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Physicochemical monitoring of Zadepleu waterfall river from Côte d'Ivoire using on-site and satellite measurements

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Abstract

Surface waters are exposed to climate variability and anthropogenic activities. This study focuses on the spatio-temporal monitoring of the physicochemical quality of the Zadepleu waterfall river in Côte d'Ivoire, combining monthly in situ measurements with satellite data. The parameters analysed include turbidity, chlorophyll-a derived from satellite data, nutrients (nitrates, phosphates), and other physicochemical parameters. The water quality index (WQI) was applied to the on-site data. The results reveal that the waters of the river, including the waterfall, are generally not potable (WQI > 100), with marked deterioration downstream of the bathing zone at station S3. The river experiences greater quality degradation during the dry season compared to the wet season, with mean WQI values of 374.50 and 217.24, respectively. Satellite data (Sentinel-2), processed using the R package Waterquality, enabled the assessment of turbidity and chlorophyll-a, showing seasonal variations with higher values during the rainy season. The average in situ turbidity value is 9.32 NTU. The indirect satellite measurements underestimate these turbidity values. The low concentrations of chlorophyll-a suggest that the water in this waterfall remains relatively in good condition in terms of nutrient levels. This study highlights the importance of sustainable management strategies to preserve this aquatic ecosystem.

Keywords: WQI; Turbidity; Chlorophyll-a; Nutrients; Sentinel-2; Zadepleu waterfall

1. Introduction

Water is an essential natural resource for life within any ecosystem [1]. Although we often rely on groundwater for our drinking water supply, surface waters remain a vital resource for sustainable development. These waters are employed for various purposes, including drinking, agricultural activities, and recreational uses such as sports and leisure. However, surface waters are potentially threatened both quantitatively and qualitatively. These threats are related to anthropogenic activities and natural phenomena. The quality of surface waters, as well as groundwater, deteriorates due to both natural and human activities [2]. Indeed, the physicochemical and microbiological properties of rivers are directly influenced by activities on the watershed drained by these watercourses [3, 4]. The potential sources of surface water pollution are linked to socio-economic activities, including agriculture, industry, fishing, and tourism [5]. Pollution can be solid (sediments) or dissolved (chemical elements). Among chemical elements, nutrients, trace metals (ETMs), chlorophyll-a, etc., are notable. While nutrients and organic matter are essential for the proper functioning of aquatic ecosystems, their excess can lead to eutrophication, characterized by excessive algal growth and oxygen depletion in the water. This phenomenon can have several adverse effects, including increased mortality risk for many aquatic organisms and the deterioration of recreational activities like swimming.

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The hydrosystem of the Zadepleu natural waterfall in Man, which is the focus of this study, is classified among the most visited tourist sites in the Tonkpi region in western Côte d'Ivoire. The activities of local populations on the watershed of the river feeding this waterfall and recreational bathing activities are likely to deteriorate surface water quality. In fact, the mountain watersheds of the Tonkpi region are experiencing advanced degradation due to the progressive disappearance of forest resources. The degradation of the slopes and summits of the mountains in Man is driven by poorly managed urbanisation, farming activities, and especially uncontrolled logging [6]. Unfortunately, this situation persists to this day. These anthropogenic activities remain potential sources of irreversible water body pollution if no action is taken. In the long term, the physicochemical and microbiological health of the hydrosystem could become problematic, with risks of water contamination and cessation of recreational activities such as swimming.

The application of remote sensing and/or mathematical techniques to water quality issues has proven to be a powerful tool in water resource management. Several methods exist for assessing water quality [7, 8]. Among these are various water quality indices developed as mathematical tools [2, 9]. These approaches utilize in situ data for water quality assessment and also employ remote sensing methods, which indirectly evaluate water quality using signals captured by satellites. The R package 'waterquality' converts quickly and easily satellite-based reflectance imagery into one or many well-known water quality indices designed for the detection of Harmful Algal Blooms (HABs) using the following pigment proxies: chlorophyll-a, blue-green algae (phycocyanin), and turbidity. Currently, this package is able to process 40 algorithms for the following satellite-based imagers: WorldView-2, Sentinel-2, Landsat-8, MODIS, MERIS, and OLCI [10]. This study aimed to monitor, using both in situ measurements and satellite data, the effects of environmental changes on the water quality of the river feeding the natural Zadepleu waterfall. The methodology for water sample collection and analysis is first described. Subsequently, the results obtained are interpreted and discussed. These findings could assist policymakers in implementing sustainable management strategies for the hydrosystem of the Zadepleu waterfall.

