release pathogens, such as bacteria, viruses, and parasites, into groundwater if wastewater is not adequately treated. These pathogens can cause various waterborne diseases (Bartram and Ballance, 1996)
- **Nutrients:** Septic systems release nutrients, such as nitrogen and phosphorus, which can contribute to eutrophication in nearby surface water bodies.
- **Organic matter and chemicals:** Septic systems can also release organic matter, household chemicals, and pharmaceuticals into groundwater, potentially impacting water quality and ecosystem health (EPA, 2012).

Proper design, installation, and maintenance of septic systems are crucial for minimizing the risk of groundwater contamination and protecting public health and the environment.

1.9 Evaluation of Surface Water Resources

1.9.1 Surface Water Hydrology and Catchment Characteristics

1.9.1.1 Introduction to surface water hydrology:

Surface water hydrology delves into the science behind the occurrence, distribution, movement, and characteristics of water found on the Earth's surface, encompassing rivers, streams, lakes, reservoirs, and wetlands (Subramanya, 2009). Grasping the principles of surface water hydrology is paramount for effective water resource management, as it unveils valuable insights into water availability, flood risks, and the influence of human activities and climate change on water systems (Maidment, 2002). By meticulously studying the processes governing surface water flow and storage, we can make well-informed decisions regarding water allocation, infrastructure development, and environmental protection.

The hydrologic cycle depicts the continuous movement of water between the Earth's surface and the atmosphere, acting as the driving force behind the distribution of water resources (Todd and Mays, 2004). Key components of this cycle include precipitation, evaporation, transpiration, infiltration, runoff, and groundwater flow, all intricately interconnected. Precipitation, such as rain and snow, delivers water to the Earth's surface. Evaporation from water bodies and transpiration from plants return water to the atmosphere. Infiltration allows water to seep into the soil and replenish groundwater resources. Runoff occurs when precipitation surpasses infiltration capacity, leading to surface water flow in streams and rivers. Groundwater flow contributes to baseflow in streams and sustains aquatic ecosystems during dry periods. This dynamic interplay of processes determines the distribution and availability of water resources, shaping the hydrological landscape we observe.

A watershed or catchment serves as the fundamental unit for studying surface water hydrology. It represents the area of land where all precipitation falling within its boundaries converges and drains to a common outlet, such as a river, lake, or ocean (Ffolliott et al., 2002). Watersheds encompass various landscape features, including hills, valleys, and streams, and their size and characteristics significantly influence the hydrological processes occurring within them. Understanding the intricacies of a watershed is essential for managing water resources effectively. It allows for the assessment of water availability, flood risks, and the impacts of human activities on water quality and quantity, ultimately guiding sustainable water resource management strategies.

1.9.1.2 Rainfall-runoff processes:

The transformation of rainfall into runoff involves a series of interconnected processes that determine the partitioning of water between infiltration and surface flow (Subramanya, 2009). Infiltration refers to the downward movement of water from the surface into the soil. Several factors influence infiltration rates, including soil type, vegetation cover, and antecedent moisture conditions (Rawls et al., 1989). Sandy soils with larger pore spaces generally exhibit higher infiltration rates compared to clayey soils with smaller pore spaces. Vegetation cover plays a crucial role in promoting infiltration by protecting the soil surface from raindrop impact, enhancing soil structure, and increasing organic matter content (Morgan et al., 2004). Antecedent moisture conditions, or the amount of water already present in the soil, also influence infiltration rates. Dry soils tend to have higher initial infiltration rates, which gradually decrease as the soil becomes saturated. Infiltration is critical in determining the amount of runoff generated, as higher infiltration rates reduce surface runoff and contribute to groundwater recharge.

Overland flow occurs when the rate of rainfall exceeds the infiltration capacity of the soil, leading to the horizontal movement of water across the land surface (Dunne et al., 1991). Overland flow can manifest in various forms, including sheet flow, rill flow, and gully flow. Sheet flow is a thin, uniform layer of water flowing over the land surface. Rill flow occurs when water concentrates in small channels, forming rills that can erode the soil surface. Gully flow occurs in larger, well-defined channels, often resulting from the enlargement of rills and posing a significant erosion hazard. The occurrence and magnitude of overland flow are influenced by factors such as rainfall intensity, slope, soil type, and vegetation cover (Horton, 1945). Steep slopes and impermeable soils promote rapid overland flow, while dense vegetation cover can retard flow and reduce erosion.

Channel flow refers to the movement of water within defined channels, such as rivers and streams. The characteristics of channel flow, including flow velocity and discharge, are influenced by factors such as channel geometry, slope, and the roughness of the channel bed (Leopold, 1982). Flow velocity generally increases with increasing slope and channel size, while rougher channel beds create greater resistance to flow, reducing flow velocity. Discharge, the volume of water passing through a given cross-section of the channel per unit time, is determined by the balance between precipitation inputs, evapotranspiration losses, and groundwater contributions. Channel morphology, or the shape and form of the channel, is influenced by a complex interplay of factors, including flow regime, sediment transport, and the erodibility of the channel banks and bed (Rosgen, 2001). Understanding these processes is crucial for predicting flood risks, managing water resources, and protecting aquatic ecosystems.

1.9.1.3 Factors influencing streamflow and water availability:

Climate and precipitation patterns play a pivotal role in determining streamflow and water availability within a catchment (Nagy et al., 2016). Rainfall intensity, duration, and distribution directly influence the amount of water available for runoff generation and infiltration (Dingman, 2015). Regions with high annual rainfall and frequent intense storms tend to exhibit higher streamflow and greater water availability compared to arid regions with limited precipitation. The timing and distribution of rainfall also impact streamflow patterns, with concentrated rainfall events leading to rapid runoff and potentially causing flash floods.

Topography and drainage patterns exert a significant influence on the rate and direction of runoff, the formation of stream networks, and the overall water balance of a catchment (Hersi et al., 2023). Steep slopes promote rapid runoff, while gentle slopes allow for slower flow and greater opportunity for infiltration. The arrangement of hills, valleys, and other topographic features dictates the direction of runoff and the formation of drainage networks, ultimately influencing the connectivity and flow paths within the catchment. The overall water balance, or the distribution of water between various components of the hydrologic cycle, is closely linked to topography, as it determines the proportion of precipitation that becomes runoff, infiltrates into the soil, or is lost through evapotranspiration.

Land use and land cover significantly impact surface water hydrology by altering infiltration rates, runoff generation, and streamflow patterns (Leopold, 1982). Forests, with their dense vegetation cover and rich organic soils, generally promote high infiltration rates and reduce surface runoff. Agricultural land, depending on the specific practices employed, can exhibit varying impacts on hydrology. Croplands may have lower infiltration rates than forests, leading to increased runoff and potential soil erosion. Urban development, characterized by impervious surfaces such as roads and buildings, significantly reduces infiltration and increases runoff volumes and velocities, often leading to heightened flood risks and degraded water quality in receiving streams (Arnold Jr and Gibbons, 1996).

1.9.1.4 Catchment characteristics and their impact on surface water resources:

Catchment size and shape significantly influence the time it takes for runoff to reach the outlet and the magnitude of peak flows (Singh et al., 2006). Larger catchments generally have longer flow paths and greater travel times for runoff, leading to a delayed and attenuated peak flow response to rainfall events. Conversely, smaller catchments with shorter flow paths exhibit faster runoff response times and potentially higher peak flows. Catchment shape, particularly the degree of elongation or compactness, also affects flow routing and peak discharge. Elongated catchments tend to have lower peak flows due to the desynchronization of runoff contributions from different parts of the catchment, while compact catchments experience more synchronized runoff, leading to higher peak flows.

Slope and relief within a catchment directly impact runoff velocity, erosion potential, and sediment transport (Strahler et al., 2006). Steeper slopes promote rapid runoff and higher flow velocities, increasing the erosive power of water and the potential for soil erosion and sediment transport. Areas with high relief, or significant elevation differences, tend to experience greater erosion and sediment transport due to the increased gravitational forces acting on water and soil particles. Sediment transport can impact water quality, infrastructure, and aquatic ecosystems, highlighting the importance of considering slope and relief in catchment management.

Geology and soils play a crucial role in determining water storage capacity, infiltration rates, and the overall water balance of a catchment (Freeze and Cherry, 1979). The underlying geological formations influence the presence and characteristics of aquifers, which contribute to groundwater storage and baseflow in streams. Soil type and properties, such as texture, structure, and permeability, affect infiltration rates and water-holding capacity. Sandy soils with high permeability allow for rapid infiltration and limited water storage, while clayey soils with lower permeability exhibit slower infiltration and greater water retention. Understanding the geological and soil characteristics of a catchment is essential for assessing water resources and managing potential risks such as flooding and drought.

The spatial distribution of different land uses within a catchment influences surface water hydrology and water quality through their combined effects on infiltration, runoff generation, and contaminant transport (Allan, 2004). The proportion of impervious surfaces, agricultural land, and forested areas within a catchment dictates the overall hydrological response to rainfall events. Urbanized areas with extensive impervious surfaces generate higher runoff volumes and velocities, potentially leading to increased flood risks and reduced water quality due to the transport of pollutants from urban sources (Walsh et al., 2005). Agricultural land, depending on the specific practices employed, can contribute to nutrient loading and sediment runoff, impacting water quality in receiving streams. Forested areas, on the other hand, generally improve water quality by filtering pollutants and reducing sediment loads. The spatial arrangement of these land uses and their proximity to water bodies significantly affect the overall health and sustainability of the catchment's water resources.

1.9.1.5 Case studies of catchment hydrology:

Case studies from diverse regions and climates showcase the wide range of catchment characteristics and their influence on surface water resources. The Amazon River basin, encompassing a vast area with dense rainforest cover, exemplifies the role of vegetation in regulating hydrological processes. The rainforest canopy intercepts rainfall, promotes infiltration, and reduces surface runoff, contributing to the Amazon River's massive discharge and relatively stable flow regime (McClain, 2002). In contrast, the Murray-Darling Basin in Australia, characterized by a drier climate and significant agricultural land use, experiences more variable streamflow and greater vulnerability to drought. Water resource management in the Murray-Darling Basin faces challenges related to balancing water demand for irrigation with environmental flow requirements and ensuring the sustainability of the basin's ecosystems (Ross and Connell, 2016).

Several case studies highlight the impacts of land use changes, climate variability, and human activities on streamflow, water quality, and flood risks. The Chesapeake Bay watershed in the United States has experienced significant land use changes, with increasing urbanization and agricultural intensification leading to elevated nutrient and sediment loads, impacting water quality and ecosystem health in the bay (Boesch et al., 2001). Climate variability, including changes in precipitation patterns and increased frequency of extreme events, has affected streamflow regimes and heightened flood risks in many regions. The Rhine River basin in Europe has witnessed increased flood magnitudes and frequencies due to a combination of climate change and land use modifications (Kundzewicz et al., 2010). These case studies emphasize the need for integrated and adaptive water management strategies that consider the dynamic interactions between climate, land use, and hydrology.

Lessons learned from these case studies offer valuable insights for managing water resources in Kribi Town. The importance of preserving and restoring natural vegetation cover, particularly in sensitive areas near water bodies, is highlighted by the Amazon basin example. The challenges faced in the Murray-Darling Basin emphasize the need for careful water allocation and balancing competing demands for water resources, while also ensuring adequate environmental flows to sustain aquatic ecosystems. The Chesapeake Bay case study underscores the significance of controlling non-point source pollution from agricultural and urban areas to protect water quality and ecosystem health. Considering these lessons, Kribi Town can develop water management strategies that prioritize sustainable land use practices, protect water quality, and adapt to changing climatic conditions.

1.9.2 Precipitation-Runoff Modeling for Water Resource Assessment

1.9.2.1 Introduction to precipitation-runoff modeling:

Precipitation-runoff modeling involves the use of mathematical representations to simulate the transformation of precipitation into runoff within a catchment. These models integrate data on rainfall, topography, land use, and other relevant factors to predict streamflow and understand the hydrological processes governing the movement of water through a catchment (Singh et al., 2006). Precipitation-runoff models play a crucial role in understanding and managing water resources, as they allow us to assess water availability, predict flood risks, and evaluate the potential impacts of climate change and land use modifications on water systems.

Precipitation-runoff models are essential tools for water resource assessment, providing valuable information for water management decisions. By simulating streamflow under various conditions, these models help estimate water availability for different uses, such as drinking water supply, irrigation, and hydropower generation. They also aid in predicting flood risks and designing flood mitigation measures, such as dams and levees. Moreover, precipitation-runoff models enable the evaluation of potential impacts of climate change and land use changes on water resources, providing insights for developing adaptation strategies and ensuring long-term water security.

Precipitation-runoff models represent hydrological processes through a series of mathematical equations and algorithms. These models typically include components that simulate infiltration, evapotranspiration, and runoff routing. Infiltration models estimate the amount of water that enters the soil, considering factors such as soil type, vegetation cover, and rainfall intensity. Evapotranspiration models estimate the amount of water lost from the soil and vegetation through evaporation and transpiration. Runoff routing models simulate the movement of water over the land surface and through stream channels, accounting for factors such as topography, channel geometry, and flow resistance. By incorporating these hydrological processes, precipitation-runoff models provide a comprehensive framework for understanding and predicting the transformation of rainfall into runoff within a catchment.

1.9.2.2 Types of precipitation-runoff models:

1.9.2.2.1 Conceptual models:

Conceptual models of precipitation-runoff processes rely on empirical relationships and simplified representations of hydrological processes to simulate the transformation of rainfall into runoff. These models often utilize parameters derived from observed data or regional relationships to estimate runoff volumes and flow rates. Conceptual models typically do not explicitly represent the physical processes governing infiltration, evapotranspiration, and runoff routing, but rather use simplified equations or look-up tables to approximate these processes.

Several widely used conceptual models exist for simulating precipitation-runoff processes. The Soil Conservation Service (SCS) Curve Number (CN) method is a popular conceptual model that estimates runoff based on rainfall, soil type, land use, and antecedent moisture conditions (Natural Resources Conservation Service, 2019). The CN method utilizes a dimensionless CN, ranging from 0 to 100, to represent the runoff potential of a catchment, with higher CN values indicating greater runoff potential. Another widely used conceptual model is the unit hydrograph method, which characterizes the runoff response of a catchment to a unit of rainfall excess (Sherman, 1932). The unit hydrograph is a time-based hydrograph representing the runoff resulting from a unit depth of rainfall excess over a specified duration.

Conceptual models offer several advantages, including simplicity, ease of use, and relatively low data requirements. They are often suitable for preliminary assessments or applications where detailed data on catchment characteristics and hydrological processes is limited. However, conceptual models also have limitations. Their reliance on empirical relationships may lead to inaccuracies in predictions, particularly in catchments with complex hydrological processes or where conditions differ significantly from those used to develop the model parameters. Additionally, conceptual models may not adequately capture the spatial variability of hydrological processes within a catchment, potentially leading to oversimplification of the system and reduced accuracy in runoff predictions.

1.9.2.2.2 Physically-based models:

Physically-based models of precipitation-runoff processes utilize mathematical equations to represent the physical principles governing the transformation of rainfall into runoff. These models explicitly simulate hydrological processes such as infiltration, evapotranspiration, and runoff routing, considering factors like soil properties, vegetation characteristics, topography, and channel geometry. Physically-based models aim to provide a more realistic and accurate representation of catchment hydrology compared to conceptual models, as they are based on fundamental physical laws and principles.

One commonly used physically-based model is the kinematic wave model, which describes the movement of water over the land surface and through channels using the principles of continuity and momentum conservation (Lighthill and Whitham, 1955). The kinematic wave model assumes that the flow velocity is primarily determined by the water depth and the slope of the terrain or channel bed. Other physically-based models, such as the Green-Ampt infiltration model and the Penman-Monteith evapotranspiration model, provide detailed representations of specific hydrological processes, considering factors such as soil properties, vegetation characteristics, and climatic conditions (Green and Ampt, 1911; Monteith, 1965).

Physically-based models offer several advantages, including greater accuracy, predictive capability, and the ability to simulate the impacts of changes in catchment characteristics or climatic conditions. They are particularly suitable for applications where a detailed understanding of hydrological processes is required, such as flood forecasting, water quality modeling, and climate change impact assessments. However, physically-based models also have limitations. They are often more complex and require significantly more data than conceptual models, which can be challenging to obtain, particularly in data-scarce regions. Additionally, physically-based models can be computationally demanding, requiring specialized software and expertise to run and interpret the simulations.

1.9.2.2.3 Semi-distributed models:

Semi-distributed models offer a hybrid approach to precipitation-runoff modeling, combining elements of both conceptual and physically-based models. These models divide the catchment into sub-basins or Hydrological Response Units (HRUs) and apply different model structures or parameterizations to each unit based on its unique characteristics. This allows for a more detailed representation of spatial variability within the catchment while still maintaining a level of computational efficiency. Semi-distributed models often utilize conceptual representations for certain hydrological processes, such as infiltration or evapotranspiration, while incorporating physically-based principles for runoff routing or channel flow.

The Hydrologic Modeling System (HEC-HMS) software, developed by the US Army Corps of Engineers, is a widely used example of a semi-distributed model (Castro and Maidment, 2020). HEC-HMS allows for the representation of a catchment using a network of sub-basins, reaches, junctions, and reservoirs. Users can select from a variety of model components to simulate different hydrological processes, including infiltration, evapotranspiration, snowmelt, and runoff routing. HEC-HMS offers flexibility in model structure and parameterization, making it suitable for a wide range of applications, from flood forecasting to water supply planning.

Semi-distributed models offer several advantages, including greater flexibility than conceptual models and reduced complexity compared to fully physically-based models. They allow for the representation of spatial variability within a catchment and can be applied to different catchment scales, from small watersheds to large river basins. However, semi-distributed models also have limitations. They require more data than conceptual models, and the process of dividing the catchment into HRUs and selecting appropriate model structures can be subjective. Additionally, semi-distributed models may still rely on empirical relationships for certain hydrological processes, potentially introducing uncertainties into the simulations.

1.9.2.3 Model development and data requirements:

Developing a precipitation-runoff model involves a series of key steps to ensure the model accurately represents the hydrological processes and characteristics of the catchment. Model selection is the initial step, considering factors such as the model's complexity, data requirements, and intended application. Data collection follows, gathering information on rainfall, topography, land use/land cover, soil properties, and streamflow. Parameterization involves assigning values to the model's parameters, often based on observed data or regional relationships. Calibration is the process of adjusting model parameters to achieve a good fit between simulated and observed streamflow data. Validation assesses the model's ability to predict streamflow under different conditions or for periods not used in the calibration process (Srinivas et al., 2018).

Data requirements for precipitation-runoff models vary depending on the model type and complexity. Rainfall data, including rainfall intensity, duration, and spatial distribution, is essential for all models. Topographic data, such as Digital Elevation Models (DEMs), provides information on slope, aspect, and drainage patterns. Land use/land cover maps are crucial for characterizing the spatial distribution of different land uses and their impact on hydrological processes. Soil data, including soil type, texture, and permeability, is important for simulating infiltration and water storage. Streamflow records provide observed data for model calibration and validation.

Challenges associated with data availability and quality can significantly impact the development and accuracy of precipitation-runoff models. Data gaps, particularly in remote or data-scarce regions, may limit the applicability of certain models or require the use of alternative data sources, such as remote sensing or regional datasets (Sahu et al., 2020). Data quality issues, such as errors in measurement or inconsistencies in spatial or temporal resolution, can introduce uncertainties into the model simulations. Strategies for addressing these challenges include data interpolation and extrapolation techniques, data assimilation methods, and sensitivity analysis to assess the impact of data uncertainties on model predictions.

1.9.2.4 Applications of precipitation-runoff models:

Precipitation-runoff models play a crucial role in water availability assessment by providing estimates of streamflow and water yield from rivers and streams. These models consider factors such as rainfall patterns, catchment characteristics, and water demands to determine the amount of water available for various uses. By simulating streamflow under different hydrological conditions and water management scenarios, models help assess the reliability of surface water sources and inform decisions regarding water allocation and infrastructure development. For instance, models can be used to estimate the yield of a proposed reservoir, assess the impact of water withdrawals on downstream flow regimes, or evaluate the potential for water scarcity during drought periods (Visweshwaran, 2017).

Precipitation-runoff models are valuable tools for assessing the potential impacts of climate change and land use changes on water resources and flood risks. By incorporating climate projections into the models, we can simulate how changes in precipitation patterns, temperature, and evapotranspiration may affect streamflow, water availability, and the frequency and magnitude of floods. Similarly, models can be used to evaluate the potential impacts of land use changes, such as urbanization or deforestation, on runoff generation, sediment transport, and water quality (Tassew et al., 2019). This information is crucial for adaptation planning and sustainable water management, as it allows for the identification of potential vulnerabilities and the development of strategies to mitigate the negative impacts of climate change and land use modifications on water resources.

1.9.2.5 Case studies of precipitation-runoff modeling:

Numerous case studies demonstrate the application of various precipitation-runoff models for water resource assessment in diverse regions and contexts. In the Upper Blue Nile basin of Ethiopia, the HEC-HMS model has been successfully used to simulate streamflow and assess water availability for hydropower generation and irrigation (Tassew et al., 2019). The model's ability to represent complex hydrological processes, including snowmelt and reservoir operations, has proven valuable for understanding the basin's water resources and supporting sustainable water management decisions. In the Krishna River basin of India, the HEC-HMS model has been used to simulate runoff and assess the impacts of land use changes on water resources (Visweshwaran, 2017). The study highlighted the model's capability to represent the spatial variability of hydrological processes and predict changes in streamflow patterns due to urbanization and agricultural expansion.

While precipitation-runoff models have demonstrated success in water resource assessment, challenges exist in their application. Accurate flood forecasting, for example, requires models that can capture the rapid and dynamic nature of flood events. This often necessitates the use of high-resolution data, real-time monitoring systems, and advanced modeling techniques to predict flood peaks and inundation extents. Similarly, estimating water availability in data-scarce regions or catchments with complex hydrological processes can be challenging, requiring careful model selection, parameterization, and validation to ensure reliable predictions. Uncertainty in model inputs, such as rainfall data and catchment characteristics, can also propagate through the simulations and affect the accuracy of water availability estimates. Addressing these challenges requires a combination of improved data collection, advanced modeling techniques, and a thorough understanding of the limitations and uncertainties associated with precipitation-runoff models.

1.9.3 Evaluating the Potential of Rivers as Water Sources

1.9.3.1 Introduction to river basin assessment for urban water supply:

Rivers are increasingly important water sources for urban areas, especially in regions facing groundwater depletion or limitations due to overexploitation, contamination, or saltwater intrusion (Vörösmarty et al., 2015). As urban populations grow and water demands increase, surface water sources like rivers offer an alternative or supplemental supply to meet the needs of cities and towns. River basin assessment plays a crucial role in evaluating the potential of rivers for urban water supply and developing sustainable water management strategies.

Several key factors must be considered when evaluating the potential of rivers for urban water supply. Water availability, including the quantity and variability of river flows, is essential for ensuring a reliable and sustainable supply. Water quality is another critical factor, as it determines the suitability of the water for drinking and other uses, and the need for treatment before distribution. Environmental flow requirements, or the minimum flows necessary to maintain the ecological health and functions of the river ecosystem, must also be considered to ensure the sustainability of the water source and protect aquatic biodiversity (Arthington et al., 2006). Additionally, infrastructure needs, such as water intakes, treatment plants, and distribution networks, must be assessed in terms of their feasibility, cost, and potential environmental impacts.

A comprehensive and integrated approach is essential for river basin assessment, balancing water supply demands with ecological sustainability. This involves considering the entire river basin as a system, understanding the interconnectedness of water resources, and recognizing the potential impacts of water withdrawals on downstream users and ecosystems (Gleick, 2000). IWRM principles provide a framework for this approach, emphasizing stakeholder participation, collaborative planning, and the equitable allocation of water resources to meet the needs of both human and ecological systems (GWP, 2000).

1.9.3.2 Assessing water availability:

1.9.3.2.1 Hydrological data analysis:

Collecting and analyzing long-term hydrological data, such as streamflow records, is crucial for understanding flow variability, identifying trends, and estimating reliable water availability from rivers (Canton, 2021). Streamflow data provides insights into the historical patterns of river discharge, including seasonal fluctuations, inter-annual variability, and the occurrence of extreme events such as floods and droughts. This information is essential for assessing the reliability of a river as a water source and determining the potential risks and uncertainties associated with its use. Long-term hydrological data also allows for the detection of trends in streamflow, which may be indicative of climate change impacts or changes in land use within the catchment.

Several methods exist for analyzing hydrological data to characterize flow regimes and assess the reliability of water supply from rivers. Flow duration curves depict the percentage of time that a given flow rate is equaled or exceeded, providing a comprehensive picture of the flow regime and the frequency and duration of low flows (Searcy, 1959). Low flow frequency analysis involves statistically analyzing historical low flow data to estimate the probability of low flows of a certain magnitude occurring in the future, which is crucial for assessing drought risks and planning water supply infrastructure (Stahl et al., 2010). Statistical techniques, such as trend analysis and time series analysis, can be used to identify long-term changes in streamflow and assess the potential impacts of climate change or human activities on water resources. These methods provide valuable insights for water resource planning and management, ensuring the sustainable and reliable use of river water for urban water supply.

1.9.3.2.2 Precipitation-runoff modeling:

Precipitation-runoff models, as discussed in Section 1.9.2, are valuable tools for estimating water availability from rivers under different climate and land use scenarios. By simulating the hydrological response of a catchment to various rainfall patterns and land cover conditions, these models provide insights into how changes in climate or land use may affect streamflow and water availability. For instance, models can be used to assess the potential impacts of climate change on rainfall patterns and evapotranspiration, and how these changes may influence river flows and water resources. Similarly, models can simulate the effects of urbanization or deforestation on runoff generation and infiltration, providing valuable information for understanding the potential consequences of land use modifications on water availability (Srinivas et al., 2018).

Precipitation-runoff models can be used to predict future water availability and assess the potential impacts of climate change and urbanization on river flows. By incorporating climate projections and land use change scenarios into the models, we can simulate future hydrological conditions and estimate potential changes in streamflow, water yield, and the frequency and severity of droughts and floods. This information is crucial for long-term water resource planning and management, as it allows for the identification of potential vulnerabilities and the development of adaptation strategies to ensure water security in the face of changing climatic and land use conditions (Halwatura and Najim, 2013). For instance, models can help evaluate the effectiveness of different water conservation measures, identify potential sites for reservoir development, or assess the need for infrastructure upgrades to accommodate future water demands.

1.9.3.2.3 Environmental flow requirements:

Environmental flows refer to the quantity, timing, and quality of water flows necessary to sustain freshwater ecosystems and their ecological functions (Arthington et al., 2006). Maintaining adequate environmental flows is crucial for protecting riverine ecosystems and the biodiversity they support, as it ensures the availability of water for various ecological processes, such as fish migration, nutrient cycling, and sediment transport. Environmental flows also contribute to the overall health and resilience of river systems, supporting riparian vegetation, maintaining water quality, and providing habitat for aquatic organisms.

Several methods exist for determining environmental flow requirements, each with its strengths and limitations. Hydrological methods, such as the Tennant method or the range of variability approach (RVA), analyze historical flow data to identify key flow characteristics and establish flow regimes that support ecological functions (Richter et al., 1997; Tennant, 1976). Hydraulic methods, such as the wetted perimeter method or the R2CROSS method, focus on maintaining suitable hydraulic conditions, such as water depth and velocity, for aquatic organisms and habitat (Gore and Nestler, 1988; Jowett, 1997). Habitat-based methods, such as the Physical Habitat Simulation System (PHABSIM), directly link flow regimes to the availability of suitable habitat for specific species or groups of organisms (Milhous et al., 1989).

Balancing water extraction for human use with the need to maintain adequate environmental flows is essential for sustainable water resource management. Over-extraction of water from rivers can lead to reduced flows, altered flow regimes, and degradation of aquatic ecosystems, impacting biodiversity and ecosystem services. It is crucial to consider environmental flow requirements in water allocation decisions and develop water management strategies that ensure the long-term health and sustainability of river systems while meeting the water needs of urban populations.

1.9.3.2.4 Reservoir storage potential:

Reservoirs play a crucial role in augmenting water availability from rivers, particularly during dry seasons or periods of drought (Loucks and Gladwell, 1999). By capturing and storing water during periods of high flow, reservoirs provide a buffer against water scarcity and ensure a more reliable water supply for various uses, including urban water supply, irrigation, and hydropower generation. Reservoirs can also help mitigate flood risks by attenuating peak flows during storm events and releasing water gradually downstream.

Several factors influence the storage potential of reservoirs, including catchment size, topography, and geological suitability for dam construction. Catchment size determines the amount of water available for storage, with larger catchments generally offering greater potential for reservoir development. Topography influences the feasibility and cost of dam construction, as steeper valleys often require higher dams to create sufficient storage capacity. Geological suitability is crucial for ensuring the stability and safety of dams, as the underlying rock formations must be able to support the weight and pressure of the impounded water (Bharti et al., 2020).

Assessing reservoir capacity, sedimentation rates, and potential downstream impacts is essential for sustainable reservoir management. Reservoir capacity is determined by the volume of water that can be stored behind the dam, considering factors such as dam height, reservoir area, and sedimentation rates. Sedimentation, the accumulation of sediment within the reservoir, can reduce storage capacity over time and impact the lifespan of the reservoir (Morris and Fan, 1998). Downstream impacts of reservoirs include changes in flow regimes, altered sediment transport, and potential effects on aquatic ecosystems and water quality. Methods for assessing these impacts include hydrological modeling, sediment transport modeling, and ecological studies to evaluate the potential consequences of reservoir operations on downstream river systems and ecosystems.

1.9.3.2.5 Case studies of river basin management:

Several case studies showcase successful river basin management approaches that balance water supply needs with environmental sustainability. The Rhine River Basin in Europe provides a prime example of IWRM implementation. Through international cooperation and collaborative planning, the Rhine River Basin countries have addressed challenges related to water pollution, flood management, and navigation, while also ensuring the ecological health of the river system (Petry and Dombrowsky, 2007). The Murray-Darling Basin Authority in Australia has implemented a comprehensive basin plan that aims to balance water extraction for irrigation and urban use with environmental flow requirements to protect the basin's unique ecosystems and biodiversity (Hart, 2016). These case studies highlight the importance of stakeholder engagement, adaptive management, and a holistic approach to river basin management for achieving sustainable water use and environmental protection.

Successful reservoir projects around the world demonstrate the potential for balancing water supply needs with environmental considerations. The Hoover Dam on the Colorado River in the United States provides water storage for multiple states, supports hydropower generation, and offers recreational opportunities while also managing flood risks and ensuring a minimum flow downstream (Karambelkar, 2018). The Itaipu Dam on the Paraná River, shared by Brazil and Paraguay, is one of the largest hydroelectric power plants in the world, generating clean energy while also incorporating environmental mitigation measures, such as fish passages and conservation programs, to minimize impacts on the river ecosystem (Llamosas, 2023). These examples showcase the potential for reservoir projects to contribute to sustainable water management and regional development when environmental considerations are integrated into planning and operation.

1.10 GIS and Multi-Criteria Decision Analysis for Water Resource Management

1.10.1 Applications of GIS in Water Resource Management

1.10.1.1 Introduction to GIS and its role in water resource management:

Geographic Information Systems (GIS) are powerful tools for storing, analyzing, and visualizing spatial data, encompassing geographic features, their attributes, and their relationships in a spatial context (Clarke and Rowley, 1995). GIS allows for the integration of diverse datasets, such as maps, satellite imagery, and field observations, into a single platform, enabling comprehensive analysis and visualization of spatial patterns and relationships. This capability makes GIS a valuable decision-support tool for water resource management, providing insights into the distribution and dynamics of water resources, potential risks and vulnerabilities, and the effectiveness of different management strategies.

GIS plays a crucial role in water resource management by providing a platform for integrating diverse datasets, conducting spatial analysis, and communicating information effectively. By bringing together data on topography, land use, hydrology, and water quality, GIS enables a holistic understanding of water resources and their interactions with the environment and human activities. Spatial analysis tools within GIS allow for the identification of potential water sources, assessment of flood risks, delineation of watersheds, and evaluation of the impacts of land use changes on water resources. Additionally, GIS facilitates effective communication of complex spatial information to stakeholders and decision-makers, using maps, visualizations, and spatial models to convey key findings and support informed decision-making.

The applications of GIS in water resource management are wide-ranging, encompassing various aspects of planning, monitoring, and decision-making. Watershed delineation using GIS helps define the boundaries of a catchment and identify areas contributing runoff to specific water bodies. Infrastructure planning benefits from GIS by allowing for the optimal placement of water supply and wastewater treatment facilities, considering factors such as population density, topography, and environmental constraints. Environmental monitoring utilizes GIS to track changes in water quality, land use, and other environmental parameters, providing insights into the health of water resources and the effectiveness of management strategies. Additionally, GIS plays a crucial role in flood risk assessment, mapping flood-prone areas, and developing flood mitigation plans (Malczewski, 2004).

1.10.1.2 Reservoir siting and analysis:

GIS plays a crucial role in identifying potential sites for reservoirs by facilitating the analysis of spatial data on topography, land use, geology, and proximity to demand centers (Jankowski and Nyerges, 2001). By overlaying and analyzing these datasets within a GIS environment, suitable locations for reservoir construction can be identified based on criteria such as valley shape, land availability, geological stability, and distance to water users. GIS tools can be used to assess the catchment area contributing runoff to the potential reservoir site, estimate water availability, and evaluate potential environmental impacts, such as inundation of land and displacement of communities.

GIS applications extend beyond site selection to encompass the calculation of reservoir storage capacity, assessment of environmental impacts, and optimization of reservoir design and operation. GIS tools can be used to generate DEMs of the proposed reservoir area, allowing for the calculation of storage capacity at different water levels. Spatial analysis within GIS can assess the potential impacts of reservoir construction and operation on surrounding ecosystems, including changes in land cover, habitat fragmentation, and potential effects on downstream water quality and flow regimes. Optimization techniques within GIS can be used to determine the optimal size, shape, and operation of the reservoir to maximize water storage, minimize environmental impacts, and meet water demands efficiently (Qureshi, 2010).

Case studies from around the world demonstrate the successful application of GIS in reservoir siting and management. In the Dez River basin of Iran, GIS was used to identify potential sites for dams and reservoirs based on criteria such as topography, geology, land use, and environmental sensitivity (Nourani and Andaryani, 2020). The study highlighted the effectiveness of GIS in facilitating a multi-criteria decision-making process for reservoir site selection. In the Upper Blue Nile basin of Ethiopia, GIS was used to assess the potential impacts of the Grand Ethiopian Renaissance Dam on downstream water resources and ecosystems (Wheeler et al., 2016). The study demonstrated the value of GIS in evaluating the complex spatial and temporal dynamics of reservoir operations and their potential consequences for downstream water users and the environment.

1.10.2 MCE Methods

1.10.2.1 Introduction to MCE and its role in decision-making:

MCE is a decision-support tool used to evaluate complex problems involving multiple, often conflicting, criteria. MCE methods provide a structured framework for considering various factors, both quantitative and qualitative, in decision-making processes. These methods allow for the explicit identification of relevant criteria, the weighting of criteria based on their relative importance, and the evaluation of alternatives based on their performance against the established criteria. By providing a systematic approach to decision-making, MCE helps to ensure that all relevant factors are considered and that the chosen solution reflects the priorities and values of stakeholders involved (Qureshi, 2010).

MCE plays a crucial role in facilitating informed and transparent decision-making, particularly in environmental and resource management contexts. Environmental and resource management problems often involve complex trade-offs between competing objectives, such as economic development, environmental protection, and social equity. MCE methods provide a transparent framework for evaluating these trade-offs and making informed decisions that consider the various perspectives and priorities of stakeholders. By explicitly identifying and weighting criteria, MCE allows for a clear understanding of the basis for decision-making and promotes accountability and stakeholder buy-in (Arulbalaji et al., 2019).

The basic principles of MCE involve a series of steps to guide the decision-making process. First, relevant criteria are identified through stakeholder engagement, literature review, and expert consultation. These criteria represent the key factors that influence the decision, such as cost, environmental impact, social acceptability, and technical feasibility. Next, the criteria are weighted based on their relative importance, reflecting the priorities and values of stakeholders. Weighting methods can range from simple ranking to more complex techniques, such as pairwise comparisons or Analytical Hierarchy Process (AHP) (Arulbalaji et al., 2019; Qureshi, 2010; Shao et al., 2020). Finally, alternatives are evaluated based on their performance against the established criteria, using scoring systems, ranking methods, or other evaluation techniques. The results of the MCE process provide a basis for selecting the most preferred alternative or developing a compromise solution that balances the various criteria and stakeholder interests.

1.10.2.2 Analytical Hierarchy Process (AHP):

The Analytical Hierarchy Process (AHP) is a widely used MCE method based on pairwise comparisons of criteria and alternatives. Developed by Thomas L. Saaty in the 1970s, AHP provides a structured approach to decision-making by breaking down complex problems into a hierarchy of criteria and alternatives, and then using pairwise comparisons to assess the relative importance of each element in the hierarchy (SAATY, 2002). AHP is a versatile method that can handle both quantitative and qualitative criteria, making it suitable for a wide range of decision-making problems.

The AHP process involves several key steps. First, a hierarchy is constructed, with the overall goal or objective at the top, followed by levels of criteria and sub-criteria, and finally the alternatives at the bottom. Next, pairwise comparisons are conducted, where each element in a level is compared to every other element in the same level in terms of its relative importance or preference. This is done using a numerical scale that reflects the intensity of preference. The results of the pairwise comparisons are then used to construct a pairwise comparison matrix for each level of the hierarchy. Finally, the eigenvector corresponding to the largest eigenvalue of each matrix is calculated, which represents the weights or priorities of the elements in that level. These weights are then aggregated throughout the hierarchy to determine the overall priorities of the alternatives.

AHP offers several advantages as an MCE method. Its structured approach provides a clear and transparent framework for decision-making, allowing for the explicit consideration of multiple criteria and their relative importance. AHP can handle both quantitative and qualitative criteria, making it versatile for various decision-making problems. Additionally, AHP allows for the assessment of consistency in judgments, ensuring that the pairwise comparisons are logical and reliable. However, AHP also has limitations. The process of pairwise comparisons can be subjective and time-consuming, particularly for complex problems with numerous criteria and alternatives. Additionally, AHP assumes that the criteria are independent, which may not always be the case in real-world decision-making problems.

1.10.2.3 Applicability of MCE to water resource management:

MCE methods find numerous applications in water resource management, addressing complex decision-making problems that involve multiple, often conflicting, criteria. In reservoir site selection, MCE provides a framework for evaluating potential sites based on criteria such as environmental impact, social considerations, and economic feasibility. Environmental criteria may include factors like habitat loss, water quality impacts, and downstream flow alterations. Social considerations may involve displacement of communities, cultural heritage preservation, and recreational opportunities. Economic feasibility criteria may include construction costs, land acquisition costs, and potential benefits from water supply, hydropower generation, or flood control. By weighting and evaluating these criteria, MCE helps identify the most suitable reservoir site that balances the various objectives and stakeholder interests.

MCE is valuable for groundwater vulnerability assessment, helping to identify areas where aquifers are more susceptible to contamination (Jankowski and Nyerges, 2001). Criteria for vulnerability assessment may include hydrogeological characteristics, such as depth to water table, aquifer type, and soil permeability. Land use factors, such as the presence of industrial activities, agricultural land, or waste disposal sites, are also important considerations. Potential contaminant sources, such as USTs or areas with known contamination, further contribute to vulnerability assessment. By weighting and evaluating these criteria using MCE methods, vulnerability maps can be created to guide land-use planning decisions, prioritize monitoring efforts, and implement preventative measures to protect groundwater resources.

MCE methods are also applicable to water allocation and management, helping to allocate water resources among competing users and evaluate the trade-offs between different water management strategies. Criteria for water allocation may include water rights, economic value of water use, environmental flow requirements, and social equity considerations. MCE methods can be used to develop water allocation plans that balance the needs of various users while ensuring the sustainability of water resources and protecting aquatic ecosystems. Additionally, MCE can be used to evaluate the effectiveness of different water management strategies, such as conservation measures, water reuse, or desalination, considering factors like cost, environmental impact, and social acceptability.

1.10.3 GIS-Based MCE for Water Resource Planning and Management

1.10.3.1 Data requirements and preparation:

GIS-based MCE for water resource management requires a variety of spatial data to comprehensively represent the physical, environmental, and socioeconomic factors influencing decision-making. Topography and elevation data, often in the form of DEMs, provide information on slope, aspect, and drainage patterns, crucial for understanding hydrological processes and identifying potential water resource development sites. Land use/land cover maps depict the spatial distribution of different land uses, such as forests, agriculture, and urban areas, influencing infiltration, runoff generation, and water quality. Soil data and geological maps provide insights into the physical properties of the subsurface, including soil permeability, water-holding capacity, and the presence of aquifers or geological hazards. Hydrological data, such as stream networks and rainfall patterns, is essential for understanding water availability and flow dynamics (Qureshi, 2010). Socioeconomic data, including population density and infrastructure, helps assess water demands and potential social impacts of water management decisions. Environmental data, such as protected areas and sensitive habitats, is crucial for identifying areas that require special consideration in water resource planning and development.

Data preparation is a critical step in GIS-based MCE, ensuring the quality, consistency, and compatibility of spatial data for analysis. Data acquisition involves obtaining relevant datasets from various sources, such as government agencies, research institutions, or commercial providers. Data cleaning involves identifying and correcting errors or inconsistencies in the data, such as missing values, outliers, or topological errors. Format conversion may be necessary to ensure compatibility between different data formats, such as converting raster data to vector data or vice versa (Arulbalaji et al., 2019). Georeferencing is the process of assigning real-world coordinates to spatial data, ensuring that all datasets are aligned and can be accurately overlaid for analysis.

Standardizing data to a common scale is essential for comparison and analysis in GIS-based MCE. Different datasets may have different measurement units, scales, or resolutions, making direct comparison difficult. Standardization methods, such as normalization or rescaling, transform data to a common scale, allowing for meaningful comparison and analysis. For example, elevation data may be normalized to a range of 0 to 1, or land use data may be rescaled to a common classification scheme (Qureshi, 2010). Standardization ensures that all criteria are considered equally in the MCE process and that the results are not biased by differences in data scales or units.

