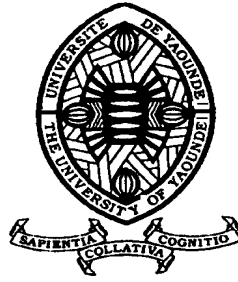


RÉPUBLIQUE DU CAMEROUN

Paix – Travail – Patrie

**UNIVERSITÉ DE YAOUNDÉ I
FACULTÉ DES SCIENCES**

**CENTRE DE RECHERCHE ET DE
FORMATION DOCTORALE EN
SCIENCES, TECHNOLOGIE
ET GÉOSCIENCES**



REPUBLIC OF CAMEROON

Peace – Work – Fatherland

**UNIVERSITY OF YAOUNDE I
FACULTY OF SCIENCE**

**POSTGRADUATE SCHOOL
OF SCIENCES,
TECHNOLOGY AND
GEOSCIENCES**

DEPARTMENT OF EARTH SCIENCES

DÉPARTEMENT DES SCIENCES DE LA TERRE

DOCTORAL RESEARCH UNIT FOR GEOSCIENCES AND APPLICATIONS

*UNITE DE RECHERCHE ET DE FORMATION DOCTORALES EN GEOSCIENCES ET
APPLICATIONS*

**LABORATORY OF GEOSCIENCES OF SUPERFICIAL FORMATIONS AND
APPLICATIONS**

*LABORATOIRE DE GEOSCIENCES DES FORMATIONS SUPERFICIELLES ET
APPLICATIONS*

**IMPACT OF MINING EXPLOITATION ON SEDIMENTS
AND WATER IN THE BATOURI GOLD DISTRICT
(EAST-CAMEROON)**

**Dissertation presented as Partial Fulfilment for the requirements for obtaining the MSc
degree in Earth Sciences**

Specialty: Geology of surface formations

Option: Mining Geology and Petroleum resources

By

TALLA Donardson Simnjoh

Registration N°: 19F2981

BSc. in Earth Sciences

Under the supervision of

NDAM NGOUPAYOU Jules Rémy

Professor

University of Yaoundé I



Academic year 2023/2024

DEDICATION

TO

MY LATE FATHER TALLA JOSIAH AND MY MOTHER TALLA Emmerencia NYEH

ACKNOWLEDGEMENT

As this work ends, I would like to express my sincere thanks to all those people without whom the expected results would not have been achieved.

Firstly, I will like to express my deepest gratitude to God for his guidance, wisdom, and strength throughout this journey. Without His blessings, this achievement will not have been possible.

I am profoundly grateful to my supervisor, Professor NDAM GOUPAYOU Jules Remy, whose expertise, patience, and support have been invaluable. Your insightful feedback and continuous encouragement have significantly shaped the direction and quality of this work.

I would also like to thank:

The head of department of Earth sciences at the University of Yaoundé 1, Professor BISSO Dieudonne who facilitated the administrative duties, ensuring a smooth progression of this work and equally the training I received from him during my academic course.

All the Lecturers of the department of Earth Sciences at the University of Yaoundé 1 for all the knowledge transmitted. This appreciation goes particularly to Professor ; NDJIGUI Paul Désiré, NJILAH Isaac KONFOR, YONGUEU FOUATOU Rose, NGOS III Simon, TCHOUANKOUE Jean Pierre, ONANA Vincent Laurent, GANNO Sylvestre, METANG Victor, NGEUTCHOUA Gabriel, YENE ATANGA Joseph, EKOMANE Emile, NKOUMBOU Charles, TEMGA Jean-Pierre, SABABA Elisée, to Doctors KOAH Serge parfait, FEUMBA Roger, NGO'O ZE Arnaud, ANABA ONANA Achille, and TEHNA Nathanaël.

A special thank you goes to Mr NJIAYOUOM NGAH Mohamed who accompanied me to the field, advised and guided me throughout this work.

All my friends, classmates and students of my promotion, and especially to PELLA Bruno buma, ELONE praise MECHANE, NDI Silas Melung, WIRGO Rebecca KIBONG, MEYONG NKENLIFACK Cedric Lauren, for their support, advice and encouragement.

Finally, I would like to express profound gratitude to my family members for supporting me spiritually, financially and physically throughout this journey and especially to my mother Mrs TALLA Emmerencia Nyeh who saw the financial obligation of this work, to Mrs TALLA Blessing, TARLA Sylvia, LINDA Nkupsi, NGUI Joel Chilas, NGUIYEDIUM Kelly Sandra, NJILAH Ernest, NFOR Antionette, and TARLA Handson thank you for your constant encouragement, sacrifices, and the countless ways you have supported this journey

TABLE OF CONTENTS

DEDICATION	i
ACKNOWLEDGEMENT	ii
LIST OF FIGURES	vi
LIST OF TABLES	vii
ABSTRACT	ix
RÉSUMÉ	x
CHAPTER I: GENERALITIES ON THE STUDY AREA AND PREVIOUS STUDIES	1
Introduction	4
I.1 BIOPHYSICAL AND HUMAN FRAMEWORK	4
I.1.1 Physical framework.....	4
I.1.1 Geographical and Administrative situation	4
I.1.2 Climate.....	5
I.1.3 Orohydrography.....	7
I.1.4. Vegetation.....	8
I.1.5. Geology.....	9
I.2. Human Framework	10
I.2.1. Population	10
I.2.2. Socio Economic activities.....	10
II. PREVIOUS WORKS	11
CONCLUSION	12
CHAPTER II: MATERIALS AND METHODS	4
Introduction	14
II.1. Bibliographic Research	14
II.2. Research materials	14
II.3. Field work	15
II.3.1. Reconnaissance and localization of the study site	15
II.3.2. Choice and Description of sampling points	16
II.3.3. Sampling and preparation of water and sediment samples	17
II.3.4. In-situ measurements of physicochemical parameters of water.....	21
II.4. Laboratory work	22

II.4.1. Filtration and conditioning of water samples	22
II.4.2. Estimation of Total Suspended Solids	22
II.4.3. Analysis of trace metal elements in sediment and water	23
II.4.4. Data processing (treatment)	24
II.4.4.1. Estimation of the intensity of metal contamination in water	24
II.4.4.2. Estimation of the intensity of metal contamination in sediments	28
CONCLUSION	30
CHAPTER III: RESULTS.....	15
Introduction.....	32
III.1. State of the sites and mode of gold exploitation in Batouri.....	32
III.1.1. Artisanal gold mining.....	32
III.1.2. Artisanal semi-mechanized gold mining.....	33
III.1.2.1. Mining area and associated infrastructure.....	33
III.1.2.2. Exploitation technique.....	33
III.1.2.3. Mining waste and wastewater management.....	34
III.1.2.4. Gold Extraction	34
III.2. Level of variation of physicochemical, physical and chemical quality of sediment and water in the Djengou and Mongoukele watershed.....	35
III.2.1. In-situ physicochemical quality of water (pH, Temp, EC, TDS).....	35
III.2.2. Physical Quality of water (TSS).....	35
III.1.3. Chemical Quality of sediments and water.....	36
III.1.3.1. Results of the chemical quality of stream sediments of the study area.....	36
III.1.3.2. Results of the chemical quality of surface water in the study area	37
Conclusion	38
CHAPTER IV: INTERPRETATION AND DISCUSSION OF RESULTS	33
Introduction.....	39
IV.1. Distribution, origin, and comparative study of heavy metals in sediments obtained from the study area from those of other mining sites	39
IV.2. Spatial variation of physicochemical Quality of water and comparative study	42
IV.2.1. Hydrogen potential (pH) and Electrical Conductivity (EC)	42
IV.2.2. Physical Quality of water (TSS)	43

IV.2.3. Water quality index, Heavy metal pollution index, and Degree of contamination of water	43
IV.2.4. Comparison of physicochemical and physical quality of water of the study area with other study areas	48
IV.2.5. Correlation of physicochemical and physical quality of water.....	49
IV.3. Impacts of Mining Exploitation on the Sediments and Water Quality of Batouri	50
IV.3.1. Impacts of mining exploitation on sediment quality.....	50
IV.3.2. Impacts of mining exploitation on water quality	51
IV.3.3. Environmental Impacts associated to the mode of exploitation in the study area ..	54
IV.3.4. Health impacts Associated to the physicochemical quality of sediments and water.	57
IV.4. Some Recommendations to Mitigate these Impacts.....	58
Conclusion	59
GENERAL CONCLUSION AND PERSPECTIVE	58
BIBLIOGRAPHY	62
ANNEX	xi

LIST OF FIGURES

Figure 1: Geographical and Administrative location of the study area: a) Cameroon in Africa; b) East region in Cameroon; c) Kadey division in the East region; d) Study area in the Kadey division (Extract from SRTM image 2017).....	4
Figure 2. The Ombrothermic diagram of Batouri from 1993-2022.....	6
Figure 3: Morphology of Batouri subdivision (modified from SRTM 30m images)	7
Figure 4: Hydrographic network of the Kadey watershed showing the Djengou River (MINEPAT/SRADDT-East 2017).....	8
Figure 5: The Geologic map of the Batouri subdivision (modified from Jean-Claude et al., 2019)	10
Figure 6: Localisation of the Djengou River in the Kadey basin (Extract of SRTM image 2017, modified using ArcGIS 10.8.2).....	16
Figure 8: Water sample collection a (Mongoukele) and b (Patere Lobi) (TALLA, August and May respectively).....	19
Figure 9: Collection of sediment sample at Patere Lobi and on a mining site at Kambele (TALLA, August and May respectively).....	20
Figure 7: Sampling Map (Extract of SRTM image 2017, modified using ArcGIS 10.8.2).	20
Figure 10: Tools used in artisanal gold mining in Batouri	32
Figure 11: Deviation of watercourse (a) and mechanical shovel (b).....	33
Figure 12: Level of variation of physicochemical parameter of water	36
Figure 13: The spatial variation of Total suspended solids in Waters of the study area	36
Figure 14: Deterioration of water (a) and reduction in water volume (b).....	52
Figure 15: land degradation at Kambele leading to creation of artificial lakes	55
Figure 16: Deforestation	56
Figure 17: Children swimming in the Djengou River leading to exposure to contaminants.....	57

LIST OF TABLES

Table 1: Average monthly and annual precipitation values, and temperatures (1993-2022) and aridity index of the city of Batouri (source: climatchart.com).....	5
Table 2: Location and geographical coordinates of water sampling points	17
Table 3: Location and geographical coordinates of sediment sampling points.	18
Table 4: Relative weight of each parameter based on the WHO standard (2017)	26
Table 5: Different classes of water quality index (WQI)	26
Table 6: Different classes of degree of contamination	28
Table 7: Contamination factor and contamination levels.....	29
Table 8: Degree of contamination and contamination level	29
Table 9: Classes defined by the geo-accumulation index	30
Table 10: Level of variation of physicochemical parameter of water.....	35
Table 11: Results of heavy metal analysis in sediments	37
Table 12: Results of certain trace metal elements in water of each sampling point	37
Table 13: Results of Contamination Factor (CF), Degree of Contamination and Pollution Load Index (PLI).....	40
Table 14: Comparative Studies of average heavy metal obtained in this study from those of other mining areas in Cameroon and around the world	41
Table 15: The Pearson correlation matrix of metallic elements in sediment	41
Table 16: Relation between electrical conductivity and mineralization (Detay. 1993)	42
Table 17: Variation and standard of the Physical quality (TSS) of Water in Batouri defined by the WHO (2017) for drinking water	43
Table 18: Results of the water quality index on the mining site at Kambele (BSW02)	44
Table 19: Results of the water quality index after the mining site at Patere Lobi (BSW03).....	44
Table 20: Results for Heavy Metal Pollution Index (HPI) of the Djengou and Mongoukele watercourse	45
Table 21: Degree of contamination of heavy metal in water	48
Table 22: Comparing average values of physicochemical parameters present in Djengou River (present study) with those of waters of other rivers and streams in Ghana, Cameroon and Colombia.....	49
Table 23: Correlation matrix of physicochemical and physical parameters	50

LIST OF ABBREVIATIONS

As	:	Arsenic
ASGM	:	Artisanal Small-scale Gold Mining
BS	:	Batouri Sediment
BSW	:	Batouri stream water
BVD	:	Basin Versant de Djengou
CAFB	:	Central African Fold Belt
CC	:	Congo Craton
CF	:	Contamination Factor
DEM	:	Digital Elevation Model
Fe	:	Iron
GPS	:	Global Positioning System
Hg	:	Mercury
HPI	:	Heavy Metal Pollution Load Index
Igeo	:	Geo-accumulation index
IPE	:	Individual Protection Equipment
IRGM	:	Institute of Geological and Mining Research
LAGE	:	Laboratoire d'Analyse Géochimique des eaux
Pb	:	Lead
PLI	:	Pollution Load index
TDS	:	Total Dissolved Solids
TSS	:	Total Suspended Solids
WHO	:	World Health Organisation
WQI	:	Water Quality Index
XRF	:	X-ray Florescence,
		Zn :
		Zinc

ABSTRACT

Artisanal and semi-mechanized gold mining in developing countries has raised significant concerns about the degradation of sediment and water quality. It is in this context that this study aims to assess the impacts of gold mining on the sediment and water quality of the Djengou watershed in eastern Cameroon. To do this, in addition to an intense bibliographic research, field and laboratory observations and investigations were carried out such as: in-situ measurement of physicochemical parameters, sampling of sediments and water in the dry season (May) and rainy season (August) during the year 2024, determination of total suspended solids (TSS) and analysis of heavy metals (Hg, As, Pb, Fe and Zn) of the collected samples. There are two modes of gold mining exploitation in the study area which are artisanal gold mining characterized by small motor pumps, sluices, pans, barrels, shovels and pick axes and semi-mechanized gold mining characterized by the use of mechanical shovels, and chemical products such as mercury for gold amalgamation. On the physicochemical level, the waters of the Djengou watershed (BVD) are slightly acidic to slightly basic ($6.5 \leq \text{pH} \leq 7.3$), weakly to moderately mineralized ($145 \leq \text{EC} \leq 662 \mu\text{S/cm}$). Total suspended solids range from 3 to 681.5 mg/l, with an average of 225.5 mg/l. Seasonal and spatial variations in physicochemical parameters indicate severe pollution related to artisanal and semi-mechanized gold mining practices. The use of assessment tools such as the water quality index (WQI), the heavy metal pollution load index (HPI), the degree of contamination (DC) for water, the contamination factor (CF), the pollution load index (PLI) and the geo-accumulation index (I_{geo}) for sediments, revealed the presence of heavy metals such as Hg, As, Pb, Fe and Zn at concentrations higher than the WHO standard values. The latter have higher concentrations in the rainy season than in the dry season due to increased runoff and leaching. Heavy metal contamination of sediments and water objectively justifies the major problems (access to drinking and domestic water, health problems and extinction of aquatic species) encountered in this locality. Recommendations to mitigate these environmental and health impacts include drilling boreholes away from active mining sites, the use of natural filters (charcoal and sand), implementation of IWRM, sensitization and education of the local population to support water resource management.

Keywords: environment, Artisanal mining, Heavy metals, Sediments, physicochemical.

RÉSUMÉ

L'exploitation artisanale et semi-mécanisée de l'or dans les pays en voie de développement ont suscité d'importantes inquiétudes sur la dégradation des sédiments et qualité de l'eau. C'est dans ce contexte que la présente étude vise à évaluer les impacts de l'exploitation aurifère sur la qualité des sédiments et eaux du bassin versant de Djengou à l'Est-Cameroun. Pour ce faire, outre une intense recherche bibliographique, des observations et investigations sur le terrain et en laboratoire ont été effectuées comme : la mesure in-situ des paramètres physico-chimiques, le prélèvement des sédiments et l'eau en saison sèche (mai) et de pluies (août) durant l'année 2024, la détermination des matières en suspension (MES) et l'analyse des métaux lourds (Hg, As, Pb, Fe et Zn) des échantillons prélevés. Il existe deux modes d'exploitation de l'or dans la zone d'étude qui sont l'exploitation artisanale caractérisée par de petites pompes à moteur, des écluses, des casseroles, des barils, des pelles et des pioches et l'exploitation semi-mécanisée caractérisée par des pelles mécaniques et des produits chimiques tels que le mercure pour l'amalgamation de l'or. Sur le plan physico-chimique, les eaux du BVD sont légèrement acide et légèrement basique ($6.5 \leq \text{pH} \leq 7.3$), faiblement à moyennement minéralisé ($145 \leq \text{CE} \leq 662 \mu\text{S}/\text{cm}$). Les matières en suspension oscillent de 9,5 à 681,5 mg/l, pour une moyenne de 225.5 mg/l. Les variations saisonnières et spatiales des paramètres physicochimiques indiquent une pollution sévère liée aux pratiques d'exploitation artisanale et semi-mécanisée de l'or. L'utilisation des outils d'évaluation tels que l'indice de qualité de l'eau (IQE), l'indice de charge de pollution par les métaux lourds (IPM), le degré de contamination (DC) pour l'eau, le facteur de contamination (FC), l'indice de charge de pollution (PLI) et l'indice de géo-accumulation (Igeo) pour les sédiments, ont révélé la présence de métaux lourds tels que Hg, As, Pb, Fe et Zn à des concentrations supérieures aux valeurs standards de l'OMS. Ces derniers ont des concentrations plus élevées en saison des pluies qu'en saison sèche en raison de l'augmentation du ruissellement et du lessivage. La contamination des sédiments et l'eau par les métaux lourds justifiant objectivement les problèmes majeurs (accès à l'eau potable et domestique, problème sanitaire et extinction des espèces aquatiques) rencontrés dans cette localité. Les recommandations pour atténuer ces impacts environnementaux et sanitaires incluent les forages de puits loin des sites miniers, l'utilisation de filtres naturels (charbon et sable), mise en œuvre de la GIRE, la sensibilisation et l'éducation de la population pour soutenir la gestion des ressources en eau.

Mots-clés: environnement, exploitation artisanal, Métaux lourds, Sédiments, physico-chimique.

GENERAL INTRODUCTION

Of all the natural resources necessary for living, water is essential to sustain all kinds of life on Earth. Although water is plentiful, it is frequently scarce and characterized by an uneven spatiotemporal distribution (Melesse, 2011; Brooks et al., 2013; Wang et al., 2019). Majority of these resources is saline and in Oceans. Fresh water, which is essential for human, plant and animal life, constitutes only 2.5% of the total water on earth. Of this fresh water, a significant portion is locked in ice caps, glaciers, and underground aquifers, with only a small fraction available as surface water in rivers, lakes, and swamps (Hinton et al., 2003). In recent years, there has been significant increase in water demand due to rapid urbanization, industrial development, irrigation, population increase, poor water management, improvements in the standard of living, and gold mining exploitation (Zhang et al., 2009).

Globally, water resources have been a subject of debate on the environment and sustainable management. These resources are subject to several pressures (Mining activities, climate change) which results in stream sediment contamination and water quality degradation (Ayiwouo et al., 2022). Stream sediment contamination, resulting from erosion and runoff, further exacerbates the problem by affecting aquatic habitats and the organisms that depend on them (Smith and Huyck, 2018). These impacts are not confine to a single region but are observe in various mining areas around the world (World Bank, 2019; Ralph et al., 2018). This stream sediment contamination and water quality degradations is due to uncontrolled urbanization, agriculture, mining exploitation associated with climate variability and/or change.

Cameroon, which is a developing country in Africa, also experiences the degradation of its natural water resources despite being African in Miniature due to its geographical position. The water resources in Cameroon are unevenly distributed from the north to the south and from rural to urban areas. These resources are divided into two zones, which are the basement zone and the sedimentary zone (Sighomou. 2004). The basement zone represents approximately 90% of the national territory compared to 10% for sedimentary zone (MINEE, 2009). Water resources in Cameroon have undergone significant degradation from mining activities. Studies have shown that rivers and streams near mining sites contain elevated levels of heavy metals, such as mercury and lead, which pose serious health risks to local communities and wildlife (Ayiwouo et al., 2022). The stream sediment contamination disrupts aquatic ecosystems, leading to a decline in biodiversity and the degradation of habitats. Additionally, Mambou Ngueyep et al. (2021) highlighted the impact of gold mining activities on the Lom River in Wakaso, Cameroon, noting

significant contamination with heavy metals and the potential of *Moringa Oleifera* seeds for pollutant removal.

The Batouri gold district in the East region of Cameroon has been a significant site for gold mining activities over the past few decades. These activities have contributed to the economic development of the region and provided livelihoods for many local residents. (Ralph et al., 2018; Jean Claude et al. 2019). However, the environmental consequences of gold mining, particularly on sediment quality and water resources, have raised considerable concerns. Gold mining in the Batouri district involves extensive land excavation, the use of heavy machinery, and the application of various chemicals for ore processing (Kouankap et al., 2017). These practices have led to the disruption of natural landscapes, increased sedimentation in water bodies, and contamination of both sediment and water with hazardous substances such as heavy metals (Mambou Ngueyep et al. 2021). The resultant environmental degradation not only affects the local ecosystem but also poses health risks to communities dependent on these natural resources.

