Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 9 (8): 1517-1523, 2009
ISSN 1812-5654

Physicochemical Characterization of the Waters of the Coastal Rivers and the Lagoonal System of Cote d'Ivoire

K.V. Kouame, O.B. Yapo, V. Mambo, A. Seka, A.S. Tidou and P. Houenou
Laboratoire des Sciences de l'Environnement, UFR-SGE, Université d'Abobo-Adjamé,
02 BP 801 Abidjan 02, Côte d'Ivoire

Abstract: The aim of this study is to evaluate physicochemical parameters in the lagoonal system and coastal rivers of Côte d'Ivoire to appreciate their spatial variation. Water samples were collected at 16 stations for phosphorus, nitrogen, pH, salinity, temperature and conductivity analyses. Sampling was carried out during two seasons, characterizing the water of the lagoonal system of Côte d'Ivoire, October 2006 for wet season and March 2007 for dry season. These samples were collected in four rivers and two lagoons. It was found that, the phosphorus concentrations (1.77 mg L^{-1}), as well as the ammonia-nitrogen (0.65 mg L^{-1}) and nitrate-nitrogen concentrations (1.09 mg L^{-1}) were high throughout the area, indicating extensive pollution. Although, the nitrite-nitrogen concentration was relatively low, it is at the upper end of what might be considered normal, thereby indicating an anthropogenic origin. The highest concentrations of nutrients obtained in the area of Azito in the Ebrié lagoon are indicative of high stress on a lagoonal system from a particular industrial pollution. The study revealed also that the dilution of the water of the lagoonal system during the dry season by the oceanic water reduces considerably the concentrations of nutrients and increases conductivity and water salinity.

Key words: Coastal water, lagoons, nutrients, salinity, conductivity

INTRODUCTION

As on many other coastlines of the world, the West African Coast is dominated by a series of shallow coastal lagoons, most of which are oriented parallel to the shore (Marcovecchio *et al*., 2005). The anthropogenic enrichment of coastal waters with nutrients indicates high stress on a river system from a variety of human activities. It is well known that the response of a fluvial ecosystem is maximal during warm, dry and drought conditions, when the river flow is low and nutrient concentrations are highest. High flows normally result in a rapid through put of high volumes of water with low nutrient concentrations. In this case, degradation will result from the accumulated loads entering the downstream receiving waters and reservoirs along the course of rivers. In order to maintain high-quality ecosystems within receiving waters and within a rivers system itself, it is necessary to maintain low nutrient level that reflects normal or natural conditions of the coastal waters. However, as it has been stressed by several investigators, even though nutrients are the primary cause of eutrophication in coastal zones and estuaries, there are many other factors that determine the ultimate level and type of eutrophication symptoms (Nixon *et al*., 2001; Boesch, 2002; Bricker *et al*., 2003). Moreover, the relationship between nutrient pressure and estuarine changes of state is so complex and variable that a general dynamic model is still considered an ambitious goal (Bricker *et al*., 2003). This underlinesthe importance of several factors.

The lagoonal system of Côte d'Ivoire is a place of transit of rivers water before reaching the sea. It is located in a very urbanized zone of the country, including the economic capital (Abidjan) and its suburbs. Hence, the lagoonal system is influenced by the urban and agricultural practices. Wastewater treatment is practically non-existent and agricultural practices require fertilizer addition.

The lagoonal system of Côte d'Ivoire is characterized by two seasons (Durand and Chantraine, 1982). A dry and warm season where the continental provisions of water are negligible, evaporation is maximum and the marine influence is dominating. A wet and cold season characterized by the highest precipitations associated with the provision of the coastal rivers, involving a significant fall of the salinity of lagoon water. The coastal lagoonal system of Côte d'Ivoire consists of three distinct lagoons (Durand and Chantraine, 1982): lagoon of Grand-

Corresponding Author: K.V. Kouame, Laboratoire des Sciences de l'Environnement, UFR-SGE, Université d'Abobo-Adjamé, 02 BP 801 Abidjan 02, Côte d'Ivoire Tel: 0022507672119 Fax: 0022520304256

