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# Characterization of the hydrosedimentary dynamics of the estuary of Ouémé River in Cotonou, Benin.

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**Abstract**— The present paper aims to characterize the hydrosedimentary dynamics of the estuary of Cotonou, a small channel of the ouémé river. This channel is used as a link of communication between the NokoueLakeand the Atlantic Ocean. So, this channel is an estuary of Ouémé River which has been the focal point of all the hydraulic and hydrologic exchanges between the lake and the ocean. That channel, artificial estuary, was built in 1885 to evacuate the floods of Nokoué lake, and to restrict this exchange between the lake and the ocean. To limit that exchange, one dam was built on the estuary in 1979. The construction of that dam had created a lot of environmental problems and had provocatedachangement of the hydraulic boundary conditions of the channel.

The construction of the seaport of Cotonou, mainly the dam are the principal causes of the hydraulic changes which took place in the estuary. That dam is particularly responsible for the trapping of majority of the sediments discharged into the lagoon of cotonou by the Nokoué lake.

This characterization of hydrosedimentary dynamics is based on the Shields parameter and the reading of the so-called Huljström diagram, on one part, and using the geometrical model established, depending of the bathymetry of the estuary, a modelization which leads to a better appreciation of the evolution of the sediments in the river.

**Index Terms**—estuary; hydro-sedimentary dynamics; dam; trapping; Shields Parameter;modelization; Shallow water equations.



## *Nomenclature:*

U : Medium Velocity
$\rho$ : Water Density
$\vartheta$ : Kinematic Viscosity
$\gamma$ : Specific weight
P : Pressure
g : gravity
$P_0$ : constant pressure on the free surface
Z : vertical axis
H : water height
Q : Fluid flow
$\tau$: Shear stress
$R_h$ : hydraulicradius
S : inclination index
D : Diameter of grains
$\rho_s$: Density of grains
$u^*$ : Friction Velocity
$u_c^*$ : Critical Friction Velocity
$\theta_s$ : Parameter of Shields
$R^*$ : Reynolds Number
$\theta_{cr}$ : Critical Parameter of Shields
$d^*$:Adimensional Diameter
$\Delta$: Relativedensity of grains
$D_{50}$ : Median diameter
$D_m$ : Medium Diameter
$W_s$ :Velocity of fallen grains

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$L_k$: width of glassywater
$l_k$: width on top
$y_k$;:draught
C : Global Coefficient of Chézy
C′ : Relative Coefficient of Chézyof grains
K : Coefficient of roughness
$\mu$ : Coefficient of wrinkles

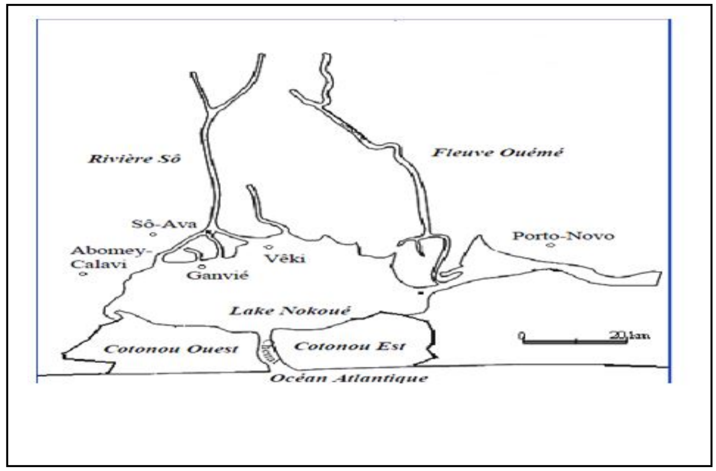
## 1 INTRODUCTION

This paper is initiated to analyze the hydrosedimentary dynamics of the lagoon of Cotonou, estuary of the Ouémé river. In Benin, the lagoon of Cotonou is a small channel 1.5 km long, 300m wide and 5m to 10m deep, where continental waters are in contact with the oceanic salt waters. It was built in 1885, to get access to the Atlantic Ocean and to be the outlet for annual floods of Nokoué Lake. Since its opening, it is the place where estuary dynamics is taking place. It occupied a big part of the so-called the Nokoué River and Porto-Novo lagoon dynamic lagoon complex completed with the three bridges and the dam, all built on them.[1] [3] [9]

Since the construction of that dam, the estuary bottom geometrical dimensions models varies because of the opening of the channel on Atlantic ocean, and then partial studwork filling of the channel was registered.[2] Nowadays, that created environmental problems; as an example, the continental erosion on the site.[4]

After the analysisof the drillings and wells realized through the bed of the estuary, from the bottom to up at 20-25m, figure 1 , we remarked the presence of clay, fine sand, alluvium, medium sand to rough sand. That conglomerate is the bed of free aquifer of sweet water which is in equilibrium with oceanic water, so consequently the capacity for infiltration of rainwater is very limited. The interest of this study is to appreciate theoretically the erosion in the channel of Cotonou.


