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1D-2D Hydraulic Modeling of a Diversion Channel on the Cavally River in Zouan-Hounien, Cote d'Ivoire

Kouassı Kouakou Lazare*, Brou Loukou Alexis, Yao Affoué Berthe, Kouadıo Zilé Alex, Konan Kouakou Séraphin, Konan Koffi Félix, Koffı Bérenger

Department of Geology, University Jean Lorougnon GUEDE, Daloa, Cote d'Ivoire
Email: *k_lazare@yahoo.fr

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Abstract

On the Cavally River, located on the border between Côte d'Ivoire and Liberia, several hydraulic structures such as bridges and diversion channels are planned to be made in recent years in the operating perimeter of the Ity mining company. A 1D-2D hydraulic model was developed to design a diversion channel to cut a meander of the Cavally River in order to ensure hydraulic operation similar to the initial conditions of the river (water levels, flow and velocities). This model was designed with a flow rate of 240 m^3/s and a Manning coefficient of 0.052 $m^{1/3}\cdot s^{-1}$ for the minor bed and 0.06 $m^{1/3}\cdot s^{-1}$ for the major bed. The results from the hydraulic model show that the hydraulic conditions (water levels, velocities) in the channel before and after the diversion remain almost like those of the Cavally River.

Keywords

Hydraulic Modeling, Diversion Channel, Cavally River, Ity, Côte d'Ivoire

1. Introduction

Intensification of human activities on watersheds in general is one of the factors that favor erosion phenomena and roughness modification as well as the section of rivers [1]. Among these activities, mining activities and infrastructure construction (dams, bridges, diversion of waterways, etc.) occupy a prominent place. Therefore, an understanding of these developments through hydrological and hydraulic studies is necessary to ensure the protection of the environment in general and hydro systems in particular [2] [3] [4] [5] [6]. To provide precise answers to their understanding, several studies have already been conducted using different hydraulic models [7]. Among the main anthropogenic causes of the modification of the functioning of rivers, some authors such as Alexeevsky *et al.* (2013) [8] and Maio *et al.* (2013) [9] underlined the preponderant role of the construction of infrastructures or their suppression on the modification of river geometry. Côte d'Ivoire has four major rivers (Cavally, Sassandra, Bandama and Comoe). Their basins undergo anthropogenic activities of all kinds. The Cavally River, located on the border between Côte d'Ivoire and Liberia, crosses the Ity Mining Company (SMI) exploitation zone in Zouan-Hounien. The Cavally River has a lot of meanders in this area and the stream bed is heavily disturbed by illegal miners. Several hydraulic structures such as bridges and diversion channels are planned to be constructed on the watercourse namely the construction of a diversion channel on the river bed. Therefore, the diversion of watercourses can have undesirable social and environmental consequences, namely the modification of social structures and the hydrological dysfunction of the watershed concerned. In addition, whole villages may be engulfed or people may be forced to find new livelihoods or change their way of life [8] [10]. In view of all the consequences that such a project can generate, in-depth studies must be carried out to size the diversion channel to ensure hydraulic conditions like the initial state of the watercourse. The main objective of this study is to establish a 1D-2D hydraulic model to design a diversion channel capable of ensuring flow conditions hydraulically like the initial conditions of the watercourse.

2. Material and Methods

2.1. Study Area

The Cavally River is a lower cross border watershed between Guinea, Ivory Coast and Liberia. Located in the west of Côte d'Ivoire, the Cavally River begins in Guinea, in the North of Mount Nimba with more than 1000 meters as approximate altitude (**Figure 1**). The lower watershed covers a complete area of 28,800 Sq. km at Tate hydrometric station located at 60 km from the mouth. Côte d'Ivoire doesn't possess but about 15,000 Sq. km of watershed [11]. In the framework of this study, the chosen outlet is the hydrometric station of Floleu located at downstream of the Ity station in the Zouan-Hounien region. The low watershed has an area of 3647.53 Sq. km. The region of Zouan-Hounien is in the mountain region of Côte d'Ivoire; its relief is hilly. Zouan-Hounien is in the forest area and its climate is the mountain climate with two seasons: one rainy season from May to October and one dry season from November to March. The annual average temperature is 25.6˚C. The annual average precipitation is 1866 mm. The driest month is January with a precipitation of 15 mm. The most important precipitations are recorded in September and they are 357 mm in average [12].

2.1.1. Characterization of Derivation Area

The meander of the Cavally River that will be cut is located in the vicinity of the Ity mining company between kilometer point PK7 + 400 and PK10 + 400. The meander is 3 km long (**Figure 2**).