A certain number of works has been carried out concerning the degradation of stream sediment and water resources in Batouri. We can cite amongst others the work of Kouankap et al., 2017 who carried out his study at Kambele and Mongonam; Mambou Ngueyep et al. 2021 who worked in the upstream of all mining sites in Batouri, Along the Djengou and downstream of all mining sites in the Kadey; Jean Claude et al. 2019. Previous studies may have focused on isolated aspects such as water quality or soil contamination. However, this study integrates the analysis of both sediment contamination and water quality, providing a holistic view of the impacts of gold mining exploitation on sediment and water quality. The main objective of this study is to determine the impacts of mining exploitation on sediment and water quality. To carry out this study effectively specific objectives were fixed which include:

- Identifying the mode of gold mining exploitation ;
- determining the quality of sediment and watercourse that erodes these sediments ;
- evaluating the impacts of mining exploitation on sediment and water quality ;
- proposing practical recommendations for remediation efforts to mitigate the identified impacts of mining exploitation on sediments and water.

This work begins with a general introduction and ends with a general conclusion; it is structured into four chapters

- the first chapter presents the study area and previous complimentary work
- the second chapter presents the materials and methods used for data collection
- the third chapter presents the results obtained from the field and the laboratory
- Finally, chapter four focuses on the interpretation of results, impact of mining exploitation on sediments and water quality and the recommendations.

**CHAPTER I: GENERALITIES ON THE STUDY AREA AND
PREVIOUS STUDIES**

Introduction

This chapter presents the physical and human framework of the Batouri subdivision and previous works carried out in Geology, mining and hydrogeology in the study area and its surrounding.

I.1 BIOPHYSICAL AND HUMAN FRAMEWORK

I.1.1 Physical framework

I.1.1 Geographical and Administrative situation

The Batouri subdivision, which is the zone chosen for this study, is located in the East region of Cameroon more precisely in the Kadey Division. It extends between 4°25'N and 4°30'N latitude and 14°20'E and 14°25'E longitude covering a surface area of 5786 km² of the territorial space. The Batouri subdivision is limited to the North by the Kette subdivision, to the East by the Central African Republic (CAR), to the south East by Kenzout, at the south it is limited by the Mbang and Ndelele sub-division and to the west its shares its boundary with Lom and Djerem divisions (Figure 1).

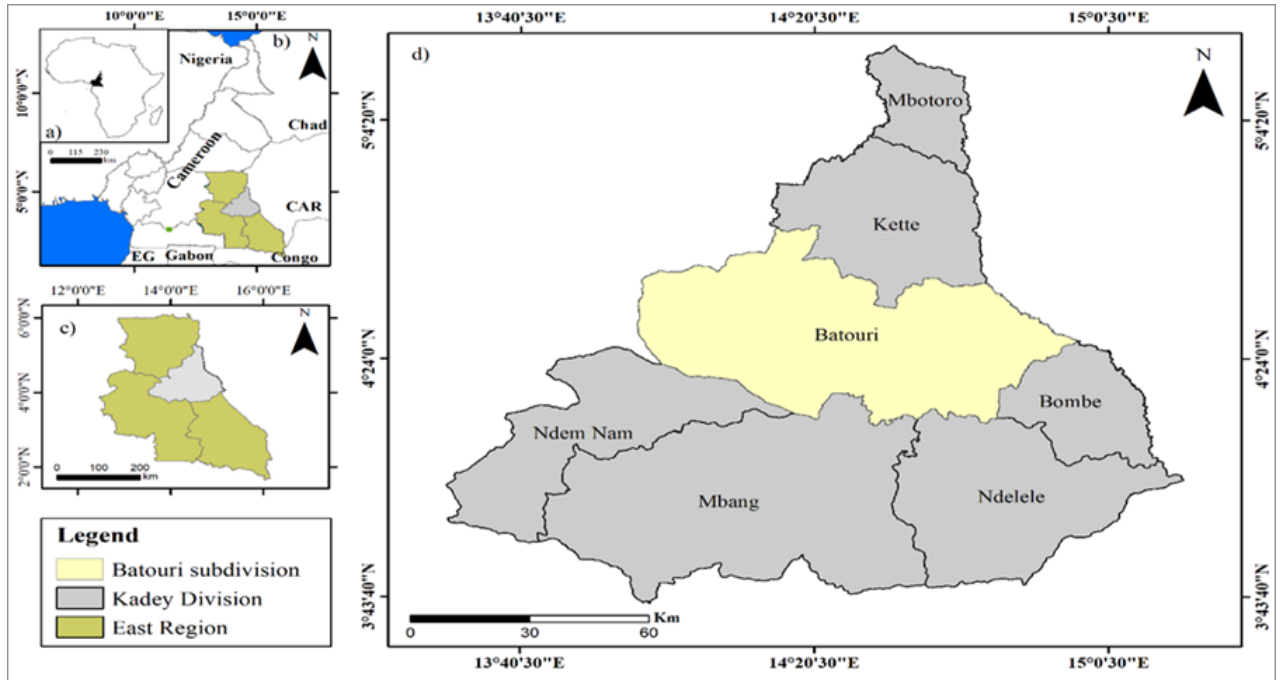


Figure 1: Geographical and Administrative location of the study area: a) Cameroon in Africa; b) East region in Cameroon; c) Kadey division in the East region; d) Study area in the Kadey division (Extract from SRTM image 2017).

I.1.2 Climate

The climatic data collected from weather base allowed us to characterise the climate of Batouri and its surroundings. The parameters taken into consideration are precipitation and Temperature.

I.1.2.1 Precipitation

Precipitation plays an important role in the distribution of water resources in the region. The total annual rainfall of Batouri and its surrounding is 1525mm for a period of 29years (1993-2022). The rainiest month is October with 257.8mm of rainfall and January is the most dried month with 18.2mm of rain. The area has a transitional equatorial and tropical climate type (Olivry, 1986; Suchel, 1988; Sighomnou, 2004) with two rainy seasons interspersed with two dry seasons; a short rainy season from mid-march to June; a short dry season from June to mid-August; a long rainy season from mid-August to mid-November; and a long dry season from mid-November to mid-march.

I.1.2.2 Temperature

The inter-annual monthly average temperature is 24.5⁰C for the period 1993-2022. The hottest month is March (24.9⁰C) and July is the coldest month (23.7⁰C) (Table 1)

Table 1: Average monthly and annual precipitation values, and temperatures (1993-2022) and aridity index of the city of Batouri (source: climatchart.com)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Av/S
P(mm)	18.2	30.5	102.5	131.3	177.8	155.7	128.9	163.9	231.7	257.8	99.3	27.4	1525
T(°C)	24.1	25.5	25.9	25.8	25.1	24.2	23.7	23.8	23.9	24.2	24.3	23.8	24,5
I _a	6.40	10.31	34.26	44.01	60.79	54.63	45.90	58.19	82.02	90.46	34.74	9.73	44.29

Key P: precipitation, **T:** temperature, **I_a:** aridity index, **Av:** Annual average, **S:** Sum

I.1.2.3 DE Martonne aridity index

The DE Martonne aridity index (1942), denoted I_a, is a parameter that distinguishes months considered dry from the months considered to be wet during a given period. It is given by the relationship:

$$I_a = \frac{Pm(mm) \times 12}{T(^{\circ}C) + 10}$$

With; Ia: DE Martonne aridity; Pm (mm): average monthly precipitation; T (°C): average monthly temperature.

According to DE Martonne:

- if Ia < 20, the month is considered a dry month
- if 20 < Ia < 50, the month is said to be sub-dry
- if Ia > 50, the month is considered to be humid

The periods from 1993-2022 shows that the month of January, February and December are considered to be dry months, the month March, April, July and November are considered sub-dry meanwhile the month of May, June, August, September, and October are humid months (Table 1).

I.1.2.4 Ombrothermic diagram of Bagnouls and Gausson (1957)

This diagram obtained from the rainfall (mm) and thermal (°C) data of a given region makes it possible to distinguish the dry months from the rainy months.

A month is said to be dry if the average monthly rainfall obtained is less than double the temperature obtained during the month considered ($P < 2T$) according to this diagram (figure 2), the months of December, January, and February are dry months while the month of March, April, May, June, July, August, September, October and November are rainy.

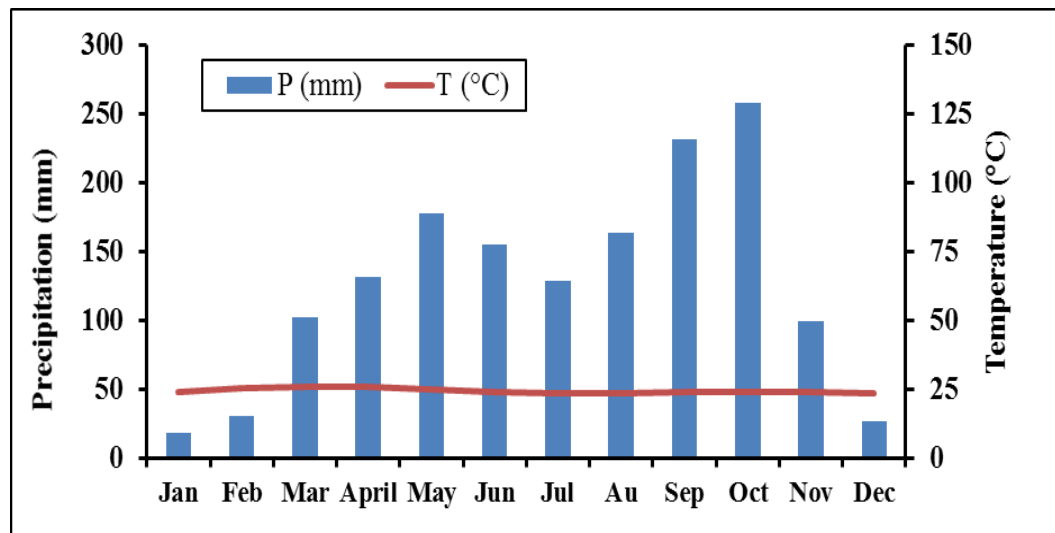


Figure 2. The Ombrothermic diagram of Batouri from 1993-2022.

I.1.3 Orohydrography

I.1.3.1. Orography

The East region lies on the south Cameroon plateau. The dominant relief of the Batouri subdivision is relatively flat with an average altitude that varies between 600m and 1000m above sea level (Figure 3). The landscape of this area includes features known as half-oranges, which are gently rolling hills; supporting a forest and savannah cover. A large granite outcrop called Mt. Pandi is situated about 25 km north of Batouri town. Steep slopes is observe, but it remains much localized.

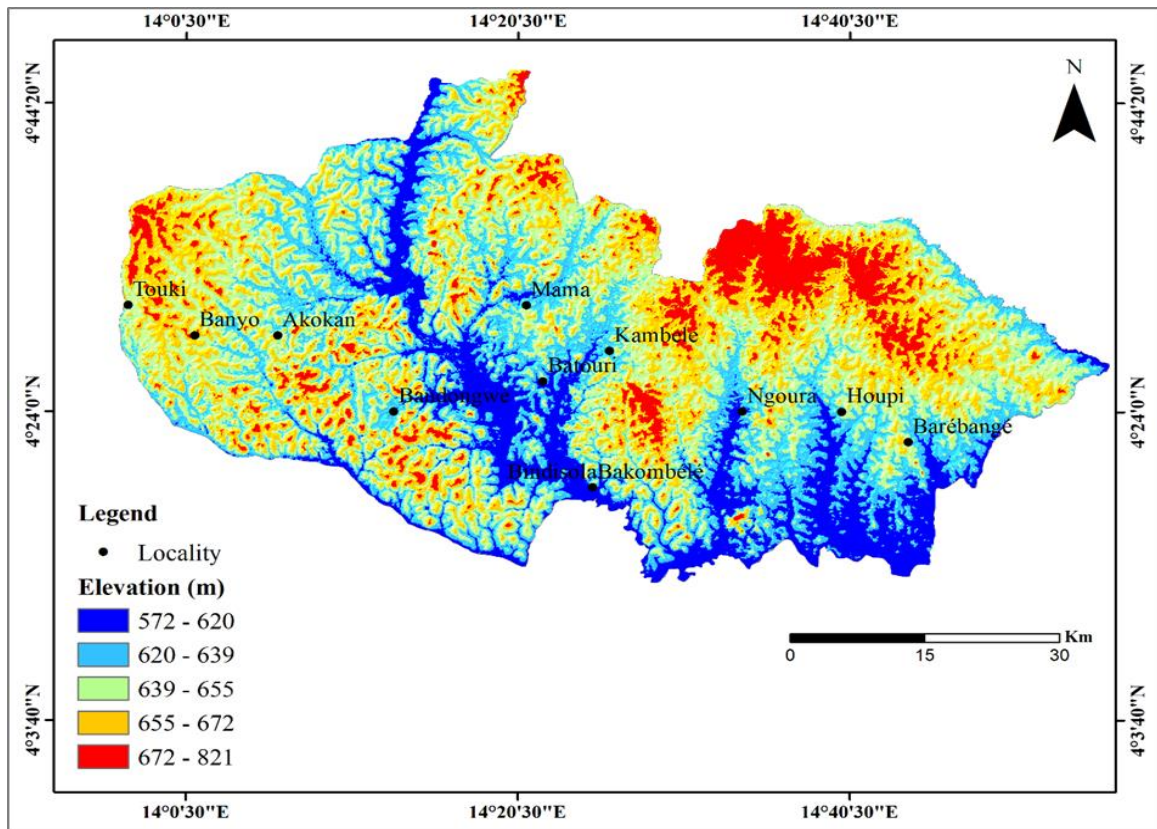


Figure 3: Morphology of Batouri subdivision (modified from SRTM 30m images)

I.1.3.2 Hydrography

The study area belongs to the Kadey watershed. The Kadey River, the main right-bank tributary of the Sangha, drains this. The Kadey rises at an altitude of around 900 m before the town of Garoua Boulai in the Lom and Djerem Division, in a small village called Badjéré. To the east, it forms the border between Cameroon and the Central African Republic, running some 180 km from the south to the north of the country via one of its tributaries: Boumbé II, which rejoins the

main river on its left bank at Kenzout. From west to east, the river joins on its right bank the Koubou downstream of Ngoura and the Doumé near the town of Mindourou, just before its outlet at Pana (Figure 4).

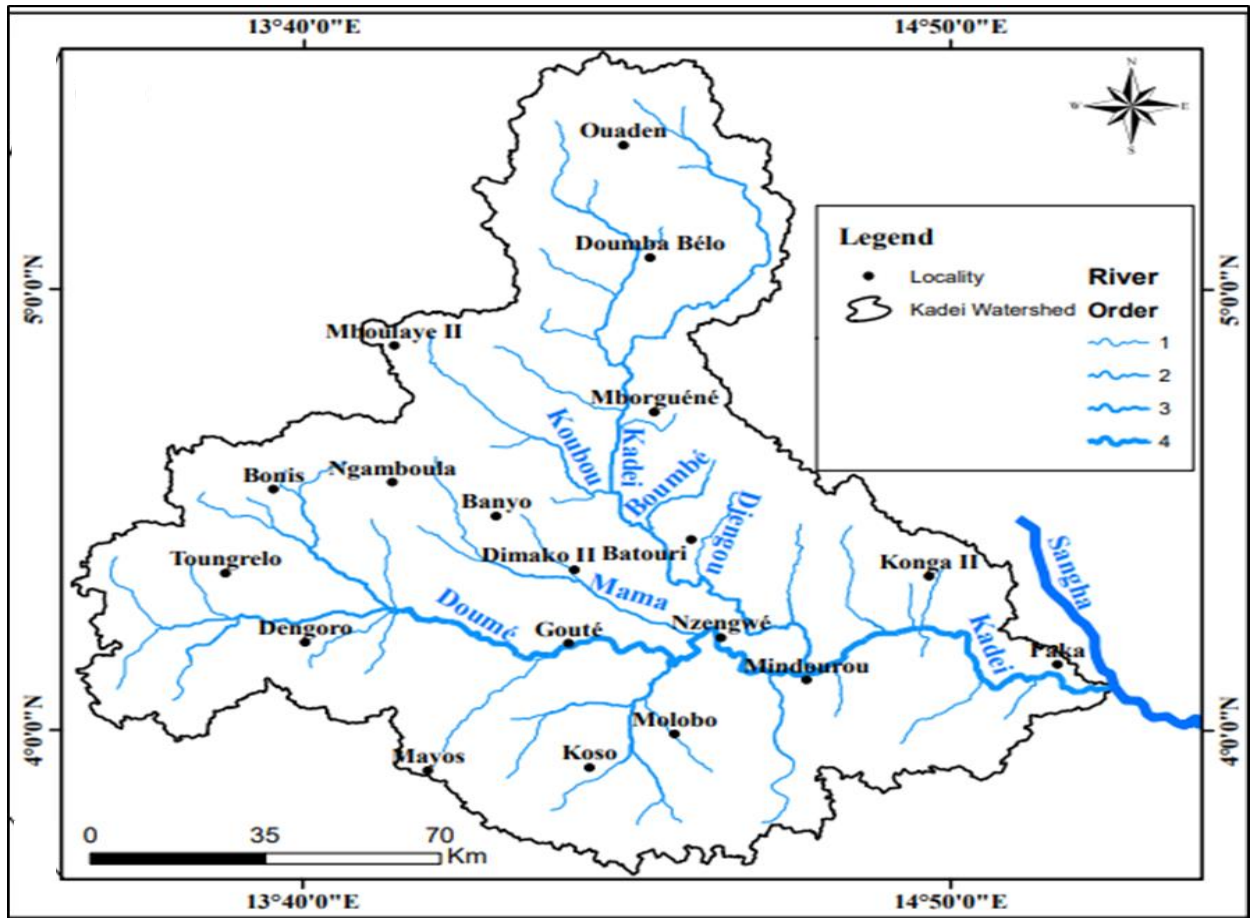


Figure 4: Hydrographic network of the Kadey watershed showing the Djengou River (MINEPAT/SRADDT-East 2017)

I.1.4. Vegetation

The study area belongs to the dense humid semi-deciduous forest with bimodal rainfall (Letouzey, 1968; Olivry, 1986; IRAD, 2008). The area has a grassy savannah forest in the north and lush forest in the south. The district presents alternations of grassy savannahs, forest galleries that give way to large forest penneplain to the south which are lower from the northwest to the southeast at an average altitude of 700m. This vegetation varies how however according to the characteristics of the substrate soil. The bottom of the valleys occupied by a relatively dense forest made up of trees with relatively high stems (20-30 m). In the areas of lateritic carapace, rocky and cuirassed outcrops, the shrub cover is not very dense.

I.1.5. Geology

I.1.5.1. Rock type

The study area falls within the Adamawa-Yade domain (Asaah et al., 2015; Vishiti et al., 2015; Tchakounté et al., 2017). Orthogneiss and granitoids such as tonalite, granodiorite, syenomonzo-granite, and alkaline granite and other metamorphic rocks characterize this domain. The gold in Batouri is hosted by orthogneiss and migmatites (Figure 5), which are significant hosts for gold mineralization (Jean-Claude et al., 2019). The geological setting of Batouri is controlled by tectonics and lithology, and the gold deposits are considered epigenetic, emplaced in an orogenic setting during the post-collisional stage of the Central African Fold Belt (CAFB) and the Congo Craton (CC) (Jean-Claude et al., 2019).

I.1.5.2. Soil type

The soils of Batouri develop by the alteration of the underlying granitoids, orthogneisses and migmatites. There are four (4) main types of soil in the area;

- **The lateritic soils**

These are soils found in the upper parts of landscape and are formed from intense weathering of rocks, particularly under high temperatures and high rainfall conditions.

- **The ferralitic soils**

These soils evolve and develop from the weathering of granitoids, orthogneisses and migmatites. Primarily made up of minerals like quartz, kaolinite, gibbsite, hematite, muscovite and anatase. Over time, these soils have experienced intense leaching and the accumulation of iron and aluminium oxides, leading to their characteristic reddish or yellowish colours. On the ferralitic soils, we schematically observe the yellow sandy clay soils, and the gravelly sandy soils. The ferralitic soils are poor in nutrients, acidic and fragile, covered by the forest, very permeable and rich in humus.

- **Hydromorphic Soils**

These are marshy soils saturated with water, found around water bodies. Characterized by a high accumulation of organic matter. They are black soils, poorly drained, with high porosity and acidic pH.