2. Materials and methods

2.1. Study Area

Located in the Man department in western Côte d'Ivoire, the watershed encompassing the Zadepleu waterfall (Man) is situated between longitudes 07°34'00'' W and 07°37'30'' W, and latitudes 07°28'30'' N and 07°24'50'' N. This watershed covers an area of 23.85 km^2 (see Figure 1).

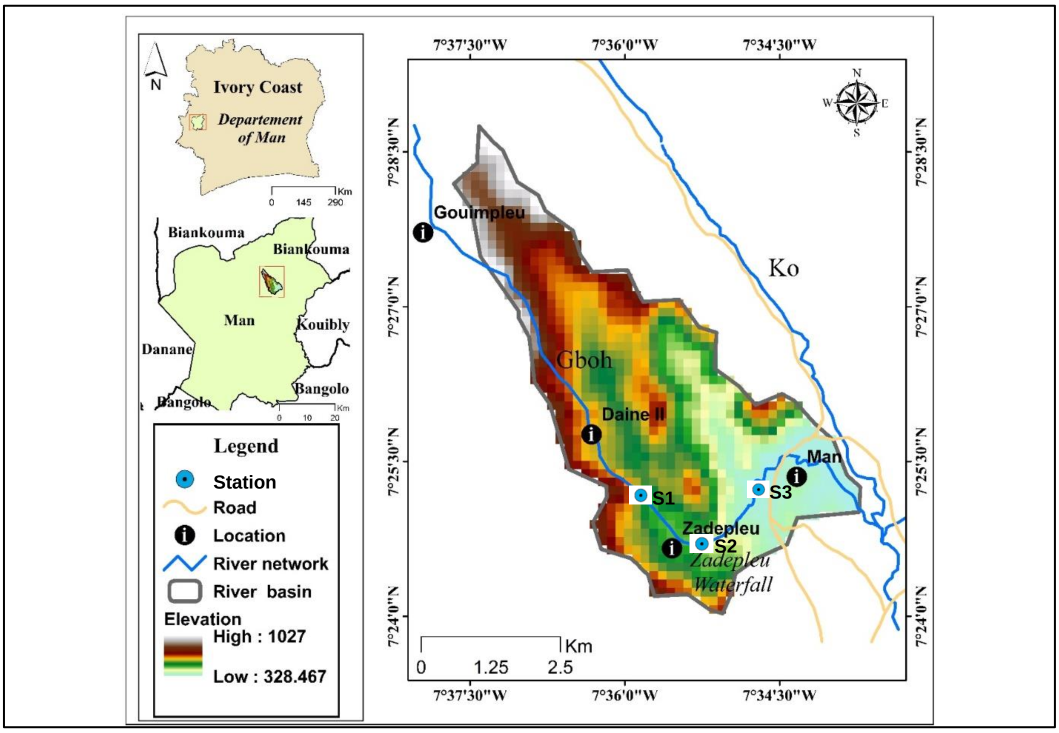

Figure 1 Geographical location of the study area and water sampling stations

Man is a city in western Côte d'Ivoire, serving as the capital of the Mountain District and the Tonkpi Region. Known as the "City of the 18 Mountains," Man is situated in a basin surrounded by mountain ranges. The city is approximately 600 km from Abidjan and also functions as a prominent tourist destination in Côte d'Ivoire. The climate in the watershed reflects that of the city-province of Man. It is characterized as tropical, hot, and humid. The rainy season extends from April to the end of October, followed by a dry season from November to March. In Man, the rainy season is generally humid, oppressive, and cloudy overall, while the dry season is very hot, oppressive, and partially cloudy. Throughout the year, temperatures typically range from 19°C to 34°C, rarely dropping below 15°C or exceeding 41°C. As in other regions of the country, the economy of the Man region is primarily based on agriculture. The department hosts several tourist sites, including waterfalls, the Dent de Man, and the sacred forest of Gbepleu, among others [11]. These various activities practiced within the watershed are potential sources of land degradation.

