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HYDRODYNAMIC MODELING DOWNSTREAM OF TUCURUI HYDROELECTRIC POWER PLANT FOR ANALYSIS OF SITES TO SET UP OF HYDROKINETIC TURBINES

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Abstract. *Brazil's has a vast and dense hydrographic network. In Para state's Tucuruí municipality, about 300 km south of Belem, there's a hydroelectric central which is considered large – the UHE Tucuruí located on Tocantins River. Study area of this current work is restricted to a stretch of Tocantins River starting from the UHE Tucuruí downstream until Tucuruí city. The flow has been modeled for the evaluation of sites where hydrokinetic turbines can be installed to take advantage of UHE Tucuruí remaining potentials. This potential can be used to supply communities still isolated in the region. This study guides on the hydrodynamic modeling of the stretch mentioned above, starting from bathymetric data collecting and substrate composition, elaboration of terrain's elevation model and substrate model. Hydrodynamic simulations have been established by the Saint-Venant Model. Modeling results, i.e., velocities and depths analyzed in the study area, serve to the evaluation and determination of sites to set up hydrokinetic turbines to explore remaining power.*

Keywords: Hydrodynamic Modeling, Hydrokinetic Potential, UHE-Tucuruí, Tocantins River, Amazonia

1. INTRODUCTION

Hydrodynamic models have been used in many studies about fluvial hydraulic, water circulation in lakes, lagoons, bays, estuaries, hydroelectric reservoirs and so on. Such models are frequently used to explain the behavior of field variation of velocities and depths in function of space and time.

In Brazil, water resources have decisive importance in the economic plan. That country is provided with a vast and dense hydrographic net. In Para's state, there is a large hydroelectric power plant – the Tucuruí's UHE, the biggest genuinely Brazilian, located on Tocantins River. Figure 1 shows the stretch of Tocantins River, UHE Tucuruí's downstream until the city of Tucuruí. In this case, the flow has been modeled for assessing locations where hydrokinetic turbines can be installed to take advantage of Tucuruí's UHE remaining potentials. Evaluations of these sites depend on stream and depths, because the larger the velocities the larger will be turbines' power; and the larger depths the larger the rotors of these machines and, consequently, the larger also will be the powers. Modeling results, i.e., velocities and depths of the analyzed stretch will serve for the determination of the site to set up of hydrokinetic turbines. This turbines

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are hydraulic machines that convert the kinetic energy of moving water and then into electrical energy, without interrupting the flow of current.

Source: Guia Geográfico, available in: http://www.mapas-brasil.com/para.htm

Source: Google Earth 2013

Figure 1. Location Map and Satellite Image of Study Area

2. METHODOLOGY

The development of hydrodynamic modeling primarily requires obtaining substrate and bathymetric data. The bathymetric data are used for assembly the Terrain Elevation Model (TEM), whereas the substrate composition data are used for setting the Manning coefficient. The TEM plus the roughness model and boundary conditions provided the data for the Saint-Venant shallow water equations that are solved, thus allowing for simulating the velocities and depths of Tocantins River.

2.1 Numerical tools

The present analysis employs the *Modeleur* and *Hydrosim* software developed at INRS-ETE, Université du Québec, Canada (Secretan and Leclerc, 1998; Secretan *et al*., 2000, Heniche *et al*., 2000). *Modeleur* is a combination of a Geographic Information System (G.I.S.) and a powerful Finite Element pre- and post-processor. It allows for the creation of Numerical Terrain Models (N.M.T) with information concerning topography, riverbed substrate, wind, and aquatic plants. *Modeleur* also enables division of the analyzed region into partitions associated with data sets from the M.N.T. An automatic data treatment procedure in the partition interfaces is used to generate the finite element mesh utilized by hydrosim, the 2-D Saint-Venant shallow flow model with a drying/wetting capability to follow the moving shoreline (Secretan and Leclerc, 1998). Studies conducted by Blanco *et al*. 2009, Barros *et al.* 2011 and Holanda *et al*. 2011, corroborate the efficiency of the model for the region of application, thus allowing the flow simulation and the consequent estimate of velocities.

2.2 Bathymetric Data

In the present study, bathymetric data were supplied by the company Eletronorte/Eletrobras. These data came from the company AHIMOR - Administração das Hidrovias da Amazônia Oriental and date back from September 2004, being collected through the single beam echo sounder. Figure 2 shows 2004 topography raw data of Tocantins River in the analyzed stretch, these points, 105.537 in total, are used to generate TEM.

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Figure 2. Topography Raw Data

2.3 Roughness model

Substrate data come from observations in outcropping and submerged rocks observed in three fieldworks. First in may 2012, which served for terrain recognizing; second in June 2012, aiming flow measures and water level observations, and third with the same objectives of second's. After these fieldworks, substrate composition for the river bed was determined as being 100% rock.

The Manning friction coefficient (n) is calculated by the following expression (Secretan *et al.*, 2000),

$$n = \frac{1}{34.9\left[-\log\left(d_{med}\right)\right]^{0.31} + 0.00017} \qquad (1)$$

With this information, *Modeleur* determined a Manning coefficient (n) for the region of 0.051. If this value is replaced in the equation (1), 0.7 m average diameter (d_{med}) to the rocks of that region of Tocantins River was obtained.

