YURI JACQUES AGRA BEZERRA DA SILVA

INTERFERENCE OF HYDRAULIC ROUGHNESS GENERATED BY UNSUBMERGED VEGETATION ON SEDIMENT TRANSPORT IN CAPIBARIBE RIVER

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Dissertation presented to Rural Federal University of Pernambuco, as part of the demanding of Graduate Program in Soil Science to obtain the Master Degree.

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“Aprendi que os sonhos transformam a vida numa grande aventura. Eles não determinam o lugar aonde você vai chegar, mas produzem a força necessária para arrancá-lo do lugar em que você está.”

(Augusto Cury)

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DEDICATE

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A = watershed area;
α = total projected plant area per unit volume;
A_i = influence area of the vertical segment;
A_p = total area projected with plant;
B = bottom of the River;
BC = Box Coefficient;
C_D' = vegetation drag coefficient;
C_{Dv} = drag coefficient (dimensionless);
d = stem diameter;
D = distance between crosses sections;
D_l = leaf diameter;
d_{50} = median grain diameter;
F_D = vegetation resistance force;
Fr = Froud number;
f_v = vegetation friction factor;
g = gravitational acceleration;
h = flow depth;
K = constant of variable proportionality;
K_f = form coefficient;
L = length of the main watercourse;
L_x = equivalent width;
M = suspended sediment mass;
m = mass of sediment from bedload transport;
n = Manning's coefficient;
n' = Manning's coefficient due to grain roughness;
n'' = Manning's coefficient due to form roughness;
n_b = Manning coefficient for unsubmerged vegetation;
P_w = wetted perimeter;
Q = water discharge;
QB = bedload discharge;
Q_i = water discharge in each vertical segment;
Re = Reynolds number;
Re_{plant} = plant Reynolds number;
R_h = hydraulic radius;
R_v = vegetation Reynolds number;
r_v = vegetation-related hydraulic radius;
S = slope of the channel bottom;
s = stem spacing;
S_f = surface flow;
SSC = suspended sediment concentration;
$\overline{SSC}$ = average of suspended sediments concentration;
SSC_i = suspended sediment concentration at each vertical;
SSQ = suspended solid discharge;
S_w = water line slope;
T = temperature in degrees Celsius;
t_1 = minimum time of the suspended sediment sampling;
t_2 = sampling time of bedload transport;
V = average flow velocity;
V_i = average flow velocity in the sampled vertical segment;
Vol_{sample} = sample volume;
Vt = transit rate;
V_v = average pore velocity;
ν = kinematic viscosity of water;
w = width of nozzle (US BLH – 84);
α = relation between flow depth and vegetation thickness;
ρ = density of water;
λ = factor of vegetation density;
τ = shear stress;

LIST OF ABBREVIATIONS

ANA - Brazilian National Water Agency

CNPq - Brazilian National Council for Scientific and Technological

USDA - U.S. Department of Agriculture

PE – Pernambuco state

EWI - Equal Width Increment

PCA - Principal Component Analysis

HCA - Hierarchical Cluster Analysis

DH - Depth Hand

BLH - Bedload Hand

CPRH - State Agency of Environment

RMR - Metropolitan Region of Recife

SUDENE - Superintendence of Northeast Development

USGS - United State Geological Survey

LAMEPE - Meteorological Laboratory of Pernambuco

RESUMO

A vegetação desempenha um papel importante nos processos de transporte de sedimentos, sendo essencial melhorar o conhecimento sobre a interferência da vegetação emersa neste processo. Dessa maneira, o principal objetivo desta pesquisa foi avaliar a interferência da rugosidade hidráulica gerada pela vegetação emersa no transporte de sedimentos, com base na relação entre o coeficiente de arraste vegetal (C_D’) e o número de Reynolds da planta (Re_{planta}) do Rio Capibaribe. Campanhas de medição direta foram realizadas seguindo a metodologia de amostragem por igual incremento de largura (IIL), usando o amostrador US DH-48 para amostragem de sedimento em suspensão e o amostrador US BLH 84 para amostragem de sedimento de fundo. Foi avaliada a resistência gerada pela espécie *Echinodorus macrophyllus* por meio do coeficiente de arraste vegetal (C_D’) e da força de arraste vegetal (F_D), bem como a influência destes parâmetros no transporte de sedimentos da bacia hidrográfica do rio Capibaribe. Além disso, foram realizadas análise de componentes principais (ACP) e análise de agrupamento hierárquico (ACH) para escolher as variáveis mais importantes associadas ao transporte de sedimentos e classificar as treze campanhas de medição direta em grupos de acordo com a similaridade, respectivamente. O C_D’ atingiu um valor máximo igual a 11,13 m^{-1}, indicando a resistência hidráulica gerada pela *Echinodorus macrophyllus*. Os dois primeiros componentes extraídos tiveram autovalores iguais a 6,74 e 3,15, representando 90,03% da variância total explicada. A ACH revelou cinco grupos em que o segundo foi formado pelas campanhas de medição direta realizadas com vegetação emersa ao longo da seção transversal (C2, C4 e C6). Estas medições apresentaram os valores mais baixos, sobretudo para a tensão de cisalhamento e descarga sólida de fundo. O último grupo foi formado pelas campanhas de medição direta (C10, C11, C12 e C13), que reuniram principalmente os maiores valores para o raio hidráulico, vazão, descarga sólida de fundo e tensão de cisalhamento. Sendo assim, a análise multivariada foi considerada uma ferramenta adequada para avaliar a influência da vegetação emersa no transporte de sedimentos da bacia hidrográfica do rio Capibaribe.

Palavras-chave: coeficiente de arraste vegetal, análise de agrupamento hierárquico e análise de componentes principais.

ABSTRACT

The vegetation plays an important role on sediment transport processes, being essential to improve the knowledge regarding the unsubmerged vegetation interference in this process. Thus, the main aim of this research was to assess the hydraulic roughness interference generated by unsubmerged vegetation on sediment transport, based on relationship between vegetation drag coefficient (C_D') and Reynolds number of vegetation (Re_{plant}) from Capibaribe River. Direct measurements campaigns were carried out according to the equal-width-increment (EWI), using the US DH-48 sampler to suspended sediment sampling and US BLH 84 sampler to bedload sampling. It was evaluated the resistance generated by *Echinodorus macrophyllus* by means of the vegetation drag coefficient (C_D') and vegetation drag force (F_D) as well as the influence of these parameters on sediment transport of Capibaribe watershed. Furthermore, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were performed to choose the most important variables associated with the sediment transport and classify the thirteen direct measurement campaigns in groups according to the similarity, respectively. The C_D' reached a maximum value equal to 11.13 m^{-1}, indicating the hydraulic resistance generated by *Echinodorus macrophyllus.* The first two components extracted had eigenvalues equal to 6.74 and 3.15, accounting for the 90.03% of the total variance explained. The HCA revealed five clusters in which the second was formed by the direct measurement campaigns carried out with unsubmerged vegetation along the cross section (C2, C4 and C6). These measurements showed the lowest values, chiefly to the shear stress and bedload discharge. The last cluster was formed by the direct campaigns (C10, C11, C12 and C13) which mainly gathered the largest values of hydraulic radius, water discharge, bedload discharge and shear stress. As a result, the multivariate analysis was considered an adequate tool for evaluating the interference of unsubmerged vegetation on sediment transport of Capibaribe watershed.

Keywords: vegetation drag coefficient, hierarchical cluster analysis and principal component analysis.

1. LITERATURE REVIEW

1.1. Importance of sediment transport in watersheds

The sediment transport researches are way too important in several aspects. The sustainability of watersheds is strictly associated with sediment transport along their watercourses in which excessive sediment fluxes generated by extreme flows can destabilize River channels. As a result, provokes damages to property and also public structure, narrows down the quality of water as well as increases flooding problems (Frey and Church, 2011). Therefore, it is fundamental go into more depth for learning to deal with this complex scientific trouble.

In addition, comprehension regarding sediment transport in watersheds is useful for providing an adequate management of streams and reservoirs. Data on amount of sediment which has been transported by Rivers is essential in the planning of hydraulic structures, such as, dams and irrigations channels, as well as the features and amount of sediment transported from the drainage basins provides information to predict stream changes (Edwards and Glysson, 1999).

Several cities were originated on the banks of Rivers, mainly because water resources contribute to the development of the area under its influence. Recife is one of these cities which had the formation and expansion influenced by Capibaribe River, the major water resource of the city (Mayrinck, 2003). Moreover, this River has a historical and economic importance for Pernambuco state (Brazil), where has been developing activities associated with sugar-cane industry. In spite of the importance of Capibaribe River, responsible by the water supply of several cities, a portion localized in low Capibaribe – Recife was classified as polluted water. Furthermore, the estuary has been suffering due to anthropogenic activities (CPRH, 2006).

There are several problems related with sediment transport in watersheds. For instance: increases the cost of water treatment; modifies the size of channel; acts as a carrier of bacteria and viruses; increases the transport of pollutants, chiefly the cohesive sediment; narrows down the flow depth, damaging the sea transport and increasing the possibility of floods. On the other hand, there are not only damages but also benefits associated with sediment transport. For example: decreases the erosion action of water in River runoff; improves the quality of water due to reduction of some pollutants; allows the chemistry reactions on sediment surface; carries organic matter, improving the aquatic life for some microorganisms (Carvalho, 2008).

1.2. Suspended sediment and bedload transport

First of all, sediment transport in watersheds is classified into two groups, such as, suspended and bedload transport. Suspended sediment is a term applied to particles which are maintained suspended by the vertical component of velocity in turbulent flux while is transported by the horizontal component of velocity in the same flux. Furthermore, the suspended sediment transport is chiefly governed by the flow velocity, whilst the coarsest sediments might move only occasionally and remain at rest much of the time (Edwards and Glysson, 1999).

The objective of suspended sediment sampler is to acquire a representative sample of the water sediment mixture moving in the stream. It is essential to carry out an isokinetic and point-integrating suspended sediment sampling in which each vertical along the cross section presents two zones, sampled and unsampled (Figure 1). Furthermore, depending on velocity and flow turbulence the amount suspended sediment moving in the verticals may represent or not the large portion of the total suspended sediment (Edward and Glysson, 1999).

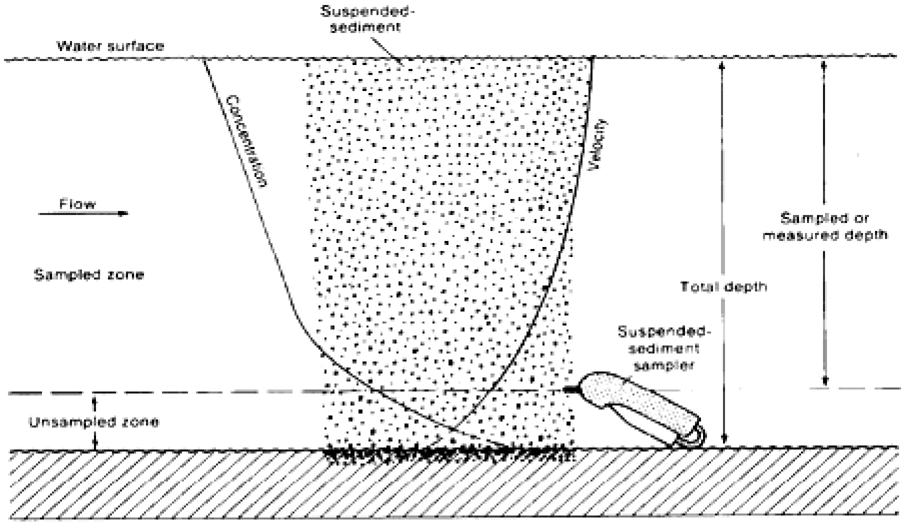

Figure 1. Sampled and unsampled zone of each vertical in Capibaribe watershed (Edwards and Glysson, 1999).

The lack of accuracy and frequency in suspended sediment concentration measurements are usually associated with mistakes in suspended sediment flux estimates, chiefly because a large share of annual suspended sediment is transported in short period of time, generally corresponding to a few flood events during the hydrological cycle (Meybeck et al., 2003). Thus, high intensity sampling associated with an adequate sampling is fundamental for evaluating the suspended sediment transport in watersheds.