2.2. Data

In this study, the data primarily consist of physicochemical analyses of surface waters obtained from multiple sampling campaigns along the river upstream of the waterfall, within the bathing zone of the waterfall, and downstream of the waterfall. The parameters measured include electrical conductivity, turbidity, salinity, dissolved oxygen (DO), oxidation-reduction potential (Eh), ammonium, nitrate, sulfate, phosphate, and chloride. Satellite data from Sentinel-2 images (bands B1, B2, B3, B4, B5, B6, B7, B8, and B9) were used to extract information related to water quality, specifically turbidity and chlorophyll-a. These images are freely available and can be downloaded from the European Space Agency (ESA) website (https://www.esa.int/Space_in_Member_States/France). The images analyzed correspond to October, November, and December 2022, as well as January, February, March, and April 2023.

2.3. Sampling strategy and analytical measurements

Sampling for physicochemical analysis is a critical operation that requires meticulous attention. The sampling containers are rinsed with distilled water, followed by two rinses with water from the sampling site to prevent contamination. Water samples were collected from three stations—S1, S2, and S3—located along the main river channel feeding the Zadepleu waterfall (see Figure 1), over seven months (October 2022 to April 2023). Sampling was conducted biweekly during this period, resulting in a total of 15 campaigns and thus 45 samples. Station S2 is situated at the bathing area, while S1 and S3 are located upstream and downstream of the bathing zone, respectively. Samples were labeled with the station name, sample number, and date of collection, then carefully stored in a cooler with ice packs before being transported to the central laboratory at the University of Man. The purpose of selecting these stations is to evaluate the water quality of this hydrosystem before bathing, during bathing, and after bathing. A multi-parameter device of the HANNA type was used to measure on-site physicochemical parameters such as conductivity, turbidity, salinity, dissolved oxygen (DO), oxidation-reduction potential (Eh), and total dissolved solids. Chemical samples were kept at temperatures below 8°C for subsequent laboratory analysis, focusing on chemical elements including chloride, nitrates, sulfate, phosphate, and ammonium.

2.3.1. Estimation of turbidity and chlorophyll-a from satellite images

Turbidity reflects the clarity or transparency of water, indicating the presence of suspended particles such as soil, clay, phytoplankton, and other solid materials. High turbidity may cause water to appear murky and often signals pollution or contamination of water quality. Chlorophyll-a refers to the nutrient richness or fertility of a water body, which influences phytoplankton growth and, consequently, the ecological productivity of the environment. After pre-processing and atmospheric correction, water quality algorithms were applied using the R package "waterquality." This package employs well-established algorithms designed for assessing water quality based on remotely sensed imagery. These algorithms detect the spectral response of the uppermost portion of the water column (up to approximately 1 meter below the surface). The algorithms and their calculation steps are detailed in Johansen et al. [10]. The extracted values for turbidity and chlorophyll-a allowed classification of water quality based on specific criteria (see Tables 1 and 2).

Table 1 Water quality criteria based on turbidity [8]

Turbidity (NTU)	Water Quality
<5	Clear water
5≤Turbidity≤30	Slightly turbid water
>30	Turbid water

Table 2 Water quality criteria based on chlorophyll-a [8]

Trophic state	Chlorophyll level (µg/L)	Ecological status
Oligotrophic	<3	Good
Mesotrophic	[3-8]	Moderate
Eutrophic	>8	Poor

2.3.2. Calculation of Water Quality Index (WQI)

Several methods exist for calculating water quality indices. In this study, the weighted arithmetic index method [9, 12] was chosen to evaluate the influence of natural and anthropogenic factors on the water quality of the Man waterfall hydrosystem. The parameters used for calculating the Water Quality Index (WQI) include: pH, dissolved oxygen (DO), electrical conductivity (EC), sulfate, phosphate, nitrate, ammonium, total dissolved solids (TDS), chloride, and turbidity.This index is a classification technique that compares water parameters with international standards set by the World Health Organization (WHO) (see Table 3). The WQI simplifies extensive water quality data into meaningful categories such as Excellent, Good, Poor, Very Poor, etc. The WQI is calculated using the following equation (Equation 1):

$$WQI = \frac{\sum_{i=1}^{n} Qi * Wi}{\sum_{i=1}^{n} Wi} \quad \text{..........(1)}$$

where: Qi is the quality rating for parameter i, based on its measured value and standard limits; Wi is the weight assigned to parameter i, reflecting its relative importance; n is the number of parameters considered. In this approach, a numerical value known as the relative weight (Wi), specific to each physicochemical parameter, is calculated according to the following formula.