2.4 Boundary Conditions

Another underlying element for formulating the hydrodynamic model includes the appropriate boundary conditions. In the current work were used water levels from June to December 2012. Table 1 shows water levels in the boundaries south and north as shows Figure 2. The table also shows the flows in the stretch analyzed of the Tocantins River

Table 1. Dam and Tucuruí's water-level scale and Flows

Ano 2012	Nível na barragem fronteira sul (m)	Nível em Tucuruí fronteira norte (m)	Vazão (m^3/s)
21/06	6.75	6.10	7,466
24/07	5.45	4.80	5,466
30/08	6.45	5.40	8,032
25/09	5.40	4.85	5,116
13/11	4.90	4.50	3,841
13/12	6.95	6.15	8,442

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2.5 Hydrodynamic Model

In the model, the mass conservation and momentum equations were integrated over the depth in the vertical direction and discretized in the horizontal plane. The problem then became two-dimensional, with the computed values obtained for velocities and the free surfaces elevations. Furthermore, the Saint-Venant shallow water model is subject to the following hypothesis (Heniche *et al*., 2000):
- the water column is mixed in the vertical direction and the depth is small in comparison to the width and the length of the water volume;
- the waves are of small amplitude and long period (tide waves). The vertical acceleration component is negligible, allowing for hydrostatic pressure approximation.

Suitability of these 2D models to the study of the hydrodynamic behavior of the Tocantins River is justified by: absence of thermal stratification; minor salinity variations; small velocity components in the vertical direction. These characteristics make it reasonable to use a Saint-Venant shallow water model for simulations flow patterns in Tocantins River.

Equations (2) to (4) are the conservative form of the Saint-Venant shallow water equations. Equation (2) is the mass conservation equation, while Equations (3) and (4) are the equations for conservation of momentum:

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0 \tag{2}$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial q_x \frac{q_x}{H}}{\partial x}+\frac{\partial q_x \frac{q_y}{H}}{\partial y}=\sum F_x \tag{3}$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial q_y \frac{q_x}{H}}{\partial x}+\frac{\partial q_y \frac{q_y}{H}}{\partial y}=\sum F_y \tag{4}$$

In which x and y are horizontal Cartesian directions; q_x and q_y are flow rates in the x and y directions; t is time; h is free surface elevation above the mean water level; H is the depth of the water column, and F_x and F_y are the volume force components in the x and y directions. F_x and F_y are calculated using equations (5) and (6).

$$\sum F_x=-gH\frac{\partial h}{\partial x}-\frac{n^2 g|\vec{q}|q_x}{H^{1/3}}+\frac{1}{\rho}\left(\frac{\partial(H\tau_{xx})}{\partial x}\right)+\frac{1}{\rho}\left(\frac{\partial(H\tau_{xy})}{\partial y}\right)+F_{cx}+F_{wx} \tag{5}$$

$$\sum F_y=-gH\frac{\partial h}{\partial y}-\frac{n^2 g|\vec{q}|q_y}{H^{1/3}}+\frac{1}{\rho}\left(\frac{\partial(H\tau_{yx})}{\partial x}\right)+\frac{1}{\rho}\left(\frac{\partial(H\tau_{yy})}{\partial y}\right)+F_{cy}+F_{wy} \tag{6}$$

where g is the acceleration of gravity; n is the Manning coefficient; $|\vec{q}|$ is the flux magnitude; ρ is the water density; F_{cx} and F_{cy} are the Coriolis force components in x and y directions; and F_{wx} and F_{wy} are the wind force components, in the x and y directions; and τ_{ij} is the Reynolds stress tensor; $\tau_{ij}=\nu\left(\frac{\partial\overline{U_i}}{\partial x_j}+\frac{\partial\overline{U_j}}{\partial x_i}\right)$

where $\overline{U_i}$ is the mean velocity in the direction i; and ν is the kinematic eddy viscosity.

The turbulence model is a zero equation model of mixing length (L_m) type according to Rodi (1993) where L_m is the distance between the wall and a point in the flow from which the wall itself ceases to influence the turbulence. This model assumes a balance between creation and dissipation of energy. In this case, the kinematic turbulence viscosity is given by:

$$\upsilon_t=L_m^2\sqrt{2D_{ij}D_{ij}} \tag{7}$$

where D_{ij} represents the ij components of the deformation tensor, given by

$$D_{ij}=\frac{1}{2}\left(\frac{\partial\overline{U_i}}{\partial x_j}+\frac{\partial\overline{U_j}}{\partial x_i}\right) \tag{8}$$

The influence of the wind is not taken into account herein. The Coriolis Effect is neglected due to the location and size of the domain, near the Equator.

