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Evolutive Trend of Water Level in the Ebrie Lagoon by Reconstitution of the Tide Gauge Time Series in Front of the Abidjan Coastline (Côte d'Ivoire)

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Abstract

The latest Intergovernmental Panel on Climate Change (IPCC) report shows that sea-level rise, which has been accelerated since the 19th century resulting to the global warming, threatens coastal areas with high population growth. A Global Sea Level Observing System (GLOSS) assessment highlighted the lack of data in Africa, and in Côte d'Ivoire in particular. In order to estimate the evolutionary trend of sea level along the Ivorian coast, and to draw up preventive plans to protect properties and populations, we digitized 65 years of historical tidegrams recorded in the Ebrie Lagoon, using the "Surfer" and "Nunieau" software, then processed them using "T-Tide" and "U-Tide" software. The average levels were calculated using the Demerliac filter from complete daily (day and night) recordings for providing a usable database of 31 years of hourly lagoon data from 1979 to 2015. Our results show that a mean water level in lagoon is 1.04 m. The evolutionary trend in sea level, estimated in the lagoon via the Vridi canal, during the rainy season is the most significant at 2.93 mm/year. This is followed by the dry season, with a trend of 2.89 mm/year. The flood season trend is 2.78 mm/year. This suggests that marine water inflows dominate continental inflows. Our results highlight the vulnerability of Côte d'Ivoire's coasts to the risk of marine submersion.

Keywords

Tide, Mean Water Level, Temporal Variability, Vridi Channel, Marine Submersion

1. Introduction

Assessing and quantifying the temporal mean sea level change is useful to provide fundamental information on the climatic role on the oceans and their general circulation. Today, almost 2/3 of the world's coasts are retreating due to sea-level rise [1] Most coastal countries have carried out studies to assess its impact on coastal resources and population in order to adapt to climate change [2] [3] and [4]. In Africa, particularly in the Gulf of Guinea, there are many challenges to be met in order to reliably estimate sea level change. There are at least seven (7) stations in Africa for which more than 40 years of measurements are available at the *Permanent Service for Mean Sea Level* (PSMSL) [5]. These stations include Cueta, Dakar, Takoradi, Alexandria, Port Nolloth, Simons Bay, Mossel Bay [6] (**Figure 1**). In Côte d'Ivoire, no long tide gauge time series is available. However, records of 65 years of tidal measurements are reportedly still in paper format. So far, few or any studies have been carried out to estimate with accuracy sea level elevation.

The aim of reconstructing and monitoring the analog series of water heights observed in the Ebrié lagoon is to safeguard the centuries-old historical observations of sea level in Abidjan and to study variations in water level over the more or less long term. In view of climate change, this is a major challenge for society today. In addition, the tide gauge time series at the station scale is necessary for the study of climate change and applied climatology. The series is also useful for coastal development projects and helps to assess coastal vulnerability.

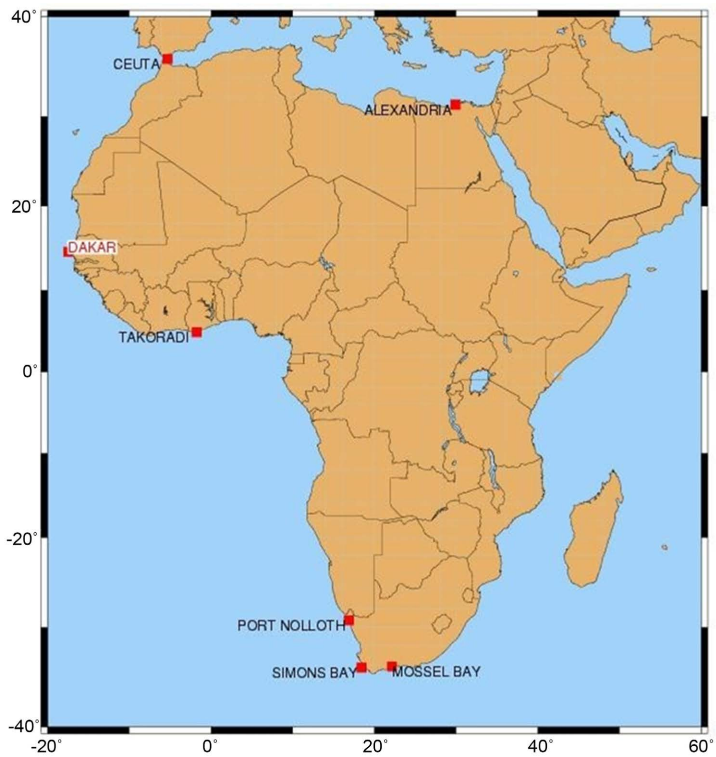


Figure 1. Mean sea level series for the 7 stations in Africa with monthly data available in the PSMSL database over a period of more than 40 years [6].