Lahou in the west, Ebrié in the center and Aby in the East. They are fed by seven rivers (Comoé, Bandaman, Boudo, Agnéby, Mé, Bia and Tanoé). This unit was largely studied with regard to the physical environment (Dufour, 1982), the exchanges of nutritive elements dissolved between water and sediment (Metongo, 1989) and the influence of the conditions of the area on the biological breakdown of the organic matter. Nevertheless, the data available are relatively old and rare are the studies devoted to date to the whole of the lagoonal system and that connect the physicochemical components to their spatial variability. Efforts to understand and quantify the interactions across the land-ocean boundary have led to an increasing focus on the fluxes of water, salt and nutrients through the mouth of lagoonal estuaries (Simpson *et al*., 2001). These fluxes can producedrastic changes of the physical and chemical characteristics that are the basis of high productivity in a coastal lagoon. For a better management of the lagoonal system, it is important to know, in addition to flows, the physico-chemical characteristics of these waters. Similar studies in estuarine and lagoonal environments for the determination of water quality have been undertaken by other authors in diverse parts of the world (Uncles and Lewis, 2001; Allanson, 2001; Sylaios *et al*., 2004; Pereira *et al*., 2008).

This contribution was initiated to fill this gap and to contribute to a better management of the lagoonal system of Côte d'Ivoire. The objective is to evaluate physicochemical parameters in the lagoonal system and coastal rivers to appreciate their spatial variation.

MATERIALS AND METHODS

The study was conducted in the lagoonal system of Côte d'Ivoire, in West Africa, which falls within latitudes 2°9' W and 5° W and longitudes 5°12' N and 5°35' N. Water samples were collected at 16 stations (Fig. 1). Stations were located on four rivers (Bia, Tanoé, Comoé and Bandaman) and two lagoons (Aby and Ebrié). Thirty two Samplings (16 for rivers and 16 for lagoons) were carried out during the two seasons, characterizing of the water of the lagoonal system water of Côte d'Ivoire, October 2006 for wet season and March 2007 for dry