Map 2: Lagoon of Cotonou and its estuary (Google Map)




Map 1: Lake Nokoué

This estuary , confined channel, 5 km long where salt water and sweet water are in equilibrium, is affected by the presence of solids sediments from the continental erosion, which are the first component of sediments transported by the hydrographic system when rivers flows are able. This characteristic is named the capability to transport solid.
This capability of solid transport depend essentially of the undermining of the bottom of the river and the granularity and the granulometry of the sediments in one part.
In second part, the cohesion of solids is an important characteristic of the erosion and for the transport of the fine sediments too. It means that between $\tau_{co}$ the resistance to the erosion (critical Shear stress) and $\tau_b$ the flow erosive strength. If$\tau_b > \tau_{co}$ then there is erosion, but
If$\tau_b < \tau_{co}$, then, there is no erosion [11]. And the sediment deposit is possible if $\tau_b < \tau_{cd}$ ; where $\tau_{cd}$ is the critical deposit stress.

The theoretical aspect of the phenomenon of solid transport shows that, when the fine sediments are transported without touching the bottom of the lagoon , it is the case of suspension; but if the rough sediments are transported by rolling or sliding, then it is the case of overthrusting. The last case is the saltation.

The solid flow is defined as the total weight of solids transported by the stream through a section of the stream during a unity of time.

The main objective of this paper is in section1, to check up the channel, to simulate it and then analyze its hydro sedimentary dynamics through a mathematical bi-dimensional model. In section 2, we investigated the sediments granularity and its relationship with their fall velocity. In section 3, we present the mathematical model used, and then the obtained results of the model are presented

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and commented.

## 2 Position of the Problem

### 2.1 Context

Benin is a country in the West African sub-region which surrounded by 5 large basins. One of these basins is that of Ouémé and Yéwa. This basin contains the Ouémé River which is extended over more than 500 km². The Ouémé River receives its water from Okpara and Zou in Atakora and ends up splitting in two parts which are discarded in the lake Nokoué and in Porto-Novo lagoon before joining the sea.

Thelagoon of Porto-Novoand the lake Nokoué, thereby, constitute the estuary of Ouémé River. The lake Nokoué leads its waters to the sea through the channel that connects them. This channel is a Lagoon of Cotonou. The lagoon of Cotonou has a length of 4.5 km and a width of 300m approximately. It was built during the colonial period, in order to connect the lake Nokoué to the sea, to evacuate the floods of the lake. This lagoon is therefore a small estuary of the lake Nokoué and is a center of exchange sea-lake. In order to limit this exchange, a dam has been built in 1979 on the lagoon of Cotonou but instead of solving the problems for which it has been built, it was created other no less serious ones.

This hydrosedimentary study will allow therefore to expose the problems linked to the lagoon of Cotonou. During this study we have to solve some questions which have been imposed. Some are as follows:

- What is the solid transport which governs the lagoon of Cotonou?
- What is the bathymetry of this lagoon?
- To what extent this solid transport will influence the minor bed of the lagoon?