All these details are essential because the suspended sediment concentration allows to calculate the suspended solid discharge, which in the most cases represents 95% of the total solid discharge, ranging in function of watercourse, flow velocity, flow depth, sediment grain-size, runoff type, cross section position and so on (Carvalho, 1994; Carvalho et al., 2000).

In contrast of the rating curve which relates the water discharge with the flow depth, the sediment rating curve can not be understood at the same way due to high variability and complexity associated with suspended sediment transport. In addition, it is possible to observe three situations in relation the peak of suspended sediment concentration and the peak of water discharge (Figure 2).

Therefore, if it is observed low flow on stream channel or short distance of transport from the point of erosion, the peak concentration of suspended sediment usually takes place at same time of the water discharge. Otherwise, the suspended sediment concentration can anticipate the peak of the water discharge. This idea is supported by the fact which the first direct runoff provoked by a high intensity rainfall results in more losses of soil particles because these particles are readily available for the motion. Finally, the peak of suspended sediment concentration may even lag far behind the peak of the flow if the fine material was originated far upstream or if the stream channel contains large volumes of water having low sediment concentrations before high intensity of runoff (Heidel, 1956).

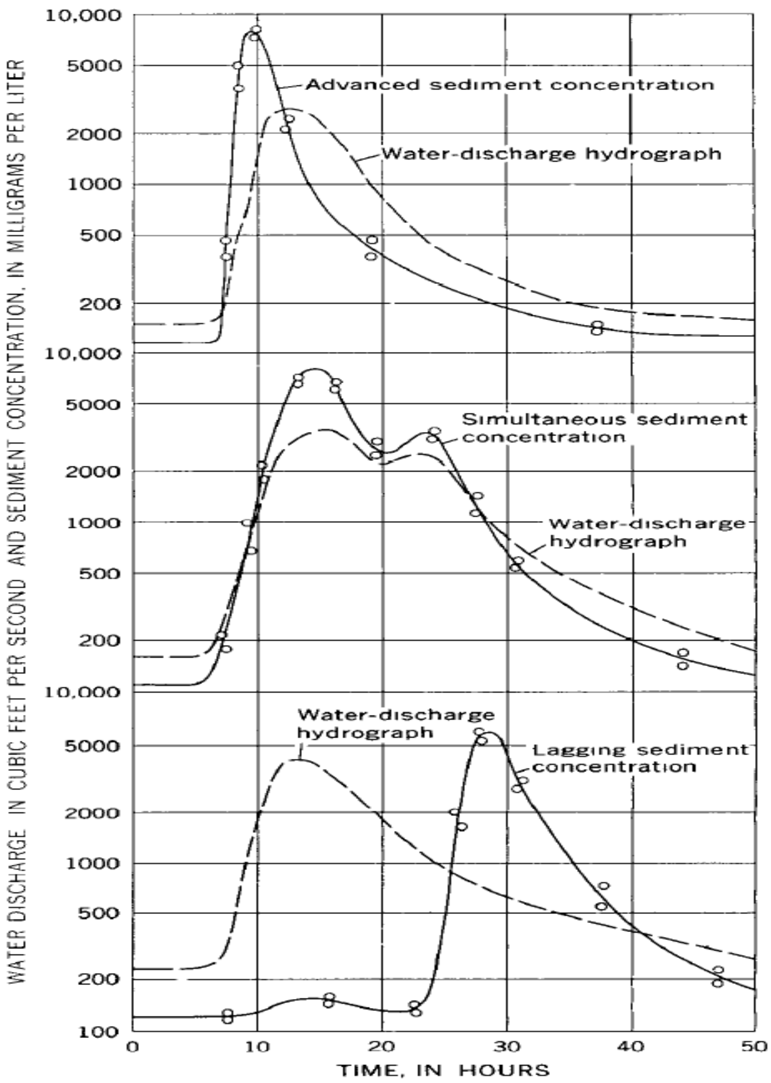

Figure 2. Advanced, simultaneous, and lagging sediment-concentration graphs as related to the temporal distribution of their respective water-discharge hydrographs, Heidel (1956).

The bedload moves near the streambed, on the contrary from suspended sediment which predominantly moves in suspension. It is ordinary to observe these particles moving rolling and sliding in contact with streambed as well as a third sort of motion known as saltation. Nevertheless, occurrences of high intensity flows maintain momentarily the bedload in suspension (Frey and Church, 2011).

Bedload transport usually ranges from 5 to 25% of suspended sediment transport (Yang, 1996). In addition, the movement of coarser sediments is controlled by selective transport capacity which indicates the concentration of different sizes of sediments in the cross section. In Figure 3 it is observed the selective transport capacity which influences the concentration of different sizes of sediments in the cross section, located in Missouri River at Kansas City (Guy, 1970).

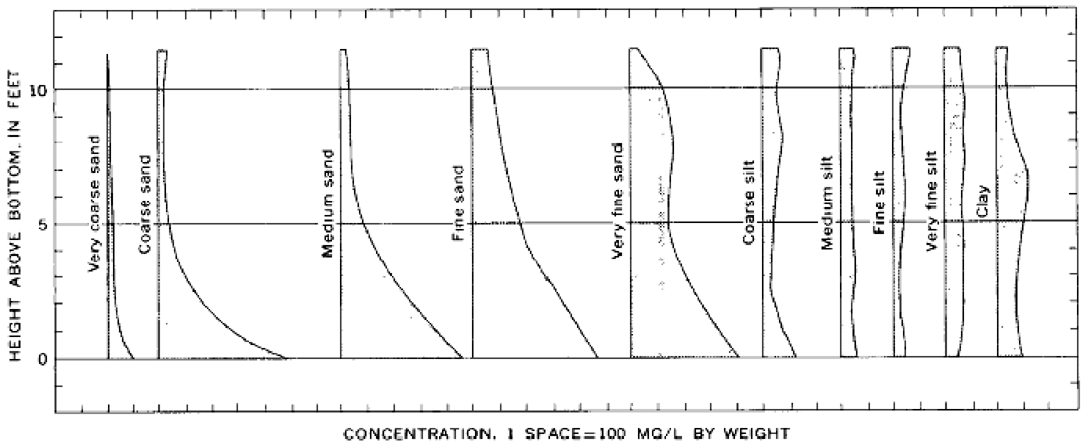

Figure 3. Discharge-weighted concentration of suspended sediment for different particle-size groups at a sampling vertical in the Missouri River at Kansas City.

1.3. Impact of vegetation on sediment transport

The vegetation plays an important role on sediment transport processes, affecting erosion, transport and also deposition in watersheds. First of all, the flow resistance in Rivers was previously associated predominantly with streambed roughness. However, current researches have shown which in vegetated cross sections the presence of vegetation is the main responsible by the largest amount of energy losses in Rivers (Nepf and Vivoni, 2000). Thereby, several researches have been carried out to quantify vegetation roughness, but it is essential associate the vegetation roughness with sediment transport.

The necessity of performing studies in watersheds regarding vegetation roughness generated by emergent or submerged vegetation are getting increasingly important, chiefly because the most studies for evaluating flow resistance in vegetated channels or the sediment transport have been developed and validated under flume conditions (Wu et al., 1999; Järvelä, 2002; Wang Chao and Wang Pei-fang, 2009).

Emergent or unsubmerged vegetation in watersheds has provoked changes on biological and physical processes in aquatic environments. Furthermore, these impacts extend to sediment transport phenomenon, mainly because the vegetation induced drag reduces flow discharge in open channels.

As a result, increasing flood attenuation and also sediment deposition (Cheng and Nguyen, 2011).

In addition, the bedload transport capacity decreases concurrently with the increases of flow resistance generated by vegetation on the watercourses. Thereby, the diameter and density stem are considered fundamental features in controlling bedload transport in open channels due to its reduction with an increase of both characteristics (James et al., 2001). Furthermore, these characteristics are positively correlated with the friction factor and negatively correlated with flow velocity (Ishikawa et al., 2003).

1.4. Flow resistance and vegetation

In spite of current efforts, adequate assessment of flow resistance in open channel remains a challenge. Resistance to flow with a movable boundary is previously divided in two parts (Einstein, 1950). Firstly, the roughness directly associated to grain size, which is called grain roughness. The other part is the roughness due to the existence of bed forms and its changes, called form roughness, which include the effects of vegetation (Yang, 1996). The total roughness of an alluvial channel if the Manning's coefficient is used can be expressed as:

$$n = n' + n'' \tag{1}$$

in which n' is the Manning's coefficient due to grain roughness and n'' is the Manning's coefficient due to form roughness.

The presence of vegetation in watersheds provokes some changes in flow resistance. Moreover, the features of vegetation, such as, the spatially heterogeneous distribution, form, dimension, rigidity, plant population per unity area influences the drag exerted in flow by vegetation (Lee et al., 2004). Furthermore, some factors, such as, diameter and density of stems can change the flow resistance of a vegetation. According to Järvelä (2002) which studied the flow resistance of natural grasses, sedges and willows in a laboratory flume an increase of 50% of natural semi-rigid willow stem density leads to a proportional increase of the friction factor. In addition, Thornton et al. (2000) analyzing a shear stress at the interface between a main channel in a vegetated and unvegetated floodplain observed which the flow resistance of stiff vegetation also increases with the density and diameter stem.

1.4.1. Conventional resistance coefficients

The hydraulic resistance on the watercourses determines not only the water level but also the flow distribution. Conventional resistance equations, such as, Manning, Chézy and Darcy-Weisbach have been used in several experiments. Nonetheless, it is clear which there are difficulties involved in using conventional equation, such as, Manning to evaluate resistance generated by vegetation (Yen 2002; Zima and Ackermann, 2002).

The common approach regarding Manning equation, as well as others approaches cited above are incoherent for situations as the presence of vegetation in Rivers, because if the cross section is vegetated it is important not only consider the resistance by boundary shear but also generated by stems and foliage (Cheng and Nguyen, 2011). In addition, these equations are considered inappropriate for vegetated flow because the resistance is generated predominantly by drag on the stem along the flow depth, being negligible the roughness of the channel bottom (James et al., 2004).

Based on the description of the drag force was developed a prediction of Manning coefficient as a function of flow depth and vegetation features (Petryk and Bosmajian, 1975). Even though not consider the bending influence of the vegetation this approach was explored by several researchers (Nepf, 1999; Nepf and Vivoni, 2000; Nezu and Onitsuka, 2001) due to complexity of flow-vegetation interaction.

The Manning coefficient for unsubmerged vegetation can be expressed as a function of drag coefficient according to Petryk and Bosmajian, (1975).

$$n_b = \left(\frac{h^{2/3}}{\sqrt{2g}} \right) \sqrt{C_D{'}} \quad (2)$$

in which n_b is the Manning coefficient for unsubmerged vegetation, h is the flow depth, g is the gravitational acceleration and C_D’ is the vegetation drag coefficient (λC_D), being λ the factor of vegetation density.

Furthermore, the roughness coefficient of unsubmerged vegetation is influenced only by flow depth irrespective of the streambed or water surface slope. Moreover, Wu et al. (1999) testing five different bed slopes observed which under the same Reynolds number the value of C_D’ is greater for the steeper bed. Through regression analysis was obtained the following expression (R^2 = 0.99):

$$C_D' = \frac{(3.44x10^6)S^{0.5}}{R^k} \qquad (3)$$

in which S is the energy slope and k is equal to 1. Replacing equation 3 into 2 and using the expression of $R = D^{5/3}S^{1/2}/n_b v$ it was acquired:

$$n_b = \left[\frac{(3.44x10^6)v}{2g}\right]h^{-1/3} \qquad (4)$$

in which v is the kinematic viscosity of water. This expression indicates which the roughness coefficient of the emergent vegetation is dependent only on the flow depth irrespective of bed slope which was properly explained by (Wu et al., 1999).