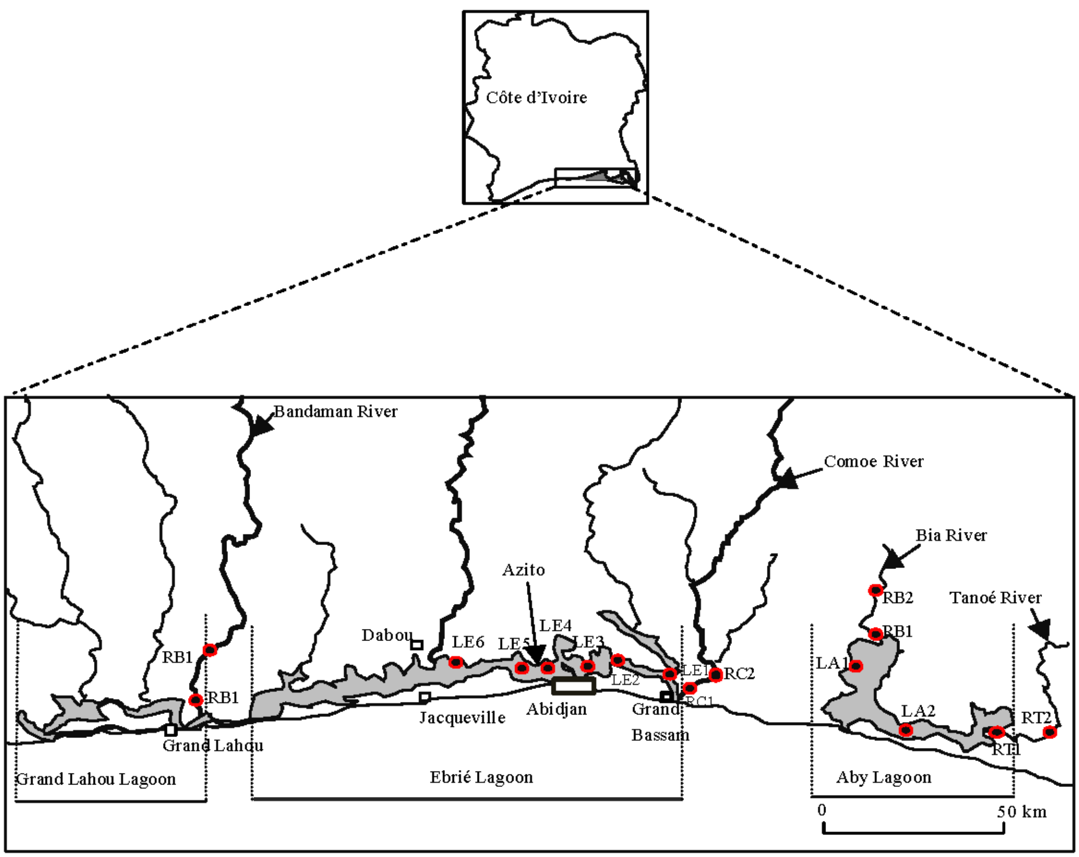

Fig. 1: Localization of sampling stations

season. Water samples for nutrient analyses were collected in acid-cleaned and rinsed 1000 mL polyethylene bottles. The bottles were rinsed 3 times with river water before being filled with the sample. The samples were collected by direct immersion of the bottle into the river. Samples were kept cool in thermos with ice and taken to the laboratory for analysis as soon as possible, but mainly within 48 h. The samples collected were analysed at the water chemistry laboratory of Abobo-Adjame University, according to AFNOR standards (AFNOR, 2001).

Samples were analysed for phosphate-phosphorus (PO_4-P), Total Phosphorus (PT), ammonia-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N) and nitrite-nitrogen (NO_2-N). Temperature, pH, conductivity and salinity were measured in situ using a multiple-sonde (WTW 330i).

The data were compared statistically through the test of Mann-Whitney at 5% level of significance using STATISTICA 7.1 software.

RESULTS AND DISCUSSION

Physicochemical parameters: A summary of mean, maximum and minimum values of temperature, salinity, pH, conductivity and nutrients are shown in Table 1, with the mean for all the rivers and lagoons stations. The temperature and pH in each river or lagoon remained constant, regardless of the period of sampling. The mean values are 29.71°C for the temperature and 7.51 for pH. Variability range for salinity (4.91) and conductivity (5584.28 μS cm^{-1}) is very broad as shown by the high standard deviations values.

The range of values for all nutrients is large (Fig. 2c, d), as indicated by the standard deviation values. The mean values are also high, suggesting a high level of

Table 1: Summary of statistics of physico-chemical characteristics of all water samples analysed

Characteristics	Mean value	SD	Maximum value	Minimum value	N
PT (mg L^{-1})	1.77	0.83	3.91	0.66	32
PO_4-P (mg L^{-1})	0.62	0.31	1.52	0.18	32
NH_4-N (mg L^{-1})	0.65	0.29	1.34	0.12	32
NO_3-N (mg L^{-1})	1.09	0.55	2.17	0.18	32
NO_2-N (mg L^{-1})	0.18	0.09	0.48	0.06	32
Temperature (°C)	29.71	0.92	32.00	27.40	32
pH	7.51	0.60	8.81	6.47	32
Salinity	4.91	7.06	27.50	0.20	32
Conductivity (μS cm^{-1})	5584.28	11779.72	42400.00	2.26	32

PT: Total-Phosphorus, PO_4-P: Phosphate-phosphorus, NH_4-N: Ammonia-nitrogen, NO_3-N, nitrate-nitrogen, NO_2-N: Nitrite-nitrogen, N: No. of samples, SD: Standard deviation