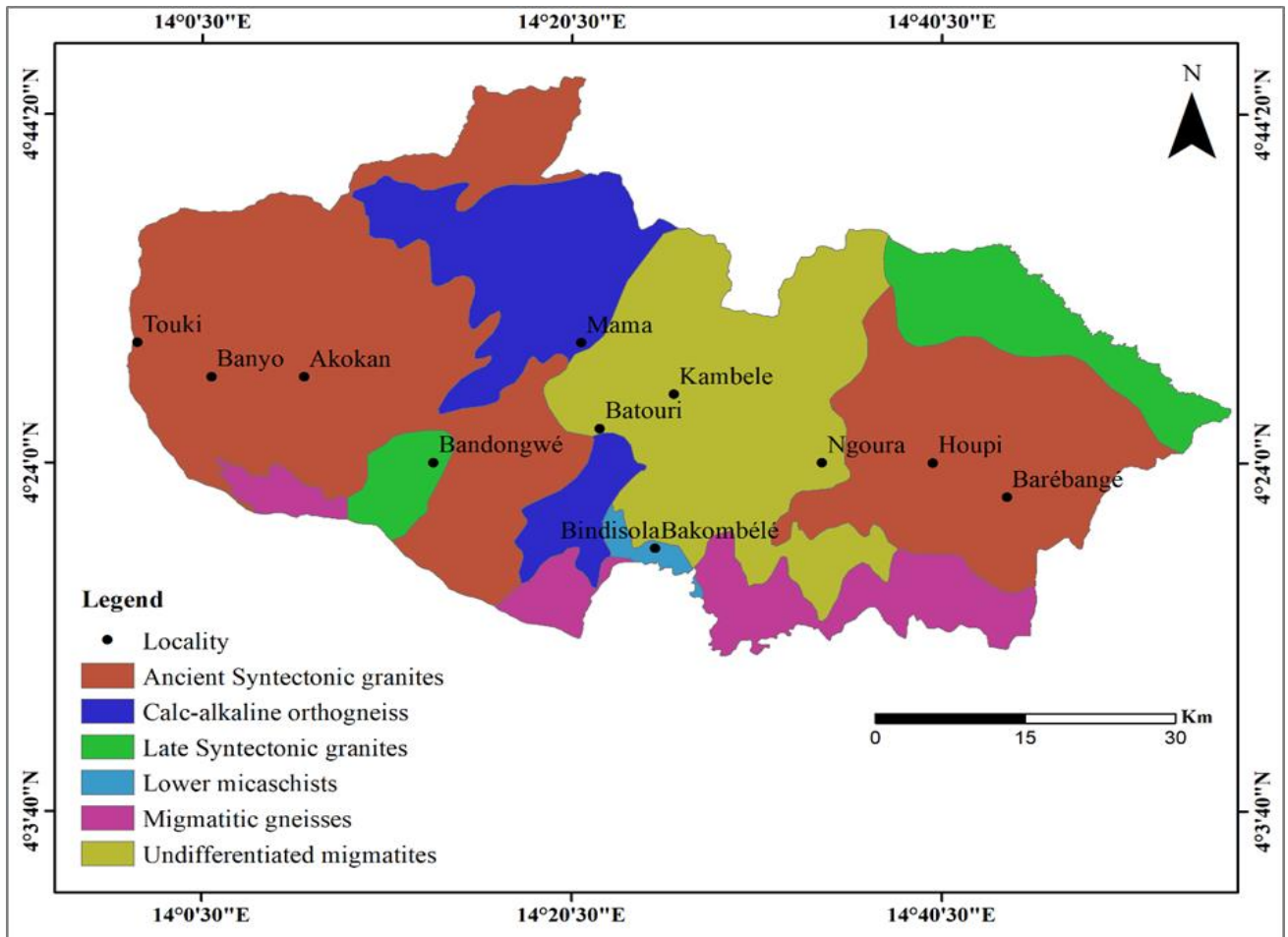


Figure 5: The Geologic map of the Batouri subdivision (modified from Jean-Claude et al., 2019)

I.2. Human Framework

I.2.1. Population

According to the population census of 2015 (National Institute of Statistics (NIS)), the population of Batouri subdivision was estimated at 89,462. Amongst these populations, 20,000 people are living in urban areas and 64,462 inhabitants in rural areas. This area has a mixture of tribes made up of the Fulbe (Fulani), Baya, Yangele, and Mezime. Additionally, there are many recent immigrants from the southern parts of Cameroon, and Central African Republic. The area also has notable Muslim population, who resides in the Mokolo quarter.

I.2.2. Socio Economic activities

Socio-economic activities refer to agriculture, livestock, trade, crafts, mining activities, and tourism. Agriculture is the main activity of the populations of the Batouri subdivision. The main crops cultivated are food crops (Cassava, maize, groundnuts, and plantain) and market

gardening (carrots, cucumber, peppers, lettuce, and tomatoes). Many artisans in the area practice traditional crafts, such as weaving, pottery, and woodcarving. Artisanal gold mining is one of the major activities in the area. The area has gold deposits that is been exploited by local miners for many years.

II. PREVIOUS WORKS

Artisanal small-scale gold mining (ASGM) and Semi-mechanized mining is a significant economic activity in many developing regions, particularly in sub-Saharan Africa. Gold mining, especially in small-scale and artisanal settings, has long been recognized for its significant environmental impacts. In regions such as the Batouri gold district in the East Region of Cameroon, mining activities often rely on rudimentary techniques, including mercury amalgamation, which can have severe consequences on both water and sediment quality. This review highlights the impacts of ASGM and semi-mechanized gold mining on sediments and water quality. Artisanal gold mining involves various processes from excavation to the final product, as detailed by Ashley and Carney (1999), Hinton et al. (2003), Hilson (2009). These various processes can lead to significant environmental degradation such as land usage, land cover change, deforestation, open pits, construction of camps and infrastructures (Kamga et al, 2020; Ngoa Manga et al.2024). The measurement of physicochemical parameters is essential for assessing the quality of sediments and water in mining-affected regions. Parameters such as pH, turbidity, dissolved oxygen, and temperature provide critical insight into the extent of contamination and the ecological health of water bodies. Simate and Ndlovu (2014) focus on acid mine drainage (AMD), a common problem in mining regions where acidic water, often rich in heavy metals, flows into rivers and streams, leading to significant deterioration in water quality. Kounkap et al. (2018) investigated the environmental effects of gold mining on the quality of surface water; their study found out that the degradation of water quality through the leaching of toxic substances into nearby rivers is as a result mining activities. Mambou Ngueyep et al. (2019) examined the socio-environmental impacts of gold mining highlighting the complex relationship between mining activities, local communities, and environmental degradation, focusing on the contamination of water sources that local populations rely on for drinking and agriculture. There has been detection of high levels of mercury contamination, linked to ASGM activities in the Lom River Basin, leading to concerns about both ecological and human health. The findings of this study shows physicochemical parameters like pH, total suspended solids and

total mercury to be above the drinking water standard. Water quality varies seasonally and spatially with better water quality during the high water periods (Bella Atangana et al., 2023). According to the study of Mambou Ngueyep et al. (2021), mining activities in Batouri has increased the levels of suspended solids and heavy metals such as Ni, Fe, Cr, Se, Pb, As, Hg and Cd in the water making it unsuitable for human consumption. Additionally, the water is acidic to slightly basic, weakly conductive, and turbid, further indicating water quality degradation (Mambou Ngueyep et al., (2021).

There have been lapses in the mining regulations in Cameroon, which turn to have negative effects on the health of the ignorant local miners and children who are exposed to mercury from sediment and water. The mean blood mercury and lead levels among miners is $2.27 \pm 8.85 \mu\text{g/L}$ and $12.73 \pm 32.73 \mu\text{g/L}$ respectively, and 9.1% of them are chronically intoxicated with mercury, reporting ≥ 4 symptoms possibly related to mercury intoxication (Kouankap et al.,2017; Ralph et al., 2018; Yannick.,2022).

The mining environment fosters negative social impacts on the local population through Health problems, high rates of prostitution, low levels of education, alcoholism and poor hygiene contributing to the spread of disease (Kouankap et al., 2017). ASGM and mechanized gold mining represents a double-edged sword offering economic opportunities while simultaneously posing significant impacts on sediments and water quality. Comprehensive studies and assessments are necessary to develop effective management strategies that mitigate these risks while still supporting the livelihoods of those engaged in ASGM.

CONCLUSION

The town of Batouri is the area chosen for this study. It is located in the East region of Cameroon, more precisely in the Kadey division between $4^{\circ}25'N$ and $4^{\circ}30'N$ latitude and $14^{\circ}20'E$ and $14^{\circ}25'E$ longitude. The study area is located on the south Cameroon plateau with the average morphological units ranging between 600m to 1000m and with a dendritic hydrographical network drains. The region falls within the transitional equatorial and tropical climates marked by four (4) seasons interspersed making it favourable for the development of semi-deciduous forest, grassy savannah and lush forest. The area lies on the Pan-African formation composed of Granodiorite, tonalite, syeno-monzogranite, differentiated orthogneiss, leucogranite and alkaline granite. The coming of Artisanal and semi-mechanized gold mining has led to significant disturbance of the environment. This work has as aim to study the impact of

Artisanal and semi-mechanized gold mining on the physicochemical, physical and chemical parameters of sediment and water in the Batouri gold district.

CHAPTER II: MATERIALS AND METHODS

Introduction

To achieve the objectives set in this work, this chapter presents bibliographic research and briefly describes the materials that were mobilize and methods used in the field and in the laboratory in order to achieve the expected results.

II.1. Bibliographic Research

This step made it possible to develop a synthesis of the work carried out in the study areas (Batouri subdivision) and its surroundings as well as those carried out in areas with the same climatic and geological context. Scientific works (articles, dissertations and doctoral thesis). Cartographic documents, satellite images, and aerial photographs of the study area were also consulted.

II.2. Research materials

The realisation of this work was done thanks to different materials and logistical means from different documents to technical materials:

- Research attestation issued by the head of department in Earth sciences at the University of Yaoundé 1 to ease access to the different localities;
- topographic map and existing literature of Batouri to better know the area before embarking on the field;
- GPS (Global Positioning System) to take the geographical coordinates of the study area and sampling points;
- a laptop of mark (DELL) for typing, saving and treatment of collected data;
- an android cell phone with the application Mapme installed in it for orientation in the field and to capture images of the study sites;
- individual Protection Equipment's (IPE) to protect against possible risk in the field;
- pens, pencil, Eraser and notebook to record data in the field;
- multipara meter with 3 electrode to measure the physicochemical parameter of water in-situ;
- 1.5L polyethylene bottles for the collection of water samples;
- bucket and plastic sample bag for sediment sampling and packaging;
- high power tape and marker for codification;

Digital tools or Applications used include;

- Microsoft word 2010 for typing texts and equations;
- Microsoft excel 2010 for calculation of data and drawing of curves;
- google Earth, Mapme, for Aerial photographs;
- ArcGIS for realisation of thematic maps and exploratory analysis.
- Excel Analysis tool Pak for statistical analysis of data and multivariate statistical analysis.

II.3. Field work

The fieldwork consisted of the reconnaissance and localization of the study site, the choice and description of sampling points, the collection and conditioning of water and sediment samples for laboratory analysis and the in-situ physicochemical parameters of water.

II.3.1. Reconnaissance and localization of the study site

A reconnaissance campaign of the study site (Batouri) was carried out in the month of May 2024. Its aim was to assess all the difficulties in order to have an idea of the area and the work to be done. The campaign also made it possible to identify the watercourses around the mining sites of Batouri (Djengou and Mongoukele watercourse; Describing the physical and human framework; Meeting administrative leaders, traditional leaders and other stakeholders (chef chantier) involved in the semi-mechanised artisanal gold mining chain of Batouri; Describing the exploitation site and the practical technics of exploitation.

The site selected for this study is the Djengou and Mongoukele watershed. It is located in the Kadey division (East region of Cameroon) between latitudes $4^{\circ}28'N$ and longitude $14^{\circ}24'E$ in Kambele. The Djengou River is the main watershed and collector in Kambele including Mongoukele who empties itself in the Djengou flowing from the northern to the southern part of Batouri subdivision (figure 6). The river facilitates gold mining in the various mining sites of Kambele and Patere Lobi etc.

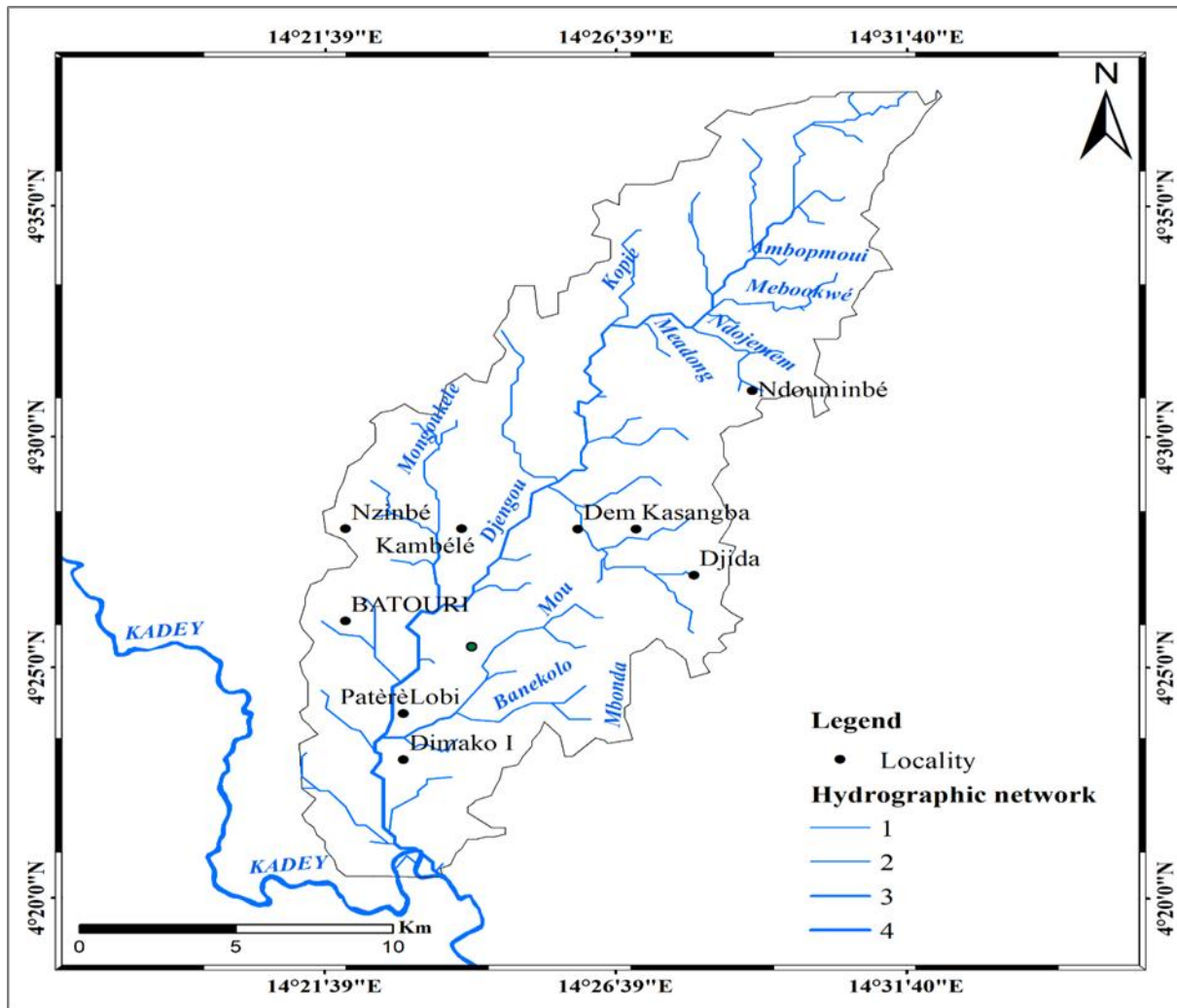


Figure 6: Localisation of the Djengou River in the Kadey basin (Extract of SRTM image 2017, modified using ArcGIS 10.8.2).

II.3.2. Choice and Description of sampling points

A certain number of reasons prompted the choice of the study area. They include;

- High mining activity in the area;
- environmental concerns as previous studies have highlighted severe environmental issues in the area;
- the unique geological features of the area;
- easy Access to the area through tarred and village roads fairly well maintained.

To carry out sampling in this region we choose Mongoukele stream as our control point since no mining activities are taking place there. Kambele locality was the area we focused on evaluating the water quality and sediment quality degradation due to intense mining activities taking place along the Djengou stream, which is the main water body in the area. We also went to the Patere Lobi locality 8.7km from Kambele mining site downstream of the Djengou stream. Seventeen (17) samples were collected from these three (3) localities; twelve (12) water samples and five (5) sediment samples.

II.3.3. Sampling and preparation of water and sediment samples

Water Sampling

For the collection of water samples, four (4) sampling campaigns were done throughout this study from the month of May to the month of August 2024. Twelve (12) water samples were collected. Sampling was done once every month for 4 months including 1 month of dry season (May) and three months of rainy season (June, July and August). Samples BSW00 were collected on the control site; BSW01 on a new mining site; BSW02 on the mining site at Kambele; BSW03 downstream of the gold mining site (figure 7). The coordinates of these points were taken with a GPS and recorded in the notebook with a pen. The location and geographical coordinates of the water sampling points are presented in Table 2.

Table 2: Location and geographical coordinates of water sampling points

Water sample	Latitude (N) (°)	Longitude (E) (°)	Altitude (m)	locality
BSW00	4.4639183	14.3918233	623	Mongoukele (upstream)
BSW01	4.4513889	14.3924667	613.75	Mongoukele (downstream)
BSW02	4.4675333	14.4161111	619	Kambele
BSW03	4.4039517	14.3795783	602.51	Patere-Lobi

Sediment Sampling

The sediment sample collected was very fine silt to clay material because these fine fractions have the tendency to absorb more metallic ions and thus gives a stronger response for the target elements. A 700grams of fine grained materials less than 0.18 mm were collected without excluding organic matter because their capacity to absorb metals is very high that real

anomalies can result. Some contaminants present in very low concentrations in water such as organic and micro-contaminants are easily detectable in sediments. The sediment samples taken at the same points or near the geographical coordinates of the water sample (BSW00-BS00, BSW02-BS01 and BSW03-BS02).

Five (5) sediment samples collected for laboratory analysis. Two (2) samples were taken during the dry season (May) and three (3) were taken in the rainy season (August). One (1) sample at Mongoukele stream where no mining activities are taking place and considered the control site (reference point) for comparison purposes. Two (2) samples at the operating site in Kambele (along the Djengou stream) and two (2) samples downstream at the Patere-Lobi locality (figure 7). The geographical coordinates of the sampling points is shown in Table 3.

Table 3– Location and geographical coordinates of sediment sampling points.

Water sample	Latitude (N) (°)	Longitude (E) (°)	Altitude (m)	locality
BS00	4.4639183	14.3918233	623	Mongoukele (upstream)
BS01	4.4675333	14.4161111	619	Kambele
BS02	4.4039517	14.3795783	602.51	Patere-Lobi

Water sampling procedure

The collection of water sample for heavy metal analysis needs many precautions in order to have good results and hence the interpretation to be given to them. The sample collected must be representative and homogenous and obtained without modifying the physicochemical characteristics of the water (Rodier, 2009). The sampling protocol used in this study was adopted from studies carried out in river waters of the Nyong and sanaga hydrographic network in Cameroon (Olivry and Naah, 1978; Ndam Ngoupayou, 1997; Lienou, 2007; Kpoumie, 2015; Ndam Ngoupayou et al; 2016) and the standard procedures (European Standards-SR IS05667-23, 2011; European Standards-SR 1505667-3, 2013). The water samples were collected in 1.5 litres of plastic bottles (Figure 8), following the ten (10) conditions for collecting surface water samples for physicochemical and chemical analysis:

- Identify sampling locations that is at a given point depth and time;
- use a manual method in a suitable container;

- take samples about 50cm below the surface;
- rinse the bottle and its screw cap 3 times with the water to be sampled;
- drain the bottle by shaking the neck downward;
- turn the bottle upside down, leaving it tilted at an angle of about 45° , neck in the upper position, facing the direction of water flow;
- fill the bottle slowly without bubbling;
- rinse the screw cap by shaking in the direction of water flow;
- close the bottle with the screw cap carefully, but quickly so as not to trap air bubbles.

Figure 8 shows the collection of water samples.