1.10.3.2 MCE methods and criteria weighting in a GIS environment:

The Analytical Hierarchy Process (AHP) can be effectively integrated within a GIS framework to facilitate multi-criteria decision-making for water resource management. AHP allows for the hierarchical structuring of decision criteria and the use of pairwise comparisons to determine the relative weights or priorities of each criterion. GIS tools can be used to visualize the hierarchy, conduct pairwise comparisons, and calculate the resulting weights (Arulbalaji et al., 2019). Additionally, GIS can facilitate the spatial analysis of criteria and the creation of suitability maps based on the weighted criteria, providing a comprehensive and transparent approach to decision-making.

Several techniques exist for weighting criteria within a GIS environment (Arulbalaji et al., 2019; Jankowski and Nyerges, 2001; Jiang and Eastman, 2000; Qureshi, 2010), considering factors such as expert judgment, stakeholder input, and the use of pairwise comparison matrices. Expert judgment involves eliciting weights from experts in relevant fields, such as hydrologists, ecologists, or economists. Stakeholder input can be gathered through surveys, workshops, or public meetings, ensuring that the weights reflect the values and priorities of the community. Pairwise comparison matrices, a key component of AHP, involve comparing each criterion to every other criterion in terms of its relative importance, using a numerical scale to represent the intensity of preference. The resulting weights reflect the consensus or aggregated judgment of experts or stakeholders.

Weights are applied to spatial data layers within a GIS environment to create weighted suitability maps for different criteria (Arulbalaji et al., 2019). Each spatial data layer represents a specific criterion, such as elevation, slope, land use, or soil type. The values within each data layer are multiplied by the corresponding weight, resulting in a weighted suitability map that reflects the relative importance of each criterion. These weighted suitability maps can then be combined using overlay analysis techniques to create a composite suitability map that represents the overall suitability of different locations for the specific water resource management objective.

1.10.3.3 Spatial analysis and suitability mapping:

GIS tools provide a powerful suite of spatial analysis techniques for suitability mapping in the context of MCE, enabling the identification of optimal locations for water resource development projects (Jiang and Eastman, 2000; Qureshi, 2010). Overlay analysis involves combining different weighted suitability maps, each representing a specific criterion, to create a composite suitability map that reflects the overall suitability of different locations based on the combined criteria. This is often achieved through operations such as weighted sum or weighted product, where the values of each suitability map are multiplied by their respective weights and then summed or multiplied to produce a final suitability score for each location.

Distance analysis is a valuable tool for assessing proximity to features or areas of interest, such as rivers, settlements, or infrastructure. Distance analysis tools within GIS can calculate the distance from each location to the nearest feature of interest or generate distance buffers around these features. This information is crucial for considering factors such as accessibility to water sources, potential impacts on communities, and the cost of infrastructure development (Qureshi, 2010).

Buffer analysis involves creating buffer zones around sensitive features, such as protected areas, wetlands, or water bodies, to establish areas of exclusion or protection. Buffer zones serve as a spatial planning tool to prevent or mitigate potential impacts of water resource development projects on sensitive ecosystems or areas of high conservation value. The size of the buffer zone is typically determined based on the specific sensitivity of the feature and the potential impacts of the proposed development (Qureshi, 2010).

Suitability maps are interpreted by analyzing the spatial distribution of suitability scores and identifying areas with high suitability for the specific water resource development project. High suitability scores indicate locations that meet the desired criteria and offer a balance between the various objectives and stakeholder interests considered in the MCE process. These maps provide valuable information for decision-making, guiding the selection of optimal locations for water resource development projects while minimizing potential environmental and social impacts (Arulbalaji et al., 2019).

1.10.3.4 Case studies of GIS-based MCE applications:

Reservoir Siting:

Numerous case studies demonstrate the successful application of GIS-based MCE in identifying suitable locations for reservoirs. A study in the Tigris River basin of Turkey utilized GIS and MCE to evaluate potential dam sites based on criteria such as topography, geology, land use, and environmental impact (Demirel and Tüzün, 2011). The results indicated that GIS-based MCE effectively identified sites that maximized water storage capacity while minimizing environmental and social impacts. Similarly, a study in the Awash River basin of Ethiopia employed GIS and MCE to assess potential reservoir locations considering factors like land suitability, water availability, and proximity to demand centers (Zeleke and Hurni, 2001)..

These studies showcase the effectiveness of GIS-based MCE in optimizing reservoir site selection, leading to more informed and sustainable water resource development decisions.

Groundwater Vulnerability Mapping:

GIS-based MCE has been widely applied in assessing the vulnerability of aquifers to contamination, generating valuable information for groundwater protection and land-use planning. A study in the Campania region of Italy utilized GIS and MCE to evaluate groundwater vulnerability based on factors such as depth to water table, soil permeability, and land use (Chitsazan and Akhtari, 2009). The resulting vulnerability maps helped identify areas where aquifers were more susceptible to contamination, guiding the implementation of preventative measures and land-use restrictions to protect groundwater resources. Similarly, a study in the Gaza Strip employed GIS and MCE to assess aquifer vulnerability, considering factors such as hydrogeological characteristics and potential contaminant sources (Vrba et al., 2007). The vulnerability maps generated in these studies served as valuable tools for developing groundwater protection strategies and informing land-use planning decisions to minimize contamination risks.

Land-Use Planning for Water Resource Protection:

GIS-based MCE supports land-use planning decisions aimed at protecting water resources by identifying critical source areas for pollution control and designating areas for conservation or restoration. A study in the Lake Tana basin of Ethiopia employed GIS and MCE to identify critical source areas of sediment and nutrient loading, guiding land-use planning efforts to reduce erosion and improve water quality in the lake (Haregeweyn et al., 2012). Similarly, a study in the Mantiqueira Range of Brazil utilized GIS and MCE to identify priority areas for forest conservation and restoration based on their importance for water resource protection and biodiversity conservation (Rodrigues et al., 2011). These studies showcase the effectiveness of GIS-based MCE in promoting sustainable land use practices, protecting water quality, and maintaining the ecological integrity of watersheds.

1.11 Conclusion

This literature review has highlighted the multifaceted nature of urban water resource management, particularly in coastal settings like Kribi Town. Existing research emphasizes the need for integrated approaches like IWRM that consider both groundwater and surface water resources, assess water quality risks, and explore sustainable solutions for supply augmentation. While studies in Cameroon provide a general understanding of the national water context, targeted research focusing on Kribi's specific hydrogeological characteristics, potential contamination sources, and the feasibility of utilizing the Kienke River remains limited. This research aims to address these knowledge gaps, providing a comprehensive evaluation of Kribi's water resources and proposing tailored strategies to ensure a secure and sustainable water future for the town.

2 CHAPTER TWO: MATERIALS AND METHODS

2.1 Introduction

This chapter outlines the step-by-step approach taken to evaluate Kribi Town's water resources and explore sustainable solutions for urban water supply. Combining field investigations, data analysis, and computer modeling, the methodology aims to address the research objectives and provide a comprehensive understanding of the available water resources. We'll delve into the specifics of each method employed, from geophysical surveys to assess underground aquifers to hydrological modeling of the Kienke River. This chapter provides the framework for understanding how the research was conducted and the data upon which the conclusions are based.

2.2 Hydrogeological Assessment:

2.2.1 ES Surveys:

2.2.1.1 Survey Design and Equipment

- **Survey Objectives:** The primary objectives of the ES surveys are to:
    - Identify zones of high permeability within the Kribi Town aquifer system.
    - Characterize the heterogeneity of the aquifer in terms of permeability variations.
    - Provide subsurface data that will be integrated with other datasets to develop a comprehensive hydrogeological model.
- **Survey Design:** The ES surveys will be conducted along transects designed to provide coverage across the Kribi Town area.
    - **Transect Layout:** there is no veritable determining factor to the creation of transects, apart from the understanding that the coast of Kribi will be well covered. No detailed geological maps nor groundwater flow paths exist for public consumption, so these were not used to determine our transects. A mesh was created in ArcGIS, with an average inter-point profile grid spacing of 200m into the continent and variable along the shore. This low-resolution grid spacing was used to have a representative coverage of the area of interest to extract the hydrological structures and parameters.
    - **Spacing:** The spacing between the seismic source and receiver electrodes will be optimized to maximize the signal-to-noise ratio of the ES response while providing adequate resolution for identifying permeability variations. The optimal spacing will be comprised between 5cm and 25 cm from the electrode.

  - **DOI:** The DOI will depend on the energy of the seismic source and the attenuation characteristics of the subsurface materials. However, the processed depth is determined by the access level of the current user account. ATS Processing Server offers different Access Level depending on the subscription of the user, as seen in Table 2-1.

Table 2-1: ATS GeoSuite software – processing time and approximate investigation depth (ATSGeoConsultants., 2019).

Access Level	Processing Time (ms)	Cost($US)	Approximate Min Processing Depth (m)	Approximate Max Processing Depth (m)
0	5	Free	20	30
1	10	200	40	60
2	25	500	100	150
3	50	1000	200	300
4	75	1500	300	450
5	100	2000	400	600

- **Equipment:** The following equipment will be utilized for the ES surveys:
  - **Seismic Source:** A sledgehammer impacting a metal plate will be used as the seismic source. The sledgehammer, 5 kg in weight, provides a portable and readily available source of seismic energy.
  - **Receiver Electrodes:** Two stainless steel pins will be used as receiver electrodes. These electrodes will be inserted into the ground about 30 cm along the survey lines at a spacing and orientation optimized for signal quality and resolution.
  - **Data Acquisition System:** The ATS GeoSuite mobile application, installed in a Samsung Galaxy Phone, will be used for data acquisition and processing. The GeoSuite app allows for the recording of electrical signals from the electrodes in sync with the seismic source impacts. These are seen in Figure 7.

Figure 7: Survey Equipment for the ES Method

2.2.1.2 Data Acquisition Procedures

- **Field Procedures:** The following field procedures will be followed as in Figure 8:
    - **Site Preparation:** At each survey point, the area around the seismic source and receiver electrodes will be cleared of any vegetation or debris that might interfere with signal transmission.
    - **Electrode Emplacement:** The two stainless steel pins will be inserted into the ground to a depth of at least 30 cm, ensuring good electrical contact. Salt solution may be used to enhance electrical coupling in areas with dry or sandy soils.
    - **Seismic Source Operation:** The sledgehammer will be used to impact the metal plate repeatedly at a consistent rate and with consistent force.
    - **Data Recording:** The GeoSuite app will be used to record the electrical signals from the receiver electrodes, synchronized with the seismic source impacts. The recording duration and sampling rate will be set within the app.

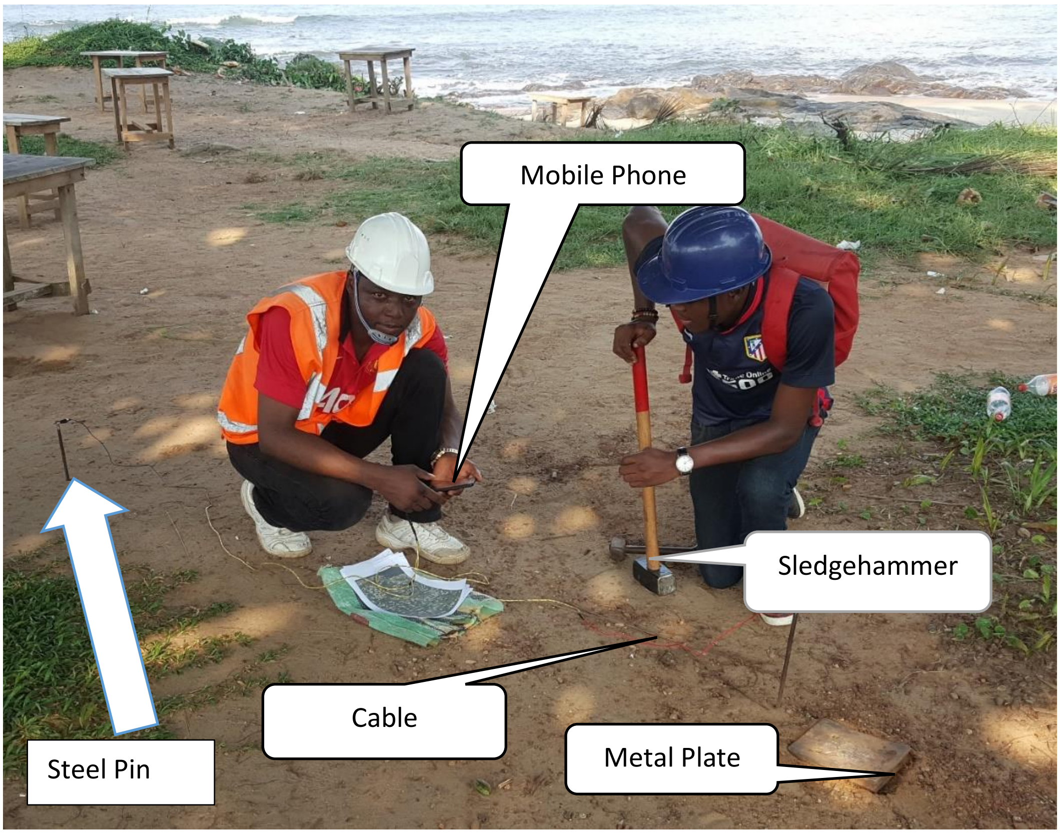


Figure 8: Field setup for ES Data Collection

  - **Quality Control:** Visual inspection of the recorded data will be conducted to identify any potential problems or anomalies.
- **Data Acquisition Parameters:**
  - **Sampling Rate:** The sampling rate will be set to between 15 and 20 recordings corresponding to the number of sledgehammer strikes.
  - **Recording Duration:** Each recording will be 40 seconds in duration, allowing for multiple seismic source impacts.
  - **Gain Settings:** Gain settings within the GeoSuite app will be adjusted as needed to optimize the signal-to-noise ratio while preventing signal clipping.

2.2.1.3 Data Processing and Analysis

- **Data Pre-Processing:**
  - **Filtering:** The recorded data will be filtered to remove unwanted noise from sources such as power lines, wind, and electrical interference. The GeoSuite app provides automated filtering algorithms.

    - **Time Synchronization:** The seismic and electrical data will be synchronized to ensure accurate correlation and analysis of the ES response. The GeoSuite app performs this synchronization automatically.
- **ES Response Analysis:**
    - **Stacked ES Signals:** Multiple ES recordings at each survey point will be stacked to improve the signal-to-noise ratio and enhance the visibility of the ES response. Stacking involves averaging the recordings, effectively reducing random noise while preserving the coherent signal.
    - **Correlation Analysis:** Correlation analysis will be performed between the seismic and electrical signals to identify the arrival times of the ES waves and estimate the electrokinetic coupling coefficient. The electrokinetic coupling coefficient is a measure of how effectively seismic energy is converted into electrical energy and is related to the permeability of the subsurface materials.
- **Estimation of Electrokinetic Properties:** Methods within the GeoSuite app will be used to estimate electrokinetic properties of the subsurface, including:
    - **Zeta Potential:** The zeta potential is a measure of the electrical charge at the interface between mineral surfaces and the pore fluid, influencing the magnitude of the ES effect. This site variable is indicated by the ES Coupling Coefficient Tomography (ESCCT), which describes the normalize, relative coupling efficiency for the conversion of the seismic pressure wave to the resultant electromagnetic wave field, expressed in percentages (ATSGeoConsultants., 2019).
    - **Streaming Potential:** This coefficient relates the pressure gradient induced by the seismic wave to the resulting streaming potential, providing insights into the electrokinetic properties and permeability of the aquifer. This site variable is described by the ES Hydraulic Conductivity Tomography (ESKT) and the ES Interface Tomography (ESIT) datasets, which show the relative inferred normalized hydraulic conductivity on the one hand and the positions of interfaces between formations with differing electrical an elastic properties on the other hand.

2.2.1.4 Presentation of Results

- **Maps and Profiles:** The results of the ES surveys will be presented as:

  - **Maps:** 2D maps will be generated showing the spatial distribution of estimated electrokinetic properties, such as zeta potential and the streaming potential.
  - **Profiles:** Vertical profiles will be created along selected transects if necessary to visualize the variation of electrokinetic properties with depth, aiding in the identification of permeable zones.
- **Data Interpretation:** The ES results will be interpreted in conjunction with other geological and hydrological data to:
  - Delineate zones of high permeability within the Kribi Town aquifer system.
  - Characterize the heterogeneity of the aquifer in terms of permeability variations.
  - Understand the influence of geological structures and lithology on groundwater flow patterns.

2.2.2 VES

2.2.2.1 Survey Design and Equipment

- **Survey Objectives:** The objectives of the VES surveys are to:
  - Determine the depth, thickness, and resistivity of subsurface layers, aiding in the identification and characterization of potential aquifers and aquitards.
  - Map the lateral variations in subsurface resistivity, providing insights into geological structures and the spatial extent of aquifers.
  - Provide data for the development and calibration of a 3D hydrogeological model.
- **Survey Design:** The VES surveys will be conducted using the Schlumberger array configuration, known for its effectiveness in mapping both vertical and horizontal resistivity variations.
  - **Sounding Locations:** Sounding locations will be strategically distributed across the study area, prioritizing proximity to existing boreholes to enable calibration of VES results against known lithology. Spatial coverage will be optimized to capture representative data on subsurface resistivity variations.
  - **Electrode Spacing:** The spacing between current electrodes (AB/2) will be progressively increased to investigate the subsurface at increasing depths. The maximum AB/2 spacing will be determined based on the expected depth of the target aquifer and practical limitations in the field.
- **Equipment:** The following equipment will be used for VES surveys:

  - **Current Source:** An ABEM Terrameter SAS-4000 resistivity meter will be used as the current source, providing a controlled direct current for injection into the ground.
  - **Potential Electrodes:** Non-polarizing electrodes will be used to measure the potential difference between two points on the ground surface.
  - **Resistivity Meter:** The ABEM Terrameter SAS-4000 will also serve as the resistivity meter, measuring the potential differences and calculating apparent resistivity values.

2.2.2.2 Data Acquisition Procedures

- **Field Procedures:** The VES surveys will be conducted according to the following steps:
  - **Site Selection:** Suitable sites for VES soundings will be selected based on accessibility, minimal interference from electrical noise sources, and proximity to existing boreholes for calibration purposes.
  - **Electrode Emplacement:** The four electrodes (two current electrodes, A and B, and two potential electrodes, M and N) will be positioned in a straight line, according to the Schlumberger array configuration. The potential electrodes will be placed close to the center of the array, while the current electrodes will be progressively moved further apart to increase the DOI.
  - **Current Injection and Potential Measurement:** A controlled direct current will be injected into the ground through the current electrodes, and the resulting potential difference between the potential electrodes will be measured by the resistivity meter.
  - **Data Recording:** The resistivity meter will automatically record the apparent resistivity values for each electrode spacing.
  - **Quality Control:** During data acquisition, the quality of the measurements will be continuously monitored to identify any potential errors or anomalies. Repeat measurements will be taken if necessary to ensure data accuracy.
- **Data Acquisition Parameters:**
  - **Current Intensity:** The current intensity will be adjusted based on the ground conditions and the desired DOI.

  - **Voltage Measurement Range:** The resistivity meter will be set to an appropriate voltage measurement range to accurately capture the potential differences.
  - **Electrode Spacing:** The electrode spacing will be progressively increased to achieve a range of depths of investigation.

2.2.2.3 Data Processing and Inversion

- **Data Processing:**
  - **Apparent Resistivity Calculation:** The measured potential differences will be used to calculate apparent resistivity values for each electrode spacing using the formula:

    $\rho a = (K * \Delta V) / I$

    Where:
    - ρa = Apparent resistivity
    - K = Geometric factor (specific to the Schlumberger array configuration)
    - ΔV = Measured potential difference
    - I = Injected current
- **Data Inversion:** The ZondIP1D software will be used for data inversion. The software employs a smooth inversion algorithm to generate layered earth models from the VES data.
  - **Smooth Inversion:** This algorithm minimizes the roughness of the resistivity model, promoting smoother transitions between layers and reducing the influence of noise in the data. This approach is particularly suitable for sedimentary environments, where resistivity changes are often gradual.
  - **Model Parameters:** The inversion process will estimate the thickness and apparent resistivity of each subsurface layer, providing a vertical profile of the subsurface electrical properties at each sounding location.

2.2.2.4 Interpretation and Correlation

- **Resistivity Model Interpretation:** The layered earth models generated from VES data will be interpreted to identify potential aquifer units and aquitards based on their resistivity characteristics.

  - **Typical Resistivity Ranges:** Reference values for typical electrical resistivity ranges of various geological materials will be considered. For example, sands and gravels (potential aquifers) typically exhibit higher resistivity compared to clays (potential aquitards).
  - **Geological Context:** The interpretation will be conducted in the context of the known or inferred geological setting of Kribi Town. This includes considering the presence of sedimentary formations, fractured bedrock, and the potential influence of saltwater intrusion.
- **Correlation with Borehole Data:** The VES results will be correlated with available borehole data to refine the interpretation and establish a robust relationship between resistivity values and lithology.
  - **Visual Comparison:** VES-derived resistivity profiles will be visually compared with lithological logs from nearby boreholes to identify distinct changes in resistivity that correspond to known geological units. This calibration process allows for the interpretation of lithology based on resistivity values, even in areas lacking direct borehole data.

2.2.2.5 Presentation of Results

- **Spatial Visualization:**
  - **Resistivity Maps:** Maps showing the spatial distribution of resistivity values at different depths will be generated using GIS software. This will aid in visualizing the lateral and horizontal variations in subsurface electrical properties and identifying potential aquifer zones.
  - **Cross-Sections:** Vertical cross-sections will be created along selected transects to visualize the resistivity structure of the subsurface. These cross-sections will provide a clearer understanding of the geometry and spatial relationships between different geological units.
- **Data Integration:** The VES results will be integrated with other hydrogeological data, including ES survey results and borehole data, to develop a comprehensive understanding of the aquifer system.

2.2.3 Water Sample Collection and Analysis

2.2.3.1 Sampling Strategy and Locations

- **Objectives:** The water sample collection aims to:

  - Calibrate the ES data by establishing relationships between the water table layer from the samples and the geophysical data.
  - Conduct hydrogeochemical analysis to assess water quality, identify potential contamination sources, and evaluate the suitability of groundwater for various uses.
- **Sample Locations:** Water samples will be collected from existing wells and boreholes: Samples will be taken from both hand-dug wells and boreholes, representing various aquifer units and depths.
- **Location Selection Criteria:**
  - Proximity to ES Survey Lines: Sampling points will be selected close to the ES survey lines to enable direct correlation between water table depths and geophysical data.
  - Suspected Contamination: Additional sampling points will be targeted near potential sources of contamination, such as landfills, industrial areas, and agricultural zones.

2.2.3.2 Sample Collection and Analysis

- **Collection Procedures:** Standard protocols for groundwater sampling will be strictly followed to ensure sample integrity and prevent contamination. This includes:
  - Purging: Wells will be adequately purged before sample collection to remove stagnant water and ensure that the collected sample represents the groundwater within the aquifer.
  - Filtering: Samples intended for dissolved constituent analysis will be filtered in the field using a 0.45-micron membrane filter.
  - Preservation: Samples will be preserved using appropriate methods, such as refrigeration and acidification (for metal analysis), to maintain sample integrity during transport and storage.
- **Laboratory Analysis:** Collected water samples will be analyzed for a comprehensive suite of parameters:
  - **Physical Parameters:**
    - Temperature
    - pH
    - EC

        - TDS
    - **Chemical Parameters:**
        - Major Ions (e.g., calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate)
        - Nutrients (e.g., nitrate, nitrite, ammonium, phosphate)
        - Trace Elements and Heavy Metals (e.g., arsenic, lead, mercury, cadmium, chromium)
    - **Analytical Methods:** Standard methods for water quality analysis, such as ion chromatography, atomic absorption spectroscopy, and inductively coupled plasma mass spectrometry, will be used to ensure accuracy and reliability of the results.

2.2.3.3 Data Integration and Utilization

- **Data Integration:** The water quality data will be integrated with the hydrogeological and geophysical datasets to:
    - Develop a robust hydrogeological model that accurately reflects the chemical and physical properties of the aquifer system.
    - Assess groundwater quality and its suitability for various uses, including drinking water, irrigation, and industrial applications.
    - Identify potential contamination sources and pathways.
- **Utilization:** The integrated data analysis will support:
    - The development of sustainable water management strategies for Kribi Town, ensuring a secure and reliable water supply.
    - The formulation of recommendations for water treatment and protection measures to safeguard public health and the environment.

2.2.4 Borehole Data Collection and Analysis

- **Data Sources:** Borehole data will be collected from the GEOFOR Company: Seven borehole logs from the defunct GEOFOR Company, documenting lithology and well construction details, will be analyzed.
- **Data Analysis:** Borehole data will be analyzed to:
    - Refine the understanding of aquifer geometry, boundaries, and hydraulic properties.

    - Identify and characterize different aquifer units based on lithology and hydraulic parameters.
    - Assess long-term trends in groundwater levels and potential impacts of pumping.
    - Calibrate and validate the hydrogeological model.

2.2.5 Hydrogeological Model Development: 3D Implicit Geological Modeling

- **Software:** Leapfrog Geo software will be used for 3D implicit geological modeling. The software offers a user-friendly interface for data visualization, geological interpretation, and model construction, particularly suitable for complex geological settings.
- **Data Integration:** The following datasets will be integrated into Leapfrog Geo to build the 3D geological model:
    - ES Survey Data: ES-derived maps and profiles of electrokinetic properties and permeability.
    - VES Data: Layered earth models from VES soundings, providing information on resistivity, thickness, and boundaries of subsurface layers.
    - Borehole Data: Lithological logs, well construction details, and hydraulic parameters from borehole data.
    - Geological Maps: Existing geological maps, if available, will be digitized and incorporated.
- **Model Building:**
    - **Defining Geological Units:** Based on the integrated datasets, different geological units will be defined within the model, representing distinct rock types or hydrogeological units.
    - **Establishing Relationships:** Relationships between geological units, such as contacts, faults, and folds, will be established based on geological interpretation and data analysis.
    - **Model Validation:** The model will be validated against available data, including borehole observations and geophysical interpretations, to ensure geological accuracy and consistency.

2.2.6 Groundwater Resource Quantification

- **Aquifer Storage Capacity:** The hydrogeological model will be used to estimate the total volume of water stored within the aquifer system.

2.3 Hydrogeochemical Assessment

2.3.1 Groundwater Sampling and Analysis

- **Sampling Objectives:** The groundwater sampling program aims to:
    - Assess the suitability of groundwater for various uses, including drinking water, irrigation, and industrial applications, by comparing physicochemical parameters to relevant water quality standards and guidelines.
    - Characterize the hydrogeochemical processes influencing groundwater quality, such as water-rock interactions, mixing between different water sources, and potential impacts of saltwater intrusion, to gain a deeper understanding of the aquifer system.
- **Sampling Strategy:** A purposive sampling strategy will be employed, targeting locations that are most likely to provide information relevant to the research objectives. This approach is justified given the limited resources available for sampling and the need to focus on areas of particular interest.
- **Location Selection Criteria:** Sampling locations will be selected based on the following criteria (Figure *9*):
    - Representation of Aquifer Units: Sampling points will be chosen to represent different aquifer units identified through field investigations, including the shallow unconfined aquifer and the deeper confined aquifer.
    - Proximity to Potential Contamination Sources: Sampling locations will be targeted near suspected sources of contamination, such as industrial areas, landfills, agricultural zones, and areas with a high density of septic systems (dense agglomerations). This will enable the assessment of potential contamination risks and the identification of specific contaminant sources.
    - Accessibility and Logistical Considerations: Sampling locations will be chosen to ensure accessibility and feasibility of sample collection, considering factors such as road access, land ownership, and safety.

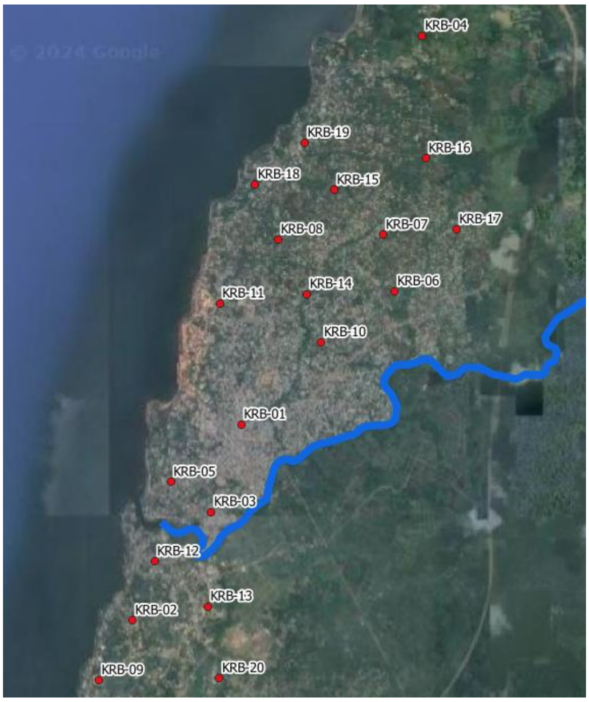


Figure 9: Location of sampling points for physicochemical analyses

- **Field Equipment:** The following field equipment will be used for groundwater sample collection:
  - Sampling Devices: Dedicated bailers will be used to collect groundwater samples from wells and boreholes, ensuring minimal disturbance and preventing cross-contamination between sampling points.
  - Sample Containers: Clean and sterilized sample containers will be used to store collected water samples. The containers will be made of appropriate materials, such as high-density polyethylene (HDPE) or glass, depending on the parameters to be analyzed.
  - Field Measurement Instruments: these (Figure 10) consisted of a Garmin Dakota TM 10 GPS device, used to record the geographical coordinates of the water sampling points; a HANNA multi-parameter meter, which was used to measure physicochemical parameters in situ, characterizing four parameters: temperature, pH, dissolved oxygen, and EC; an ion chromatograph for the analysis of major ions in the water samples, and finally a SHIMADZU EDX-7000 fluorescence spectrometer. These samples were analysed in the National Veterinary Laboratory (LaNaVét) in Douala, Cameroon.

(d)

(a) (b) (c)

Figure 10: Field equipment composed of (a) Garmin Dakota TM 10 GPS device, (b) a HANNA multi-parameter meter, (c) an ion chromatograph, and (d) a SHIMADZU EDX-7000 fluorescence spectrometer

- **Sample Collection and Preservation:** Strict protocols were followed to prevent contamination during sample collection and preserve sample integrity during transport and storage. These protocols include:
    - Aseptic Techniques: Gloves and other appropriate protective gear were worn during sample collection to minimize the risk of contamination.
    - Filtration: Samples intended for dissolved constituent analysis were filtered in the field using a 0.45-micron membrane filter to remove suspended solids.
    - Preservation: Samples were preserved using appropriate methods, depending on the parameters to be analyzed. This may include:
        - Refrigeration: Samples will be kept cool (at around 4°C) to inhibit biological activity and prevent degradation of certain chemical constituents.
        - Acidification: Samples intended for metal analysis will be acidified using nitric acid (HNO3) to a pH of less than 2 to prevent precipitation and adsorption of metals onto container walls.
        - Chemical Addition: Specific preservatives, as recommended by the analytical methods, may be added to certain samples (e.g., sodium thiosulfate for chlorine residual analysis).
- **Analytical Parameters:** The chemical parameters will be measured in the collected groundwater samples. These include:

    - Major Ions: Calcium (Ca2+), Magnesium (Mg2+), Sodium (Na+), Chloride (Cl-), Sulfate (SO_4^{2-}), Silica (SiO2), Bicarbonate (HCO3), Carbonate (CO3), Isotope of Hydrogen (2H).
    - Nutrients: Nitrate (NO3-),
    - Trace Elements and Heavy Metals: Arsenic (As), Lead (Pb), Mercury (Hg).
- **Analytical Methods:** Standard analytical methods, such as those outlined in the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017) or equivalent international standards, will be used for measuring the various parameters. Specific analytical techniques will include:
  - Ion Chromatography (IC): For the analysis of major anions.
  - For the analysis of trace elements and heavy metals the SHIADZU EDX-7000 spectrometer is used. To do this, the water samples taken out of the cold room were introduced into a small polyethylene beaker covered with a plastic film called "Mylar paper" and then placed in the spectrometer. The emitted X-rays pass through the "Mylar paper" to excite the atoms contained in the sample. After excitation, X-ray fluorescence is emitted, which is characteristic of the atoms being sought. Each concentration corresponds to an absorbance, the curve of which is plotted. From this curve, the spectrometer gives readings of the element concentrations after measuring the absorbance of each sample

2.3.2 Data Analysis and Interpretation

- **Comparison to Standards:** The measured physicochemical parameters will be compared to the relevant water quality standards and guidelines, including:
  - WHO Guidelines for Drinking-water Quality (WHO/UNICEF, 2015): To assess the suitability of groundwater for drinking water purposes.
- **Suitability Classification:** Based on the comparison with standards and guidelines, groundwater samples will be classified according to their suitability for various uses (e.g., suitable for drinking water, suitable for irrigation with restrictions, unsuitable).
- **Spatial Analysis and Mapping:** Spatial patterns in water quality data will be analyzed and visualized using GIS software. This will involve:

  - Creating maps of key parameters: Generating maps showing the spatial distribution of parameters that indicate potential contamination, such as chloride, nitrate, and heavy metals.
  - Overlaying with potential contamination sources: Overlaying these maps with data on potential contamination sources, such as industrial areas, agricultural zones, landfills, and septic system density, to identify correlations and potential source areas.
- **Statistical Analysis:** Statistical analysis will be conducted to:
  - Identify significant correlations between water quality parameters and potential contamination sources.
  - Determine the spatial extent and magnitude of potential contamination plumes if applicable.
  - Assess temporal trends in water quality and identify any changes that might indicate increasing contamination.
- **Hydrogeochemical Facies and Water Types:** Hydrogeochemical facies and water types will be determined using methods such as:
  - Piper Diagrams: To visualize the major ion composition of groundwater samples and identify dominant water types.
- **Interpretation:** The analysis of hydrogeochemical facies and water types will provide insights into:
  - Water-Rock Interactions: The influence of geological formations on groundwater chemistry.

2.4 Surface Water Assessment: Evaluating the Kienke River as a Potential Water Source

2.4.1 Data Collection

- **Streamflow Data:**
  - **Source:** Monthly discharge data for the Kienke River (1955-1977) will be obtained from The Global Runoff Data Centre (GRDC), a reputable international repository for river discharge information (GRDC, 1977). This is shown in
  - **Gap Filling:** If necessary, missing streamflow data points will be estimated using interpolation techniques or regional regression equations based on data from nearby gauging stations.

- **Rainfall Data:**
    - **Source:** Monthly-averaged rainfall data (Table 2-2) for the Kienke River basin will be obtained from the National Oceanic and Atmospheric Administration's (NOAA’s) Global Historical Climatology Network Daily dataset (NOAA/NCEI, 2022).
    - **Gap Filling:** Missing rainfall data points will be filled using interpolation from nearby station data or regional rainfall patterns and statistics calculated using Mann-Kendall Test.

- **Land Use/Land Cover Data:**
    - **Source:** The land use and land cover characteristics of the Kienke River watershed for the period of streamflow record (1955-1977) are not readily available. One land use/land cover datasets will be utilized, as well as soil datasets for the area of interest:
        - **Historical soil data (circa 1960):** To represent land cover conditions during the study period, the Harmonized World Soil Database (HWSD) v1.2 (Nachtergaele et al., 2010) land use map will be used. This global dataset provides a generalized representation of land use patterns around 1960.
        - **Current Land Use (2022):** To understand changes in land use patterns over time and assess their potential impacts on hydrology, a current (2022) land use/land cover map will be obtained from the Global Land Cover dataset within the Watershed Modeling System (WMS) software.

Table 2-2: Monthly Averaged and Summed Rainfall Data within the Kienke Watershed.

Month	**1955**		**1956**		**1957**		**1958**		**1959**		**1960**	
	Ave.	**Sum**	**Ave.**	**Sum**	**Ave.**	**Sum**	**Ave.**	**Sum**	**Ave.**	**Sum**	**Ave.**	**Sum**
Jan			5.82	180.3	2.88	89.3	0.71	22.1	3.83	118.8	0.60	18.6
Feb			2.49	72.1	0.65	18.2	0.24	6.7	1.44	40.3	2.18	63.2
Mar			6.28	194.6	4.95	153.6	2.89	89.6	10.93	338.8	3.27	101.4
Apr			8.66	259.9	7.02	210.7	8.65	259.5	7.50	224.9	6.58	197.5
May			4.21	130.4	5.82	180.3	5.01	155.3	10.13	313.9	9.71	301.0
Jun	15.67	470.1	12.53	376.0	14.17	425.1	17.93	537.8	16.98	509.4	10.43	312.8
Jul	18.36	569.3	33.94	1052.0	21.87	678.0	19.73	611.7	24.14	748.4	19.47	603.5
Aug	21.62	670.2	20.28	628.8	29.30	908.4	29.05	900.4	36.55	1133.2	42.89	1329.7
Sep	14.34	430.3	5.00	300.0	6.24	187.1	19.77	593.0	19.77	593.0	24.34	730.3
Oct	8.25	255.8	12.98	402.3	10.02	310.7	13.48	417.9	14.11	437.4	11.68	362.1
Nov	4.50	135.0	6.05	181.4	5.61	168.2	9.27	278.2	4.55	136.6	1.97	59.1
Dec	0.94	29.1	3.71	115.1	2.27	70.4	1.21	37.4	0.50	15.4	2.44	75.7

- **Justification for Using Two Datasets:** The use of both historical soil data and current land use datasets is essential for:
  - Model Calibration: The historical land use data will be used to parameterize the HEC-HMS model for the study period.

        - Impact Assessment: Comparing historical and current land use patterns will enable an assessment of how changes in land use have affected runoff generation and streamflow in the Kienke River.

2.4.2 Data Analysis

- **Streamflow Analysis:** The GRDC streamflow data will be analyzed to:
    - Characterize the Kienke River's flow regime, including:
        - Mean annual discharge
        - Seasonal variations in flow
        - Flow duration curves
    - Identify potential trends in streamflow over time, considering natural variability and potential anthropogenic influences. This analysis will be conducted using the Mann-Kendall trend tests.
- **Rainfall Analysis:** The NOAA rainfall data will be analyzed to:
    - Characterize precipitation patterns in the Kienke River basin, including:
        - Mean annual rainfall
        - Seasonal variations in rainfall
        - Rainfall intensity and duration statistics
    - Investigate relationships between rainfall patterns and streamflow, such as the lag time between rainfall events and peak flows.
- **Land Use Change Analysis:** The historical and current land use/land cover maps will be compared to:
    - Quantify changes in land use patterns over time, such as the extent of urbanization, deforestation, or agricultural expansion within the Kienke River watershed.
    - Assess the potential impacts of these land use changes on hydrological processes, such as infiltration, runoff generation, and streamflow characteristics.

2.4.3 Precipitation-Runoff Modeling using HEC-HMS

- **Software:** The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) software will be used to simulate the rainfall-runoff processes in the Kienke River watershed. HEC-HMS is a widely used and well-regarded hydrological modeling software, particularly suitable for simulating event-based runoff and analyzing the impacts of land use change on hydrology (Castro and Maidment, 2020).

- **Watershed Delineation and Parameterization:**
    - **WMS:** The WMS software will be used to delineate the Kienke River watershed using the DEM, divide the watershed into sub-basins, and calculate key hydrologic and geometric parameters, such as sub-basin area, slope, longest flow path, and time of concentration.
    - **HEC-HMS Basin Model:** The delineated sub-basins and their characteristics from WMS will be imported into HEC-HMS to create the basin model.
- **Meteorological Model:**
    - **Rainfall Data:** The processed monthly-averaged rainfall data will be used as input for the meteorological model in HEC-HMS.
    - **Hypothetical Storms:** To assess the river's response to various rainfall events, hypothetical storms with varying intensities and durations will be defined and simulated.
- **Hydrologic Methods and Parameters:** The following methods and parameters will be used within HEC-HMS:
    - **Loss Method:** The SCS CN method will be used to estimate infiltration losses. CN values will be assigned to each sub-basin based on land use, soil type, and antecedent moisture conditions, as determined by WMS using the historical land use/land cover map.
    - **Transform Method:** The SCS Unit Hydrograph method will be employed to convert rainfall excess into runoff hydrographs at the sub-basin outlets.
    - **Routing Method:** The Muskingum method will be used to route the runoff hydrographs through the river channels. The Muskingum K and X parameters will be estimated based on channel geometry and flow characteristics.
- **Calibration:**
    - **Data:** Observed streamflow data from the GRDC (1955-1977) will be used to calibrate the HEC-HMS model.
    - **Procedure:** Model parameters will be adjusted within acceptable ranges to achieve a good fit between simulated and observed streamflow hydrographs.

  - **Metrics:** The Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) will be used to evaluate model performance during calibration. NSE is given by the equation (2.1):

$$NSE = 1 - \frac{\sum_{t=1}^{T} (Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q_0})^2} \tag{2.1}$$

    Where $\bar{Q}_o$ is the mean of observed discharge, Q_m^t is modeled discharge, Q_o^t is observed discharge at time *t*. An NSE value of 1 indicates a perfect match, while values less than 0 suggest that the mean of observed data is a better predictor than the model (Nash and Sutcliffe, 1970). However, NSE does not indicate whether the model underestimates or overestimates observations, necessitating the use of Percent Bias (PBIAS), given by equation (2.2):

$$PBIAS = \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t) \text{x} 100}{\sum_{t=1}^{T} (Q_o^t)} \tag{2.2}$$

    PBIAS measures the average tendency of the simulated values to be larger or smaller than the observed values (Gupta et al., 1999). Positive PBIAS indicates underestimation, while negative PBIAS indicates overestimation.

- **Validation:**
  - **Data:** Due to the limited availability of streamflow data, a separate validation period cannot be established.