**Picture 1: T**he Estuary of the Ouémé River in Cotonou

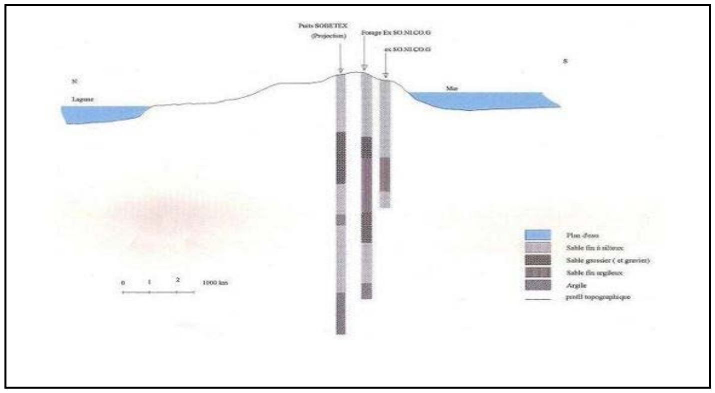


**Fig 1:** Geological cross-section of drillings in the bed of estuary in Cotonou [SERHAU-SA. 2004]

## 3 Collected Data

During the study, many kinds of dataes have been used; as hydrologic, hydraulic, topographic, bathymetric, geologic and geographic dataes. The hydrologic data has been collected to ASECNA. Other dataes have been collected directly from internet or from institutions which worked on the lake Nokoué : DG Eau, Institute of Research and Development (IRD) for example.

Whit those dataes we realized a graph which showed the variation of rainfall on the 50 last years (1964-2014); we determined the hottest years and had the most impressive rainfall and then we got the influence of hydrologic phenomena (precipitation, infiltration, percolation, evaporation, run-off…..) on the lagoon of Cotonou. Thus we knew the characteristic of layers of ground at the bottom of the lagoon and we formulated the hypotheses on the infiltration of water. To have samples of sand required for granulometric analysis, we got sample issue from dredging in the lagoon of Cotonou.

## 4 Sedimentary Behavior

The behavior of the sediments is varietal according to the types of sediments we got. Those are cohesive sediments or not cohesive sediments. The fine sediments are more cohesive than the rough sediments.

### 4.1 Erosion of Particles

The movement of the particles took place beyond a critical friction speed, the particles of a given granulometry lost their equilibrium and generated a non-zero movement. To determine the critical stress due to the movement of the particles, many approach methods exist [11].

Those different methods are based on:

- The average speed of flow, for example, the diagram Hjulström (1935) established for non-cohesive sediments, of homogeneous granulometry.

- The shear stress exerted by water on the river bed, for example the diagram of Shields (1936) established too for non-cohesive sediments.

### 4.2 Determination of the Limit Speed of Transport of Sediment

According to its speed, the water flow can have three distinct behaviors (Hjulström, 1935):

- the sedimentation : the particles are at rest and the current velocity is not strong enough to mobilize them

- the transport : the current velocity become high enough to start transporting of particles

- the erosion : the current velocity become strong enough to pull the average and large grains out of river bed

These three distinct behaviors are exposed in the following diagram so-called diagram de Hjulström.

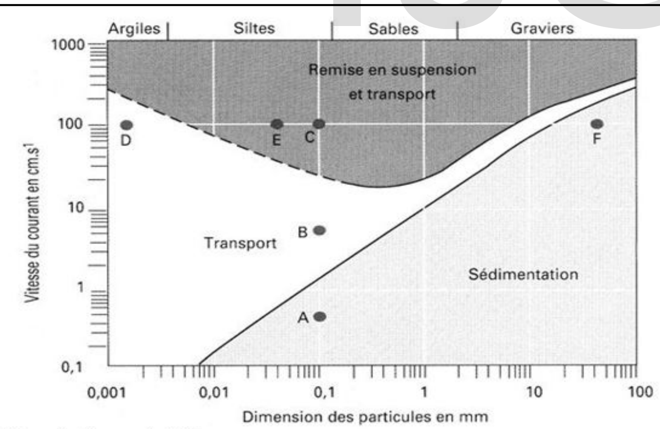


**Fig3:** Diagram de Huljström

The diagram of Huljström illustrates the various behaviors of particles according of the size of sediments and the current velocity of watercourses. For the strong speed, the particles are torn of the ground: it is the erosion of particles. We see in the upper part of diagram, that the clay needs very high speeds before eroding. Moreover, it can also be seen that the portion representing the erosion of medium to coarse particles (fine sand with pebbles) seems logical: the current velocity required to mobilize the grains increase with the particle size distribution. On the other hand, for the fine particles, the curve shows a current velocity increase with the reduction in particles size. This is due to its cohesive behavior but also to the fact that clay offers a smoother bottom in the bed of watercourses. The bottom part of the graph shows the relation between the particles size and the current velocity during the deposit[12].