Figure 7: Water sample collection a (Mongoukele) and b (Patere Lobi) (TALLA, August and May respectively)

Sediment sampling procedure

The sampling of fine materials done manually using a small plastic or stainless steel shovel, and placed in a plastic bag or sample bag and labelled. For sediments, only the upper layer of sediment (surface sediments) is collected (0 to 10 cm) manually since analysis must reflect recent phenomena of the year. Figure 9 shows the collection of sediment samples



Figure 8: Collection of sediment sample at Patere Lobi and on a mining site at Kambele (TALLA, August and May respectively)

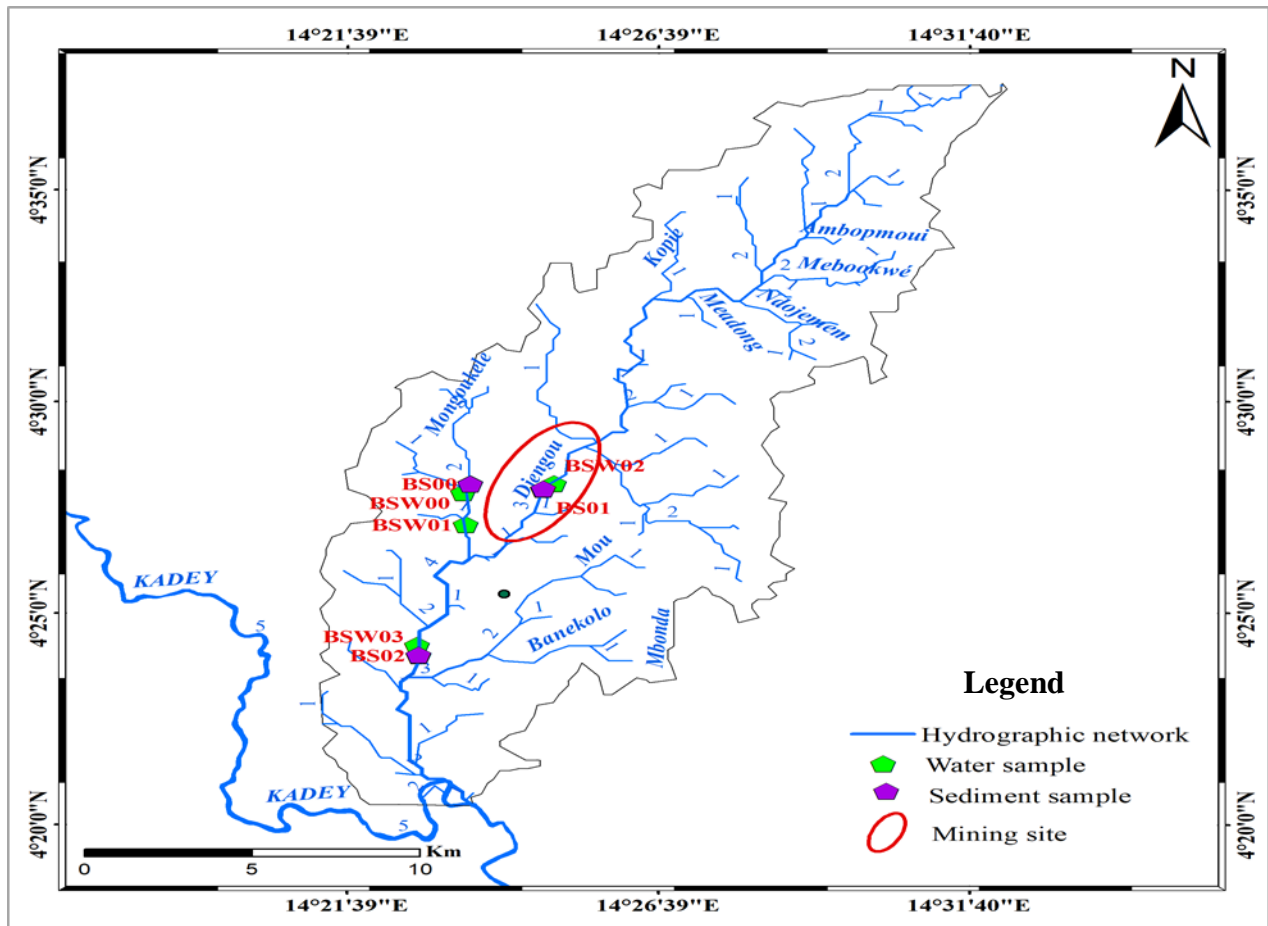


Figure 9: Sampling Map (Extract of SRTM image 2017, modified using ArcGIS 10.8.2).

Preparation of water and sediment samples

After the collection of each water sample, the bottles carefully coded using a seal tape and permanent marker and stored in a fridge. The samples destined for laboratory analysis transported within 3 days.

The sediment samples were placed in sterilized polyethylene bags ensuring that no air or air bubbles were found in the bags and it was carefully closed, coded and stored in a fridge after which it was transported for heavy metal analysis in the laboratory within 7 days.

II.3.4. In-situ measurements of physicochemical parameters of water

Six (6) physicochemical parameters, which are very sensitive to environmental conditions (temperature, pH, electrical conductivity, total dissolved solids, dissolved oxygen and salinity), were measured in-situ using the multipara meter with three (3) electrodes which are very sensitive to environmental conditions and likely to vary significantly.

a) Hydrogen Potential (pH)

Hydrogen potential is a fundamental characteristic of water as it indicate if water is basic or acidic on a scale from 0 to14. A pH of 7 is neutral, below 7 is acidic and above 7 is basic (Sawyer et al. 2003) pH is an expression of hydrogen ion (H^+) and hydroxide ions (OH^-)concentration in water.

On-site pH calibration consists of first choosing buffer solutions that include the expected value. On-site calibration done at two points from the buffer solution at pH 4.01 and pH 7.02.

b) Total dissolved solids (TDS)

This is the total concentration of dissolved substances in water, including inorganic and organic substances (APHA, 2017). It is usually measured in parts per million (ppm) which is equivalent to mg/L. High TDS levels can affect the taste of water, making it taste metallic or salty.

c) Electrical conductivity (EC)

EC measures the water's ability to conduct electricity, which is related to the concentration of dissolved salts and other ions (Hem, 1985).

d) Temperature

Temperature affects the chemical and biological processes in water. Higher temperatures can decrease oxygen levels and increase the rate of chemical reactions (Wetzel, 2001).

It has a significant influence on other water characteristics, particularly on conductivity and dissolved oxygen levels.

e) Dissolved oxygen (DO)

Dissolved oxygen (DO) is the amount of oxygen gas dissolve in water. It is essential for aquatic life. Low DO levels can harm fish and other aquatic organisms (Horne and Goldman, 1994).

f) Salinity

This is the amount of dissolved salts in a water body, typically measured in grams of salt per litre (g/L).

After each in-situ measurement, rinse the probes with distilled water to avoid contamination insert the probe into the water sample. The meter will display the values of each parameter. After taking measurement, rinse the probe with distilled water and store it properly to maintain its accuracy.

II.4. Laboratory work

After sampling, the samples sent to the laboratory for various analysis and treatment. Six (06) water samples, (3 samples in the dry season and 3 sample in the raining season) and five (05) sediment sample (two samples in the dry season and three samples in the rainy season) were sent to the laboratory of geochemical analysis of water at LAGE/IRGM (Laboratory for geological and environmental analyses/Institute Of Geological and Mining Research) at Nkolbisong in Yaoundé for heavy metal analysis while a total of 12 water samples were sent to the Laboratory of superficial formations of the University of Yaoundé 1 for the analysis of Total suspended solids.

II.4.1. Filtration and conditioning of water samples

The different water samples for heavy metal filtered with 0.45µm cellulose acetate membranes using a Millipore polycarbonate filtration unit. Generally, the quantity of water filtered is 500 ml. The samples labelled and stored in a cool place at temperatures of 4⁰C before the analysis of heavy metals in the samples.

II.4.2. Estimation of Total Suspended Solids

Total Suspended Solids refers to the concentration of un-dissolved minerals or organic elements in a sample such as silt, sediments, plant materials, and insect larvae.

TSS is determined by the difference in weight between the weight of the filter before and after filtration. The diameter of the filters used in this study was 47mm. The filters dried in an oven at 105^o C for 24 hours and weighed using an electronic analytical balance after passing through a desiccator. After filtration, the filters dried in the oven and after 24 hours the weights after filtration taken. Taking into account the volume filtered for each filter, the results finally expressed in mg/L of TSS as shown on the equation below:

$$\text{Tss} = \frac{\text{M2}-\text{M1}}{\text{v}} * 1000 \quad \text{Eq.1}$$

Where TSS is the Total suspended solids in mg/L; M1 is the mass in mg of the filter before filtration; M2 the mass in mg after filtration and drying and V the volume of the water filtered in ml.

II.4.3. Analysis of trace metal elements in sediment and water

Five (5) trace metals analyzed in sediment and water samples include Hg, As, Pb, Zn and Fe. Calibration standard for these trace metals were prepared from a certified mixed element standard. After calibration by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry), samples introduced into ICP for detection. All data reported in mg/L.

The samples first crushed and dried in an oven. Then 0.2 g of powder obtained and added in the mineralization cells, 4 mL of sulfuric acid (H₂SO₄) concentrated at 95%. These solutions then incubated for about 5 minutes in the Hach brand digesdahl mineralizer, first at low temperature, then by gradually increasing the temperature to 440 °C until the mixture cleared. During the incubation, more precisely between the 3rd and 4th minute (after boiling), 10 mL of hydrogen peroxide (H₂O₂) were gradually added drop by drop using a syringe. The mineralized sample obtained (4-5 mL) are brought to 70 mL in a graduated flask with distilled water. The elements then determined by X-ray fluorescence spectrometry.

The analytical method used is X-ray florescence spectrometry, the choice of this method lies on the fact that it has been widely used in the determination of heavy metals in sediments and soil. (Song et al., 2019; Sano et al., 2020; Xing et al., 2022). This method is rapid, nondestructive and multi-elemental with sensitivity of the order of 10⁻⁸g (depending on the element of interest).

The Trace Metal Elements (TMEs) assay performed by X-ray fluorescence spectrometry, using a Bruker XRF spectrometer, type Pioneer S4, at the WDS wavelength (Wavelength Dispersive Spectrometry). To do this, place the sample in an oven at 800°C for about an hour. The ash obtain is placed in a small polyethylene jar, which is covered with a polypropylene film, then placed in the spectrometer. The X-rays emitted pass through the polypropylene film to excite the atoms contained in the sample. After excitation, X-ray fluorescence characteristic of the atoms sought is emitted. Each concentration corresponds to an absorbance whose curve is plotted. From this curve, the spectrophotometer gives by reading, after measuring the absorbance of each sample, the concentration of the metal contained in this sample.

Heavy metal contents (expressed in mg/L) are determined using the Spectra-Plus software. The process is the same for liquid samples that are neither filtered nor diluted before being introduced into the spectrometer in the same jar above without being heated but just subjected to x-rays that pass through the polypropylene in which it was placed to receive the x-rays in order to obtain the absorbance according to the different concentrations of the samples.

II.4.4. Data processing (treatment)

This section is concerned with designing the various maps and graphs used in this manuscript. The various maps produced in this study were design using ArcGIS software from the geological division of Batouri at 1/500000, shape files and digital elevation model of the republic of Cameroon. The graphs, tables were produce using Microsoft office word 2010, and Excel 2010 software.

II.4.4.1. Estimation of the intensity of metal contamination in water

To estimate the intensity of contamination of surface water, three water assessment tools are used, namely water quality index (WQI); heavy metal pollution indices (HPI), and the Degree of water contamination (DC).

– Water Quality Index (WQI)

The water quality index (WQI) is a numerical representation that summarizes the overall quality of water. It aims to provide the public with information about the possibilities of usage, in particular if it is suitable for human consumption. It was developed by Horton in the United States in 1965, since then it has been widely applied across countries in Europe, Africa and Asia (Batabyal and Chakraborty, 2015; Abdel-Satar et al, 2017; Sener et al., 2017 as cited by

Ayiwouo et al., 2022). Many authors have given several formulations to the WQI according to the objective set by this study (Horton, 1965; Brown et al., 1970., Cude., 2001).

WQI is use to assess the overall water quality and the sustainability of its use for human consumption by assessing physicochemical parameters like pH, DO, NTU, Pb, Hg, As, Zn and Fe. This index helps reduces huge amounts of measurable information about water into a single index value in an intelligible format (Horton, 1965; Stambuk-Giljanovic1999). The WQI can be calculated in five (5) steps:

- Assigning weights (w_i);
- determining the relative weight (W_i);
- assess the quality (q_i);
- determining the sub-index (SL_i);
- calculating the sum of the sub-indices (WQI).

Each parameter is given a numerical value, or weights (w_i), in a range from one (the least) to five (the highest), in order to determine the water quality index (WQI) of drinking water. The ranking based on the importance of parameters for water quality, with the most relevant factors receiving a weight of five (Tables 4).

The second thing is calculating the relative weight (W_i) of the chemical parameter using Eq. (2):

$$W_i = (w_i) \div (\sum_{i=1}^n w_i) \quad \text{Eq.2}$$

Where W_i is the relative weight; w_i weight of assign parameter; n is the number of parameters.

Third is the quality rating (q_i) of each parameter being estimated using Eq. (3):

$$q_i = \left(\frac{C_i}{S_i} \right) \times 100 \quad \text{Eq.3}$$

Where q_i is the quality rating, C_i the mean concentration (mg/L) of respective parameter for each water sample, S_i the drinking water standard (mg/L) as per international guidelines (WHO, 2017).

Fourth, sub-index of the i th parameter (SL_i) is calculated for each parameter using Eq. (4):

$$SL_i = W_i \times q_i, \quad \text{Eq. 4}$$

Where SL_i is the sub-index of i th parameter; W_i is the relative weight; q_i is the quality rating.

Finally, sum of the sub-index of all analysed parameters were estimated using Eq. (5):

$$WQI = \sum_{\{i=1\}}^n \times SLi \quad Eq. 5$$

Seven (7) different parameters, along with their assigned weights and relative weights, served as the basis for the calculation in the current investigation. These parameters are listed in Table 4. Five categories make up the WQI (Sener et al., 2017) as shown on Table 5:

Table 4: Relative weight of each parameter based on the WHO standard (2017)

parameter	Unit	WHO (2017)	Weight (wi)	Relative weight (Wi)
Temp	°C	15-25	2	0.083
pH		6.5-8.5	3	0.125
EC	µS/cm	1500	4	0.167
TDS	mg/L	1000	3	0.125
TSS	mg/L	80	5	0.208
DO	mg/L	14	5	0.208
Salinity	mg/L	250	2	0.083

Table 5: Different classes of water quality index (WQI)

Range	Quality
<50	Excellent
50-100	Good
100-200	Poor
200-300	Very poor
>300	Unfit for consumption

– **Heavy Metal Pollution Index (HPI)**

The heavy metal pollution index (HPI) is metric used to evaluate the degree of heavy metal contamination of water. Each element is given a weight or index between zero and 1denoted (Wi) based on how much it contributes to the deterioration of water quality (Prasad and

Sangita, 2008; Singh and Rakesh, 2016; Ayiwouo et al., 2022). Three (3) steps are involved in its calculation (Mohan et al., 1996):

Firstly, determine the relative weight or index (W_i) of any metal using the formula below:

$$W_i = \frac{k}{S_i} \quad \text{Eq. 6}$$

Where k is the constant of proportionality, S_i is the standard value of metal according to the WHO standard (2011, 2017).

Secondly, calculate the values of the sub-indices (Q_i) for each parameter; they are obtained using the following formula:

$$Q_i = 100 \times \frac{V_i}{S_i} \quad \text{Eq. 7}$$

Where V_i is the value of the parameter obtained in the field and S_i is the limit or standard value of the said parameter permitted by WHO standards.

Thirdly, calculate the HPI:

$$HPI = \frac{\sum_{\{i=1\}}^n W_i Q_i}{\left[\sum_{\{i=1\}}^n W_i \right]} \quad \text{Eq. 8}$$

– Degree of Water Contamination (DC)

As in HPI, the degree of water contamination (DC) shows the general level of heavy metal contamination in the water. It combines the effects of a number of measurements of water quality that are thought to be dangerous (Backman et al., 1997). The contamination index is calculated using Eq. (9) and (10) as follows:

$$DC = \sum_{\{i=1\}}^n Fci, \quad \text{Eq. 9}$$

$$Fci = \frac{CAi}{CNI} - 1 \quad \text{Eq. 10}$$

Where Fci is the contamination factor for the i -th component; CAi is its analytical value and CNi is the maximum allowable concentration (N <<stands for the normative value>>).

Table 6 displays the classes for DC, which were provided by Backman et al. (1997), and Edet and Offiong (2002).

Table 6: Different classes of degree of contamination

Class	Degree of contamination (DC)
DC<1	Low contamination
1<DC<3	Medium contamination
DC>3	High contamination

II.4.4.2. Estimation of the intensity of metal contamination in sediments

To estimate the intensity of contamination of stream sediments, two-sediment quality assessment tool were use, namely the contamination factor, Degree of contamination, pollution load index, and geo-accumulation index.

- **Contamination Factor (CF), Degree of Contamination (DC) and Pollution Load Index (PLI)**

The contamination factor (CF), DC and the PLI is use to determine the anthropogenic contribution of heavy metals in sediments and the levels of metal pollution. The CF accounts for the contamination of a single element. The CF is a ratio that measures the level of contamination in sediments by comparing the concentration of heavy metals in sediments sample to values of heavy metal in sediments of the control site (BS00) in this study the Turekian and Wedepohl (1961) background values were also used were certain anomalies were experienced. They are calculated as follows (Hakanson, 1980):

$$CF = \frac{Cm[sample]}{Cm[background]} \quad \text{Eq. 11}$$

Where Cm [sample] is the measured concentration of heavy metal in the stream sediment and Cm [background] is the value of the background metal in the continental crust given by Turekian and Wedepohl (1961). The contamination factor values to describe the level of contamination is given in Table 7.

Table 7: Contamination factor and contamination levels

Contamination factor (CF)	Contamination level
CF < 1	Low contamination
1 < CF < 3	Moderate contamination
3 < CF < 6	Considerable contamination
CF > 6	Very high contamination

The degree of contamination is the sum of all contamination factors and represents the integrated degree of pollution of the environment. It can be calculated using the formula below and the various classes are given in Table 8.

$$DC = \sum CF \quad \text{Eq. 12}$$

Table 8: Degree of contamination and contamination level

Degree of contamination	Contamination levels
DC < 8	Low contamination
8 ≤ DC < 16	Moderate contamination
16 ≤ DC < 32	Considerable contamination
DC > 32	Very high contamination

The pollution load index (PLI) (Tomlinson et al., 1980) used to calculate overall pollution load, variation and pollution severity. It is calculated using the formula below:

$$PLI = (CF_1 \times CF_2 \times CF_3 \dots \times CF_n)^{\frac{1}{n}} \quad \text{Eq. 13}$$

Where n is the number of metals analyze. When:

PLI < 1 indicates no pollution

PLI = 1 indicates the reference levels of metals

PLI > 1 indicates pollution.

– **Geo-Accumulation Index (Igeo)**

A quantitative measure of the level of heavy metal contamination in soils and sediments is the geo-accumulation index (Igeo). Müller created it in 1969, and it is widely used in environmental studies to assess the level of contamination. Given a concentration, this

empirically based index compares it to a value known as the geological background value. It is given by the formula below:

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5B_n} \right] \quad \text{Eq.14}$$

Where *Igeo* is the geo-accumulation index, \log_2 is, C_n is the concentration of the metal in the study area, B_n is the background value of the corresponding metal (n) and 1.5 is the background correction factor for lithogenic differences in the sediments (Salomons and Forstner 1984).

Igeo is divided into 6 classes that represent the level of contamination (Müller, 1969) as shown in Table 9.

Table 9: Classes defined by the geo-accumulation index

Value of <i>Igeo</i>	Class	Contamination intensity
$I_{geo} < 0$	0	Uncontaminated
$0 > I_{geo} < 1$	1	Uncontaminated to moderately contaminated
$1 < I_{geo} < 2$	2	Moderately contaminated
$2 < I_{geo} < 3$	3	Moderately to highly contaminated
$3 < I_{geo} < 4$	4	Highly contaminated
$4 < I_{geo} < 5$	5	Highly to very highly contaminated
$I_{geo} > 5$	6	Extremely contaminated

CONCLUSION

The Djengou watershed around the Kambele and Patere Lobi Localities are the sites chosen for this present study. It is located in the East region of Cameroon precisely in Batouri subdivision between latitudes 4°28'North and longitude 14°24'East. The Mongoukele watercourse (reference point for this study). A total of twelve (12) water samples and Five (5) sediment samples collected through four campaigns from May to August 2024, representing both dry and rainy seasons after the physicochemical parameter was carried in-situ on the sites. The analyses of the chemical parameters (trace metal elements) carried out at LAGE/IRGM

(Laboratory for geological and environmental analyses/Institute Of Geological and Mining Research) at Nkolbisong in Yaoundé using the ICP-OES (Inductively Coupled Plasma Atomic Emission Spectrometry) and X-ray fluorescence spectrometry, using a Bruker XRF spectrometer, type Pioneer S4. On the other hand, the Physical parameter (TSS) carried out in the laboratory of superficial formation university of Yaoundé 1 with filters of diameter 47mm. The analytical results obtained processed using various hydro geochemical methods and assessment tools to provide results that will be presented in the next chapter.

CHAPTER III: RESULTS

Introduction

This chapter presents the results from comprehensive field and laboratory analyses conducted to assess the sediment and water quality of the study area. It starts with the presentation of the state of the study site (mode of exploitation), the in-situ physicochemical quality of water measured in the field to capture the immediate water quality and environmental conditions and finally the results from Laboratory analyses to evaluate the Total suspended solids (TSS) and Heavy metal analyses in sediments and water samples along with the results from data processing.