$$Wi = \frac{K}{si} \quad \text{.............. (2)}$$

where K is the proportionality constant calculated using Equation 3:

$$K = \frac{1}{\sum_{i=1}^{n}\left(\frac{1}{Si}\right)} \quad \text{................. (3)}$$

where n is the number of parameters, and Si is the maximum allowable value for the chemical element according to WHO standards (see Table 3).

Next, a quality assessment scale (Qi) is determined for each parameter by dividing the concentration by the standard limit of that parameter and then multiplying the result by 100, as expressed in Equation 4:

$$Qi = 100 \times \left(\frac{Vi}{si}\right) \quad \text{........... (4)}$$

where Qi represents the quality assessment scale for each parameter, and Vi is the concentration of each analysed parameter.

Based on the values of the Water Quality Index (WQI), five quality classes (see Table 4) can be identified.

Table 3 Drinking water quality standards [13]

Parameter	pH	Turbidity	NO_3^-	PO_4^{3-}	OD	TDS	NH_4^+	SO_4^{2-}	Cl^-	EC
Unit		NFU	mg/l	mg/l	mg/l	ppm	mg/l	mg/l	mg/l	(µS/cm)
Value	6.5	5	50	1	7	500	0.3	500	250	600

Table 4 Classification and possible use of water based on WQI values [14]

WQI Class	Quality criterion	Possible use
0 – 25	Excellent quality	Drinking water, irrigation, and industrial applications
25 – 50	Good quality	Drinking water, irrigation, and industrial applications
50 – 75	Poor quality	Irrigation and industrial applications
75 – 100	Very poor quality	Only for irrigation
> 100	Non-potable water	Appropriate treatment is required before use

3. Results

3.1. Descriptive statistics of the physicochemical parameters

The statistical parameters employed include minimum, maximum, mean, and standard deviation (see Table 5). The mean pH value is close to neutrality, with only slight variation among the three stations (ranging from 6.45 to 6.60). Turbidity averages range between 9.11 and 9.96 NTU. The mineralization of the water from the Man cascade is relatively low, with electrical conductivity averaging between 30.53 and 33.67 µS/cm. Dissolved oxygen concentrations vary between 2.48 and 2.53 mg/l, with the minimum value of 0.85 mg/l recorded at station S2. Ammonium concentrations reach a maximum of 3.59 mg/l at station 2. The mean nitrate levels are below 0.46 mg/l, with higher values observed in the bathing zone (S2), which reaches a maximum of 0.83 mg/l. Overall, the waters from the Zadepleu natural cascade hydrosystem are less enriched with sulphates and chlorides.

Table 5 Descriptive parameters of the physicochemical measurements at the three monitoring stations

Stations		pH	CE	Turbidity	NO_3^-	PO_4^{3-}	OD	NH_4^+	SO_4^{2-}	Cl^-
S1	*Minimum*	5.73	15	1.80	0.28	0.02	1.33	0.18	0.28	0.10
	Mean	6.6	33.67	9.96	0.42	0.03	2.79	1.16	4.41	1.56
	Maximum	8.43	68	50.5	0.68	0.07	7.6	3.44	15.71	2.88
	SD	0.65	15.3	11.76	0.1	0.01	1.45	0.97	5.23	1.1
S2	*Minimum*	5.59	16	1.9	0.33	0.02	0.85	0.32	0.30	0.1
	Mean	6.45	31.8	9.91	0.46	0.04	2.48	1.22	3.98	1.34
	Maximum	7.22	57	49.3	0.83	0.13	5.10	3.59	10.82	2.81
	SD	0.38	11.98	11.82	0.15	0.03	0.94	0.97	3.70	1.03
S3	*Minimum*	5.58	15	1.6	0.26	0.02	1.42	0.24	0.33	0.22
	Mean	6.47	30.53	8.11	0.36	0.03	2.53	1.32	3.92	1.05
	Maximum	6.98	57	21	0.52	0.05	4.15	3.21	15.78	1.9
	SD	0.38	12.79	5.45	0.08	0.01	0.71	0.99	4.87	0.53

