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Article

Spatio-Temporal analysis and Water Quality Indices (WQI): case of the Ébrié Lagoon, Abidjan, Côte d'Ivoire

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Abstract: For decades, the Ébrié Lagoon in Côte d'Ivoire has been the receptacle of wastewater effluent and household waste transported by runoff water. This work assesses the spatio-temporal variability of the Ébrié lagoon water quality at the city of Abidjan. The methodological approach used in this study is summarized in three stages: the choice and standardization of the parameters for assessing water quality for uses such as aquaculture, irrigation, watering, and sports and recreation; the weighting of these parameters using the Hierarchical Analysis Process (AHP) of Saaty; and finally, the aggregation of the weighted parameters or factors. Physicochemical and microbiological analysis data on the waters of the Ébrié lagoon for June and December of 2014 and 2015 were provided by the Ivorian Center for Anti-Pollution (Centre Ivoirien Anti-Pollution, CIAPOL) and the concentrations of trace elements in sediments (As, Cd, Cr, Pb, Zn) were used. The aggregation of standardized and weighted parameters allowed the determination of the Water Quality Indices (WQI) by usage for each bays of the lagoon. The results show that in both 2014 and 2015, the waters of the Ébrié lagoon were generally of poor quality for the different uses examined in this study (aquaculture, irrigation, watering and sport and recreation) with an accentuation in 2015. However, some bays of the lagoon have waters of dubious to satisfactory quality. This study contributes an improved evaluation of the Ébrié lagoon waters.

Keywords: water quality indices; spatio-temporal analysis; ébrié lagoon; surface water; Abidjan

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1. Introduction

The coast of Côte d'Ivoire has a remarkable lagoon system. Although originally exceptional, the natural environments associated with this lagoon complex are now severely degraded, due to the intense human pressure exercised on this fragile space over decades. Since the 1970s and because of the development of the city of Abidjan, there has been increasing concern about this damage. Indeed, Côte d'Ivoire's industrial development has been heavily concentrated in the metropolitan area of Abidjan. In 2010, the National Institute of Statistics (Institut national de la statistique, INS) determined that 92.8% of the 2822 industrial establishments in the country are located in the only economic capital of the country (Abidjan) and 60% of these establishments are installed around the Ébrié lagoon. The Ébrié lagoon has several bays in which untreated or insufficiently treated wastewater effluents (domestic, industrial wastewater and so forth) or solid waste have been discharged for decades [1]. The biodegradable waste causes an intense eutrophication phenomena, especially in the low renewal areas such as bays [2]. To determine the quality of Ébrié lagoon water many studies have been conducted since the 1980s [2–16]. These studies were focused on the assessment of biological and microbiological quality, pollution by oil, metal sediment contamination,

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and solid waste. Additionally, the Ivorian Center of Anti-Pollution (Centre Ivoirien d'Anti-Pollution, CIAPOL) as part of its mission, systematically and periodically analyzes the natural waters from its National Observation Network (Réseau National d'Observation, RNO). Thus, the water quality of the Ébrié lagoon is periodically analyzed in situ and in a laboratory, as part of the monitoring of this water body. Based on this important existing knowledge base on the Ébrié Lagoon, it is now necessary to introduce a Water Quality Indices (WQI) approach, which summarizes large quantities of data on water quality in to simple terms of water quality (Excellent, Good, Bad, and so forth), in order to supply synthetic and comprehensive information to the decision makers and the general public. WQIs minimize the volume of data and simplify the expression of water quality status based on a number of physicochemical and bacteriological parameters [17]. The first attempts to classify water by degree of purity date back to the mid-twentieth century [18]. Horton's pioneering efforts have been followed by number of researchers; various WQIs have been formulated and used by water supply and water pollution control agencies around the world [19–32].

Because the Ébrié lagoon plays an important role in Côte d'Ivoire's economic development, it is necessary to develop indicators on the quality of these waters that are simplified and easily understood to support valuation of the lagoon waterbody. Thus, the main objective of this study is to perform a spatio-temporal assessment of the Ébrié lagoon water quality for uses such as aquaculture, irrigation, watering and sport and recreation using a multicriteria analysis method.

2. Materials and Methods

2.1. Study Area

The Ébrié lagoon is part of the Ivorian lagoon complex that was formed by tectonic depressions, causing a lagoon fault [33]. The Ébrié lagoon area is 523 km^2 [34]. The volume of this lagoon is about 2.5 billion of m^3, the average depth is 4.8 m and some pits near Abidjan exceed 20 m in depth. The lagoon waters are separated from the Gulf of Guinea (Atlantic Ocean) by a set of recent dune cordons formed in the Holocene period less than 10,000 years ago.