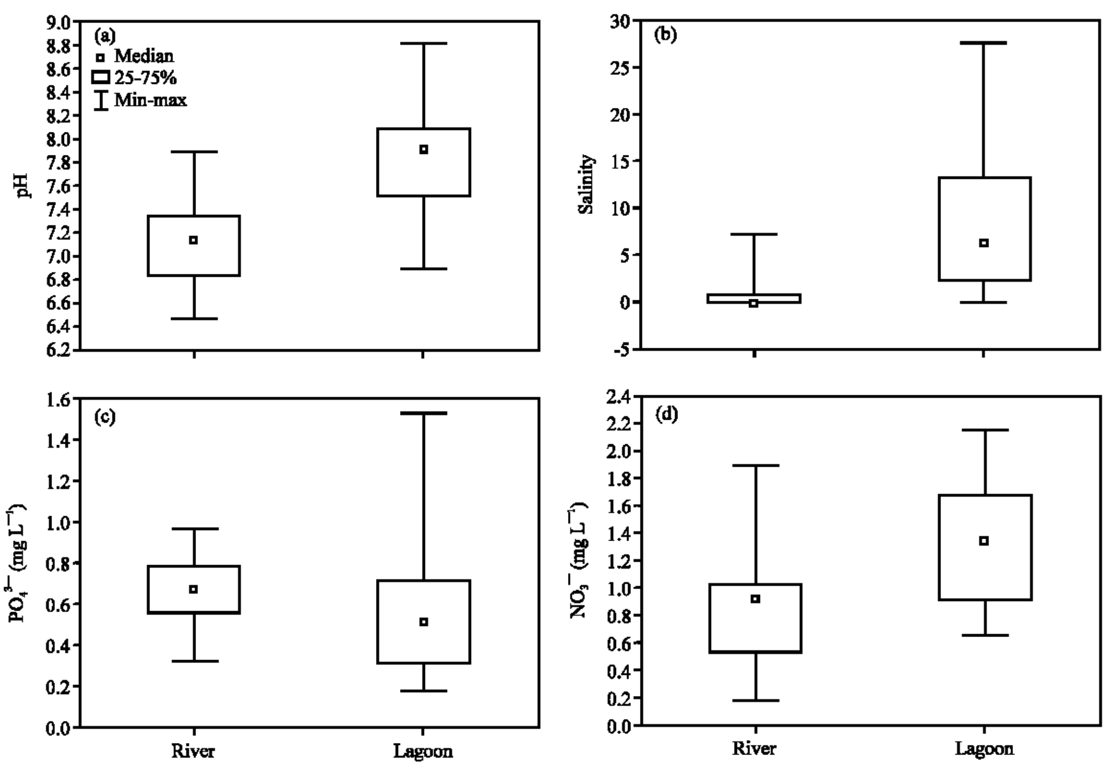

Fig. 2: Statistical comparison of physicochemical parameters of Lagoon and River and box plot of (a) pH, (b) salinity, (c) PO_4^{3-} and (d) NO_3^-

nutrient enrichment of the waters of these coastal rivers and lagoonal system. The mean of total phosphorus (1.77 mg L^{-1}, Table 1), indicates the very high nutrient levels existing in this water system.

According to Chapman (1996) NH_4-N concentration in unpolluted waters should normally be lower than 0.1 mg L^{-1} and can occasionally reach 0.2 mg L^{-1}. Concentrations higher than this value suggest organic pollution from sources such as domestic sewage, industrial wastes and fertilizer run-off.

For Côte d'Ivoire coastal rivers and lagoonal water, the NH_4-N concentration exceeds the above-noted 0.1 mg L^{-1} value, averaging 0.65 mg L^{-1}, with the highest individual concentration being 1.34 mg L^{-1}. These values are higher than those obtained in the maritime area of Togo (West Africa) by Akpavi *et al.* (2005). That could be related to the anthopic sources. The NO_3-N values range from 0.18 to 2.17 mg L^{-1} with a mean of 1.09 mg L^{-1} of lagoonal system of Côte d'Ivoire are similar to that obtained in dry season in Ghana by Lamptey and Armah (2008), West of Côte d'Ivoire. Nitrate-nitrogen is the most common form of nitrogen (N) in fresh water, seldom exceeding a concentration of 0.1 mg L^{-1} (Chapman, 1996). This concentration can be enhanced by municipal and industrial waste waters, leachates from waste disposal and from fertilizers. The high values of NO_3-N in lagoonal system of Côte d'Ivoire could be due to the intense agricultural activity of the area with fertilizer application and domestic wastewater (Figueiredo *et al.*, 2002; Powlson *et al.*, 2008).

Nitrite-nitrogen concentrations in fresh water are normally very low, being in the order of 0.001 mg L^{-1}. Values higher than 1 mg L^{-1} rarely occur and algal stimulation can occur in lakes and reservoirs at concentration higher than 0.2 mg L^{-1}. Higher NO_2-N concentrations are often indicative of industrial effluents (Chapman, 1996).

Generally, one can say that the quality of lagoon waters with respect to nutrients depends on the different nutrient sources, the morphology of the basin and the renewal of water with the adjacent coastal sea (Sylaios and Theocharis, 2002). The transport of nutrients to the lagoon is either from land or from the adjacent sea. According to Sylaios *et al.* (2004) increasing nutrient concentrations with salinity and conductivity reveals transport from the sea and decreasing reveals transport from land sources.