1.4.2. Drag coefficient, plant Reynolds number and vegetation resistance force

The drag coefficient (C_D’) is a dimensionless variable which measures the resistance of an object (in our case “vegetation”) in a fluid environment as water, which has been described by many authors through several ways. In addition, there are several definitions of Reynolds number in literature, including some length and velocity scales. Wu et al. (1999) using a horsehair mattress to attempt simulate the vegetation on the watercourses only used the flow depth in definition of Reynolds number. Nonetheless, it is essential to consider vegetation characteristics as well done by Lee et al. (2004) who showed that other Reynolds number could be assumed using vegetation features, such as, stem diameter (d) or stem spacing (s). Other approaches were performed by Cheng and Nguyen (2011) who studied the resistance generated by simulated unsubmerged vegetation in open-channel flows. The Table 1 provides examples of Reynolds number that have been used in some studies.

Table 1. Some definitions of Reynolds number for nonvegetated vegetated open channel.

Investigator	Reynolds number	Note
Wu et al. (1999)	Vh/ν	$V = Q/A$
Lee et al. (2004)	Vh/ν; Vs/ν; Vd/ν	$V_\nu = V/(1-\lambda)$;
Cheng and Nguyen (2011)	$V_\nu r_V/\nu$	$r_V = (\pi/4)[(1-\lambda)/\lambda]d$

V: average flow velocity; h: flow depth; ν: kinematic viscosity of water; Q: water discharge; A: area; s: stem spacing; d: stem diameter; V_ν: average pore velocity; r_V: vegetation-related hydraulic radius and λ: vegetation density.

The vegetation drag coefficient can be expressed by assuming that the gravitational force is equal to the drag of vegetation and the friction at the streambed of the channel is negligible in the presence of vegetation (Wu et al., 1999):

$$C_D' = \alpha \frac{2gS}{V^2} \tag{5}$$

in which C_D’ is the vegetation drag coefficient (m^{-1}), g is the gravitational acceleration (m s^{-2}), S is the slope of the channel bottom (m m^{-1}), V is the mean flow velocity (m s^{-1}), and “α” is the ratio between h and y, flow depth (m) and vegetation thickness (m), respectively. For unsubmerged vegetation, α equals 1.

Expanding the description of vegetation resistance force previously introduced by several authors (Kao et al., 1977; Maheshwari, 1992), Lee et al. (2004) considered in their experiment flow through a vertical segment, with plants in multiple spatial arrangements, and found the total vegetation resistance force as:

$$F_D = \frac{C_D a \rho V^2}{2} \tag{6}$$

in which: F_D is the vegetation resistance force (N m^{-3}), a is the total projected plant area per unit volume (m^2 m^{-3}) given the diameter of the *Echinodorus macrophyllus* leaves, ρ is the density of water (kg m^{-3}). To make C_D’ dimensionless, it must be multiplied by an equivalent flow width.

This approach is supported by Li and Shen (1973), who studied the effects of tall non-submerged or emergent vegetation on flow resistance by investigating the wake caused by various cylinder set-ups. It were observed four factors which should be considered in calculating drag force, such as, the effect of blockage, the free surface effects, the effect of non-uniform velocity profile and the effects of open-channel turbulence. Following studies as was developed by Lindner (1982), cited by Järvelä (2004), concluded which under densely vegetated conditions both the effect of non-uniform velocity profile and the effects of open-channel turbulence are less important and can be considered insignificant. Thus, becoming appropriate the usefulness of equations 5 and 6 under turbulent conditions.

On the other hand, the most researches have been carried out in flume. One of the approaches defined the drag force for each cylindrical stem in the streamwise (Kothyari et al., 2009; Tanino and Nepf, 2008).

$$F_D = \frac{C_{Dv}\rho h d V_v^{\ 2}}{2} \qquad (7)$$

in which C_{Dv} is the drag coefficient (dimensionless). The size of the frontal area is obtained through the product between flow depth (h) and stem diameter (d), V_v is the average pore velocity approaching the stem. The total drag per unit-bed area is formally expressed by:

$$\frac{4\lambda}{\pi d^2} F_D = \frac{4\lambda}{\pi d^2} C_{Dv} \rho h d \frac{V_v^{\ 2}}{2} = C_{Dv} \frac{2\lambda \rho h V_v^{\ 2}}{\pi d} \qquad (8)$$

This approach is equivalent to the streamwise component of the gravitational force for the condition of uniform flows:

$$C_{Dv} \frac{2\lambda \rho h V_v^{\ 2}}{\pi d} = (1-\lambda)\rho g h S \qquad (9)$$

By means of this approach the shear forces by bed and sidewalls are considered negligible. Otherwise, from equation (9):

$$C_{Dv} = \frac{1-\lambda}{2\lambda V_v^{\ 2}} g S \pi d = 2 \frac{g r_v S}{V_v^{\ 2}} \qquad (10)$$

The C_{Dv} determined by means of equation 10 had been proposed before (James et al., 2008; Tanino and Nepf, 2008) following the expression:

$$f_v = \frac{8 g r_v S}{V v^2} \quad (11)$$

in which f_v is the vegetation friction factor. Comparing equation 10 with equation 11 is obtained the following equation:

$$C_{D v} = \frac{1}{4} f_v \quad (12)$$

This approach is applied to justify the appropriate condition of C_{Dv} and R_v (vegetation Reynolds number - $V_v r_v / v$) for the description of resistance generated by vegetation in open-channel flows. “All variables above are used according international system units”.

Therefore, the major motivation of this research was the lack of studies in natural conditions associated with the necessity of improving the knowledge about the interference of the specie known as *Echinodorus macrophyllus* in hydraulic roughness and sediment transport under emergent conditions through direct measurement campaigns of suspended sediment and bedload in Capibaribe watershed.

2. OBJECTIVES

The major aim of this research was to assess the interference of hydraulic roughness generated by unsubmerged vegetation on sediment transport, based on relationship between vegetation drag coefficient (C_D') and Reynolds number of vegetation (Re_{plant}) from Capibaribe River.

The specific objectives were:

- To determine the liquid and solid discharge by means of direct measurement campaigns in Capibaribe watershed;
- To assess the hydraulic roughness generated by unsubmerged vegetation along the control section;
- To obtain parameters of hydraulic roughness effect in retention and reduction of bedload and suspended sediment transport of Capibaribe watershed.

3. HYPOTHESIS

The flow resistance generated by emergent vegetation has influenced the sediment transport phenomenon, being responsible by the reduction in the rate of bedload and also suspended sediment transport of Capibaribe River.

4. MATERIALS AND METHODS

4.1. Study area description

The Capibaribe watershed covers 7,557 km^2 and is located in the state of Pernambuco (Brazil). In addition, the Capibaribe River is divided in high, medium and low Capibaribe (Figure 4), crossing from the end of semiarid area until the east coast, including the Metropolitan Region of Recife (MRR) in approximately 250 km (ANA, 2010).

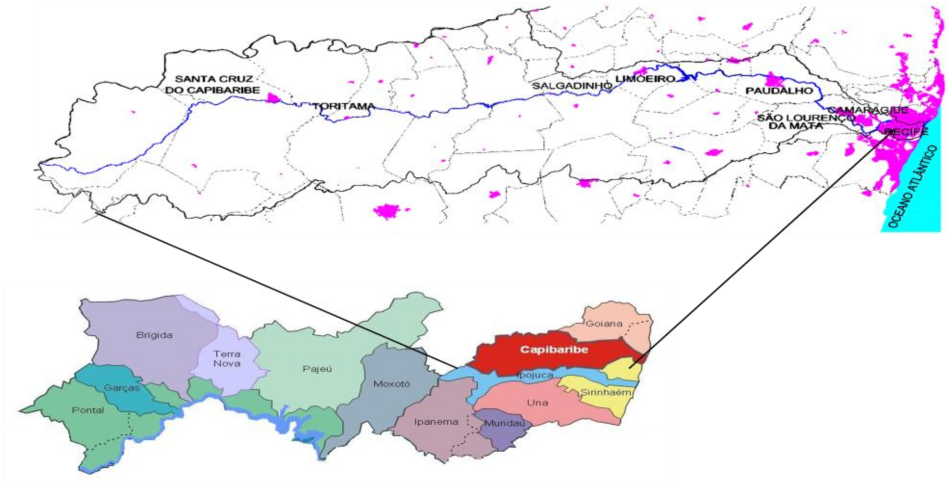

Figure 4. Location of Capibaribe watershed and its major watercourse in Pernambuco state map (ANA, 2010).

Climate in the semiarid region is (As' type), according to the Köppen classification, known as dry, with dry summer and the largest rainfall taking place between April and July, ranging from 550 mm to 700 mm year^{-1}. Furthermore, rains are characterized by irregular distribution on time and space, as well as an average temperature equal to 24°C, approximately. Through the same classification, but toward the portion located in the east coast the climate is classified as (Ams' type) with the largest rainfall taking place between July and May, ranging from 1,700 mm to 2,500 mm (SUDENE, 1990).

The climate has a large influence on soil and vegetation formation along the Capibaribe watershed. Main soil types and its municipalities were listed (Table 2), according to Jacomine (1973) who provided the Exploratory Survey – Recognition of Soil from Pernambuco State. The vegetation is composed by shrubs (caatinga) in semiarid portion and partially covered by sugar cane and pasture in the eastern part of the watershed (ANA, 2010).

Table 2. Predominance of some classes of soils in Capibaribe watershed (USDA, 1999).

Watershed division	Relevant Municipalities	Predominant Soils
High Capibaribe	Santa Cruz do Capibaribe; Brejo da Madre de Deus; Belo Jardim; Pesqueira; Poção; Taquaritinga do Norte; Brejo da Madre de Deus and so on.	Oxisols; Ultisols Albaquults; Vertisols; Alfisols and Entisols.
Middle Capibaribe	Caruaru; Limoeiro; Gravatá; Salgadinho; Toritama; Bezerros; Limoeiro; Feira Nova; Frei Miguelino and so on.	Entisols; Albaquults; Vertisols and Inceptisols.
Low Capibaribe	Paudalho; Glória de Goitá; Pombos; São Lourenço da Mata; Tracunhaém; Vitória de Santo Antão; Camaragibe; Recife and so on.	Oxisols; Ultisols and Entisols (Aqu-alf-and-ent-ept-)

4.2. Physical-hydric characteristics of Capibaribe Watershed

The physical-hydric characteristics of Capibaribe watershed and its hydrological response can be found in (Table 3). The form coefficient was determined following the equation proposed by (Ponce, 1989).

$$Kf = \frac{A}{L^2} \tag{13}$$

in which Kf is the form coefficient (dimensionless), A is the watershed area (km^2), L is the length of the main watercourse (km).

The water line slope was calculated according to Simons and Senturk, (1997):

$$S_w = \frac{(h^2_{downstream} - h^2_{upstream}) + (V^2_{downstream} - V^2_{upstream})/2g}{D} \tag{14}$$

in which S_w is the water line slope (m m^{-1}); h is the flow depth (m); V is the average flow velocity (m s^{-1}), g is the gravitational acceleration (m s^{-2}) and D is the distance between crosses sections.

Table 3. Physical-hydric characteristics of the Capibaribe watershed.

Characteristics	Values
Area	7,557 Km^2
Main lenght	250 Km
Form coefficient	0.12 (dim.)
Maximum elevation	1,200 m
Minimum elevation	2.0 m
Watershed slope	0.039 m m^{-1}
Water surface slope	0.0076 m m^{-1}
Concentration time	30 h

4.3. Crosses sections and direct measurement campaigns

This research was performed by means of thirteen direct measurement campaigns of water discharge and solid discharge during 2011 year, evaluating different conditions, such as, the effects of presence and absence of emergent vegetation on sediment transport phenomenon. Thereby, during four months (January, February, March and April) were carried out eight campaigns for making a comparison between nonvegetated and vegetated crosses sections, both with the same water surface slope. The remainder campaigns were carried out in a cross section without vegetation due to the high level of water discharge which provides the removal of aquatic specie.

The crosses sections were located in a community known as Mussurepe, located in Paudalho – PE, 35°05'23.6'' W e 07°55'06'' S (Figure 5). First of all, it was essential to choose adequate crosses sections before carrying out the direct measurements campaigns. Therefore, both were situated on a flat stretch and free from effects that could cause disturbances in the flow, such as backwater effects; well-defined banks and no flow reduction downstream.

