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Pollutants dispersion in tropical coastal lake based on numerical modeling approach: A case study of Nokoué Lake in the republic of Benin

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Abstract

In the frame of the fluxes study in the Nokoué Lake, a numerical model for pollutant dispersion was then developed. It is coupled with a hydrodynamic model. This paper aims mainly to show the evidence of pollutant concentration evolution in the lake Nokoué under the influence of tides, flows and winds. The three dimensional (vertical, horizontal and transversal) structure of general circulation in the coastal lake is showed by a smooth mesh. This work has been carried out using the MIKE 21 for hydrodynamics and MIKE 3 coupled with MIKE 21 for dispersion study both developed by Danish Hydraulics Institute (DHI). The numerical modeling and simulations were performed using field measurements data and the results for critical scenario are presented in the paper. Different simulations have been one by varying flow and winds. The present study discusses a water quality model coupled with a hydrodynamic and advection-dispersion model to describe the important physical, chemical and biological processes. The hydrodynamic and advection-dispersion model simulates the flow forcing, transport, mixing and dispersion of water quality. The results clearly show that the phenomenon of pollutant dispersion in the lake which occurs from lower layer to upper layer by mixing because of tides, flow and winds. The performance of the model is encouraging and shows that it is reliable tool for better assessing environmental monitoring but requires the availability of more data to improve the calibration of the model for better assessing environmental pollution impact on Nokoué Lake.

Keywords: water quality, pollution, Mike model, Lake, dispersion

1 INTRODUCTION

The mathematical modeling of spatio-temporal evolution of "river-type" systems has an important role in predicting the behaviour of these systems. Knowing the concentration of the pollutant field distribution in time and space contributes significantly to the prediction of exceptional phenomena [1]. A coastal lagoon is a distinct dynamic environment where interplay of different energy forces from land-sea- atmosphere operates in a shallow body of water which is partly enclosed by a barrier and has restricted or ephemeral communication with the sea through one or more inlets [2]. They serve as buffer zones for nutrients storage and fluxes coming from adjacent continental drainage to the marine environment. These shallow water bodies, formed by a mixture of brackish and sea water consists of a main basin with a parallel to the coast orientation, being separated partially from the adjacent sea by sand bars formed at their mouths [3]. They serve as buffer zones for nutrient storage and fluxes coming from adjacent continental drainage to the marine environment. They are characterized by a high spatial and temporal heterogeneity. Several forcing mechanisms such as wind, pressure, astronomical tide and fluvial discharges of the lagoon can function simultaneously in the lagoon. The water circulation within a coastal lagoon is mostly characterized by low tidal oscillations, on which residual water circulations are superimposed. These may be generated by the non-linear interactions, density gradients, wind stress and the mass input due to fresh water discharges into the system [4]. Instantaneous and residual currents and fluxes through the lagoon mouth boundary can produces drastic changes in the balance of ecological processes and alter the fluctuations of the physical and chemical characteristics that are the basis of high productivity in a coastal lagoon [5]. Water fluxes control the flushing of the coastal lagoon, thereby maintaining water quality, and provide a mechanism for planktonic inward/outward transport. Salt fluxes determine the estuarine characteristics of the lagoon and define floral and faunal community structure and the spatial distribution of fish.

Pollutants dispersion processes are often encountered when a quantity of pollutant water is discharged into the natural environment, in a controlled or uncontrolled regime. By introducing a pollutant in an aquatic environment, its polyphone constituents are dispersed through the whole volume of water. The discharged constituents enhance the aqueous environment with nutrients and organic substances, which are decaying and change the natural characteristics of the environment and make it unsuitable for any use [6]. The effectiveness of the dispersion of pollutants quickly reduces the concentration around the vicinity of sources and can considerably vary under the natural conditions [7]. The fundamental intent of

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wastewater disposal is to mix the effluent thoroughly with large volumes of ambient water. If the ocean is stratified then the diluted pollutant may reach an equilibrium level below the surface of the ocean and the ocean currents transport the effluent, it is further diluted by the surrounding turbulence [8]. The Nokoué Lake is classified hyper-trophic [9]. So all kinds of pollutants are pouring and had studied the future of pollutants because a fiew scientific work has focused on pollutants future studied in the study area.