In this study, we will try to reconstruct a reliable tide gauge series for the Ivorian coastline, in order to analyze the evolving trend of sea level in the more or less long term and to evaluate its impact on the Ivorian coasts.

1.1. Study Area

The Ebrié Lagoon is located in the south of Côte d'Ivoire, between latitudes 5˚15' and 5˚20'N and longitudes 3˚40' and 4˚50'W. It covers an area of around 560 km^2 with an average depth of 4.8 m and a length of 130 km running east-west. It features numerous shallow bays and channels. The Ébrié lagoon is in constant communication with the Atlantic Ocean via the Vridi Canal "**Figure 2**". A total of three (3) tide gauges were installed during the course of our work. However, only the Quai Nord tide gauge station, located between latitude 005˚18.231'N and longitude 004˚01.568'W, will be studied, given the long range of the data.

1.2. Meteorological Context

The City of Abidjan (Côte d'Ivoire) is subject to a transitional equatorial climate of the type divided into four (4) seasons in the annual cycle. The major dry and rainy seasons extent from December to April and from May to July, respectively. The minor dry and rainy seasons lie between July and September and from October to November, respectively [7]. The precipitation, continental inflow from rivers and oceanic inflow via the Vridi canal are the three main types of water that feed the Ebrie Lagoon. Fluvial inputs to the lagoon come from the Me and

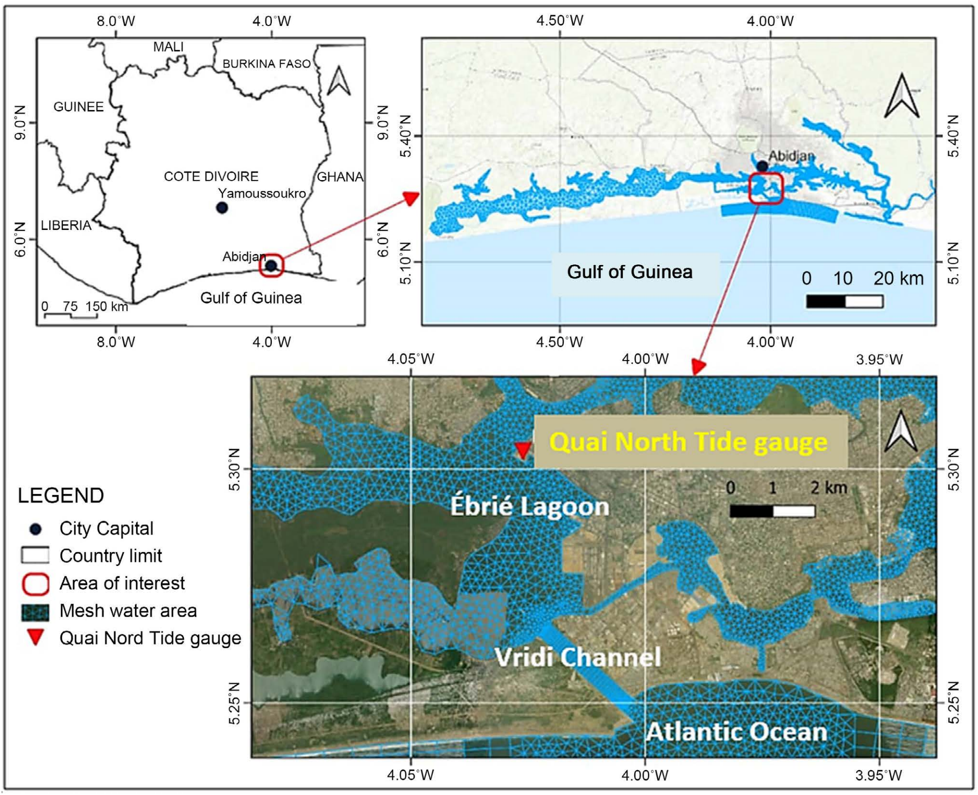


Figure 2. Presentation of the study area.