### 4.3 Critical Stress and Shear Threshold

In order to understand the formulas which give the transport capacity as a function of the hydraulic quantities, it is important to know the different forces exerted on the particles at the bottom of the channel. The three main forces exerted on the watercourses are:

- The gravityacceleration
- The pressure
- The Shear stress

The shear stress is the parameter determining the movement mechanism in the bottom of the channel. It is also called a critical tension or a tangential stress and is noted $\tau$. The tractive force is expressed according to the relation:

$$\tau = \rho . g . R_h . S \qquad (1)$$

The shear stress can also be expressed in dimensionless form as a function of the particle size distribution. The relation is written:

$$\tau^* = \frac{\tau}{(\rho_s - \rho).g.D} \qquad (2)$$

We introduce the friction speed u* which is a measure of the shear effect on the bottom with :

$$u^* = \sqrt{\frac{\tau}{\rho}} (3)$$

Since 1936, the Shields approach remains, a reference in the field of sediment transport. From the channel measurement, Shields proposed a diagram showing the movement threshold of particles. This experimental curve of particle movement, has been stalled in the rectangular channel with flat bottom with mono dispersed pseudo-spherical particles. It should not be considered as an absolute criterion; however, it corresponds to a significative displacement of particles. It is therefore a threshold curve of tearing. In his experimentation, Shields has introduced the notion of Shields parameter$\theta_s$. This parameter establishes the ratio between the fluid friction force and force of

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submerged sediment weight. The parameter $\theta_s$ is given by the relation:

$$\theta_s = \frac{\tau_0}{(\rho_s - \rho) g d_{50}} \quad (4)$$

The movement threshold of particles ($\tau^*_{cr}$) is defined by a dimensionless quantity calling Reynolds number of sediment [12]:

$$R^* = \frac{U^*_{cr}.d}{v} \quad (5)$$

When the friction stress becomes critical, it is required to define the critical Shields number noted: $\theta_{cr}$.
The critical Shields number depends of the hydraulic conditions close to the bottom, of the particles size and of the position of each particle compared to others and is defined by:

$$\theta_{cr} = \frac{\tau_{cr}}{(\rho_s - \rho) g d} (6)$$

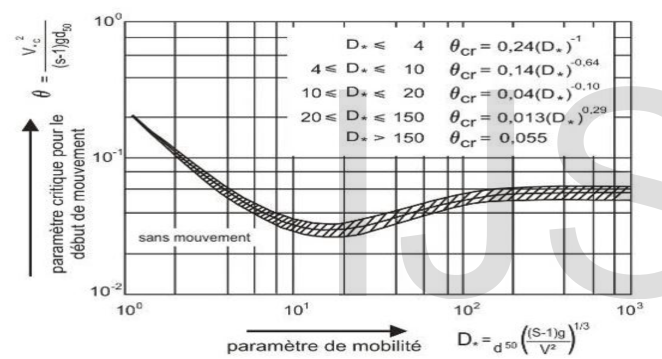
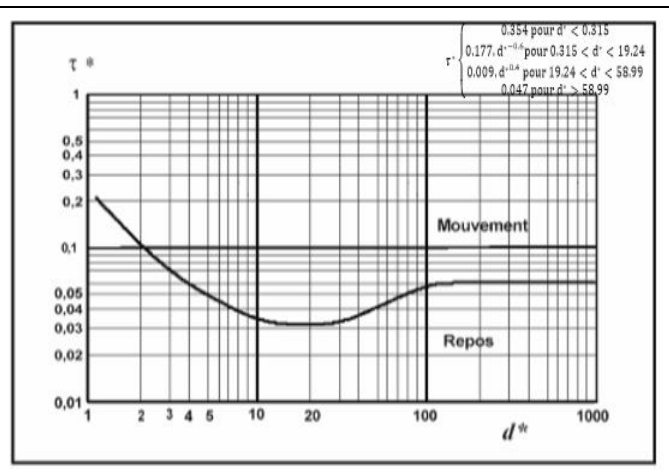



**Fig4:** Shields Curve

In order to facilitate the reading of the curve of Shields, Yalin has transformed in 1972 the Shields relation between $\tau^*$ and $d^*$with:

$$d^* = d\left(\frac{g.\Delta}{v^2}\right)^{1/3} \quad (7)$$

Where $\Delta = \frac{\rho_s - \rho}{\rho}$ is the relative density ofparticles.Above the critical value, the grains are in movement while underneath they are at rest.




In extended particle size, we can be tempted to apply a movement threshold of this type of grains taken separately. In so doing, we neglected the phenomenon of masking. It is preferable to use one of the specific methods to the extended particles size exposed below. Some authors, such as Julien (1998), have decomposed the curve of Shields in several straight line to simplify his quantification.