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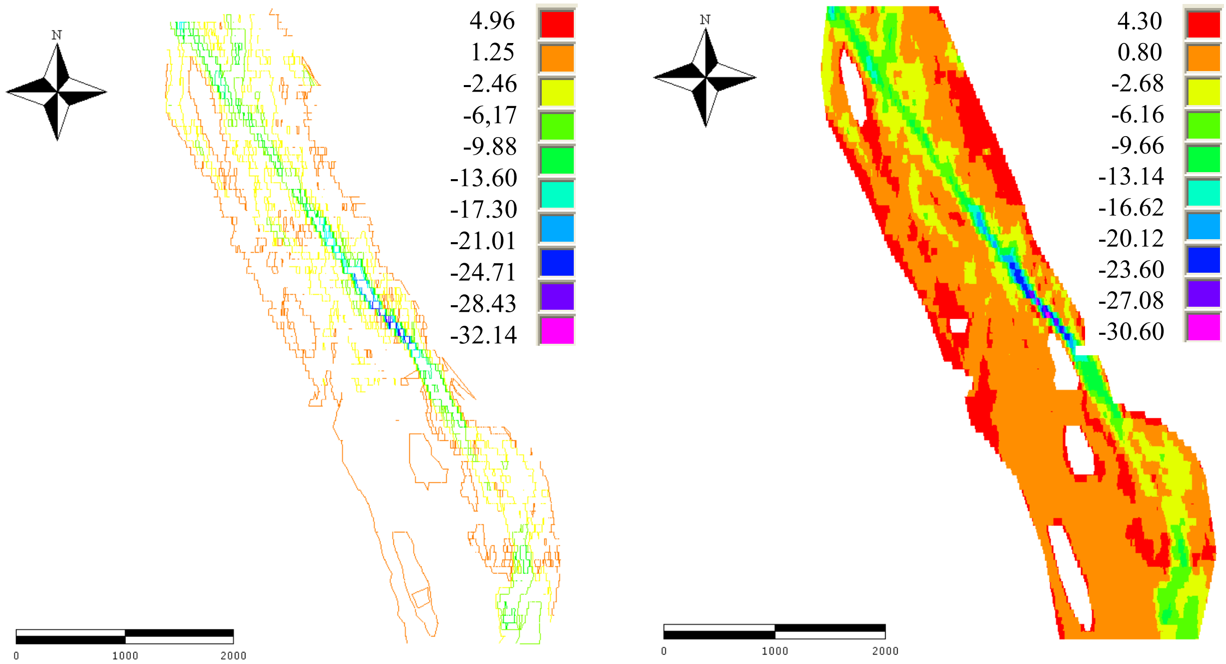
3. RESULTS

Hydrodynamic regime considered in this study was stationary, in other words, without tidal influence, which is one good hypothesis, considering that water levels and flow are controlled much more by the UHE Tucuruí operation than by possible tidal variation, which still may affect Tocantins River close to Tucuruí.

3.1 Terrain Elevation Model

Figure 3 shows raw and interpolated terrain elevation model of analyzed domain. From Figure 3 can be seen the formation of a channel close to the islands, where the larger velocities must be found enabling hydrokinetic turbines set up.



(a) (b)

Figure 3. Raw (a) and Interpolated (b) Terrain Elevation Model (m)

3.2 Hydrodynamic Mesh

With terrain elevation model, *Modeleur* generated the hydrodynamic mesh (Figure 4). The mesh stores all input variables required for the resolution of Saint-Venant shallow water equations, as well as the resulting variables for the simulation of the two-dimensional flow (v_x, v_y and depth). For the model considered herein, the input variables are: coordinates x, y and z, interpolated via TEM and transferred to the hydrodynamic mesh, the Manning friction coefficient value calculated and the boundary conditions defined previously.

Hydrodynamic mesh on Figure 4, with 19,943 nodes, 9,629 triangular elements and with larger edge equals to 22m was generated from a frontal isotropic algorithm that uses just one space parameter and tries to generate triangles the more regular possible (Secretan *et al.*, 2000).

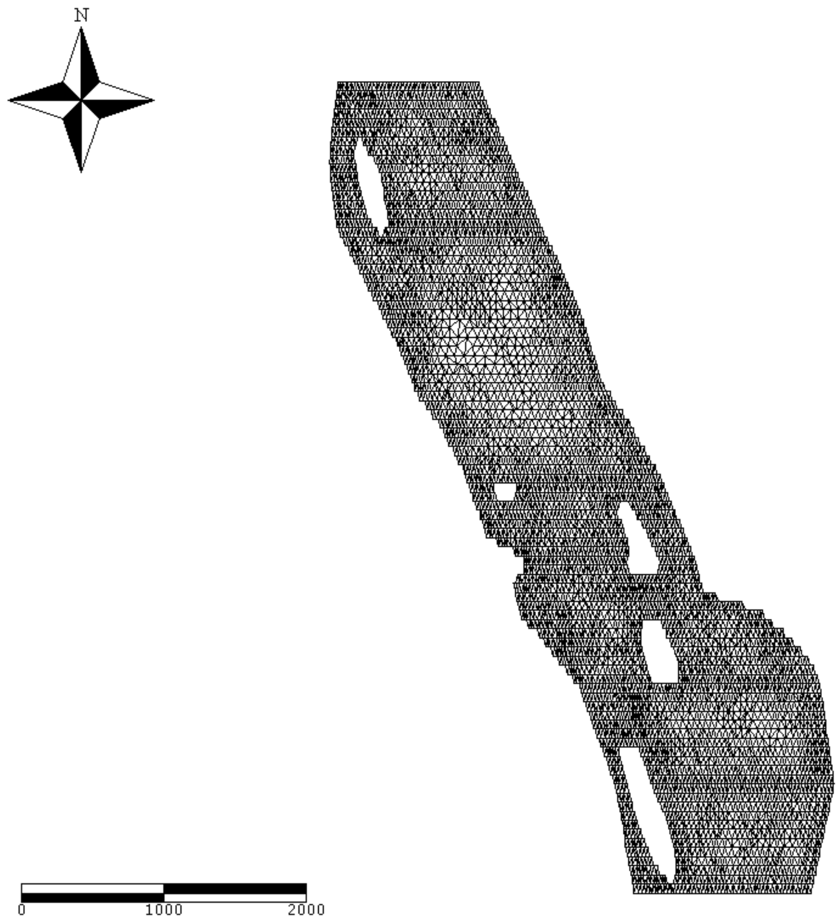


Figure 4. Finite Elements Mesh for the Hydrodynamic Model

Hydrodynamic simulations from period considered was carried out a study from meshes 30, 22 and 15 m. The mesh 22 m presented a better result, i.e. computational model converged in a satisfactory way, in relation percentage error of the maxima velocity (Table 2) found in channel of the Figure 3. Simulations were taken in a computer with processor Intel Core 2 DUO (2.93 Ghz).