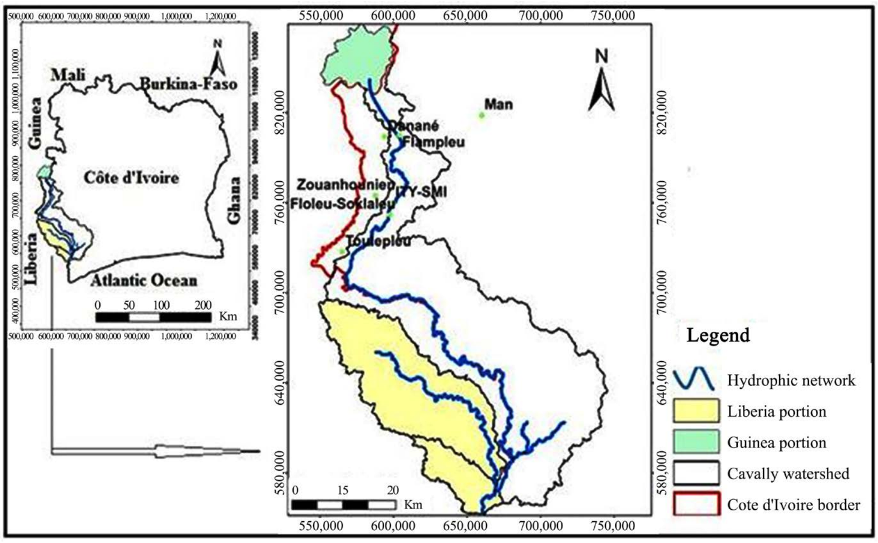

Figure 1. Study area of sub-watershed of Cavally River.

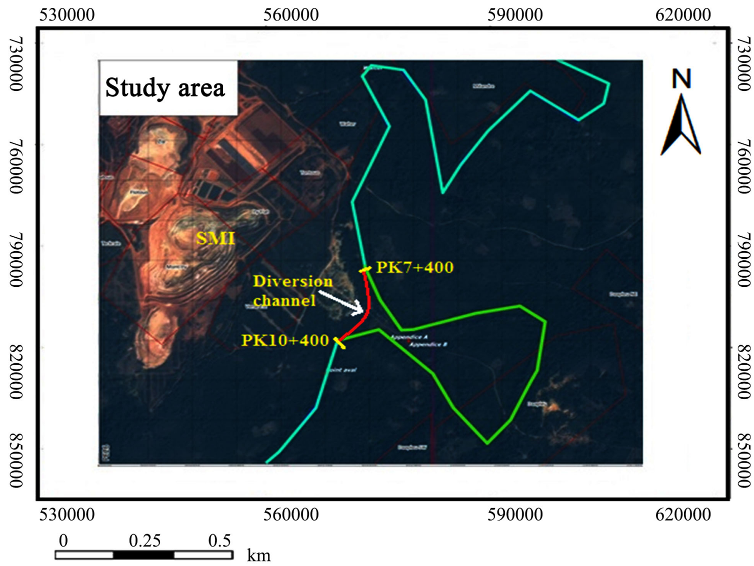

Figure 2. Implementation area of the diversion channel on the Cavally River bed.

2.1.2. Data Acquisition and Analysis

The measurements of water flows and the profiles of water levels between Ity station (upstream) and Floleu station (downstream) of the diversion channel were respectively carried out from July to October 2015, in October 2018 (rainy season) and February 2019 (dry season). The flows of the river were measured by means of an Acoustic Doppler current profiler (ADCP). The measurements of the profiles of water levels were realized by means of a differential Global Positioning System (GPS) models STONEX S8 Plus. Displacements on the river were carried out using an outboard motor boat made for 26 km along the Cavally River with a step of 200 m between 2 points of measurements. A digital elevation model (DEM) with 90 m resolution was used for the determination of altitudes and the slopes (https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/).

This DEM was corrected by combining with a Lidar image of 1.30 m resolution using the Global Mapper version 15 triangulation tools.

2.2. Methods

2.2.1. Diversion Channel Design Criteria

The diversion channel was designed for a return period of 2 years with a flow rate of 240 m^3/s, after flood estimation by frequency analysis. The Cavally River hydrology was studied using records from three hydrometric stations: Flampleu, Ity and Toulepleu (see **Figure 1**). Long term daily flow (1955-2001) and water level measurements were used.

The diversion channel was designed to not to increase in the water flow elevation of the river during the floods. To this end the channel will have approximatively similar cross section area as the river in natural condition.

In order to avoid sediment deposition and erosion of the slab the average flow velocity in the channel was maintained between 0.5 m/s and 1.5 m/s as recommended by several authors [4] [13]. The hydraulic parameters determined are presented by Equations (1), (2) and (3) and (**Figure 3**).

- Wet section (S)

$$S = (b + my) y \tag{1}$$

- Wet perimeter (P)

$$p = b + my \tag{2}$$

- Hydraulic radius (R_h)

$$R_h = \frac{S}{P} = \frac{(b + my) y}{b + my} \tag{3}$$

where: b: width of the channel bottom; y: depth; m: slope coefficient.

2.2.2. Modeling Water Surface Elevation by HEC-RAS

Frequency Analysis was used to select the law that best fits the flood estimation of the Ity station to obtain the most appropriate return period for the derivation channel sizing. The model allowed understanding the evolution of the distribution of the hydraulic parameters which are among others the velocities, the water levels and the flows before the realization of the diversion channel while considering the results of the frequency analysis.