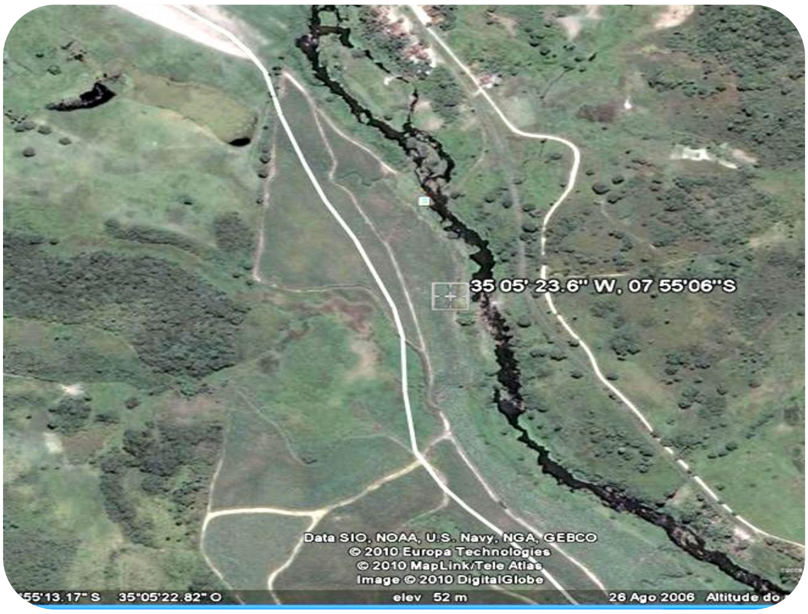

Figure 5. Location of crosses sections in Capibaribe River.

In addition, the crosses sections were chosen far from watershed outlet aiming to narrow down or eliminate the effect of tidal advection on sediment transport measurements (Araújo et al., 2008).

4.4. Velocity measurement

During the campaigns in Capibaribe River the flow velocity was determined by rotating current meter (Figure 6), which is based on the proportionality between the angular velocity of the rotation device and the flow velocity. In others words, the flow velocity was acquired by counting the number of revolutions of the propeller in a measured time interval, which was thirty seconds for all campaigns. The depth-average velocity was obtained in the cross section through a measurement velocity profile. In some campaigns, mainly during low water discharges was used the Hidromec mini model due to low flow depth.

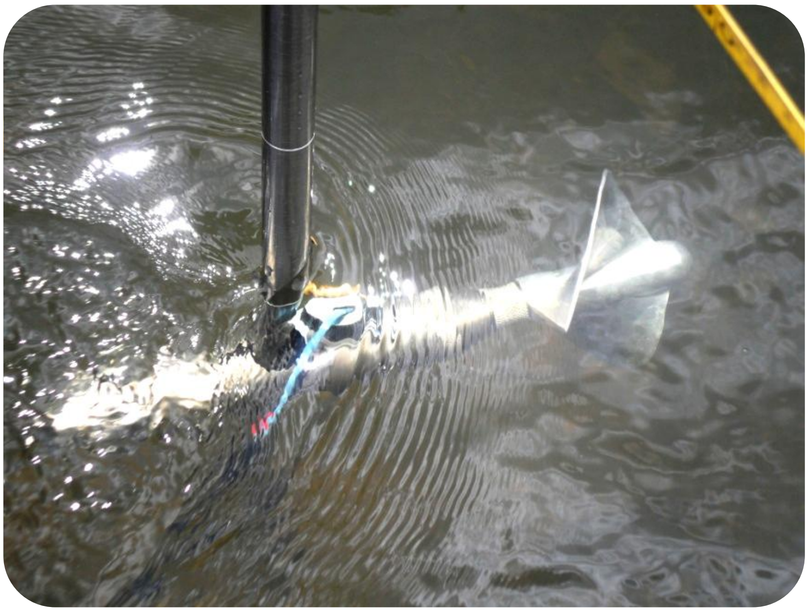

Figure 6. Rotating-element current meter used in Capibaribe River.

The number of positions which the rotating-element current meter was adjusted in each vertical in function of the flow depth, according to Back (2006) described in (Table 4).

Table 4. Measurement of average flow velocity according to flow depth.

Positions	V (m s^{-1})	h (m)
0.6h	$V = V_{0.6h}$	< 0.6
0.2 and 0.8h	$V = \frac{V_{0.2P} + V_{0.8h}}{2}$	0.6 - 1.2
0.2; 0.6 and 0.8h	$V = \frac{V_{0.2h} + 2V_{0.6h} + V_{0.8h}}{4}$	1.2 - 2.0
0.2; 0.4; 0.6 and 0.8h	$V = \frac{V_{0.2h} + 2V_{0.4h} + 2V_{0.6h} + V_{0.8h}}{6}$	2.0 - 4.0
S_f; 0.2; 0.4; 0.6; 0.8 and B	$V = \frac{Vs + 2(V_{0.2h} + V_{0.4h} + V_{0.6h} + V_{0.8h}) + V_b}{10}$	> 4.0

S_f: flow surface and B: bottom of the River.

4.5. Water discharge measurement

At first, the width of the crosses section were measured by affixing a measuring tape parallel to the flow surface and transverse to the direction of flow from the left bank of the stream to the right bank and the flow depth of each vertical was obtained by specific measuring rule. The crosses sections were divided into a series of vertical lines with the same width, varying according to the total width of the water flow at the moment of measuring, according to the equal-width-increment (EWI), method proposed by Edwards and Glysson (1999).

The crosses sections areas were determined obtaining the area of each vertical through the assumption which the first and last segments can be consider a triangular shape and others as trapezium. Therefore, the total area of each cross section was acquired by the sum of all vertical.

The water discharge was determined by computing the product of the mean flow velocity (m s^{-1}) and the area of influence (m^2) for each segment in the section and then summing these products over all segments (Equation 15).

$$Q = \sum Q_i = \sum A_i V_i \tag{15}$$

in which Q is the water discharge (m^3 s^{-1}), Q_i is the water discharge in each vertical segment (m^3 s^{-1}), A_i is the influence area of the vertical segment (m^2), and V_i is the average flow velocity in the influence area of each vertical segment (m s^{-1}).

4.6. Suspended sediment sampling

For sediment suspended sampling was used the sampler US DH – 48 model (Figure 7). The advantage of this model is the facility for using due to low weight (3.3 Kg). Furthermore, the US DH-48 sampler features a streamlined aluminum casting 13 inches long that partly encloses the sample container. The container, usually a glass milk bottle, is sealed against a gasket recessed in the head cavity of the sampler by a hand-operated spring-tensioned pull-rod assembly at the tail of the sampler. This instrument was calibrated with an intake nozzle l/4 inch in diameter (Carvalho, 2008).

Figure 7. Suspended sediment sampling (sampler - US DH-48) in Capibaribe River.

The methodology used to the measurements of suspended sediment concentration (SSC) was EWI (Figure 8), which is a specific method indicated for resulting in the collection of discharge-weighted, depth-integrated, isokinetic samples, proposed by Edwards and Glysson (1999). The basic approach of this method is which a cross section is divided in equally spaced segments and the sampler is carried out in the middle part of each segment. Moreover, during the sampling the descending and ascending transit rate must be the same along the traverse of each vertical, resulting in a volume of water proportional to the flow in each vertical (Edwards and Glysson, 1999).

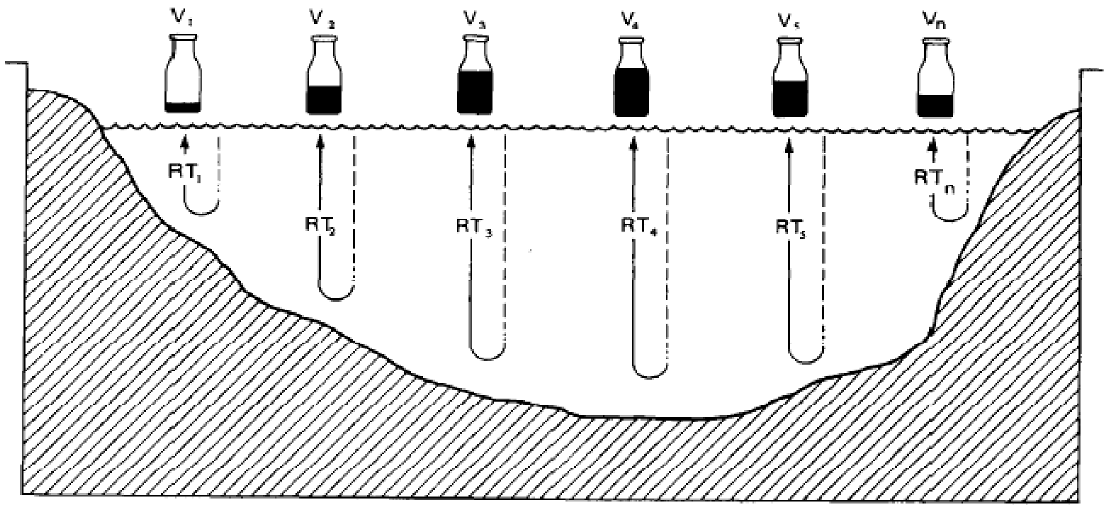

Figure 8. Equal-width-increment vertical transit rate relative to sample volume, which is proportional to water discharge at each vertical.

The transit rate depend on several features, such as, sample volume collected, size of the nozzle in sampling equipment, depth of the sample taken and flow velocity (Wilde and Radtke, 1998). Thereby, according to USGS (2005) the transit rate was expressed as:

$$Vt = \overline{V}_i K \qquad (16)$$

in which Vt is the transit rate (m s^{-1}), and K is the constant of variable proportionality according to each different nozzle used, which was 0.4 for the ¼" nozzle of the sampler. Nevertheless, the information used during sampling was not the transit rate, but the time for the sampler to descend to the streambed and return to the water surface, calculated by the expression proposed by Carvalho et al. (2000); Merten and Poleto (2006).

$$t_1 = \frac{2h}{Vt} \qquad (17)$$

in which t_1 represents the minimum time of the suspended sediment sampling (s). A small distance was subtracted from the value of h to account for the fact that the equipment would not contact the streambed (10 or 15 cm).

All collected samples in each segment (vertical) of the crosses sections in Capibaribe River were individually preserved to determine the SSC in Soil Conservation Engineering Laboratory at UFRPE, which was determined through the ratio between the suspended sediment mass and liquid volume of the sample, according to evaporation method (USGS, 1973).

$$SSC = \frac{M}{Vol_{sample}} \tag{18}$$

in which *SSC* is the suspended sediment concentration in the sampled vertical (mg L^{-1}), M is the suspended sediment mass (mg) and Vol_{sample} is the sample volume (L). For checking the accuracy of suspended sediment sampling was calculated the Box coefficient (*BC*), following the proposed by USGS (2005).

$$BC = \frac{\overline{SSC}}{SSC_i} \tag{19}$$

in which BC is the Box Coefficient (dimensionless), $\overline{SSC}$ is the average of suspended sediments concentration (mg L^{-1}) and SSC_i is the suspended sediment concentration at each vertical (mg L^{-1}).

After obtaining the Q and SSC_i in each vertical was acquired the suspended solid discharge (SSQ), which represents the amount of suspended sediment crossing the cross section per day, in the form of an expression found in Horowitz (2003).

$$SSQ = \Sigma(SSC_i Q)0.0864 \tag{20}$$

in which SSQ is the suspended solid discharge (t day^{-1}) and 0.0864 is a constant for unit adjustment.

4.7. Bedload discharge and particle size distribution

The bedload discharge was determined in each campaign by means of a bedload sampler US BLH – 84 model (Figure 9), which was projected for collecting sediments ranging from 1 to 38 mm (Diplas et al., 2008).

Figures 9. Bedload sampling with the sampler US BLH – 84 model.

After sampling, the bedload discharge was calculated according to Gray (2005):

$$QB = \sum \frac{m}{wt_2} L_x 0.0864 \qquad (21)$$

in which QB is bedload discharge (t day^{-1}), m is the mass of sediment from bedload transport in each vertical (g), w is the width of nozzle which is considered 0.075 m, t_2 is the sampling time of bedload transport (30 s), L_x is the equivalent width (m).

Understanding regarding particle size distribution is fundamental for several quantitative and qualitative purposes. This sort of study can be useful for providing information about the source and travel distance of sediment, as well as predict channel form and stability (Bunte and Abt, 2001).