2-Material and Methods

Nokoué Lake is located in southern Benin, in West Africa, between 6 °25 'N and 2°36 E. It is located in the sub-equatorial area with two rainy seasons and two dry seasons of unequal durations. The mean annual rainfall is 1309 mm, the average temperature of 27.7° C with the maxima up to 33° C and minimum at 23 ° C. It covers an area of 150 km2 and is the largest lake of the country. This lake is connected to Porto-Novo's lagoon at the East by the Totchè Canal, in the south by the Atlantic Ocean through the channel of Cotonou, and at north by the river Sô and Ouémé stream on which it depends [10]. The connection with the surrounding water bodies, together with the impact of natural flood of Sô and Ouémé rivers, causes very significant seasonal variations of salinity which is parameter of that the variations during the year are the most important [11]. The lake could be considered shallow ranging from 0.4 m to 3.4 m Depths

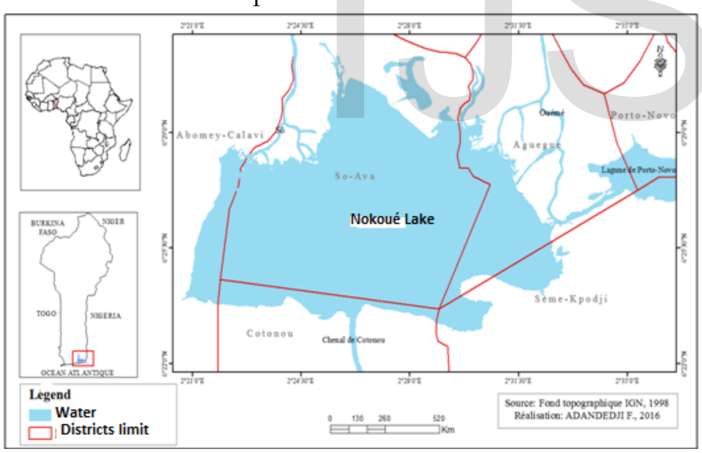

Fig 1. Location of Nokoué Lake

The general equation of advection- dispersion is considered: ([12].; [13].)

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}(uC)+\frac{\partial}{\partial x}(vC)+\frac{\partial}{\partial x}(wC)=\frac{\partial}{\partial x}(\varepsilon x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\varepsilon y\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(\varepsilon z\frac{\partial C}{\partial z})+Dm(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial y^2})+S(x,y,z,t)$$

Eq. 1

Where $\varepsilon x, \varepsilon y, \varepsilon z$ are longitudinal, transversal and vertical dispersion coefficients; u, v and w are velocity component; Dm is diffusivity (m^2/s); C is pollutant concentration (mg.L-1) and S is pollutant source. A complete solution of this equation, where the equations of motion and continuity must be attached, is impossible to obtain because of the dependence of dispersion coefficients on the flow regime, the nature, form and size of dispersed particles. Because of this, a simplified model was applied. To simplify the equation the orthogonal Cartesian system Oxy is considered and the dispersion equation becomes:

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}(uC)+\frac{\partial}{\partial x}(vC)=\frac{\partial}{\partial x}(\varepsilon x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\varepsilon y\frac{\partial C}{\partial y})$$

Eq. 2

([14])

2.1. Sampling and experimental set-up

In situ, monitoring of physiochemical parameters and major nutrients (NO_3^- $NH4^+$, PO_4^{3-}) were undertaken for the surface water body. For laboratory analysis, water samples were collected at 0.5 m depth under low flow condition. Van-Dorn water samples were deployed to collect samples. Water samples were stored in 1.5L bottles and immediately preserved in an ice-box after carried to laboratory for nutrient analysis. During analysis of nutrient concentration, water samples were filtered by using 0.45 µm glass fiber filter paper to minimize the changes of nutrient content due to biological activity. The ascorbic acid and Nesslerization methods were used to determine phosphate and ammonia respectively. A DR 2800 spectrophotometer was used for estimating nutrient the concentration in water.