3.2. Spatio-temporal variation of some parameters by satellite analysis

3.2.1. Case of turbidity

It should be noted that the satellite-estimated values of turbidity at the three stations are predominantly underestimated compared to in situ measurements, which average around 3 to 4 NTU. In October, the estimated turbidity value is notably low at 1.18 NTU, with an average of 2.22 NTU, and the maximum value of 3.98 NTU, which is the highest during our analysis period (Figures 2a, 2b, 2c, 2d, 2e, and 2f). In November, turbidity values of 3.01 NTU and 1.31 NTU were respectively recorded as the maximum and minimum, with a mean of 1.93 NTU. December is characterised by a minimum turbidity of 1.42 NTU and a maximum of 3.00 NTU, with an average of 1.97 NTU. The months of January and February show a similar variation in turbidity, with minimum values around 1.2 NTU, maximum values reaching 2.7 NTU, and an average of 1.88 NTU. In March, turbidity increases compared to January and February, showing an average of 1.95 NTU, a maximum of 3.04 NTU, and a minimum of 1.34 NTU. The turbidity of the waters in October (the rainy season) is higher than during the other sampling months, which fall within the dry season. In addition to temporal variability, the maximum turbidity values are observed in the south-eastern area of the water body, as well as in channels near village communities, regardless of the month of sampling.