Comoe rivers at the east, and the Agneby at the west. These river inflows, estimated at 8.40×10^9 m^3, accounts for 65% of the water entering the lagoon [8]. The only Comoe river accounts for 75% of river water [9]. As continental water inflows decrease, marine influence becomes more important in the Ebrié lagoon. This marine influence is almost non-existent during flood periods and significant during low-water periods at the mouth [10]. Seiches are small periodic variations in the surface of the water can be generated by a disturbance such as a strong wind, a strong current, a sudden change in atmospheric pressure or even a tsunami [11]. Their periods range from a few minutes to a few hours, and their amplitudes vary from centimetres to metres [12].

2. Methodological Approach

The project for reconstructing historical time series of water levels observed in the Ebrié lagoon can be broken down into 4 main stages according to [13]. These stages include 1) data and documentary archive research, 2) data digitization and control from the "Surfer and Nunieau" software, 3) exploitation and analysis of the results and 4) valorization of the results. Valorization consisted in performing a quality control on all our data, while calculating the standard deviation of residuals. For better readability of data quality, a number and color code, inspired and recommended by [14], was used to qualify monthly water level data "**Table 1**". Harmonic analysis was then carried out using the "T-Tide" and "U-Tide" software packages to perform an in-depth study of variations in sea level components.

The Daily, monthly, and annual mean sea levels were calculated for the different seasons observed in Abidjan. Several linear filters are available for calculating mean daily sea level [15]. The choice of one depends on the temporal resolution of tidal gauge datasets. So, the Demerliac filter used in this study is recommended by the Hydrographic and Oceanographic Service of the Navy (SHOM), as it uses a symmetrical vector of 71 coefficients. Monthly and annual averages were calculated according to Permanent Service for Mean Sea Level (PSMSL) rules. The monthly average is obtained from the arithmetic mean of the daily averages. This value is not calculated if more than 15 days of data are mixed. The annual average is obtained from the arithmetic mean of the monthly averages, weighted by the number of days actually observed during the month. The value is calculated if at least 11 monthly values are actually available. The

Table 1. Numbers and color codes for monthly residue quality sea level (GLOSS, 2009).

Code		Signification	Criteria
1	(green)	Good quality	Monthly residual < 10 cm
2	(yellow)	Probably good	10 cm ≤ Monthly residual < 15 cm
3	(orange)	Probably bad	15 cm ≤ Monthly residual < 20 cm
4	(red)	Bad quality	Monthly residual ≥ 20 cm
9		Data missing	Number of value < 15

various trends are then estimated by calculating linear regression and quadratic regression using the method of least squares [16]. Reference [17] and [18] believe that the selection criterion for studying trends should be set at 50 years, but that series older than 30 years can also be used after detailed analysis.

3. Results and Interpretation

3.1. Inventory and Validation of Tide Gauge Data in Abidjan

The Abidjan tide gauge time series spans 65 years (1951-2016) of measurement "**Table 2**". However, some periods of these batches of data are missing and could not be exploited. So a series of 38 years of tide gauge measurements were identified. Among these series, 33 years covering the period from 1979 to 2011 would still be in paper format and 5 years of data in digital format.

After digitizing the 33 years of data from 1979 to 2011, it was necessary to take into account the quality of the datasets before considering any sea level study. The validation consists of checking the quality of the newly digitized series [19]. The analysis of time series shows that about 28% of the 33 years of data recorded with the float tide gauge were missing and, 2% that have poor quality data were deleted. This represents 70% of existing data "**Figure 3**".

This percentage is sufficient for sea-level studies [14]. After analysis, 90.48% of the data recorded from the digital tide gauge was classified as good, and no data with poor quality was identified. On the other hand, 81.05% of the data recorded from the float tide gauge were identified as good, and 8% defined as poor quality were subsequently removed "**Figure 4**, **Figure 5**".

The tide gauge time series from the station called "north quay" of the port of Abidjan was reconstructed from 38 years of hourly recordings, from 1979 to 2016. Among this dataset, 33 years come from analog tide gauges and 5 years from digital tide gauges "**Figure 6**".

Table 2. Details of historical tide gauge measurement documents inventoried and recovered from archive centers.