2.4.4 Evaluation of the Kienke River as a Potential Water Source

The calibrated HEC-HMS model will be used to evaluate the suitability of the Kienke River as a potential supplemental water source for Kribi Town. This evaluation will consider:

- **Water Availability:** The model will be used to estimate the reliable yield of the Kienke River, considering seasonal variations in flow and potential impacts of drought.
- **Water Demand:** Projected water demand for Kribi Town will be calculated based on population growth projections and estimated per capita water use. Water Demand Calculation for public water supplies is very fundamental in municipal water supply

systems. This results in a framework to take management decisions such as an extension of the supply network and locations and the creation of new facilities as deemed necessary (Arunkumar and Mariappan, 2011). In the context of this study, the analysis is imperative in order to better evaluate the amount of potable water that could be supplied from the Kienke River and treated within a sustainable limit. The water demand analysis was made using the Maximum Day Demand (MDD) according to Arunkumar and Mariappan (2011). MDD is the largest volume of water delivered to the system in a single day expressed in litres per day. The water supply system, the treatment plant, and the transmission lines should be designed to handle the MDD. The population of the Kribi town was estimated to be 60,000 in 2007 according to SNH (2008). Given that there is no further data on the population of the area as at now, at per census data open to the public, and considering the degree of urbanization within the area since 2007, we would estimate the population at present using the 7% per annum proposed by Yongsi (2011) for the town of Yaoundé-Cameroon. The estimated population is gotten using Euler’s Formula, given in equation (2.3).

$$N_t = N_0 \quad e^{rt} \tag{2.3}$$

where *r* is the per capita growth rate in percentage and *t* is the time in years.

- **Environmental Flow Requirements:** Environmental flow requirements for the Kienke River, necessary to maintain the ecological health of the river ecosystem, will be considered. The assessment will draw upon existing environmental flow guidelines or methodologies relevant to the region or similar river systems if available.

2.5 GIS-Based Assessment and Decision Support: Optimizing Reservoir Siting and Integrated Water Management

Due to the large extent of the Kienke watershed, that cannot encompass the areas of the Kribi Town on which geophysical data were collected and analyzed as well as the hydrogeochemical analyses, the lone alternative for now will consist in considering the surface water assessment results, in order words calculating the reservoir storage potential.

The MCE method will be employed within a GIS environment to identify optimal locations for potential reservoirs, considering a range of criteria that encompass environmental, social, and economic factors.

- **Criteria:** The following criteria will be used to evaluate the suitability of potential reservoir sites:
    - **Environmental Factors:**
        - Land Use/Land Cover: Minimize impacts on sensitive land use types (e.g., forests, wetlands, protected areas) by assigning higher suitability scores to areas with lower conservation value.
        - Slope: Avoid steep slopes to reduce erosion, sedimentation, and construction challenges. Assign higher suitability scores to gentler slopes.
        - Distance to Rivers/Streams: Ensure proximity to water sources for efficient reservoir filling. However, also consider potential impacts on riverine ecosystems and downstream users by assigning lower suitability scores to areas too close to rivers.
    - **Social Factors:**
        - Distance to Settlements: Minimize impacts on communities by avoiding proximity to existing settlements. Assign lower suitability scores to areas closer to settlements.
        - Land Ownership: Consider land ownership patterns and potential challenges for land acquisition.
    - **Economic Factors:**
        - Construction Costs: Estimate and consider the relative costs of construction in different locations based on topography, geology, and accessibility. Assign higher suitability scores to areas with lower estimated construction costs.
        - Accessibility: Evaluate accessibility for construction, operation, and maintenance, considering factors such as road networks and proximity to existing infrastructure. Assign higher suitability scores to more accessible areas.

In summary, the reservoir location criteria were given in Table 2-3.

Table 2-3: Reservoir location criteria

No	Criterion	Consideration
1	Away from settlements (2000 m from settlement area)	Safety
2	Within areas of water availability (within 500 m from the Kienke River)	Water Management
3	Gentle slope (<10 degrees)	Environmental safety
4	Elevation (<=100 m)	For optimum supply with regards to demand
5	The area should be contiguous	For easy calculation of the area for the sites
6	The area should be greater than or equal to 2 hectares	Enough to contain the structures and other facilities.

- **Weighting:** The Analytical Hierarchy Process (AHP) will be used to determine the relative weights or priorities of each criterion. AHP involves pairwise comparisons (Table 2-4) of criteria to establish their relative importance in the decision-making process.
- **Data Standardization:** All data layers representing the criteria will be standardized to a common scale (e.g., 0-1) to enable comparison and analysis.
- **Weighted Overlay:** The standardized data layers will be multiplied by their respective weights and summed to create a composite suitability map. This map will show the overall suitability of different locations for reservoir development, considering the combined weighted influence of all criteria.
- **Dam Site Evaluation:** The MCE-derived suitability map will be used to identify promising locations for dam construction within the Kienke River watershed. Suitable dam sites will be those with high suitability scores and appropriate topographic conditions.
- **Catchment Area Delineation:** For each potential dam site, the contributing catchment area will be delineated using the DEM and hydrological analysis tools within the GIS software.

Table 2-4:Pairwise judgement Scale (Qureshi, 2010)

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance.

- **Storage Capacity Estimation:** The potential storage capacity of reservoirs at different dam sites will be estimated using topographic data and reservoir volume calculation tools within GIS.
- **Environmental Impact Assessment:** Potential environmental impacts of reservoir construction and operation will be assessed, considering factors such as:
    - Land Inundation: Quantify the area of land that would be inundated by the reservoir and assess potential impacts on existing land use, including agriculture, forestry, and settlements.
    - Habitat Loss: Evaluate potential impacts on terrestrial and aquatic ecosystems, including habitat fragmentation and loss of biodiversity.
    - Downstream Flow Alterations: Assess potential changes in downstream flow regimes due to reservoir operation and their impacts on aquatic ecosystems and water users.
    - Water Quality: Evaluate potential changes in water quality within the reservoir and downstream due to factors such as increased sedimentation or nutrient loading.

2.6 Conclusion

This chapter has outlined a comprehensive methodology for evaluating water resources and developing sustainable water management strategies for Kribi Town. By combining hydrogeological investigations, hydrogeochemical assessments, surface water analysis, and GIS-based spatial analysis and decision-making tools, this research will provide a holistic understanding of the available water resources, their quality and sustainability, and the potential challenges and opportunities for ensuring a secure and reliable water supply for Kribi's future. The proposed methodology will contribute valuable insights and practical solutions for sustainable water resource management in Kribi Town, serving as a model for other growing urban areas facing similar water challenges.

3 CHAPTER THREE: RESULTS AND DISCUSSION

3.1 Hydrogeological Assessment

3.1.1 ES Surveys

3.1.1.1 Quality assessment of datasets

The effectiveness of ES surveys in delineating hydrogeological features heavily relies on the quality and reliability of the acquired datasets. In this study, 250 ES data points were collected across Kribi Town. However, rigorous quality assessment revealed that only a subset of these datasets met the criteria for robust interpretation and inclusion in the hydrogeological model.

The **correlation index**, a crucial indicator of ES data quality, quantifies the coherence between the recorded seismic and electrical signals, reflecting the strength and clarity of the ES response. Higher correlation index values indicate a more reliable signal. Figure 11 visually depicts the spatial distribution of the ES survey points and their corresponding correlation index values.

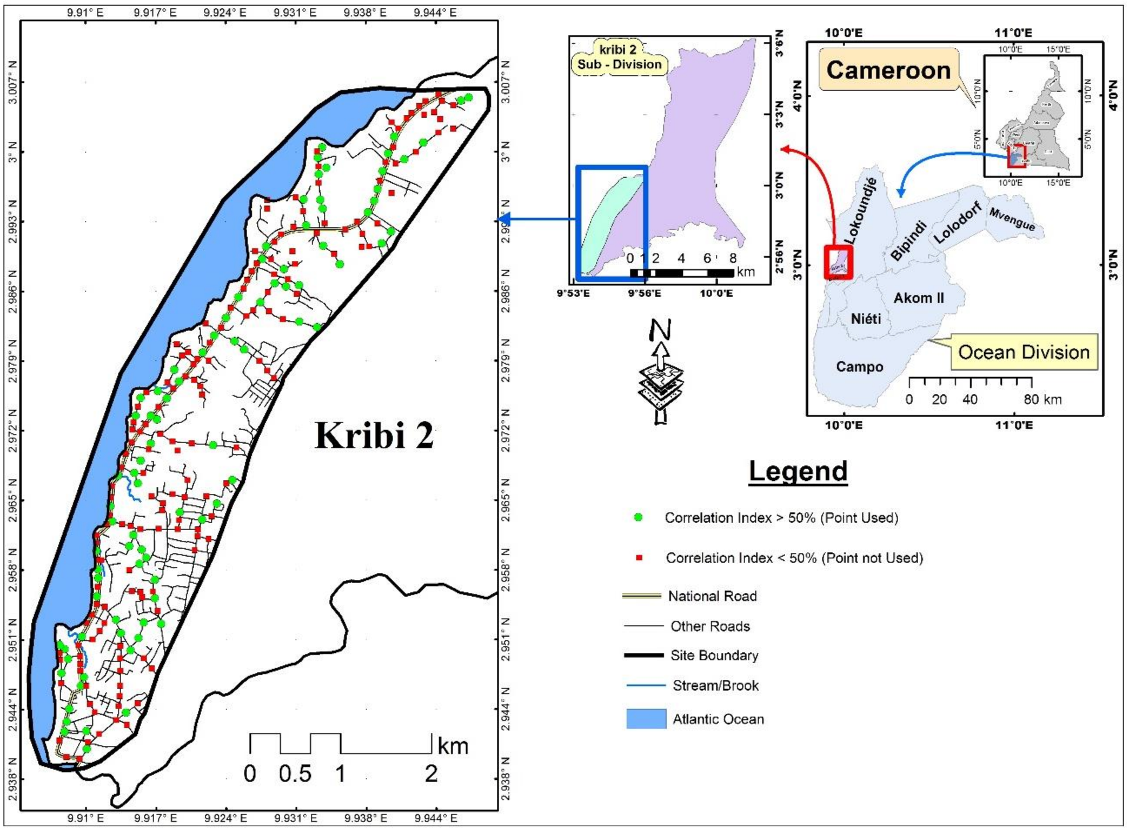


Figure 11: ES survey points with their correlation index values

Analyzing the correlation index values for our 250 datasets, we found that only 87 (34.8%) surpassed the threshold of 50%. This threshold, determined based on our understanding of signal processing and noise levels in ES surveys, was crucial to ensure a sufficiently strong and consistent ES signal for reliable interpretation.

Several factors likely contributed to the lower quality (correlation index below 50%) observed in the remaining 163 datasets:

- **Environmental Noise:** Kribi Town's urban environment likely introduced significant electrical noise from sources such as power lines, machinery, and other infrastructure. This interference can mask the subtle ES signal, leading to lower correlation indices.
- **Subsurface Heterogeneity:** Variations in lithology, fluid content, and electrical properties within the subsurface can also affect the propagation and conversion of seismic and electrical energy, potentially degrading the ES response and lowering correlation indices.
- **Equipment Limitations:** The sensitivity and resolution of the ES equipment used can also play a role in data quality. While we employed a standard setup for data acquisition, limitations in equipment performance could have contributed to the variability in correlation indices.

Furthermore, we evaluated data quality using two additional parameters calculated by the ATS GeoSuite software:

- **Point Noise Risk:** This parameter provides an empirical quantification of the risk that filtered noise within the dataset poses to its overall quality. Higher noise risk levels indicate lower data quality and reliability. In our survey, the Point Noise Risk ranged from 9% to 25%, suggesting relatively low noise levels and thus higher data quality for the majority of sounding locations. This distribution is depicted spatially in Figure 12a.
- **Total ES Sounding Risk:** This parameter combines the correlation index and Point Noise Risk to provide a comprehensive risk assessment of data quality at each sounding location. This percentage reflects the reliability of the recorded ES data. In our survey, the Total ES Sounding Risk varied between 40% and 73%, with 63.13% of the locations exhibiting values between 50% and 73%, as seen in Figure 12b. This distribution suggests that while the majority of locations provided reliable data, the Kribi Town environment presented some challenges for ES surveying, likely due to the method's sensitivity to noise and its suitability primarily for shallow investigations.

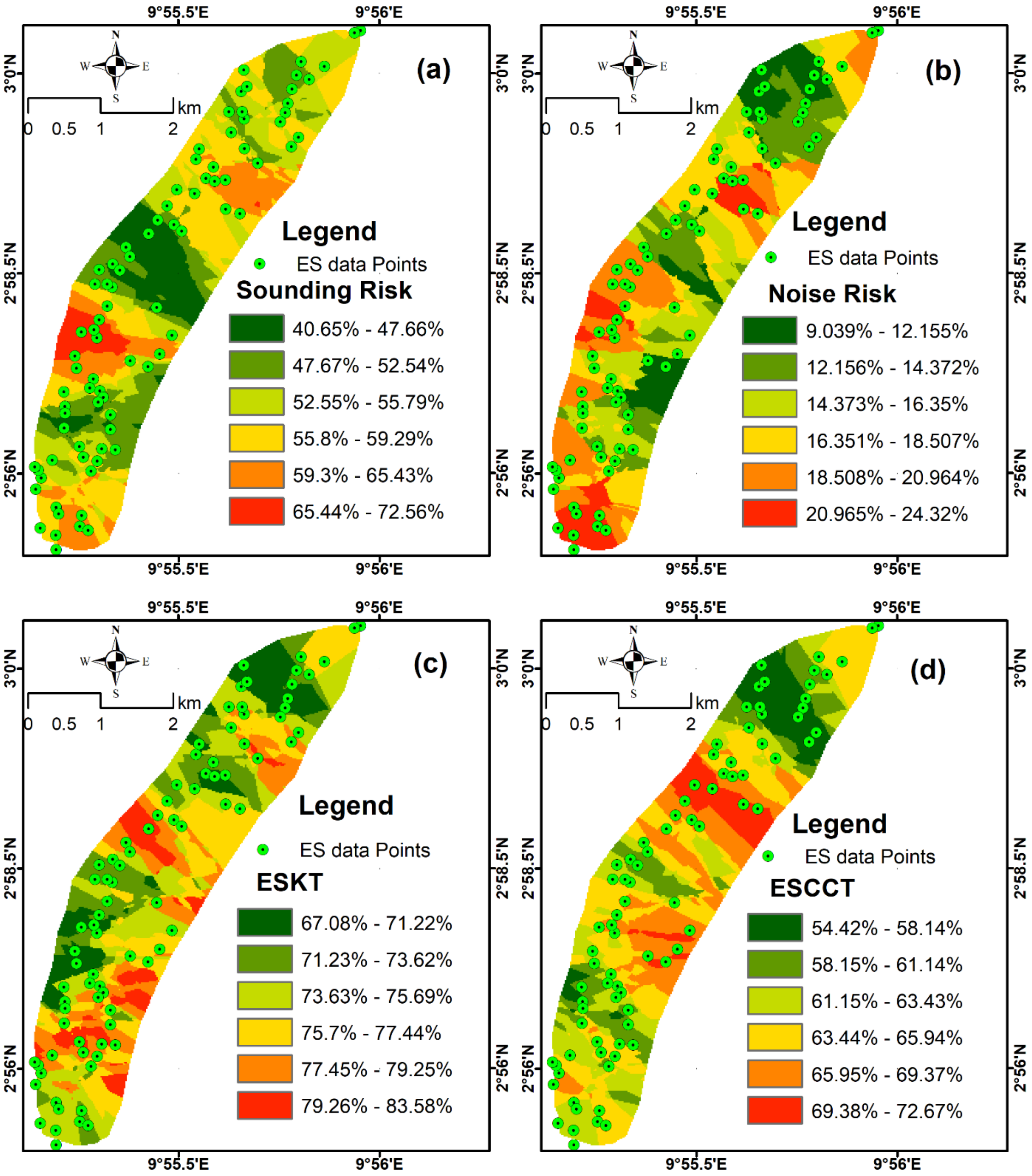


Figure 12: Spatial Distribution of ES data quality [(a) & (b)] and the estimated electrokinetic properties [(c) & (d)].

3.1.1.2 Interpretation of ES Response

Analysis of the ES data revealed distinct patterns in electrokinetic properties across the study area, providing insights into permeability variations and aquifer heterogeneity. Figure 12 (c) and (d) depict the spatial distribution of the Electroseismic Hydraulic Conductivity Tomography (ESKT) and Electroseismic Coupling Coefficient Tomography (ESCCT) datasets, respectively, at mean-sea-level elevation.

Higher ESKT values, particularly prominent along the coastline stretching from the southwestern to the southeastern edges of Kribi Town, suggest zones of enhanced permeability. These high ESKT values likely correspond to the presence of coarser-grained sediments, such as sands and gravels, which are known to have higher hydraulic conductivity. In contrast, lower ESKT values observed further inland likely indicate finer-grained materials like silts and clays, which typically exhibit lower permeability.

The spatial distribution of ESCCT values complements the ESKT findings, with higher values observed in similar coastal zones. This reinforces the interpretation that these areas are characterized by enhanced permeability and likely represent preferential pathways for groundwater flow. The coincidence of high ESKT and ESCCT values with the general location of the shallow unconfined aquifer, identified through water table measurements, further supports this interpretation.

The water table grid plotted on Figure 13, constructed from field measurements, highlights the heterogeneous nature of the aquifer system. Variations in water table depth are evident, with shallower depths observed along the coastline and gradually increasing depths as one moves inland. This pattern aligns with the observed ESKT and ESCCT distributions, suggesting a correlation between shallower water table depths and higher permeability zones. This heterogeneity in the unconfined aquifer can significantly influence groundwater flow paths, recharge rates, and the effectiveness of water extraction strategies.

While the ES data provides valuable information on permeability and heterogeneity, it does not offer conclusive evidence regarding the presence of specific geological structures like faults or fractures nor a comprehensive understanding of the hydrogeology. Further investigations using complementary geophysical methods, such as seismic surveys, are recommended to better understand the role of geological structures in influencing groundwater flow patterns and aquifer connectivity in Kribi Town. But due to the costly nature of the seismic survey, the electrical resistivity sounding method was used for a thorough understanding of the hydrogeological model of the area.

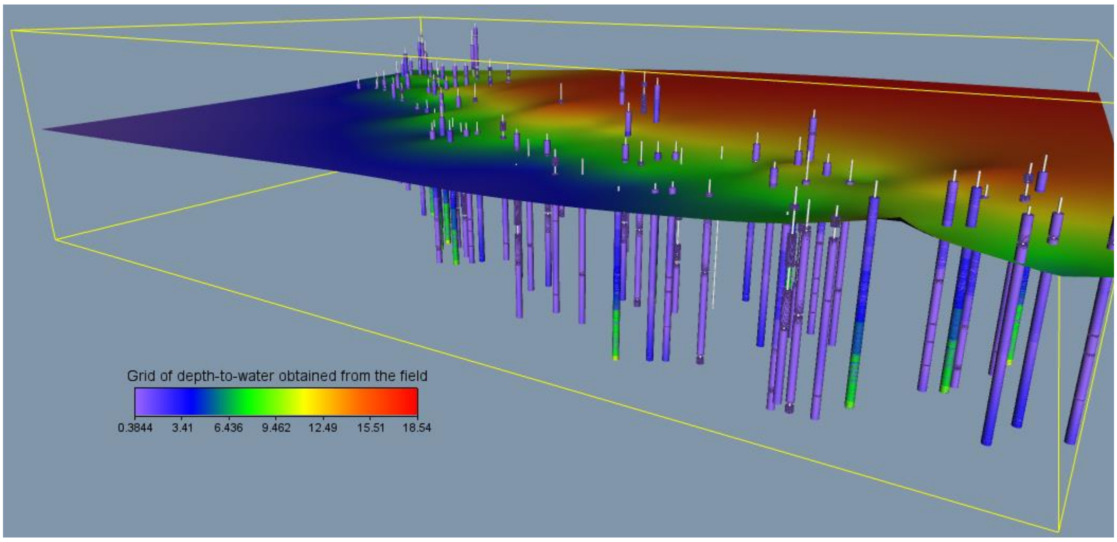


Figure 13: ES dataset calibration in Voxler software with the water table grid, reflecting the existing shallow aquifer system. The slope falls to sea level from about 19 m above it.

3.1.1.3 Geological Model Construction

3.1.1.3.1 Introduction

The geological model is constructed from the ES data using Leapfrog Geo software. The geological model component of the software incorporates five sub-components: model boundary, fault system, lithologies, surface chronology, and output volume. The boundary inherits the clipped boundary set at the topography level, which automatically defines the upper boundary. The fault system and lithologies sub-components are self-explanatory. However, the lithology field can be overwritten manually if the dataset lacks lithological information. The surface chronology component manages all contact surfaces, arranging them in chronological order with the youngest first. These surfaces and their chronology determine how the volume within the model is divided into lithological units. The output volumes encompass all volumes generated during the model-building process, arranged chronologically from youngest to oldest.

Leapfrog Geo can create various surface types, including, but not limited to, the stratigraphic sequence type. The stratigraphic sequence was chosen for this model for two reasons. First, it is suitable for modeling a series of continuous layers separately. Second, given that this is a sedimentary basin, the lithologies can be modeled as layered horizontal blocks.

3.1.1.3.2 Converting ES datasets into borehole-like data

The Electroseismic Hydraulic Conductivity Tomography (ESKT) dataset effectively describes aquifer systems beneath a site in one, two, or three dimensions. The ESKT data consist of normalized, relative hydraulic conductivity values ranging from 0 to 100%. In other words, the data are not calibrated to an absolute field reference point with a known hydraulic conductivity at depth. The maximum normalized value is obtained by assigning 100% to the maximum recorded hydraulic conductivity value and normalizing all other values against it (ATSGeoConsultants., 2019), thus identifying aquifer locations. This dataset was then used to construct a lithological model (Table 3-1). The classified dataset was imported into Leapfrog Geo, where the aquifer model was developed.

Table 3-1: ESKT value classes and anticipated lithologies used to construct a lithological model for the site.

ESKT Value Classes (%)	Probable Lithology
[100,60]	Sand
[60,30]	Fine sand
[30,10]	Clayey and/or silty sand
[10,0]	Silt and/or clay

The Electroseismic Interface Tomography (ESIT) dataset, derived from processing ES data, indicates the positions of interfaces between formations with differing electrical and elastic properties. It is based on the interfacial effects generated by ES conversion as pressure waves pass between these formations. The dataset represents all detected interface responses, regardless of amplitude. This means strong and weak reflectors have equally weighted responses, highlighting geological features that might be missed when solely considering reflector strength. The data show the reflector's total gradient polarity (Table 3-2). Blue responses indicate negative polarity reflectors, while red responses indicate positive polarity reflectors. Visual inspection and the subsequent combination of some interfaces/media led to the development of the geological model. Figure 14 displays these datasets in Leapfrog Geo with the corresponding geological model in Figure 15.

Table 3-2: ESIT values and associated interpretation used in constructing the geological model.

Interface Tomography Values (%)	**Probable Lithology**
-100	Blue response
0	Material medium with normal wave propagation (uniform acoustic impedance).
100	Red response

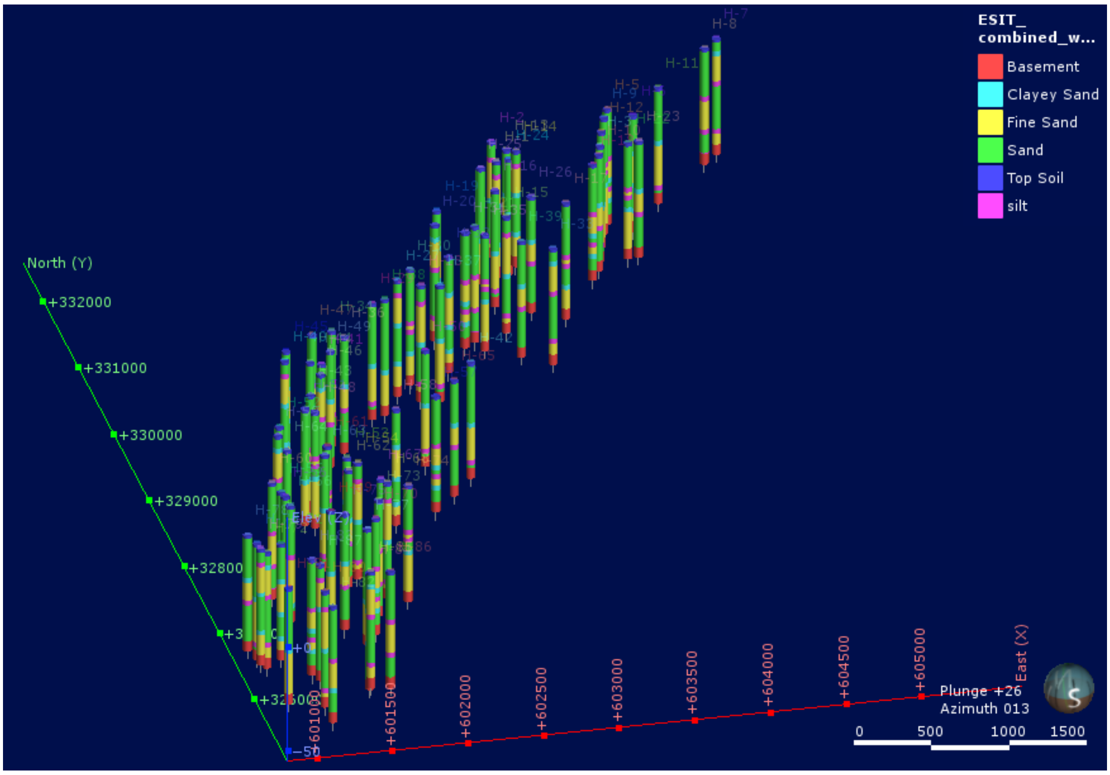


Figure 14: ES datasets converted to pseudo-drilling data and uploaded into Leapfrog Geo software (vertical exaggeration = 10x)

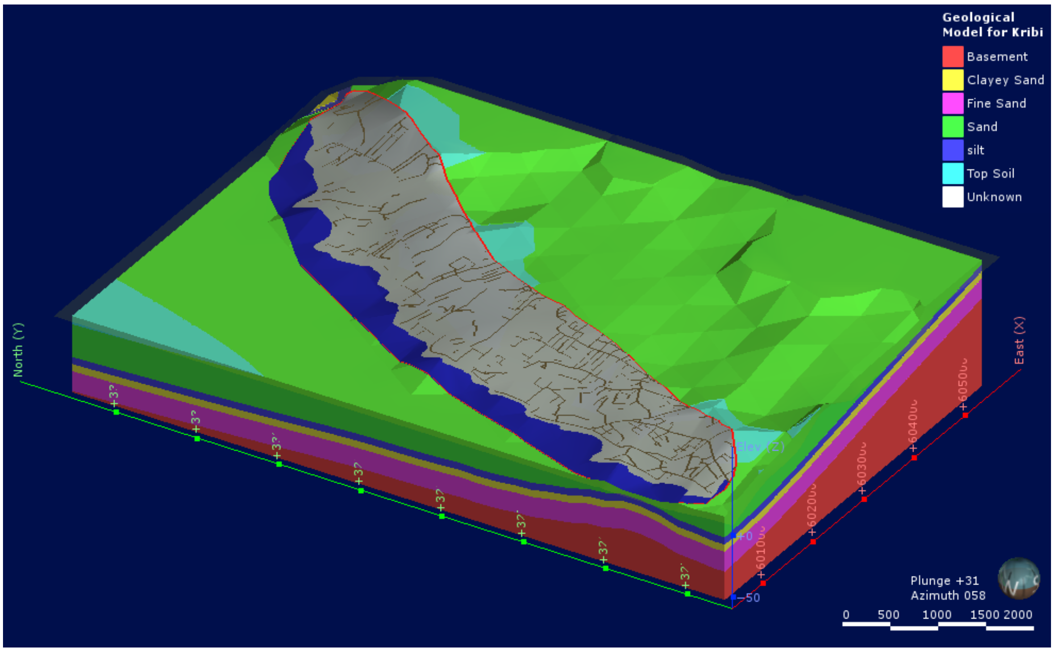


Figure 15: Geological model generated in Leapfrog Geo from ES datasets (vertical exaggeration = 10x)

3.1.1.3.3 Dataset calibration

The analyzed datasets were converted to resemble drilling data and imported into Voxler software. The water table surface grid, prepared in Golden Surfer 16 software, was also imported into Voxler (Figure 13). The resulting model portrays a well-fitting system, comprising a shallow unconfined aquifer along the length of the coast. In other words, the datasets accurately reflect the geological and hydrogeological formations. This layer was then visually compared with the unconfined water table constructed from the ES datasets, as it was assumed that the collected depths primarily fell within the phreatic aquifer.

3.1.1.3.4 Elements for the geological method

- Boundary

The boundary defines the outer limit of the geological model. Geological models are created with a basic set of rectangular extents. These extents can be used to restrict modeling to a particular area of interest. For example, modeling can be restricted to a known distance from drill holes by applying a distance function as a lateral extent. When topography is defined for the project, it is automatically applied as the geological model's upper boundary during model creation. The other boundary element used in creating this geological model is the extent of the study site, as shown in Figure 16.

- Lithologies

The Lithologies object describes all lithological units to be modeled and the colors used to display them on the screen. It is generated automatically from all lithologies identified in the selected drill hole data when the model is created. The lithologies used for building the geological model are shown in Figure 17.

- Surface Chronology

The Surface Chronology object describes the contact surfaces in the model, organized chronologically from youngest to oldest. These surfaces and their chronology determine how the volume within the model extents is divided into lithological units. The created lithological contact surfaces are shown in Figure 18. Errors encountered during this process are shown in Figure 19.

- Output Volume

The Output Volumes folder contains all the volumes generated in building the geological model in chronological order, from youngest to oldest. This is shown in Figure 20.

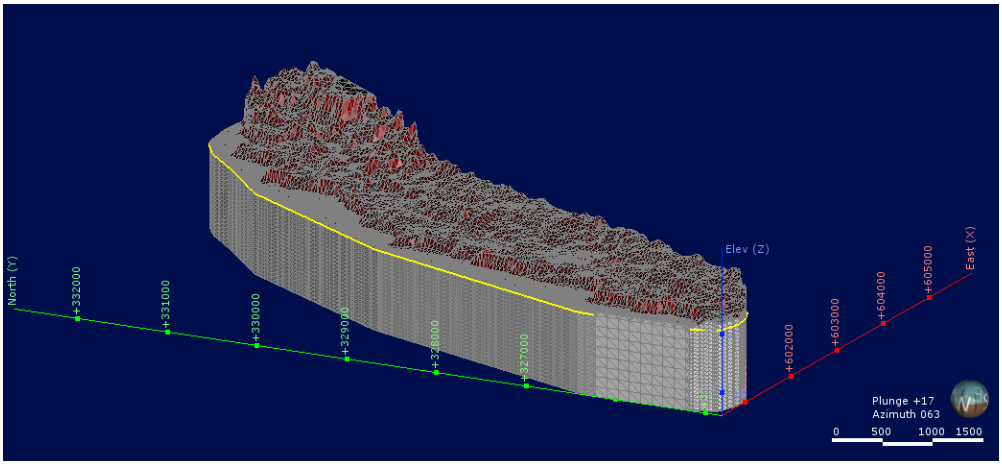


Figure 16: Geological Model boundary in Leapfrog Geo software.

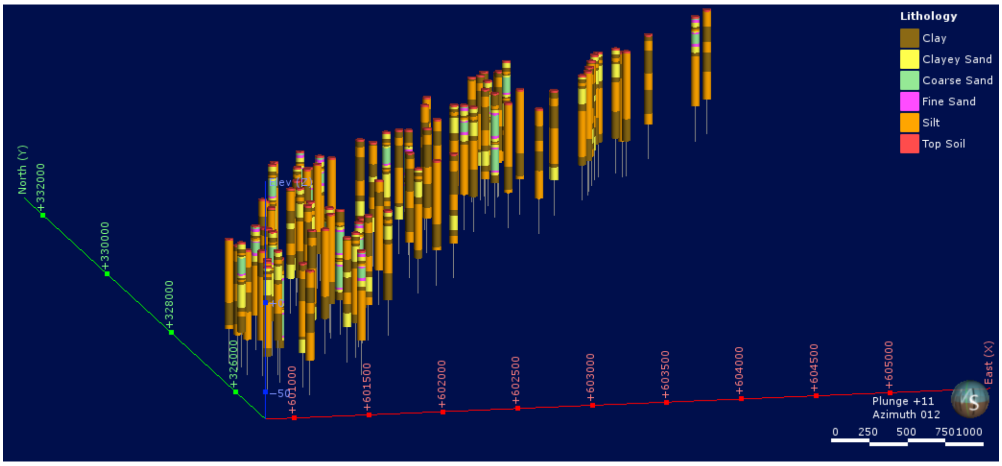


Figure 17: Modelling lithology for Geological Model in Leapfrog Geo software.

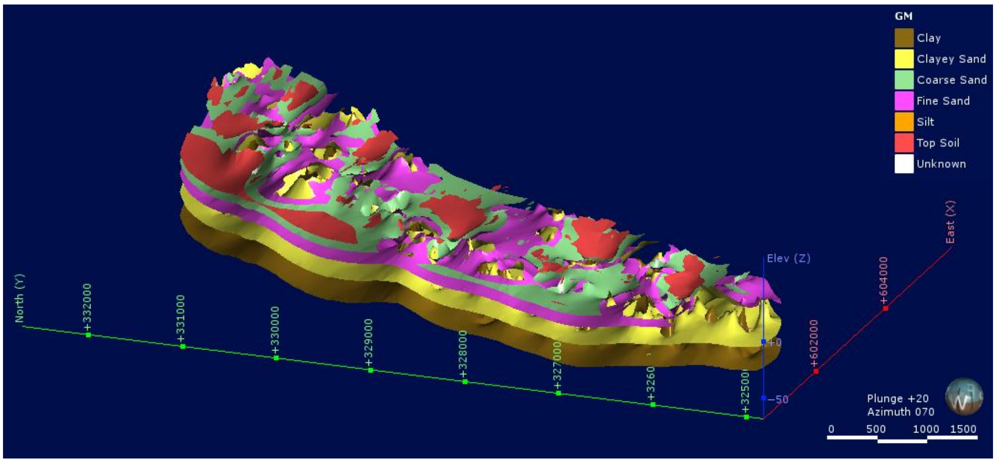
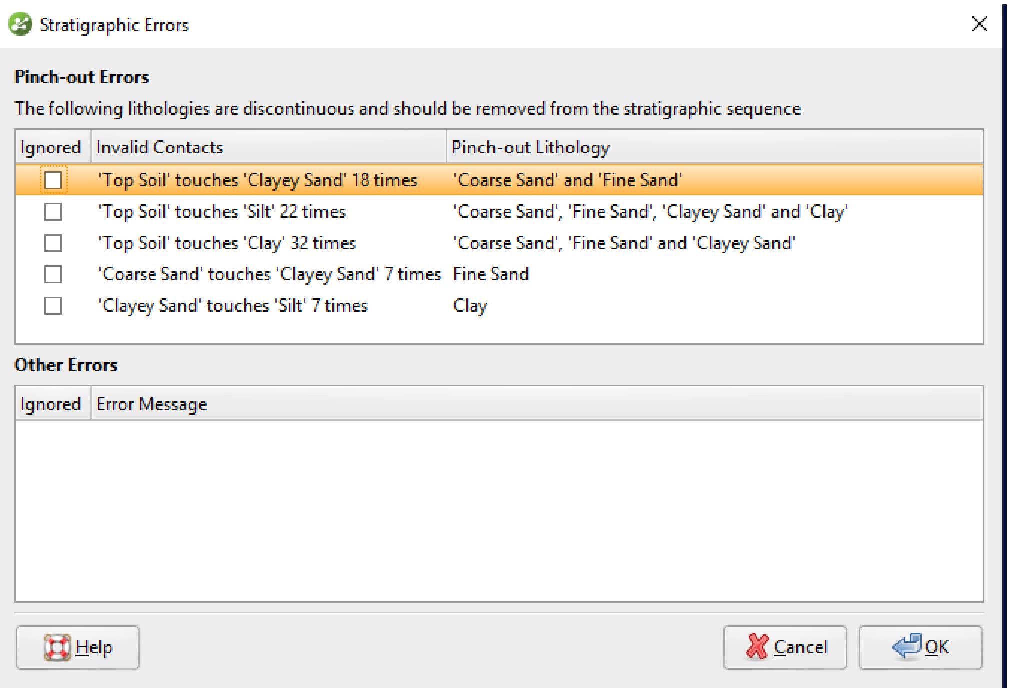


Figure 18: Modelling surface chronology for Geological Model in Leapfrog Geo software.



Stratigraphic Errors

Pinch-out Errors

The following lithologies are discontinuous and should be removed from the stratigraphic sequence

Ignored	Invalid Contacts	Pinch-out Lithology
☐	'Top Soil' touches 'Clayey Sand' 18 times	'Coarse Sand' and 'Fine Sand'
☐	'Top Soil' touches 'Silt' 22 times	'Coarse Sand', 'Fine Sand', 'Clayey Sand' and 'Clay'
☐	'Top Soil' touches 'Clay' 32 times	'Coarse Sand', 'Fine Sand' and 'Clayey Sand'
☐	'Coarse Sand' touches 'Clayey Sand' 7 times	Fine Sand
☐	'Clayey Sand' touches 'Silt' 7 times	Clay

Other Errors

Ignored	Error Message

Figure 19: Pinch-out-errors during creation of stratigraphic surfaces in Leapfrog Geo software.

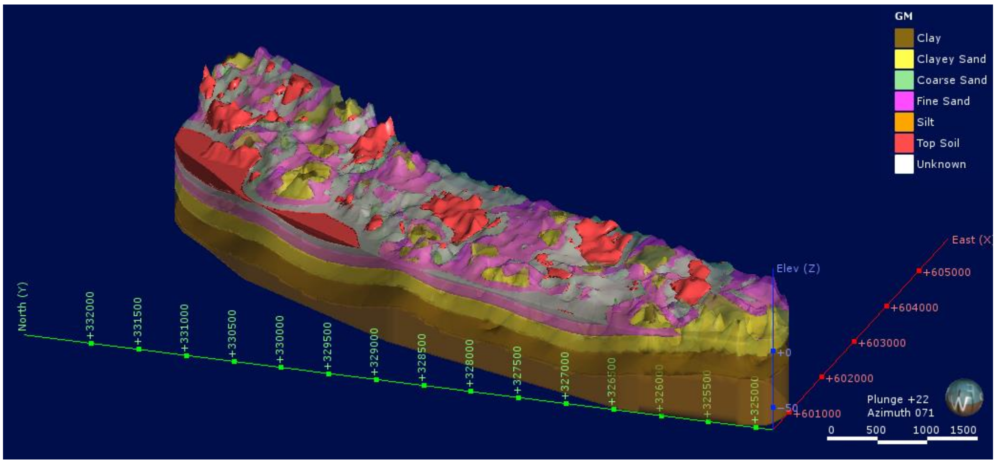


Figure 20: Modelling output volume for Geological Model in Leapfrog Geo software.

3.1.1.3.5 Aquifer system

An aquifer system was developed from the geological model by resolving the pinch-out errors shown in Figure 19. The modeled unconfined aquifer is shown in Figure 21, designated as Aquifer 1. This modeled aquifer was then compared with the unconfined aquifer generated from the water table grid (Figure 22). As evident in the figures, the two layers generally coincide, with minor discrepancies occurring only in regions of extreme extrapolation. The final aquifer system determined for the study area is presented in Figure 23.