Spatial variation in water characteristics: Both total phosphorus and PO_4-P were high in Bandaman and Tanoe rivers samples (2.85 and 0.75 mg L^{-1}, respectively) and low in the lagoon samples (1.56 mg L^{-1} for total phosphorus and 0.57 mg L^{-1} for PO_4-P). This difference can be explained by generalized source of phosphorus in the rivers, the area being a strongly agricultural zone (Table 2). However, NH_4-N and NO_3-N concentrations remained constant in all the studied reservoirs. The high values were in the lagoon (1.34 mg L^{-1} for NH_4-N and 2.17 mg L^{-1} for NO_3-N) and the values were low in rivers (0.12 mg L^{-1} for NH_4-N and 0.18 mg L^{-1} for NO_3-N). It was noticed that higher concentrations of total phosphorus and nitrate-nitrogen (3.91 and 2.17 mg L^{-1}, respectively) were obtained around the Azito (Fig. 1) area (District of Abidjan) where industrial wastewaters of Yopougon (Abidjan) are dumped.

Homogeneous values observed in the other stations indicate that the nutrients can originate from the same source or sources. The NO_2-N concentrations in all samples are uniformly low (Table 2).

Table 2: Water characteristics of the four rivers, compared to the mean value of lagoons water

	Rivers				
Parameters	Bia	Tanoe	Comoe	Bandaman	Lagoon water
PT (mg L^{-1})					
X	1.77	1.68	1.60	2.85	1.56
SD	0.32	0.22	0.74	0.81	0.89
N	4.00	4.00	4.00	4.00	16.00
PO_4-P (mg L^{-1})					
X	0.70	0.75	0.59	0.66	0.57
SD	0.20	0.09	0.21	0.19	0.41
N	4.00	4.00	4.00	4.00	16.00
NH_4-N (mg L^{-1})					
X	0.18	0.62	0.70	0.63	0.77
SD	0.05	0.16	0.09	0.09	0.31
N	4.00	4.00	4.00	4.00	16.00
NO_3-N (mg L^{-1})					
X	0.25	0.95	1.39	0.91	1.31
SD	0.05	0.11	0.52	0.13	0.47
N	4.00	4.00	4.00	4.00	16.00
NO_2-N (mg L^{-1})					
X	0.10	0.13	0.22	0.14	0.21
SD	0.03	0.05	0.03	0.03	0.12
N	4.00	4.00	4.00	4.00	16.00
Temperature (°C)					
X	29.30	28.88	29.83	29.35	30.08
SD	1.04	1.16	0.80	0.72	0.79
N	4.00	4.00	4.00	4.00	16.00
pH					
X	7.33	6.90	6.77	7.52	7.89
SD	0.24	0.19	0.21	0.28	0.55
N	4.00	4.00	4.00	4.00	16.00
Salinity					
X	0.83	0.00	0.58	2.23	8.81
SD	1.65	0.00	1.08	3.40	8.06
N	4.00	4.00	4.00	4.00	16.00
Conductivity (µS cm^{-1})					
X	76.22	125.18	267.15	3614.32	10147.84
SD	56.71	20.13	376.44	7030.79	151666.83
N	4.00	4.00	4.00	4.00	16.00

PT: Total-phosphorus, PO_4-P: Phosphate-phosphorus, NH_4-N: Ammonia-nitrogen, NO_3-N: Nitrate-nitrogen, NO_2-N: Nitrite-nitrogen, X: Mean value, SD: Standard deviation, N: No. of samples