The total bedload mass of each campaign was dried in oven (65 °C). Afterward, it was used to obtain the particle size distribution. The process consists in sieving each sample in a electromagnetic shaker, Viatest VSM 200 model (Figure 10) equipped with a group of sieves in decrease diameters order (3.35; 1.7; 0.85; 0.60; 0.425; 0.30; 0.212; 0.150; 0.20; 0.106; 0.076 e 0.053 mm), during 10 minutes under 90 vibrations per second. As a result, it was possible to obtain the particle size distribution curve and also calculate the median grain diameter (d_{50}) through the Curve Expert 1.3 (2005) programmer.

Figure 10. Test sieve shaker used to determine the particle size distribution.

4.8. Hydraulic characteristics and vegetation resistance parameters

To measure the wetted perimeter was necessary to divide the crosses sections into vertical segments of equal width, as well done to the area and other variables calculated in the project. Then, it was obtained the hydraulic radius, which was calculated by the ratio of cross-section area to wetted perimeter.

Reynolds and Froud numbers relate the inertia forces to the viscous forces usually involved wherever viscosity is fundamental as in slow movement of fluid in small passages or around small objects and with the gravitational effects considered important wherever the gravity effect is dominant, respectively. These variables are formally expressed according to Simons and Sentürk (1992).

$$\mathrm{Re} = \frac{VR_h}{v} \tag{22}$$

$$Fr = \frac{V}{\sqrt{gR_h}} \tag{23}$$

in which Re is the Reynolds number (dimensionless), Fr is the Froud number (dimensionless) and R_h is the hydraulic radius (m).

The kinematic viscosity of water was estimated using the equation proposed by Julien (1995).

$$v = [1.14 - 0.031\,(T - 15) + 0.00068\,(T - 15)^2]10^{-6} \tag{24}$$

in which v is kinematic viscosity of water ($m^2\ s^{-1}$) and T is the temperature of water in degrees Celsius. The plant Reynolds number was calculated using an approximation proposed by Lee et al. (2004):

$$\mathrm{Re}_{plant} = \frac{Vs}{v} \tag{25}$$

in which Re_{plant} is dependent on vegetation type (dimensionless), *s* is the spacing between plants (m).

The vegetation drag force was calculated using the Equation 6, as proposed by Lee et al. (2004) and the plant drag coefficient was obtained applying Equation 5, according to Wu et al. (1999).

4.9. Description and structural parameters of vegetation

The *Echinodorus macrophyllus* is known as leather hat, aquatic vegetation native from Brazil. Grow at tropical temperatures with plenty of light and a rich substrate. In relation of major features the *Echinodorus macrophyllus* has stem upright and cylindrical.

The aquatic specie was identified by the Biology Department at University Federal Rural of Pernambuco. The structures parameters of *Echinodorus macrophyllus,* such as, stem diameter, leaf diameter, stem length and spacing between stem were measured in all direct measurement campaigns with presence of this vegetation along the cross section (Figure 11).

These parameters are essential to obtain the Reynolds number, drag coefficient (C_D') and vegetation drag force (F_D). The area of plant was acquired through the following expression:

$$A_p = \frac{\pi D_l^2}{4} \tag{26}$$

in which A_p is the total area projected with plant (m^2) and D_l is the average leaf diameter (m).

Figure 11. Measurement of vegetation structural parameters.

In brief, the characteristic of stem upright is far too important for considering negligible the flexible effects of this specie, evaluated under emergent conditions, which is fundamental to provide an adequate assessment of vegetation drag coefficient and vegetation drag force.

4.10. Statistical analysis

Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were performed through the STATISTICA 7 software, considering the sediment transport of thirteen direct measurement campaigns carried out in Capibaribe River along 2011. The regression analysis was used to analyze the relationship between some parameters, such as, flow depth, water discharge, suspended sediment concentration, vegetation drag force, vegetation drag coefficient and vegetation Reynolds number.

5. RESULTS AND DISCUSSION

5.1. Rainfall in Capibaribe River

The average rainfall for the rainy and dry seasons of the years 2010 and 2011, as well as the historical average monthly are shown in Figure 12. The highest rainfall was observed for the direct measurement campaign carried out in Capibaribe River in May with a value equal to 574 mm, exceeding the historical average for this month.

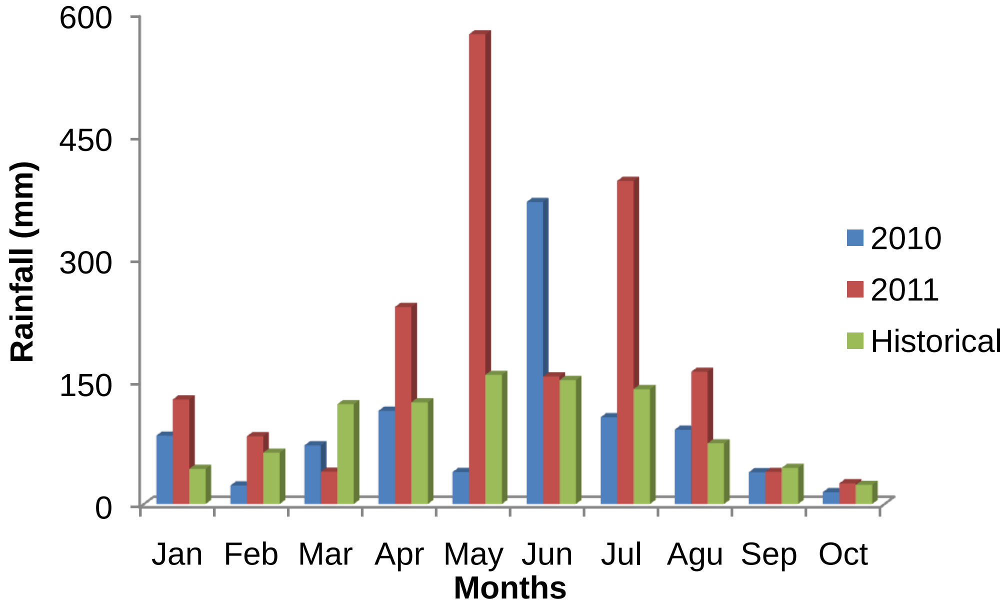

Figure 12. Distribution of average annual rainfall for non-rainy and rainy 2010 and 2011, as well as the historical average in Capibaribe River (LAMEPE, 2011).

5.2. Hydraulic characteristics and rating curve of Capibaribe River

The hydraulic radius ranged from 0.51 m for a shear stress (τ) equal to 37.87 N m^{-2} until 0.82 m for a τ equal to 61.35 N m^{-2}. Moreover, the highest τ equal to 61.35 was responsible by the highest value of bedload transport equal to 5.82 t day^{-1} (Table 5).

Combined effect of viscosity and gravity provided the regime of flow in Capibaribe watershed, which was classified as turbulent subcritical due to the Reynolds numbers greater than 2500, and Froud numbers less than a unity (Simons and Sentürk, 1992). As a result, the viscous forces are weak in comparison with the inertial forces and the fluid particles move in irregular paths. The median grain diameter (d_{50}) predominantly showed a great uniformity of the particles transported in the stream bed with a standard deviation equal to 0.05 (Table 5), except for the direct measurement campaign performed in August.

Table 5. Hydraulic variables of direct measurements campaigns performed under nonvegetated conditions in Capibaribe River.

Campaigns	R_h	Re	Fr	τ	d_{50}	Texture
	m	-------dim.-------		N m^{-2}	mm	
25/1/2011	0.60	238382.88	0.15	44.65	0.51	coarse sand
3/2/2011	0.51	205453.60	0.15	37.87	0.53	coarse sand
18/3/2011	0.52	247756.83	0.18	38.54	0.49	medium sand
13/4/2011	0.66	444072.41	0.23	49.36	0.51	coarse sand
29/5/2011	0.71	294539.20	0.13	53.18	0.64	coarse sand
26/8/2011	0.82	163084.61	0.06	61.35	0.61	coarse sand
14/9/2011	0.79	142632.13	0.06	58.93	0.52	coarse sand
6/10/2011	0.76	201543.25	0.08	56.93	0.27	fine sand
13/10/2011	0.73	156385.58	0.07	54.72	0.56	coarse sand
Mean	**0.68**	**232650.05**	**0.12**	**50.61**	**0.52**	

R_h: hydraulic radius; Re: Reynolds number; Fr: Froude number; τ: shear stress; d_{50}: median grain diameter.

In Figure 13 it was observed the particle size distribution curve of the direct measurement campaign carried out in 29/05/2011 with the d_{50} equal to 0.64 mm.

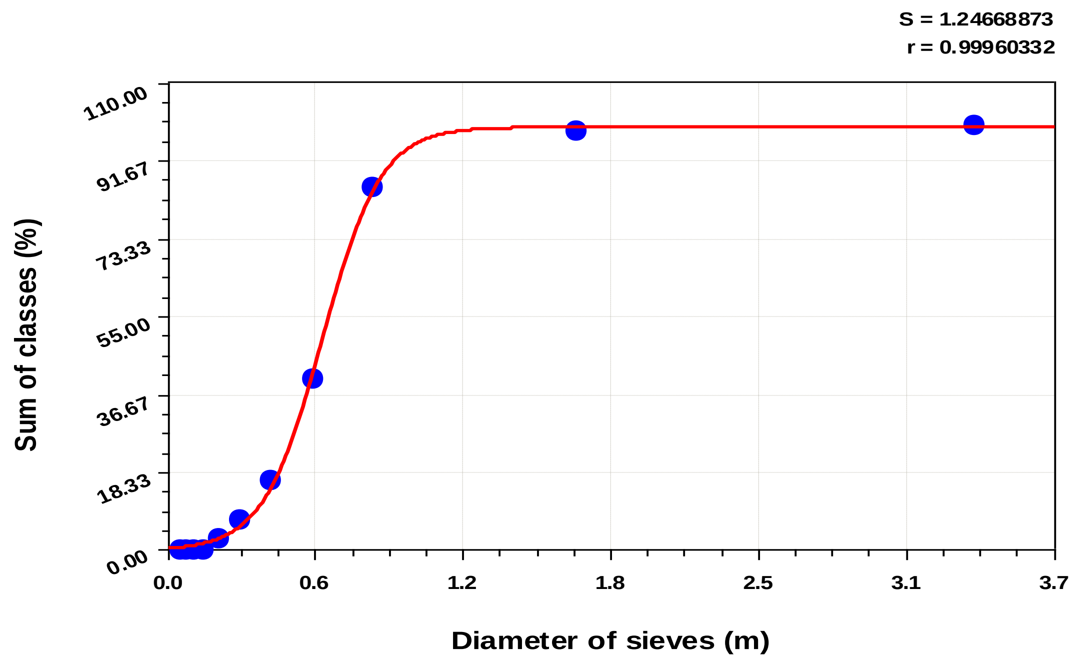

Figure 13. Particle size distribution curve of sediment transported in the streambed by Capibaribe River in 29/05/2011.

The rating curve relating water discharge (Q) and flow depth (h) provided a determination coefficient equal to 0.74, considering the direct measurement campaigns carried out without vegetation along the crosses sections and Q ranging from 0.97 to 3.76 m^3 s^{-1} (Figure 14). Souza (2011), studying the same watershed obtained a determination coefficient equal to 0.84 (power function) through twelve direct measurement campaigns. The better adjustment was acquired due to the higher amplitude of Q evaluated, which ranged from 0.19 to 11.60 m^3 s^{-1}. Thereby, the number of measurement and also the variation between minimum and maximum values improve the effectiveness of the rating curve (Carvalho, 2008).