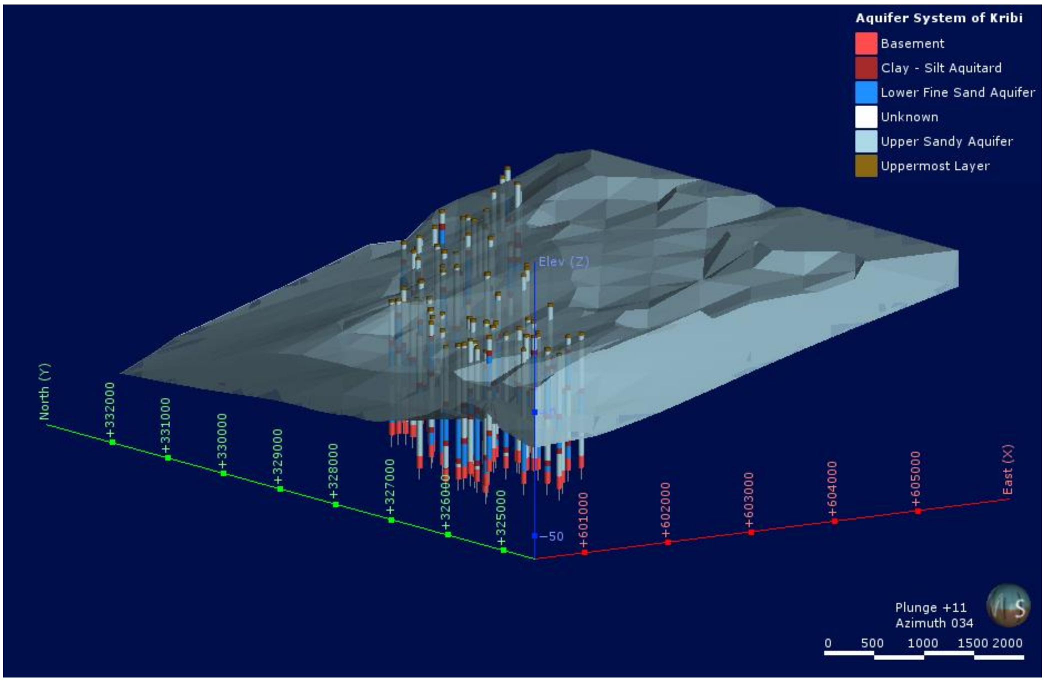


Figure 21: Unconfined aquifer as modelled using Leapfrog Geo and the ES datasets (vertical exaggeration = 10x)

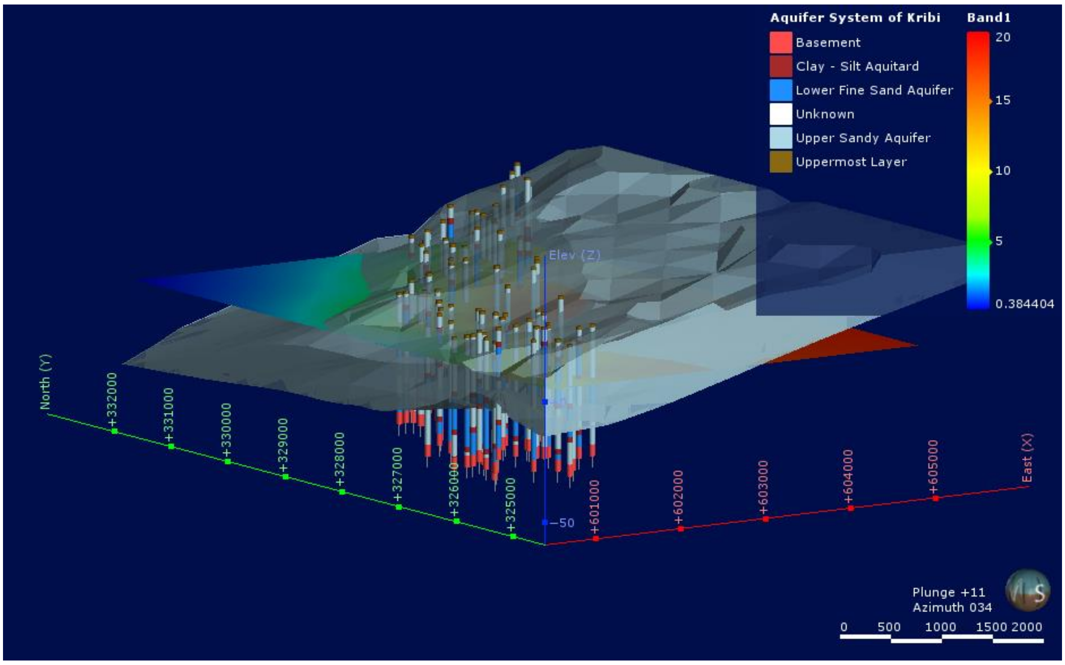


Figure 22: Unconfined aquifer as modelled in Leapfrog Geo compared with the water table grid developed from measured values (see Figure 6) (vertical exaggeration = 10x)

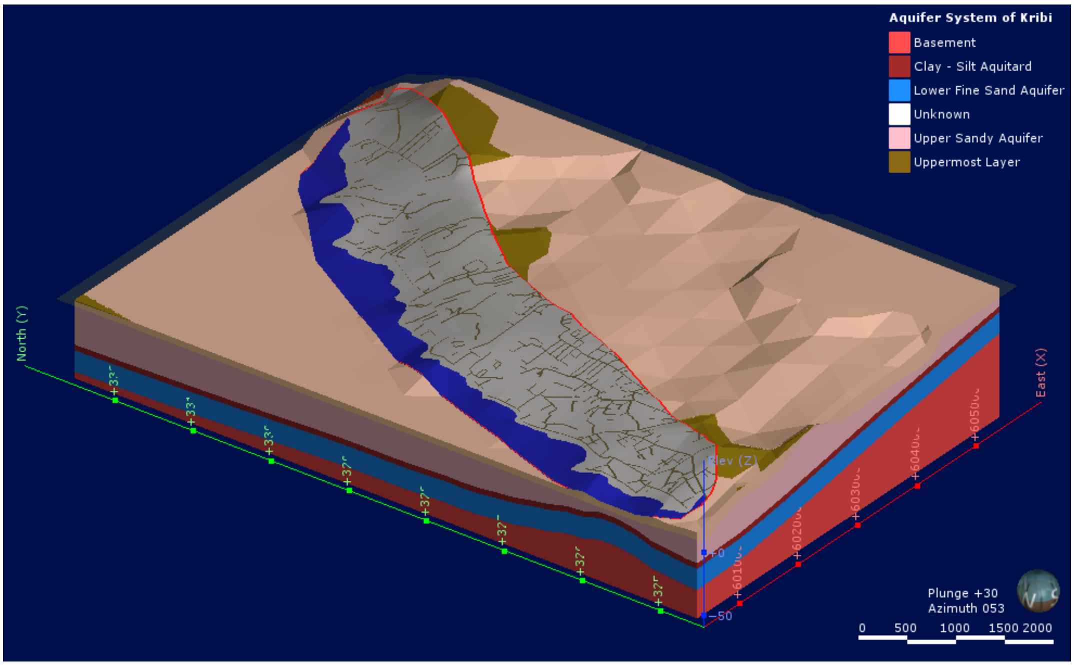
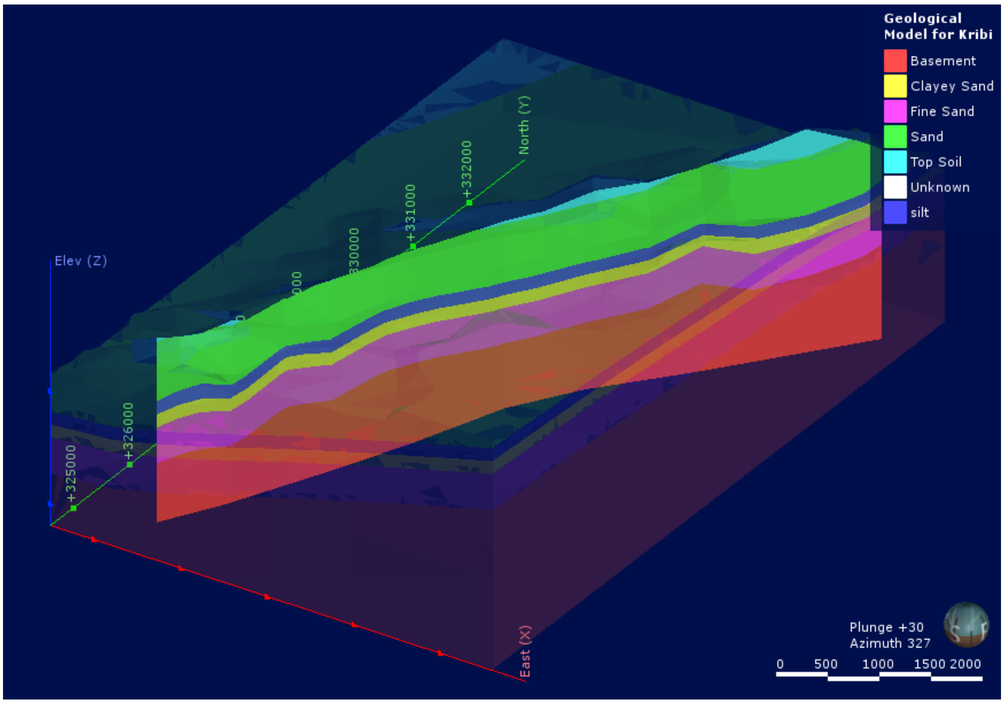


Figure 23: Aquifer system within Kribi town as derived from analyses of ES data.

3.1.1.3.6 Fence Sections

Two fence sections were drawn in Leapfrog Geo to show the lithologic variations within the geological model. They run along the landward side of the study area (Figure 24 (a) and (b)) and the other across the area towards the ocean (Figure 25 (a) and (b)).



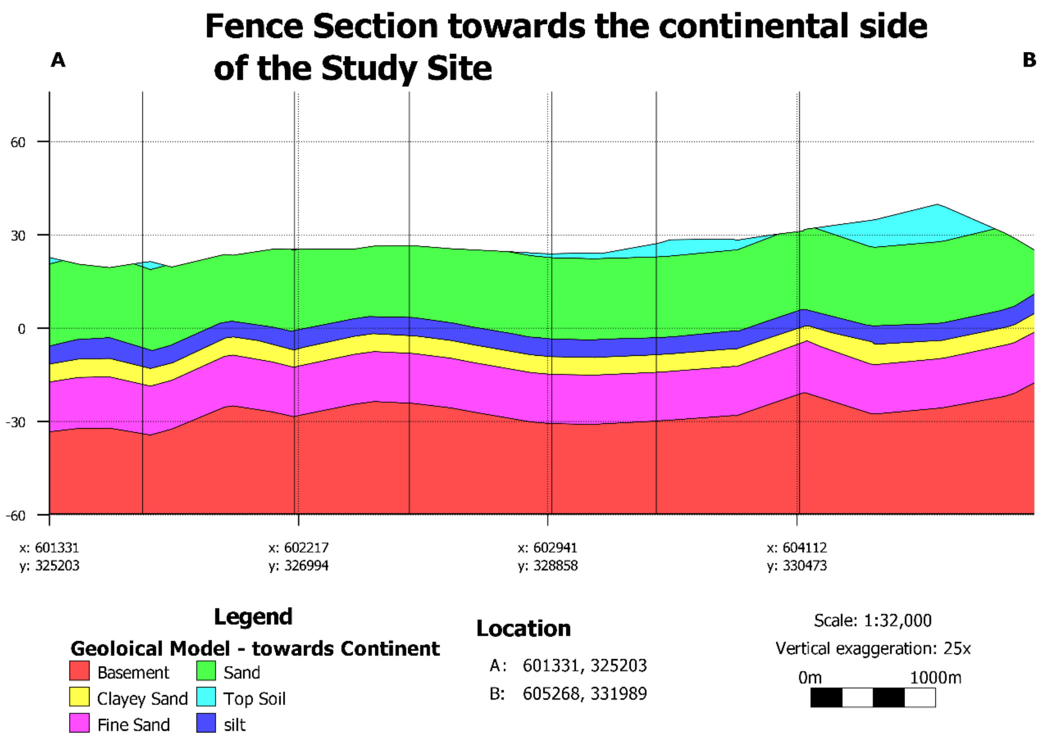
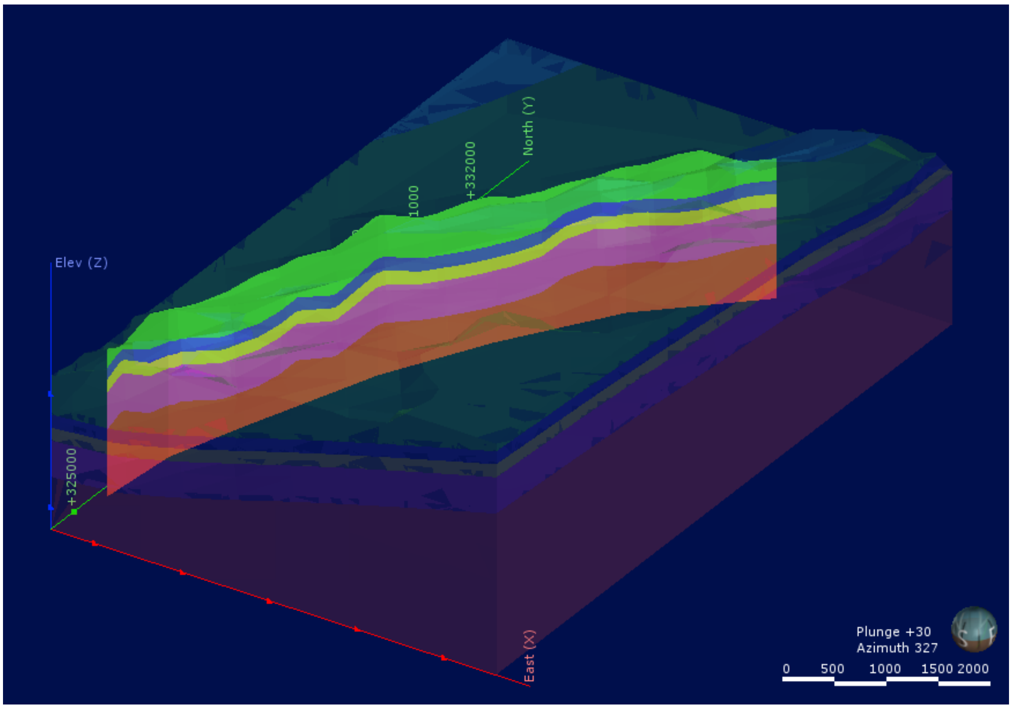


Figure 24: (a) Landward side fence section of the study area through the geological model; (b) Fence section layout; loess (top soil) occurs sparingly and but is commoner along the landward side.



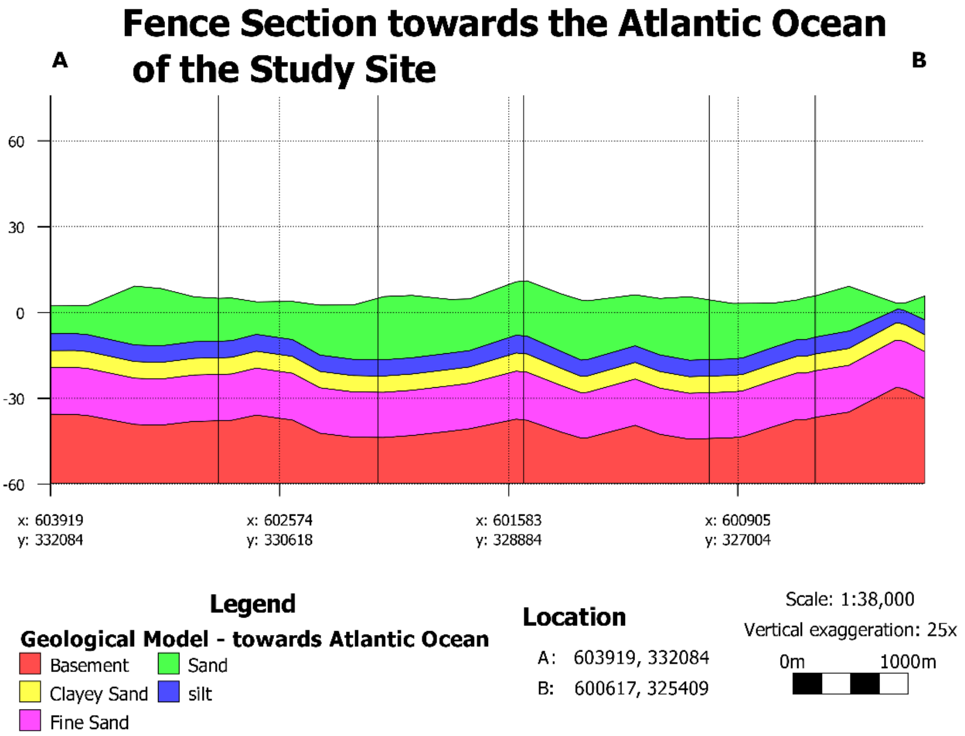


Figure 25: (a) Fence section across the study area approximately perpendicular to the coast; (b) Fence section layout. The loess (top soil) is completely absent towards the ocean because the coastal zone is sandy.

3.1.1.3.7 Hydrogeological Model

The conceptual model developed in Leapfrog Geo was converted into surfaces and exported as Surfer grid files to build the hydrogeological model in Visual MODFLOW Flex. This basic, high-level representation of the hydrogeological system, being grid and simulator independent, will form the basis for other numerical models developed in Visual MODFLOW Flex.

The flow condition chosen for the groundwater model was saturated (constant density) flow, with no transport objective defined. After defining the model structure, the model's property zones were defined using the synthetic hydraulic conductivity values presented in Table 3-3. Kx, Ky, and Kz values were assumed equal due to the lack of additional information. The resulting hydrogeological model is shown in Figure 26.

3.1.1.4 Discussion

The ES survey results provide valuable insights into the spatial distribution of permeability within Kribi Town's aquifer system, serving as a crucial foundation for guiding further hydrogeological investigations and informing sustainable water management decisions.

The identification of high-permeability zones, primarily concentrated along the coastline, aligns with our understanding of coastal sedimentary environments. These zones likely represent areas with coarser-grained sediments, such as sands and gravels, which typically exhibit higher hydraulic conductivity compared to finer-grained materials (Freeze and Cherry, 1979).

Table 3-3: Hydraulic conductivity values used to define property zones for aquifers and aquitards in the Visual MODFLOW-based hydrogeological model.

Layer	Kx, Ky and Kz
Surface layer	0.001
Upper, sandy, aquifer	0.002
Clay/Silt aquitard	0.00001
Lower, fine sand, aquifer	0.0015

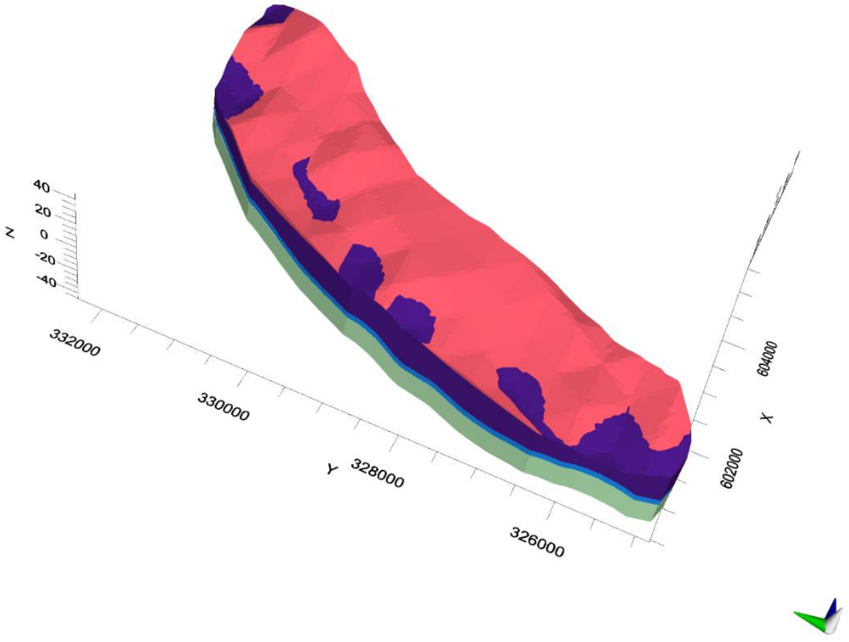


Figure 26: Hydrogeological model developed in Visual MODFLOW Flex to be used for grid generation and conversion to groundwater numerical models.

The strong correlation observed between shallower water table depths and higher ESKT and ESCCT values further reinforces this interpretation. This correlation suggests that the coastal zones identified through the ES data not only possess higher permeability but also represent areas of active groundwater flow and recharge within the unconfined aquifer. These findings are consistent with studies in other coastal settings where ES methods have been successfully employed to delineate preferential flow paths and characterize aquifer heterogeneity (Haines et al., 2004; Mikhailov et al., 1997).

However, it is crucial to acknowledge the limitations of ES surveys, particularly in complex urban environments like Kribi Town. The method's sensitivity to noise, primarily from electrical infrastructure and subsurface heterogeneity, can affect data quality and limit the DOI (Evans et al., 2012). While the rigorous quality assessment process employed in this study ensured the reliability of the interpreted datasets, the limited depth penetration of ES surveys restricts our understanding of deeper hydrogeological features.

Furthermore, ES data alone cannot provide conclusive evidence regarding the presence of specific geological structures, such as faults or fractures, which can significantly influence groundwater flow patterns and aquifer connectivity. In coastal settings, these structures can play a critical role in facilitating saltwater intrusion or creating preferential pathways for contaminant migration (Anderson et al., 1992). To address this limitation and gain a more comprehensive understanding of Kribi's subsurface geology, integrating the ES results with complementary geophysical methods, such as VES surveys, is essential.

3.1.2 VES

3.1.2.1 Quality assessment of datasets:

Before delving into the interpretation of the VES data, a thorough quality assessment was conducted to ensure the reliability and accuracy of the acquired datasets. This assessment focused on identifying and mitigating potential sources of error or noise that could affect the measured resistivity values and compromise the subsequent interpretation.

3.1.2.1.1 Data Acquisition and Initial Screening:

The VES surveys were conducted using the Schlumberger array configuration, known for its effectiveness in mapping both vertical and horizontal resistivity variations (Zhdanov and Keller, 1994). A total of 12 VES soundings were acquired across the study area, strategically distributed to provide representative coverage and prioritize proximity to existing boreholes for calibration purposes. During data acquisition, several quality control measures were implemented:

- **Site Selection:** Suitable sites were chosen to minimize interference from potential electrical noise sources, such as power lines, buried utilities, and metallic fences.
- **Electrode Contact:** Careful attention was paid to ensuring good electrical contact between the electrodes and the ground by moistening the soil around the electrodes and removing any vegetation or debris that could hinder contact.

- **Repeat Measurements:** At each electrode spacing, repeat measurements were taken to assess the consistency of the readings and identify any significant deviations that could indicate measurement errors.

3.1.2.1.2 Assessment of Data Quality:

The processed VES datasets were then visually inspected to assess the overall quality of the resistivity curves and identify any remaining anomalies or inconsistencies. Key indicators of data quality included:

- **Smoothness of Resistivity Curves:** Smooth transitions between resistivity values at different depths indicated good data quality, while abrupt changes or sharp spikes suggested potential measurement errors.
- **Consistency with Geological Context:** The observed resistivity variations were compared with the expected resistivity ranges of different geological materials in the Kribi Town area to ensure consistency with the known or inferred geological setting.
- **Agreement with Borehole Data:** Where available, VES data were correlated with lithological logs from nearby boreholes to verify the accuracy of the resistivity-based interpretations and calibrate the relationship between resistivity values and geological units.

Through this comprehensive quality assessment process, we ensured that the VES datasets used for further interpretation and model development were reliable and representative of the subsurface resistivity structure in Kribi Town. This rigorous approach minimized the potential for erroneous interpretations and strengthened the validity of the conclusions drawn from the VES data.

3.1.2.2 Resistivity Model Interpretation:

3.1.2.2.1 Hydraulic Conductivity Distribution

Hydraulic conductivity is a fundamental property governing groundwater flow within an aquifer. It quantifies the ease with which water can move through the porous medium under a hydraulic gradient. Understanding the spatial distribution of hydraulic conductivity is crucial for identifying productive zones for groundwater extraction, assessing aquifer recharge potential, and predicting groundwater flow patterns.

In this study, hydraulic conductivity values were obtained from pumping tests conducted on nineteen operational boreholes across Kribi Town. These point-based values were then interpolated using the Kriging interpolation method to generate a continuous spatial distribution map (Figure 27).

The resulting map reveals a distinct pattern of hydraulic conductivity variation across Kribi Town. Notably, the northern and southern regions exhibit relatively higher hydraulic conductivity values compared to the central section, where the Kienke River flows. This pattern aligns with the geological context of the area, which is predominantly sedimentary in nature, as suggested by previous studies (Ntamak-Nida et al., 2010; ResearchKey, 2021).

The higher hydraulic conductivity values in the northern and southern regions likely correspond to the presence of coarser-grained sedimentary deposits, such as sandstones. Sandstones, with their larger pore spaces and interconnectedness, typically exhibit higher hydraulic conductivity compared to finer-grained materials like shales or claystones. This interpretation is further supported by borehole log data collected from the field, which indicate the presence of sandy formations in these areas.

Conversely, the lower hydraulic conductivity values observed in the central section around the Kienke River suggest the presence of finer-grained materials, potentially shales or claystones. These materials, with their smaller pore spaces and lower interconnectedness, tend to impede groundwater flow, resulting in lower hydraulic conductivity values.

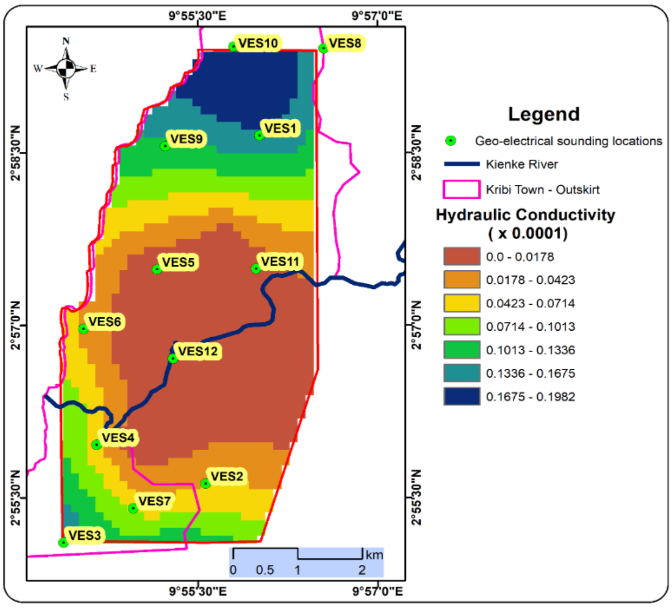


Figure 27: Spatial distribution of the hydraulic conductivity prepared from borehole data of operational wells.

3.1.2.2.2 Sounding Curves

The qualitative interpretation of the VES resistivity data yielded a variety of sounding curves, revealing the electrical properties and structure of the subsurface. These curves were categorized into distinct types: AA (VES4, VES5), AK (VES3, VES6), AKH (VES2, VES9),

KH (VES10), KQ (VES1, VES11, VES12), H (VES7), and QH (VES8), as shown in Figure 28.

- **Diagonal or Normal Shape Curves (AA and AK):**

The AA and AK curves exhibit a diagonal or normal shape, characterized by a consistent increase in resistivity with depth. This pattern indicates a relatively homogeneous subsurface material with uniform resistivity. Such curves suggest low groundwater potential, and any water present in these areas is likely to be brackish. Therefore, VES3, VES4, VES5, and VES6 likely represent zones with limited freshwater resources. Specifically, these VES points seem to delineate areas where the unconfined aquifer is the primary source of groundwater. Contamination within these zones would likely not directly impact the deeper confined aquifer, as the presence of an aquitard (a low-permeability layer) impedes vertical percolation. Any contamination of the confined aquifer in these locations would likely originate from a separate recharge area.

- **Humped Shape Curve (QH):**

The QH curve displays a humped shape, with relatively high resistivity at shallow depths, followed by a decrease to a minimum value and then a subsequent increase to a higher value at greater depths. This pattern suggests the presence of a confined aquifer sandwiched between two relatively impermeable layers. It indicates good potential for groundwater exploration, as water within the confined layer is typically well-protected from surface contamination. Therefore, VES8 exhibits high potential for freshwater resources.

- **Anti-Humped Shape Curve (KQ):**

The KQ curve exhibits an anti-humped shape, characterized by relatively low resistivity at shallow depths, followed by an increase to a maximum value and then a decrease to a lower value at greater depths. The higher resistivity layer in the middle likely acts as an aquiclude (a virtually impermeable layer), effectively isolating the underlying confined aquifer from surface infiltration. This suggests that these areas may have contaminated unconfined aquifers, while simultaneously possessing confined aquifers of good quality, depending on their recharge source. VES1, VES11, and VES12 fall into this category and are considered to have average groundwater potential.

- **Anti-Humped Followed by Humped Shape (KH):**

The KH curve resembles an anti-humped shape followed by a humped shape. This pattern indicates a very deep confined aquifer, suggesting good water quality due to its isolation from surface influences. VES10 falls within this category.

- **Flat or Horizontal Curve (H):**

The H curve is characterized by a relatively constant or nearly constant resistivity with increasing depth. This pattern indicates a relatively uniform subsurface material with consistent resistivity. It may suggest a highly productive aquifer. VES7 falls within this category.

- **KQ Curve with Leaky Aquitard (AKH):**

The AKH curve resembles a KQ curve, but with an aquitard that has slightly higher resistivity than the underlying aquifer. VES2 and VES9 exhibit this pattern. These regions typically possess an unconfined aquifer, followed by a leaky aquitard and a confined aquifer. Unlike the aquiclude in KQ zones, this leaky aquitard allows for some vertical flow, potentially influencing the quality of the confined aquifer. The AKH zones are considered to have average groundwater potential.

- **Overall Observations**

The dominance of 3-layered models, with low fitting errors for the sounding curves (ranging from 0.7% to 1.3%), highlights the complex nature of the subsurface, characterized by a mixture of sedimentary and metamorphic formations. These various curve types provide valuable insights into the different hydrogeological units present in Kribi Town, aiding in the assessment of groundwater potential and identifying zones with contrasting vulnerability to contamination.

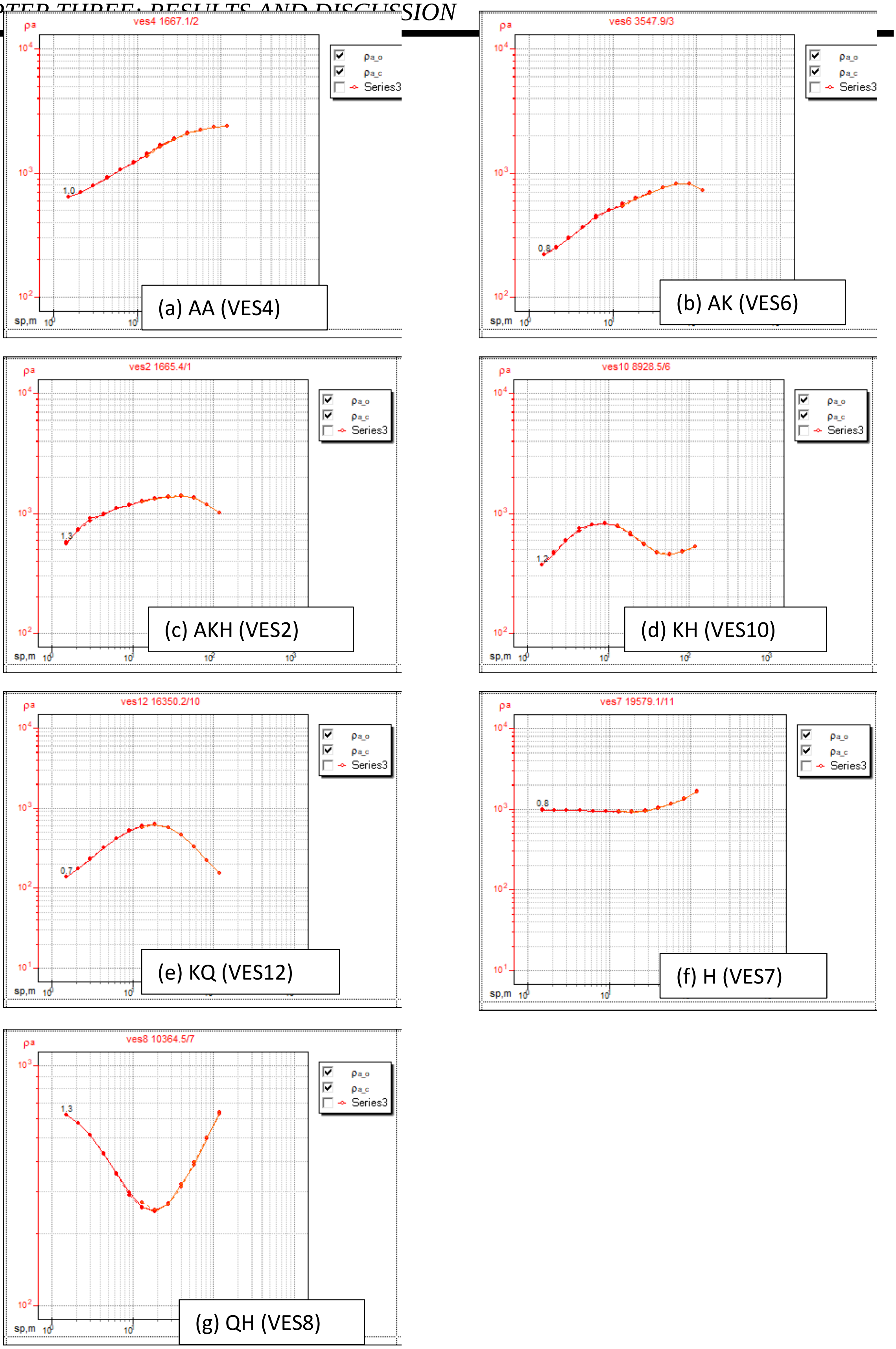


Figure 28: Excerpts of electrical sounding curves obtained in the field, with apparent resistivity (ρ_a) on the Y-axis and current electrode spacing (AB/2) on the X-axis.

3.1.2.2.3 Models of geoelectrical sections

VES curves, when interpreted through inversion techniques, provide layered-earth models that depict the subsurface electrical resistivity structure. These models, visualized as geoelectrical sections (Figure 29), offer a clear and intuitive representation of the variations in resistivity with depth, allowing for the identification of distinct geological units and their spatial relationships.

The geoelectrical sections for Kribi Town consistently reveal a three-layer structure, reflecting the complexity of the subsurface geology. Notably, a layer of lateritic clay is prominently observed, effectively separating the overlying unconsolidated materials from the underlying hard basement rocks. This lateritic clay layer acts as an aquitard, impeding vertical groundwater flow between the shallow and deeper zones.

Unconsolidated Layers: The thickness of the unconsolidated materials, primarily composed of sands and clays, varies significantly across the study area. A distinct thickening is observed towards the central part of Kribi Town and extending towards the ocean, suggesting a greater potential for groundwater storage within the unconfined aquifer in these areas.

Basement Rocks: The basement rocks, primarily composed of granites and quartz, exhibit high resistivity values, indicative of their consolidated nature and low permeability. Within the basement, a zone of weathered/fractured granite is identified, exhibiting moderately lower resistivity values. This zone represents the confined aquifer, where groundwater flow is controlled by the interconnected network of fractures.

Lateral Trends: The geoelectrical sections highlight distinct lateral trends in resistivity, reflecting the spatial distribution of different geological units. The northern and southern regions exhibit similar resistivity patterns, characterized by high values, suggesting the presence of consolidated sedimentary rocks or deep-water metamorphosed rocks. This similarity suggests that these regions may represent distinct sub-basins within the Kribi-Campo sedimentary sub-basin.

Central Zone: The central part of Kribi, in contrast, exhibits lower resistivity values, indicative of loose sediments bearing groundwater potentially influenced by saltwater intrusion. The presence of the Kienke River in this central zone likely contributes to the deposition of these unconsolidated sediments.

Geological Insights: The geoelectrical sections provide valuable insights into the complex interplay between sedimentary processes, tectonic activity, and groundwater flow in Kribi Town. The presence of the lateritic clay layer suggests past periods of intense weathering and soil formation, while the fractured/weathered granite zone within the basement highlights the influence of tectonic forces on groundwater occurrence and flow paths.

These geoelectrical sections, in conjunction with other hydrogeological data, will serve as a critical foundation for developing a comprehensive understanding of Kribi's groundwater resources and informing sustainable water management strategies for the town.

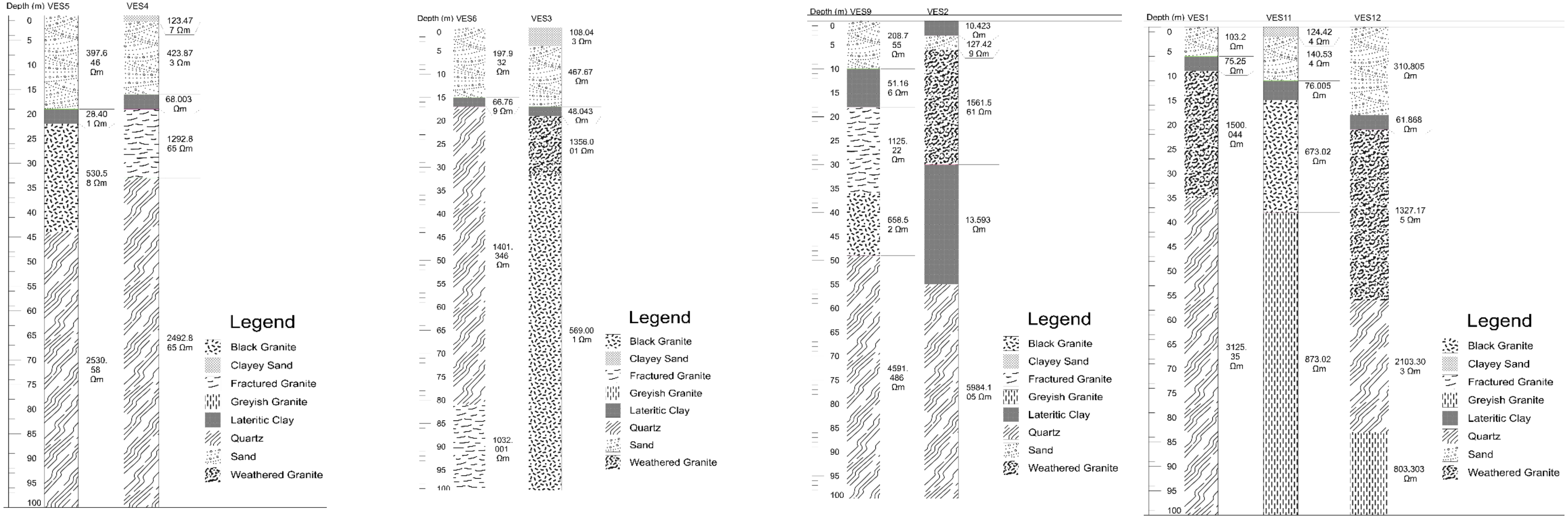


Figure 29: Models of geoelectrical section for Profiles AA, AKH, AK, KQ, from left to right.

3.1.2.3 Spatial Visualization of VES Results:

While the identification of subsurface layers and their boundaries is a key step in understanding the subsurface geology and hydrogeology of an area, the spatial distribution of resistivities at various depths provides better information for making decisions about hydrogeological activities. A key component in interpreting the aquifer system is the maximum depth at which the investigation can provide reliable results. This is generally referred to as the DOI (Pace et al., 2021). The estimated DOIs for the cases shown in Figure 30 are 1.2 m, 2.5 m, 5.3 m, and 11 m, respectively. Resistivity values generally increase with depth, with the northern and southern areas exhibiting higher values than the central part, although this trend is not uniform across all depths.

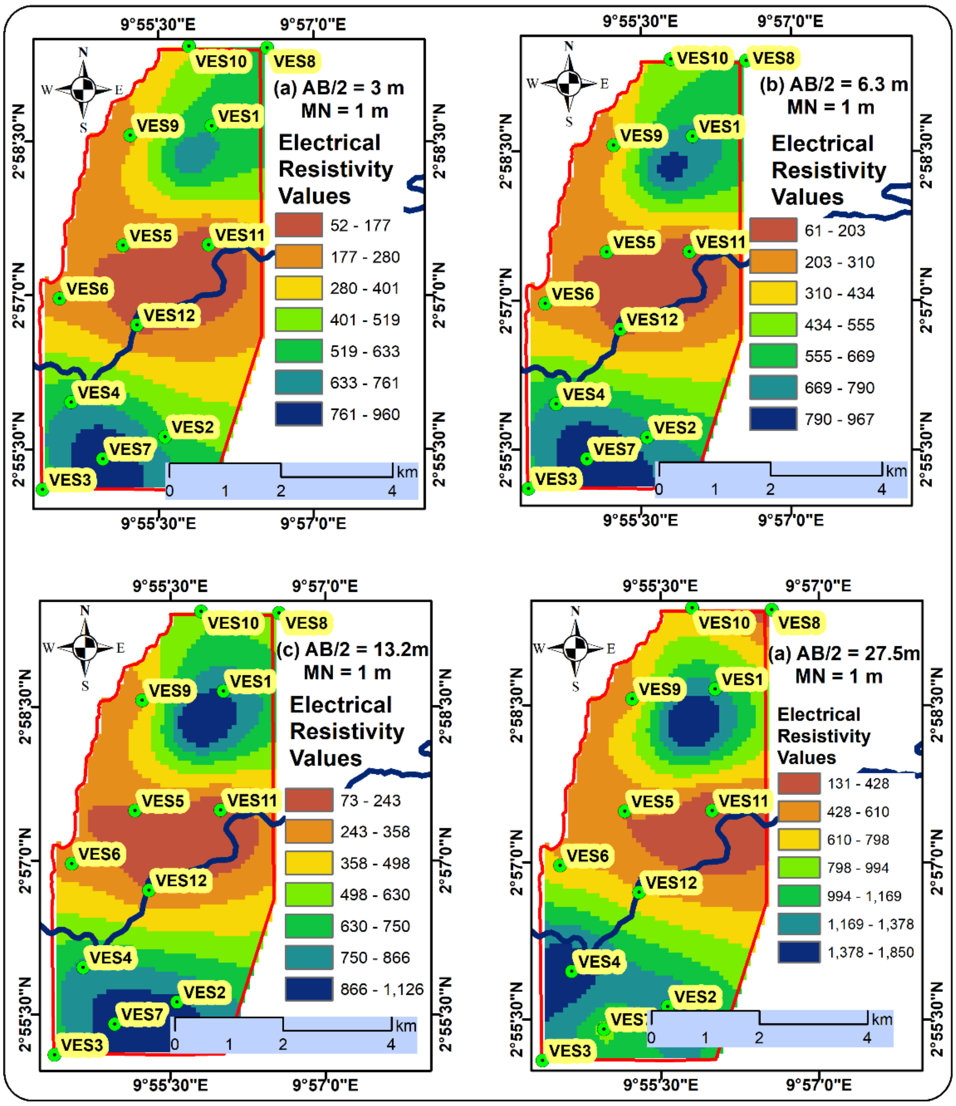


Figure 30: 2D electrical resistivity variation with depth according to current electrode spacing within Kribi, with corresponding Depths of Investigation of 1.2 m, 2.6 m, 5.3 m, and 11 m respectively from top to bottom.

3.1.2.4 Generation of subsurface models

These models were obtained from the 3D-implicit modelling technique in Leapfrog Geo version 5.1.4.

3.1.2.4.1 Lithological Model

The geophysical results were calibrated using borehole data, establishing a range of values for resistivity that corresponds to a given lithology, as shown in Table 3-4. These lithologies were then used to establish the lithology model of the area using the Leapfrog Geo software. The quartz dominates the basement, with some appearances of granite.

Table 3-4: calibrated lithology against resistivity values from geophysical datasets and borehole datasets for the Kribi town

Resistivity Values (Ωm)	**Calibrated Lithology**
Less Than 90	Lateritic Clay
90 - 130	Clayey Sand
130-500	Sand
500-700	Black Granite
700-900	Greyish Granite
900-1300	Fractured Granite
1300-1700	Weathered Granite
Greater Than 1700	Quartz

3.1.2.4.2 Geological model and aquifer system

The VES data were used to generate a geological model by building stratigraphic sequences, since the area is sedimentary in nature. These sequences resulted in the following surfaces: the Sand-Laterite surface, the Laterite – Granite surface, and the Granite – Quartz surface, after lithologies were combined. The resulting geological model is given in Figure 31a with a corresponding three-layer hydrogeological model in Figure 31b. The confined aquifer exists within fractured/weathered granite at the upper part of the granitic basement. This hydrogeological model will serve as a baseline for the subsequent sustainable management of groundwater resources within Kribi.