The climate of the region is of an equatorial type of transition characterized by four seasons with a heavy rainfall in the month of June (367 mm). The average annual rainfall in the district of Abidjan is between 1600 and 2400 mm. The Ébrié lagoon is fed mainly by continental fresh waters from the Comoé, Agnéby and Mé Rivers and has been open to marine waters since 1950 via the Vridi channel, while its natural outlet, the Comoé pass at Grand-Bassam, is now closed. The Comoé River alone is responsible for 70% of the freshwater inflow to the lagoon. The inputs of this river are charged with fertilizer and pesticide residues and, periodically, with aquatic plants (freshwater hyacinth). The central part of the Ébrié lagoon is chief concern of this study where the metropolitan area of Abidjan is located (Figure 1). The city of Abidjan, the economical capital of Côte d'Ivoire, has a population of 4.707 million inhabitants as of 2014, living in ten communes (Abobo, Adjamé, Attécoubé, Cocody, Koumassi, Marcory, Plateau, Port-Bouët, Treich-ville and Yopougon). Most of the country's industries are concentrated in Abidjan. The pollution of the lagoon is caused by excessive inputs of untreated domestic and industrial effluents (soap factories, oil mills, breweries, dairies, refineries, and so forth) and all kind of solid waste. The Ébrié lagoon is currently considered a reservoir of pathogenic bacteria.

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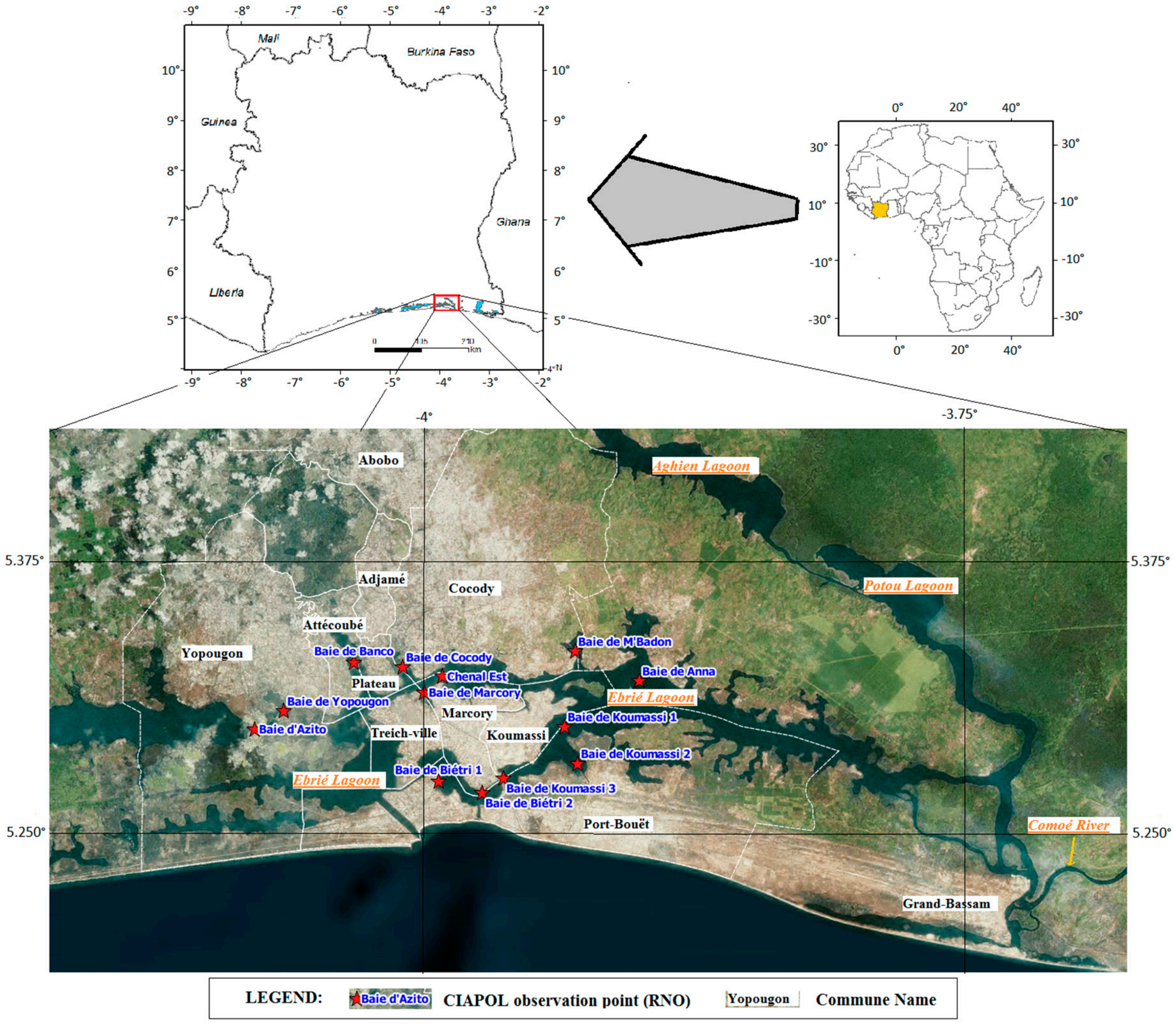

Figure 1. Presentation of Ébrié lagoon and the study area.