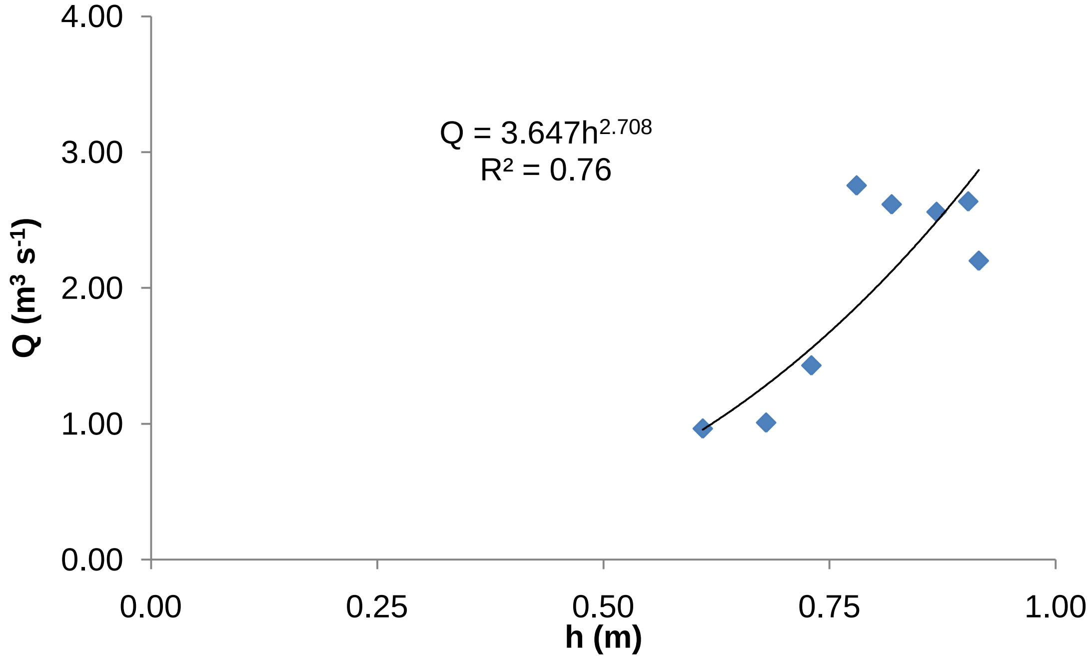

Figure 14. Rating curve of directing measurement campaigns performed under nonvegetated conditions in Capibaribe River.

5.3. Suspended and bedload transport for crosses sections under nonvegetated conditions

The water discharge ranged from 0.97 m^3 s^{-1} to 3.76 m^3 s^{-1}, with the suspended solid discharge (SSQ) equal to 69.80 t day^{-1} and 172.55 t day^{-1}, low and high water discharge period, respectively (Table 6). Furthermore, the means of bedload discharge (QB), evaluating (May-July) and (August-April) was equal to 2.26 t day^{-1}, which was considered a low rate. Moreover, Araújo et al. (2010), working in Beberibe watershed (2009/2010), one of the smallest basin in MRR, obtained a QB equal to 9.16 t day^{-1}, approximately four times higher than in Capibaribe watershed. This behavior can be associated with channel morphology and also with the presence of dams in Capibaribe watershed.

Table 6. Sediment transport variables of directing measurement campaigns performed in the crosses sections under nonvegetated conditions.

Campaigns	Q	SSQ	QB	(QB/SSQ) x100	BC
	$m^3 s^{-1}$	------t day^{-1}------		(%)	----dim.----
25/1/2011	1.43	89.32	0.19	0.21	0.86-1.13
3/2/2011	0.97	69.80	0.18	0.26	0.86-1.40
18/3/2011	1.01	75.78	0.14	0.18	0.93-1.25
13/4/2011	2.20	153.77	0.57	0.37	0.83-1.18
29/5/2011	3.76	172.55	2.14	1.24	0.74-1.36
26/8/2011	2.64	166.08	5.82	3.51	0.66-1.13
14/9/2011	2.56	172.41	2.97	1.72	0.85-1.08
6/10/2011	2.62	206.12	5.32	2.58	1.05-1.26
13/10/2011	2.75	224.84	3.85	1.71	0.86-1.12
Mean	**2.22**	**147.85**	**2.26**	**1.31**	**------**

Q: water discharge; SSQ: suspended solid discharge; QB: bedload discharge and BC: box coefficient.

The ratio between QB and SSQ ranged from 0.18% to 3.51% with the mean value equal to 1.31% (Table 6). Usually, the bedload transport rate of a River is about 5-25% of the suspended sediment transport (Yang, 1996). Nevertheless, the low rates can be attributed to the presence of dams which have been admitted to have a strong effect on sediment transport as was discussed by Preciso et al. (2011) which evidenced the reduction on sediment supply at River Reno, but without quantifying this process due to the lack of assessment before dam construction. In addition, the values of individual suspended sediment samples showed adequate box coefficient (BC), ranging from 0.9 to 1.2 or within the acceptable limits, ranging from 0.67 to 1.5 (Gray, 2005).

The relation between suspended sediment concentration (SSC) and Q was expressing by a rating curve (Figure 15). It was observed which the SSC was not influenced directly by the Q due to the low determination coefficient equal to 0.21, demonstrating the large complexity and variability associated with the SSC measurements. Furthermore, this behavior represents the effects of dams, as was discussed by Baker et al. (2011) which evaluated the downstream effects of dams, mainly in suspended sediment. In the same way, Souza (2011) working in the Capibaribe watershed obtained low adjustment between SSC and Q discharge (R^2 equal to 0.14). Moreover, the high variability between SSC and Q was emphasized by Saeidi et al. (2011) which obtained a high variability of regression coefficients.

These results are associated with the dynamic relation between Q and SSC, becoming essential to keep manual sampling to decrease the mistakes linked with SSC estimation and improve the effectiveness of the rating curves (Horowitz, 2003).

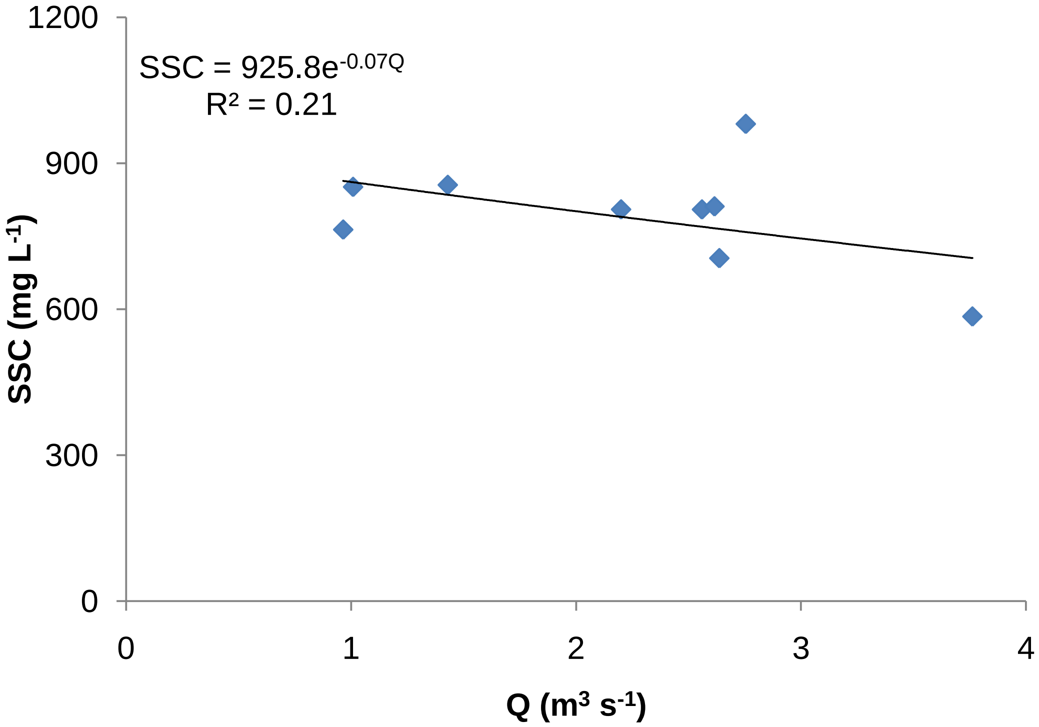

Figure 15. Sediment rating curve of Capibaribe River with instantaneous sediment concentration.

On the other hand, the rating curve relating SSQ (dependent variable) and Q (independent variable) showed a reasonable adjustment with determination coefficient equal to 0.87 (Figure 16). Nevertheless, this behavior can not be understood as the same way of the rating curve which relates the Q and h due to the high complexity linked with suspended sediment transport. Indeed, it is possible to observe the momentary behavior of the SSQ instead obtaining this variable only with the Q even if had been carried out a high number of measurements.

According to Horowitz (2008) this approach is acceptable for a suspended sediment concentration rating curve. Nonetheless, it is inadequate for a suspended solid discharge rating curve, chiefly because the Q is used for obtaining the SSQ. Accordingly, it is common to observe the increase in determination coefficient, but without increasing the importance of the rating curve relating Q and SSQ.

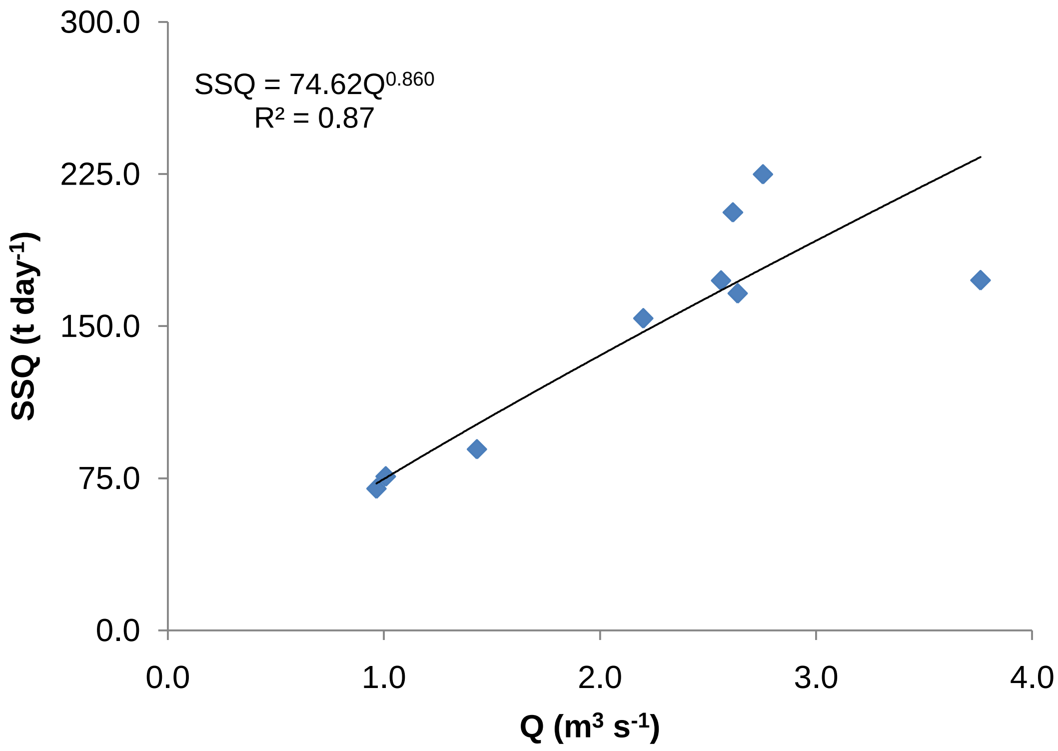

Figure 16. Suspended sediment rating curve of Capibaribe watershed.

5.4. Interference of unsubmerged vegetation on sediment transport of Capibaribe watershed

The Figures 17a and 17b represent the crosses sections evaluated in 03/02/2011, under nonvegetated and vegetated conditions, respectively. The h was more uniform in the cross section 17a. The vegetated zone in cross section (Figure 17b) leaded an increase equal to 24% in the average flow velocity at nonvegetated zone. Likely, the vegetated zone decreased the h due to an increase on sediment deposition.

According to Cheng (2008) the decrease in sediment transport capacity and an increased in sedimentation is influenced by the momentum losses generated by vegetation. Further, this tendency was highlighted by Bennett et al. (2002), which conducted an experiment with simulated emergent stiff vegetation using several densities in laboratory flume channel. In this experiment it was observed which the V decreased within the vegetated zone, directing the flow to the banks.