Period	*Duration effective*	*Instrument*	*Frequency*	*Unit measurement*	*System*	*Type archives*	*Source*
1912	3 months	Tide scale	30 min.	Metric	Time Universal	Register	SHOM (Brest
1928	9 days	Medimeter	1 day	Metric	Time Universal	Register	SHOM (Brest)
1949	1 month	Tide scale	Diurnal-15 min.	Metric	Time Universal	Register	SHOM (Brest)
1950	1 year	Shiny tide gauge	2 hours	Metric	Time Universal	Telegram	SHOM (Brest)
1951-1954	4 years	Float tide gauge	10 min.	Metric	Time Universal	Telegram	SHOM (Brest)
1964-1965	2 years	Tide gauge float switch	10 min.	Metric	Time Universal	Telegram	DDH PAA
1974-2011	37 years old	Tide gauge float switch	10 min.	Metric	Time Universal	Telegram	DDH PAA
2012-2016	5 years	Tide gauge digital	10 min.	Metric	Time Universal	Data digital	DDH PAA

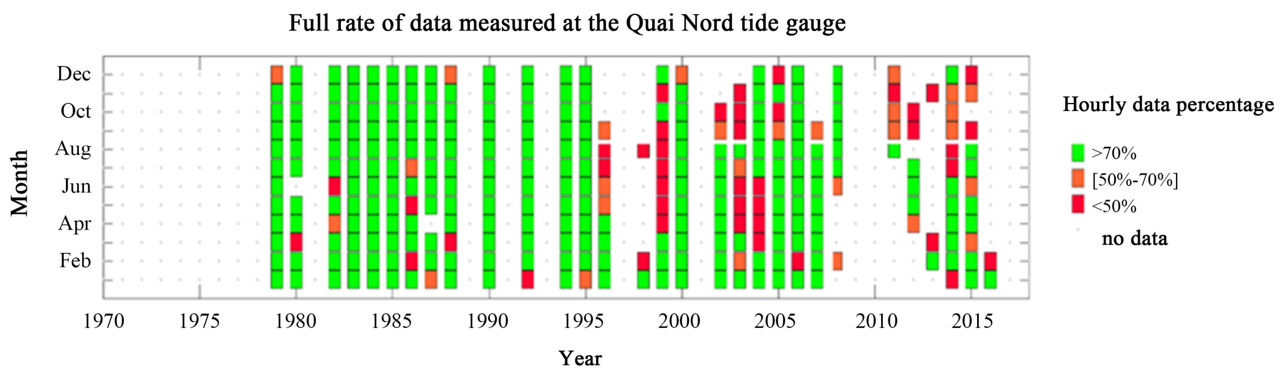


Figure 3. Existence rate of hourly data in the Abidjan tide gauge time series.

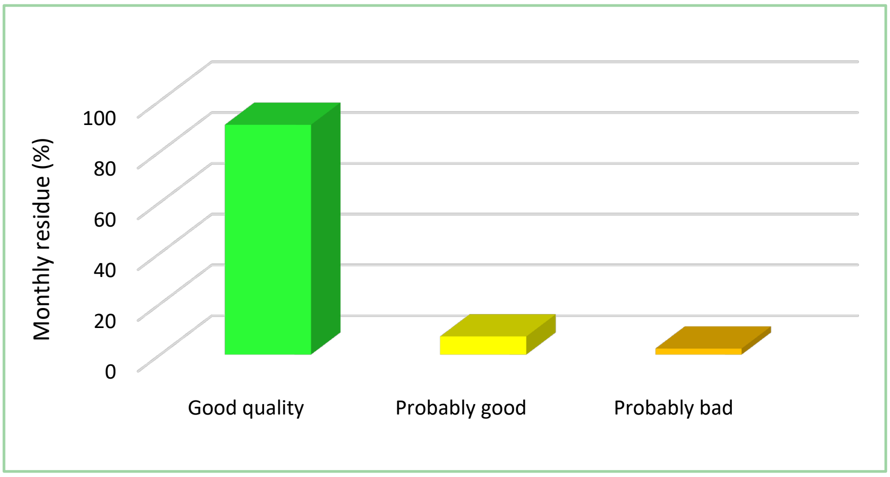


Figure 4. Quality control of data recorded with the digital tide gauge.