2.2. Data

The data used in this study are the water and sediment quality of the Ébrié Lagoon and the map of the district of Abidjan. Data on the physico-chemical and biological quality of Ébrié lagoon water have been provided by the CIAPOL. These data are the results of in situ and laboratory analyses of samples taken on the surface of the lagoon waterbody during the months of June and December in 2014 and 2015. In this study, thirteen stations of the RNO of CIAPOL located at the Ébrié lagoon were considered. Also, this study includes an analysis of the trace metal elements (Arsenic, Cadmium, Total Chromium, Lead, Zinc) present in the sediments of the Ébrié lagoon bays extracted from Kouamé et al. [15]. The map of Abidjan at 1/25000 from the "Centre d'Information Géographique et du Numérique" (CIGN) of the "Bureau National d'Etude Technique et de Développement" (BNETD) was used to extract the limits of the lagoon and the communes of Abidjan. All of the data were analyzed using the free open source software, Quantum GIS (QGIS) as well as the maps composition. QGIS is a GIS software which supports a number of data formats: vector (Shapefile, ArcInfo, Mapinfo, GRASS GIS, etc.), raster (GRASS GIS, GeoTIFF, TIFF, JPG, etc.) and spatial databases.

2.3. Methods

2.3.1. Parameters of Different WQIs by Use and Their Classification

Various parameters were selected for each type of use (see Table 1): Irrigation, watering, aquaculture, and sports and recreation. This parameters are those use in the SEQ-eau (Système

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d'Evaluation de la Qualité de l'eau). SEQ-eau is a tool used to evaluate and characterize the physical-chemical and microbiology of surface water or groundwater.

Table 1: Parameters used for different uses.

Usages	Parameters
Sports and recreation	Total suspended solids (TSS), Total Coliform (C.Total), Enterococci, Thermotolerant Coliforms (C.Thermo), SECCHI Transparency (Secchi)
Irrigation	Total Coliform (C.Total), Thermotolerant Coliforms (C.Thermo), Lead (Pb), Copper (Cu), Nickel, Total Chrome (Cr), Arsenic (As), Cadmium (Cd), Zinc (Zn), Chlorides, Selenium
Watering	NO_2^-, Nitrates (N), Sodium, Calcium, Sulfate, Free cyanide, Zinc (Zn), Copper (Cu), Selenium, Arsenic (As), Mercury, Lead (Pb), Nickel, Cadmium(Cd), Total Chrome (Cr)
Aquaculture	Chlorophyll a + pheopigments, NO_2^-, Free Cyanides, Mercury, NH4+, Phosphor (P), Oxygen (O), Calcium, Copper (Cu), Zinc (Zn), Nitrates (N), TSS, pH, DBO_5, Mercury, Lead (Pb), Nickel, Cadmium (Cd), Total Chrome (Cr)

According to the uses and the observed values, each parameter was qualitatively classified in terms of: Good quality, satisfactory quality, dubious quality, poor quality, and very bad quality. This classification was carried out according to the SEQ-eau model. Then, for each class we assigned a code (codification) ranging from 0 to 100, which was used in the analysis as the quality that estimates the parameter; 80 corresponds to good quality and 0 corresponds to a very poor quality of water (Table 2).

Table 2. Water quality index classes and codes.

Aptitude class	Color	Description
80 **(80–100)**	Blue	Good quality
60 **(60–80)**	Green	Satisfactory quality
40 **(40–60)**	Yellow	Dubious quality
20 **(20–40)**	Orange	Bad quality
0 **(0–20)**	Red	Very bad quality

2.3.2. Evaluation Method: Weighted Factor Aggregation

The assessment of the different Water Quality Indices (WQI) of the Ébrié Lagoon consisted of the aggregation or combination of weighted factors (parameters). Thus, these indices were calculated using the following formula:

$$\mathrm{WQI} = \frac{\sum q_i w_i}{\sum w_i} \quad (1)$$

where,

q_i is the quality that estimates the n^th parameter;

W_i is the weight of the n^th parameter.

In this study, the method used to determine the weights of the parameters is the Analytic Hierarchy Process (AHP) created by Saaty [35]. The weighting of the decision criteria was performed using pair-wise comparisons through the Analytic Hierarchy Process (AHP).