### 4.3 Movement Threshold

The diameter used for the calculation of shields parameter depends of the nature of particle size. When the particle size is uniform, the average diameter is a diameter used in the calculation of the shields parameter as follows:

$$\tau^* = \frac{\tau_0}{(\gamma_s - \gamma).g.d} \quad (8)$$

For extended particles size, these are the median diameters $d_{50}$ which will used to calculate the shields parameter:

$$\tau^* = \frac{\tau_0}{(\gamma_s - \gamma).g.d_{50}} \quad (9)$$

The movement threshold are such as:

- movement threshold: 0,027<τ∗<0,047 for uniform particle size distribution
- movement threshold: 0,088<τ∗<0,138 for extended particle size distribution

However, another practical and easy to use classification is proposed by Ramette in table form [13],

| For uniform particle size distribution | |
|---|---|
| τ∗<0,027 | The grains are at rest on a flat bottom |
| 0,027<τ∗<0,047 | Appearance of the very first movements, but not enough to generate a solid flow |
| 0,047<τ∗<0,062 | Carriage on flat Bottom |
| 0,062<τ∗<0,25 | Carriage by dunes |
| 0,25<τ∗<2,5 | Transport in suspension by dune |
| τ∗>2,5 | Transport in suspension in a flat bottom |

Table 1 : Movement threshold for uniform particle size distribution

| For extended particle size distribution | |
|---|---|
| <0,088 | There is no movement ; |
| 0,088<τ∗<0,138 | There is appearance of the very first movements but not enough to generate a solid flow |
| τ∗>0,138 | All of grains of the substrate feed the solid flow rate |

Table 2 : Movement threshold for extended particle size distribution

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### 4.4 Fall Velocity

The fall velocity results of balance between drag force and submerged weight. It is noted $W_s$ and can be calculate by the Stokes law:

$$W_s = \frac{(s-1)gD^2}{18\upsilon} \quad (10)$$

## 5 Results and Discussion

### 5.1 Size distribution of the particles of the sediments of the lagoon of Cotonou

The transport of sediments in estuary depends of the type of its constituant substances, results of the erosion and on the dimensions of the sediments components

. So, the granularity has an important function in the process of transport, and consequently has a relationship with the velocity of the sediments components; that is the raison of the importance of the granularity of sediments in this phenomenon.

The different type of soils havegenerally different classes of diameters and different granularity curves. After the analysis of the different types of the grains of the sediments of the estuary,in the national laboratory, CNERTP., we got the results of the granulometric analysis, wich are represented as down.

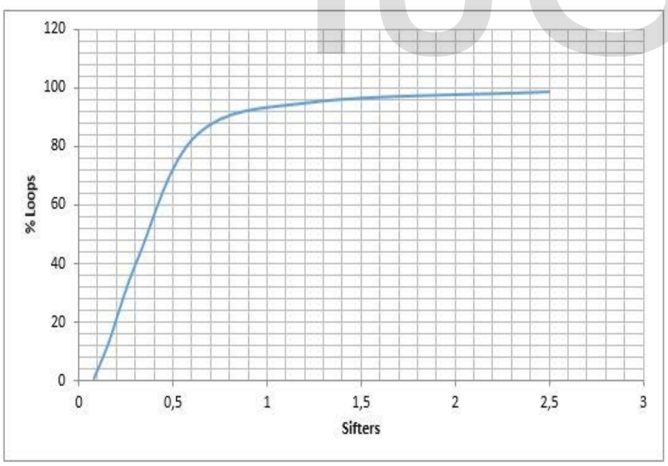


**Fig 6**:The results of granulometric analysis obtained on the sand of the estuary.

After the different granulometric analysis we experimented,the obtained results are the following sands:

For the clays and for another sediments derived from clays, the diameters are between 0.002 mm and 0,05mm; for the fine sands we got, their diameters of its grains are between 0.05mm and 2 mm; from the medium sand to the rough sand, the grains diameters are higher than 2mm.

The uniformity coefficient of the grains gave the opportunity to know the type de granularity of grains we got. itcan-calculated by the following expression:

$$Cu = \frac{D_{60}}{D_{10}} \quad (11)$$

Exploiting that expression we got the following result:

$$Cu = \frac{0.48}{0.14}$$

So $Cu = 3.43$

For the values of uniformity coefficients smaller than 3, we got the uniform granulation, while for the values bigger than 3, we have theextended granulation. In the case of lagoon of Cotonou, the uniformity coefficient Cu is equal to 3.43. So it proved that the type of granulation of the sand of the lagoon obtained is an extended granulation.