III.1. State of the sites and mode of gold exploitation in Batouri

The type of mining activity practiced in the Batouri gold district is artisanal and semi-mechanized.

III.1.1. Artisanal gold mining

The Kambele and Patere Lobi localities are known for its gold panning in the live bed along the Djengou watercourse, on the banks, and terraces. The mining technique here is mixed because the actors use machines at certain stages of the mining process and traditional tools at other stages. Since the arrival of mining companies, majority of the sites have been handed over to them and the traditional occupants who cannot find a place in the beds go back up and occupy the quarries, given the difficulties in extracting quarry deposits, which requires many efforts. These gold prospectors use small motor pumps, sluices, pans, barrels, shovels and pick axes (Figure 10a and 10b)

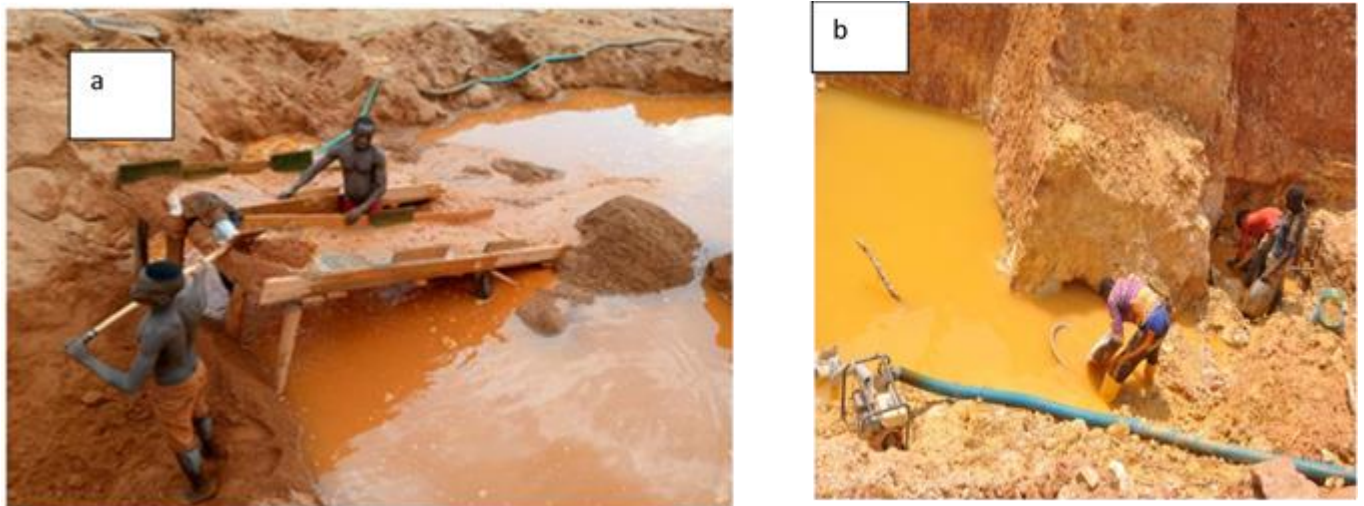


Figure 10: Tools used in artisanal gold mining in Batouri

III.1.2. Artisanal semi-mechanized gold mining

The Chinese companies were operating at Kambele at the time of this study. The deposits exploited are alluvial deposits. The exploitation is of the semi-mechanized artisanal open-pit type and is practice along the Djengou watercourse and surrounding water bodies on the banks and terraces. They have the same operating system and equipment's, but differ in their number.

III.1.2.1. Mining area and associated infrastructure

Each mining site forms a mining area (working area). It takes into account a set of facilities necessary for carrying out mining operations. They include;

- Opening an access road to the mine;
- construction of a base camp, each base camp has a general store, a garage, a car and fuel park, and tents;
- the ground borrow area;
- the exploitation area.

III.1.2.2. Exploitation technique

Exploitation begins with the construction of a dam in a live bed and the diversion of the watercourses (figure 11a) into a drainage channel dug along the latter. This technique requires cutting trees of varying diameters and lengths and driving two rows of the stake through the riverbed with palisades on either side. The interval is then fill with soil taken from the riverbanks or from digging the diversion channel to strengthen the dam. Then a water retention basin dug in the riverbed for subsequent washing of gravel. Finally, access to the mineralized gravel is achieve by stripping a surface horizon of soil along the rivers on the banks and the terraces. Mechanical shovels are used for excavation (figure 11b), earth works and extraction of ore or mineralized gravel.



Figure 11: Deviation of watercourse (a) and mechanical shovel (b)

III.1.2.3. Mining waste and wastewater management

On the mining sites, the huge amount of sterile materials extracted is systematically set aside. The ore processing residues are stored directly on the already excavated areas at the level of the watercourses in order to guarantee a systematic rehabilitation. The waters discharged from the washing plants joins the diversion channels or are trapped in the dug basins and pools created without prior isolation or treatment

III.1.2.4. Gold Extraction

Gold extraction is done on site using three (3) methods:

- The method by gravity using floating installations, made up in particular of bulldozers and dredges. Digging of gold gravel using shovels and lifting from the bottom of rivers to the tank at the top of the boat where the first separation will occur. The coarse elements separated from the sand containing the gold and evacuated directly into the watercourse; while the sand is carried towards the carpet, the second stage of separation process will occur on these carpets. Most of the sand (less dense than gold and ferromagnesian elements) is carried by the water current and flows into the watercourse. The gold, ferromagnesian elements are a small part of the sand, which will settle under the carpets base on high density. The carpet containing the gold, the “black sand” (ferromagnesian elements) and the remaining sand is remove and placed in a collection bin. The contents put into buckets and transported to a box where the separation will continue on “shaking the table”.

- Separation mechanism on shaking the table: The contents obtained during separation at the boat level is placed on the feeding hopper of the shaking the table. The different parameters of the table include water flow, ore feed rate, the inclination of the table and the vibration frequency of the table, which are adjusted carefully. When the engine starts, the table begins to perform vibration movements. These vibrations and the flow of water will set the ore in motion. The different substances will move between the rifts of the shaking table in a precise direction depending on their density. The heavier the gold and ferromagnesian element will remain between the rifts and be carried in the table direction towards the lower part while the lighter sand will undergo displacements between the rifts and will be carried transversely on the side.

– Formation of the amalgam and recovery of gold. The operations that occur during this stage can be summarized as follows: the concentrate consisting of gold and ferromagnesian elements is recovered at the exit of the shaking the table and placed in a container; it is mixed with mercury, detergent (blue) and water; the mercury will form an amalgam with the gold which allows it to be separated from the ferromagnesian elements; the gold-mercury amalgam is wrapped in a cloth and compressed to drive out the mercury. On the contrary, the amalgam can be heated and instead promote the evaporation of mercury. Finally, we obtain the gold from which the other impurities eliminated during melting.

III.2. Level of variation of physicochemical, physical and chemical quality of sediment and water in the Djengou and Mongoukele watershed

III.2.1. In-situ physicochemical quality of water (pH, Temp, EC, TDS)

The study area shows values of pH varying between 6.54 and 7.32 with an average value of 6.92. The values of Temperature is from 23.1⁰C to 28.5⁰C having an average value of 25.48⁰C. EC has values ranging from 145 μ S/cm to 662.4 μ S/cm or an average of 300.24 μ S/cm. While the TDS values oscillate between 96mg/l to 355mg/L for an average of 181.67mg/L (Table 10 and Figure 12). The other parameters are presented in the Annex 1.

Table 10: Level of variation of physicochemical parameter of water

parameter	Temp	pH	TDS	EC
Max	28.5	7.32	355	662.43
Min	23.1	6.54	96	145
Av	25.48	6.92	181.67	300.24

III.2.2. Physical Quality of water (TSS)

The results of total suspended solids (TSS) of water samples reveals that points BSW02, BSW03, BSW01 and BSW00 records maximum contents of 681.5mg/L, 363mg/L, 26.33mg/L and 9.5mg/L respectively (Figure 13). The points located on the site (BSW02) where mining activities are intense, shows an average content of 265.75mg/L. A big difference can be observed between the contents along the Djengou watercourse (BSW02 and BSW03) with an average

content of 225.25mg/L from those of Mongoukele water course (BSW00 and BSW01) with an average content of 10.71mg/L.

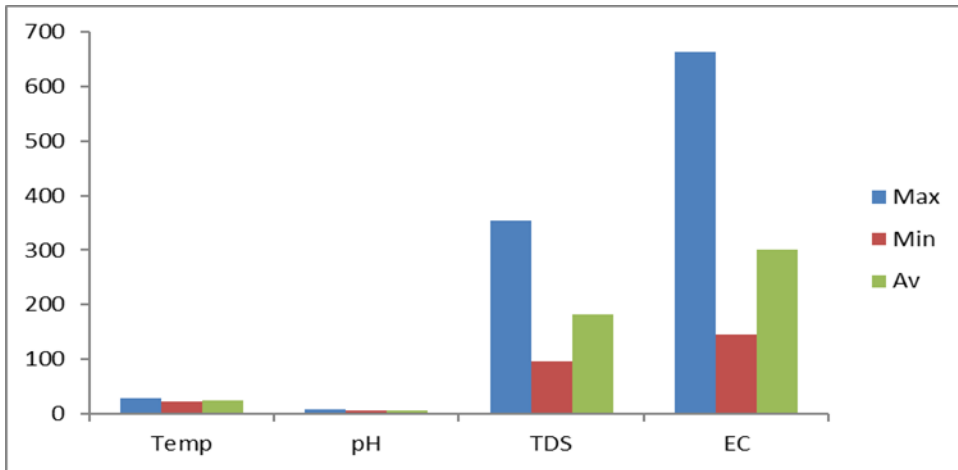


Figure 12: Level of variation of physicochemical parameter of water

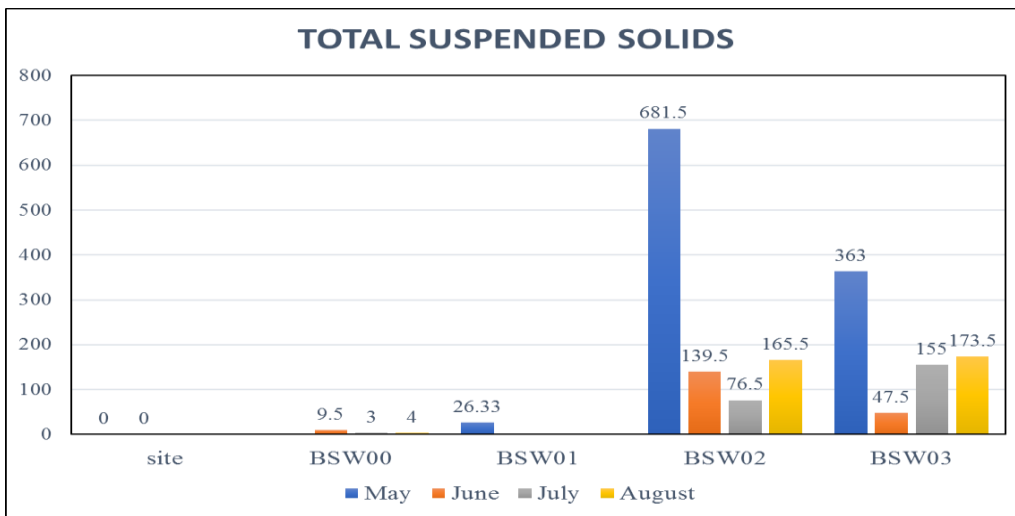


Figure 13: The spatial variation of Total suspended solids in Waters of the study area

III.1.3. Chemical Quality of sediments and water

III.1.3.1. Results of the chemical quality of stream sediments of the study area

The results of the trace metallic elements (TME's) obtained in sediments samples (BS01 and BS02) shows extremely high values compared to that of the reference point BS00. The order of the average abundance of the measured elements is as follows Pb > Zn > As > Fe > Hg (Table 11)

Table 11: Results of heavy metal analysis in sediments

	Dry season		Rainy season								
SAMPLES	BS01	BS02	BS00	BS01	BS02	max	min	average	S.D	Units	
Hg	5.34	3.25	0.00	11.59	9.50	11.59	0.00	5.94	4.68	mg/kg	
As	11.03	18.02	0.00	1.31	0.00	18.02	0.00	6.07	8.12	mg/kg	
Pb	31.32	52.46	3.16	7.28	12.00	52.46	3.16	21.24	20.52	mg/Kg	
Fe	12.56	8.56	1.54	9.57	5.55	12.56	1.54	7.56	4.19	mg/kg	
Zn	42.12	35.13	0.12	2.16	0.14	42.12	0.12	15.93	20.88	mg/kg	

BS=Batouri stream sediment max=maximum min=minimum S.D= Standard Deviation

III.1.3.2 Results of the chemical quality of surface water in the study area

The results of trace metal elements (Hg, As, Pb, Fe and Zn) obtained in surface waters at points BSW00, BSW01, BSW02, and BSW03 shows variable concentrations in trace metal elements (Table 12). The concentrations of Hg is maximum at point BSW02 with values 9.78mg/L and minimum at point BSW01 with values 2.26mg/L. Point BSW00 was taken as the reference point 0mg/L. The other metallic elements As, Pb, Fe and Zn showed maximum values 13.41mg/L, 37.52mg/L, 15.43mg/L and 27.79mg/L respectively.

Table 12: Results of certain trace metal elements in water of each sampling point

	Dry season			Rainy season									
SAMPLES	BSW01	BSW02	BSW03	BSW00	BSW02	WHO (2017)	BSW03	Max	Min	Av	S.D	Units	
Hg	2.26	7.90	5.50	0.00	9.78	0.01	6.15	9.78	0.00	4.51	3.84	mg/l	
As	6.81	13.41	8.21	0.10	9.63	0.01	5.48	13.41	0.01	6.24	4.90	mg/l	
Pb	37.52	24.15	17.53	4.16	28.65	0.01	22.04	37.52	0.01	19.15	13.26	mg/l	
Fe	4.57	11.25	7.47	0.93	15.43	0.30	8.72	15.43	0.30	6.95	5.48	mg/l	
Zn	11.33	27.79	15.26	0.35	17.30	3.00	12.85	27.79	0.35	12.55	9.16	mg/l	

BSW= Batouri Stream water sample BSW00= Control site BSW01= Away from the mining site
BSW02= on the mining site BSW03= after the mining site downstream
Max=Maximum Min=Minimum Av=Average S.D=Standard Deviation

Conclusion

In general, two types of gold mining exploitation were identified in the study area. Artisanal gold mining which uses non-industrial, manual and little mechanized tools, methods and processes and semi-mechanized gold mining which use mechanical means. The results of the analysis carried out on surface water quality highlights waters with Temperature, pH, TDS, and EC values ranging from $23.1^{\circ}\text{C} \leq \text{Temp} \leq 28.5^{\circ}\text{C}$, $6.54 \leq \text{pH} \leq 7.32$, $96\text{mg/l} \leq \text{TDS} \leq 355\text{mg/L}$ and $145\mu\text{S/cm} \leq \text{EC} \leq 662.4\mu\text{S/cm}$ respectively. The total suspended solids oscillate between 47.5 mg/L to 681.5 mg/L along the Djengou watercourse and between 3 mg/L to 26.33 mg/L at the control site. As for the stream sediments quality, the metallic elements measured are presented in the order of abundance $\text{Pb} > \text{Zn} > \text{As} > \text{Hg} > \text{Fe}$ which all exceed WHO standards. The heavy metals analyzed (Hg, As, Pb, Fe and Zn) in water revealed values far exceeding the WHO standards. These results will be interpreted and discussed in the next chapter.

**CHAPTER IV: INTERPRETATION AND DISCUSSION OF
RESULTS**

Introduction

This chapter aims to interpret and discuss the results obtained, to understand the origin of the elements from the spatial variations and inter-element correlations. In this way, it helps us to identify the various impacts of mining exploitation on sediment and water quality in order to propose mitigation measures.

IV.1. Distribution, origin, and comparative study of heavy metals in sediments obtained from the study area from those of other mining sites

The Contamination Factor (CF), Degree of Contamination and Pollution Load Index (PLI) calculated to estimate the metal contamination in the stream sediments of the study area (Table 13).

The contamination factor during the dry season, at BS01 (on the mining site) shows a very high contamination level for mercury (Hg) with a CF of 106.84mg/kg and Zinc (Zn) with a CF of 113.85mg/kg. Lead (Pb) and Iron (Fe) showed very high contamination with a CF of 9.91mg/kg and 8.16mg/kg respectively. Arsenic (As) had a moderate contamination level with CF of 2.21mg/kg. Downstream at BS02, the CF values were also high but generally, lower than those at BS01; Hg, Zn, and Pb showed very high contamination with CF's of 65.02mg/kg, 94.93mg/kg, and 16.60mg/kg respectively. Fe and As had a considerable contamination with a CF of 5.56mg/kg, and 3.60mg/kg respectively.

In the Rainy season, BS01 continued to show significant contamination levels, with Hg having a very high CF of 231.88mg/kg, which increased significantly from dry season. Fe also had very high contamination with CF of 6.21mg/kg. Zn showed a reduction with a CF of 5.84mg/kg, indicating considerable contamination. As had a low concentration level with a CF of 0.26mg/kg, Pb had moderate contamination with a CF of 2.30mg/kg. At BS02 downstream, the CF for Hg remained high at 190mg/kg, indicating low contamination. Zn showed a significant drop to a CF of 0.36mg/kg, indicating low contamination. Arsenic's CF fell to zero, showing no contamination. Pb had considerable contamination with a CF of 3.80mg/kg, and Fe had considerable contamination with CF of 3.60mg/kg. The average values of the contamination factor of all the sampling points is greater than 6 suggesting a very high contamination level of the sediments of Kambele and Patere Lobi.

The degree of contamination (DC) values, which represents the cumulative contamination, is very high for both sites in both seasons. At BS01, the DC is 240.96mg/kg during the dry season and 246.49mg/kg in the rainy season. Similarly, at BS02, the DC is 185.72mg/kg in the dry season and 197.77mg/kg in the rainy season. The result shows that the DC increases from the dry season to the rainy season. These values underscore the significant cumulative contamination levels across all heavy metals.

The pollution load index (PLI) values provide an overall measure of pollution. At BS01, the PLI was 18.5mg/kg during the dry season and 5.51mg/kg in the rainy season, indicating severe pollution. At BS02, the PLI values were 18.30mg/kg in the dry season and 3.94 in the rainy season, still indicating severe pollution but less severe than at BS01.

During the dry season, both BS01 and BS02 exhibited very high contamination levels, particularly for Mercury and Zinc. The rainy season showed some reduction in Zinc contamination at both sites but an increase in Mercury contamination at BS01. The Degree of Contamination (DC) values confirmed significant cumulative contamination for both sites and seasons. The Pollution Load Index (PLI) values indicated severe pollution at BS01 and significant pollution at BS02, with slightly lower values in the rainy season.

Table 13: Results of Contamination Factor (CF), Degree of Contamination and Pollution Load Index (PLI)

	Dry season		Rainy season		
CF	BS01	BS02	BS01	BS02	Units
Hg	106.84	65.02	231.88	190.00	mg/kg
As	2.21	3.60	0.26	0.00	mg/kg
Pb	9.91	16.60	2.30	3.80	mg/Kg
Fe	8.16	5.56	6.21	3.60	mg/kg
Zn	113.85	94.93	5.84	0.36	mg/kg
	Statistics				
Min	2.21	3.60	0.26	0.00	mg/kg
Max	113.85	94.93	231.88	190.00	mg/kg
Average	48.19	37.14	49.30	39.55	mg/Kg
DC	240.96	185.72	246.49	197.77	
PLI	18.5	18.30	5.51	3.94	

In order to establish relationships between metals and verify their sources in sediments, a correlation matrix was carried out. According to Table 14, a very good positive correlation equal to one (1) would exist between almost all metals As, Pb, Fe and Zn except Hg, which has a weak

correlation with all the other metals. This clear and perfect correlation raises the hypothesis of a common origin linked to excavation work, a homogenous distribution and/or similar behaviour with respect to the physicochemical processes taking place in the environment (Mseddi and Ben Mammou, 2014). Hg has weak negative correlation with other metals except Fe (0.4) where it has a moderate positive correlation. This weak negative correlation confirms the hypothesis of a foreign origin attributed to Hg in the environment and which would be linked to gold amalgamation in the area.

Table 14: The Pearson correlation matrix of metallic elements in sediment

	<i>Hg</i>	<i>As</i>	<i>Pb</i>	<i>Fe</i>	<i>Zn</i>
Hg	1.0				
As	-0.3	1.0			
Pb	-0.2	1.0	1.0		
Fe	0.4	0.6	0.5	1.0	
Zn	-0.3	0.9	0.9	0.7	1.0

Table 15: Comparative Studies of average heavy metal (in mg/kg) obtained in this study from those of other mining areas in Cameroon and around the world.