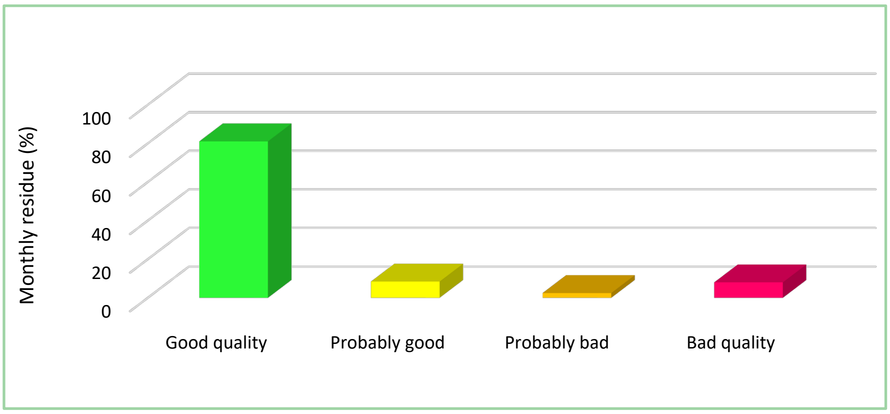


Figure 5. Quality control of data recorded with the float tide gauge.

3.2. Temporal Variability of Sea Level along the Abidjan Coast

Using the reconstructed 38-year hourly tidal series for the Abidjan coast, various tidal averages were calculated according to PSMSL rules. The analysis of the daily averages revealed an anomaly in the recent recorded data. From 1979 to 2009, sea level trends were fairly regular. Then, from 2009 to 2016, a sudden rise in low water is observed "Figure 7".

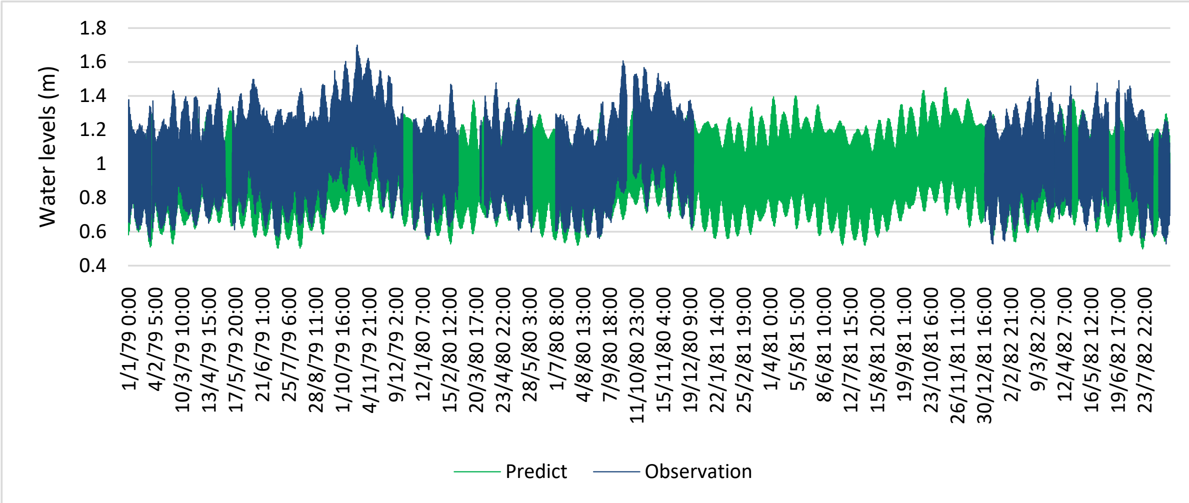


Figure 6. Tide gauge time series from the North Quay station in the port of Abidjan, reconstructed using 38 years of hourly recordings.

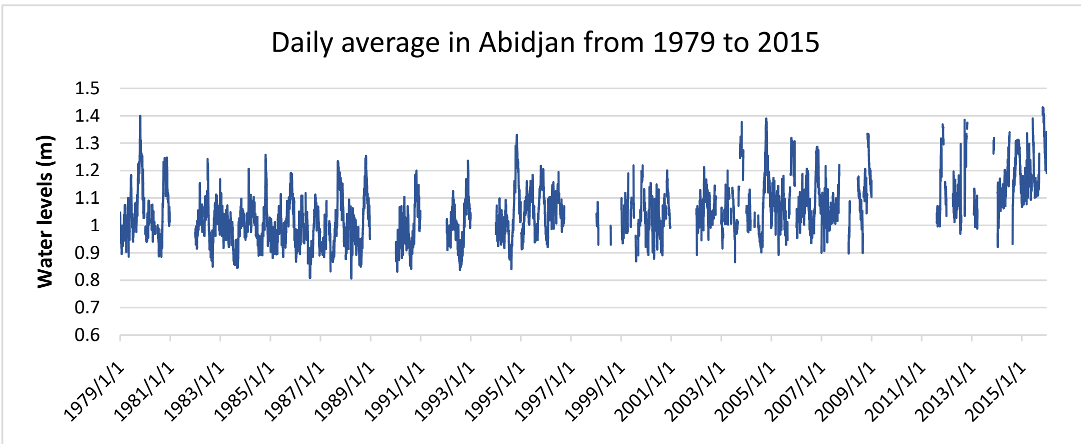


Figure 7. Anomaly detected in daily averages from 2009 to 2015.