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3. Results

3.1. Weighting of Parameters Per Usage

Through the AHP method, the parameters weights of the different uses were determined to allow the evaluation of the Water Quality Indices. Table 3 summarizes the different weights obtained for the WQIs of aquaculture, sports and recreation, irrigation and watering. For each use the sum of the weights for each index is equal to 1.

Table 3. Parameter weights for different uses.

Aquaculture		Sport and recreation		Irrigation		Watering	
Parameter	weight	**Parameter**	weight	**Parameter**	weight	**Parameter**	weight
Cd	0,16	**TSS**	0.33	**As**	0.135	**As**	0.16
Pb	0,13	**Secchi**	0.23	**Pb**	0.2	**Pb**	0.2
Zn	0,15	**C.Total**	0.19	**Cd**	0.2	**Cd**	0.17
O	0,08	**C.Thermo**	0.11	**Zn**	0.21	**Zn**	0.2
P	0,05	**Enterococci**	0.14	**Cr**	0.18	**N**	0.04
pH	0,035	**Sum**	1	**C.Total**	0.041	**NO_2^-**	0.08
Cr	0,13			**C.Thermo**	0.034	**Cr**	0.15
MES	0,03			**Sum**	1	**Sum**	1
N	0,07						
NO_2^-	0,08						
NH_4^+	0,085						
Sum	1						

3.2. Spatio-Temporal Analysis of WQIs

3.2.1. Water Quality Index for Aquaculture

Figure 2a shows the water quality of the lagoon for the month of June 2014. There is bad to very bad water quality in the bays located in the north of the Ébrié Lagoon except at the Bay of Yopougon where the quality is dubious. The southern bays have bad quality water for aquaculture except Koumassi 1 where the quality is dubious. During the same month (June) in 2015, the waters of the bays of Ébrié lagoon are generally of bad to very bad quality (Figure 2b). In December 2014, the quality of the waters of the bays located in the north of the lagoon is generally worse than those of the south (Figure 2c). This trend is statistically conserved in the same month of 2015 (Figure 2d).

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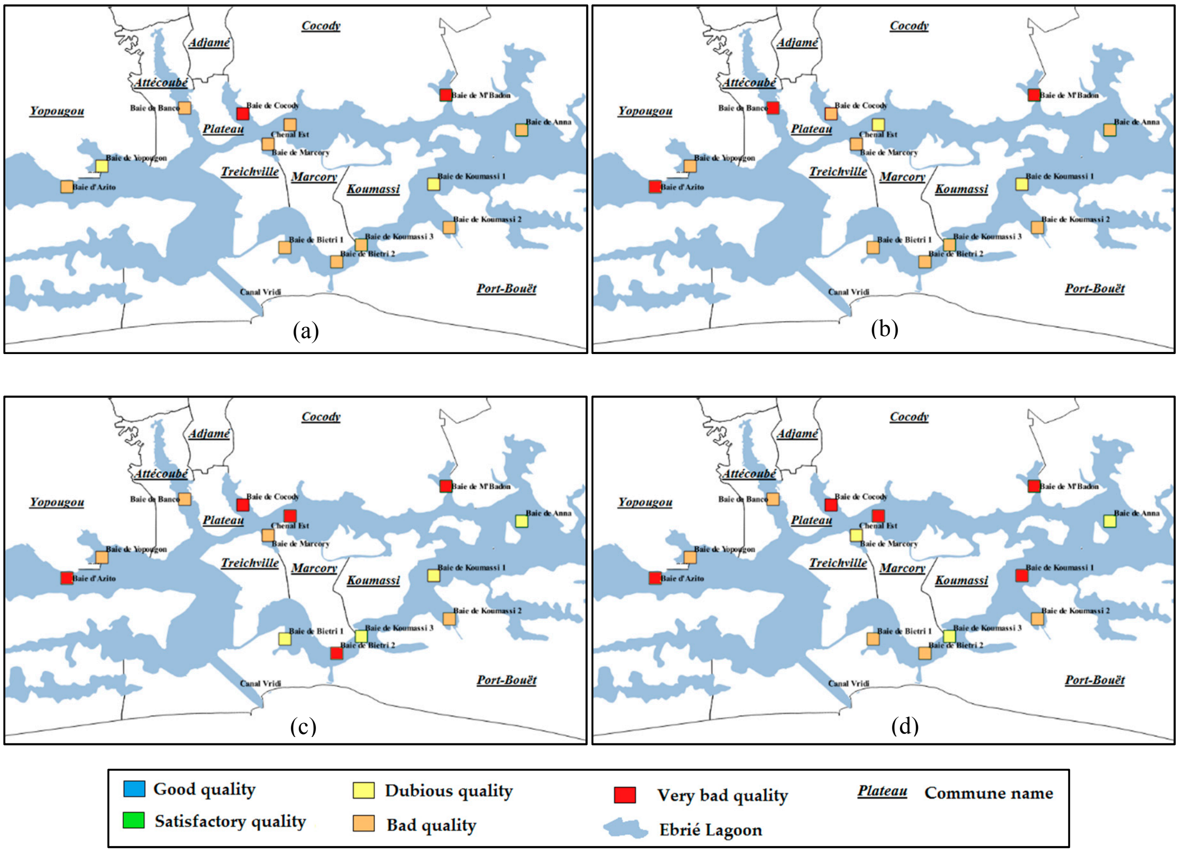