2.3. Modelling

The hydrodynamics and water quality of the lagoon was investigated with the aid of DHI's Mike 21 model. It is one of the proven models available worldwide to simulate water environment such as oceans, coasts and estuaries. The hydrodynamic (HD) module is the basic computational component to simulate hydrodynamics and ECO Lab simulates ecological parameters coupled offline with the forcing parameters generated in HD module.

2.4. Hydrodynamic model

The HD module simulates water level variations and flows in response to a variety of forcing functions in lagoons, estuaries and coastal regions. The HD module calculates the resulting flow and distribution of salt and temperature subjected to a variety of forcing, sources and boundary conditions. The model is based on the solution of the two- dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure [15]. The governing equations of the model consist of continuity equation and horizontal momentum equations. In the present study the values considered for drying depth hdry = 0.005m, flooding depth hflood=0.05m and wetting depth hwet=0.1m which obeys the rule hdry<hflood<hwet.

2.4.1. MIKE 21 modelling

For the simulation process, the hydrodynamic and Ecolab modules of MIKE 21 numerical model were used. The MIKE 21 is a two dimensional mathematical models which can be used to simulate water flow, waves, water quality and sedi-

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ment. Ecolab can be used for water quality simulation, forecast of water quality, water environment impact assessment, restoration of water environment and water environment planning. The hydrodynamic model coupled with water quality software was used to simulate the current situation at study area. This hydrodynamic module calculated the hydrodynamic behavior of water in response to variety forcing functions, while the Ecolab modules described the chemical, biological and ecological responses and interactions between the stated variables. The local continuity conservation of mass Equation is written as:

$$\frac{\partial A_x}{\partial t} + \frac{\partial Q}{\partial x} = q \quad \textbf{Eq. 3}$$

The St. Venant for momentum and how the simpler forms may be derived by dropping terms are shown as follows. Equations show local advective pressure gravity friction acceleration force.

$$\frac{\partial Q}{\partial t} + \partial \frac{\frac{\partial Q^2}{A}}{\partial x} gA(S_0 - S_f) = 0 \quad \textbf{Eq. 4}$$

$$\frac{\partial Q}{\partial t} = gA(S_0 - S_f) - gA\frac{\partial y}{\partial x} - \partial(\frac{\frac{\partial Q^2}{A}}{\partial x}) \quad \textbf{Eq. 5}$$

where, A is the wetted area (or reach volume per unit length), t is the time, Q is the discharge, x is the distance downstream, q is the lateral inflow per unit length, g is the acceleration due to gravity, y is the depth, a is a momentum coefficient, S0 is the bed slope and Sf is the friction slope.

2.4.2. Domain meshing

An unstructured finite-element model domain having 15229 elements with 8099 nodes was prepared covering the major islands including artificial islands and both inlets. The measured bathymetry conducted during April 2014 was used for modeling the domain (Fig 2). The domain was discredited by the subdivision of the continuum into non-overlapping elements/cells. The resolution of the mesh, combined with the water depths and chosen time-step governs the Courant numbers (restricted to 0.8) in a model set-up. As a result of this, the effect on simulation time of a fine resolution at deep water can be relatively high compared to a high resolution at shallow water. Simulations were made for 5th May 2015, to 8th May, 2015, with a 30s time interval (5760 time steps). An approximate Riemann solver is used for convective fluxes, which makes it possible to handle the discontinuous solutions. For the time integration a Runge Kutta 4th order was used. Due to the stability restriction an explicit scheme selected for the time step interval to keep the Courant-Friendrich-Levy (CFL) number is less than 1. The horizontal eddy viscosity was determined through the Smagorinsky concept, while for the vertical direction, eddy viscosity was determined from a one-dimensional k–ε model. Initial and boundary conditions were given from measurements. Tides from Lomé, Lagos and Cotonou were used as boundaries. Wind forcing was used from the observation of METEO STATION at Cotonou as varying in time and constant in domain.