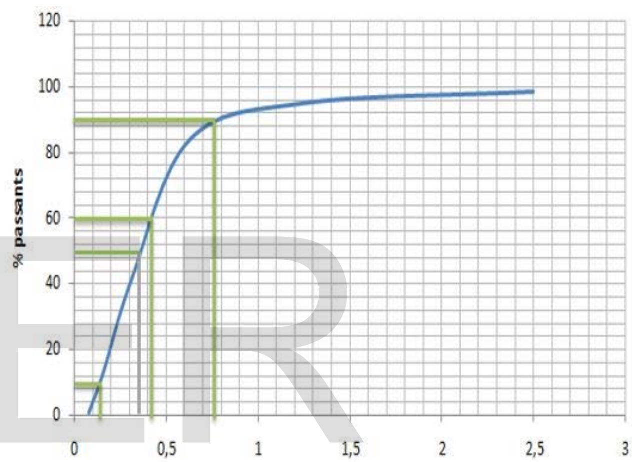


**Fig 7**: Determination of different diameters with the granulometric curve;

The different values of diameters, we calculated are shown in the following table.

Table 3 :**Calculation of theValues of different diameters**

| Diameters | $D_{10}$ | $D_{50}$ | $D_{60}$ | $D_{90}$ | D* |
|---|---|---|---|---|---|
| Values | 0.14 | 0.375 | 0.48 | 0.78 | 9.4828 |

### 5.2 Approach of the determination of the velocities of sediments in the Estuary

The fall velocity of sediments is an important parameter which governs the vertical repartition of suspended materials and the speed of the sedimentation during the period when the streams are low. This fall velocity helps to distinguish, in equilibrium state, the sediments. Velocities of flows in lagoon of Cotonou are in relations with Lake Nokoué and OuéméRiver. So it is necessary to know speeds of stream of lake Nokoué, if we want to appreciate flow velocities of lagoon of Cotonou. Theoritically, for this study, we didn't succeed to calculate velocities, we took into account the flows datafile of Ouémé river enregistrated the Bonou station, which is the nearest data enregistration station of the lagoon of Cotonou. The flows velocities used for this study, are between 1 and 3 m/s.

The variation of flows of the river Ouémé are shown on the following figure 9

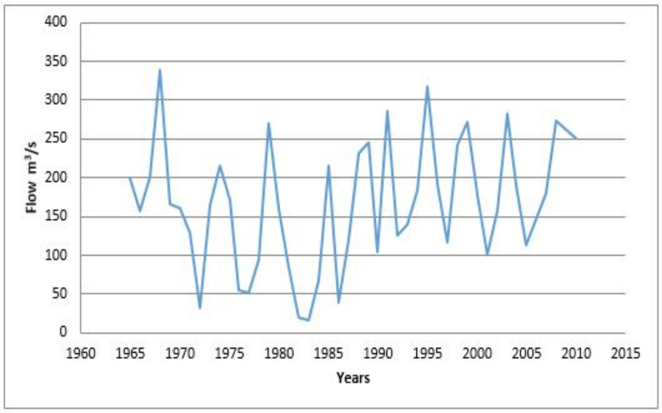


**Fig 8:**Variation of flows in Ouémé River at Bonou

## 5.3 Mouvementthreshold

To calculate the shear stress$\tau^*$, we will use the median diameter $D_{50}$ being given that the particles size distribution of Cotonou channel is extended.

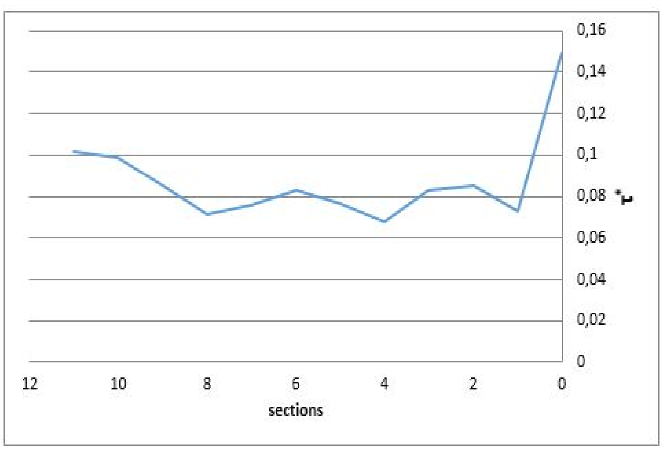


**Fig 9:**Variation of the dimensionless shear stress

The particles size distribution of the lagoon of Cotonou being extended, the movement threshold is $\tau^* = 0.138$. In most of the sections on the lagoon of Cotonou, we see that $\tau^*$< 0,138 (in sections 1 to 11).