Table 2. Mesh Study

Month/2012	Mesh (m)	Velocity (m/s)	Error (%)	Computacional Time
June	22/15	1.507	1.41	4min:59s
July	22/15	1.384	1.24	2min:60s
August	22/15	1.470	1.30	2min:33s
September	22/15	1.379	1.17	2min:16s
November	22/15	1.329	0.98	2min:18s
December	22/15	1.525	1.39	2min:43s

3.3 Simulated Depth

Modeleur simulates depths through the Equation (9), using interpolated bottom topography via FEM in the hydrodynamic mesh.

$$\text{Prof} = \text{NA} - \text{Cota} \tag{9}$$

Where: Prof is depth (m); N.A. is water level (m); and Cota is the terrain topography (m).

Figures 5, 6 and 7 present respectively depth isosurfaces from June until December 2012. The figures also show numbers cross the channel for analyzing the depths. It can be observed that model has simulated depths well, such fact

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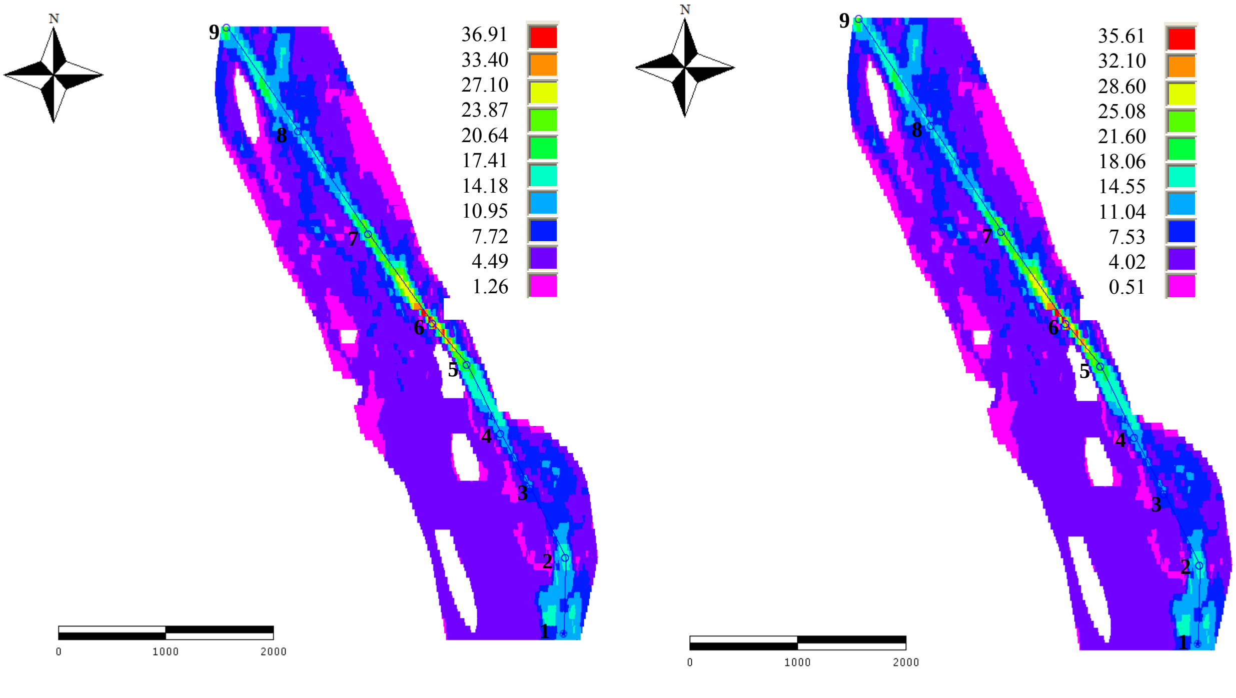
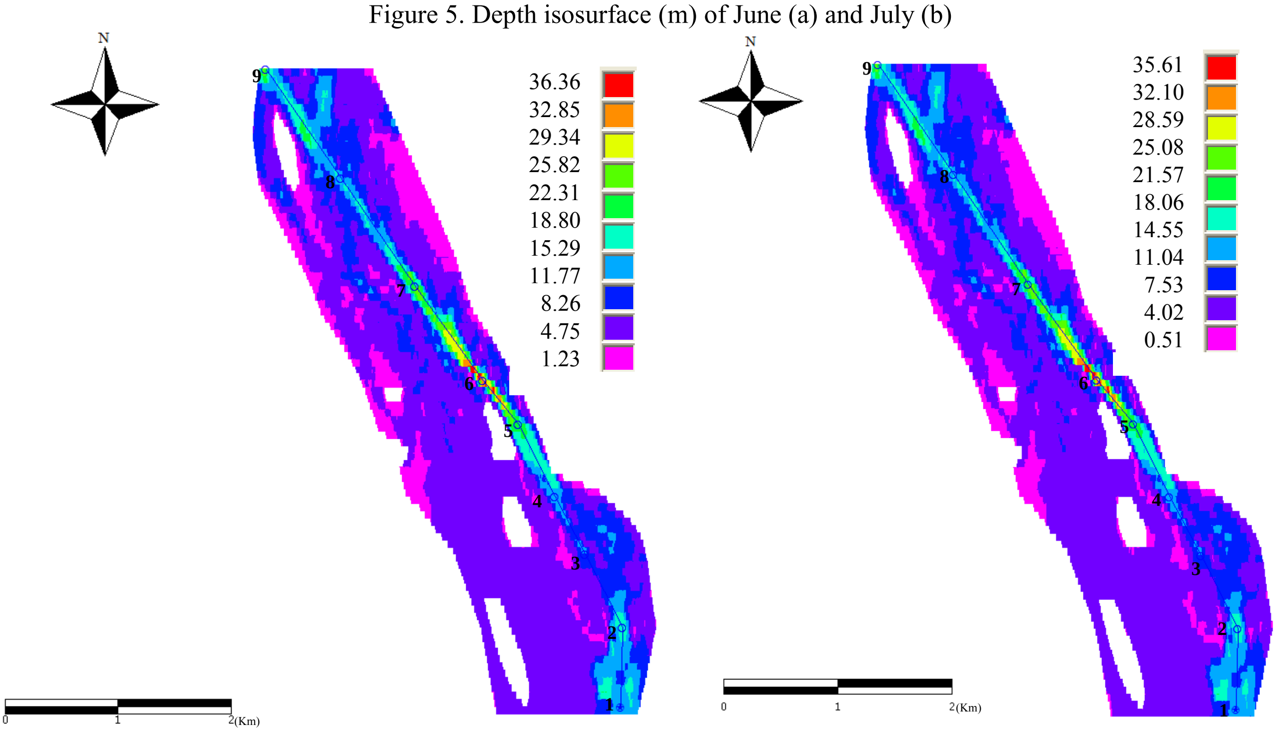
validates interpolated bottom terrain by *Modeleur,* making sure that terrain used in Saint-Venant shallow water equations solution represents well river Tocantins channel in the actual configuration.