The method used to determine the dispersion area was based on mathematical and numerical simulations. The method used for this work began with the construction of the model made by the means of the bathymetric data collected in April, 2014 on transects with a resolution of 1500m. These data permit building the hydrodynamic model (MIKE 21 HD). To supplement the bathymetric data a Digital Elevation Model (DEM) with a resolution of 30 meter is used for area subject to inundation during floods. The considered forcing are the wind and the river flows upstream to Bonou. Also tides data are collected by field measurements. The MIKE 3 model was coupled with Mike 21 hydrodynamics model (HD) to simulate under the forcing the future of chemical pollutants in the Lake Nokoué. The 3D meshing was built from the same bathymetry data. It was limited to the sea, to the lake and to the lagoon (Fig 2).

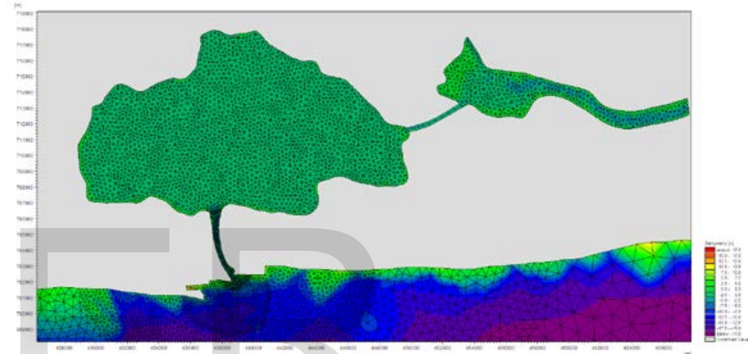


Fig 2: 3D model mesh generated in MIKE simulation tool

The tidal forcing at the eastern and western boundaries of the coarse grid model is used to drive the circulation within the fine grid model. The surface elevations at the eastern boundary (Lagos) and the western boundary (Lomé), are taken from tidal measurements observed for a period of 18 days. The same has formed as the boundary conditions for the HD simulations. The observed tides at Lomé, Lagos and Cotonou used as boundary conditions of HD model are presented in Fig. 3a, 3b and 3c, which shows that the tidal range of the area.