Similar work in the world	Hg	As	Pb	Fe	Zn
Djengou river in a gold mining site at Kambele (present study)	7.33	9.18	23.09	10.72	18.3
Betare-Oya (Cameroon) (Tehna et al 2019).	-	-	13	25647	60.75
Djengou and Kadey river in the Batouri gold district (Cameroon).	0.013	0.011	2.2	1.7	-
Lom river in a gold mining site at Gankombol (Cameroon).	0.0047	0.17	0.24	1.7	-
Lom river in a gold mining site at Wakaso (Cameroon).	0.66	0.19	-	4.03	-
Bou Regreg (morocco)	-	-	128.05	19517.50	196.69
Idrija river, Slovenia (Effects of mercury mining regions from North Dinarides on quality of stream sediments (Stanislav et al., 2005).	17.1	9.1	55	27600	68.6

Comparing the results of the average content of heavy metals from Kambele to other mining sites, we see that Kambele has a significant mercury (Hg) concentration of 7.33mg/kg, which is notably higher than values obtained along Djengou and Kadey River in the Batouri gold district (Mambou et al., 2020a) and Lom river in a gold mining site at Wakaso (Ayiwouo et al., 2021). Average Hg is lower than values obtained at river Idrija, Slovenia where Hg levels reach

17.1 mg/kg (Stanislav et al., 2005). The average As content (9.18mg/kg) is similar to Idrija and much higher than Djengou and Kadey River in the Batouri gold district and the gold mining site at Wakaso. The Pb levels at Kambele are moderate compared to the extremely high Pb content at Bou Regreg, morocco but higher than those found in Batouri (Mambou et al., 2020a). The average Fe content is considerably lower than in mining sites at Betare-Oya and Idrija. Finally, the average Zn contents are significantly lower than mining sites at Bou Regreg but still present (Table 15)

IV.2. Spatial variation of physicochemical Quality of water and comparative study

IV.2.1. Hydrogen potential (pH) and Electrical Conductivity (EC)

The Djengou River draining the Kambele and Patere Lobi localities is characterized by slightly acidic to near neutral pH in the dry season (6.54-6.9) and near neutral to slightly basic in the rainy season (6.63-7.32) (Annex 1 and figure 12). The lowest pH values obtained along the Djengou River could be attributed to the weathering of sulphide minerals such as pyrite, arsenopyrite and galena that oxidize when exposed to water, constituting the mineral paragenesis of gold in the East and Adamawa region of Cameroon (Suh et al. 2006; Vishiti et al., 2019; Ndonfack et al., 2021; Ayiwouo et al 2022). The pH in the waters drops because of this oxidation.

Electrical conductivity (EC) measures the capacity of water to conduct electric current and depends on the dissolved charge. Consequently, it provides information on the degree of mineralisation of water (Derwich et al. 2010). EC of this area fluctuates between 145µS/cm to 662.4µS/cm or an average of 300.24µS/cm. The average value is between 200µS/cm and 400µS/cm and according to the Detay classification (1993) it is slightly elevated to moderate mineralization (Table 16). We have high EC during the rainy season this reflects the properties of dissolve rock minerals due to leaching and increased runoff, which carry dissolved salts, or minerals from the soil into water bodies.

Table 16: Relation between electrical conductivity and mineralization (Detay. 1993)

Electrical conductivity	Mineralization
<100	Very low
100-200	Low
200-400	Slightly elevated
400-600	Average
600-1000	Important
>1000	

IV.2.2 Physical Quality of water (TSS)

A suspended solid represents all the mineral and organic particles contained in water. They include clays, sands, silts, organic matter and fine grain minerals, plankton and other microorganisms in the water (Harouna, 2017). The concentration of Total suspended solids ranges from 26.33mg/L to 681.5mg/L in the dry season and from 3mg/L to 175.5mg/L in the rainy season (figure 13 and Annex 1). These values are well above the limits defined by the World Health Organisation (WHO), which recommends the total absence of TSS in drinking water (Table 17). TSS decreases with increasing precipitation. It is also important to note that during the rainy season, gold mining is less intensive due to high rainfall. Thus, the high concentration of TSS is associated to semi-mechanized and traditional gold mining techniques this techniques includes dredging, excavation works and deforestation along the Djengou River. The highest values are recorded on the mining site (BSW02) while the lowest values are recorded on the reference point (BSW00) where there is no mining activities going on and downstream of the gold exploitation site.

Table 17: Variation and standard of the Physical quality (TSS) of Water in Batouri defined by the WHO (2017) for drinking water								
	Dry season	Rainy season			WHO Guideline (2017)	max	min	Av
sample	May	June	July	August				
BSW00		9.5	3	4	Total absence	9.5	3	5.5
BSW01	26.33				Total absence	26.33	26.33	26.33
BSW02	681.5	139.5	76.5	165.5	Total absence	681.5	76.5	265.75
BSW03	363	47.5	155	173.5	Total absence	363	47.5	184.75

IV.2.3. Water quality index, Heavy metal pollution index, and Degree of contamination of water

– Water quality index

The water quality index (WQI) describes the overall status of water quality in a single term, which is useful for selecting the appropriate treatment technology and addressing the issues at hand. The values of water quality index of the Djengou River from the mining site at Kambele to the Patere lobi locality presented in Table 18 and 19.

Table 18: Results of the water quality index on the mining site at Kambele (BSW02)

Parameter	Units	Dry season						Rainy season			
		Measured value	Ideal values	SPV (WHO 2017)	Weight (wi)	Relative weight(Wi)	Absolute Qi	SLI	Measured value	Qi	SLI
Temp	°C	28.5	24.1	25	2	0.083	488.89	40.74	25.1	111.11	9.26
pH		6.54	6.5	8.5	3	0.125	2.00	0.25	7.27	38.50	4.81
EC	µS/cm	215	28	1500	4	0.167	12.70	2.12	326	20.24	3.37
TDS	mg/L	141	19.31	1000	3	0.125	12.41	1.55	209	19.34	2.42
TSS	mg/L	681.5	3	80	5	0.208	881.17	183.58	165	210.39	43.83
DO	mg/L	7.76	5	14	5	0.208	30.67	6.39	0.8	46.67	9.72
Salinity	mg/L	0.07	0.0001	250	2	0.083	0.03	0.00	0.1	0.04	0.00
Total					24	1					
WQI								234.6			73.4

Table 19: Results of the water quality index after the mining site at Patere Lobi (BSW03)

Parameter	Units	Dry season						Rainy season			
		Measured value	Ideal values	SPV (WHO 2017)	Weight (wi)	Relative weight(Wi)	Absolute Qi	SLI	Measured value	Qi	SLI
Temp	°C	26.28	24.10	25	2	0.083	242.22	20.19	23.5	66.67	5.56
pH		6.9	6.50	8.5	3	0.125	20.00	2.50	7.32	41.00	5.13
EC	µS/cm	208	28.00	1500	4	0.167	12.23	2.04	662.43	43.10	7.18
TDS	mg/L	132	19.31	1000	3	0.125	11.49	1.44	355	34.23	4.28
TSS	mg/L	363	3.00	80	5	0.208	467.53	97.40	173.5	221.43	46.13
DO	mg/L	8.81	5.00	14	5	0.208	42.33	8.82	9.31	47.89	9.98
Salinity	mg/L	0.07	0.0001	250	2	0.083	0.03	0.00	0.24	0.10	0.01
Total					24	1.000					
WQI								132.38			78.26

WQI=Water Quality Index DO=Dissolve Oxygen TDS=Total Dissolve Solids

EC=Electrical Conductivity pH=Hydrogen Potential TSS=Total Suspended Solids

Table 18 and 19 shows the water quality index of the Djengou stream at Kambele (BSW02) on the mining site and Patere Lobi locality downstream of the mining site at Batouri. The WQI values for points BSW02 and BSW03 classify them as unsuitable for drinking during

the dry season according to the classification of Robert E. Horton 1965, with WQI values of 234.6 and 132.38 respectively falling within the poor to very poor water quality range (100-300). During the rainy season, the WQI values improve to 73.4 for BSW02 and 78.26 for BSW03, classifying them as fair to good water quality respectively. The primary parameters responsible for these high WQI values are TSS (681.5 mg/L at BSW02 and 363 mg/L at BSW03), temperature (28.5°C at BSW02 and 26.28°C at BSW03), meanwhile EC, and TDS also contribute to the degradation of water quality though they fall under the permissible limits. These values indicate heavy pollution due to mining activities. While the DO levels are within acceptable limits, the stress from other pollutants is evident.

– **Heavy metal pollution index**

Table 20: Results for Heavy Metal Pollution Index (HPI) of the Djengou and Mongoukele watercourse

Parameter	Units	Control site	WHO standards	wi	Wi	Dry season			Rainy season	
						BSW01	BSW02	BSW03	BSW02	BSW03
Hg	mg/L	0	0.01	5	0.29	2.26	7.89	5.50	9.78	6.15
As	mg/L	0.01	0.01	4	0.24	6.81	13.41	8.21	9.63	5.48
Pb	mg/L	0.01	0.01	5	0.29	37.52	24.15	17.53	28.65	22.04
Fe	mg/L	0.3	0.3	2	0.12	4.57	11.25	7.465	15.43	8.72
Zn	mg/L	0.35	3	1	0.06	11.33	27.79	15.26	17.29	12.85
Total				17	1					
HPI						199.77	141784.8	98168.35	155510.2	108185.8

Table 20 shows the heavy metal pollution load index across different samples in Batouri along the Mongoukele and Djengou stream. During the dry season, the HPI values indicate significant pollution across different sampling sites. At BSW01, the HPI value is 199.77, highlighting considerable contamination even though there is no mining activities taking place on the site yet, the high values of Pb can be associated to the excavation works on the site. The BSW02 site exhibits an extremely high HPI value of 141784.8, reflecting severe pollution due to direct impact from mining activities. Downstream, at BSW03, the HPI value is 98168.35, suggesting that while contamination decreases with distance from the source, it remains

significantly high due to lower water levels which lead to the re-suspension of sediments containing heavy metals, increasing their concentration downstream (Appiah-Opong et al., 2021)

In the rainy season, the HPI values are higher, reflecting increased runoff and leaching of contaminants from mining sites, soil erosion and transported into the water bodies downstream. Seasonal variations in heavy metals in water and sediment are significant during the rainy season. The control site, BSW00, shows lower contamination levels, serving as a baseline for comparison. At BSW02, the HPI value rises to 155510.2, indicating that rainfall exacerbates the spread of heavy metals, resulting in more severe pollution. Similarly, at BSW03, the HPI value increases to 108185.8, further supporting the idea that rainy season conditions lead to higher contaminant mobility and intensify the pollution levels. The HPI values highlights the severe impact of mining activities on water quality in the Batouri locality, with both the dry and rainy seasons showing high levels of heavy metal contamination. At the mining site (BSW02), the HPI values are extremely high in both seasons, reflecting severe pollution from mining activities. During the dry season, the contamination is significant, but in the rainy season, the situation worsens due to increased runoff. Downstream at BSW03, the HPI values are high in both seasons, showing significant contamination from the mining site, which intensifies during the rainy season. The control site shows relatively lower levels of heavy metals, providing a baseline for understanding the extent of pollution at other sites. The presence of heavy metals even at the control site suggests some background contamination, but it is significantly lower than the levels found near the mining areas. The values of HPI of all the sampling points are far above the global unacceptable limits (100) (Ayiwouo et al. 2023) this indicates that the Djengou river is being polluted by the mining sites around Kambele and Patere Lobi as it traverses to the Kadey watershed

– **Degree of contamination of water**

Calculations of the degree of contamination (DC) of the Djengou watercourse at the mining site of Kambele and Patere Lobi locality based on the concentrations of heavy metals (Table 21)

The result in Table 21 shows that during the dry season, the degree of contamination (DC) for various heavy metals in water samples from different sites indicates significant pollution. At BSW01, the DC values are considerably high, with mercury (Hg) at 376.45, arsenic (As) at 681.1, lead (Pb) at 3752.4, iron (Fe) at 15.23, and zinc (Zn) at 32.85. These elevated values suggest substantial contamination, even though there is no mining activities on the site. At

the mining site, BSW02, the DC values are alarmingly high. For instance, mercury (Hg) shows a DC of 1316.17, arsenic (As) at 1341.2, lead (Pb) at 2414.7, iron (Fe) at 37.51, and zinc (Zn) at 80.56. These values reflect severe pollution directly resulting from mining activities. Downstream from the mining site, BSW03 also exhibits high DC values, although somewhat lower than at BSW02. The DC for mercury (Hg) is 916.8, arsenic (As) is 821.4, lead (Pb) is 1752.8, iron (Fe) is 24.88, and zinc (Zn) is 44.2. This decrease in contamination levels suggests that while the pollution diminishes as the water flows downstream it remains significantly high. During the rainy season, the degree of contamination remains high, with some variations. At BSW02 (mining site), the DC values remain extremely high, reflecting severe pollution exacerbated by the rainy season. For mercury (Hg), the DC is 1629.67, arsenic (As) is 963.2, lead (Pb) is 2865.4, iron (Fe) is 51.42, and zinc (Zn) is 50.14. These values indicate that the rainy season intensifies the spread of contaminants from the mining site. Similarly, at BSW03 (downstream of the mining site), the DC values are high but generally lower than at BSW02. The DC for mercury (Hg) is 1024.33, arsenic (As) is 547.5, lead (Pb) is 2203.5, iron (Fe) is 29.07, and zinc (Zn) is 37.26. This further supports the notion that contamination decreases with distance from the source but remains significantly high. All the sampling points have values of the DC > 3 and according to Backman et al. (1997), and Edet and Offiong (2002) the waters of Kambele and Patere Lobi falls within the high contamination range.

The DC shows that the water quality in Kambele and Patere Lobi locality is heavily influence by mining activities, with both the dry and rainy seasons showing high levels of heavy metal contamination. However, the contamination levels are generally higher during the rainy season, which can be attributed to increased runoff and leaching of contaminants into the streams (Appiah-Opong et al., 2021). During the dry season, the degree of contamination is significant, particularly at the mining site (BSW02) and downstream (BSW03). These sites exhibit alarmingly high DC values, indicating severe pollution due to mining activities. Even at BSW01 where there is a new mining site shows considerable contamination, suggesting the widespread impact of mining on the water quality. In the rainy season, the contamination levels increase further, with all sites showing higher DC values compared to the dry season. This seasonal variation highlights the importance of addressing pollution during the rainy season when contaminant mobility is higher, leading to more severe pollution levels.

samples	Units	control site	Dry season			Rainy season	
			BSW01	BSW02	BSW03	BSW02	BSW03
Hg	mg/l	0.006	376.45	1316.17	916.80	1629.67	1024.33
As	mg/l	0.01	681.10	1341.20	821.40	963.20	547.50
Pb	mg/l	0.01	3752.40	2414.00	1752.80	2865.40	2203.50
Fe	mg/l	0.3	15.23	37.51	24.88	51.42	29.07
Zn	mg/l	0.35	32.85	80.56	44.23	17.30	37.26

IV.2.4 Comparison of physicochemical and physical quality of water of the study area with other study areas

The average pH value (6.92) found in this study area is similar to Surface and underground water in the gold district of Betare-Oya (6.72) (Rakontontrabe et al., 2017b), Lom river in a gold mining site at Djouzami (6.52) (Ayiwouo et al., 2020), the artisanal gold mining site of Cauca Colombia (6.60) (Corredor et al., 2021).

The average conductivities (300.24 $\mu\text{S/cm}$) are similar to those observed in Akyem Abuakwa (Ghana) (234.2 $\mu\text{S/cm}$) Attua et al., 2014 and Lom river in a gold mining site at Wakaso (Cameroon) (323.14 $\mu\text{S/cm}$) Ayiwouo et al., 2021. These values are greater than those observed around the Lom River in a gold mining site at Gankombol (39.16 $\mu\text{S/cm}$), the artisanal gold mining site of Cauca (70.50 $\mu\text{S/cm}$) and Tamboral (117.74 $\mu\text{S/cm}$) in Colombia, Djengou and Kadey river in the Batouri gold district (19.50 $\mu\text{S/cm}$).

The mean values of TSS (225.25mg/L) are higher than those obtained in the Lom River in a gold mining site at Gankombol (104.77mg/L) (Ayiwouo et al., 2023) and also those of the artisanal gold mining site of Cauca Colombia (18.30mg/L) (Corredor et al., 2021). They are similar to mining sites in Tamboral, Colombia (221.85mg/L) and also the gold mining site at Djouzami (211.50mg/L) along the Lom River in Cameroon (Ayiwouo et al., 2020).

The comparison of the average values of the physicochemical and physical quality of waters of the present study with those of the waters of other rivers and streams in the context of gold mining is presented in Table 22.

Table 22: Comparing average values of physicochemical parameters present in Djengou River (present study) with those of waters of other rivers and streams in Ghana, Cameroon and Colombia.

Similar works in Cameroon and the world		pH	EC(μ S/cm)	TSS(mg/L)	References
Akyem Abuakwa(Ghana)		6.4	234.2		Attua et al., (2014)
Surface and underground water in the gold district of Betare-Oya (Cameroon)		6.72	41.76	283.58	Rakontontrabe et al., (2017b)
Lom river in a gold mining site at Djouzami(Cameroon)		6.56	19.50	211.5	Ayiwouo et al., (2020)
Djengou and Kadey river in the Batouri gold district(Cameroon)		6.08	36.04	2020	Mambou et al., (2020a)
Rivers associated to artisanal gold exploitation in the department of Cauca (Colombia)	Tamboral	8.31	117.74	221.85	Corredor et al., (2021)
	Cauca	6.60	70.50	18.30	
Lom river in a gold mining site at Wakaso (Cameroon)		7.19	323.14	389	Ayiwouo et al., (2021)
Lom river in a gold mining site at Gankombol (Cameroon)		5.96	39.16	104.77	Ayiwouo et al., (2023)
Djengou river in a gold mining site at Kambele and Patere Lobi (Cameroon, present study)		6.92	300.24	225.25	

IV.2.5. Correlation of physicochemical and physical quality of water

The correlation matrix shows a positive correlation between temperature (1) and TSS (0.8) which indicates that as temperature increases, the TSS tend to increase. There is negative correlation between temperature and pH (-0.4), TDS (-0.6), and EC (-0.5) indicating that at higher temperatures we observed low pH, TDS, and EC. High pH tends to correlate with high TDS (0.7) and EC (0.7) but inversely related to temperature and TSS (-0.4). TDS and EC strongly correlate due to their interdependence on dissolved ions. A study on the Wouri river sediment revealed significant positive correlations between TSS and temperature, attributed to urban runoff and industrial activities (Besack et al., 2021). The study also noted negative

correlations between temperatures and pH, similar to those observed in this study, indicating that higher temperatures might lead to more acidic conditions in the water (Table 23)

Table 23: Correlation matrix of physicochemical and physical parameters

	<i>Temp</i>	<i>pH</i>	<i>TDS</i>	<i>EC</i>	<i>TSS</i>
Temp	1.0				
pH	-0.4	1.0			
TDS	-0.6	0.7	1.0		
EC	-0.5	0.7	1.0	1.0	
TSS	0.8	-0.4	-0.1	-0.1	1.0

IV.3. Impacts of Mining Exploitation on the Sediments and Water Quality of Batouri

IV.3.1. Impacts of mining exploitation on sediment quality

– Physical quality of sediments (TSS)

TSS represents the primary indicator of sediment quality on the physical aspect. Mining activities especially semi-mechanized mining significantly disturb soils and sediments leading to; increased erosion and sediment runoff into water bodies; high particulate deposition downstream which alters the sediment quality; degradation of aquatic habitats and smothering of benthic organisms and sediment build up in rivers. Drastic increase of TSS on the mining site (681.5mg/l) and downstream indicates erosion and heavy sediment runoff. This elevated TSS reduces the water clarity and impedes photosynthesis in aquatic plants.

– Sedimentation, Erosion and impacts on the chemical quality of sediments

Sedimentation occurs when mining activities disturb the soil and rock layers, leading to increased erosion and movement of the sediments into the nearby water bodies. This can result in siltation of rivers and streams, which disrupts aquatic ecosystems and reduces water quality. This is the case of the Djengou water shed at Kambele and Patere Lobi as there is sedimentation going on due to excavation works carried during semi-mechanized gold mining by the Chinese company, sediments become instable and are then eroded by wind, rainfall and deposited in the Djengou watercourse. These sediments settle under water when the velocity of water decreases forming sediment layers over time. Sediment-laden can also clog irrigation systems and affect Agricultural productivity downstream. Sediment degradation is a broader term that encompasses

the decline in sediment quality due to various factors, including contamination with heavy metals and chemicals used during mining processes. These pollutants can persist in sediments for long periods leading to several outcomes such as bioaccumulation. Heavy metals can be released back into the water column from sediments leading to water quality degradation. The presence of heavy metals in sediments can disrupt the natural balance of ecosystems, harming plants, animals and microorganisms that rely on sediment for habitat; contaminated sediments can pose direct and indirect health risks to humans, especially if used for agricultural, drinking or recreation. This study assessed the contamination of heavy metals like Hg, As, Pb, Fe, and Zn in sediments and the sediments along the Djengou stream has been significantly impacted by these heavy metals. The heavy metal concentration were higher during the dry season from the mining site to the downstream while in the rainy season they dropped with some heavy metals like As being at 0 downstream but that on the mining site (BS01) was still higher than that of the control site (BS00). This can be explained based on the fact that heavy metals turn to accumulate in sediments during low water periods.