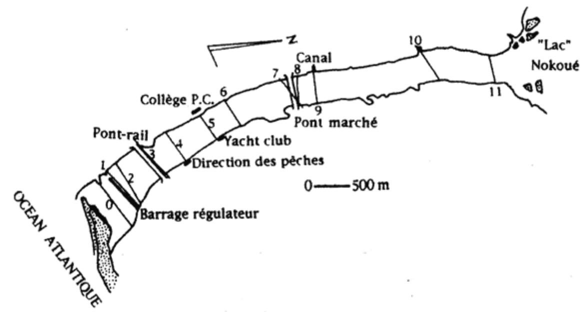


**Fig 10:**Position of the section in the lagoon of Cotonou

The only section for which the dimensionless shear stress $\tau^*$>0,138 (in section 0) which is between the regulatory dam and Atlantic Ocean.

Moreover, we noted in the section 10 and 11, an appearance of a so-called very first movements ($\tau^*$> 0.088) but those movements are not strong enough to generate a solid flow. On other hand, in the section 1 to section 9; there is no movement because the dimensionless shear stress$\tau^*$< 0.088.

## 5.4 Calculation of solid flow

### 5.4.1 Choice of the Model

The choice of the model of Van Rijn has been made according with the values contained in the table n °4. That is to say of the range of diameter, as well as the slope of the watercourse. In addition, the data available to us correspond perfectly to input data of the model of Van Rijn. The model of Van Rijn allows to calculate the carriedsolid flow of the watercourses.

The input data of model of van Rijn are: the average velocity, the median diameter, the diameter to 90% of passers-by, the gravity acceleration, the cinematic viscosity and the hydraulic radius. The calculation of volumetric solid flow by the method of Van Rijn goes through many intermediate calculations. We used the software Matlab to write a program calculating the solid flow by the model of Van Rijn. This program calculates:

-the dimensionless diameter,

-the friction force relative to grains,

-the critical friction velocity

-the volumetric friction flow

Before the calculation of the critical friction speed, the software of Van Rijn based on Matlab, chooses itself the coefficients $\alpha$ and β of the Shields curve according with the values of result of the calculation of dimensionless diameter.

This software based on Matlab is written as follows:

Procedure

```
%enter the values
%coeficient of gravity
g=9.8
% cinématic viscosity
v=0.000001
% medium velocity
u=input('enter the medium velocity u=')
% median diameter
d50=input('enter the median diameter  d50=')
%diameter for 90% de passants
d90=input('enter the diameter  for 90% passants d90=')
%hydraulic radius
R=input('enter the medium hydraulic radius R=')
%Relative Density
s=input('enter the relative density s=')
%calculation of the adimensionnal diameter Dstar
Ds=d50*(g*(s-1)/v.^2).^(1/3);
%calcuation of the grains friction strengh
us=sqrt(g)*u/(18*log(4*R/d90));
%choice of the coefficients a and b of the Shields curve
if Ds<4
   a=0.24
   b=-1
elseif Ds>4|Ds<10
   a=0.14
   b=-0.64
elseif Ds>10|Ds<20
   a=0.04
   b=-0.1
elseif Ds>20|Ds<150
   a=0.013
   b=0.29
else Ds==150
   a=0.055
   b=0
end
%calculation of the critical friction velocity
uc=sqrt(g*(s-1)*d50*(a*Ds.^b))
T=(us.^2-uc.^2)/(uc.^2);
%calculation of the volumicdébit of the solid in m²/s
qv=0,053*sqrt(g*(s-1)*d50.^3)*T.^2.1/(Ds.^0.3))
plot(qv,u)
```



### 5.4.2 Solid Flow

The volumetric solid flow (m³/s/m ou m²/s) has been calculated by the program Matlab thanks at model of Van Rijn considering that the speed in the channel of Cotonou is between 1 à 3 m/s. the figure 23 shows the evolution of the solid flow according to these speed. From the calculations we wrote a software with Matlab, we have plot a tendency curve of the power type with Microsoft Excel. which helped us to find an equation in function with the speed to the solid flow in the channel of Cotonou.