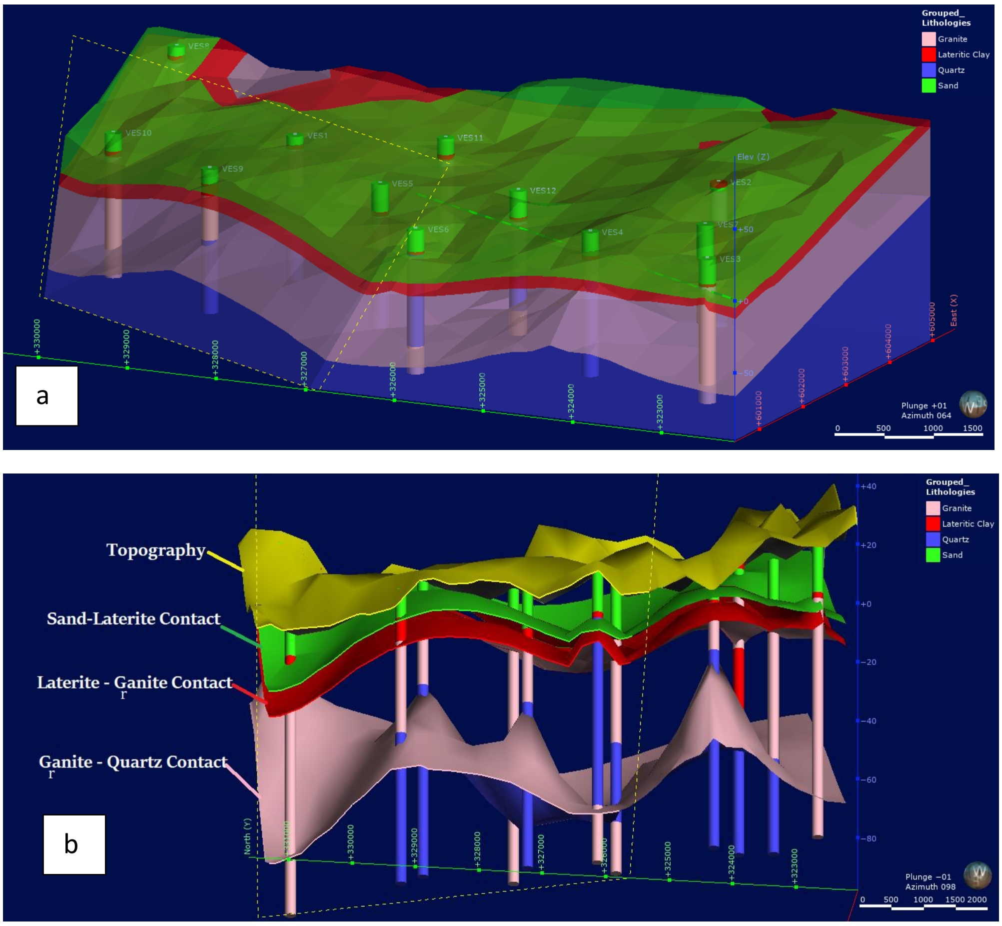


Figure 31: Geological / Hydrogeological Model developed in Leapfrog Geo from VES data (vertical exaggeration = 15x)

3.1.2.4.3 Aquifer thickness spatial distribution

Aquifer mapping is a fundamental aspect of any sustainable groundwater management project, providing essential information for understanding and managing groundwater resources. It addresses the critical question of how to best utilize and protect these valuable resources. Mapping the aquifer, a key outcome of hydrogeological studies, involves delineating its spatial extent and thickness.

In this study, aquifer thicknesses were determined by analyzing the sounding curves from the VES datasets and integrating them with the geological model generated using Leapfrog Geo software. This spatial distribution of aquifer thickness is presented in Figure 32.

The thickness of the unconsolidated sedimentary aquifer is predominantly between 14 m and 16 m, representing 27.9% of the total aquifer thickness within the study area (Figure 33). This indicates a significant potential for groundwater storage within the unconfined aquifer. Proper management of this resource could lead to water self-sufficiency within Kribi. These areas of substantial aquifer thickness are primarily located in the central and southern parts of the town.

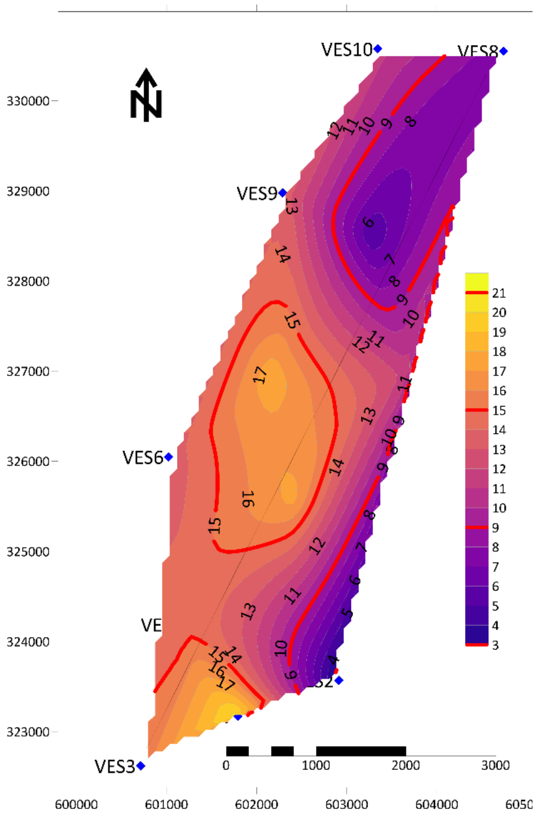


Figure 32: unconfined aquifer thickness spatial distribution

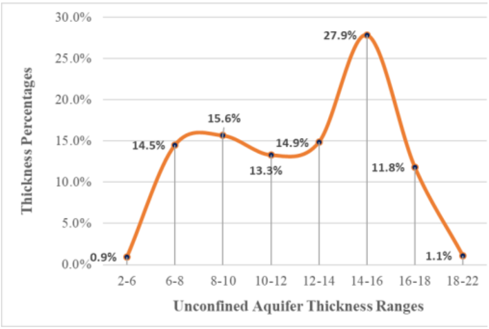


Figure 33: percentage of unconfined aquifer thickness distribution around Kribi and environs

3.1.2.4.4 Estimating groundwater potential of Kribi

With a comprehensive understanding of Kribi's geological and hydrogeological settings, we can estimate the available groundwater resources. The static groundwater reserve within the unconfined aquifer is determined by considering the volume of the saturated zone, which is the space between the static groundwater levels measured in wells within the geophysical study area. The estimated static groundwater volume for the unconfined aquifer is 50,179,381 cubic meters.

The extent of the confined aquifer is estimated by considering the volume encompassing the region between the base of the aquitard and the fractured/weathered zone at the top of the granitic basement. The central part of Kribi, as shown in Figure 34, exhibits the greatest volume of water within the unconfined aquifer. This area also corresponds to the town center. The southern part also holds substantial groundwater potential within the unconfined aquifer.

The estimated static groundwater reserve within the confined aquifer is 317,118,946 cubic meters, as shown in Figure 34. The southern part exhibits the highest confined groundwater potential, followed by the northern part and then the central part. Quantifying the available groundwater resources is a crucial first step towards effective management and sustainable utilization of this vital resource in Kribi.

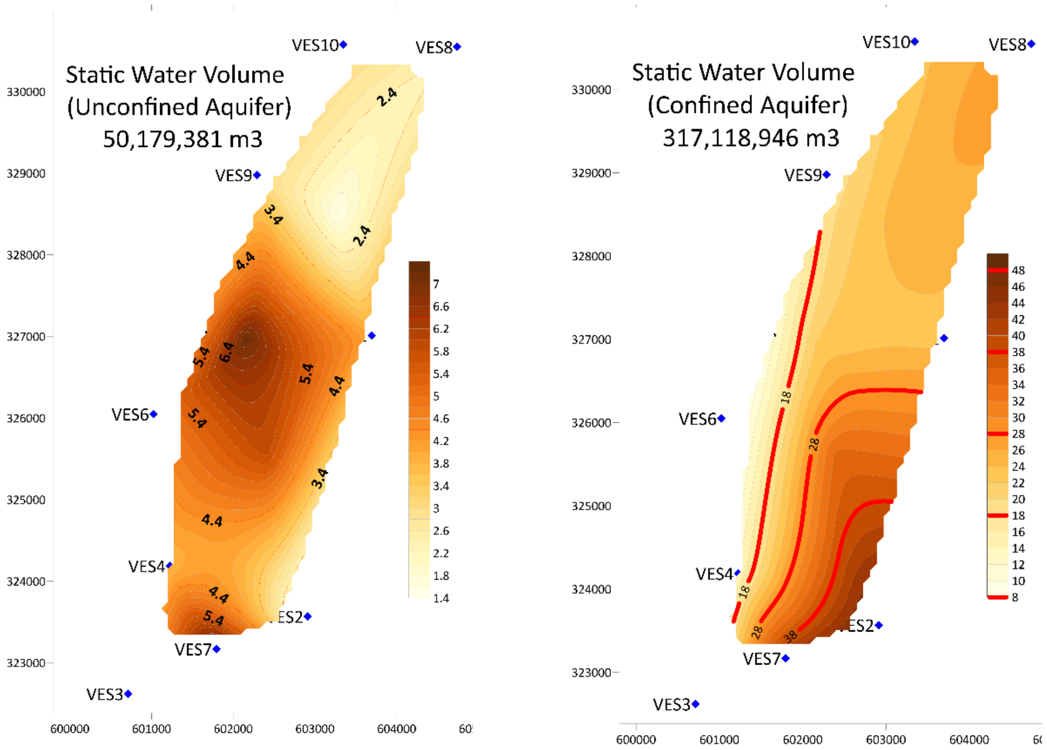


Figure 34: Estimated Static Water Volume for unconfined aquifer(left) and confined aquifer (right).

3.1.2.4.5 Fence Sections

Several fence sections were constructed in Leapfrog Geo to visualize the variations in hydrogeological materials within the study area and their implications for groundwater management. These fence sections, based on the profiles obtained from the various VES curve types (AA, AK, KQ, and AKH), are shown in Figure 35 to Figure 38.

The modeled unconsolidated aquifer exhibits varying thicknesses, transitioning from thin layers further inland to thicker zones along the coast. The southern part of Kribi shows a greater aquifer thickness compared to the northern part. Beyond the surface layer, the internal structures display a consistent pattern, reminiscent of sedimentary formations characterized by a layered sequence of materials.

The presence of several bowl-shaped structures within the subsurface poses a potential challenge for groundwater management. Water accumulating in these depressions may be susceptible to contamination from both land-based and marine sources, and remediation efforts in such confined settings could prove difficult.

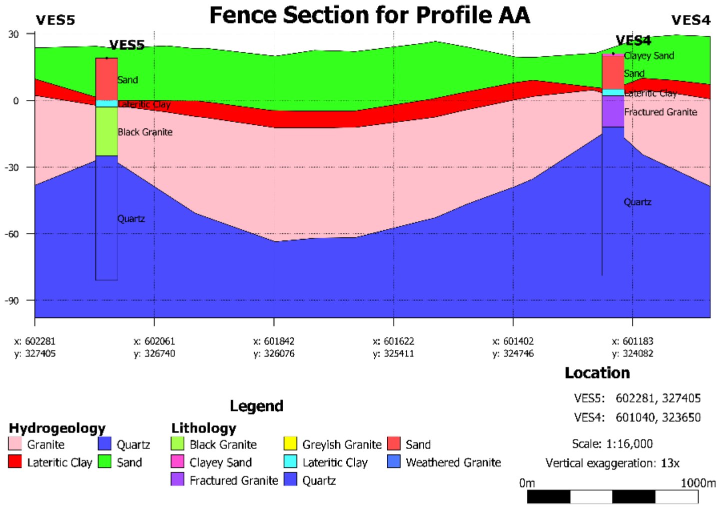


Figure 35: Fence section for Profile AA

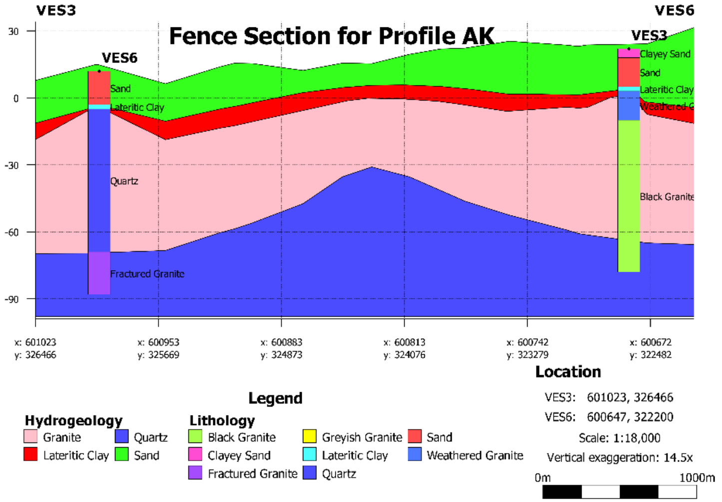


Figure 36: Fence section for Profile AK

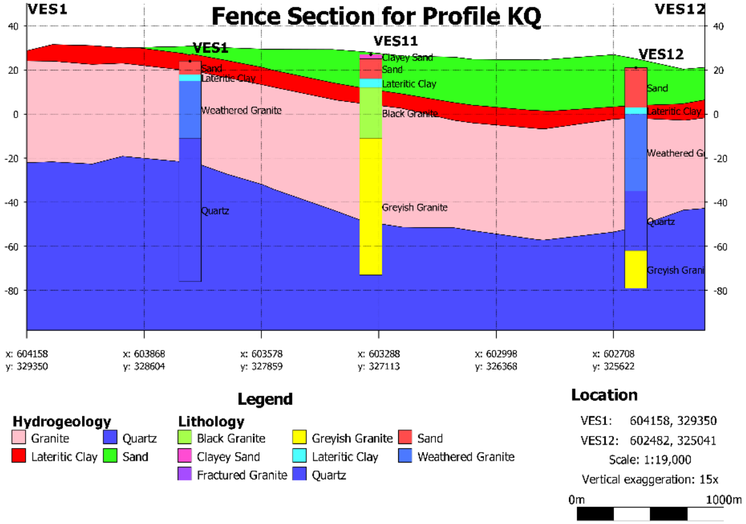


Figure 37: Fence section for Profile KQ

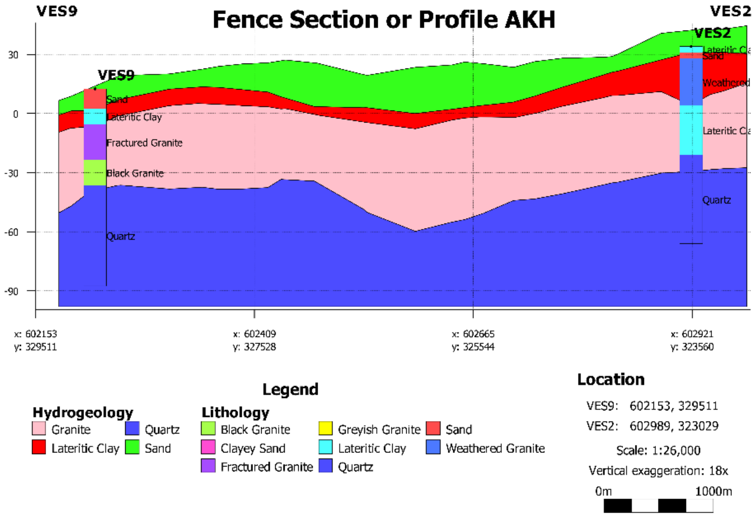


Figure 38: Fence section for Profile AKH

3.1.2.4.6 Groundwater head distribution and indication on pumping rates

Groundwater head distributions within Kribi were determined and plotted alongside borehole pumping rates, as shown in Figure 39. Water heads generally increase towards the inland areas. Figure 37 reveals the presence of granites at the surface in the northern part of Kribi, indicating that the unconfined aquifer is either very thin or absent in some areas. Consequently, the water table distribution in this region is primarily influenced by the confined aquifer.

Water head values greater than or equal to 14 m are associated with the confined aquifer and represent promising areas for water supply in Kribi. These areas, located in the northern and southern parts of Kribi, also exhibit high pumping rates, as shown in Figure 39. The increasing pumping rates towards the inland areas and southward could be attributed to several factors:

1. **Lower Population Density:** The northern and southern parts of Kribi are less densely populated compared to the central town, resulting in lower overall groundwater withdrawal rates.
2. **Higher Aquifer Productivity:** The confined aquifer in these regions may be more productive, allowing for higher pumping rates without significant drawdown.

Further investigation is needed to determine the relative contributions of these factors to the observed pumping rate patterns. This information is crucial for developing sustainable groundwater management strategies that balance water supply needs with the long-term health of the aquifer system.

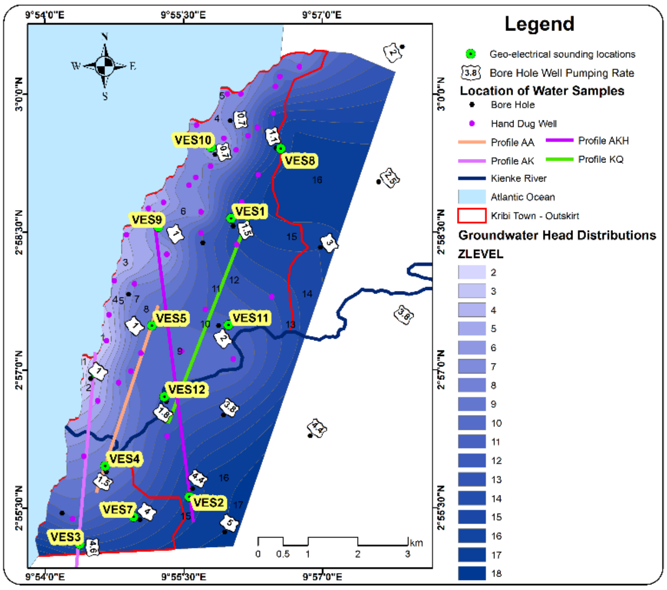


Figure 39: Groundwater Head Distribution and borehole pumping rates within Kribi.

3.1.2.5 Discussion:

A wide variety of sounding curves were observed in the study area, including AA, AK, AKH, KH, KQ, H, and QH. These represent combinations of the A, K, H, and Q types identified by José et al. (2021), reflecting the presence of more than three subsurface layers. These curves were evaluated to assess their potential for providing potable groundwater and identify regions with good water quality.

Kribi Town generally possesses adequate groundwater potential (ResearchKey, 2021). However, a significant portion of this resource is contaminated. The vertical structure derived from VES data, calibrated with borehole logs, shows that the area comprises unconsolidated layers of sand, clayey sand, and laterite, overlying a basement composed of weathered/fractured granites and quartz. While some uniformity exists in the subsurface structure observed by José et al. (2021), the lithological model developed for Kribi shows variations, partly due to the denser spacing of sampling points used in this study.

Spatially, the northern and southern areas exhibit similar resistivity patterns, characterized by high values, suggesting the presence of consolidated sediments. These high values, although greater in the south than the north, indicate that these zones are sub-basins within Kribi where consolidated sediments have accumulated over time. These rocks are either sedimentary (José et al., 2021) or deep-water metamorphized (Archean) rocks (Ntamak-Nida et al., 2010). ResearchKey (2021) also supports the presence of gneisses and granites in the central part of the Kribi-Campo sub-basin. Given this complex geology and the lack of clear linkages between rock units, fractures likely serve as primary conduits for groundwater flow. This explains why groundwater levels in most boreholes are found within fractured granites.

José et al. (2021) suggest that tectonics control subsurface flow, with prominent fracture networks or lineaments oriented along N10, N45, N50, E-W, N80, N100, N110, N145, N170, and N310 directions. Within such a fractured hydrogeological system, structural control of groundwater storage and flow is inevitable (Dochartaigh, 2019). The models, however, show that the consolidated sediments in the south are thicker than those in the north, suggesting a larger basin in the south. The basement's influence in the north is minimal due to the thickness of the overlying unconsolidated materials. The higher resistivity in the south indicates a greater degree of sediment solidification compared to the north.

The central part of Kribi exhibits lower resistivity values, indicative of loose sediments containing groundwater potentially polluted by saltwater. The unconsolidated nature of these sediments is consistent with the presence of the Kienke River.

ResearchKey (2021), aiming to map geological units and analyze physicochemical parameters and soil samples, found that the predominant rock type is gneiss, with structures like folds, veins, and joints prominently present. This corroborates the findings of José et al. (2021) regarding the intrusive nature of the geology. This intrusiveness significantly influences aquifer thickness distribution. Aquifer thicknesses between 14 m and 16 m are most prevalent, primarily in the central and southern parts of Kribi, indicating high groundwater storage potential. The southern area exhibits particularly high aquifer thicknesses within the sedimentary cover. This aligns with Owona et al. (2011), who reported that the thickest areas of the continental cover within the Kribi-Campo basin are in southern Kribi and western Edea.

With estimated static groundwater volumes of 50,179,381 cubic meters for the unconfined aquifer and 317,118,946 cubic meters for the confined aquifer, the region possesses ample water resources to meet the needs of its population. Even with a projected population increase to 80,000 (double the estimated size of 40,000 in 2018 (PAK, 2018), the area is likely to remain water self-sufficient.

The created fence sections reveal a graben structure in the central part and horst structures in the north and south, resembling the graben-horst system found within the Kribi-Campo sedimentary sub-basin (Malquaire et al., 2017). The compact nature of the subsurface is likely to prevent landslides, as suggested by Ghani et al. (2022).

Groundwater head values between 2 m and 13 m correspond to the unconfined aquifer, while values greater than 14 m correspond to the confined aquifer. Several studies corroborate these values within the Kribi-Campo zone, including those by Lordon et al. (2012) (3-6 m), José et al. (2021) (2-10 m), and Paterne et al. (2021) (3-11 m), all pertaining to the unconfined aquifer.

3.1.3 Implications for water resource management and environmental protection in the area

The integrated analysis of ES and VES data, coupled with 3D-implicit modeling techniques, has enabled the identification and delineation of potential groundwater zones crucial for sustainable water resource management in Kribi (Comte et al., 2012). These potential zones, represented in Figure 40, exhibit high groundwater potential lines (greater than two) and correspond to areas with groundwater heads greater than or equal to 13 meters (Figure 39), indicating the presence of the confined aquifer. This suggests that drilling water supply wells into these delineated zones could tap into the confined aquifer, which has demonstrated high pumping rates, thereby providing a reliable source of potable water for Kribi Town.

Managing Kribi's water resources effectively requires a comprehensive and integrated approach. Implementing IWRM, as advocated by Ako et al. (2010), presents a promising pathway. IWRM emphasizes a holistic perspective that considers social, economic, and environmental factors in decision-making. A crucial aspect of IWRM is groundwater modelling, which enables the simulation and prediction of aquifer behaviour under various stresses. As a starting point for groundwater modelling in Kribi, we can focus on the volume of land above the granitic basement (Figure 41), which encompasses the primary zone of groundwater extraction and exhibits significant variability in water table depth. This hydrogeological model, combining the unconfined aquifer layer with the aquitard/aquiclude, serves as a foundation for further modelling efforts.

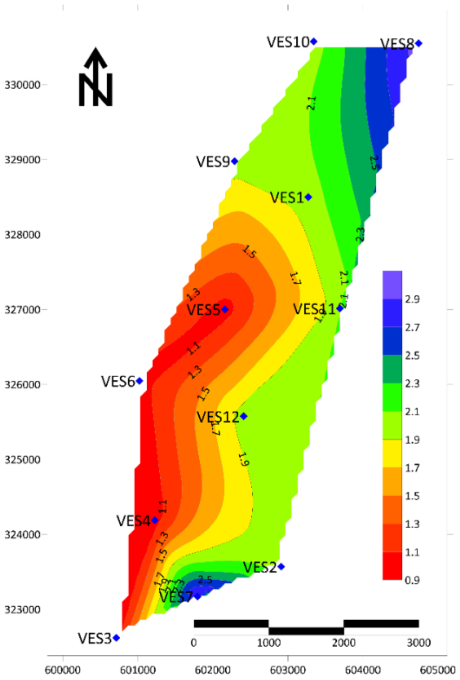


Figure 40: distribution of Groundwater Potential Zones within Kribi town for potable water provision and management of the resource.

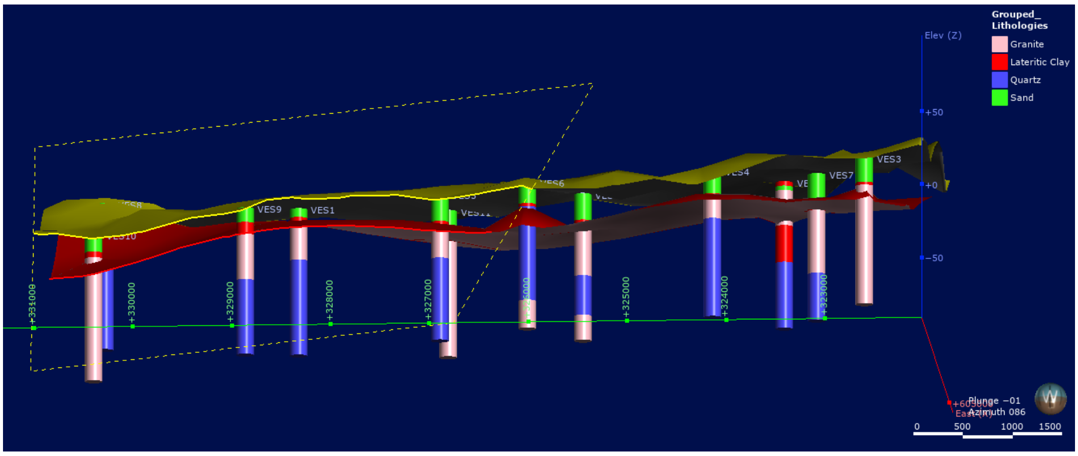


Figure 41: an area for initial groundwater modelling within Kribi and environs, constructed from the hydrogeological model of the area (vertical exaggeration = 35x).

Furthermore, the sandy nature of the upper layers and the underlying granitic basement suggest the potential for artificial groundwater recharge through methods like rainwater harvesting (Mohammed et al., 2022). Given the high precipitation rates in Kribi, implementing rainwater harvesting systems could play a significant role in combating groundwater quality degradation and enhancing the town's water security.

3.2 Hydrogeochemical Assessment

3.2.1 Groundwater Sampling and Analysis

3.2.1.1 Physicochemical Analysis Results:

To assess the suitability of Kribi Town's groundwater for various uses and identify potential contamination sources, a purposive sampling campaign was conducted. Water samples were collected from 20 existing wells and boreholes (KRB-01 to KRB-20), strategically selected to represent different aquifer units and proximity to potential contamination sources (as outlined in Section 2.3.1).

A comprehensive suite of physicochemical parameters were analysed, encompassing physical properties, major ions, nutrients, and trace elements/heavy metals. This detailed analysis aimed to provide a holistic understanding of groundwater quality and its suitability for drinking, irrigation, and other uses.

Table 3-5: Chemical composition of groundwater in Kribi Town

Sample name	pH	T	Cond	TDS	Cl	NO3	SO4	Na	Ca	Mg	As	Pb	Hg	HCO3	CO3	SiO2	O	δ^2H
		°C	mS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	‰
KRB-01	5.8	32.5	1.25	837.5	450	15	180	220	80	40	0.012	0.005	0.002	150	1	8	6	1
KRB-02	6.2	31.8	0.98	656.6	380	10	150	180	70	35	0.01	0.003	0.001	200	1.5	7.5	6.5	-0.5
KRB-03	4.9	33.2	2.8	1876	1200	25	300	480	120	60	0.018	0.012	0.004	75	0.5	9	5	3.5
KRB-04	6.5	30.5	0.55	368.3	200	5	80	100	40	20	0.006	0.001	0.0005	300	2	7	7	0.5
KRB-05	5.5	34.1	3.5	2345	1500	30	350	550	150	75	0.022	0.015	0.005	90	0.7	8.5	5.5	4
KRB-06	6.8	31.2	0.85	569.5	320	8	120	150	60	30	0.009	0.002	0.001	180	1.3	8.2	6.3	-1
KRB-07	5.9	32.9	1.1	736.5	400	12	160	200	75	38	0.011	0.004	0.0015	160	1.1	7.8	6.1	0.8
KRB-08	6.4	30.8	0.62	415.4	230	6	90	110	45	23	0.007	0.0015	0.0007	280	1.9	7.2	6.8	-2.5
KRB-09	5.7	33.5	1.3	871	470	16	190	230	85	43	0.013	0.006	0.0025	140	0.9	8.3	5.9	1.2
KRB-10	6.9	31.5	0.78	522.6	300	7	110	140	55	28	0.008	0.002	0.0008	190	1.4	7.9	6.4	-1.8
KRB-11	6.1	32.2	0.95	636.3	370	9	140	170	65	33	0.01	0.0035	0.0013	210	1.6	7.6	6.6	-1.5
KRB-12	6.6	30.9	0.58	388.4	210	5.5	85	105	42	21	0.0065	0.0012	0.0006	270	1.8	7.1	6.9	-2.8
KRB-13	5.6	33.8	1.35	904.5	490	17	200	240	90	45	0.014	0.007	0.003	130	0.8	8.4	5.8	1.5
KRB-14	7	31.3	0.75	502.5	290	6.5	100	130	50	25	0.0075	0.0018	0.0007	195	1.45	8	6.35	-2
KRB-15	6	32.6	0.92	616.4	360	8.5	130	160	62	31	0.0095	0.0032	0.0012	205	1.55	7.7	6.55	-1.2
KRB-16	6.7	31	0.6	402	220	5	90	110	43	22	0.0068	0.0014	0.0006	290	2	7.3	7.1	-3
KRB-17	5.8	33.3	1.2	804	440	14	170	210	78	39	0.012	0.0045	0.0018	155	1.05	8.1	6.05	0.9
KRB-18	6.9	31.6	0.76	509.2	295	7	105	135	52	26	0.008	0.0019	0.00075	190	1.4	7.95	6.45	-2.2
KRB-19	6.3	32	0.9	603	350	8	125	155	60	30	0.009	0.0028	0.0011	185	1.35	7.85	6.25	-1.6
KRB-20	6.5	30.7	0.56	375.2	205	5.2	82	102	41	20.5	0.0063	0.0013	0.0005	295	2.05	7.25	7.15	-3

Table 3-5 includes measurements of:

- **Physical Parameters:** Temperature, pH, EC, and total dissolved solids.
- **Major Ions:** Calcium, magnesium, sodium, chloride, sulfate, bicarbonate, and carbonate.
- **Nutrients:** Nitrate.
- **Trace Elements and Heavy Metals:** Arsenic, lead, and mercury.

Additionally, stable isotope ratios of oxygen and hydrogen ($\delta^{18}O$ and $\delta^{2}H$) were measured to provide insights into groundwater recharge sources and processes

➢ Range of Values and Exceedances of Water Quality Standards

Analysis of the physicochemical data revealed a wide range of values for several parameters, indicating spatial variability in groundwater quality across Kribi Town. Most notably, chloride concentrations exhibited significant variations, with some samples exceeding the WHO guideline value for drinking water. Figure 42 visually depicts the spatial distribution of chloride concentrations, highlighting areas where saltwater intrusion is a major concern. Similarly, elevated levels of arsenic, lead, and mercury were detected in specific areas, exceeding WHO guideline values and posing potential health risks.

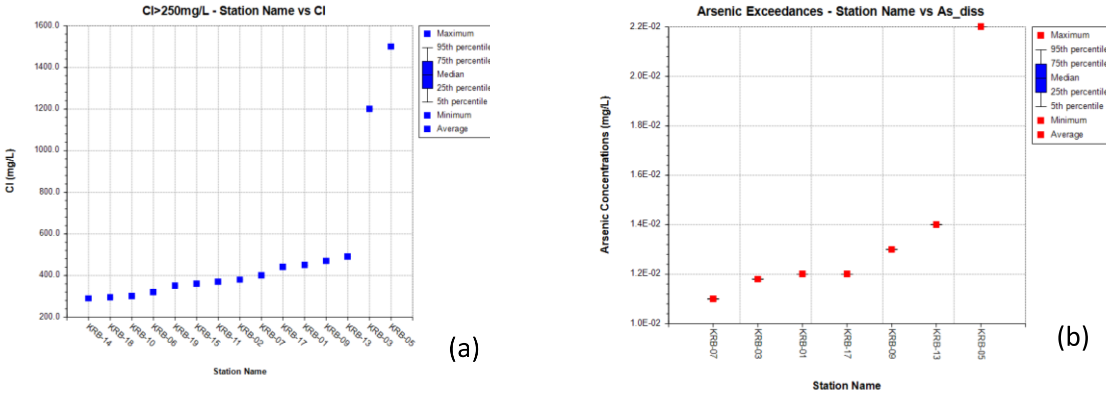


Figure 42: plots of exceedances for (a) chloride and (b) arsenic.

Table 3-6 summarizes the general water quality parameters and their comparison to WHO standards, while Table 3-7 focuses specifically on trace elements and their implications for irrigation suitability.

Table 3-6: General water Quality parameters for the study area compared to WHO standards and their suitability for irrigation.

Parameter	Unit	Sample Data	WHO Drinking Water Guideline	General Irrigation Suitability Considerations
Cond	µS/cm	0.55 - 3.5	No guideline, but related to salinity	< 3000 µS/cm generally suitable for most crops
TDS	mg/L	368.3 - 2345	500 (desirable), up to 1000 (acceptable)	< 2000 mg/L generally suitable; crop-specific tolerances vary
Cl	mg/L	200 - 1500	250 (desirable), up to 600 (acceptable)	Chloride sensitive crops may be affected at > 250 mg/L
NO3	mg/L	5 - 30	50 (as nitrate)	Essential nutrient, but excessive levels can lead to contamination
SO4	mg/L	80 - 350	250 (desirable), up to 500 (acceptable)	Can impact soil pH; some crops are sensitive
Na	mg/L	100 - 550	200 (desirable), up to 400 (acceptable)	High sodium can affect soil structure, reduce infiltration
Ca	mg/L	40 - 150	No health-based guideline	Essential plant nutrient; high levels can affect soil structure
Mg	mg/L	20 - 75	No health-based guideline	Essential plant nutrient
HCO3	mg/L	75 - 300	No health-based guideline	Important for soil buffering capacity
CO3	mg/L	0.5 - 2.0	No health-based guideline	Can raise soil pH
SiO2	mg/L	7 - 9	No health-based guideline	Generally not a limiting factor for plants
O	mg/L	5 - 7.15	Important for aquatic life	Essential for healthy root systems

- **Potential Contamination Sources**

The observed exceedances of water quality standards for chloride, arsenic, lead, and mercury suggest the presence of multiple contamination sources impacting Kribi Town's groundwater.

- **Saltwater Intrusion:** The elevated chloride concentrations, particularly in areas near the coastline, strongly indicate the influence of saltwater intrusion. This is a common concern in coastal aquifers, where over-extraction of groundwater can lower the freshwater head, allowing seawater to encroach inland.
- **Industrial Activities:** The presence of heavy metals like arsenic, lead, and mercury suggests potential contamination from industrial activities. Past or present industrial operations in or near Kribi could be releasing these contaminants into the environment, either through direct discharges or improper waste disposal practices.
- **Agricultural Runoff and Sewage:** Elevated nitrate levels in some samples point towards potential contamination from agricultural runoff or sewage. The use of fertilizers and the discharge of untreated wastewater can introduce high levels of nitrates into groundwater, posing health risks, especially for infants.

Table 3-7: Tace elements for WHO standards and irrigation suitability.

Parameter	**Unit**	**Sample Data (after dividing by 1000 where needed)**	**WHO Drinking Water Guideline**	**General Irrigation Suitability Considerations**
As	mg/L	0.006 - 0.022	0.01 (10 µg/L)	Highly toxic to plants; strict regulations for irrigation use
Pb	mg/L	0.001 - 0.015	0.01 (10 µg/L)	Can accumulate in soil; food safety concerns
Hg	mg/L	0.0005 - 0.004	0.001 (1 µg/L)	Highly toxic; bioaccumulation in the food chain is a concern

3.2.1.2 Spatial Distribution of Key Parameters:

Visualizing the spatial patterns of key water quality parameters provides crucial insights into the extent and severity of groundwater contamination in Kribi Town. This section presents maps and visualizations that illustrate the distribution of chloride, nitrate, arsenic, lead, and mercury, highlighting the areas most impacted by these contaminants and their potential sources.

➢ Chloride (Cl^-)

Chloride concentrations in the Kribi Town groundwater samples range from 205,000 µg/L (KRB-20) to a concerning 1,500,000 µg/L (KRB-05). Figure 43 depicts the spatial distribution of chloride concentrations in Kribi Town's groundwater. The map reveals a clear pattern of elevated chloride levels around the southern highly- inhabited part of the town, extending inland to varying degrees. This pattern strongly suggests the influence of saltwater intrusion, a common concern in coastal aquifers where the balance between freshwater and saltwater is disrupted. Several samples, specifically KRB-03, KRB-05, and KRB-01, exhibit chloride levels exceeding 440,000 µg/L, significantly surpassing the WHO guideline value of 250,000 µg/L. The highest chloride concentrations are observed in the southern region, indicating a more pronounced intrusion of seawater into the aquifer system in this area.

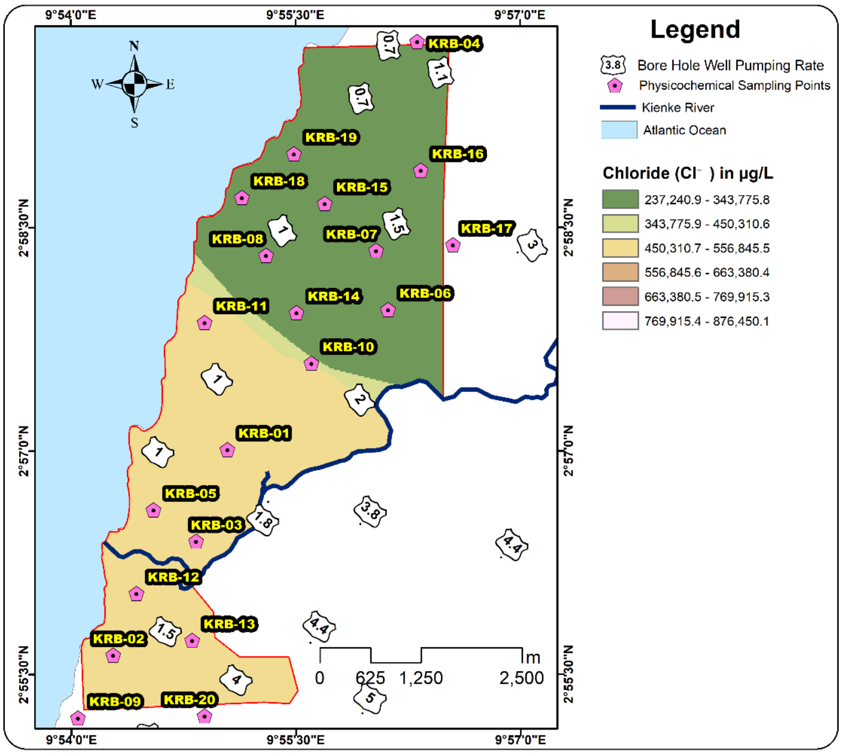


Figure 43: Chloride areal distribution map

➢ Nitrate (NO_3^-)

Nitrate concentrations in the Kribi Town groundwater samples range from 5,000 µg/L (KRB-16) to 30,000 µg/L (KRB-05). Figure 44 displays the spatial distribution of nitrate concentrations in the groundwater. While all samples exhibit nitrate levels below the WHO guideline value of 50,000 µg/L for drinking water, the map reveals localized hotspots of elevated nitrate concentrations, particularly in areas with higher population density and agricultural activity. Samples KRB-03 and KRB-05 exhibit notably higher nitrate levels compared to others, suggesting localized potential contamination from sources such as sewage, fertilizers, or animal waste.

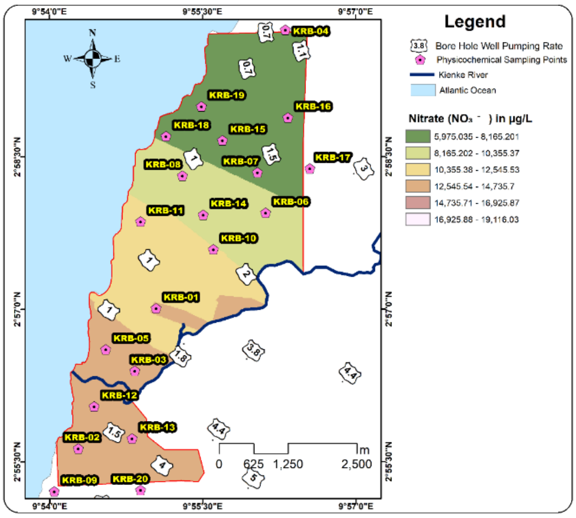


Figure 44: Nitrate areal distribution map

- **Arsenic (As)**

Arsenic concentrations in the Kribi Town groundwater samples are generally low, with most samples falling below the WHO guideline value of 10 µg/L. The spatial distribution of arsenic concentrations, as shown in Figure 45 reveals a more localized pattern of contamination compared to chloride or nitrate. Samples KRB-03 and KRB-05 exhibit concerning arsenic levels of 18 µg/L and 22 µg/L, respectively. This elevated arsenic presence suggests localized contamination, potentially from anthropogenic sources such as industrial activities or agricultural practices that utilize arsenic-containing compounds.