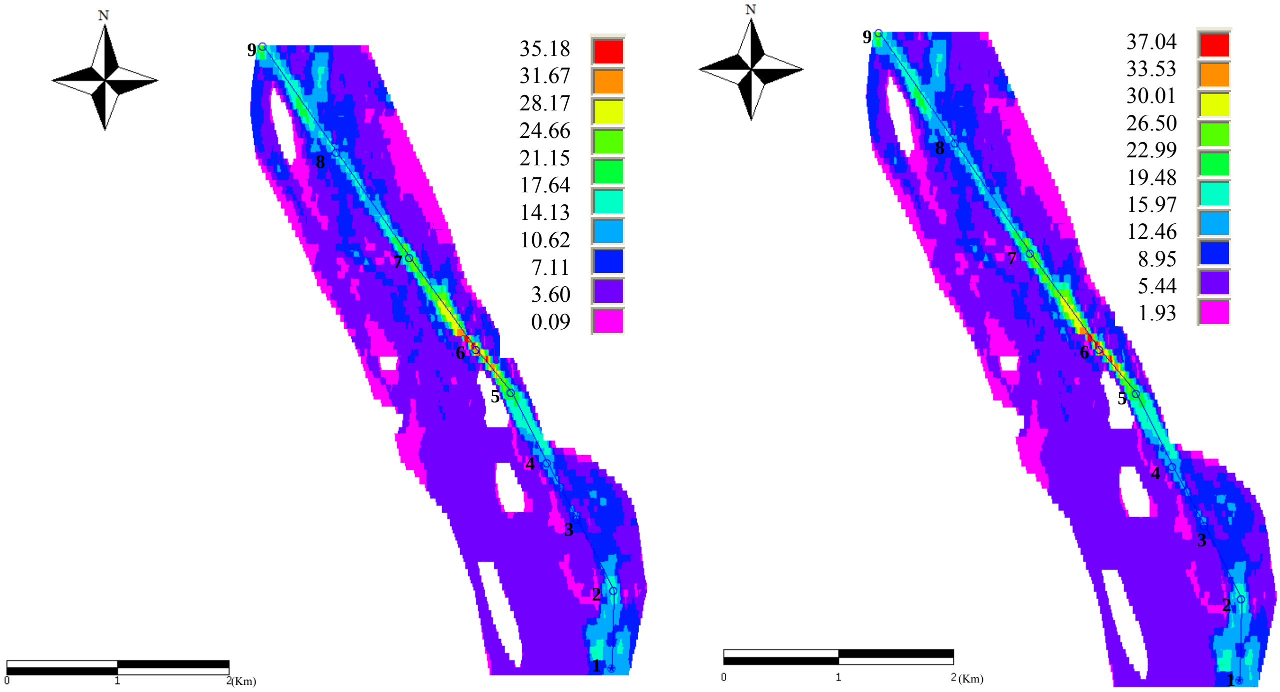
(a) (b)

Figure 5. Depth isosurface (m) of June (a) and July (b)



(a) (b)

Figure 6. Depth Isosurface (m) of August (a) and September (b)