IV.3.2. Impacts of mining exploitation on water quality

– Degradation of water resources

The diversion (diversion of Djengou river) techniques and the opening of the water retention basin lead on one hand the drying up of surface water and on the other hand the adjustments of the river beds which, during the period of heavy rain, can cause a widening of the beds and the overflow of water from their flow direction (figure 16a). The extraction and ore processing activities contribute to the dispersion of trace metals and metalloids in ecosystems (figure 16b). The results obtained from WQI, HPI and DC shows that the Djengou River is unsuitable for drinking and needs urgent intervention from the local administration and state administrations involved in mining exploitation and environmental protection.

IV.3.2.1. Impacts on the physicochemical quality of water

The water quality is impacted through multiple parameters, as shown in Table 10 and Annex 1. We observe elevated TDS indicating that dissolved minerals and metals are introduced into water from mining operations. High TDS in water affects its taste, suitability for irrigation, and aquatic life due to increased ion concentration. Increased in EC as we go downstream the mining site suggest an increase ion content, often originating from mining discharge or leaching of exposed minerals (Simate and Ndlovu, 2014) which contaminates water, reducing its suitability for drinking, aquatic life, and irrigation. pH values on the mining site during the dry

season shows slightly acidic waters this is because mining causes minor acidification, likely due to runoff or chemical inputs. Even slight changes, as seen at the mining site (6.54 at BSW02), indicate disruption of natural pH balance, which can release metals like iron, aluminum, or arsenic; there is an increased in temperature on the mining site compared to the control site and downstream the mining site (Annex 1) this is because mining operations can raise water temperatures through deforestation, disturbance of water flow, or direct discharge of heated effluents. Increased temperatures reduce dissolved oxygen, stressing aquatic life (USEPA, 2012). This study's temperature increase (28.5°C) reflects such thermal impacts. High sediment loads not only affect sediment quality but also degrade water clarity, impairing light penetration and harming aquatic life (Davies-Colley and Smith, 2001). Elevated TSS downstream (173.5 mg/L) supports findings that mining runoff leads to prolonged sedimentation in rivers (Bilotta and Brazier, 2008).

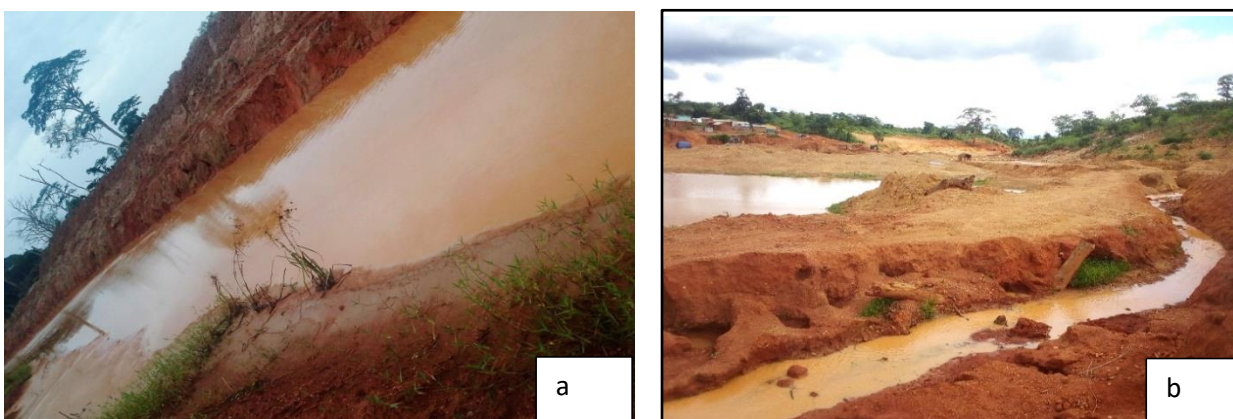


Figure 14: Deterioration of water (a) and reduction in water volume (b)

IV.3.2.2. Impacts on the chemical quality of water

Mining exploitation, particularly in artisanal and semi-mechanized gold mining, significantly increase the concentration of heavy metals in the surrounding environment. This occurs through various processes and activities associated to mining operations. The accumulation of heavy metals in the Djengou stream is significantly alarming as the levels of Hg, As, Pb, Fe and Zn have exceeded the WHO standard values.

– Mercury (Hg) contamination

At the mining site (BSW02), the Hg levels recorded as high as 7.897mg/L during the rainy season. This high concentration of Hg is because of the amalgamation processes that takes place during the extraction of gold from its ore. These high concentrations of Hg in Water has significant environmental and health effects, as it could enter into the food chain affecting both wildlife and human population relying on contaminated water sources. In addition, exposure to Hg can lead to neurological, behavioral disorders and bioaccumulation.

– **Arsenic (As) contamination**

Arsenic shows maximum levels on the mining site at Kambele during the rainy season with 13.412mg/L indicating severe pollution. This metal is often associated with gold deposits, As is released during mining, contaminating water sources. Long-term exposure to Arsenic can lead to cancer, skin lesions and developmental effects.

– **Lead (Pb) contamination**

The presence of lead at the mining site shows its peak at 24.147mg/L in the rainy season showing significant contamination along the Djengou stream. Sources of lead in surface waters are often associated to corrosion of pipelines and leaching of soils and rocks in watersheds. These sources can be natural (leaching of minerals like galena) or anthropic: mining, battery manufacturing, coal combustion, paint and pigment (Fashola et al., 2016). Lead intoxication can have negative effects on humans such as high blood pressure, neurological damages, reduced fertility, renal damage, learning deficits, hyperactivity and risk factor for Alzheimer's disease.

– **Iron (Fe) contamination**

The maximum iron concentrations 15.425mg/L recorded at BSW02 (on the mining site) during the Rainy season, which is higher than that of the dry season. This can be associated to increase runoff and leaching during rainfall. Iron commonly found in soils associated with gold bearing minerals. These high concentrations can be due to; Alteration of pyrite (gold bearing minerals), Quartz veins (rich in Fe), metagranites and granitoids found in the Batouri area; Leaching of lateritic ferrallitic soils of the zone. The soils of Batouri falls under red and yellow ferrallitic soil group (Olivry, 1986). While iron (Fe) is essential for health, excess concentrations can cause water discoloration and affects taste.

– **Zinc (Zn) contamination**

High levels of Zn recorded at 27.792mg/L at the mining site (BSW02) during the dry season. In this study, Zn could be originating from the weathered pyrite minerals and granitoids in the locality. Zn is a trace element present in several hundred enzymes, and participates in oxygen-carbon dioxide exchange by red blood cells. The intake of this trace element significantly reduces the occurrences of certain infections (mainly pneumonia and diarrhea) in children in developing countries, which can lead to increased life expectancy. However, like any trace element, the incorporation of Zn in large quantity can lead to toxicity. The human physiological disorders caused by this type of poisoning in a primary case include nausea and disorders of the gastro-intestinal system, and followed by complications in the respiratory system as well as the skin conditions (Yong et al., 1993). The health impacts caused by high concentrations or an overdose of Zn in the human body are significant. These include depression, gastro-intestinal irritation, impotence, Renal and hepatic failure, prostate cancer and convulsions.

In general, there is heavy metal contamination along the Djengou stream from the mining site at Kambele to the downstream at Patere Lobi 8.7km away. While BSW01 shows contamination of

heavy metals it is associated to the new mining site being put in place coupled with the natural environment as the water had a dark color which is influenced by the vegetation. Meanwhile at BSW00 upper stream of Mongoukele, which was our control site, showed only lead contamination, which can be associated with leaching of the soils and rocks in the watershed.

IV.3.3. Environmental Impacts associated to the mode of exploitation in the study area

The environmental impacts of artisanal and semi-mechanized gold mining observed in the study area which are associated with the decrease in sediment and water quality are exclusively negative they include; land degradation, loss of biodiversity and loss in air quality

IV.3.3.1. Land degradation

From the field studies conducted and through bibliographic research, it is safe to say that the artisanal semi-mechanized gold mining activities by Chinese company in Batouri particularly at Kambele has led to significant land clearing using mechanical shovels. This leads to the removal of trees and vegetation, which exposes the soil to erosion by wind, rain, leading to loss in fertile lands and increase in sedimentation along the Djengou stream. Huge quantities of waste rocks removed from extraction areas, on the banks and in the riverbed and during the construction of life bases and the opening of diversion channels. This technique creates many wells and washing pools of riverbed (Figure 15). These pits are later abandoned and filled with water during the rainy season and are the cause of the proliferation of several disease vectors including mosquitoes that cause malaria. Mining residues and waste rock stored on banks and terraces or even in riverbeds are directly subject to erosion and sedimentation processes. During engine operation, machine repairs and testing, fuel spills and pollutes the soil.

IV.3.3.2. Loss of biodiversity

Since mining exploitation involves several phases, it turns to have a negative impact that affects land habitats (Thomas, 2012). Mining operations begins with the construction of access roads to Kambele and Patere Lobi localities and various operating sites used to transport equipment and employees, which considerably fragments the territory. These cuts can prevent the displacement of species between plots and even lead to the regression of some of them. Mining activities has also led to a loss in biodiversity since trees and vegetation has been removed leading to disruption of the local ecosystems, which in turn reduces the plants and animal species that rely on forest habitat. Disruptions of the ecosystem during mining activities alter landscape, leading to deviation of watercourses; reduction in water volume; Case of the

Djengou watercourse. This disrupts the habitat of many species, forcing them to relocate or perish. The noise of machines and gold panners around the operating sites also leads to the migration of species to areas where they are in balance with their environments. Presence of numerous non-filled and abandoned mining excavations constitutes an obvious danger for the circulation of wild and domestic animals and even of men (figure 16). However, the most important are those affecting aquatic organisms and habitats. In fact, fish are strongly affected by the increase in turbidity and suspended matter in rivers. The presence of suspended matter affects their eating practices and can make them more vulnerable to pathogens by reducing their visibility to the solar rays, attacking their gills and interfering with the production of mucus (Environment Canada, 2011b).



Figure 15: land degradation at Kambele leading to creation of artificial lakes



Figure 16: Deforestation

IV.3.3.3. Loss of air quality

Mining operations generate significant air pollution through dust and emissions especially in the dry season. Mining tailings made up of particles of several sizes, but the finest ones are the most subject to wind erosion and a possible source of new contamination. These fine particles, whose size varies between 0.05 and 0.25 mm, easily transported by wind or moved by runoff water (Thomas, 2012). Once these particles suspend in air, they travel to the atmosphere and then settle in nearby bodies of water or on neighbouring land. This accumulation causes several repercussions, particularly on air quality. Dust production and gas emissions are important sources of air and atmosphere contamination. Air and atmosphere contamination in mining sites generated during the transportation of the gangue where large amount of dust particles emitted to the atmosphere, which can affect the air quality and causes respiratory health issues for nearby communities. The use of heavy machinery and vehicles during excavation works and transportation also releases pollutants such as nitrogen oxides, and sulfur dioxide, contributing to air pollution and climate change. The operations of heavy machinery generate substantial noise pollution that can disturb local wildlife and affect the quality of life for nearby residents.

IV.3.4. Health impacts Associated to the physicochemical quality of sediments and water.

The local population of Kambele and miners are exposed:

- To mercury (Hg) poisoning: many miners are being exposed to Hg during gold extraction process and through swimming along the Djengou stream by ignorant children (Figure 18). Hg is highly toxic and can lead to severe health issues such as neurological damage, kidney problems, and respiratory failure;
- Lead (Pb) poisoning: Lead intoxication can have negative effects on humans such as high blood pressure, neurological damages, reduced fertility, renal damage, learning deficits, hyperactivity and risk factor for Alzheimer’s disease. (WHO, 2017).
- arsenic causes skin lesions, respiratory issues and long-term cancer during prolonged exposure
- exposure to high levels of Zn and Fe can have adverse health effects. For example, excessive Zn can cause depression, gastro-intestinal irritation, impotence, Renal and hepatic failure, prostate cancer, convulsions, nausea, vomiting, and damage to the pancreas, while iron levels can lead to organ damage (WHO, 2017)



Figure 17: Children swimming in the Djengou River leading to exposure to contaminants

IV.4. Some Recommendations to Mitigate these Impacts

In this section, the various strategies to fight against environmental degradation are presented to manage the gold mining area of Kambele and Patere Lobi. These solutions extend beyond Kambele and Patere Lobi as it serves as a remediation strategy for other mining sites in Cameroon and around the world. These strategies include:

- **Drilling Boreholes away from gold extraction areas**

One of the primary strategies to safeguard water quality is the strategic placement of boreholes far from gold mining and extraction sites. Gold mining activities often release toxic chemicals such as mercury (Hg) and other heavy metals like the case of this study, which can contaminate nearby water sources through leaching or runoff. By ensuring that boreholes are located at considerable distance from these activities, communities can minimize the risk of groundwater contamination.

- **Utilize Natural filters to Purify Water**

The use of natural filtration systems, such as charcoal and sand, is cost-effective and sustainable method for treating contaminated water. Activated charcoal, due to its high adsorption capacity, effectively removes heavy metals, organic pollutants, and other contaminants from water. Sand filters, on the other hand, are excellent for removing suspended particles and pathogens. A combined filtration system can be deployed in local communities near mining areas, offering an eco-friendly solution to improve the quality of both surface water and groundwater. Implementing community-based water treatment programs that utilize these natural filters can enhance accessibility to clean water.

- **Implement Integrated Water Resource Management (IWRM)**

Integrated water resource management is a holistic approach that ensures the sustainable use of water resources while addressing the environmental, social, and economic impacts of gold mining. Key components of IWRM include;

- i. Encouraging active participation from communities, government agencies, and mining companies to collaboratively manage water resources;
- ii. developing and enforcing strict regulations for waste disposal and pollution control in gold mining areas to prevent contamination of water resources;

- iii. establishing regular monitoring programs to assess water quality and detect early signs of contamination;
- iv. restoring degraded ecosystems through reforestation , soil stabilization, and creation of buffer zones around mining sites to reduce runoff.

– **Sensitization and Education of the Public**

Public education and awareness campaigns play a critical role in addressing the environmental impacts of gold mining. Communities should be informed about risks of heavy metal contamination, the importance of safe water practices, and sustainable water management techniques. These campaigns can be conducted through workshops, community meetings, informational materials, and school programs. By empowering individuals with knowledge, they can make informed decisions, participate in water resource management initiatives, and contribute to the protection of their local environment.

Conclusion

At the end of this chapter, we have established that the decrease in water quality along the Djengou watercourse is by suspended matter and heavy metals such as Hg, Pb, As, Fe and Zn as well as the significant decrease of stream sediments quality by these metals, which surpasses the WHO standard guideline values. Spatial variation and inter-element correlations show that these pollutants come from one hand from the chemical alteration of rocks and land remobilized by mining and on the other hand from human and atmospheric outputs. The chapter also presents the impacts caused on the environment by the release of this pollutants to the environment highlighting; Land degradation, biodiversity loss, air pollution and sediment contamination giving the various health problems associated to this contaminants and finally, providing multiple approach incorporating drilling of boreholes away from active mining sites, the use of natural filters, implementation of IWRM, sensitization and education of the local population against the identified impacts.

GENERAL CONCLUSION AND PERSPECTIVE

The Djengou watershed is the site chosen for this study found in the Batouri gold district; it is located between latitude 4⁰25'- 4⁰30'North and longitude 14⁰20'-14⁰25'East. Batouri is a town and commune located in the Kadey division, East region of Cameroon. The climate in this locality is the transitional equatorial and tropical climate with 4 seasons interspersed. The area lies on the south Cameroon plateau with altitudes ranging between 600-1000m covered by deciduous and peri-forest savannahs. The area lies on the Precambrian basement characterised by various granitoids, orthogneisses, and migmatites and is drained by a dendritic system of water flow, into the Kadey River which is the main drainage basin of the region. Under these conditions, lateritic, red and yellow ferralitic soils and hydromorphic soils are developed.

The main objective of this study is to evaluate the impacts of artisanal and semi-mechanized gold mining activities on sediments and water quality along the Djengou watercourse in Batouri. To do this a set of objectives specifically defined and served as a methodological guide. It consisted mainly of bibliographic research, field studies and laboratory work. The field study made it possible to have first-hand information of the gold mining activities taking place in the locality. During field study, it was observed that the gold ore mining techniques led to loss of biodiversity, deviation of watercourse, deforestation that led to soil instability, sedimentation of water bodies and reduction in water volume along the Djengou watercourse from Kambele to Patere lobi. These impacts have led to changes in the physicochemical parameters of waters in the biophysical environment. Laboratory analyses carried out to assess the quality of waters and stream sediments. The results of the analysis showed that the waters are slightly acidic to slightly basic $6.54 \leq \text{pH} \leq 7.32$ and are moderately mineralized $145 \mu\text{S}/\text{cm} \leq \text{EC} \leq 662.43 \mu\text{S}/\text{cm}$. The total suspended solids ranged from $3 \text{mg}/\text{L} \leq \text{TSS} \leq 681.5 \text{ mg}/\text{L}$, the parameter causing the deterioration of water quality. In addition, the analysis revealed the presence of heavy metals such as Hg, As, Pb, Fe, and Zn at concentrations higher than the standards defined by W.H.O. While sediments are considerably contaminated, with Hg, As, Pb, Fe, and Zn, the geo-accumulation index showed that Hg and Zn are the most contaminated heavy metals in sediment during the dry season these can be explained based on the fact that heavy metals tend to accumulate during low water periods. These pollutants associated to Artisanal and semi-mechanized gold mining techniques cause problems of access to drinking water, the extinction of species, health problems, bioaccumulation and biomagnification.

These findings reflect the urgent need for effective pollution management strategies to mitigate the adverse effects of artisanal and semi-mechanized gold mining. This study provides crucial understanding for policy makers, environmentalists, and the local communities, emphasizing the necessity of drilling boreholes away from active mining sites, the use of natural filters (charcoal and sand), implementation of IWRM, sensitization and education of the local population. The recommendations aim to protect public health, restore the local environment, and foster sustainable development in the region. The assessment of water and stream sediment quality showed complex challenges posed by artisanal and semi-mechanized gold mining, advocating for a holistic approach to remediation and sustainable growth in the Batouri gold district. Results obtained from this research framework are preliminary data, which on its own cannot provide definite solutions to the impacts of mining exploitation on sediments and water in the Batouri gold district. As such, advance future works should be centralized towards:

- Sampling over a full hydrological year to capture the seasonal variability in TSS;
- increasing the sample size and spatial coverage to many localities within the study area as this study was conducted only in three (3) localities;
- monitoring programs to track the changes in heavy metal concentrations and other pollutants using advance techniques;
- conducting detailed health impact assessments to evaluate the direct and indirect effects of mining-related pollutants on local communities.

BIBLIOGRAPHY

- Abdel-Satar, A.M., Ali, M.H. and Goher, M.E. (2017).** Indices of Water Quality and Metal Pollution of Nile River. *Egypt Egyptian Journal of Aquatic Research*, 43, 21-29. <https://doi.org/10.1016/j.ejar.2016.12.006>.
- Asaah, Akwinga,V., Zoheir, B., Lehmann, B., Frei, D., Burgess, R., Suh, C.E., 2015.** Geochemistry and geochronology of the ~620 Ma gold associated Batouri granitoids, Cameroon. *International Geology Review*. 57, 1485-1509. <http://dx.doi.org/10.1080/00206814.2014.951003>.
- Ashley and D. Carney, (1999).** Sustainable Livelihoods: Lessons from Early Experience, Department for International Development, London, UK.
- Attua, E. M., Annan, S. T., Nyame, F. (2014).** Water quality analysis of rivers used as drinking sources in artisanal communities of the Akyem-Abuakwa area: A multivariate statistical Approach. *Ghana Journal of geography*, 6, 24-41
- Ayiwouo, M. N., Sriram, S., Rajapopal, K., Ngounouno, F. Y., Ngounouno, I. (2023).** Assessment of the environmental impacts of gold mining activities at Gankombol (Adamawa, Cameroon) using leopold matrix Facticeau grid and remote sensing approach *Journal of African Earth Sciences*, 207, 105650.
- Ayiwouo, N.M., Yamgouot, N.F., Mambou, N.L.L., Kingni, T.S., Ngounouno, I., (2022).** Impact of gold mining on the water quality of the Lom River, Gankombol, Cameroon. *Heliyon* 8 e12452. <https://doi.org/10.1016/j.heliyon.2022.e12452>.
- Ayiwouo, N.M., Mambou, N.L.L., Kingni, T.S., Nforsoh, N.S., Ngounouno, I., 2021.** Evaluation of the impact of gold mining activities on the waters and sediments of Lom River, Wakaso, Cameroon and the restorative effect of Moringa Oleifera seeds. *Applied Water Science*, 11(113), 1-16. <https://doi.org/10.1007/s13201-021-01445-x>.
- Backman, P.A., Bell, D.K., Ben-Yephet, Y., Beute, M.K., Black, M.C., Boswell, T.E., et al. (1997).** Compendium of peanut Disease. 2nd Edition. American Phytopathological society, Saint Paul.