The sudden rise in low tides over the past 7 years could be due to the variation in hydrographic datum over the 2009-2015 period, or to exceptional floods thus creating siltation of the stilling well instrument [20]. In the last case, high sediment accumulation has already been observed by Monde [21]. To obtain reliable trends, we were content to use data from 1979 to 2009. A continuous and reliable tide gauge time series over the 31-year period from 1979 to 2009 allowed us to determine various averages water levels in the Ébrié lagoon at daily, monthly and annual timescales "**Figure 8**". The mean daily water level calculated using Demerliac filter gives an average of 1.04 m in the lagoon between 1979 and 2015.

The annual averages of water levels calculated from monthly averages show the variation in water level over the 1979 to 2009 period "**Figure 9**".

The annual average from 1979 to 1980 is 3.6 cm higher than the mean water level in lagoon estimated at 104 cm. A peak was observed in 1979 with a water level of 106.5 cm.

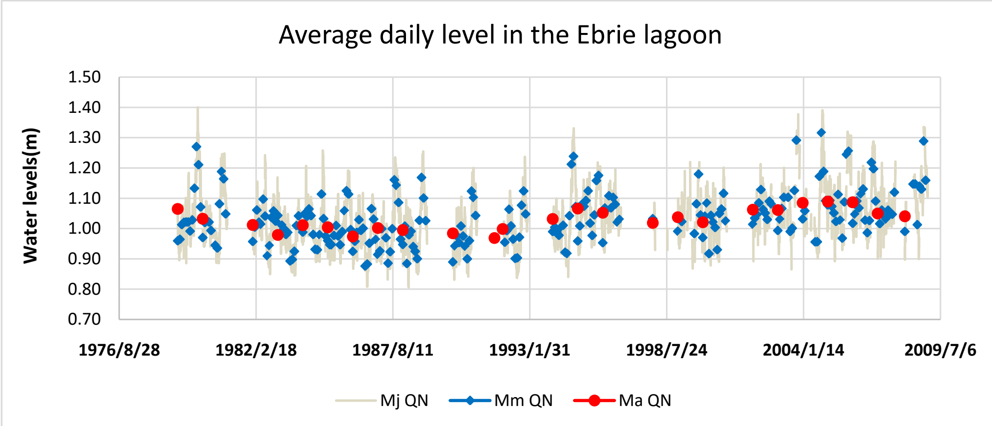


Figure 8. Interannual variation in mean levels in the Ébrié lagoon.

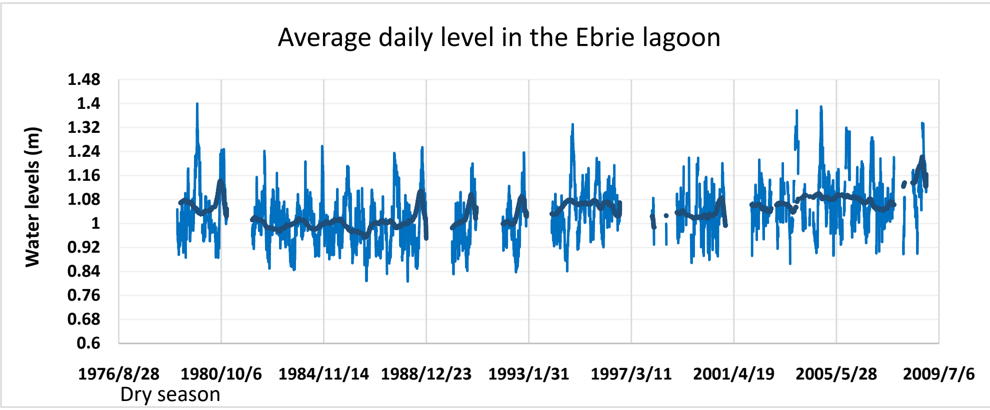
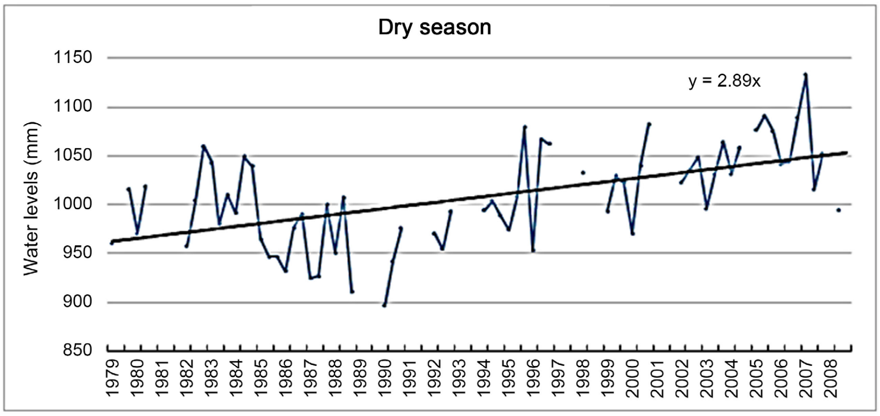