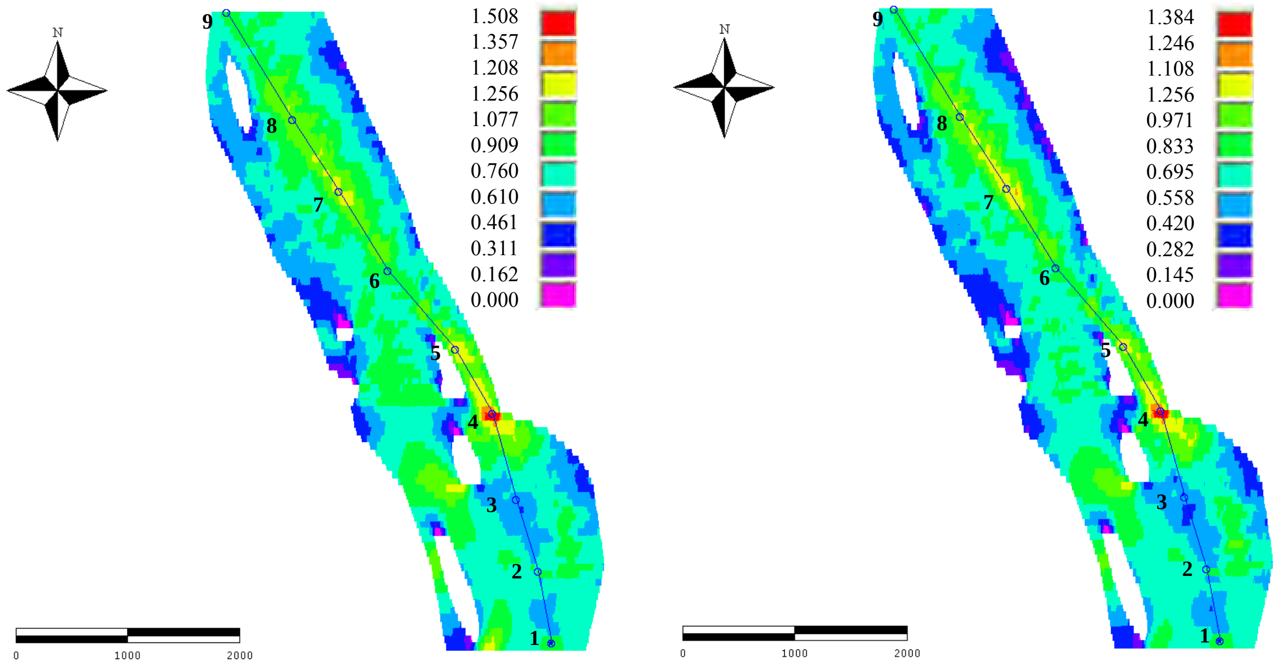


(a) (b)

Figure 7. Depth isosurface (m) of November (a) and December (b)

3.4 Velocity

Figures 8, 9 and 10 present respectively velocity magnitude isosurfaces from June until December 2012. The figures also show numbers cross the channel for analyzing the velocity magnitude values. The positions of the points are the same points used for depth.



(a) (b)

Figure 8. Velocity Magnitude Isosurface (m/s) of June (a) and July (b)