$$q_v = 2.10^{-06}\,u^4 - 3.10^{-06}\,u^4 + 4.10^{-06}\,u^4 - 5.10^{-06}\,u^4 + 3.10^{-06}$$

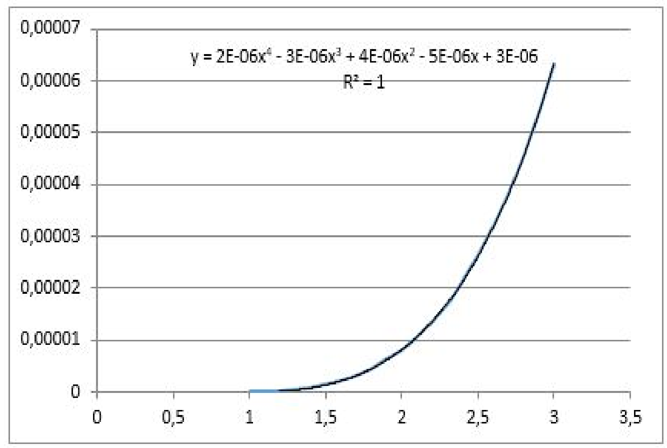


**Fig 11:Variation of volumetric solid flow in the channel of Cotonou according with the current velocity**

The sediments required to feed a solid flow of the lagoon of Cotonou are brought by the lake Nokoué and the erosion of river bank. The values in the table above represent the transport capacity of the channel without taking account of the availability of materials. To integrate the availability of the materials in our study, it is required to realize a study of solid flow in the lake Nokoué

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| Speed in $m^2/s$ | Volumetric solid flow | Solid flow in m3/s | Solid flow in kg /s | Solid flow in kg/an, |
|---|---|---|---|---|
| 1 | 2.4008E-11 | 1.2004E-07 | 3.18106E-06 | 100.3179082 |
| 1,1 | 0.00000003 | 0.00015 | 0.003975 | 125355.6 |
| 1,2 | 0.00000015 | 0.00075 | 0.019875 | 626778 |
| 1,3 | 0.00000037 | 0.00185 | 0.049025 | 1546052.4 |
| 1,4 | 0.00000075 | 0.00375 | 0.099375 | 3133890 |
| 1,5 | 0.00000129 | 0.00645 | 0.170925 | 5390290.8 |
| 1,6 | 0.00000205 | 0.01025 | 0.271625 | 8565966 |
| 1,7 | 0.00000307 | 0.01535 | 0.406775 | 12828056.4 |
| 1,8 | 0.00000438 | 0.0219 | 0.58035 | 18301917.6 |
| 1,9 | 0.0000063 | 0.0315 | 0.83475 | 26324676 |
| 2 | 0.00000807 | 0.04035 | 1.069275 | 33720656.4 |
| 2,1 | 0.00001056 | 0.0528 | 1.3992 | 44125171.2 |
| 2,2 | 0.00001355 | 0.06775 | 1.795375 | 56618946 |
| 2,3 | 0.00001709 | 0.08545 | 2.264425 | 71410906.8 |
| 2,4 | 0.00002125 | 0.10625 | 2.815625 | 88793550 |
| 2,5 | 0.0000261 | 0.1305 | 3.45825 | 109059372 |
| 2,6 | 0.0000317 | 0.1585 | 4.20025 | 132459084 |
| 2,7 | 0.00003812 | 0.1906 | 5.0509 | 159285182.4 |
| 2,8 | 0.00004545 | 0.22725 | 6.022125 | 189913734 |
| 2,9 | 0.00005377 | 0.26885 | 7.124525 | 224679020.4 |
| 3 | 0.00006314 | 0.3157 | 8.36605 | 263831752.8 |

Table 3 :Values of the solid flow according the average speed

## 6. Conclusion

The channel of Cotonou, since its digging in 1855, has undergone numerous modifications. These changes to the channel are essentially due to the edification of the three bridges, of the seaport and of the dam of Cotonou. In order to estimate the solid flow of that channel, we used the solid transport modeling of Van Rijn but this modeling don't take in account the suspended transport.

To take account the suspended transport, we need to evaluate the inputs of the channel of Cotonou, that's to say the solid flow in upstream of the channel

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