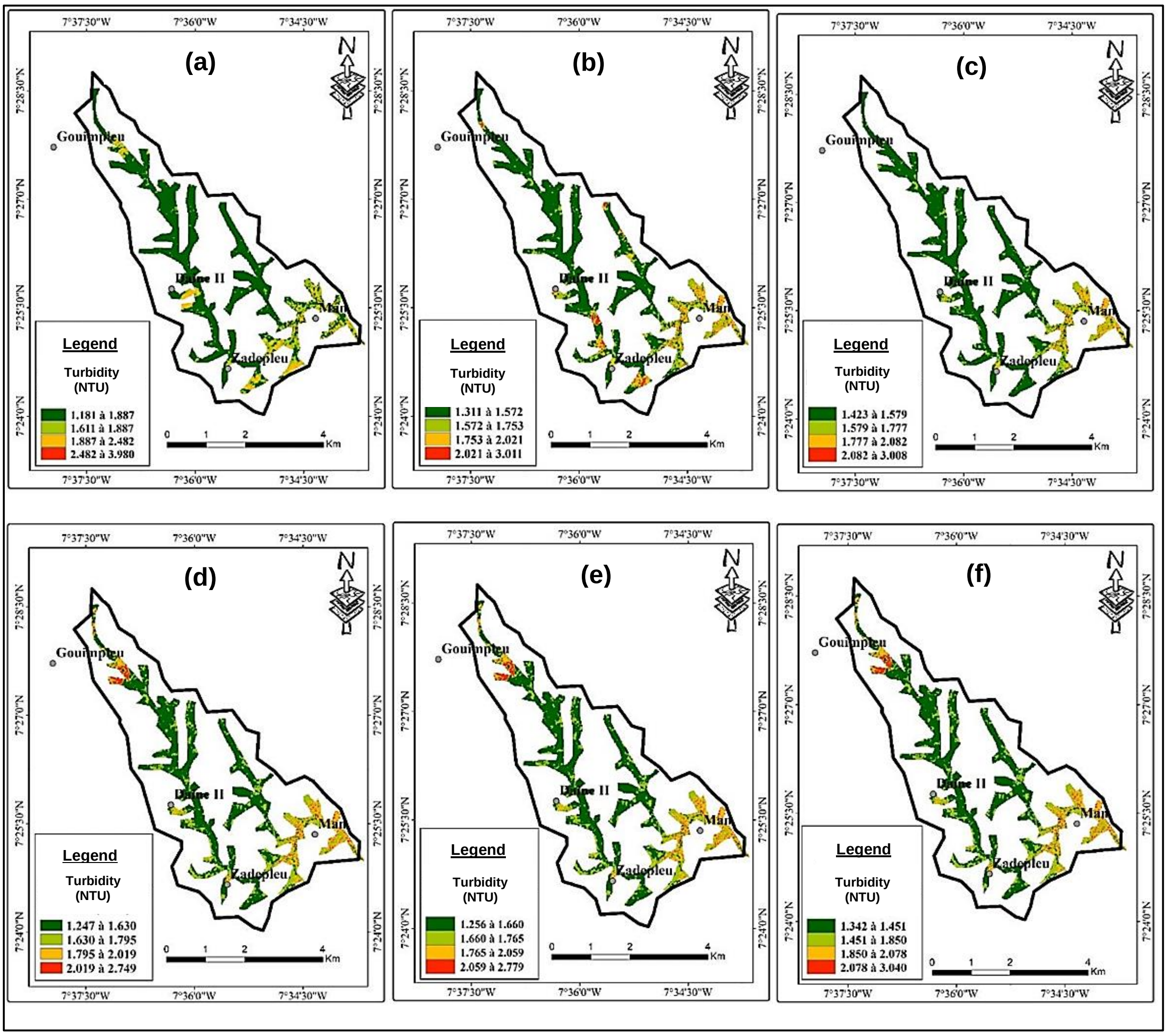

Figure 2 Monthly and spatial variation of turbidity from October 2022 to March 2023

3.2.2. Case of Chlorophyll-a

The map corresponding to December (Figure 3c) indicates high concentrations of chlorophyll-a along the watercourse, with lower concentrations in the southern part. During this month, the minimum value observed is 0 µg/l, the maximum is 0.67 µg/l, and the mean is 0.27 µg/l. In January and February (Figures 3e and 3d), similar variations in chlorophyll-a concentrations are observed, with a mean of 0.17 µg/l. During March (Figure 3f), the mean concentration remains at 0.17 µg/l, with a maximum of 0.67 µg/l and a minimum of 0 µg/l. Unlike turbidity, nearly all streams, except in the south-east and southern parts, exhibit elevated chlorophyll-a levels, although they remain below the potability standards set by the WHO for drinking water.