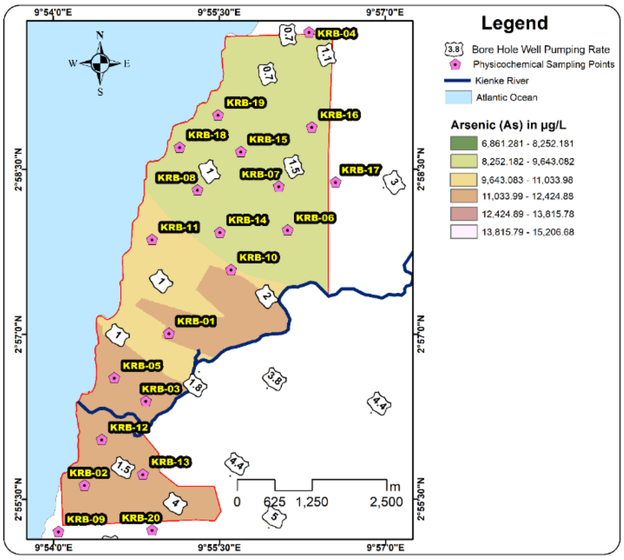


Figure 45: Arsenic areal distribution map

Lead (Pb)

Lead concentrations in the Kribi Town groundwater samples are generally low, with most samples falling below the WHO guideline value of 10 µg/L. Figure 46 illustrates the spatial distributions of lead concentrations in the groundwater. However, samples KRB-03 and KRB-05 exhibit concerning lead levels of 12 µg/L and 15 µg/L, respectively, exceeding the recommended limit. This elevated lead presence suggests localized contamination, potentially from anthropogenic sources such as industrial activities, past use of leaded gasoline, or improper waste disposal.

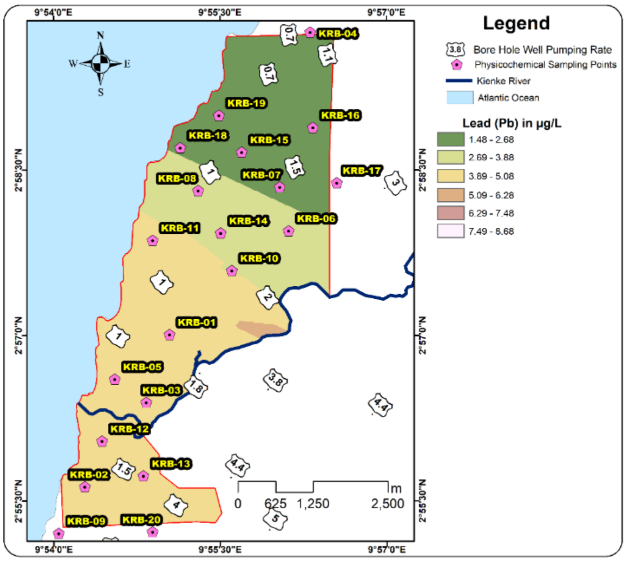


Figure 46: Lead areal distribution map

Mercury (Hg)

Mercury concentrations in the Kribi Town groundwater samples are generally low, with most samples falling below the WHO guideline value of 6 µg/L. Figure 47 illustrates the spatial distributions of mercury concentrations in the groundwater. However, sample KRB-05 exhibits a concerning mercury level of 15 µg/L, exceeding the recommended limit. This elevated mercury presence suggests localized contamination, potentially from industrial activities or improper disposal of electronic waste containing mercury.

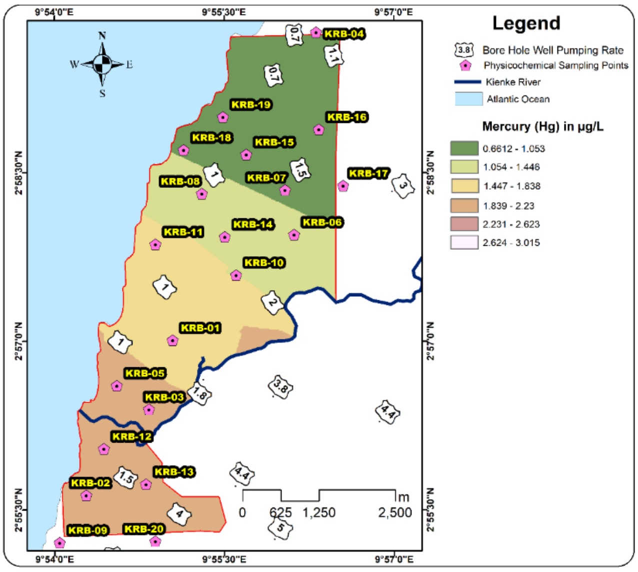


Figure 47: Mercury areal distribution map

3.2.2 Data Analysis and Interpretation

3.2.2.1 Comparison to Standards:

To evaluate the suitability of Kribi Town's groundwater for various uses, the measured physicochemical parameters were compared to the WHO Guidelines for Drinking-water Quality (WHO, 2011). This comparison revealed several exceedances of guideline values, raising concerns about the safety and usability of the groundwater for drinking and other purposes.

Table 3-6 and Table 3-7 provide a summary of the water quality parameters, their respective WHO guideline values, and general suitability considerations for irrigation. These tables highlight the parameters where exceedances were observed and their potential implications for different water uses.

➢ **Exceedances and Implications:**

- **Chloride (Cl^-):** As shown in Figure 48 a significant proportion of the sampled locations (75%) exhibit chloride concentrations exceeding the WHO guideline value of 250 mg/L. This widespread exceedance strongly suggests the influence of saltwater intrusion, particularly in the southern and central parts of Kribi Town. Elevated chloride levels can impact the taste of drinking water and pose risks to individuals on salt-restricted diets. In terms of irrigation, high chloride concentrations can lead to the build-up of salts in the soil, affecting plant growth and reducing crop yields, especially for salt-sensitive crops.

- **Arsenic (As):** Approximately 35% of the sampled sites show arsenic concentrations exceeding the WHO guideline value of 10 µg/L. This localized contamination, evident in Figure 48 poses potential health risks associated with long-term exposure to arsenic, including skin lesions, cardiovascular disease, and various types of cancer. Arsenic contamination also raises concerns about the suitability of groundwater for irrigation, as it can accumulate in plants and pose risks to human health through food consumption.
- **Lead (Pb):** Similar to arsenic, lead exceedances were observed in 10% of the sampling locations, as shown in Figure 48. These exceedances, primarily concentrated in the central and southern regions, indicate potential contamination from anthropogenic sources. Lead is a neurotoxin that poses significant health risks, particularly for children. Elevated lead levels in groundwater make it unsuitable for drinking and raise concerns about potential lead accumulation in crops if used for irrigation.
- **Mercury (Hg):** Although less prevalent than other contaminants, mercury exceedances were detected in 5% of the sampled sites, as illustrated in Figure 48. Mercury is a highly toxic heavy metal that can cause neurological damage and other health problems. Exceedances of the WHO guideline value of 1 µg/L indicate localized contamination, potentially from industrial activities or improper waste disposal, making the groundwater unsuitable for drinking and raising concerns about potential bioaccumulation in the food chain if used for irrigation.
- **TDS:** 10% of the sampled sites show exceedances of the WHO desirable limit for TDS (500 mg/L). While not as critical as heavy metal contamination, elevated TDS levels can affect the taste of drinking water and may indicate the presence of other dissolved minerals or salts. In irrigation, high TDS can affect soil structure and water uptake by plants.

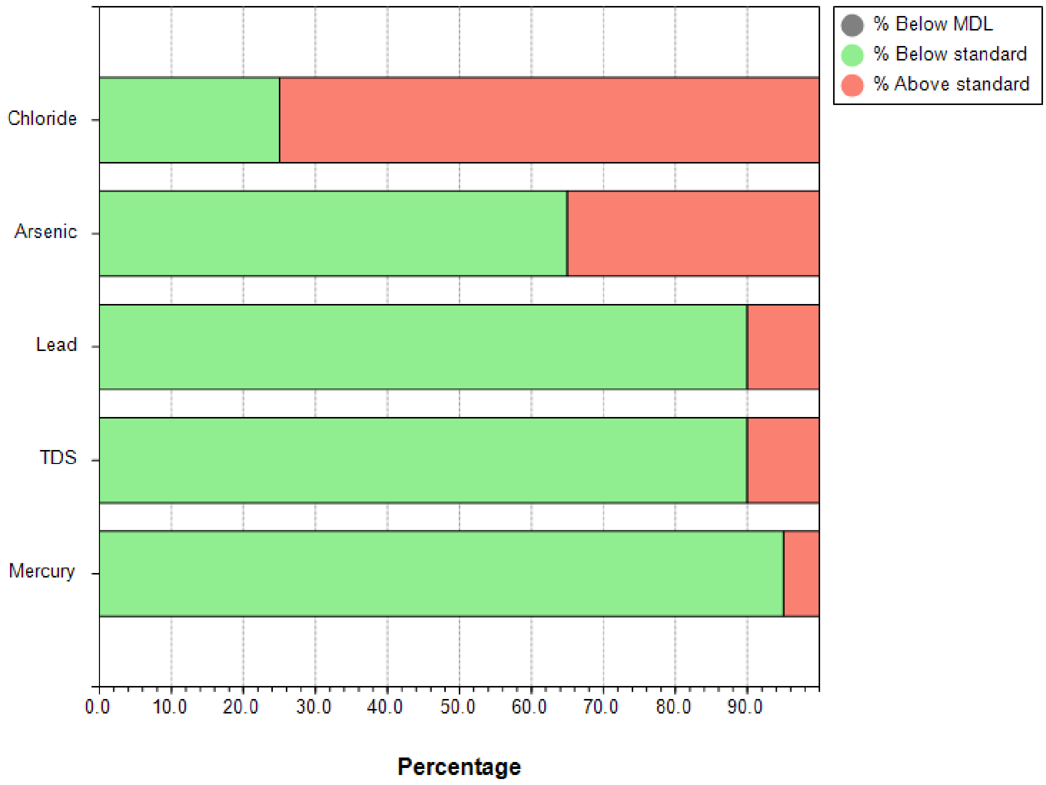


Figure 48:.detection summary for the five parameters with exceedances.

3.2.2.2 Suitability Classification:

The suitability of Kribi Town's groundwater for drinking and irrigation was assessed using the Wilcox diagram method, a widely recognized approach for evaluating water quality based on salinity and sodium hazards.

Figure 49 presents the Wilcox diagram for the analyzed groundwater samples, categorizing them into different zones based on their suitability for irrigation and drinking purposes. Table *3-8* summarizes the characteristics of each Wilcox zone and their corresponding suitability classifications.

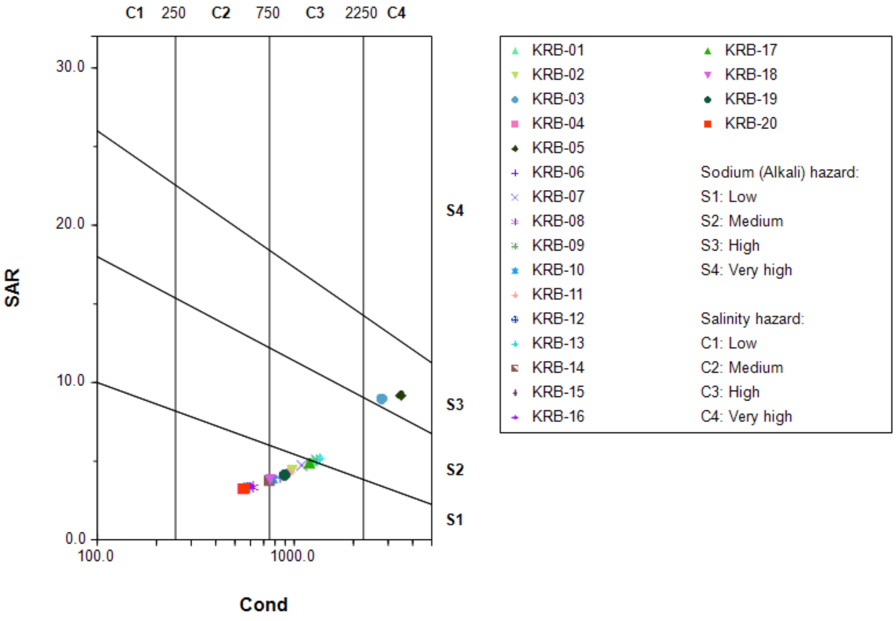


Figure 49: A Wilcox diagram for groundwater suitability classification within Kribi Town

Table 3-8: Wilcox results for drinking water and irrigation with Kribi Town.

Zone	**Salinity Hazard**	**Sodium Hazard**	**Suitability for Irrigation**	**Suitability for Drinking**
C2S1	Medium	Low	**Good**	**Possibly Suitable** (depending on specific ion concentrations)
C3S1	High	Low	**Doubtful** (may be suitable for salt-tolerant crops)	**Likely Unsuitable** (high salinity affects taste, health)
C3S2	High	Medium	**Unsuitable**	**Unsuitable**
C1S3	Low	High	**Doubtful** (may be usable with careful management)	**Unsuitable** (high sodium is a health concern)
C2S3	Medium	High	**Unsuitable**	**Unsuitable**
C3S3	High	High	**Unsuitable**	**Unsuitable**
C4S3	Very High	High	Unsuitable	Unsuitable

Analysis of the Wilcox diagram (Figure 49) reveals that:

- **75% of the sampling locations fall within the C3S1 zone, characterized by high salinity and low sodium hazards.** Groundwater in this zone is classified as "Doubtful" for irrigation, as it may be suitable for salt-tolerant crops but could pose risks to more sensitive plants. For drinking purposes, C3S1 groundwater is "Likely Unsuitable" due to its high salinity, which can affect taste and potentially pose health concerns.
- **5% of the sites belong to the C3S2 zone, indicating high salinity and medium sodium hazards.** This zone is classified as "Unsuitable" for both irrigation and drinking purposes.
- **10% of the sampling locations fall within the C2S1 zone, characterized by medium salinity and low sodium hazards.** This zone is considered "Good" for irrigation and "Possibly Suitable" for drinking, depending on specific ion concentrations.
- **10% of the sites fall within the C4S3 zone, representing very high salinity and high sodium hazards.** Groundwater in this zone is classified as "Unsuitable" for both irrigation and drinking purposes.

Figure 50, illustrating the variation of specific major ion concentrations, provides further insights into the suitability of groundwater within the C2S1 zone, which includes the potentially usable samples KRB-08 and KRB-20. This figure highlights that KRB-20 stands out as the most promising location for groundwater supply within Kribi Town, as it exhibits the lowest concentrations of major ions compared to other samples.

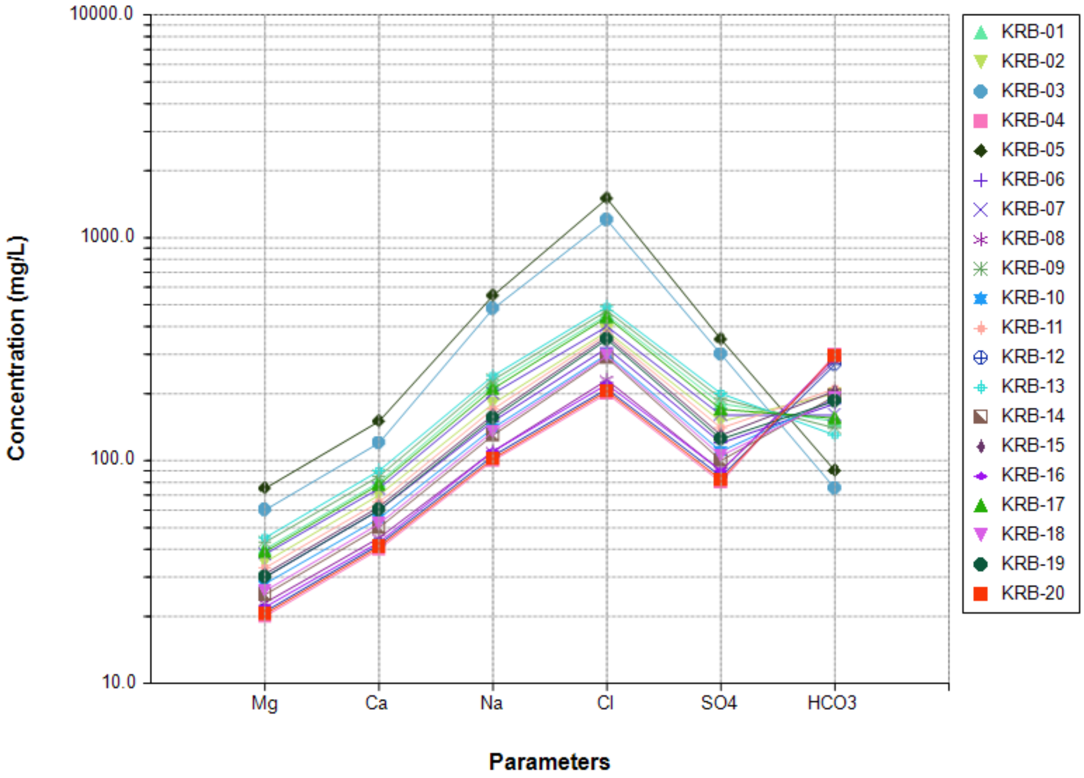


Figure 50: variation of specific major ion concentrations

3.2.2.3 Hydrogeochemical Facies and Water Types:

The Piper diagram (Figure 51) visually represents the major ion composition of the analyzed groundwater samples. The diagram clearly shows a clustering of data points towards the sodium (Na^+) and chloride (Cl^-) end-members, indicating a dominant sodium-chloride water type. This pattern strongly supports the hypothesis of seawater intrusion as a major influence on groundwater chemistry in Kribi Town. The intrusion of seawater, rich in sodium and chloride ions, alters the hydrogeochemical facies of the freshwater aquifer, resulting in a shift towards a NaCl-dominated water type.

The interpretation derived from the Piper diagram is further corroborated by the results obtained from AquaChem 10 software (Figure 52). The software, using a comprehensive database of water chemistry data and geochemical modeling algorithms, also classified the dominant water type for the Kribi Town groundwater samples as NaCl.

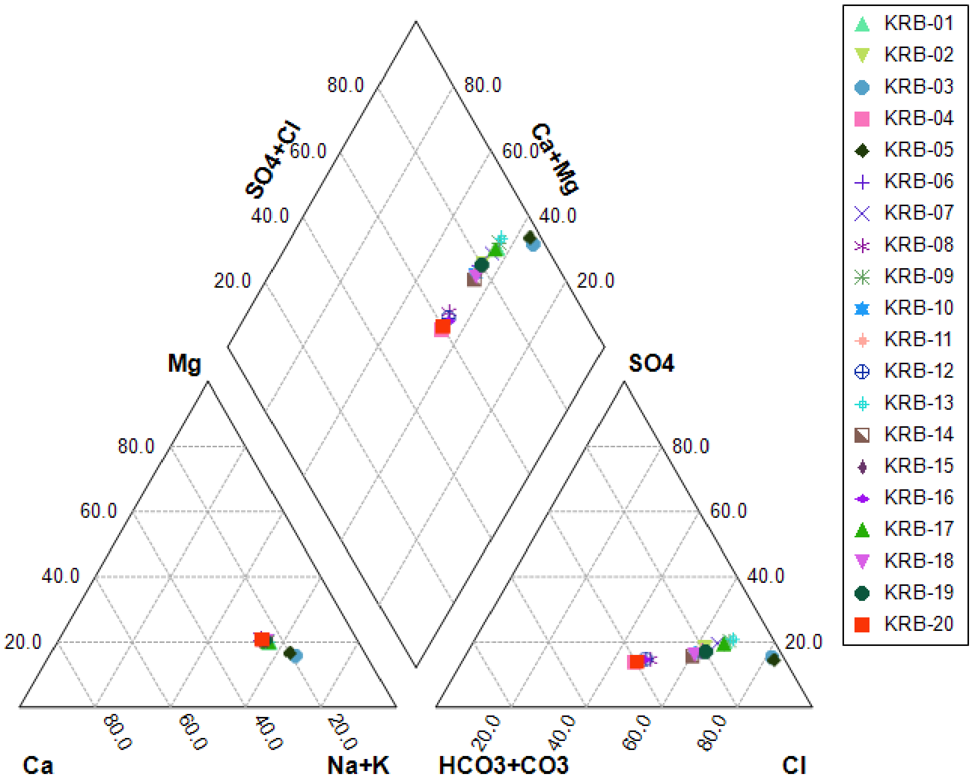
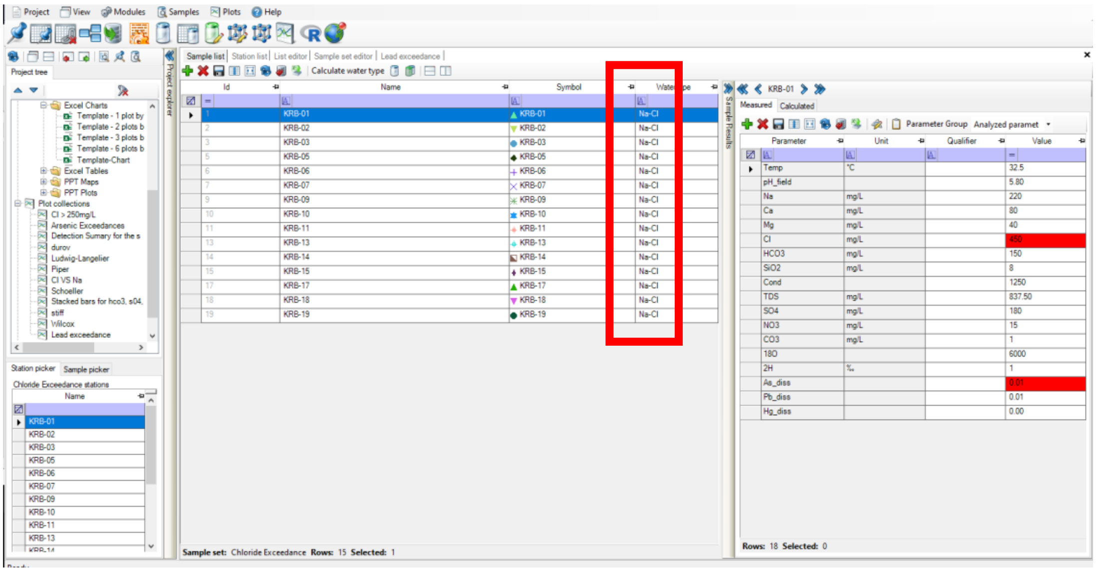


Figure 51: trends of major ions shown in Piper Plot.



Chloride Exceedance stations

Name
KRB-01
KRB-02
KRB-03
KRB-05
KRB-06
KRB-07
KRB-09
KRB-10
KRB-11
KRB-13

Id	Name	Symbol	Water type
1	KRB-01	▲ KRB-01	Na-Cl
2	KRB-02	▼ KRB-02	Na-Cl
3	KRB-03	● KRB-03	Na-Cl
5	KRB-05	◆ KRB-05	Na-Cl
6	KRB-06	+ KRB-06	Na-Cl
7	KRB-07	× KRB-07	Na-Cl
9	KRB-09	✳ KRB-09	Na-Cl
10	KRB-10	★ KRB-10	Na-Cl
11	KRB-11	+ KRB-11	Na-Cl
13	KRB-13	+ KRB-13	Na-Cl
14	KRB-14	◩ KRB-14	Na-Cl
15	KRB-15	♦ KRB-15	Na-Cl
17	KRB-17	▲ KRB-17	Na-Cl
18	KRB-18	▼ KRB-18	Na-Cl
19	KRB-19	● KRB-19	Na-Cl

Sample set: Chloride Exceedance Rows: 15 Selected: 1

Parameter	Unit	Qualifier	Value
Temp	°C		32.5
pH_field			5.80
Na	mg/L		220
Ca	mg/L		80
Mg	mg/L		40
Cl	mg/L		450
HCO3	mg/L		150
SiO2	mg/L		8
Cond			1250
TDS	mg/L		837.50
SO4	mg/L		180
NO3	mg/L		15
CO3	mg/L		1
18O			6000
2H	‰		1
As_diss			0.01
Pb_diss			0.01
Hg_diss			0.00

Rows: 18 Selected: 0

Figure 52: Water type calculated for the area using AquaChem 10 software.

3.2.3 Discussion:

The identified hydrogeochemical facies and water types provide a compelling narrative of the origins and processes shaping groundwater quality in Kribi Town. The dominance of the sodium-chloride (NaCl) water type, vividly illustrated by the clustering of data points on the

Piper diagram (Figure 3-39) and corroborated by numerical calculations in AquaChem 10 software (Figure 3-40), is a strong indicator of seawater intrusion. This intrusion, a common challenge in coastal aquifers, is likely driven by a combination of factors, including over-extraction of groundwater, the town's proximity to the coastline, and potentially even sea level rise associated with climate change.

The intrusion of seawater, with its high concentrations of sodium and chloride ions, disrupts the natural hydrogeochemical balance of the freshwater aquifer, shifting the dominant water type from a calcium-bicarbonate ($Ca-HCO_3$) facies, characteristic of fresh groundwater in many sedimentary environments (Appelo and Postma, 2004), to NaCl-dominated facies. This shift has significant implications for the suitability of groundwater for various uses. Elevated chloride levels impact the taste of drinking water, posing concerns for palatability and potential health risks for individuals on salt-restricted diets (WHO, 2011). In terms of irrigation, high salinity can lead to the accumulation of salts in the soil, affecting soil structure, reducing infiltration, and potentially harming salt-sensitive crops (Reddy et al., 2019).

The spatial distribution of chloride concentrations (Figure 3-31) further emphasizes the severity of saltwater intrusion in Kribi Town. The highest concentrations are observed near the coastline, particularly in the southern region, where the aquifer is likely more vulnerable due to a combination of shallower water table depths, higher permeability, and potentially even the presence of geological structures facilitating seawater encroachment. These findings align with other studies in coastal areas where saltwater intrusion has been identified as a major threat to groundwater resources (Barlow and Reichard, 2010; Werner et al., 2013).

However, the hydrogeochemical story of Kribi is not solely defined by saltwater intrusion. The localized contamination from arsenic and lead, exceeding WHO guideline values, points towards anthropogenic influences impacting groundwater quality. The presence of these heavy metals, primarily concentrated in the central and southern regions, suggests potential sources such as industrial activities, past use of leaded gasoline, or improper waste disposal practices. This localized contamination poses significant health risks to residents who rely on groundwater for drinking water, and also raises concerns about potential accumulation of these heavy metals in crops if the contaminated water is used for irrigation (WHO, 2014).

The hydrogeochemical assessment, therefore, reveals a complex interplay of natural and anthropogenic processes shaping groundwater quality in Kribi Town. Saltwater intrusion, driven by the town's coastal location and potentially exacerbated by groundwater over-extraction and sea level rise, alters the dominant water type and poses widespread challenges for drinking and irrigation. Additionally, localized contamination from heavy metals, likely originating from anthropogenic sources, necessitates targeted mitigation measures to protect public health and ensure the sustainable use of groundwater resources.

These findings highlight the need for a comprehensive and integrated approach to water resource management in Kribi Town. Protecting aquifer recharge areas from contamination, implementing strategies to mitigate saltwater intrusion, and controlling industrial and agricultural discharges are crucial steps towards ensuring the long-term viability of groundwater resources. Furthermore, exploring alternative water sources, such as surface water from the Kienke River or developing rainwater harvesting systems (Mohammed et al., 2022), could provide much-needed relief and diversify the town's water supply portfolio.

This hydrogeochemical investigation serves as a powerful example of how a detailed understanding of water chemistry can unravel the intricate stories embedded within our water resources. It highlights the interconnectedness of natural and anthropogenic processes and emphasizes the need for responsible stewardship to safeguard this vital lifeline for Kribi Town and communities worldwide.

3.3 Surface Water Assessment: Evaluating the Kienke River as a Potential Water Source

3.3.1 Data Analysis

3.3.1.1 Streamflow Analysis:

Analysis of the Kienke River's streamflow data, obtained from the Global Runoff Data Centre (GRDC) spanning the period from 1955 to 1977, provides valuable insights into the river's flow regime and its potential as a water source for Kribi Town.

- **Flow Regime and Variability:**

The Kienke River exhibits a dynamic flow regime, characterized by substantial seasonal and annual variability. The mean annual discharge stands at 49.346 m³/s, with a standard deviation of 38.027 m³/s (Table 3-9). This considerable variation highlights the need for careful planning and management to ensure reliable water availability throughout the year.

Table 3-9: Summary statistics for the streamflow data

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
flow in m^3 / s	262	51	262	6.000	625.000	49.346	38.027

- **Seasonal Fluctuations:**

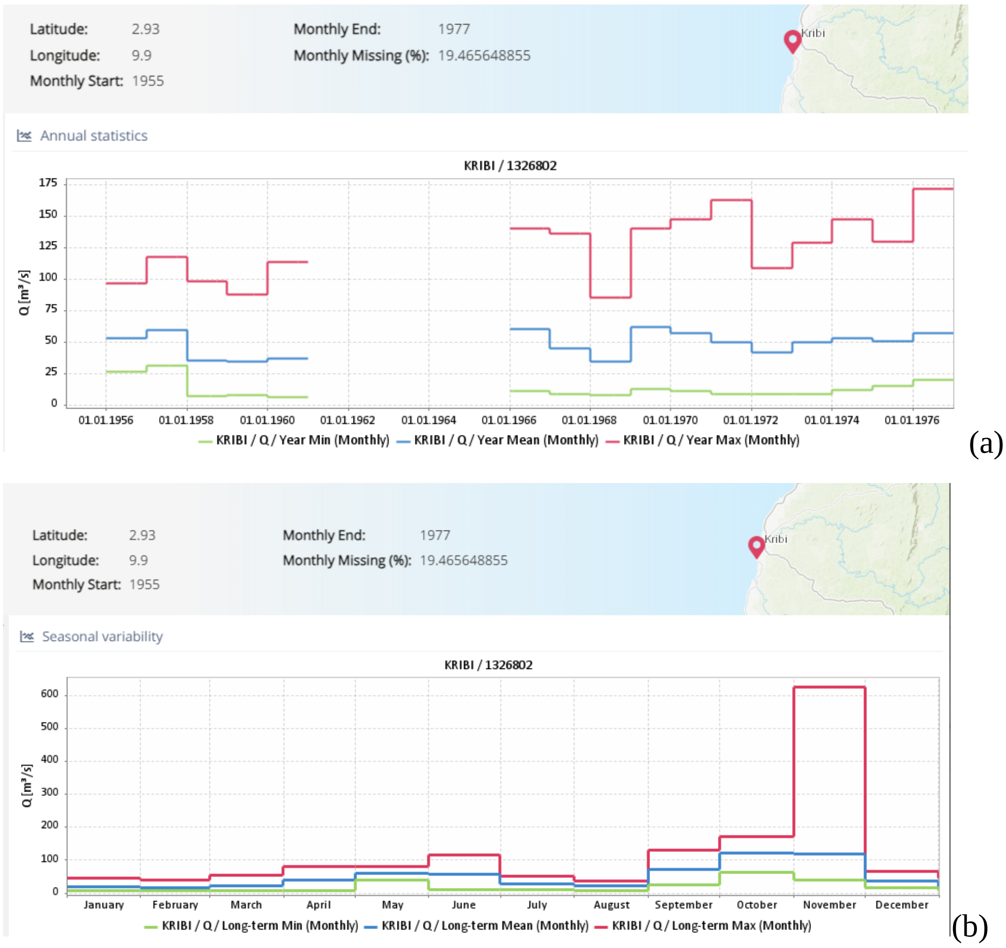
Figure 53 reveals pronounced seasonal fluctuations in both the mean and maximum monthly discharge values. The highest flows typically occur during the wet seasons, peaking in July and August, coinciding with the region's primary rainfall period. Conversely, the lowest flows are observed during the dry season, with minimum values typically recorded in February. These distinct seasonal patterns emphasize the need for storage infrastructure, such as reservoirs, to capture excess water during the wet season for use during drier periods.

- **Long-term Trends:**

A Seasonal Mann-Kendall trend test (Table 3-10) indicated a statistically insignificant negative trend in streamflow over the study period. However, visual inspection of the trend shape (Figure 54) suggests a potential declining tendency in discharge, warranting further investigation with longer-term data to assess the possible influence of climate change or land use modifications on the Kienke River's flow regime.

Table 3-10: Two-tailed test for Seasonal Mann-Kendall Test for stream data

Kendall's tau	-0.019
S'	-30
Var(S')	7987.000
p-value (Two-tailed)	0.746
Alpha	0.05



Latitude: 2.93
Longitude: 9.9
Monthly Start: 1955
Monthly End: 1977
Monthly Missing (%): 19.465648855

Latitude: 2.93
Longitude: 9.9
Monthly Start: 1955
Monthly End: 1977
Monthly Missing (%): 19.465648855

Figure 53: seasonal and annual variability for discharge values for Kienke.

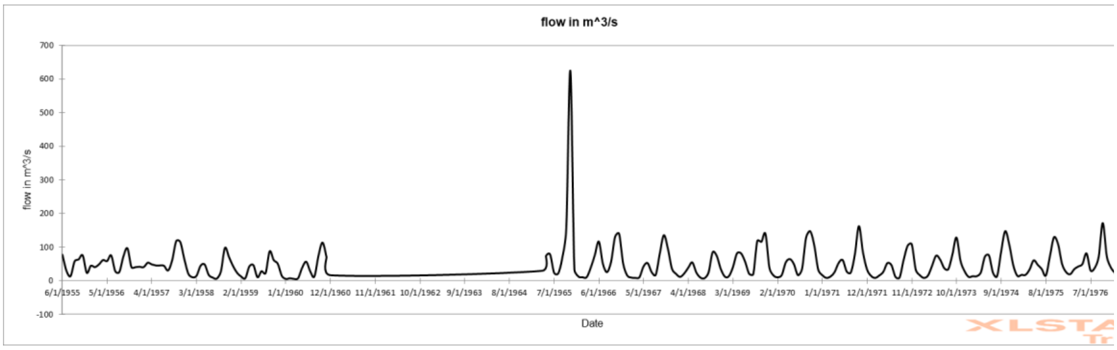


Figure 54: Trend shape after Mann-Kendall Test for streamflow data

➢ Flow Duration Curve:

The flow duration curve for the Kienke River (Figure 55) provides a comprehensive picture of the river's flow regime, depicting the percentage of time that specific flow rates are equaled or exceeded. The curve's steep slope indicates a high degree of variability in flow, with a rapid transition from high flows during the wet season to lower flows during the dry season.

The average discharge of 51.4 m³/s is surpassed approximately 50% of the time, highlighting the river's potential for providing substantial water resources. However, the curve also reveals periods of low flow, occurring approximately 25% of the time, underscoring the need for storage or supplemental sources to ensure year-round water availability.

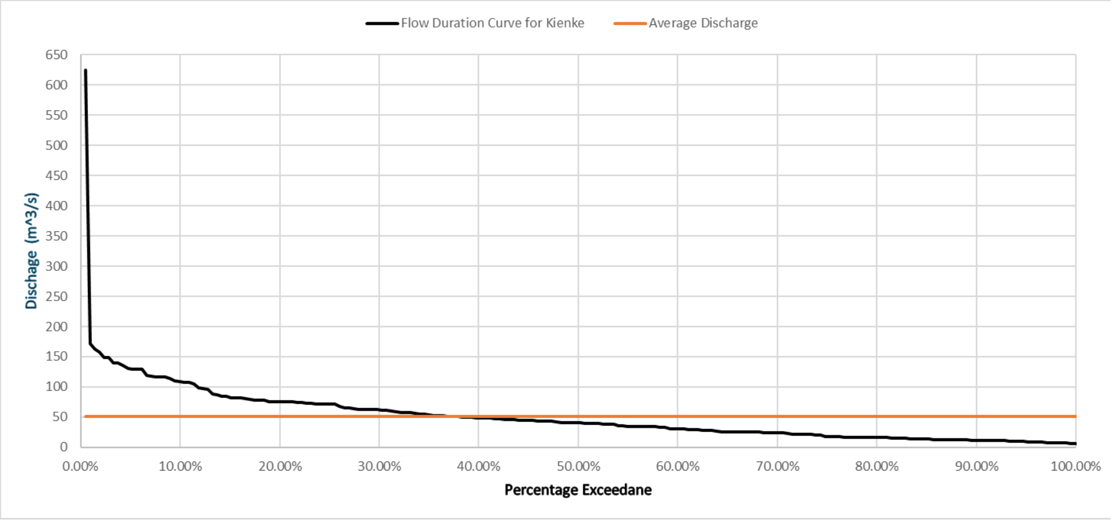


Figure 55: Flow Duration Curve for Kienke River

3.3.1.2 Rainfall Analysis:

Understanding the rainfall patterns within the Kienke River basin is crucial for comprehending the river's flow dynamics and assessing its potential as a water source. The analysis of monthly-averaged rainfall data, sourced from the NOAA's Global Historical Climatology Network Daily dataset, spanning the period of streamflow records (1955-1977), reveals key insights into precipitation characteristics.

- **Rainfall Characteristics:**

The Kienke River basin experiences a tropical monsoon climate, characterized by distinct wet and dry seasons. The mean annual rainfall for the basin stands at 10.901 m, with a standard deviation of 9.539 m (Table 3-11). This indicates considerable inter-annual variability in rainfall, suggesting the potential for both periods of abundant water availability and drought conditions.

Table 3-11: Summary statistics for the rainfall data

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum		Maximum	Mean	Std. deviation
Rainfall	67	0	67	0.240		42.890	10.901	9.539

- **Trends in Rainfall:**

A Seasonal Mann-Kendall trend test (Table 3-12) indicated a statistically insignificant positive trend in rainfall over the study period. However, visual inspection of the trend shape (Figure 56) suggests a potential increasing tendency in rainfall, possibly reflecting broader climate change patterns. Further investigation with longer-term data is necessary to confirm this trend and assess its implications for water availability in the Kienke basin.

Table 3-12: Two-tailed test for Seasonal Mann-Kendall Test for rainfall data

Kendall's tau	0.126
S'	15
Var(S')	238.000
p-value (Two-tailed)	0.364
Alpha	0.05

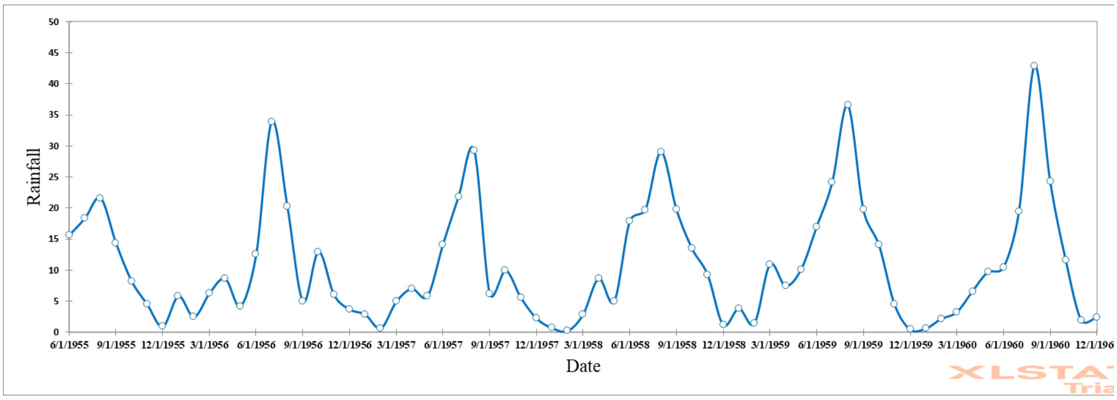


Figure 56: Trend shape after Mann-Kendall Test for rainfall data

- **Relationship to Streamflow:**

The close relationship between rainfall and streamflow in the Kienke River basin is evident in Figure 57. Peaks in discharge closely follow periods of high rainfall, demonstrating the direct influence of precipitation on the river's flow regime. The lag time between rainfall events and peak flows is likely due to the large size of the catchment, with water taking time to travel from the furthest points of the basin to the river's outlet.

- **Relationship to Rainfall:**

Figure 57 illustrates the clear relationship between rainfall and discharge in the Kienke River basin. Peaks in discharge closely follow periods of high rainfall, with a noticeable lag time due to the large size of the catchment. This relationship underscores the strong influence of rainfall patterns on the river's flow regime and highlights the importance of incorporating rainfall data in water resource planning and management.

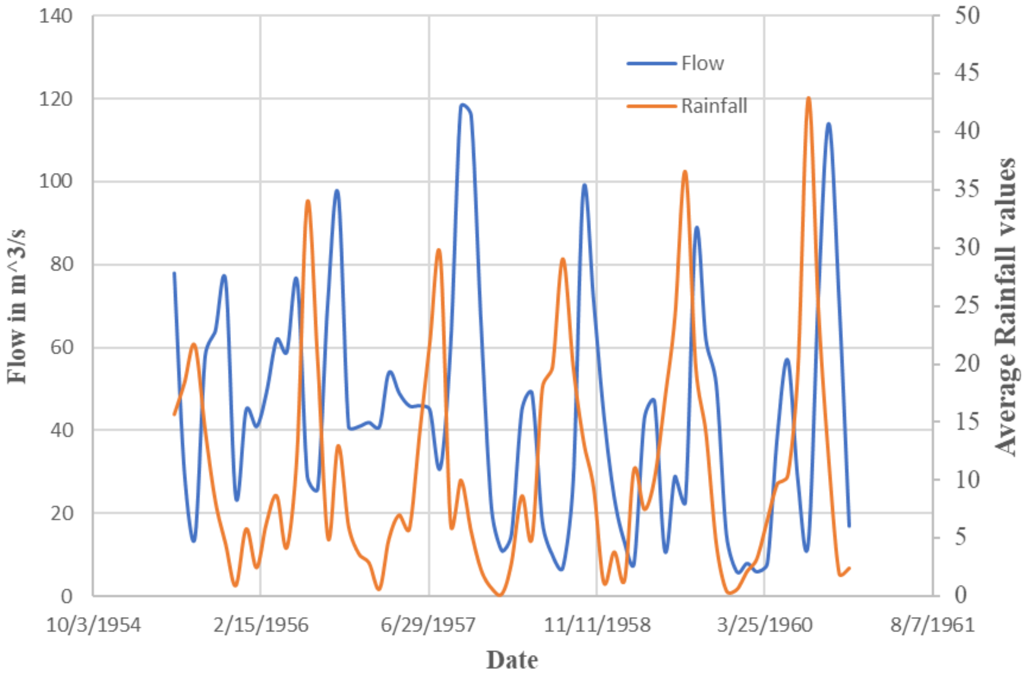


Figure 57: relationship between discharge and rainfall from June 1955 to December 1960.