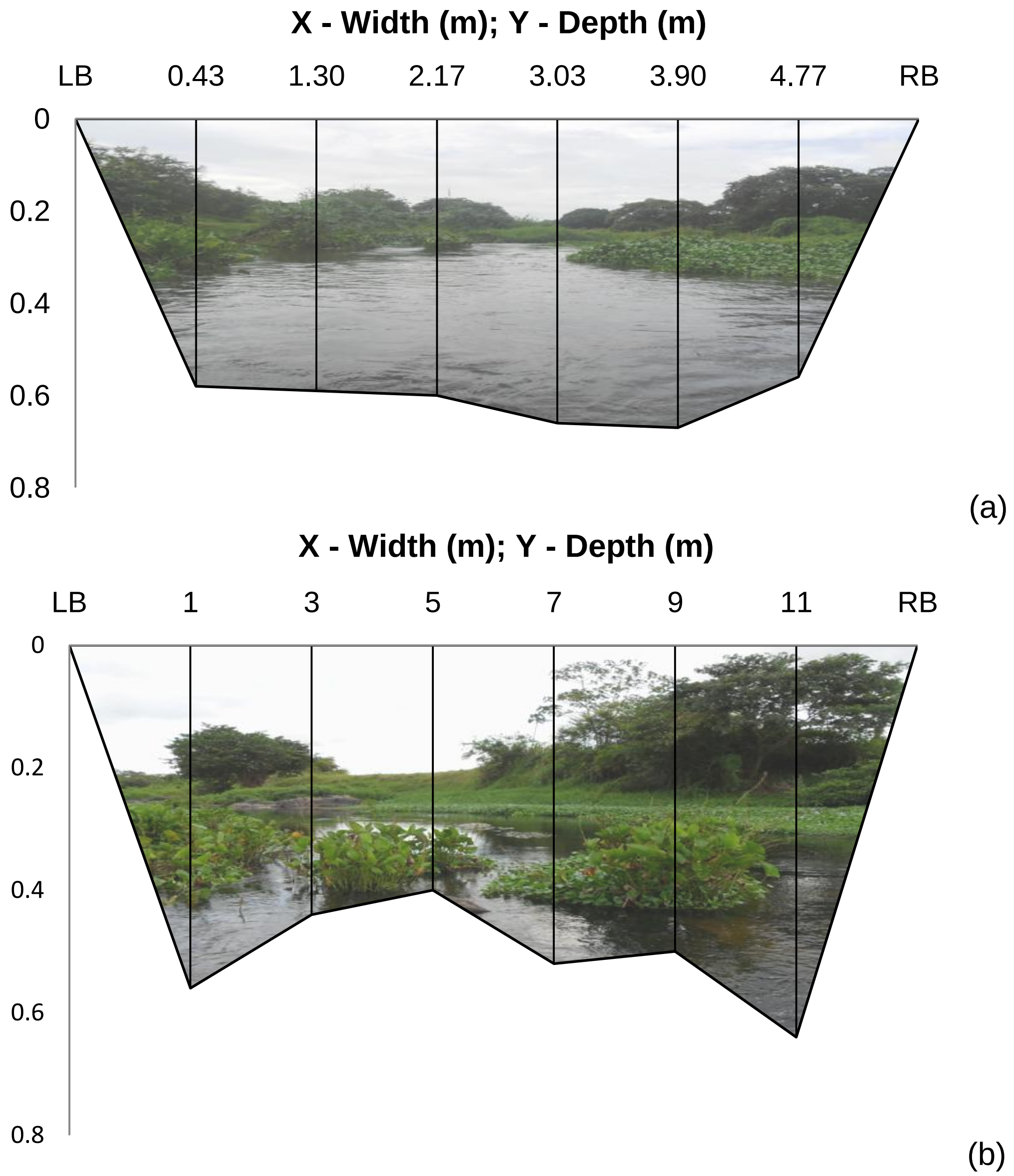

Figure 17. Comparison between crosses sections under absence and presence of unsubmerged vegetation.

The drag coefficient variation (C_D') of *Echinodorus macrophyllus* in function the combined method ($n{\sim}VR_h$) demonstrated a great adjustment with a determination coefficient equal to 0.97 (Figure 18). In this case, both varied similarly, evidencing the response to the turbulence generated by *Echinodorus macrophyllus.* Further, the C_D' reached a maximum value equal to 11.13 m^{-1} for the minimum value evaluated for (VR_h) equal to 0.05 $m^2\ s^{-1}$. This behavior is likely attributed to the stem density, which provided a reduction in the V. Thereby, the C_D' is an indicator of hydraulic resistance generated by

Echinodorus macrophyllus, which provides a better comprehension regarding interaction between sediment, water surface and vegetation.

Melo (2008), studying the hydraulic roughness generated by submerged and unsubmerged vegetation in a semiarid stream obtained a better adjustment (R^2 equal to 0.96). The better comprehension was obtained due to higher numbers of measurements and amplitude of data, resulting in C_D' ranging from 3.07 m^{-1} to 10.16 m^{-1} and 0.86 to 3.46 m^{-1}, unsubmerged and submerged vegetation, respectively.

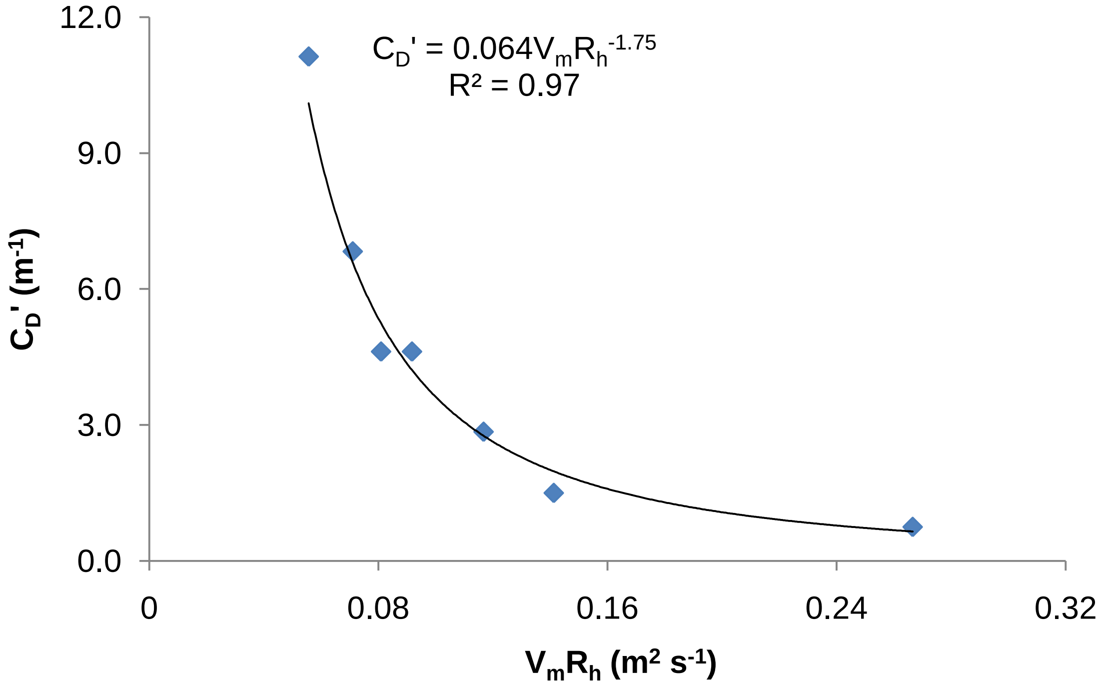

Figure 18. Relationship between the individuals' values of C_D' and (VR_h).

It was observed the variation of C_D' with turbulence elevation (Figure 19). Even though, the low number of direct measurement campaigns performed with unsubmerged vegetation in Capibaribe watershed, the reasonable R^2 convey the adequacy of this approach which has been used by several researches for estimating the passage of flow trough a vertical structure and spatial arrangement (Cheng and Nguyen, 2011; Lee et al., 2004).

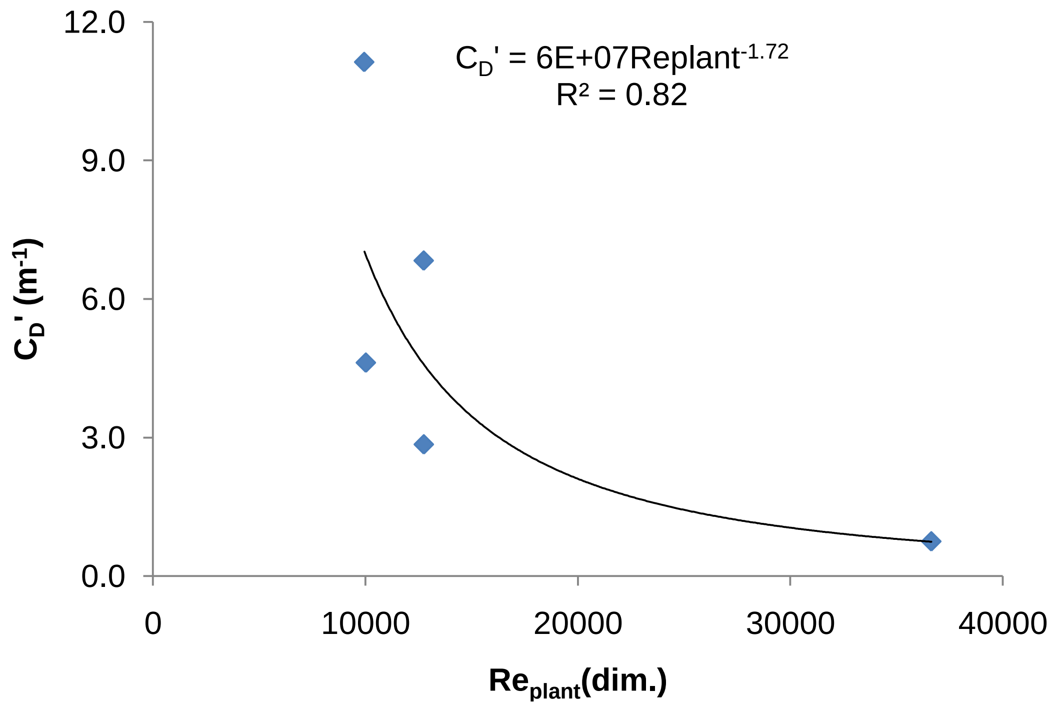

Figure 19. Drag coefficient of *Echinodorus macrophyllus* in function of plant Reynolds number for the flow evaluated in Capibaribe River.

The effect of the resistance generated by *Echinodorus macrophyllus* was evidenced (Figure 20), which showed a comparison among the period under vegetated (January-April/2011) and nonvegetated (May-October/2011) crosses sections for some variables, such as, drag force (F_D), shear stress reduction and bedload reduction.

It was realized two distinct moments. At first, during the vegetated period, it was observed a reduction not only in the bedload but also in the shear stress. Nonetheless, this reduction was getting increasingly lower due to the accumulative effect of vegetation in both processes. Secondly, it was evidenced a tendency of stabilization in the rates of both variables.

Additionally, the second moment represents the transitional period, which indicates the complete removal of *Echinodorus macrophyllus* by passing the flow to high levels. As a result, it was admitted which the reduction of τ and also QB became increasingly negligible between crosses sections. In others words, the amount of QB from this period crossing both crosses section can be considered the same.