- Bagnouls, F., Gaussen, H., 1957.** Les climats biologiques et leur classification. In: Annales de Géographie 66 (355), 193-220.
- Batabyal, A.K and Chakraborty, S. (2015)** Hydrogeochemistry and Water Quality Index in the Assessment of Groundwater Quality for drinking uses. Water Environment Research, 87, 7. <https://doi.org/10.2175/106143015X14212658613956>.
- Bella Atangana, M. S., Ndam Ngoupayou, J. R.; Deliege, J. F. (2023).** Hydro geochemistry and Mercury Contamination of Surface Water in the Lom Gold Basin (East Cameroon): Water Quality Index, Multivariate Statistical Analysis and Spatial Interpolation. Water 2023,15,2502. <https://doi.org/10.3390/w15132502>.
- Besack, F., Ebongue, E. S., and Ndjeng, E. (2021).** Spatial and Temporal variations of the hydrological parameters in the Wour-Nkam section of the Cameroon Estuary, Central Atlantic Coast. Journal of water and climate change, 12(4), 1237-1249.
- Bilotta, G. S., Brazier, R. E. (2008).** Understanding the influence of suspended solids on water quality and aquatic biota. Water Research.
- Bo, L., Wang, D., Li, T. et al.** Accumulation and risk assessment of heavy metals in water, sediments, and aquatic organisms in rural rivers in the Taihu Lake region, China. Environ Sci Pollut Res 22, 6721–6731 (2015). <https://doi.org/10.1007/s11356-014-3798-3>.
- Brooks, K.N., Ffolliot, P.F., Magner, J.A. (2013)** Hydrology and the management of watersheds, 4th edn. Wiley, Iowa.
- Corredor, J. A. G., Perez, E. H, Figueroa, R., casas, A. F. (2021).** Water quality of streams associated with gold mining: Suarez Department of Cauca, Colombia. Heliyon.
- Cude, C. (2001)** Oregon Water Quality Index: A Tool for Evaluating Water Quality Management Effectiveness. Journal of the American Water Resources Association, 33, 125-137. <https://dx.doi.org/10.1111/j.1752-1688.2001.tb05480.x>
- Davies-Colley, R. J., Smith, D. G. (2001).** Turbidity, suspended sediment, and water clarity: A review. Journal of the American Water Resources Association

- Detay, M., 1993.** Forage d'eau (réalisation, entretien et minéralisation). Edition Masson, Paris, 280 pp.
- Edet, A.E., & Offiong, O.E. (2002).** Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani Area, lower cross River Basin (southeastern Nigeria). *Geojournal*, 57(3), 295-304. <https://doi.org/10.1023/B:GEJO.0000007250.92458.de>
- Environnement Canada (2011b).** Erosion and sedimentation. <http://www.ec.gc.ca/eau-water/default>.
- European Standards – SR ISO 5667-23, 2011.** Ghid general pentru tehnicile de prelevare (General guide for surface water sampling techniques).
- European standards – SR ISO 5667-3, 2013.** Calitatea apei. Prelevare. Partea 3: Conservarea si manipularea probelor de apa (Water quality. sampling. Part 3: Conservation and handling of water samples).
- Fashola, M. O., Ngole-Jeme, V. M., & Babalola, O. O. (2016).** Heavy metal pollution from gold mines: Environmental effects and bacterial strategies for resistance. *Applied Microbiology and Biotechnology*, 100(12), 5681-5697.
- Funoh, K.N., Nkwemoh, C.A., Chupezi, J.T., and Moupou, M. (2017).** Artisanal gold mining and its adverse impacts on the Ngoyla-Mintom massif, Cameroon. *International Journal of Resource and Environmental management*.
- Hakanson, L. (1980).** An Ecological Risk Index for Aquatic pollution control: A sedimentological Approach. *Water Research*, 14(8), 975-1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8).
- Hentschel, T., Hrushka, F., Priester, M. (2002).** Draft Global Report on Artisanal And Small-Scale Mining, Working Paper For Mining, Minerals And Sustainable Development, November, 2001, pp, 59.

- Hilson, G. and Banchirigah, S.M. (2009).** Are Alternative Livelihoods Projects Alleviating Poverty In Mining Communities? Experiences from Ghana. *Journal of Development Studies*, 45, 172-196. <https://doi.org/10.1080/0020380802553057>.
- Hinton, J. J., Veiga, M. M., & Veiga, A. T. C. (2003).** Clean artisanal gold mining: a utopian approach? *Journal of Cleaner Production*, 11, 99–115. [https://dx.doi.org/10.1016/S0959-6526\(02\)00014-4](https://dx.doi.org/10.1016/S0959-6526(02)00014-4).
- Hinton, J.J., Viega, M.M., and Veiga, A.T.C. (2003).** Clean artisanal mining: A Utopian approach? *Journal of Cleaner production*, 11(2), 99-115. [https://doi.org/10.1016/S0959-6526\(02\)00043-4](https://doi.org/10.1016/S0959-6526(02)00043-4).
- Horton, R.K. (1965).** An index number system for rating water quality. *Journal of the water pollution control federation*, 37,300-306.
- IRAD. (2008).** Deuxième rapport sur l'état des ressources phytogénétiques pour l'alimentation et l'agriculture au Cameroun. National Herbarium of Cameroon.
- Jean-Claude, B. , Rigobert, T. , Joachim, E. , Périclex, F. and Basile, D. (2019)** Geological Context Mapping of Batouri Gold District (East Cameroon) from Remote Sensing Imaging, GIS Processing and Field Works. *Journal of Geographic Information System*, 11, 766-783. doi: 10.4236/jgis.2019.116046.
- Kamga, M.A., Nguembe Fils, S.C.F., Ayodele, M.O., Olaburaba, C.O., Nzali, S., Adenikinju, A., Khalifa, M. (2020)** Evaluation of land use/land cover changes due to gold mining activities from 1987 to 2017 using Landsat imagery, East Cameroon. *Geojournal* 85(1097-1114). <https://doi.org/10.1007/s10708-019-10002-8>.
- Kamga, M.A., Olaburaba, C.O., Atteh, M.M., Nzali, S., Adenikinju, A., Mbitaso, T.Y., Ngatcha, R.B. (2018)** Perception of environmental degradation of gold mining on socio-economic variables in Eastern Cameroon, *European journal of sustainable development research*, 2(2), 23. <https://doi.org/10.20897/ejosdr/85117>.
- Kouankap, N.G.D., Clifford, T.B., Pierre, W., Alice, M., Kuma, C.J., Joëlle Flore, T.D. (2017).** Artisanal gold mining in Batouri area, East Cameroon: Impacts on the mining

population and their environment. *Journal of Geology and mining Research*, 9(1), 1-8.
<https://doi.org/10.5897/JGMR2016.0263>

Kouassy Kalédjé, P.S., Ndam Ngoupayou, J.R., Kpoumié, A., Fouébé Takounjou, A., Mvondo Ondoua, J., 2016. Analysis of climate variability and its influence on the hydrological response of the catchment area of Kadey (East Cameroon), *International Journal of Geosciences*, 7, 539-547. <http://dx.doi.org/10.4236/ijg.2016.74041>

Kpoumie, A. (2015). Hydro climatologie et transports solides dans un écosystème tropical anthropise d'Afrique centrale dans un contexte déficitaires : Cas du bassin versant de la Sanaga au Cameroun. Thèse de Doctorat/Ph.D, Université de Yaoundé 1-Cameroun

Letouzey, R. (1968). Etude phytogéographique du Cameroun. Paris p.311

Mambou Ngueyep, J., Tchatchouang, R., Nganou, P. A. (2019). Socio-environmental impacts of gold mining in the East Region of Cameroon: The case of Batouri. *Environmental Science and Policy*, 101, 43-52. <https://doi.org/10.1016/j.envsci.2019.08.004>.

Mambou Ngueyep, L.L., Takaougang Kingni, S., Ayiwouo Ngounouno, M. et al (2021). The impact of mining exploitation of the physicochemical quality of water: Case of Batouri (Cameroon). *Int J Energ water Res* 5, 159-173(20210) <https://doi.org/10.1007/s42108-020-00106-0>.

Mambou, V. M., Ngangom, B. L., & Ndzomo, N. F. (2020a). Impact of gold mining on the water quality of the Lom River, Gankombol, Cameroon. *Journal of Environmental Science and Technology*, 14(4), 512-525.

Melesse, A.M., McClain, M., Abira, M., and Mutayoba, W. (2008) Hydro meteorological analysis of the Mara River Basin Kenya/Tanzania, proceedings of the World Environment and water resources Congress 2008, ASCE Conf.Proc.doi:10.1061/4097(316)589, 2008.

MINEE, GWP-Cmr. (2009). Etat des Lieux du secteur de l'eau au Cameroun : Connaissances et Usages de Ressources en Eau (Tome1). Technical Report, Yaoundé, 184p.

- Mohan, S.V., Nithila, P., Reddy, S.J., 1996.** Estimation of heavy metal in drinking water and development of heavy metal pollution index. *J. Environ. Sci. Health A31*, 283–289.
- Mseddi, H., Ben Mammou, A., 2014.** Évaluation de la contamination des sédiments des oueds Rémir et Siliana par les rejets miniers d’El Akhouat (Bassin versant de Siliana, Nord-Ouest de la Tunisie). *Geo-Eco-Trop*, 38(2), 305-316.
- Müller, G. (1969).** Index of Geoaccumulation in the sediments of the Rhine River. *GeoJournal*, 2(3), 108-118. ScienceOPEN.com.
- Stambuk-Giljanovic, N. (1999).** “Water Quality Evaluation by Index in Dalmatia,” *Water Research*, vol.33, No. 16, 1999, pp.3423-3440.
- Ndam, N.J.R. (1997).** Bilans hydrogéochimiques sous forêt tropicale humide en Afrique du bassin expérimental de Nsimi-Zoetele aux réseaux hydrologiques du Nyong et de la Sanaga (Sud-Cameroun). Thèse de Doctorat (Ph.D), Université de Paris VI, p. 214
- Ndam, N.J.R., Dzana, J.G., Kpoumie, A., Tanwi, G.R., Fouepe, T.A., Braun, J.J., Ekodeck, G.E. (2016).** Present-day sediment dynamics of the Sanaga catchment (Cameroon): from the total suspended sediments (TSS) to erosion balance. *Hydrological Sciences Journal*, 61(6), 1080-1093. <https://doi.org/10.1080/02626667.2014.968572>.
- Ndonfack, K. I. A., Ebongue, E.S., Kamgang, J., and Tcheumenack, M. (2021).** Genesis and Mineralization style of Gold occurrences of the lower Lom Belt, Betare-Oya District, Eastern Cameroon. *Journal of African Earth sciences*, 181,103875.
- Ngoa Manga, E.S., A.Z. Ekoa Bessa., Mbomo, R.E.A., Akono, J.V., Dairou, B., Pierre, K. (2024).** Evaluation of surface water contamination and its impacts on health in the mining districts of Kambele and Betare-Oya (Eastern-Cameroon). *Heliyon*.
- Nowrouzi, M.; Pourkhabbaz, A.** Application of Geoaccumulation Index and Enrichment Factor for Assessing Metal Contamination in the Sediments of Hara Biosphere Reserve, Iran. *Chem. Special. Bioavailable* 2014, 26, 99–105.
- Olivry, J.C., 1986.** Fleuves et rivières du Cameroun. Monographie hydrologique. ORSTOM, N° 9. Ed. MESRES-ORSTOM.733p.

- Olivry, J.C., Naah, E. (1978).** Qualité des eaux de quelque rivière du Cameroun méridional. Rapport. ONAREST, Yaoundé, P. 39.
- Prasad, B., Kumary, S., 2008.** Heavy metal pollution index of ground water of an abandoned open cast mine filled with fly ash: a case study. *Mine Water Environ.* 27, 265–267.
- R.M. Brown et al., 1970.** “A Water Quality Index-Do we dare,” *Water Sewage Works*, Vol. 117, 1970, pp. 339-343.
- Rakotondrabe, F., Ngoupayou, J.R.N., Mfonka, Z., Rasolomanana, E.H., Abolo, A.J.N., Asone, B.L., Ako, A.A. and Rakotondrabe, M.H. (2017)** Assessment of Surface Water Quality of Bétaré-Oya Gold Mining Area (East-Cameroon). *Journal of Water Resource and Protection*, 9, 960-984.
- Ralph, O., Gilles, N., Fon, N., Luma, H., Greg, N. (2018)** Impact of artisanal gold mining on Human health and the environment in Batouri Gold district, East Cameroon. *Academic journal of interdisciplinary studies*, 7(1) <https://doi.org/10.2478/ajis-2018-0003>.
- Rodier, J. (2009).** L’analyse de l’eau naturelle, eaux résiduaires, eau de mer, 9eme édition, Dunod, Paris, p. 1383.
- Salomons, W., & Forstner, U. (1984).** *Metals in the hydro cycle.* Springer-verlag, Berlin, Heidelberg, New york, Torkeyo. Link.springer.com.
- Sano, T., Tani, K., Murch, A.P. (2020).** Major and Trace element analyses of igneous rocks and sediments by X-ray florescence spectrometry using glass bead and pressed powder pellet. *Bulletin of the National museum of Nature and Sciences Series C*, 46, 1-14.
- Sener, S., Sener, E., Davraz, A., 2017.** Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). *Sci. Total Environ.* 584–585, 131–144.
- Sighomnou, D., 2004.** Analyse et redéfinition des régimes climatiques et hydrologiques du Cameroun : perspectives d’évolution des ressources en eau. Thèse de doctorat d'Etat, Université de Yaoundé I. 291p.

- Simate, G. S., & Ndlovu, S. (2014).** Acid mine drainage: Challenges and opportunities. *Environmental Science and Pollution Research*, 21(15), 14138-14143. <https://doi.org/10.1007/s11356-014-2969-1>.
- Singh H, Pandey R, Singh SK, Shukla DN (2017)** Assessment of heavy metal contamination in the sediment of the River Ghaghara, a major tributary of the River Ganga in Northern India. *Appl Water Sci* 7:4133–4149.
- Smith, K.S., & Huyck, H.L.O. (1999).** An overview of the relative abundance, relative mobility, bioavailability, and human toxicity of metals. In G.S. plumlee \$M.J. Logsodon (Eds), *The environmental geochemistry of mineral deposits, part A: Processes, techniques, and health issues* (pp. 29-70). Society of economic geologists
- Song, J., Liu, Q., Sheng, Y. (2019).** Distribution and risk assessment of trace metals in riverine surface sediments in gold mining areas. *Environmental Monitoring and Assessment* 191, 1-13. <https://doi:10.1007/s10661-019-7311-9>.
- Spiegel, S., Veiga, M.M., (2009).** Artisanal and small-scale mining as an extra legal economy: De Soto and the redefinition of „formalization“. *Resources Policy*, 34(1–2): 51–56. Shandro, J.A., Veiga, M.M., Chouinard, R., 2009. Reducing mercury pollution from artisanal gold mining in Munhena, Mozambique. *Journal of Cleaner Production* 17 (5), 525–532
- Suchel, J.B., 1988.** Les climats du Cameroun. Thèse Univ. Saint Etienne 1188 p
- Suh, C. E., Lehman, B., Mafany, G. T. (2006).** Geology and Geochemical aspects of lode gold mineralization at Dimako-Mboscorro, SE Cameroon *Geochemistry: Exploration Environmental analysis*, 6, 295-309. <https://doi.org/10.1441/1467-7873/06-110>
- Tchakounte, J., Ntep, M. L., & Kamguia, J. (2017).** The Adamawa-Yadé Domain, a piece of Archaean crust in the Neoproterozoic Central African Orogenic Belt (Bafia area, Cameroon). *Precambrian Research*, 292, 10-22.

- Tomlison, D.L., Wilson, J.G., Harris, C.R., & Jeffrey, D.W. (1980).** Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgong Marine Research*, 33,566-575. <https://doi.org/10.1007/BF02414780>
- Torrance, K.W., Redwood, S.D. & Cecchi, A. (2021).** The impact of artisanal gold mining, ore processing and mineralization on water quality in Marmato, Colombia. *Environ Geochem Health* 43, 4265–4282 (2021). <https://doi.org/10.1007/s10653-021-00898-y>.
- Turekian, K.K., and Wedepohl, K.H. (1961).** Distribution of the Elements in Some Major Units of the Earth's Crust. *Geological society of America Bulletin*, 72(2), 175-192. [https://dx.doi:10.1130/0016-7606\(1961\)72\[175:DOTAIS\]2.0CO;2](https://dx.doi:10.1130/0016-7606(1961)72[175:DOTAIS]2.0CO;2)
- USEPA (2012).** Water quality standard handbook. United States Environmental Protection Agency.
- Velasquez-Lopez, P.C.; Veiga, M.M.; Hall, K. (2010)** Mercury balance in amalgamation in artisanal and small scale gold mining: Identifying strategies for reducing environmental pollution in Portovelo-Zaruma, Ecuador. *J. Clean. Prod.* 2010, 18, 226–232.
- Vishiti, A., Etame, J., Suh, C. E. (2019).** Features of gold-bearing quartz veins in an artisanal mining dominated terrain, Batouri gold district, Eastern region of Cameroon. *Episodes*, 42(3), 199-212. <https://doi.org/10.18814/epiugs/2019/019016>.
- Vishiti, A., Ndjeng, E., & Kamgang, J. (2015).** Gold grade variation and particle microchemistry in exploration pits of the Batouri gold district, SE Cameroon. *Journal of African Earth Sciences*, 105, 1-10.
- Wang, J., Qin, L., He, H. (2019)** Assessing temporal and spatial inequality of water footprint base on socioeconomic and environmental factors in Julin Provence, China. *Water (Switzerland)* 11:19. <https://doi.org/10.3390/w11030521>
- World Bank report. (2019)** Quality unknown: the invisible water crisis. <https://www.worldbank.org/en/news/featur/2019/08/20-inknown>
- World Health Organization (WHO), 2011.** World Health Organization Guidelines for Drinking-Water Quality. Recommendations. Fourth ed., Geneva.

- World Health Organization (WHO), 2017.** Guidelines for Drinking-Water Quality: First Addendum to the. Switzerland, Geneva.
- Xing, J., Gao, L., & He, L. (2022).** Species distribution and concentration pollution of soil heavy metals in coal mine reclamation areas. *Frontiers in Environmental Science*, 10, 925074. <https://doi.org/10.3389/fenvs.2022.925074>.
- Yannah, M., Suh, C.E., Mboudou.,M.G.M. (2015)** Quartz veins characteristics and Au Mineralization within the Batouri Au District, East Cameroon. *Sci. Res.* 2015, 3, 137–149.
- Yong, R. N., Nakano, M., & Pusch, R. (1993).** Contaminant transport in clay-water systems. *Geoenvironmental Science and Engineering*, 23(2), 145-160.
- Zhang, M.Y., Cui, L.J., Sheng, L.X., Wang, L.F.** Distribution and enrichment of heavy metals among sediments, water body and plants in Hengshuihu Wetland of Northern China. *Ecol. Eng.* 2009, 35, 563–569.

ANNEX

Annex 1: Spatio-temporal variation of physicochemical quality of water compared to WHO standard

The In-situ Physicochemical Parameter of water in Batouri (Mougoukele and Djengou)								
Parameter	Units	WHO standard	Dry season (May)			Rainy season		
			Samples					
			BSW01	BSW02	BSW03	BSW00	BSW02	BSW03
Temp	°C	15-25	26.3	28.5	26.28	23.1	25.1	23.6
pH		6.5-8.5	6.89	6.54	6.9	6.63	7.26	7.32
TDS	mg/L	1000	96	141	132	157	209	355
EC	µS/cm	1500	145	215	208	245	326	662.43
Sali	mg/L	200-250	0.04	0.07	0.07	0.08	0.1	0.24
DO	mg/L	5-14	8.79	7.76	8.81	3.54	0.8	9.31
TSS	mg/L	-	26.33	681.5	363	4	165.5	173.5

ANNEX 2: Laboratory work and instruments



a) Determining TSS with the help of a filter
(for heavy metal determination in sediment and water)



b) Atomic adsorption spectrophotometer



Field work and materials used to determine in-situ physicochemical quality of water at the control site along the Mongoukele (a) and on the mining site at Kambele along the Djengou watershed (b) using a multi-parameter.



Collected water and sediment samples