Figure 2. Spatio-temporal variation of the Water Quality Index for aquaculture: (**a**) June 2014 (**b**) June 2015, (**c**) December 2014 and (**d**) December 2015.

3.2.2. Water Quality Index for Sport and Recreation

During the month of June 2014 we observe that the quality of the Ébrié lagoon waters is dubious to bad for sport and recreation (Figure 3a). Only the Bay of Anna has satisfactory water quality. In 2015, during the month of June the quality of the waters of the lagoon deteriorated further (Figure 3b). In particular, water in the bay of Cocody went from bad to very bad. The December 2014 results (Figure 3c) show that the water quality varies from dubious to very bad (bays of Biétri 1 and 2 and Koumassi 3). The spatial variation in water quality in December 2015 (Figure 2d) is identical to the variation in December 2014: the changes are at the bays of Koumassi 1 and Canal Est, where the quality went from dubious in 2014 to bad quality in 2015.

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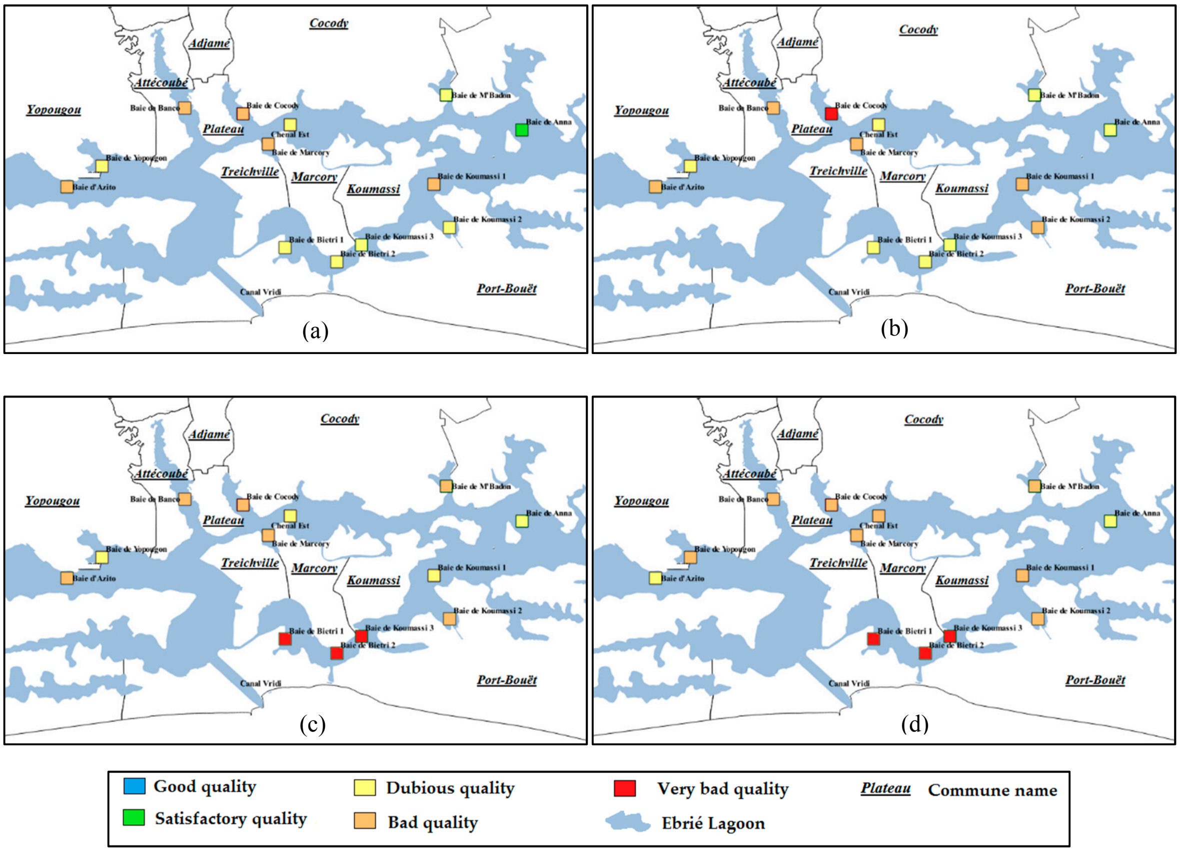

Figure 3: Spatio-temporal variation of the Water Quality Index for sports and recreation: (**a**) June 2014 (**b**) June 2015, (**c**) December 2014 and (**d**) December 2015.