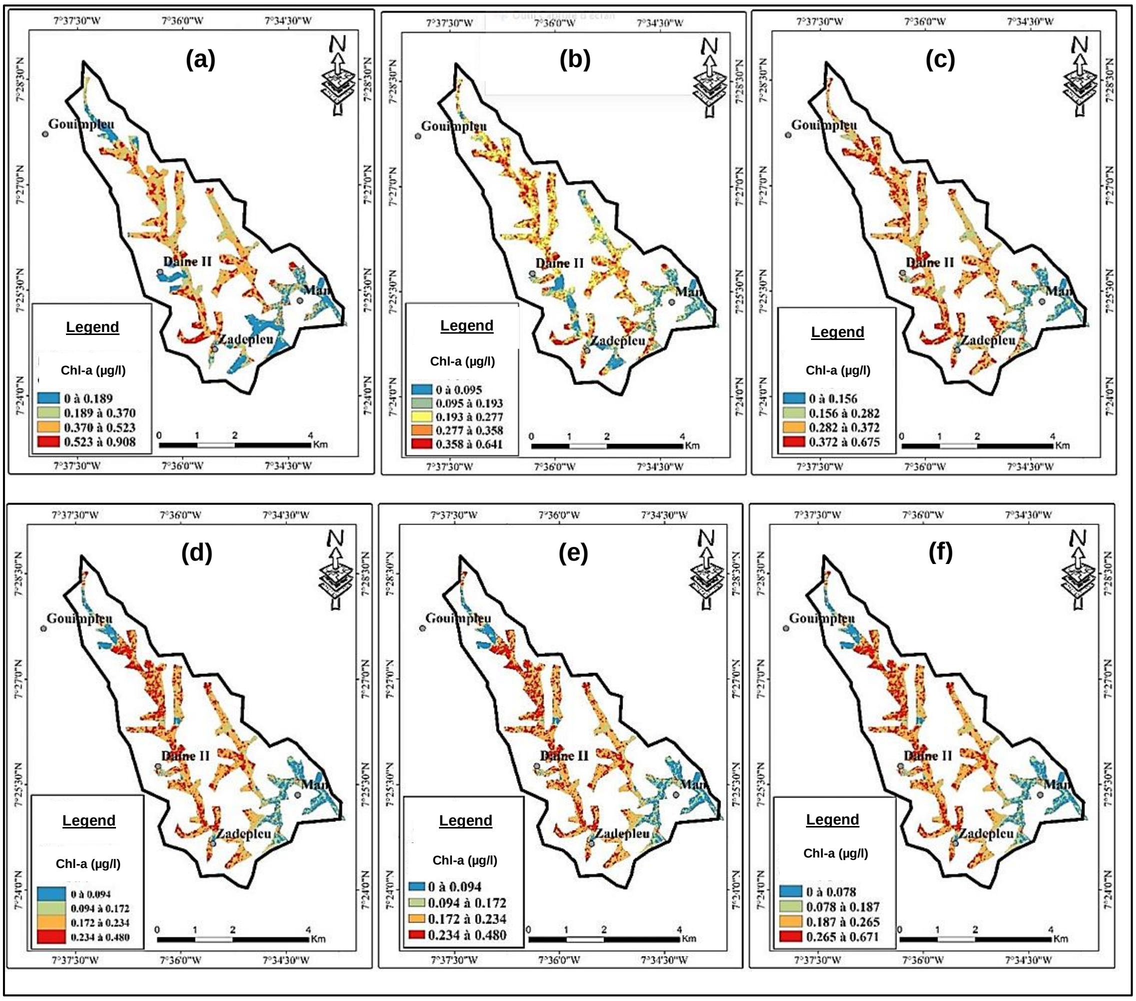

Figure 3 Monthly and spatial variation of chlorophyll-a concentrations from October 2022 to March 2023

3.3. Monthly variation of the Water Quality Index (WQI)

The results of the overall water quality index (WQI), calculated using the physicochemical analysis data and the standard potability values defined by WHO surface water standards, are presented (Figure 4). The water quality class was determined for 45 samples collected from the three monitoring stations. The non-potable water class was observed during all sampling campaigns at station S2, which corresponds to the bathing zone, with an average WQI value of 245.47.

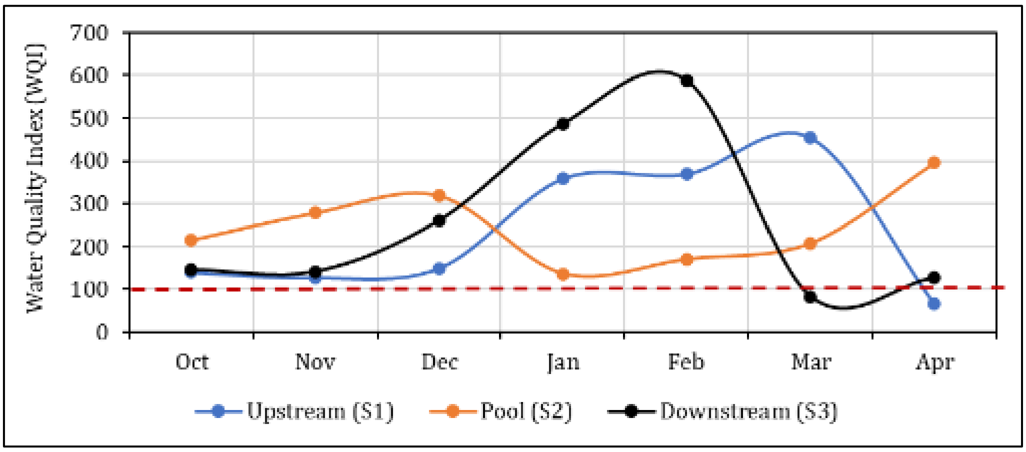

Figure 4 Monthly variation of the water quality index of the hydrosystem of the Zadepleu waterfall

Station S1 recorded a non-potable classification (WQI > 100) during the October 2022, November 2022, December 2022, January 2023, February 2023, and March 2023 campaigns, and poor quality in April 2023. The waters are classified as non-potable throughout both the dry and rainy seasons. During the dry season, the maximum WQI value is 469.83 at station S3, with a minimum of 313.93 at station S2. Conversely, the wet season records a maximum of 283.58 at S2 and a minimum of 147.43 at S3. Across all stations, the waters during the dry season are more chemically degraded than those during the wet season, as evidenced by the average WQI values for the two seasons.