Figure 9. Interannual variation in mean levels in the Ébrié lagoon.

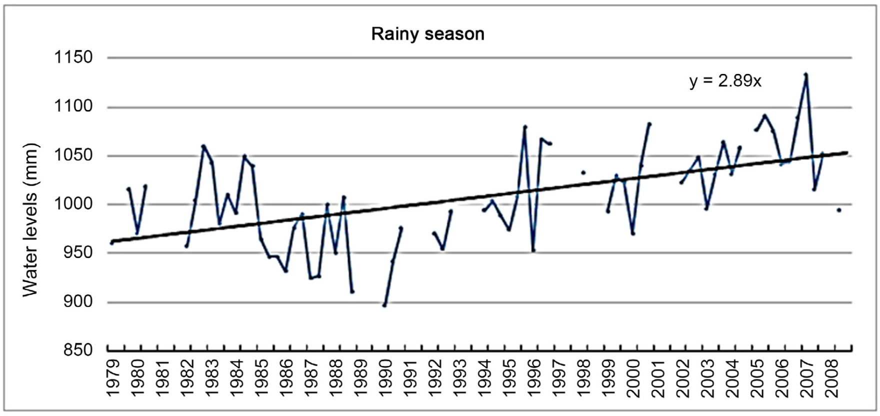
From 1982 onwards, water levels were lower than average until 1992. The minimum annual average value of 96.9 cm observed in 1991 is 6 cm lower than the mean water level in lagoon. From 1993 to 2009, water levels are above of the average level. A peak of 108.9 cm recorded in 2004 is 6 cm higher than the mean. From 1992 to 2004, water levels in the Ébrié lagoon rose by 12 cm, twice as much as in 1991. Since then, it has continued to rise with an annual rate of 2.61 mm per year "**Figure 9**".

3.3. Seasonal Trends of the Water Levels

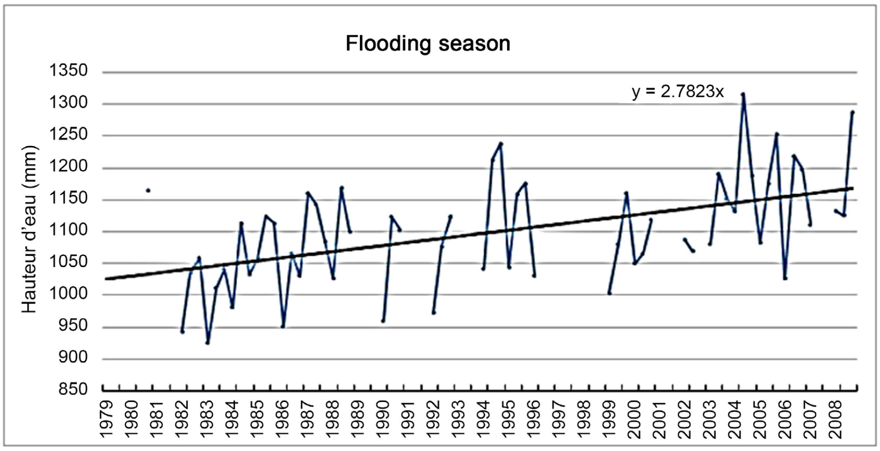
During the dry season , the mean water levels vary between 90 and 113.5 cm in the lagoon, with a drop in average levels between 1985 and 1990. They generally increase with annual rate of 2.89 mm per year over the 1979 to 2009 period "**Figure 10(a)**". An acceleration of this trend is observed since 1992. The trend observed during the main rainy season has a slope of 2.93 mm per year from 1979 to 2009 "**Figure 10(b)**". A decreasing trend is observed from 1983 and 1995 during this season. The average levels vary between 89 and 114 cm, with an increasingly high discharge since 1995. During the flooding season, one observes a gradual increase of the average levels between 1981 and 1989, followed by a slight drop between 1989 and 1994. Since 1995, the average levels are above 100 cm and continue to rise. Between 1979 and 2009, the average levels computed during the flood season rose with a rate of 2.78 mm per year "**Figure 10(c)**". The minimum and maximum water levels are ranged between 92.5 and 131.5 cm.