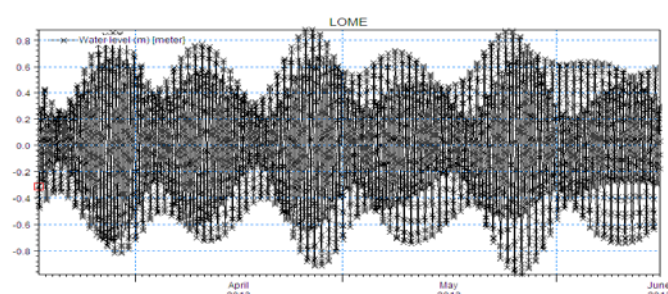


Fig 3a: Observed tide at Lomé

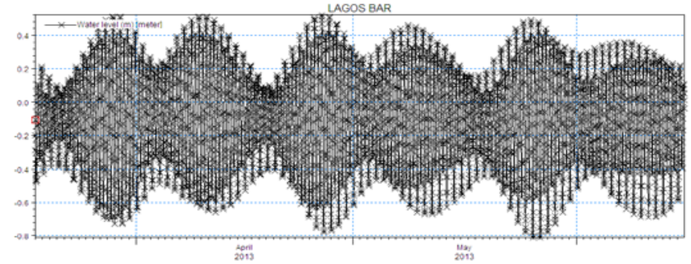


Figure 3b: Observed tide at Lagos

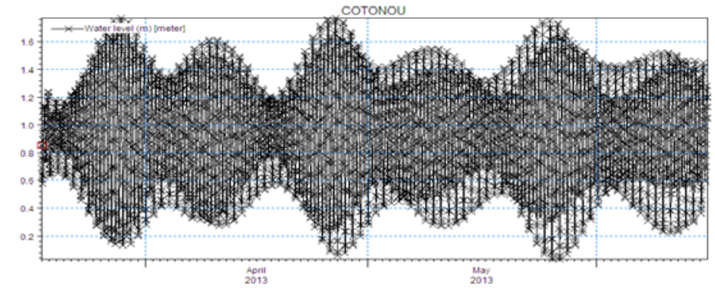


Figure 3c: Observed tide at Cotonou

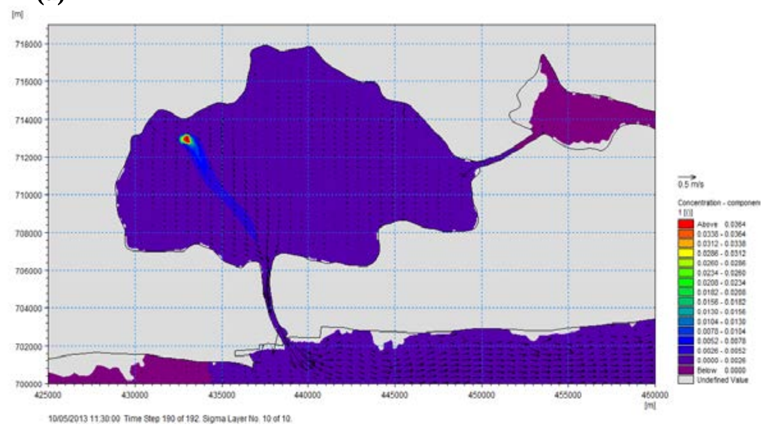
2.5. Water quality Model Set up

ECO Lab module in Mike 21 is being used for water quality modelling which solves the set of differential equations describing the physical, chemical and biological interactions involved in the degradation of organic matter, resulting oxygen conditions and excess levels of nutrients in Nokoué lake waters. In this study, five water quality variables DO, Ammonia, Nitrite, Nitrate and Phosphate were considered. Initial values for the state variable estimated from measurements data. The forcings like Temperature (temp, degree C), Salinity (sali, PSU), Water depth actual layer (meter), Wind speed (m/s) and Horizontal current speed (vsp, m/s) were input from the field observation and have been transferred from hydrodynamic model to EcoLab processing in Mike 21 [16]. There were 39 constants, 9 auxiliary variables and 21 processes, used as arguments in the differential equations that ECO Lab solves to determine the state of the state variables were included. The water quality model solves the system of differential equations that describes the chemical and biological states of the coastal waters. The Runge Kutta 4[th] Integration Method was considered for solving of the ECO Lab's differential equations. In this study, the simulations were carried out for duration of 48 hours in each case, out of which the model is allowed to warm up (stabilize) for the initial 12 hours and the results for the subsequent 48 hours were used for further analysis. The result of these simulations is formed the hydrodynamic basis for the subsequent dispersion modeling to study, the movement of the released pollutants.

3-Model Results

At first we modeled the behavior of conservative discharges and non-conservative discharges for several sources of pollution pre-identified in the Lake Nokoué. The simulations were realized by considering a discharge at Ganvié and a discharge at Cotonou, with a flow of identical pollutant, so as to compare the influence of the current on the behavior of the tracer. The contributions of rivers were taken as 500 m^3 /s (5 * 100 m^3/s) and as 1100 m^3 /s (3*200 m^3 /s + 2* 250 m^3/s). The effect of the South-West wind was also tested. The following figures show the results of the relative concentration of the tracer on surface and near the bottom. The currents are different according to the conditions of rivers flows and wind, and thus the behavior of pollutants. The numerical simulation results of a pollutant at Cotonou are shown in figure 4

(a)



(b)