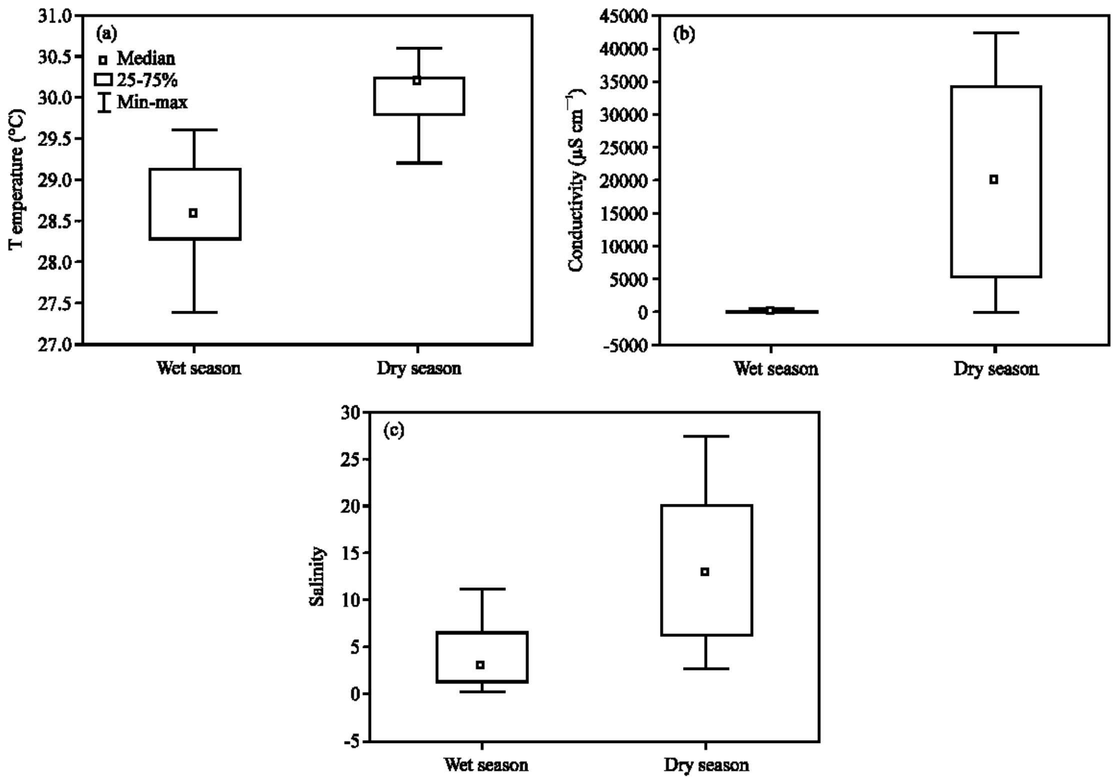

Fig. 3: Comparison of physicochemical parameters of wet season and dry season and box plot of (a) temperature of rivers, (b) conductivity of lagoons and (c) salinity of lagoons

pH values were generally uniform throughout the river and lagoonal water, contrary to salinity and conductivity. The high values of salinity and conductivity in lagoons can be related to the intrusion of oceanic water through the Vridi channel and Assinie channel, as suggested by the findings of Sylaios *et al*. (2004).

It is important to note that the spatial variation in water characteristics of lagoons and rivers shows that these two water reservoirs have a statistically significant difference according to pH, salinity, PO_4-P and NO_3-N values. Thus, pH and water salinity were higher in lagoons than in rivers while concentrations of PO_4-P and NO_3-N were lower in lagoons than in rivers (Fig. 2a, b).

Seasonal changes in nutrients and other water characteristics: A dilution of total phosphorus, PO_4-P and NH_4-N can be seen during dry season, compared to wet season. In wet season, mean concentrations of total phosphorus, PO_4-P and NH_4-N were 2.09 , 0.75 and 0.59 mg L^{-1}, respectively in river against 1.87, 0.66 and 0.83 mg L^{-1} in lagoon. The dry season was characterized by lower values (Table 3).

When considering NO_3-N and NO_2-N concentrations, the intrusion of oceanic water to lagoon does not appear to be a factor influencing the seasonal character. The source of these two forms of nutrients is different from the source of phosphorus and NH_4-N. In addition, the process of nitrification in lagoonal system could be more significant in dry season than in wet season.

In raining season, when the flow of the rivers increases, the total phosphorus concentrations increase quickly. They increase from low-water level seasons to water desalination seasons. The fact that transfers mainly occur at the times of water flood explains why the phosphorus concentrations in water vary (Blomqvist *et al*., 2004). There are phosphorus inputs during the lagoon rising. During the dry season, oceanic water, normally very low in phosphorus (Ramade, 1995), brings about a dilution of lagoonal water through the Vridi channel on Ebrié lagoon, justifying low phosphorus concentrations.