4. Discussion

Surface water quality is characterized by the various substances it contains, their concentrations, and their effects on aquatic ecosystems and human health. These substances can be of natural origin, such as bicarbonates, sulphates, sodium, calcium, magnesium, potassium, nitrogen, and phosphorus or anthropogenic, resulting from wastewater, industrial, and agricultural activities. It is the concentration of these different elements that determines water quality and its suitability for specific uses [15]. The mean pH values range between 6.45 and 6.98, indicating near-neutral conditions. This pH range is similar to that reported by Cecchi et al. [16] in small dams in Brobo, Nambègué, and Tiné. The mean nitrate concentrations are low, approximately 0.40 mg/l. Nitrates are naturally occurring compounds within the nitrogen cycle, an essential element for life and especially for plant growth. They are naturally present in soil residues necessary for the survival of plants, animals, and humans, originating from their decomposition or excretion. This average nitrate level is below the value reported by Yapo [17] in Lake Buyo Dam, which is more prone to eutrophication. Although these nitrate concentrations are generally low, they still pose pollution risks, likely due to the influx of mineral and organic fertilizers into the reservoirs.

The assessment of water quality through satellite imagery (Sentinel-2) reveals variations across the two seasons. This analysis indicated high turbidity and chlorophyll-a values during the rainy season. These elevated levels are likely related to erosion phenomena. Indeed, after rainfall, sediments often laden with pollutants are carried into the water body. Boutaghou [18] documented this phenomenon in the coastal zone of Algeria, while Coulibaly et al. [19] reached the same conclusion in a comparative study of the physicochemical characteristics of four dams in northern Côte d'Ivoire. High turbidity levels (2 to 3.98 NTU) are observed in zones with intense anthropogenic activity, particularly near village sites and the swimming area of the waterfall. The chlorophyll-a concentration in the watercourse of the Man natural waterfall is low, indicating a healthy aquatic ecosystem concerning nutrients. This is supported by the low levels of nitrates and phosphates (Table 5). Higher chlorophyll-a levels are observed in zones with lower human activity, aligning with the findings of Fernanda et al. [20].

The results of the Water Quality Index (WQI) reveal two trends: a temporal degradation from October 2022 to April 2023, and a spatial pattern across the three sampling stations (S1, S2, and S3). Overall, during the 21 sampling campaigns conducted from October 2022 to April 2023, the water quality in the Man natural waterfall is classified as non-potable (WQI > 100) for 90% of the campaigns. Station S1 exhibited poor quality (50 < WQI ≤ 75), while station S3 was characterized by very poor quality (75 < WQI ≤ 100) during the campaigns in March and April 2023. The seasonal assessment of the WQI indicates that the water remains non-potable (WQI > 100). The index tends to increase from upstream (S1) towards downstream (S3), reflecting a deterioration in water quality along the course. This decline is likely due to anthropogenic impacts on the watershed of the waterfall. Similar results have been documented by Konan et al. [21] in the Loka catchment, where recreational and agricultural activities are identified as primary factors influencing water quality deterioration. The reduction of vegetative cover, at the expense of fields, fallow land, and expanding villages, as observed elsewhere by Diallo et al. [22], could potentially expose this aquatic system to pollution.

5. Conclusion

This study was carried out on the river of the Zadepleu natural waterfall. It was used to characterize the dynamics of the chemical quality of the said water in the hydrosystem of the Zadepleu waterfall in Man. This was made possible by monthly physicochemical analyses of water samples taken and satellite data on turbidity and chlorophyll-a. The results of this study highlight a significant deterioration in the water quality of the hydrosystem, mainly due to anthropic pressures and natural processes. The water quality indices (WQIs) indicate that the water is undrinkable, with a progressive deterioration from upstream to downstream. The water needs to be treated before it can be used. Satellite and in situ analyses confirm the impact of the seasons, in particular the increase in turbidity and chlorophyll-a during the rainy season. However, the low chlorophyll-a values prove that the water in this hydrosystem, which includes the natural Zadepleu waterfall, is in more or less good condition in terms of nutrients. These findings call for urgent management measures, including the regulation of human activities and the implementation of continuous monitoring programmes. This research provides a scientific basis for guiding decision-makers towards sustainable management of this ecosystem, which is essential for local populations and tourism.

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