(a)



(b)



(c)

Figure 10. Seasonal trends of water levels in the Ebrié Lagoon (Abidjan). (a) Trend in mean tide level in the dry season; (b) Sea level trend in the rainy season; (c) Sea level trend during flood season of the Comoé River.

4. Discussions

The processing method applied to tide gauge data in Abidjan is the same as that used to qualify historical tide gauge data from the Saint-Nazaire series [13]. It is also the same as that used on tide gauge observations made since the 18th century in Charente-Maritime [22]. This method gives satisfactory results, with a total of 85.77% of data of good quality. Analysis of the data revealed the reliability of the digital tide gauge. According to [23], a variety of errors of different origins can affect sea level recordings using float tide gauges. Despite these numerous possible errors, (modernized) float tide gauges are still very common. According to a 1983 survey by the PSMSL, 90% of the world's tide gauges were float tide gauges [24]. Today, however, this situation is tending to be reversed with the advent of new equipment. The average levels observed during different seasons over the 31 years in the Ébrié lagoon are evolving at a higher annual rate than the general trend, e.g. 2.61 mm per year. This would explain why Abidjan is the most vulnerable city in Côte d'Ivoire to flooding [25]. This trend is comparable to that found by Tano [26], using altimetry data during the period 1993 to 2014, *i.e.* a trend of 3.05 mm per year. This trend is also comparable to other trends estimated in the Gulf of Guinea from altimeter data: Benin: 3.33 mm/year; Nigeria: 2.68 mm/year; Cameroon: 2.90 mm/year; Congo: 2.7 mm/year; Angola: 3.03 mm/year; Ghana: 3.05 mm/year [27] [28]. The average daily mean level is 1.04 m. There has also been a rise since 1992, which accelerated in 2004 with an increase of 6 to 12 cm. Maximum water levels were observed in 2004, possibly linked to the 2004 Indian Ocean tsunami [29]. Trends during the wet and low-water seasons show a 12-year decline in sea level between 1983 and 1995, with increasingly high rainfall rates since 1995. During the dry season, water levels evolve at a higher rate than during the Comoé River flood, e.g. 2.89 mm vs. 2.78 mm per year. This means that marine input is dominant over continental input [8] [30]. This trend also increases the risk of marine submersion in Abidjan. In addition, the average levels during flooding evolve differently, with an increase in water levels from 1982 to 2009. Now, the average water levels are barely decreasing. This poses a major threat in the years to come if nothing is done.

5. Conclusions

This article estimated the evolutionary trend of the sea level from the tidal series of the Ébrié lagoon reconstructed in Abidjan (Côte d'Ivoire) due to seasonal and climatic factors.

On average, 70% of the Autonomous Port of Abidjan tide gauge data are available, and 86% of the data extended over the 38 years have been identified as being of good quality on average after rigorous control of the measurements. Estimated trends over the different seasons in Abidjan show that marine, rainwater and river inputs contribute to the significant rise in water levels in the lagoon basins. This makes these coasts much more vulnerable to the risk of flooding in the coming years. In addition, marine submersions caused by swell storms are the most significant coastal hazard in Côte d'Ivoire. The damages observed along Côte d'Ivoire's coasts are already enormous in a fraction of a second, and could be exacerbated by human activities and climate change. In view of Abidjan's coastal infrastructures (port, airport, refinery, etc.), it seems urgent to take every precaution to limit the damages of marine forcing impacts.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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