The seasonal variation is marked by higher values for the temperature, conductivity and salinity in dry season than in wet season. There were strong significant differences in these parameters between the wet and dry seasons (Fig. 3). The highest values are measured in lagoon and during the dry season. There has been a sharp drop in salinity values towards the continental areas on

Table 3: Seasonal variation of the characteristics of the water of Côte d'Ivoire lagoon system

	Wet season		Dry season	
Parameter	Rivers	Lagoons	Rivers	Lagoons
PT (mg L^{-1})				
X	2.09	1.87	1.86	1.26
SD	0.75	0.19	0.76	0.55
N	8.00	8.00	8.00	8.00
PO_4-P (mg L^{-1})				
X	0.75	0.66	0.60	0.49
SD	0.17	0.13	0.15	0.37
N	8.00	8.00	8.00	8.00
NH_4-N (mg L^{-1})				
X	0.59	0.83	0.47	0.71
SD	0.24	0.30	0.22	0.32
N	8.00	8.00	8.00	8.00
NO_3-N (mg L^{-1})				
X	0.87	1.32	0.88	1.30
SD	0.52	0.50	0.48	0.50
N	8.00	8.00	8.00	8.00
NO_2-N (mg L^{-1})				
X	0.14	0.21	0.15	0.21
SD	0.07	0.14	0.04	0.10
N	8.00	8.00	8.00	8.00
Temperature (°C)				
X	28.64	29.81	30.04	30.34
SD	0.70	0.66	0.43	0.86
N	8.00	8.00	8.00	8.00
pH				
X	7.13	7.72	7.14	8.05
SD	0.18	0.53	0.53	0.55
N	8.00	8.00	8.00	8.00
Salinity				
X	0.11	4.19	1.70	13.64
SD	0.28	3.91	2.58	8.58
N	8.00	8.00	8.00	8.00
Conductivity (µS cm^{-1})				
X	184.62	32.54	1856.81	20263.14
SD	264.75	70.68	4971.51	16095.02
N	8.00	8.00	8.00	8.00

PT: Total-phosphorus, PO_4-P: Phosphate-phosphorus, NH_4-N: Ammonia-nitrogen, NO_3-N: Nitrate-nitrogen, NO_2-N: Nitrite-nitrogen, X: Mean value, SD: Standard deviation, N: No. of samples

both sides of Vridi channel. The maximum value of salinity (27.5) was in this area where there is a constant salted water renewal through this channel as observed by Durand and Chantraine (1982). Similar values were obtained in Ghana (Lamptey and Armah, 2008) for the same seasons. The influence of the rivers on salinity appears in wet season where the exchanges by flow occur in the direction rivers-lagoons. In wet season, rivers enrich lagoons in low salinity water. Thus, the salinity rates are much reduced during this season. The maximum value was 11.5 against 27.5 in dry season. This fall of salinity is in favour of the development of living organisms, less tolerant to salinity.

CONCLUSIONS

The characteristics of the water of the lagoonal system in Côte d'Ivoire come from the principal mechanisms of water supply and water movement in this aquatic system. A number of conclusions can be drawn from the results of this study which provide a glimpse of both the pollutant sources and the stream dynamics. These can be summarized as follows:

- Phosphorus and NH_4-N exist in high concentrations throughout this area
- NH_4-N and NO_3-N concentrations are fairly constant. This is consistent with a constant loading from a point source or point sources. The uniform concentrations suggest that the point sources are distributed in a fairly regular fashion throughout the area
- NO_3-N and NO_2-N concentrations are both at higher-than-normal levels, indicating anthropogenic sources. They are not subject to dilution. This means that their likely sources are diffuse and different from the PO_4-P and NH_4-N sources, although sewage also might contribute to the NO_3-N levels in surface water. The NO_3-N is believed to result from soil and near-surface movement of water through leaching nitrogen from fertilizer applied throughout the intensive agricultural regions of lagoonal system

A seasonal comparison of the results shows that the wet seasons are characterized by low salinity thanks to a dilution of lagoon water by fresh river water. The dry season is marked by decrease of nutrients concentrations. These phenomena could be favorable to the development and the maintenance of the invasive aquatic plants during the wet seasons.

ACKNOWLEDGMENTS

These authors would like to acknowledge Laboratory of Environment and Aquatic Biology for its assistances in sampling. We also recognize the immense assistance by Koné Y.J.M. and K.N. Kouadio during the fieldwork.