3.2.3. Water Quality Index for Irrigation

The records for the month of June 2014 show that the lagoon water quality was of bad quality for the purpose of irrigation (Figure 4a) except for the bays of Yopougon and Koumassi 1 where the waters were of dubious quality and at Azito where the quality is very bad. In June 2015, the lagoon water quality varied between bad to very bad quality (the latter being observed at Azito). During the months of December, the lagoon water quality is overall bad or very bad in both 2014 (Figure 4c) and 2015 (Figure 4d). However, we notice that the degree of pollution is greater in 2015 than it was in 2014. In fact, the bays of Cocody and Koumassi 2 which were of bad quality in 2014, deteriorated to very bad quality in 2015.

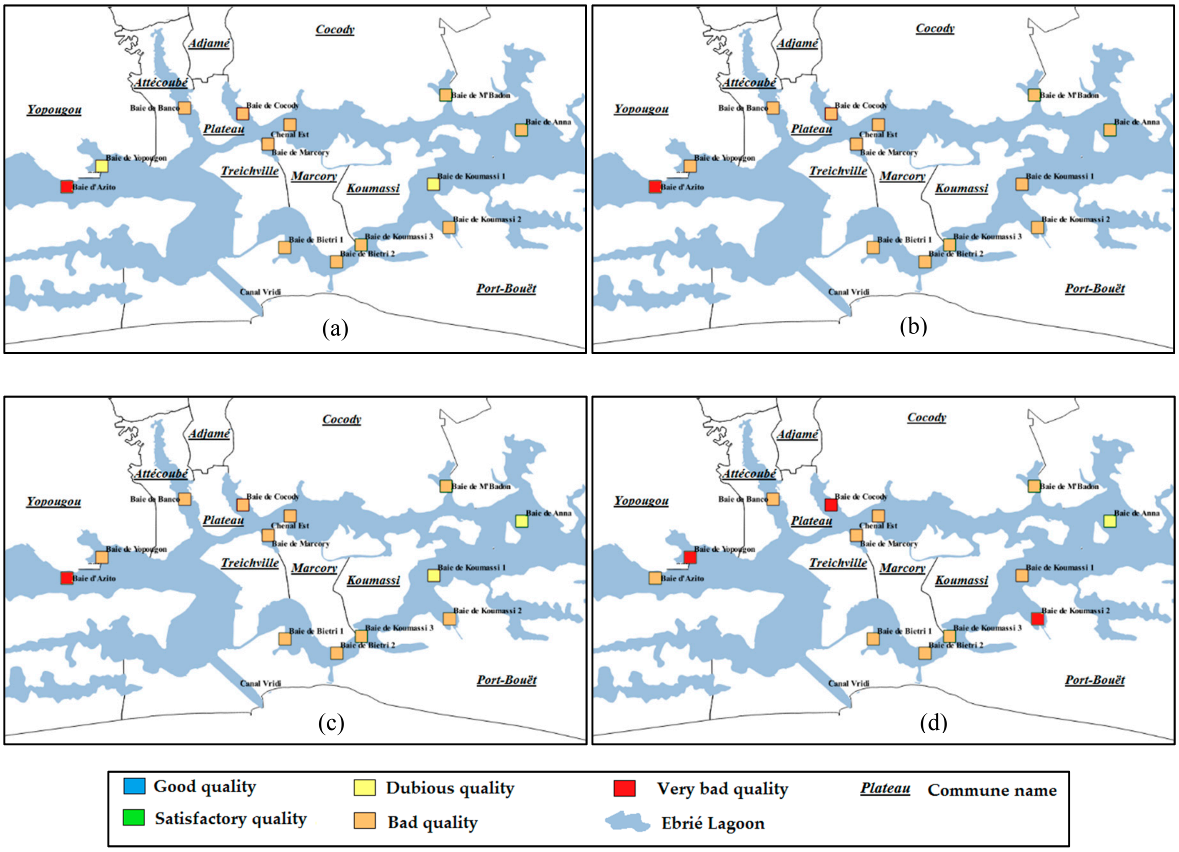

Figure 4: Spatio-temporal variation of the Water Quality Index for irrigation: (**a**) June 2014 (**b**) June 2015, (**c**) December 2014 and (**d**) December 2015.