3.3.1.3 Land Use Change Analysis:

Examining land use changes within the Kienke River watershed is crucial for understanding their potential impacts on the river's hydrology and water availability. Unfortunately, accessing detailed historical land use data for the period of streamflow record

(1955-1977) poses a significant challenge. This study utilizes the Global Land Cover dataset within the WMS software, representing land cover conditions as of 2022 (Figure 58), to assess current land use patterns and their potential hydrological implications. While this dataset doesn't directly reflect the historical conditions during the streamflow record, it offers valuable insights into the current state of the watershed and allows for inferences regarding potential changes over time.

Figure 58 illustrates the dominant land use patterns within the Kienke River watershed. The most striking feature is the extensive coverage of agricultural land, primarily dedicated to oil palm plantations, as exemplified by the SOCAPALM plantation in the southern part of the watershed. This agricultural expansion, likely occurring at the expense of forest cover over time, has significant implications for hydrological processes:

- **Reduced Infiltration:** The conversion of forests to agricultural land, particularly oil palm plantations, can reduce infiltration rates due to soil compaction and altered vegetation cover.
- **Increased Runoff:** Lower infiltration rates contribute to increased surface runoff, potentially leading to more rapid and intense peak flows in the Kienke River, particularly during the wet seasons.
- **Water Quality Concerns:** Agricultural activities, such as fertilizer and pesticide use, can introduce pollutants into the watershed, impacting both surface water and groundwater quality.

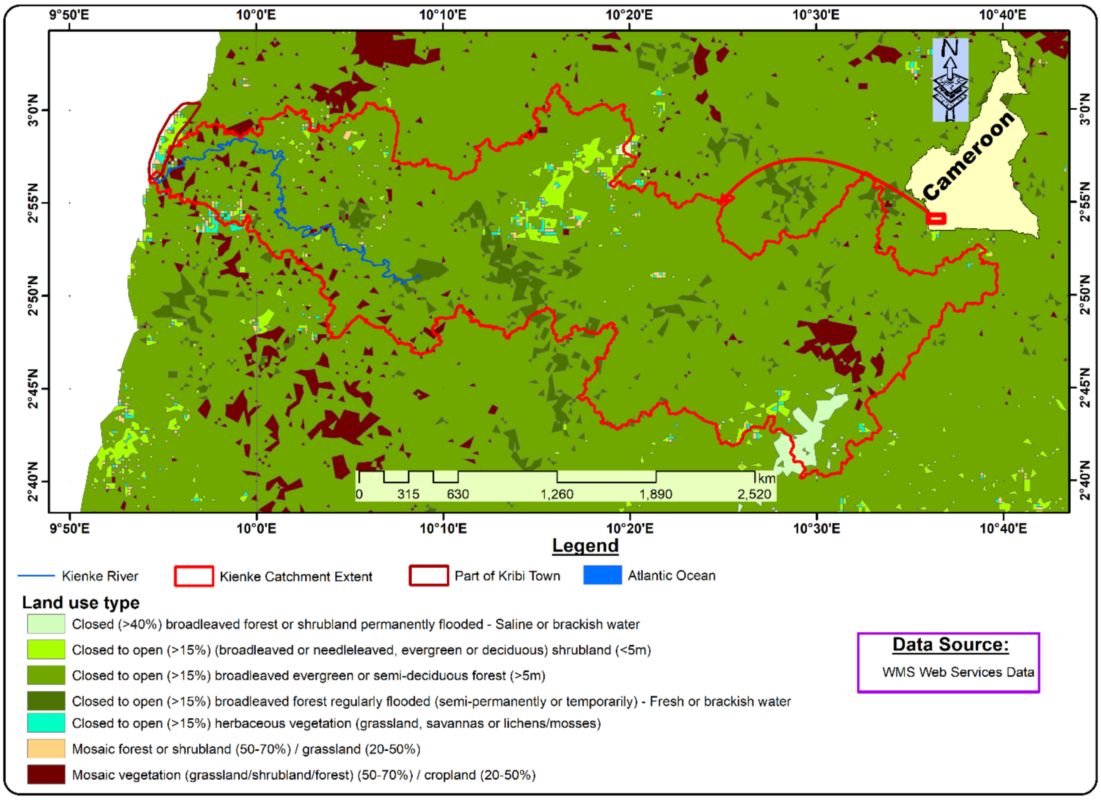


Figure 58: land use pattern within the Kienke watershed

3.3.1.4 Soil Characteristics and Runoff Potential:

Understanding the spatial distribution of soil types is crucial for assessing runoff potential within the watershed. Figure 59 displays the soil types within the study area, classified according to their Hydrologic Soil Group (HSG). The HSG classification reflects the soil's infiltration capacity and runoff potential, with Group A soils having the highest infiltration rates and Group D soils exhibiting the lowest (Table 3-13).

The Kienke watershed is dominated by Group C soils, indicating moderate infiltration rates and a susceptibility to generating runoff, particularly under intense rainfall events. This reinforces the concern regarding increased runoff due to agricultural expansion, as Group C soils are more vulnerable to compaction and degradation under intensive land use practices.

Table 3-13: HSG characteristics with respect to soil texture, after Cronshey (1986)

HSG	Soil textures
A	Sandy, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

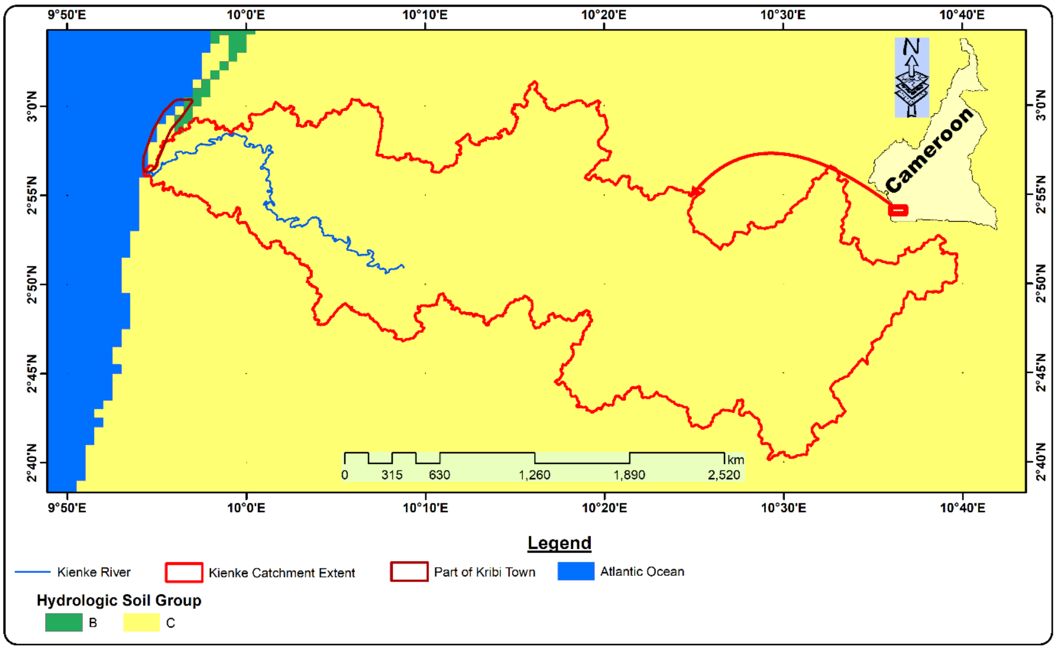


Figure 59: Soil-type shapefile

3.3.2 Precipitation-Runoff Modeling using HEC-HMS

3.3.2.1 Model Setup and Parameterization

3.3.2.1.1 Watershed delineation

Prior to simulating rainfall-runoff processes in HEC-HMS, the WMS software was employed to process the DEM and delineate the Kienke River watershed. WMS utilizes the TOPAZ program to compute flow directions and flow accumulations, providing essential information for watershed characterization (Figure 60). These computations identify flow paths based on terrain topography and highlight areas contributing to stream formation within the basin. The resulting flow accumulation network, visualized in Figure 60, was used to delineate the watershed boundary and sub-basins, and to calculate key hydrologic and geometric parameters required for HEC-HMS model setup.

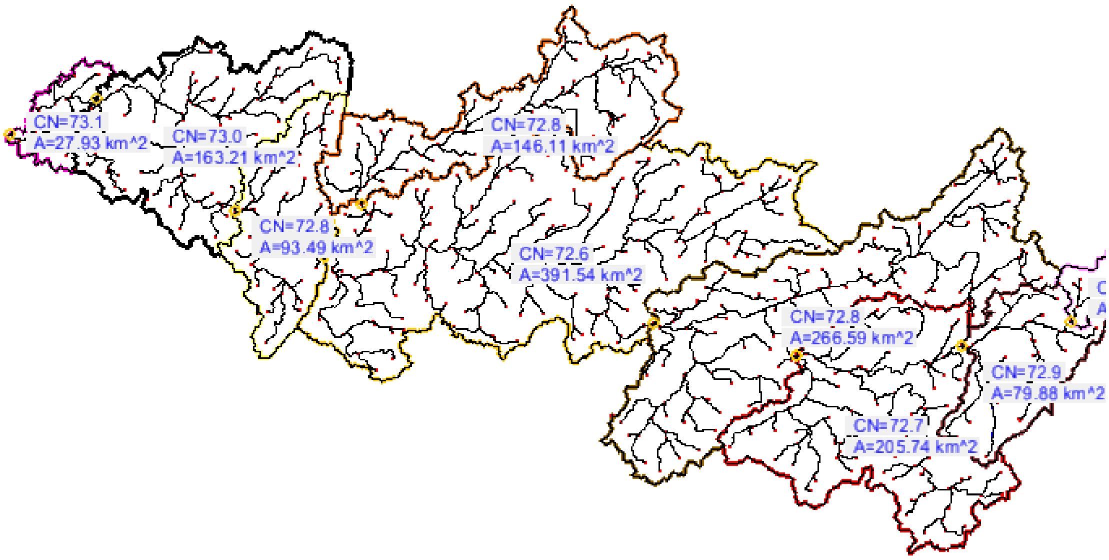


Figure 60: Kienke watershed delineated within WMS, showing values for geometric and hydrologic properties.

3.3.2.1.2 CN Determination:

A crucial step in parameterizing the HEC-HMS model involved determining the CNs for each sub-basin, which directly influence the estimation of infiltration losses and runoff generation. WMS facilitated this process by creating model coverages for soil type and land use, clipped to the delineated watershed boundary. Utilizing the land use data and the established relationship between land use, HSG, and CN values (Table 3-14), WMS calculated the composite CN for each sub-basin by taking an area-weighted average. This approach accounted for the spatial variability of soil and land use within the watershed, providing more accurate representations of runoff potential. Given the dominance of Group C soils in the study area, the initial CN values ranged from 70 to 86, reflecting moderate infiltration rates and susceptibility to runoff, particularly under intense rainfall (Cronshey, 1986).

3.3.2.1.3 Time of Concentration and Lag Time:

WMS was further employed to estimate the Time of Concentration (Tc) and lag time for each sub-basin, key parameters influencing the timing and shape of the runoff hydrograph. Tc represents the time it takes for runoff from the most hydraulically remote point in the sub-basin to reach the outlet, while lag time is the time between the peak rainfall intensity and the peak runoff discharge. The SCS method was employed to calculate both Tc and lag time, taking into account sub-basin characteristics such as area, slope, and CN values.

3.3.2.1.4 Reach Definition and Routing:

To simulate the movement of runoff through the Kienke River network, reaches were defined in HEC-HMS based on the delineated stream network from WMS. The Muskingum routing method was chosen to simulate flow through the reaches. This method requires two parameters: the Muskingum K (travel time through the reach) and X (a weighting factor between inflow and outflow). For this study, the X parameter was set to 0.5, giving equal weight to both inflow and outflow and assuming no reach storage. The K parameter was initially estimated at 5 hours based on channel geometry and flow characteristics.

Table 3-14: Table relating land use IDs to CNs for each HSG.

ID	**Land Use Description**	**Soil Group**			
		A	**B**	**C**	**D**
30	"Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)"	36	60	73	79
40	"Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)"	36	60	73	79
110	"Mosaic forest or shrubland (50-70%) / grassland (20-50%)"	35	56	70	77
130	"Closed to open (>15%) (broadleaved or needleleaved evergreen or deciduous) shrubland (<5m)"	35	56	70	77
140	"Closed to open (>15%) herbaceous vegetation (grassland savannas or lichens/mosses)"	68	79	86	89
160	"Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water"	30	55	70	77
170	"Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water"	30	55	70	77

3.3.2.2 HEC-HMS Model Calibration:

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) software was employed to simulate the rainfall-runoff processes in the Kienke River watershed, providing a quantitative basis for evaluating the river's potential as a water source. To ensure the model accurately reflects the hydrological dynamics of the basin, a calibration process was undertaken.

- **Data Utilized:**

- **Rainfall Data:** Monthly-averaged rainfall data obtained from NOAA's Global Historical Climatology Network Daily dataset (Table 2-2) served as the primary input for the meteorological model within HEC-HMS.
- **Observed Streamflow Data:** Monthly discharge data for the Kienke River, sourced from the GRDC for the period 1955-1977, provided the observed streamflow values for model calibration.

- **Calibration Procedure:**

The calibration process aimed to minimize the discrepancy between simulated and observed streamflow by adjusting key model parameters within acceptable ranges. This involved a systematic approach:

1. **Initial Parameterization:** The HEC-HMS model was initially parameterized using values derived from the WMS software, including the area-weighted composite CNs for each sub-basin (Table 3-15), the calculated lag times (Table 3-16), and an estimated Muskingum K parameter of 5 hours based on channel characteristics.

Table 3-15: Weighted-CN values calculated from WMS for the area of interest.

Sub-basin	Weighted CN
1B	72.9747
2B	72.7607
3B	72.6271
4B	72.7697
5B	72.7958

Sub-basin	Weighted CN
6B	72.6958
7B	72.8577
8B	73.0730
9B	73.0503

Table 3-16: Lag time for the various Sub-Basins, calculated in WMS

Sub-basin	Initial Lag time (mins)
1B	319.29
2B	205.326
3B	388.554
4B	293.34
5B	305.352
6B	198.432
7B	108.132
8B	97.866
9B	166.464

2. **Performance Evaluation:** Model performance was evaluated using the Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) metrics. The initial model run yielded a negative NSE coefficient (-2.325), indicating a poor fit between simulated and observed streamflow.
3. **Parameter Optimization:** The optimization module within HEC-HMS was employed to refine the CN values, as these have a strong influence on runoff generation. The optimization process focused on minimizing the root mean square error (RMSE) between simulated and observed discharge values.
4. **Optimized Parameter Values:** The optimization process resulted in significantly lower CN values compared to the initial WMS-derived values (Table 3-17). This adjustment reflects the likely difference in land use patterns between the historical period (mid-1900s) and the current land cover data used for initial parameterization (2022).

Table 3-17: Optimized CN values used to calibrate the hydrologic model.

Element	Parameter	Initial CN Value (Calculated)	Optimized CN Value	Objective Function Sensitivity
1B	SCS CN Value	72.9747	38.618	0.13
2B	SCS CN Value	72.7607	39.291	0.08
3B	SCS CN Value	72.6271	46.501	0.35
4B	SCS CN Value	72.7697	38.51	0.12
5B	SCS CN Value	72.7958	46.609	0.24
6B	SCS CN Value	72.6958	46.545	0.19
7B	SCS CN Value	72.8577	39.343	0.07
8B	SCS CN Value	73.073	39.459	0.03
9B	SCS CN Value	73.0503	39.447	0.02

5. **Calibrated Model Performance:** The calibrated HEC-HMS model achieved a significantly improved NSE coefficient of 0.507, indicating a more accurate representation of the Kienke River's hydrological response. The convergence of the objective function after 30 iterations (Figure 61) further supports the model's improved performance.

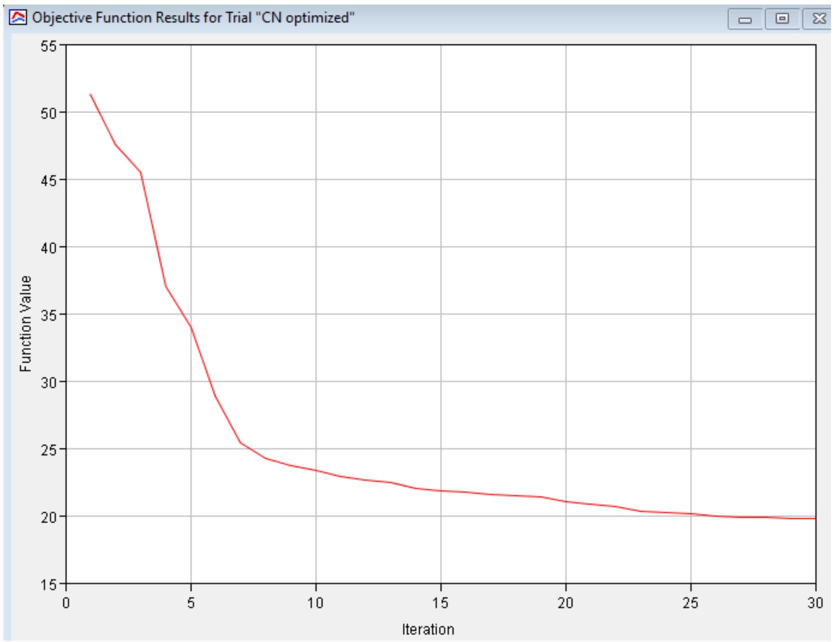


Figure 61: graph of the objective function, showing convergence after the 30th iteration

- **Visualization of Calibrated Results:**

Figure 62 displays the calibrated HEC-HMS model results, showcasing the close agreement between the simulated and observed monthly-average discharge values at the mouth of the Kienke River. The calibrated model captures the overall flow patterns and seasonal variability, providing a reliable basis for further analysis and evaluation of the river's potential as a water source.

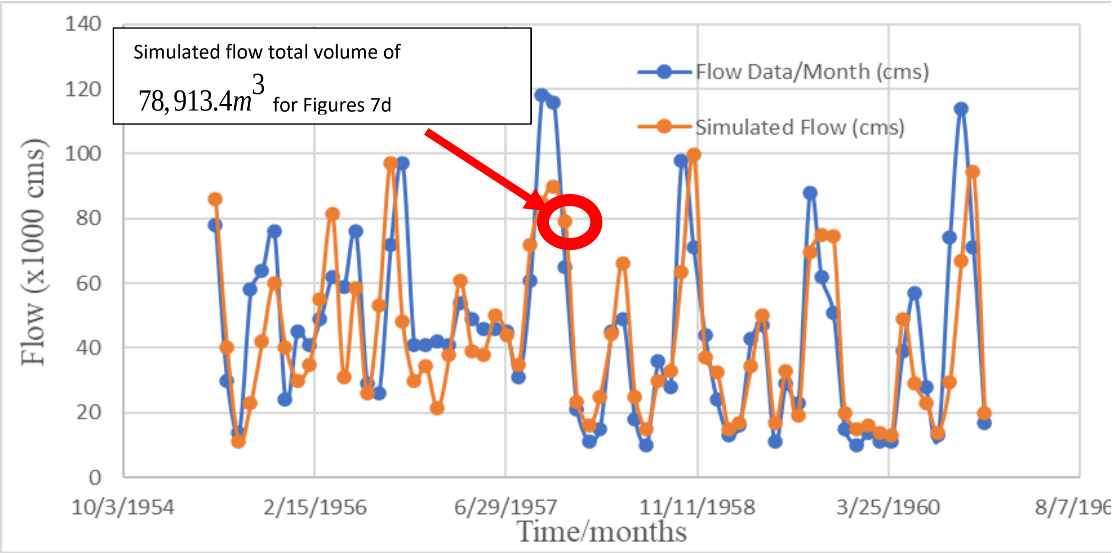


Figure 62: graphs of monthly-average observed and simulated discharge values at the mouth of the Kienke River.

3.3.2.3 HEC-HMS Model Validation:

Validating the calibrated HEC-HMS model is essential for establishing its reliability and ensuring that it can accurately predict the Kienke River's hydrological response under different conditions. However, the limited availability of observed streamflow data presented a significant challenge for traditional split-sample validation techniques.

The GRDC streamflow data, spanning 1955-1977, represents the only available long-term discharge record for the Kienke River. Splitting this dataset into calibration and validation periods would severely limit the data available for both processes, potentially compromising the accuracy and robustness of the calibrated model and reducing the statistical power of the validation assessment.

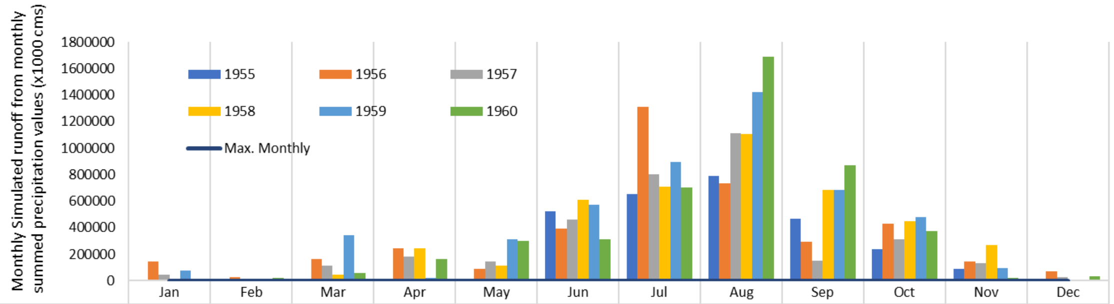
3.3.2.4 HEC-HMS Model Results and Interpretation:

The calibrated and validated HEC-HMS model provides valuable insights into the runoff dynamics and water availability of the Kienke River, enabling a quantitative assessment of the river's potential as a water source for Kribi Town. This section presents the key findings from the model simulations, focusing on runoff volumes, peak flows, and the river's response to various rainfall events.

➢ **Simulated Runoff Volumes:**

The HEC-HMS model was used to simulate the Kienke River's runoff response to both monthly-averaged and summed precipitation data, representing a range of hydrological conditions.

- **Monthly Runoff:** Using the summed monthly precipitation values as hypothetical storm events, the model generated a total simulated runoff volume of 450,204,000 m³ for the study period (Figure 63). This substantial volume highlights the river's capacity to generate significant runoff even during months with moderate rainfall.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1955						519986	653465	789995	466744	237724	90732	1590
1956	143607	27603	160990	242967	85609	394537	1309761	733906	294725	429435	144936	69012
1957	43003	350	111966	180851	143607	459805	800570	1113851	151839	308661	129122	26191
1958	227	50	43288	242454	113943	610983	710764	1102947	685477	450204	266484	4571
1959	72957	5907	345459	19858	312837	572754	896129	1420674	685477	476225	92527	123
1960	190	20475	54840	164546	296025	311401	699673	1689350	871545	376156	17428	30664
Max. Monthly	500	500	500	500	500	500	500	500	500	500	500	500

Figure 63: Runoff volume table with chart in m^3/month

- **Hypothetical Storm Event:** A specific hypothetical storm event, representing the average rainfall of October 1958 simulated over three days, resulted in a total discharge volume of 78,913.4 m³ (Figure 62). This event, with an average precipitation depth of 13.48 m, demonstrates the river's rapid response to rainfall and its potential for generating substantial runoff from individual storm events.

➢ **Peak Flows and Response Dynamics:**

The HEC-HMS model captured the river's peak flow dynamics, providing insights into the timing and magnitude of high-flow events.

- **Peak Discharge:** The hypothetical storm event representing October 1958 rainfall resulted in a peak discharge of 684.5 m³/s (Figure 64). This peak flow, occurring approximately 10 hours after the onset of rainfall, demonstrates the river's rapid response to precipitation events.

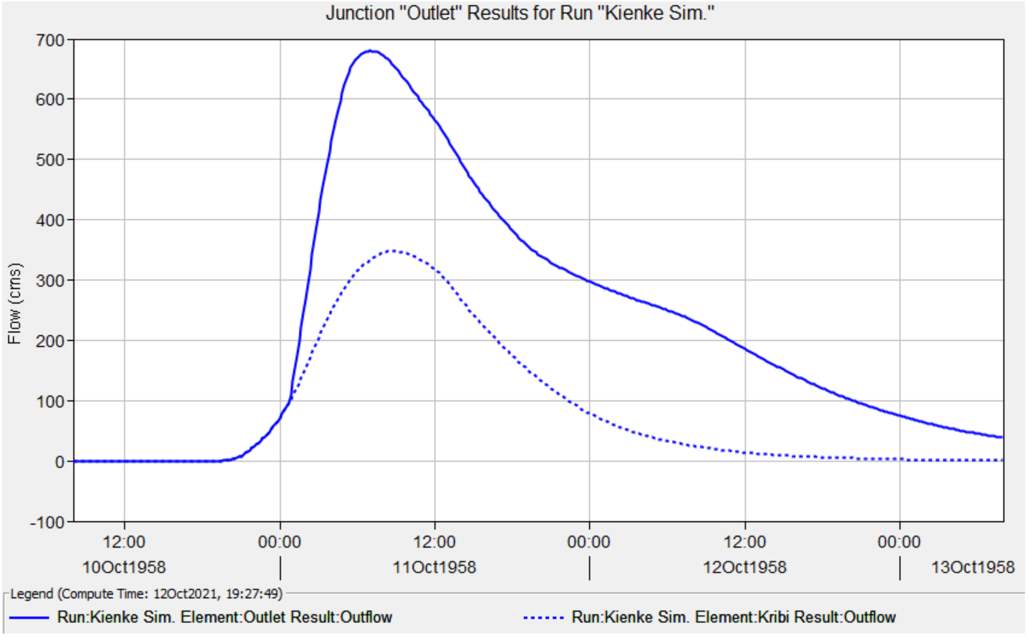


Figure 64: runoff hydrograph for the Kienke River

- **Sub-basin Contributions:** Analysing the runoff hydrographs for individual sub-basins (Figure 65, Figure 66, and Figure 67) reveals the spatial and temporal variations in runoff contributions. Sub-basins with larger areas, steeper slopes, and higher CN values tend to generate higher peak flows and contribute more to the overall runoff volume.

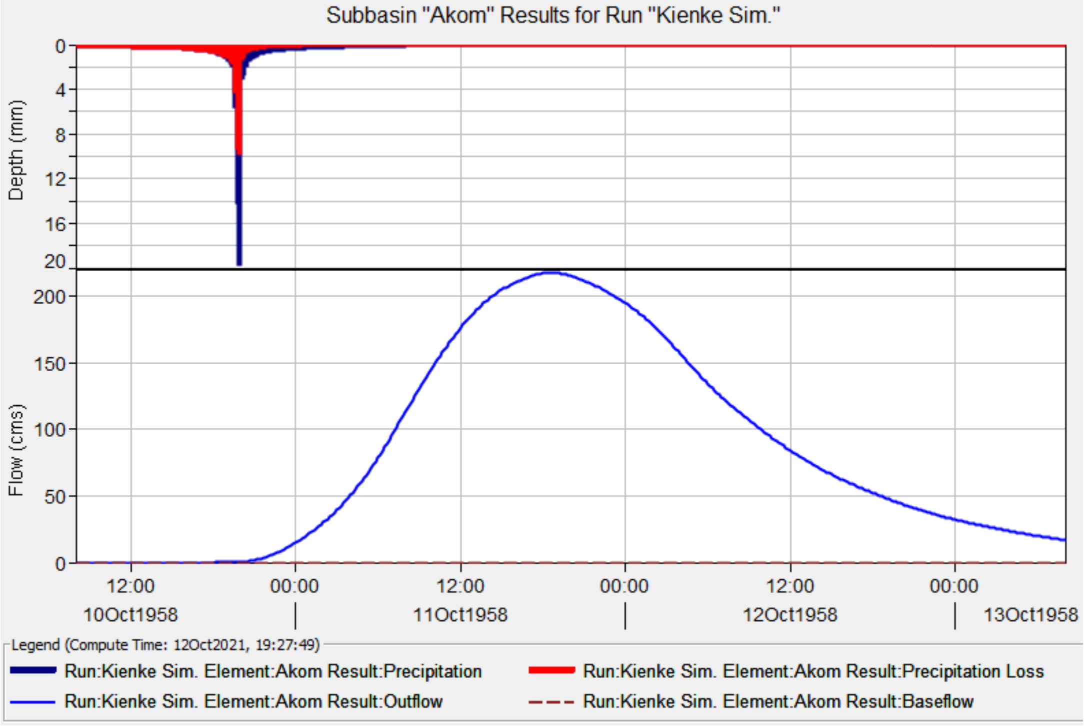


Figure 65: Sub-basin infiltration, excess precipitation and runoff for the Akom II sub basin.

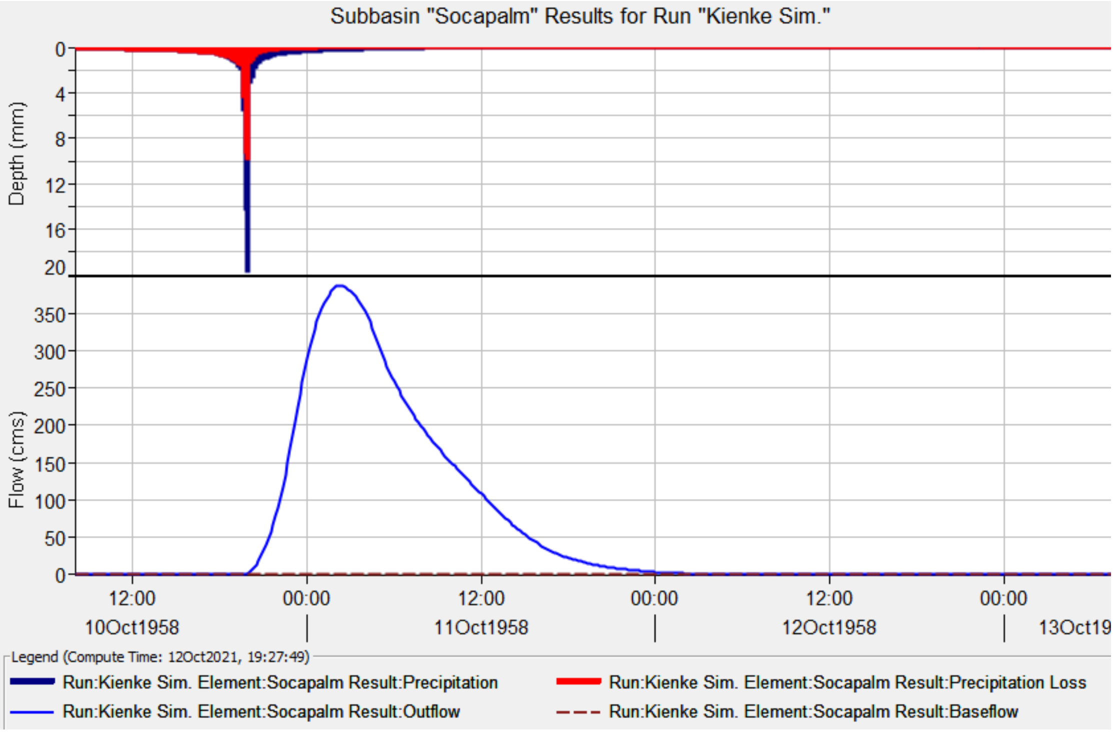


Figure 66: Sub-basin infiltration, excess precipitation and runoff for the SOCAPALM sub basin.

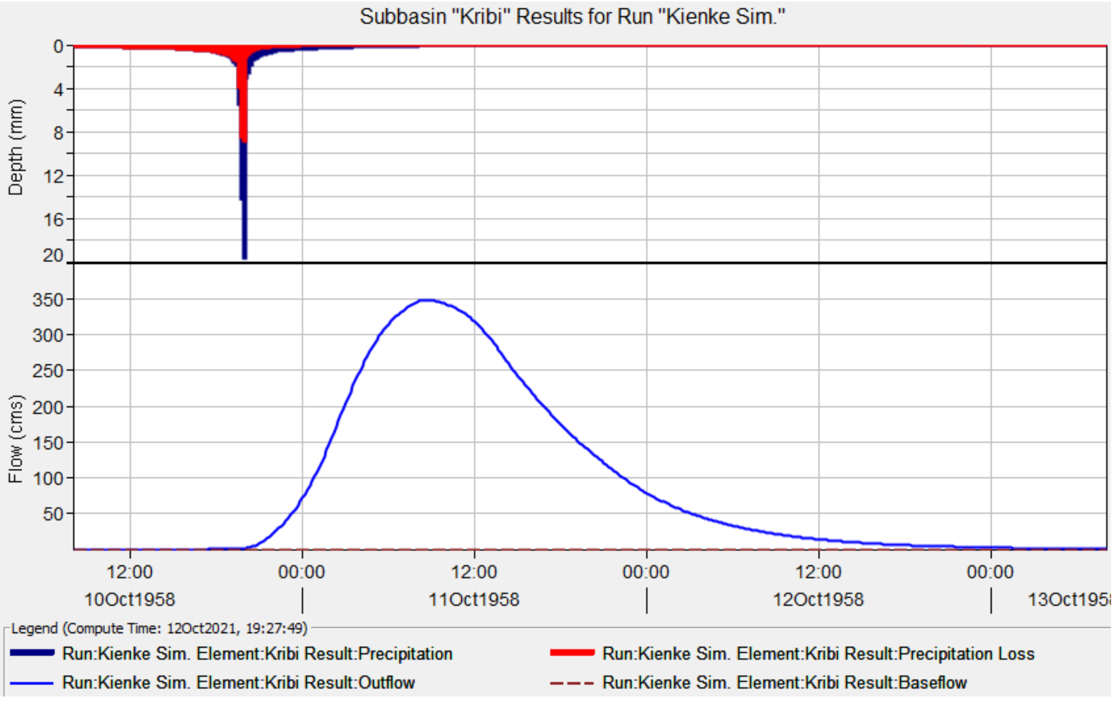


Figure 67: Sub-basin infiltration, excess precipitation and runoff for the Kribi sub basin.

- **Implications for Water Availability:**

The HEC-HMS model results underscore the Kienke River's significant potential as a water source for Kribi Town. The simulated runoff volumes far exceed the town's estimated maximum monthly water demand of 500,000 m³ (Figure 63). Even considering the potential impacts of seasonal variability and potential declining trends in streamflow, the river exhibits ample capacity to meet Kribi's current and projected water needs.

- **Water Supply Potential:**

The simulated runoff volume for the Kienke River is approximately 75 times the estimated water demand for Kribi Town. This vast difference indicates that extracting a monthly amount of 500,000 m³ from the river would have a negligible impact on the river's natural flow regime and environmental flow requirements. A water supply scheme significantly larger than the current demand could be developed, and the Kienke River would still be capable of providing ample water resources.

3.3.3 Evaluation of the Kienke River as a Potential Water Source:

3.3.3.1 Water Availability vs. Demand:

Comparing the estimated water availability from the Kienke River with the projected water demand for Kribi Town is crucial for determining the feasibility of utilizing this surface water source. This analysis considers both the present and future water needs of the town, taking into account population growth projections and estimated water consumption rates.

- **Water Demand Projection:**

Using a projected population growth rate of 7% per annum (Yongsi, 2011), Kribi Town's population is estimated to reach approximately 320,000 by the year 2030. Assuming a daily water consumption rate of 50 liters per person, the town's estimated MDD for potable water would be 16 ML (megaliters). This translates to an annual demand of approximately 6,000 ML. Additionally, considering the significant water requirements of the SOCAPALM plantation, estimated at 20 ML annually, the total water demand for Kribi Town in 2030 is projected to be around 6,020 ML.

- **Water Availability from the Kienke River:**

The HEC-HMS model simulations, using both monthly average and summed precipitation data, provide a robust estimate of water availability from the Kienke River. The total simulated runoff volume of 450,204,000 m³ (equivalent to 450,204 ML) for the historical period (Figure 63) significantly surpasses the projected annual water demand of 6,020 ML for Kribi Town in 2030.

- **Favorable Availability-Demand Ratio:**

The simulated runoff volume of the Kienke River is approximately 75 times the estimated water demand for Kribi Town in 2030. This remarkable difference highlights the river's abundant capacity to meet the town's current and projected water needs. Even considering potential variations in rainfall patterns and future land use changes, the Kienke River presents a highly favorable availability-demand ratio.

- **Implications for Water Supply:**

This analysis strongly supports the feasibility of utilizing the Kienke River as a primary water source for Kribi Town. The river's substantial runoff volume offers a reliable and sustainable alternative to sole reliance on groundwater resources, which face quality challenges and potential overexploitation.

3.3.3.2 Environmental Flow Considerations:

While the Kienke River offers abundant water resources for Kribi Town, sustainable water management necessitates careful consideration of environmental flow requirements. Environmental flows refer to the quantity, timing, and quality of water flows necessary to maintain the ecological integrity and biodiversity of the river ecosystem, and from the foregoing analyses, it does not pose any treats.

3.3.3.3 Reservoir Storage Potential:

While the Kienke River exhibits a high average discharge, its pronounced seasonal variability necessitates exploring options for augmenting water availability during drier periods and regulating flows to mitigate potential flood risks. Reservoir storage presents a promising solution to address these challenges, offering the capability to capture excess runoff during the wet seasons and release it strategically throughout the year.

3.3.4 Discussion:

The analysis of the Kienke River reveals a dynamic water system with both promising potential and inherent variability. On one hand, the river boasts a substantial average discharge significantly exceeding Kribi Town's projected water demand, even with projected population growth and industrial needs (Figure 63). This makes the Kienke a compelling candidate for augmenting Kribi's water supply. The HEC-HMS model simulations, calibrated against historical streamflow data, underscore this abundance, demonstrating that even moderate rainfall events generate significant runoff volumes (Figure 62). This makes a compelling case for diversifying Kribi's water sources beyond the increasingly strained and potentially contaminated groundwater resources (ResearchKey, 2021).

However, the Kienke's allure is tempered by its pronounced seasonal variability, with peak flows concentrated during the wet seasons and significantly lower flows during the dry season (Figure 53). This stark difference highlights the need for strategic management approaches that account for this fluctuation. While a purely direct water extraction scheme might be feasible during the wet season, additional measures are essential to ensure year-round water security.

Two primary strategies emerge to address this variability: conjunctive use and reservoir storage. Conjunctive use, integrating surface water from the Kienke with groundwater resources, could involve strategic groundwater extraction during peak flow periods and prioritizing surface water for less critical uses like irrigation during the dry season (Ako et al., 2010). This adaptive approach would maximize resource utilization while minimizing strain on any single source.

The second strategy, reservoir development, offers the potential to capture excess runoff during the wet seasons and release it strategically throughout the year (Loucks and Gladwell, 1999).

Crucially, the development of any water infrastructure, whether for direct extraction or reservoir storage, must prioritize environmental sustainability. Maintaining adequate environmental flows is critical for preserving the health and biodiversity of the Kienke River ecosystem (Arthington et al., 2006). This involves carefully assessing potential downstream impacts, such as alterations to flow regimes and effects on aquatic life, and incorporating mitigation measures into project designs.

3.4 GIS-Based Assessment and Decision Support

3.4.1 Reservoir Siting using Multi-Criteria Evaluation (MCE)

3.4.1.1 Selection and Weighting of Criteria:

Selecting a suitable location for a reservoir is a complex endeavour that necessitates carefully balancing competing environmental, social, and economic objectives. This study employed a Multi-Criteria Evaluation (MCE) approach within a GIS environment to identify optimal locations for potential reservoirs within the Kienke River watershed. This method allowed for the systematic consideration of multiple factors, their relative importance, and their spatial distribution to arrive at a data-driven and transparent decision.

The criteria selection process aimed to capture the key sustainability goals relevant to Kribi Town's context. These goals included minimizing environmental impacts, safeguarding community well-being, and ensuring the feasibility and efficiency of reservoir development. Based on these overarching goals, the following criteria were selected for evaluating potential reservoir sites:

- **Criteria Weighting:**

Determining the relative importance of each criterion was a crucial step in the MCE process. This study employed the Analytical Hierarchy Process (AHP), a widely recognized technique for quantifying subjective judgments and establishing priority weights (Saaty, 1980). AHP involves pairwise comparisons of criteria to establish their relative importance based on a numerical scale (Table 2-4).

Expert knowledge and stakeholder input informed the pairwise comparisons (Table 3-18) and normalizations (Table 3-19), reflecting a consensus on the relative importance of each criterion. The resulting weights (Table 3-20) highlight the prioritization of environmental factors, with land use/land cover receiving the highest weight, followed by slope, distance to settlements, and distance to rivers/streams. This weighting scheme reflects the commitment to minimizing environmental impacts while safeguarding social well-being.

The careful selection and weighting of criteria, guided by sustainability principles and community values, ensured that the MCE analysis provided a robust and transparent basis for identifying optimal locations for potential reservoir development in Kribi Town. This approach exemplifies the integration of diverse perspectives and objectives in achieving sustainable water management decisions.