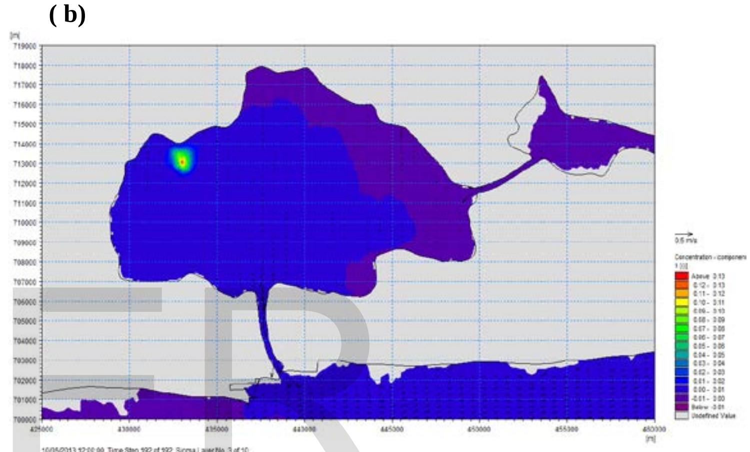
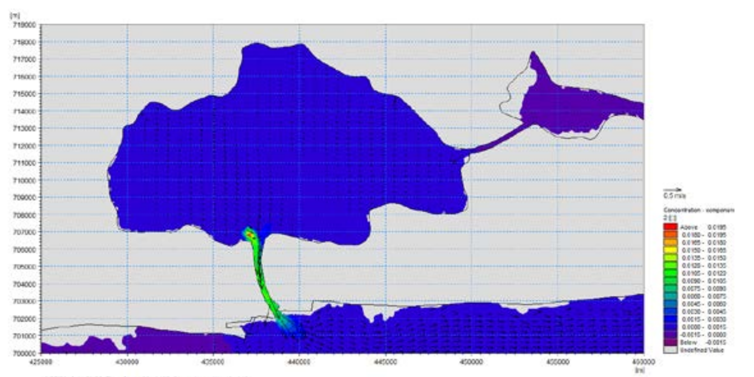
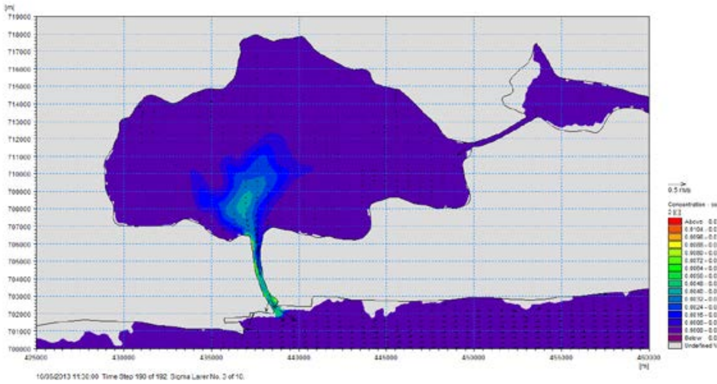


Fig 4. Flow 500 m^3/s Without wind. Relative concentration of a conservative tracer released at Ganvié, at surface (a) and bottom (b)



(c)



(d)

Fig 5. Flow 500 m^3/s – with wind South-west (5m/s). Relative concentration of a conservative tracer released at surface (c) and bottom