REFERENCES

AFNOR, 2001. Quality of water, main elements, other elements and mineral composites. 6th Edn., AFNOR.

Akpavi, S., K. Batawila, G. Djaneye-Boundjou, D. Afidégnon, B.D. Foucault, K. Akpagana and P. Bouchet, 2005. Contribution to the knowledge of the ecology of *Eichhornia crassipes* (Mart.) Solms-Laub. (Pontederiaceae) and *Pistia stratiotes* L. (Araceae) in the east maritime region of Togo. Acta Botanica Gallica, 152: 269-280.

Allanson, B.R., 2001. Some factors governing the water quality of microtidal estuaries in South Africa. Water SA, 27: 373-386.

Blomqvist, S., A. Gunnars and R. Elmgren, 2004. Why the limiting nutrient differs between temperate coastal seas and freshwater lakes: A matter of salt. Limnol. Oceanogr., 49: 2236-2241.

Boesch, D.F., 2002. Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems. Estuaries, 25: 886-900.

Bricker, S.B., J.G. Ferreira and T. Simas, 2003. An integrated methodology for assessment of estuarine trophic status. Ecol. Modell., 169: 39-60.

Chapman, D., 1996. Water Quality Assessment: A Guide to the use of Biota, Sediments and Water in Environmental Monitoring. 2nd Edn., E&FN Spon, London.

Dufour, P., 1982. Natural and human boundaries of Ebrié lagoonal system. Incidences on the hydroclimate. Hydrobiologia, 94: 105-120.

Durand, J.R. and J.M. Chantraine, 1982. Climatic environment of the lagoons of Côte d'Ivoire. Rev. Hydro. Trop., 15: 85-113.

Figueiredo, J.D.S., R.W. Duck., T.S. Hopkins and M. Rodrigues, 2002. Evaluation of the nutrient inputs to a coastal lagoon: The case of the Ria de Aveiro, Portugal. Hydrobiologia, 475-476: 379-385.

Lamptey, E. and A.K. Armah, 2008. Factors affecting macrobenthic fauna in a tropical hypersaline coastal lagoon in Ghana, West Africa. Esturaies Coasts, 31: 1006-1019.

Marcovecchio, J., H. Freije, S.D. Marco, A. Gavio and L. Ferrer *et al*., 2005. Seasonality of hydrographic variables in a coastal lagoon: Mar Chiquita, Argentina. Aq. Conservation: Mar. Freshwater Ecosyst., 16: 335-347.

Metongo, B.S., 1989. Seasonal evolution of phosphates and the dissolved mineral compounds of nitrogen in Aby lagoon (Côte d'Ivoire). Doctor Sci. Center Rech. Oceanogr., 16: 29-45.

Nixon, S., B. Buckley, S. Granger and J. Bintz, 2001. Responses of very shallow marine ecosystems to nutrient enrichment. Hum. Ecol. Risk Assess., 7: 1457-1481.

Pereira P., H. De Pablo, C. Vale, V. Franco and M. Nogueira, 2008. Spatial and seasonal variation of water quality in an impacted coastal lagoon (Óbidos Lagoon, Portugal). Environ. Monitor. Assess.

Powlson, D.S., T.M. Addiscott, N. Benjamin, K.G. Cassman, T.M.D. Kok and V. Grinsven, 2008. When does nitrate become a risk for humans? J. Environ. Qual., 37: 291-295.

Ramade, F., 1995. Elements of Ecology-Ecology Applied Human Action on the Biosphere. 5th Edn., Ediscience international, Paris.

Simpson, J.H., R. Vennel and A.J. Souza, 2001. The salt fluxes in a tidally-energetic estuary. Estuarine, Coastal Shelf Sci., 52: 131-142.

Sylaios, G. and V. Theocharis, 2002. Hydrology and nutrient enrichment at two coastal lagoon systems in Northern Greece. Water Res. Manage., 16: 171-196.

Sylaios, G.K., V.A. Tsihrintzis, C.H. Akratos and K. Haralambidou, 2004. Monitoring and analysis of water, salt and nutrient fluxes at the mouth of a lagoon. Water Air Soil Pollution: Focus, 4: 111-125.

Uncles, R.J. and R.E. Lewis, 2001. The transport of fresh water from river to coastal zone through a temperate estuary. J. Sea Res., 46: 161-175.