Table 3-18: Pairwise Comparison Matrix for the evaluation criteria

Criterion	**slope**	**settlement**	**elevation**	**River**
slope	1	7	5	1
settlement	0.14	1	4	3
elevation	0.20	0.25	1	3
River	1.00	0.33	0.33	1

Table 3-19: Normalized Pairwise Comparison Matrix

Criterion	slope	settlement	elevation	River
slope	0.43	0.82	0.48	0.13
settlement	0.06	0.12	0.39	0.38
elevation	0.09	0.03	0.10	0.38
River	0.43	0.04	0.03	0.13

Table 3-20: Relative Criteria Weights

Criterion	Weights
Slope	0.46
Settlement	0.23
Elevation	0.15
River	0.16

➢ **Environmental Factors:**

- **Land Use/Land Cover:** Minimizing impacts on sensitive ecosystems and valuable land uses was paramount. Areas with high conservation value, such as forests, wetlands, and protected areas, were assigned lower suitability scores, promoting the preservation of biodiversity and ecosystem services (SNH, 2008). In Kribi's specific context, this involved prioritizing locations outside the extensive SOCAPALM plantation (Figure 58). This criterion was assigned a high weight in the MCE analysis (Table 3-20), reflecting the critical importance of safeguarding the region's natural environment.
- **Slope:** Avoiding steep slopes is crucial for minimizing erosion, sedimentation, and construction challenges (Abushandi and Alatawi, 2015). Sites with gentler slopes received higher suitability scores, promoting the selection of locations that are both environmentally sound and feasible for reservoir construction. A slope threshold of 10 degrees was deemed appropriate for Kribi, informed by engineering considerations and the local topography (Figure 68)

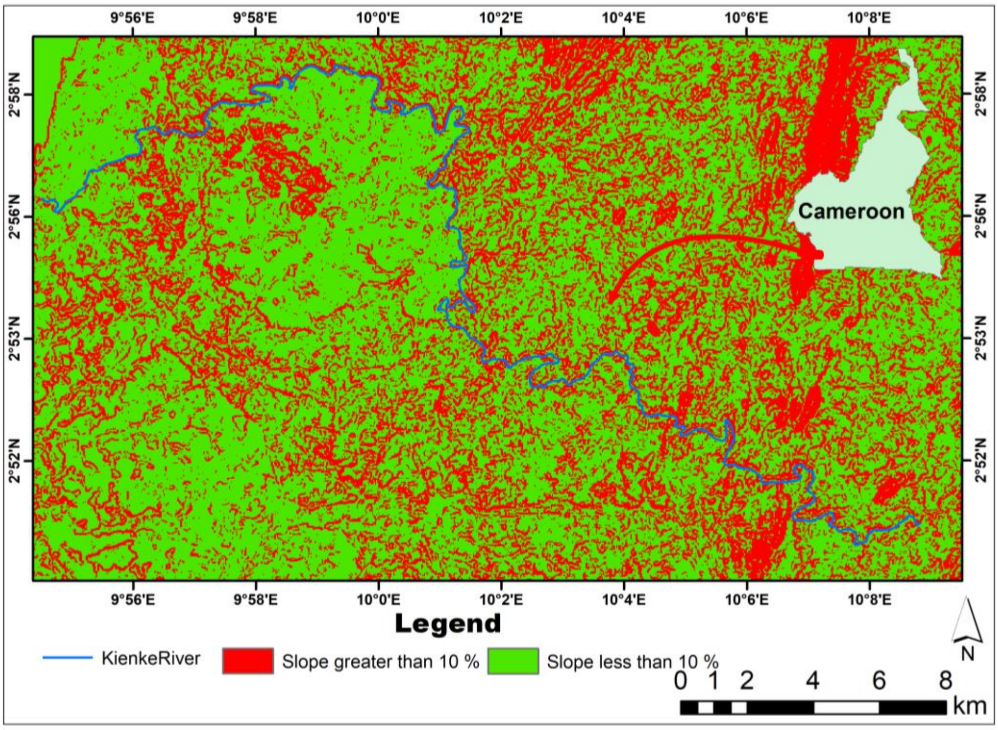


Figure 68: slope criterion implemented in GIS

- **Distance to Rivers/Streams:** Proximity to the Kienke River was essential for efficient reservoir filling and reducing water transfer needs. However, locating the reservoir too close to the river could negatively impact the riverine ecosystem and downstream water users (Allan, 2004). Balancing these considerations, a distance of 500 meters from the river was established as a criterion, promoting both water availability and ecological protection (Figure 69).

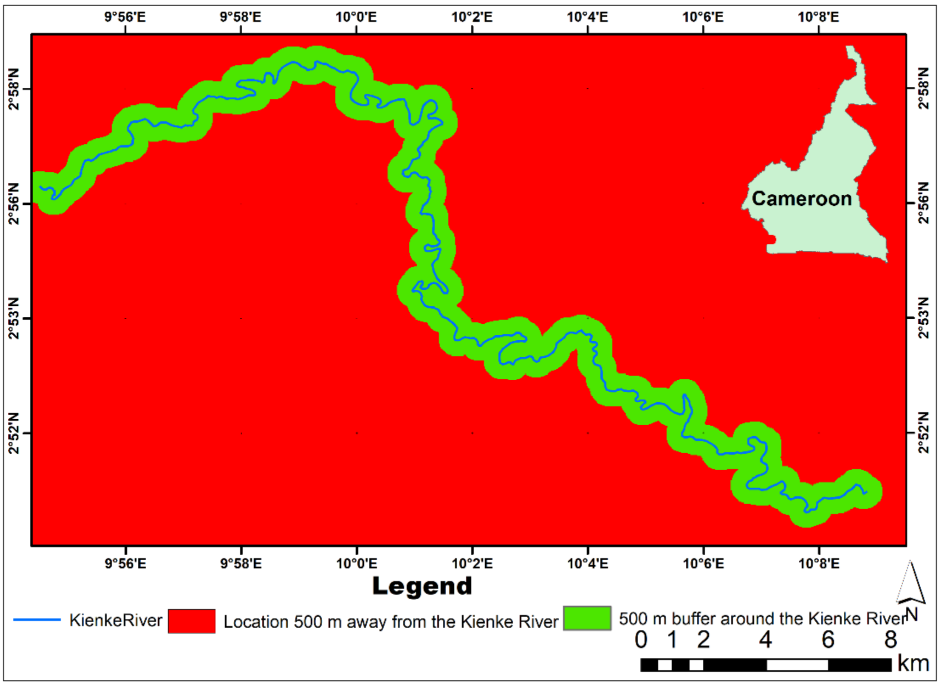


Figure 69: river criterion implemented in GIS, that is, distance from the river within 500 m

- **Social Factors:**

- **Distance to Settlements:** Minimizing disruption to existing communities and preserving social structures was a key priority (Yongsi, 2011). Locations further away from settlements received higher suitability scores, aiming to minimize potential displacement, loss of livelihoods, and social upheaval. A buffer zone of 2000 meters from settlements was established to address this criterion (Figure 70), reflecting the importance of prioritizing community well-being.

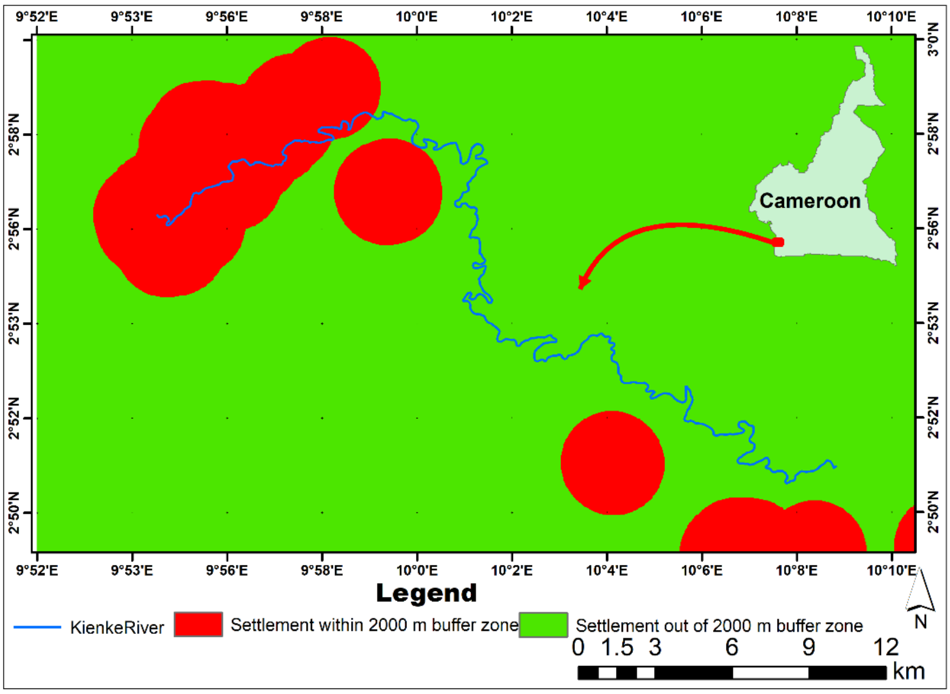


Figure 70: settlement criterion implemented in GIS

➢ Economic Factors:

While construction costs and accessibility were initially considered as potential criteria, data limitations and the overarching prioritization of environmental and social sustainability goals led to their exclusion from the final MCE analysis.

➢ Economic and Engineering Factors:

- **Elevation:** Selecting appropriate elevation ranges is critical for optimizing water supply efficiency and minimizing pumping costs. Lower elevations generally favour gravitational flow, reducing energy consumption and operational expenses. Based on an analysis of the DEM and considering the water demand distribution in Kribi Town, areas below 100 meters elevation were deemed most suitable, receiving higher scores in the MCE analysis (Figure 71).

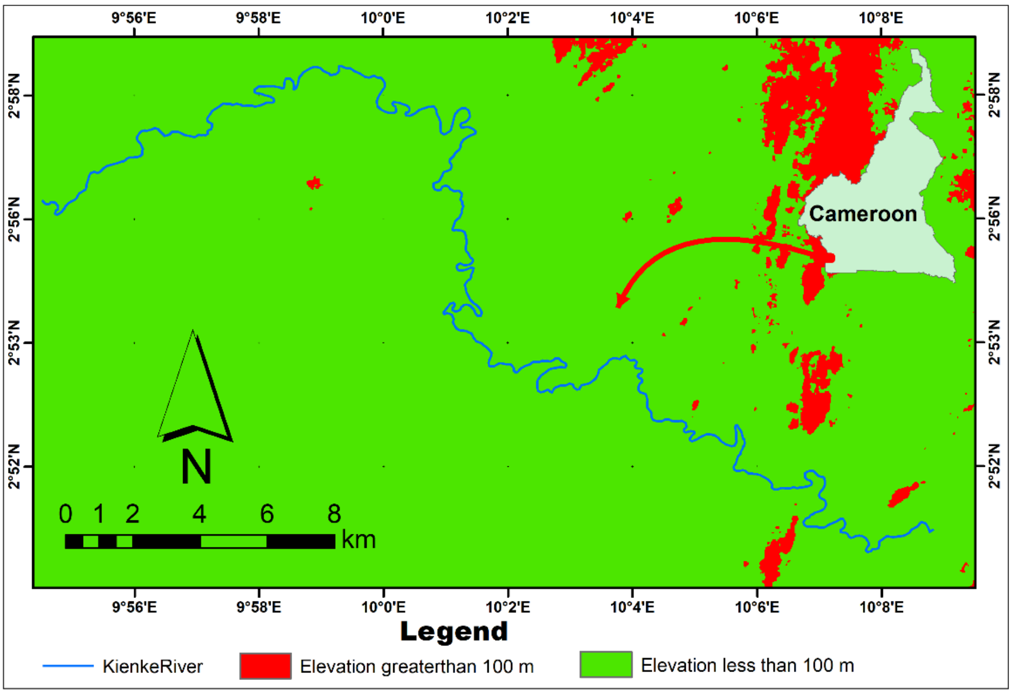


Figure 71: elevation criterion implemented in GIS

3.4.1.2 Data Standardization and Weighted Overlay:

To effectively utilize the selected criteria and their respective weights in identifying optimal reservoir sites, the spatial data representing each criterion was standardized to a common scale and then combined using a weighted overlay analysis within a GIS environment. This process ensured meaningful comparisons between criteria, allowing their weighted contributions to be synthesized into a comprehensive suitability map.

➢ **Data Standardization:**

The diverse spatial datasets representing the criteria for reservoir siting—slope, distance to settlements, distance to rivers, and elevation (derived from the DEM)—were initially in different units and scales, making direct comparison challenging. To address this, each dataset was standardized to a common dimensionless scale ranging from 0 to 1, where 1 represents the most suitable condition for that particular criterion.

- **Slope:** The slope raster, originally in degrees, was standardized using a linear function where slopes less than or equal to the 10-degree threshold received a score of 1, with suitability decreasing linearly as slopes increased (Figure 68).
- **Distance to Settlements:** The distance raster, measured in meters, was standardized using an inverse distance weighted function. Locations beyond the 2000-meter buffer

received a score of 1, with suitability decreasing as distance to settlements decreased (Figure 70).

- **Distance to Rivers:** Similar to the settlement distance raster, the river distance raster was standardized using an inverse distance weighted function, with areas beyond the 500-meter buffer receiving a score of 1 and suitability decreasing with proximity to the river (Figure 69).
- **Elevation:** The elevation raster, in meters, was standardized based on a suitability range determined by expert knowledge, favouring areas below 100 meters elevation for efficient water supply. A linear function was used, with elevations below 100 meters receiving a score of 1 and suitability decreasing as elevation increased (Figure 71).

This standardization process ensured that all criteria, regardless of their original units or scales, contributed equally to the overall suitability assessment.

- **Weighted Overlay:**

After standardization, a weighted overlay analysis was performed in ArcGIS to combine the individual suitability maps, incorporating the AHP-derived weights (Table 3-20). This involved multiplying each standardized raster by its corresponding weight and then summing the weighted rasters to produce a composite suitability map. This map reflected the combined influence of all criteria, where higher suitability scores indicated locations that better satisfied the desired conditions for reservoir development.

The resulting weighted overlay output, depicted in Figure 72, revealed the spatial distribution of suitability for reservoir placement across the Kienke River watershed. Areas with higher scores, primarily located in the northern portion of the watershed, indicated locations that balanced environmental protection, social considerations, and topographic suitability. This map served as a powerful decision-support tool, guiding the selection of promising dam sites and informing further analysis.

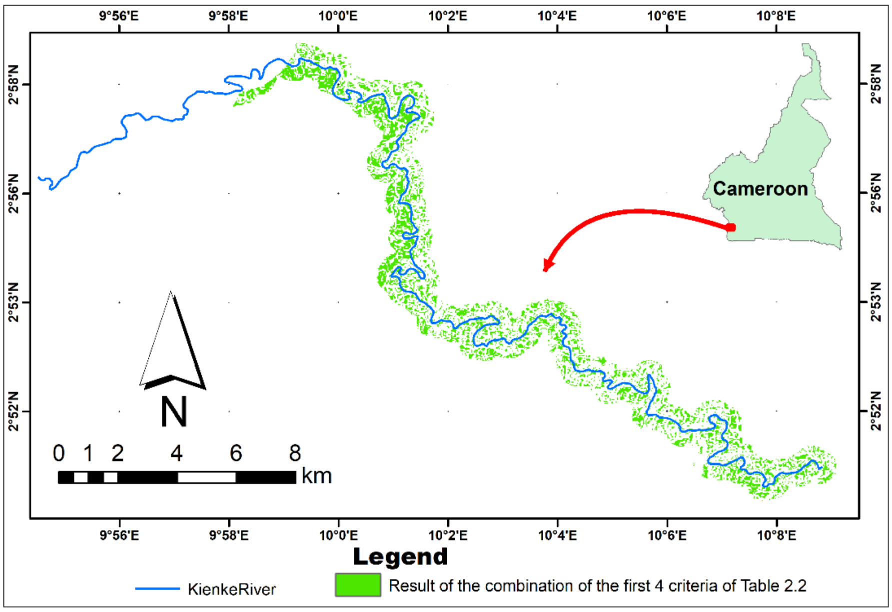


Figure 72: result of the implementation of the first 4 criteria in Table 2-3

Through this data-driven approach, combining standardization and weighted overlay techniques, the complex interplay of multiple criteria was effectively synthesized into a visual and intuitive suitability landscape. This spatial representation facilitated the identification of potential reservoir locations that best aligned with Kribi Town's sustainability goals, exemplifying the power of GIS in supporting informed and transparent water management decisions.

3.4.2 Dam Site Evaluation and Potential Reservoir Characteristics:

The weighted overlay analysis, synthesizing environmental and social criteria, produced a composite suitability map (Figure 72) revealing promising locations for potential dam construction within the Kienke River watershed. This map served as the foundation for identifying specific dam sites that balanced sustainability goals with practical feasibility considerations.

Several areas exhibited high suitability scores, primarily concentrated in the northern portion of the watershed. These locations shared several key characteristics contributing to their suitability:

- **Minimal Land-Use Conflicts:** The high-scoring areas were predominantly located outside the SOCAPALM plantation, minimizing potential conflicts with this significant land use and aligning with the prioritization of environmental protection.

- **Favourable Slope Conditions:** The identified sites generally exhibited gentle slopes, reducing the risks of erosion, sedimentation, and construction challenges. This alignment with the slope criterion (less than 10 degrees) ensured both environmental and engineering feasibility.
- **Suitable Distance from Settlements:** The high-suitability areas maintained a sufficient buffer distance from existing settlements, minimizing potential social impacts and aligning with the goal of safeguarding community well-being.
- **Proximity to the Kienke River:** While maintaining a safe distance to protect the riverine ecosystem, the promising locations were still within a reasonable proximity to the Kienke River, ensuring efficient water capture and conveyance to the reservoir.

Further Refinement:

To further refine the selection of suitable dam sites, the weighted overlay map (Figure 72) was analysed in conjunction with additional GIS-based criteria, including:

- **Contiguous Area:** Sites with a minimum contiguous area of 2 hectares were prioritized to accommodate the dam structure, reservoir, and associated infrastructure (Table 2-3). This criterion ensured the practicality and functionality of the proposed reservoir.
- **Elevation:** Areas with elevations below 100 meters were favoured to optimize water supply efficiency, considering gravitational flow and minimizing pumping requirements. This elevation constraint (Figure 71) contributed to the economic feasibility of reservoir operation.

Applying these additional criteria to the suitability map resulted in the identification of several discrete areas suitable for dam construction (Figure 73). The most promising site, highlighted in Figure 73, exhibited the highest composite suitability score and met all the feasibility criteria. Its location just above the SOCAPALM plantation boundary balanced environmental protection with efficient water capture from the Kienke River.

This multi-faceted evaluation process, integrating spatial analysis, weighted criteria, and feasibility constraints, ensured the selection of dam sites that not only maximized potential water storage but also aligned with Kribi Town's commitment to sustainable development and community well-being. This approach exemplifies the power of GIS-based MCE in supporting informed and transparent decision-making for critical water infrastructure projects.

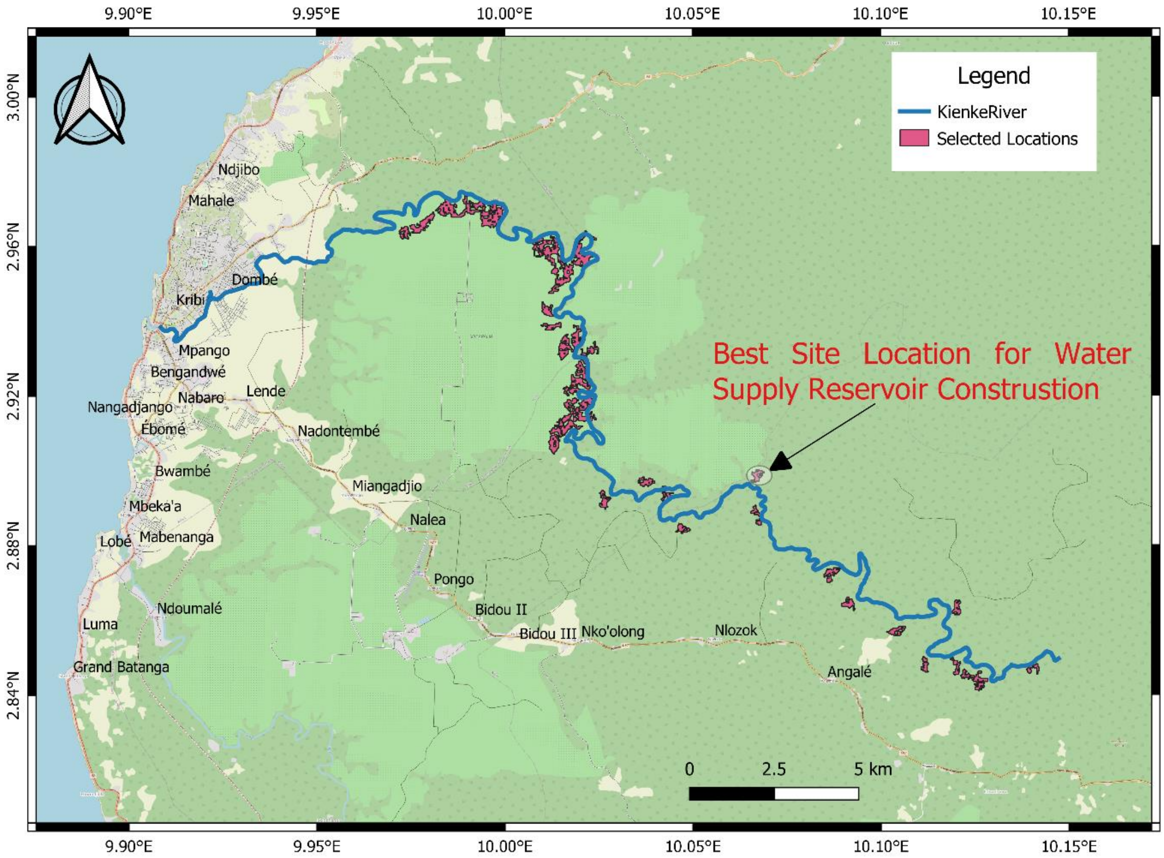


Figure 73: Suitable site selections for the construction of the Water Supply Reservoir, with the best choice indicated.

3.4.3 Discussion:

The Multi-Criteria Evaluation (MCE) analysis, integrated within a GIS environment, proved to be a powerful tool for identifying promising locations for potential reservoir development within the Kienke River watershed. This approach facilitated a transparent and data-driven decision-making process, explicitly incorporating environmental, social, and topographic considerations to arrive at a solution that balances competing priorities (Jankowski and Nyerges, 2001).

The careful selection and weighting of criteria, informed by expert knowledge and stakeholder input, ensured that the resulting suitability map accurately reflected the key sustainability goals of Kribi Town. The prioritization of environmental factors, evident in the high weights assigned to land use/land cover and slope, highlights the commitment to minimizing impacts on the region's valuable ecosystems, particularly those identified within the "Regional Environmental Assessment (REA) of the Kribi Region" (SNH, 2008). The inclusion of social considerations, particularly the distance to settlements, emphasizes the importance of protecting community well-being and avoiding disruption to existing social structures, as highlighted by Yongsi (2011) in their study on water access in Yaoundé.

The exclusion of economic factors like construction costs and accessibility, while driven by data limitations, underscores the prioritization of environmental and social sustainability in this initial phase of reservoir site selection. Future investigations could incorporate these economic factors, along with detailed geological assessments, to further refine the selection process and ensure the feasibility and cost-effectiveness of potential reservoir projects.

The identification of the most promising dam site, located just above the boundary of the SOCAPALM plantation (Figure 73), exemplifies the effectiveness of the MCE approach in balancing competing objectives. This location minimizes potential land-use conflicts, exhibits favourable slope conditions, reducing the risk of erosion as suggested by Abushandi and Alatawi (2015), maintains a sufficient buffer from settlements, and ensures efficient water capture from the Kienke River. Further investigation of this site, including detailed topographic surveys, geological assessments, and environmental impact studies, is warranted to confirm its suitability and guide the design of a sustainable reservoir project.

The MCE-based reservoir siting analysis presented here serves as a valuable example of how spatial analysis, coupled with a structured decision-making framework, can support sustainable water resource development. By explicitly incorporating environmental, social, and economic considerations, this approach promotes transparency, accountability, and community engagement in the decision-making process, ultimately contributing to a more equitable and resilient water future for Kribi Town, as demonstrated in successful reservoir projects like the Hoover Dam (Karambelkar, 2018) and the Itaipu Dam (Llamosas, 2023).

3.5 Overall Discussion and Integration of Findings: A Holistic View of Kribi's Water Resources

3.5.1 Significance of Research Findings:

This research makes several significant contributions to understanding and addressing Kribi Town's water resource challenges. The findings go beyond descriptive observations, providing actionable insights for decision-makers and establishing a baseline for future research and management efforts.

- **Filling the Knowledge Gap:**
    - Prior to this study, a comprehensive hydrogeological model for Kribi Town was lacking. This research, through its integration of geophysical surveys, borehole data, and geological modeling, fills this critical knowledge gap, providing a

    detailed picture of the aquifer system's structure, properties, and spatial distribution.
    - The identification of distinct aquifer units, their respective thicknesses, and their potential for sustainable water extraction contributes to a more nuanced understanding of groundwater resources and their potential for meeting Kribi's water needs.
- **Assessing and Mitigating Water Quality Risks:**
    - This research goes beyond simple identification of water quality issues. By pinpointing specific contaminants, such as chloride, arsenic, and lead, and mapping their spatial distribution, the study provides a basis for targeted mitigation strategies.
    - This information is essential for implementing measures to address saltwater intrusion, control pollution from potential sources like industrial activities or agricultural runoff, and ensure the safety of drinking water supplies.
- **Expanding Water Supply Options:**
    - The comprehensive assessment of the Kienke River's potential as a water source, incorporating hydrological modelling and incorporating environmental flow requirements, opens up new possibilities for diversifying Kribi's water supply portfolio.
    - The identified options for conjunctive use and reservoir development, informed by GIS-based spatial analysis and suitability mapping, provide concrete pathways for augmenting water availability and adapting to seasonal variations.
- **Promoting Sustainable Water Management:**
    - By employing the principles of IWRM, the study emphasizes a holistic approach that considers social, economic, and environmental factors.
    - This framework, coupled with the specific recommendations arising from the research, provides a foundation for developing sustainable water management policies and practices in Kribi, ensuring equitable access, efficient resource utilization, and long-term environmental health.
- **Creating a Replicable Model:**
    - The methods employed in this research, particularly the integration of geophysical surveys, hydrological modelling, and GIS-based analysis, offer a

  - valuable and adaptable model for water resource assessment, particularly in data-scarce regions.
  - By adapting these techniques and tailoring solutions to local contexts, other communities facing similar water challenges can benefit from the insights gained in this study and accelerate their own progress towards a water-secure future.

3.5.2 Roadmap for Addressing Water Scarcity:

Based on the comprehensive assessment of Kribi Town's water resources and the insights gained through this research, a multi-pronged roadmap is proposed to guide the town towards a more sustainable and water-secure future. This roadmap emphasizes a holistic approach, integrating source protection, supply augmentation, community engagement, and adaptive management strategies to address both the immediate and long-term water challenges facing Kribi.

Phase 1: Immediate Actions (Short-Term, 0-2 Years)

- **Address Urgent Water Quality Concerns:**
  - Prioritize treatment interventions for existing water sources exhibiting high levels of salinity or heavy metal contamination. This may involve exploring cost-effective and appropriate technologies like desalination, filtration systems, or community-based water treatment solutions.
  - Implement a public awareness campaign to educate residents about potential health risks associated with contaminated water sources and promote safe water handling practices, such as boiling water before consumption.
- **Initiate Groundwater Monitoring Program:**
  - Establish a systematic and regular groundwater monitoring program, focusing on key parameters like water levels, salinity, and heavy metal concentrations. This will provide crucial data for tracking changes over time, assessing the effectiveness of mitigation measures, and informing adaptive management decisions.
- **Develop Water Conservation Plan:**
  - Implement immediate water conservation measures to reduce water demand, such as promoting water-efficient appliances, fixing leaks, and encouraging responsible water use practices in households, businesses, and public spaces.

  - Establish water-saving initiatives targeted at high water-use sectors, such as agriculture and industry, encouraging the adoption of efficient irrigation techniques and water recycling systems.

Phase 2: Medium-Term Strategies (2-5 Years)

- **Develop Conjunctive Use Scheme:**
  - Conduct detailed feasibility studies for implementing a conjunctive use system, integrating surface water from the Kienke River with groundwater resources. This could involve supplementing groundwater extraction during peak flow periods, prioritizing surface water for irrigation during dry seasons, or implementing managed aquifer recharge (MAR) to enhance groundwater storage.
- **Invest in Groundwater Exploration and Development:**
  - Conduct exploratory drilling and aquifer testing in the promising northern region of Kribi, where groundwater quality is generally acceptable. This could lead to the development of new wells to augment water supply from a less contaminated source.
- **Initiate Feasibility Studies for Reservoir Development:**
  - Conduct comprehensive feasibility studies, environmental impact assessments, and social impact assessments for the most promising reservoir sites identified through the GIS-based MCE analysis.
  - Engage stakeholders, including communities potentially affected by reservoir development, to ensure transparency, address concerns, and incorporate social considerations into project planning.

Phase 3: Long-Term Vision (5+ Years)

- **Implement Sustainable Water Supply Infrastructure:**
  - Based on the findings of feasibility studies, implement the most sustainable and cost-effective water supply solutions, whether it be conjunctive use, reservoir development, or a combination of approaches.
  - Incorporate climate change projections into long-term water resource planning, anticipating potential impacts on water availability and adapting infrastructure development accordingly.

- **Establish IWRM Framework:**
    - Formalize an IWRM framework that guides all aspects of water management in Kribi Town, ensuring equitable access, efficient utilization, and environmental sustainability.
    - This framework should encompass clear policies, regulations, monitoring programs, and stakeholder engagement mechanisms to ensure a holistic and collaborative approach to water governance.

3.6 Conclusion

This chapter has provided a comprehensive and integrated assessment of Kribi Town's water resources, illuminating both the potential and the challenges facing the town's water future. By combining cutting-edge geophysical techniques, hydrogeochemical analyses, and hydrological modelling, a detailed picture of Kribi's complex water landscape has emerged.

The identification of a heterogeneous aquifer system, with both unconfined and confined aquifers exhibiting varying thicknesses and properties, highlights the need for spatially targeted water management strategies. While Kribi possesses ample groundwater resources, the concerning levels of saltwater intrusion, particularly in the southern and central regions, and the localized heavy metal contamination, necessitate a cautious approach to groundwater extraction. The northern region, with its deeper water table and generally acceptable water quality, emerges as a promising area for sustainable well development.

The Kienke River, exhibiting high runoff volumes consistently throughout the year, presents a compelling opportunity for augmenting Kribi's water supply. The substantial difference between the river's runoff and the town's projected demand suggests its capacity to meet Kribi's current and future water needs reliably. The potential for conjunctive use with groundwater and the promising locations for reservoir storage identified through GIS-based MCE analysis further strengthen the feasibility of incorporating the Kienke River into a sustainable water management strategy. The prioritization of environmental factors in the reservoir siting process ensures that any development minimizes impacts on valuable ecosystems and prioritizes the long-term health of the watershed.

This chapter's findings lay a robust foundation for developing a sustainable water management roadmap for Kribi Town. By integrating the insights gained here, the town can embark on a path towards water security, ensuring a reliable and safe water supply for its growing population while safeguarding the environment and promoting community well-being.

GENERAL CONCLUSION AND PERSPECTIVES

1. Summary of Key Findings

This research paints a comprehensive picture of Kribi Town's water resources, revealing a complex interplay of potential and challenges for both groundwater and surface water sources. Employing an integrated approach that combines geophysical surveys, hydrogeochemical analyses, hydrological modeling, and GIS-based evaluations, the study uncovered a heterogeneous aquifer system in Kribi, consisting of a shallow, unconfined aquifer composed of sand and gravel, and a deeper confined aquifer located within fractured/weathered granite. While the central and southern regions show the greatest thickness of the unconfined aquifer, this layer is threatened by significant saltwater intrusion, indicated by elevated chloride concentrations in coastal zones. Furthermore, localized heavy metal contamination, exceeding WHO guidelines for arsenic, lead, and mercury, highlights the need for careful management of groundwater resources. On a positive note, the northern region emerges as a promising area for sustainable well development due to its deeper water table and generally acceptable water quality. Shifting to surface water, The Kienke River, while a plentiful water source exceeding Kribi's 2030 projected demand by 75 times, presents challenges for direct use due to its fluctuating flow. However, this variability can be strategically managed through conjunctive use, integrating surface and groundwater resources, and by developing reservoirs at carefully selected locations identified through GIS-based analysis. This combined approach unlocks the river's vast potential while ensuring a reliable year-round water supply for Kribi.

2. Significance of the Research: Informing Sustainable Water Management in Kribi and Contributing to Cameroon's National Development Strategy (NDS)

This research directly addresses a critical knowledge gap concerning Kribi Town's water resources, providing a comprehensive assessment that aligns with Cameroon's NDS 2020-2030. By characterizing the aquifer system, evaluating water quality, and quantifying water availability, the study equips decision-makers with essential data to develop informed and sustainable water management strategies that contribute to the NDS goals:

- **Supporting Sustainable Urban Development:** The findings directly contribute to the NDS's focus on sustainable urban development by providing the information needed to ensure a reliable and safe water supply for Kribi's growing population, fostering economic growth, and improving living standards.

- **Protecting Water Resources and Ecosystems:** The identification of contamination sources and recommendations for mitigation measures align with the NDS's goal of protecting and sustainably managing natural resources, ensuring the long-term health of Kribi's water resources and the surrounding ecosystems.
- **Promoting Resilient Infrastructure:** The proposed solutions for conjunctive use and strategic reservoir placement contribute to the NDS's emphasis on developing resilient infrastructure by diversifying Kribi's water sources and mitigating the impacts of drought or climate variability.
- **Empowering Local Communities:** The research highlights the importance of community engagement in water management, supporting the NDS's focus on decentralization and local governance by advocating for stakeholder participation in decision-making processes.
- **Advancing Knowledge and Innovation:** The study's methods, particularly the integration of geophysical surveys, hydrological modeling, and GIS-based analysis, offer a valuable model for water resource assessment in data-scarce regions, contributing to the NDS's goal of promoting research and innovation.

3. Limitations and Future Research: Expanding the Scope of Knowledge and Aligning with the NDS

While this research establishes a solid foundation for understanding Kribi's water resources, its limitations should be addressed in future investigations:

- **Enhanced Data Collection:** Further efforts are needed to collect detailed borehole data, geological maps, and long-term water quality monitoring data, contributing to a more robust understanding of the aquifer system and enabling more accurate prediction of water resource availability and quality. This aligns with the NDS's emphasis on improving data collection and monitoring systems.
- **Focus on Climate Change Adaptation:** Future research should prioritize assessing the potential impacts of climate change on Kribi's water resources and develop adaptation strategies, aligning with the NDS's focus on building climate resilience.
- **Integrating Economic Considerations:** Incorporating economic analyses into future studies will contribute to a more comprehensive understanding of the costs and benefits associated with different water management options, supporting the NDS's goal of promoting sustainable economic growth.

- **Strengthening Stakeholder Engagement:** Further research should explore participatory approaches to water management, fostering community involvement in decision-making processes and ensuring the equitable distribution of water resources, in line with the NDS's emphasis on inclusive development.

4. Recommendations for Sustainable Water Management in Kribi Town: A Pathway to Achieve the NDS Goals

Based on the research findings, the following recommendations are crucial for charting a sustainable water management path in Kribi, contributing directly to the achievement of the NDS goals:

- **Implement IWRM Framework:** Establish a comprehensive IWRM framework that guides all aspects of water management in Kribi, ensuring equitable access, efficient utilization, and environmental sustainability. This aligns with the NDS's focus on integrated and sustainable development.
- **Prioritize Water Resource Protection:** Implement stringent pollution control measures, safeguard aquifer recharge zones, and develop strategies to mitigate saltwater intrusion, contributing to the NDS's goal of protecting natural resources.
- **Invest in Sustainable Water Infrastructure:** Develop a diversified water supply portfolio by exploring conjunctive use, developing new wells in the northern region, and strategically developing reservoirs based on feasibility studies and environmental impact assessments. This aligns with the NDS's emphasis on resilient infrastructure development.
- **Promote Water Efficiency and Conservation:** Implement water conservation measures and encourage water-efficient technologies and practices in all sectors, contributing to the NDS's goal of promoting sustainable resource utilization.
- **Strengthen Capacity and Collaboration:** Enhance local capacity for water resource management, promote collaborative governance, and engage stakeholders in decision-making processes, aligning with the NDS's focus on decentralization and participatory development.

5. Concluding Remarks: A Vision for a Water-Secure Future Contributing to Cameroon's Development

This research presents a vision for Kribi Town where its diverse water resources are sustainably managed to ensure a water-secure future that supports economic growth, social development, and environmental protection, aligning directly with the goals of Cameroon's NDS. By implementing the proposed recommendations, Kribi can serve as a model for sustainable water management, contributing to a more prosperous and resilient future for Cameroon and her people.

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APPENDICES

Appendix A

Electro-Seismic Data Sets

1. Electro-Seismic Hydraulic Conductivity Tomography (ESKT)
2. Electro Seismic Coupling Coefficient Tomography (ESCCT)
3. Electro-Seismic Fracture Analysis (ESFT)
4. Electro-Seismic Interface Tomography (ESIT)
5. Electro-Seismic Interface Angular Response Tomography (ESIAT)
6. Electro-Seismic Interface Angular Normalized Response Tomography (ESIANT)
7. Electro-Seismic Change in Absolute Response Tomography (ESCAGT)
8. Electro-Seismic Change in Total Response Tomography (ESCTGT)
9. Electro-Seismic Groundwater Flow Potential Tomography (ESGFPT)
10. Electro-Seismic Fractures Associated with Interfaces Tomography (ESFIT)
11. Electro-Seismic Fractures Associated with Hydraulic Conductivity Tomography (ESFKT)
12. Electro-Seismic Fractures Associated with Ground Water Flow Potential Tomography (ESFGFPT)
13. Electro-Seismic Coupling Coefficient Change in Absolute Response Gradient Tomography (ESCCCAGT)
14. Electro-Seismic Coupling Coefficient Change in Total Response Gradient Tomography (ESCCCTGT)

Electro-Telluric Data Sets

1. Electro-Telluric Tomography (ET)
2. Electro-Telluric Gradient Tomography (ETGT)
3. Electro-Telluric Interface Tomography (ETIT)
4. Electro-Telluric Interface Angular Response Tomography (ETIAT)
5. Electro-Telluric Interface Angular Normalized Response Tomography (ETIANT)

Electro-Seismo-Telluric Data Sets

1. Electro-Telluric Electro-Seismic Hydraulic Conductivity Tomography (ETESKT)
2. Electro-Telluric Electro-Seismic Coupling Coefficient Tomography (ETESCCT)
3. Electro-Telluric Electro-Seismic Change in Absolute Response Gradient Tomography (ETESCAGT)
4. Electro-Telluric Electro-Seismic Groundwater Flow Potential Tomography (ETESGFPT)
5. Electro-Telluric Electro-Seismic Coupling Coefficient Change in Absolute Response Gradient Tomography (ETESCCCAGT)
6. Electro-Telluric Electro-Seismic Groundwater Flow Potential Change In Absolute Response Gradient Tomography (ETESGFPCAGT)

Magneto-Telluric Data Sets

1. Magneto-telluric Tomography (MT)
2. Magneto-telluric Gradient Tomography (MTGT)
3. Magneto-telluric Interface Tomography (MTIT)
4. Magneto-telluric Interface Angular Response Tomography (MTIAT)
5. Magneto-telluric Interface Angular Normalized Response Tomography (MTIANT)

Magneto-Seismo-Telluric Data Sets

1. Magneto-Telluric Magneto-Seismic Hydraulic Conductivity Tomography (MTESKT)
2. Magneto-Telluric Magneto-Seismic Coupling Coefficient Tomography (MTESCCT)
3. Magneto-Telluric Magneto-Seismic Change in Absolute Response Gradient Tomography (MTESCAGT)
4. Magneto-Telluric Magneto-Seismic Groundwater Flow Potential Tomography (MTESGFPT)
5. Magneto-Telluric Magneto-Seismic Coupling Coefficient Change in Absolute Response Gradient Tomography (MTESCCCAGT)

6. Magneto-Telluric Magneto-Seismic Groundwater Flow Potential Change in Absolute Response Gradient Tomography (MTESGFPCAGT)

Appendix C: WHO drinking water guidelines (WHO, 2011)

Parameter	WHO Drinking Water Guideline (Maximum Permissible Level)	Agricultural Use Considerations	Other Uses
pH	6.5 - 8.5	6.5 - 8.5 (ideal for most crops)	Varies widely; extreme pH can corrode pipes, impact aquatic life
Temperature (Temp)	No guideline, but should be palatable	Optimal ranges vary by crop; high temps can stress plants	Industrial cooling, recreation
Electrical Conductivity (Cond)	No guideline, but related to salinity	High salinity can harm crops, reduce yields	Indicator of dissolved salts
Total Dissolved Solids (TDS)	500 mg/L (desirable), up to 1000 mg/L (acceptable)	High TDS can damage soil structure, affect water uptake	Industrial processes, boilers
Chloride (Cl)	250 mg/L (desirable), up to 600 mg/L (acceptable)	Can build up in soil, damage sensitive crops	Corrosion in pipes, impact on taste
Nitrate (NO3)	50 mg/L (as nitrate)	Essential nutrient but excessive levels can contaminate groundwater	Algal blooms in surface waters
Sulfate (SO4)	250 mg/L (desirable), up to 500 mg/L (acceptable)	Can affect soil pH, some crops sensitive	Corrosion, taste issues
Sodium (Na)	200 mg/L (desirable), up to 400 mg/L (acceptable)	Can accumulate in soil, harm sensitive crops	Hypertension concerns
Calcium (Ca)	No health-based guideline	Essential plant nutrient, but high levels can affect soil structure	Hard water issues
Magnesium (Mg)	No health-based guideline	Essential plant nutrient	Hard water issues
Arsenic (As)	0.01 mg/L (10 µg/L)	Highly toxic to plants and animals	Strict regulations for most uses

Lead (Pb)	0.01 mg/L (10 µg/L)	Toxic to plants and can accumulate in food chain	Strict regulations
Mercury (Hg)	0.001 mg/L (1 µg/L)	Highly toxic, can bioaccumulate in the food web	Strict regulations
Bicarbonate (HCO3)	No health-based guideline, but contributes to alkalinity	Important for buffering soil pH	
Carbonate (CO3)	No health-based guideline, but contributes to alkalinity	Can raise soil pH	
Silica (SiO2)	No health-based guideline	Generally not a concern for plants	
Dissolved Oxygen (O)	Important for aquatic life, no guideline for drinking	Essential for healthy root systems in soil	
Deuterium (δ^2H)	Primarily used for isotopic studies, not a health concern	Not directly relevant	