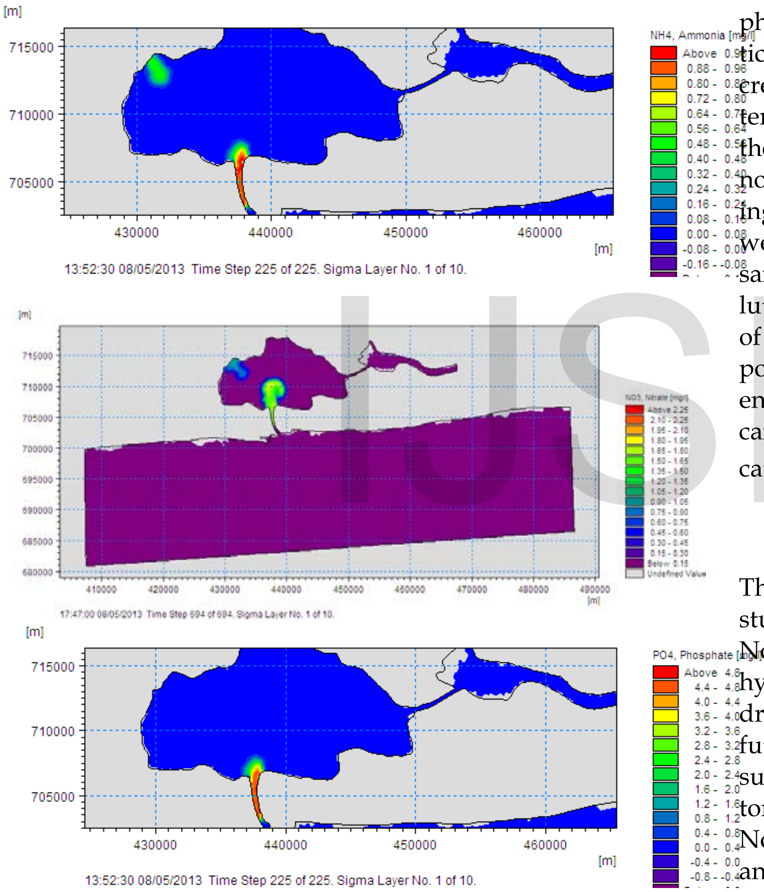


Fig 6. Concentration of nutrient as a pollutant released at Ganvié and Cotonou channel. Flow: 500m^3/s winds: 5m/s

4. Discussion

The results of this numerical modeling show the effect of the currents and the wind on the pollutants transport in Nokoué Lake. Indeed at Ganvié, the plume stretches on the surface preferentially towards the channel of Cotonou, in particular if the river flow is strong. Excepted locally, the dilution is rather fast because it is more than 95 % in the plume. By South-West wind, the plume of pollution extends eastward by staying along the north of the lake. At the bottom, the plume is less diluted because of the lower currents, and it tends to stay in the zone of Ganvié. At Cotonou, the interaction with tidal flow in the channel is strong. The plume tends to go out on surface and to go towards the center of the lake at the bottom, properly open sea and more saline ocean water flowing along the bottom towards the lake. The South-Western wind pushes the pollution at the bottom westward. These results are in agreement to those of Wang [17] and Ioana and al [14] who showed that hydrological conditions (flow) and meteorological are the main factors influencing the dispersion of pollutant in rivers and lakes. For Holzbecher [18]. and Chanson [19]., when a source of pollution is transfused into the river, due to molecular motion, turbulence, and non-uniform velocity in cross section of flow, it quickly spreads and covers all around the cross section and moves along the river with the flow. The results of the figure 6 show the future of ammonia, nitrate and phosphate, released in the lake. Addition of nutrients to aquatic environments, like streams, reservoirs and lakes, may increase plant growth rate [20]. We noticed that when they entered the Nokoué Lake, because of the tides at Cotonou and the current in the lake, they move from the channel of Cotonou to the center of the Lake but because of the current coming from Sô river the pollutants seems to change direction and were not well spreaded. According to Belcaid [21], the unsuffisant spreading of pollutants at estuary area lead to severe pollution. This can cause the death of aquatic organisms because of long term exposure. Ani and al [22]. demonstrated that as pollutant will be transported, faster dilution can help reducing environmental damages because sometimes flora and fauna can handle short exposure to large concentration, but die because of long exposure to medium and low concentration.

5. Conclusion

The pollution of surface water is worldwide problem. In this study, the objective was to know the future of pollutants in the Nokoué Lake, the biggest in Republic of Benin. The Mike 21 hydrodynamics model and Mike 3 developed by Danish Hydraulics Institute (DHI) were implemented to investigate the future of the pollutants under flows, tides and winds. The results leas to conclusion that winds, flow and tides are key factors that governs the pathways and pollutants spreading in Nokoué Lake. The numerical setup model of DHI can hence be an excellent tool to provide further information in decision making for pollution monitoring in Nokoué Lake. It can also act as an excellent tool to simulate water quality and prediction of futuristic scenarios.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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