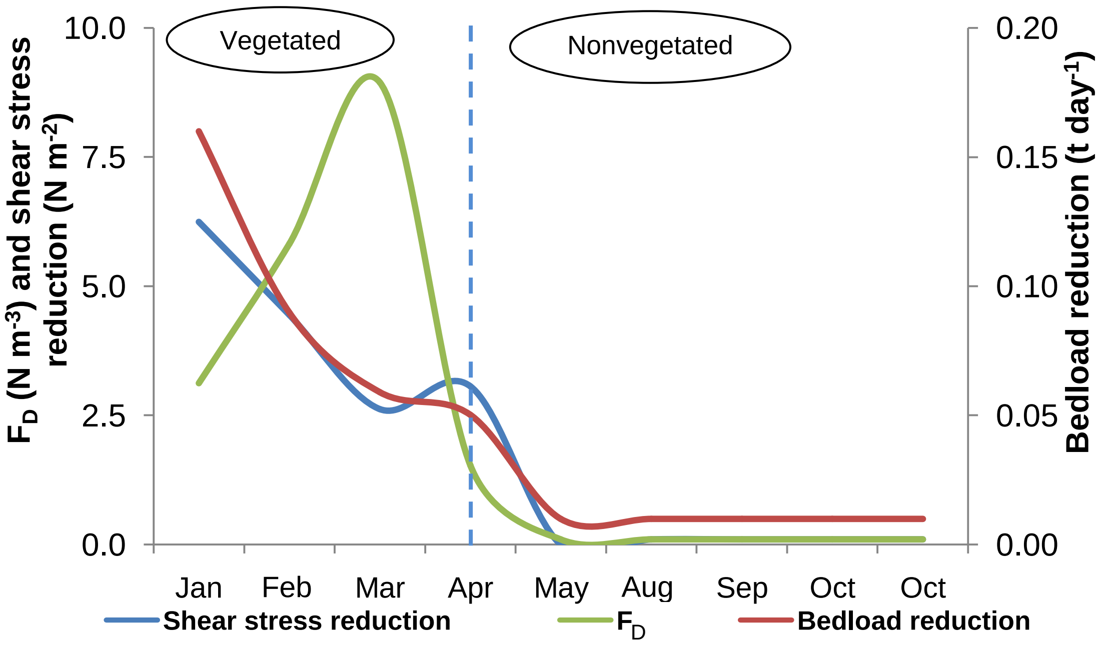

Figure 20. Relationship between drag force, shear stress reduction and bedload reduction during vegetated and unvegetated period.

5.5. Multivariate analysis

The multivariate analysis was carried out to become the discussion more practical. Therefore, it was applied principal components analysis (PCA) for selecting the major variables associated with the sediment transport in Capibaribe watershed. Afterward, the hierarchical cluster analysis (HCA) was performed to attempt distinguish the effect of flow resistance generated by *Echinodorus macrophyllus* on sediment transport phenomenon.

5.6. Principal component analysis

The principal component analysis was applied to the sixteen variables to select the most important variables for explaining the sediment transport and the effect of unsubmerged vegetation on sediment transport rate. The selection of variables was based exclusively in sequential tests for analyzing the contribution of each one.

Principal components were extracted through the correlation matrix computed for the eleven variables previously selected. The first two components extracted had eigenvalues equal to 6.74 and 3.15, accounting for the 90.03% of the total variance explained (Table 7). Furthermore, only the first two components were used because presented eigenvalues greater than 1 as well as some variables, such as, Manning number, suspended sediment concentration, kinematic viscosity, median grain diameter and also shear velocity were excluded due to the low contribution of total variance on sediment transport of Capibaribe watershed.

In addition, among the excluded variables the SSC was responsible by the large reduction in the total variance explained. In fact, this behavior can be attributed to the high variability and complexity associated with the SSC and the low correlation with other variables studied. This assumption was confirmed through the low determination coefficient (R^2 equal to 0.21) obtained with sediment rating curve relating the Q with SSC.

Table 7. Principal components loadings, eigenvalues and explained variance of six components obtained for all direct measurement campaigns performed in Capibaribe River.

Variables	PC1	PC2	PC3	PC4	PC5	PC6
h	0.692	-0.570	-0.426	0.024	-0.099	-0.049
A	0.985	0.136	0.067	0.041	0.051	-0.031
V	-0.534	-0.842	0.046	-0.013	0.043	-0.017
Q	0.750	-0.465	0.424	0.172	0.080	0.070
SSQ	0.747	-0.391	0.460	-0.222	-0.169	0.003
QB	0.925	0.052	-0.215	-0.217	0.217	0.025
P_w	0.909	0.290	0.264	0.058	0.066	-0.106
R_h	0.934	-0.260	-0.226	0.057	-0.051	0.027
Re	-0.160	-0.982	-0.007	0.022	0.056	-0.047
Fr	-0.670	-0.733	0.044	-0.046	0.079	0.001
τ	0.928	-0.285	-0.226	0.044	-0.047	0.045
Eigenvalues	6.743	3.159	0.799	0.139	0.114	0.025
VE (%)	61.30	28.72	7.270	1.270	1.040	0.230

h: flow depth; A: area; V: flow mean velocity; Q: water discharge; SSQ: suspended solid discharge; QB: bedload discharge; P_w: wetted perimeter; R_h: hydraulic radius; Re: Reynolds number; Fr: Froude number; τ: shear stress; VE: explained variance by principal components.

The PC1 explained was characterized due to the high positive loadings in the (h, A, Q, SSQ, QB, P_w, R_h, τ) and accounts for 61.30% of the total variance, whilst the PC2 explained was chiefly influenced by (V, Re, Fr) and accounts for 28.72% of the total variance (Table 7). This behavior suggests a definition of these two components associated with the variables which compose each one. Further, due to association of variables the PC1 was defined as sediment transport component and PC2 was defined as flow regime component (Figure

21), mainly because the high association of (V, Re, Fr) classified the flow regime as turbulent subcritical (Simons and Sentürk, 1992).

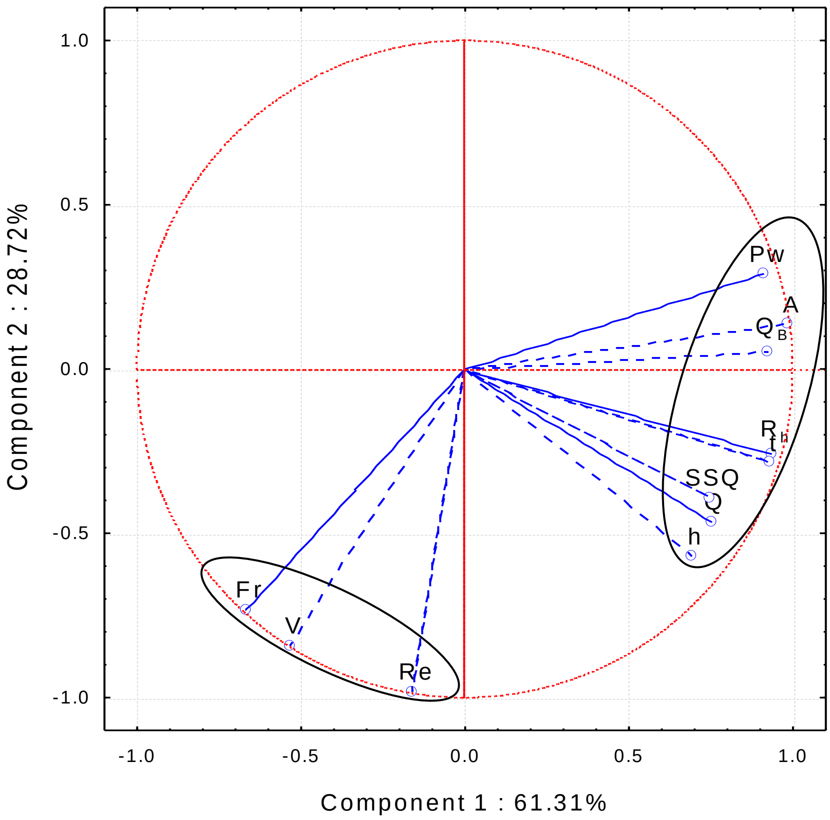

Figure 21. Projection of the variables on the factor-plane.

5.7. Hierarchical cluster analysis

The HCA classified the thirteen direct measurement campaigns into similar groups. The main idea was decrease the numbers of objects instead the number of variables, as well as evaluate if the presence of vegetation in four direct measurement campaigns could be distinguished. Therefore, the dendrogram was formed using the joining process of complete linkage after carrying out the standardization of variables previously selected by principal component analysis.

The classification of cluster for the direct measurement campaigns in Capibaribe watershed was based on visual observation of the dendrogram. This approach was proposed by Cloutier et al. (2008), which was supported by Güler et al. (2002) who discussed which the number of groups can be modified by moving the line down or up on the dendrogram, accordingly becoming the HCA a subjective evaluation. Moreover, the line was fixed in the dendrogram at a linkage distance about 40 (Figure 22). As a result, the direct measurement campaigns with a linkage distance lower than 40 were grouped into the same cluster, forming five groups in relation with the sediment transport in Capibaribe watershed.

The first group was formed by the direct measurement campaigns carried out on 25/01, 03/02 and 18/03 equivalent to C1, C3 and C5, respectively with the absence of unsubmerged vegetation along the cross sections. The second group was formed by the direct measurement campaigns performed on 25/01, 03/02 and 18/03, equivalent to C2, C4 and C6, respectively, but under the presence of *Echinodorus macrophyllus* and both condition under the same water surface slope. Thereby, considering this six first direct measurements campaigns it was possible to separate two initial groups and realize the effect of the resistance generated by *Echinodorus macrophyllus*, which mainly provided the reduction of bedload discharge and shear stress.

The third group was formed by the measurements performed on 13/04, equivalent to C7 and under the absence of unsubmerged vegetation. This campaign got separated of the campaigns carried out on the same day due to the substantial increase in the water discharge. The behavior was confirmed through the (Figure 19), which cleared up the transitional momentum between vegetated and nonvegetated conditions.

Moreover, the fourth group was integrated by the campaigns C8 under vegetated conditions and C9 under nonvegetated, performed on 13/04 and 29/05, respectively, likely due to the partly removal of *Echinodorus macrophyllus.* Finally, the last group was integrated by the direct measurement campaigns carried out on 26/08, 14/09, 06/10, 13/10 equivalent to C10, C11, C12 and C13, respectively, which mainly gathered the largest values of R_h, Q, QB and τ.

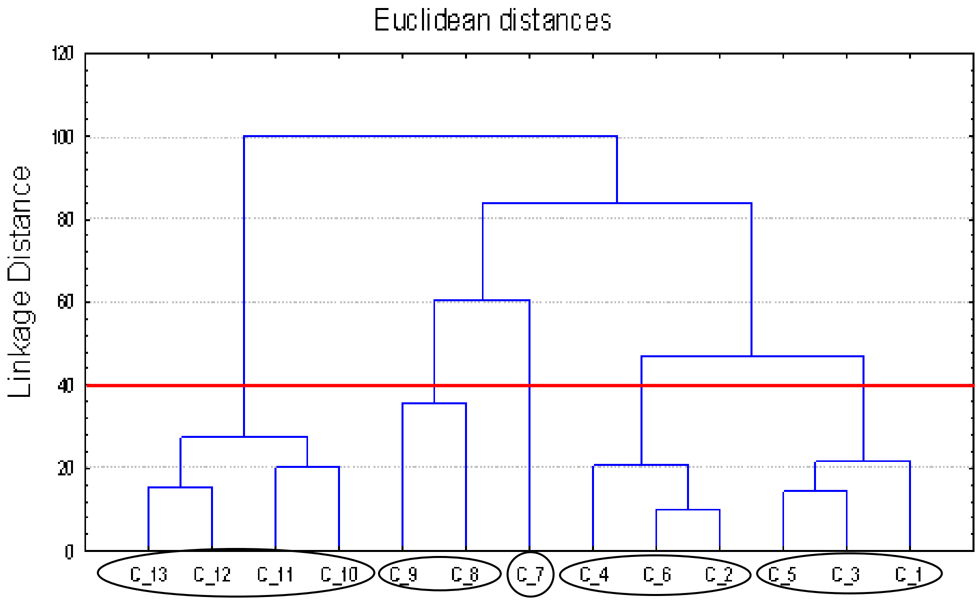

Figure 22. Dendrogram of classification for the thirteen direct measurement campaigns.

6. CONCLUSIONS

1. The effect of resistance generated by *Echinodorus macrophyllus* mainly influenced the bedload discharge, accounting for 37% of reduction in bed load transport rate between the crosses sections studied in Capibaribe River.

2. The low ratio between bedload and suspended solid discharge, which ranged from 0.18% to 3.51% with the mean value equal to 1.31% can be associated to the presence of dams along the Capibaribe watershed.

3. Total variance of sediment transport rate explained by the first two principal components equal to 90.03%, as well as the classification provided by hierarchical cluster analysis for direct measurement campaigns under vegetated and nonvegetated conditions showed the usefulness of multivariate analysis.

4. The hydraulic roughness of the cross section vegetated by *Echinodorus macrophyllus* was characterized through the mean vegetation drag coefficient (C_D') equal to 4.02 m^{-1}, demonstrating the adequacy of the method applied in Capibaribe River.

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