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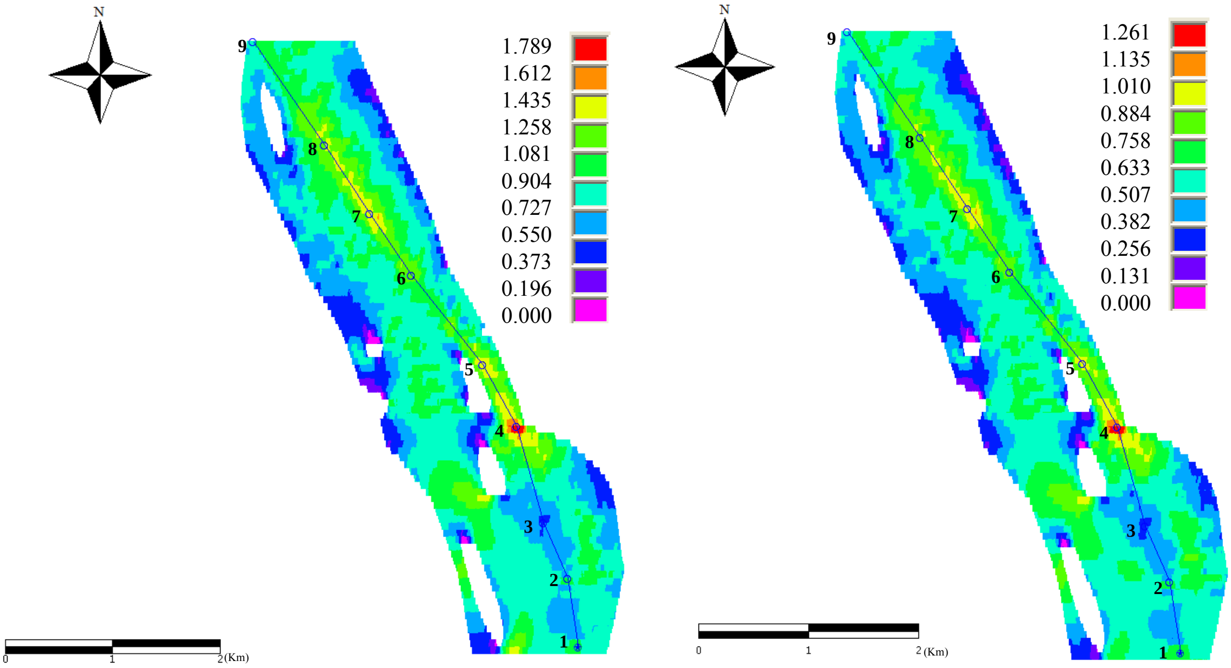
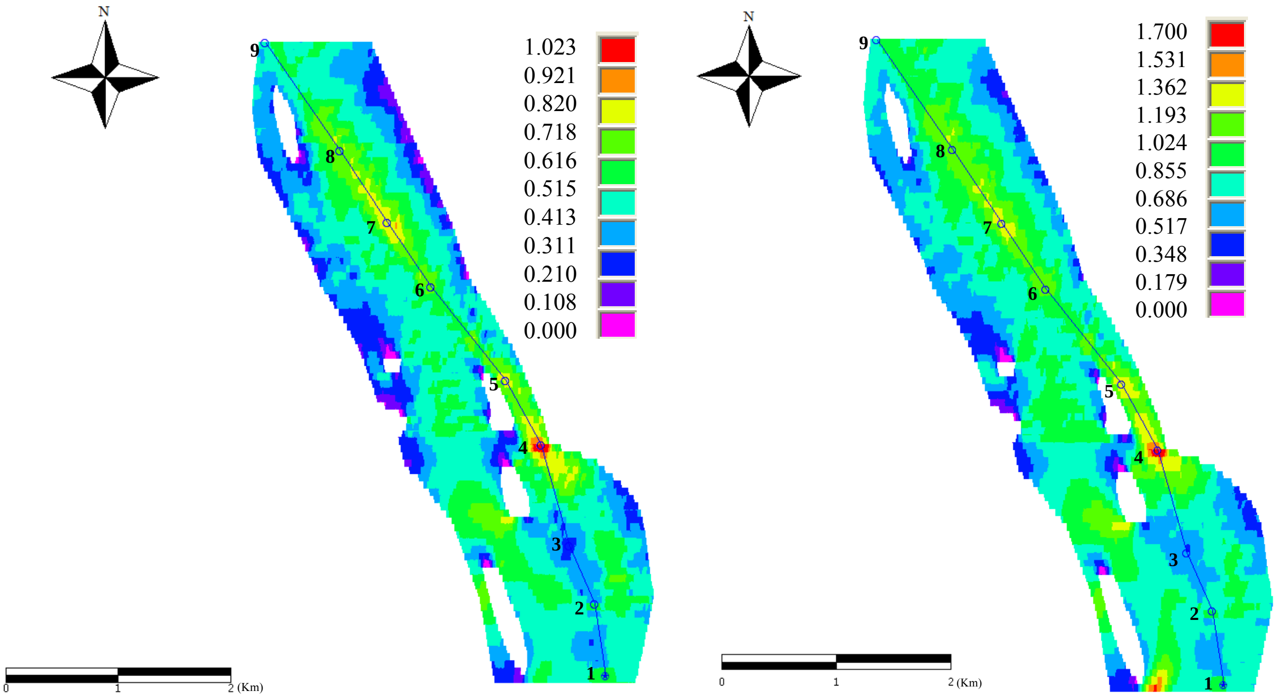


(a) (b)

Figure 9. Velocity Magnitude Isosurface (m/s) of August (a) and September (b)



(a) (b)

Figure 10. Velocity Magnitude Isosurface (m) of November (a) and December (b)

Analyzing the figures, one can observe that the velocities vary between 0.000 and 1.789 m/s. The maximum value was simulated for December 2012. These maximum velocities occur exactly at channel preferential flow of the river. This channel also has the largest depths of the river (Figures 5, 6 and 7). Figures 11, 12 and 13 present respectively velocity and depth profile graphics in the channel for the points presented in the Figures 5, 6, 7, 8, 9 and 10.