3.2.4. Water Quality Index for Watering

Figure 5a shows that the lagoon's water quality varies from dubious to very bad quality for watering in June 2014. The quality is generally bad to very bad in June 2015 (Figure 5b). The water quality in the bay of Anna remained dubious for watering from June 2014 to June 2015. In December 2014, the water quality for watering at all observation points varied from satisfactory quality (at Anna) to very bad quality at Cocody and Azito. In December 2015, the waters of the lagoon bays varied from dubious quality (bays of Banco, Koumassi 1 and Canal East) to very bad quality (bays of Yopougon and Cocody).

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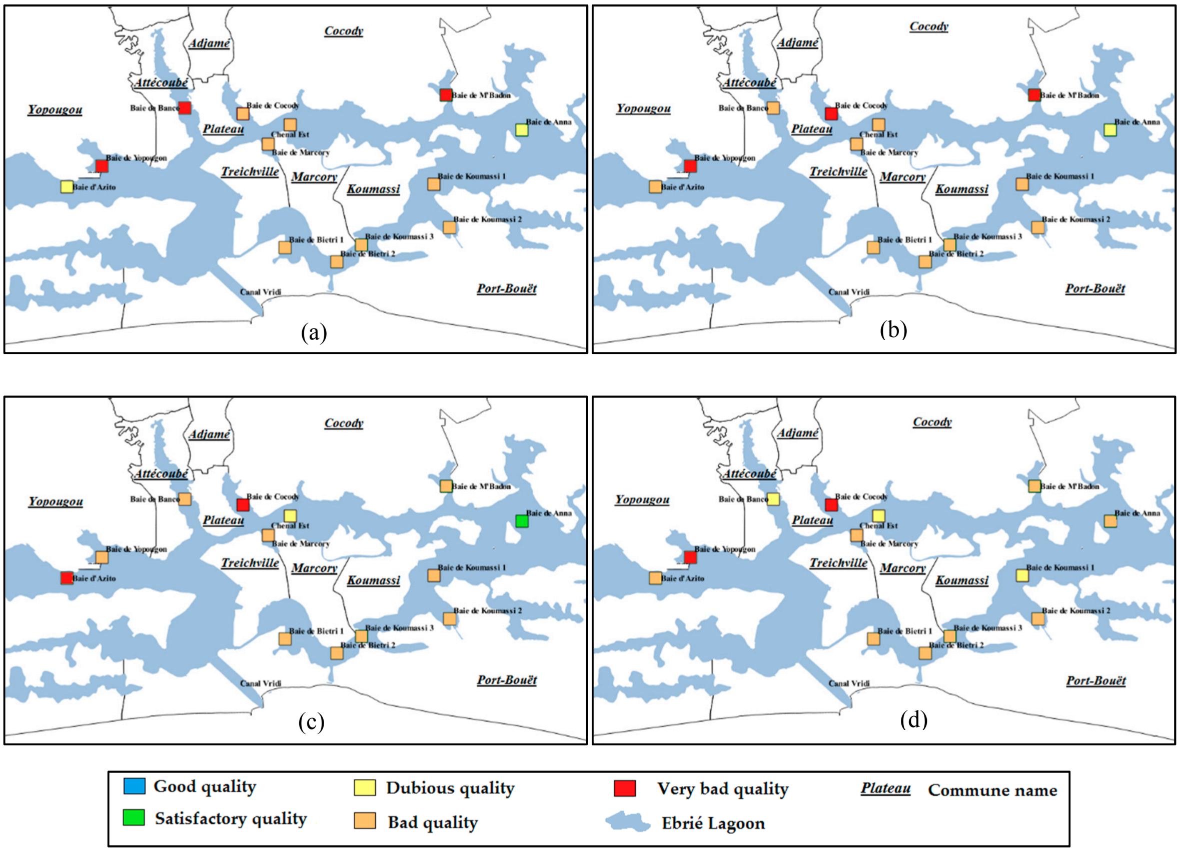

Figure 5: Spatio-temporal variation of the Water Quality Index for watering: (**a**) June 2014 (**b**) June 2015, (**c**) December 2014 and (**d**) December 2015.

4. Discussion

The water quality of the Ébrié lagoon bays was analyzed in time and space for four uses (aquaculture, irrigation, Recreation and Sports and watering) during the months of June and December of 2014 and 2015 using a Water Quality Index (WQI) method. The obtained results depend on the chosen parameters and their classification of these parameters according to their different concentrations. For example, the interpretation of these concentrations as "good" or "bad". They also depend on the weighting of the parameters or their perceived importance to the overall quality of water [36–39]. In this study, for the choice and standardization of parameters we relied on the SEQ-eau version 2 method [40–42]. Then, for the determination of the weights or relative importance of the parameters, we used the AHP method developed by Saaty [43]. This method reduces the subjectivity of the weighting process. The results we obtained generally confirm the observations on the ground which testifies to the robustness of our approach.

The Water Quality Indices (EQI) of the Ébrié lagoon calculated in this study indicate that the water's quality varies from dubious to very bad quality generally for the four uses: aquaculture, irrigation, watering and sports and recreation. These results are explained by the discharge into the lagoon of household waste, faeces, residues of food industries and waste materials for several decades. Indeed, the different bays of the Ébrié lagoon are receptacles for urban, industrial and runoff effluents from the ten communes of Abidjan [1,10,14,44]. Additionally, Koné and Aka [45] showed that all the industries of the Abidjan agglomeration dumped their wastewater in the lagoon, with a total volume estimated at 12,000 m^3 per day. These inputs are likely to contain metallic trace elements (ETM) such as lead (Pb), chromium (Cr), zinc (Zn), arsenic (As) and cadmium (Cd) [15]. Kouamé et al. [46] observed a very large bioaccumulation of Cr and Pb in crab organisms (used as indicators of metal pollution) collected in the Ébrié lagoon.

The bays of the Ébrié lagoon located in the urban area of Abidjan that are directly subjected to the domestic pollutants have water of bad quality for the uses considered in this study. The bays of Cocody, Biétri, Marcory, Azito, M'Badon and Koumassi have overall bad quality for the different uses. The bays of Yopougon, Cocody, Marcory and Koumassi are particularly exposed to pollution. In the communes of Yopougon, the various bays of the lagoon receive all effluents from households and the wastewater from the industrial zone of this commune. At the Cocody Bay, there is an outfall that receives the contaminated water and solid waste from the storm water network. This bay also receives sewage from several areas of the communes of Adjamé, Abobo and Yopougon [12]. The bay of Marcory, enclaved, receives the sewage of the commune due to frequent breakdowns in the wastewater network. M'Badon Bay is polluted by leachate from the uncontrolled landfill of the city of Abidjan upstream [14,47–48]. We note that the bay of Anna is the least polluted. This is because the drainage basin that drains this bay is the least urbanized. In some places, the obtained quality class may seem to contradict field observations. For example, at M'Badon Bay, the method used in this study resulted in a dubious quality assessment for recreation and sport, whereas it should have been bad quality, due to the outlet of leachate effluent from the uncontrolled landfill of the city of Abidjan. These exceptions can be explained by the noncompleteness of the parameters used for the evaluation of the water quality (see Table 1). As an example, we can define a "solid waste" parameter for the amount of solid waste that reaches the different banks of the lagoon. The spatio-temporal analysis pointed out that from 2014 to 2015 some bays show improving water quality—for example, from very bad to bad, or from bad to dubious, despite the fact that polluting flows are permanent and increase with time. This may be due to the hydrological regime of the Ébrié Lagoon. In fact, river flows from Comoé, Mé and Agnéby contribute towards diluting the waters of the lagoon, thus reducing pollution according to Durand and Guiral [49].

5. Conclusions

This study involved a spatio-temporal analysis of the water quality of the Ébrié lagoon at the city of Abidjan, the economic capital of Côte d'Ivoire. The selected parameters used in this analysis were those defined by SEQ-eau for the uses of: irrigation, sport and recreation, aquaculture and watering. The method consisted of calculating Water Quality Indices (WQIs) for the different selected uses using a weighted factor aggregation approach. The results of the assessment of the water quality of the Ébrié lagoon for June and December of 2014 and 2015 have shown that the quality of the water of the studied bays varies from dubious to very bad quality for all uses: Aaquaculture, irrigation, recreation and sports and watering. According to the results of this study, the projected opening of the mouth of the Comoé River could deprive the lagoon of 70% of its input water flow, which is crucial for the renewal of lagoon's waters. On this basis, it would not be judicious to open the mouth of Comoé River at Grand Bassam.

The values of the WQIs obtained in this study depend on the day of the sampling as well as the parameters considered for evaluation. Thus, to take into account the specificity of the city of Abidjan, it would be relevant to further consider how best to determine the specific Water Quality Indices for the Ébrié lagoon. A statistical approach could be used to identify relevant parameters. Also, this study can be extended to different rivers and lakes in Côte d'Ivoire, as classifying them would allow better management of the water resources of the country.

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Author Contributions: Coulibaly Naga developed the idea, Aclohou Henoc Sosthène prepared data and evaluated the WQIs. Coulibaly Naga, Coulibaly Talnan J. H. contributed to the analyses, interpretation of results and wrote the paper. Ziyanda Mpakama and Savané Issiaka revised the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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