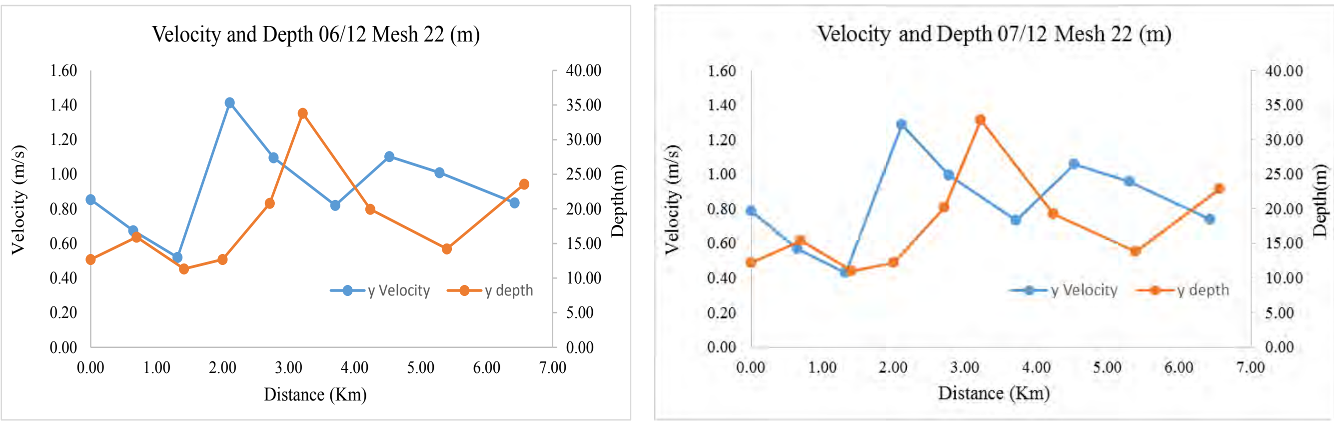


Figure 11. Velocity and depth profile graphics of June and July

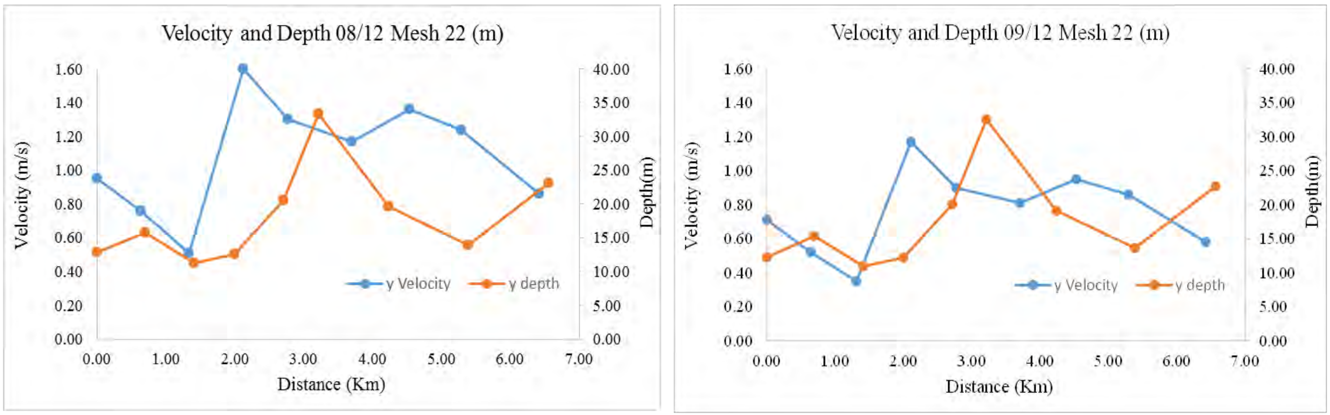


Figure 12. Velocity and depth profile graphics of August and September

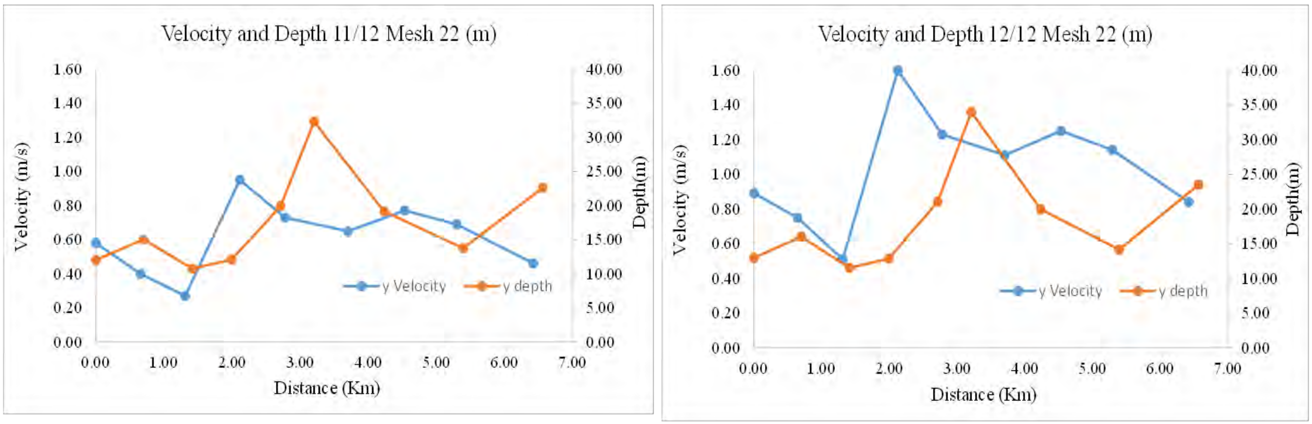


Figure 13. Velocity and depth profile graphics of November and December

Through these figures, one can analyze punctually the best places to set up the hydrokinetic turbines, considering the pair velocity-depth (allowing the largest diameters). Thus, point 6, which has largest depth of about 32.0 m, with a velocity of about 0.8 m/s; and point 4, which has largest velocity of about 1.3 m/s, with depth of about 13.0 m, are the sites to be analyzed initially to set up of hydrokinetic turbines.

4. CONCLUSIONS

Hydrodynamic modeling presented in the current work achieved to represent well terrain bottom topography in question, besides flow patterns, velocities and depths of Tocantins River analyzed stretch. Velocities and depths were simulated from June to December 2012 for the Tocantins River channel, where higher velocities and depths were found.

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In this case, this channel can be already indicated to the set up of hydrokinetic turbines, aiming to maximize generated power, which depends on the area and velocities.

The results showed that two sites can be analyzed initially to set up of hydrokinetic turbines, respecting the pair velocity-diameter magnitude. A more detailed analysis should be dedicated to these sites since they can be exploited to set up of hydrokinetic turbines within the context of the use of water poured and turbinated of the UHE Tucuruí.

It should be added that this analysis is still preliminary, since the model needs to be calibrated and the months from January to May analyzed. Mainly because during these months occur floods in the Amazon.

5. ACKNOWLEDGEMENTS

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