For the purposes of this study, flows are considered non-permanent given the variation in hydraulic parameters (flows, water levels, depths, velocities) as a function of time. The hydraulic design of the diversion channel was based on the simulation the flow using HEC-RAS 1D-2D hydrodynamic software for natural and modified conditions. The equations used in the case of a non-stationary flow are among others the conservation of the mass (Equation (4)) and the conservation of the momentum (Equation (5)) [14].

- Mass conservation

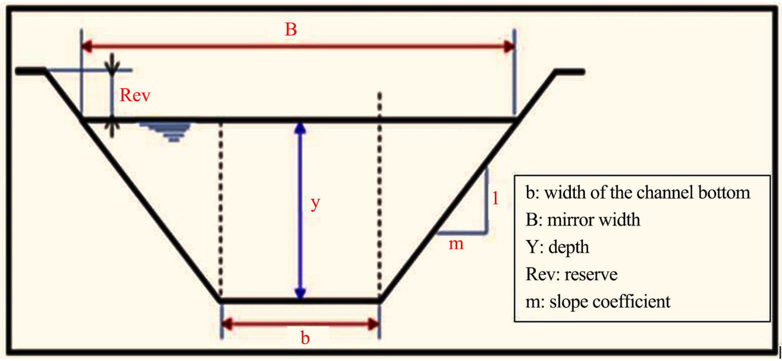

Figure 3. Diversion channel geometry.

The unsteady differential form of the mass conservation equation is:

$$\frac{\partial H}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}+q=0 \tag{4}$$

- Momentum conservation

$$\left.\begin{aligned}\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}&=-g\frac{\partial H}{\partial x}+v_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-c_f u+fv\\ \frac{\partial u}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}&=-g\frac{\partial H}{\partial y}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f v+fu\end{aligned}\right\} \tag{5}$$

where t is time, h is the water surface elevation, u and v are the velocities components in the x and y direction respectively, q is a source/sink flux term, g is the gravitational acceleration, v_t is the horizontal eddy viscosity coefficient, c_f is the bottom friction coefficient, and f is the Coriolis parameter.

The mesh of the 2D model was realized on 50 m by 50 m. The Digital Elevation Model (DEM) was created by the fusion of an airborne LiDAR survey provided by SMI and a SRTM 90 digital elevation model. The SRTM 90 was adjusted by −3.85 m to obtain the same reference system as the LiDAR.

A flood hydrograph was imposed as a boundary condition upstream during the calibration phase of the model over the period from January 01 to April 30, 1988 with a time step of one hour (1 hour) and a longitudinal slope of 0.000194 m/m downstream. The results were validated over a dry period (01 January to 26 March 1983) and a wet period (18 July to 10 October 2015) by comparing simulated results with field observations. These periods were chosen to understand the behavior of the model regardless of the season and the consistency of the data obtained on the watershed. The fit between the predicted and observed values was evaluated using two functions: the Nash coefficient and the correlation coefficient given respectively by the Equations (6) and (7):

$$Nash=1-\frac{\sqrt{\sum_{i=1}^{n}\left(q_{ci}-q_{oi}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(q_{oi}-\overline{q}_o\right)^2}} \tag{6}$$

$$r = \frac{\sum_{i=1}^{n}\left(q_{ci}-\overline{q_c}\right)\left(q_{oi}-\overline{q_o}\right)}{\sqrt{\sum_{i=1}^{n}\left(q_{ci}-\overline{q_c}\right)^2 \sum_{i=1}^{n}\left(q_{oi}-\overline{q_o}\right)^2}} \quad (7)$$

In these two expressions, n represents the height of the sequence, q_{oi} represents the observed flow for calculated flow for the pace time i in m^3/s; q_{ci} is the calculated flow for the pace time i in m^3/s; q_0 is the observed average flow in m^3/s.

3. Results and Discussion

3.1. Results

3.1.1. Diversion Channel Design

The diversion channel has a length of 280 m, the manning coefficient retained is n = 0.06 m$^{1/3}$·s^{-1}. The average speed allowed in the canal is V = 1.1 m/s, a bank fruit m = 2.5 m for a longitudinal slope of the diversion channel S_f = 0.0036 m/m, a base b = 25 m a mirror width B = 65 m; depth y = 7 m; a wet perimeter P = 54.3 m; a wet section S = 222 Sq m. The side slope of the diversion channel: 2.5H: 1.0V.

3.1.2. Hydraulic Modeling before and after the Diversion Channel Completion

Figure 4 and Figure 5 show the results of the calibration and the validation of the model after variation of the Manning coefficient. The calibration of the model lead to Manning coefficient values n = 0.052 m$^{1/3}$·s^{-1} for the minor bed and 0.06 m$^{1/3}$·s^{-1} for the major bed. The flows used are those of the year 1983, 1988 and 2015. The graphical observation (Figure 4 and Figure 5) shows a good synchronism between the simulated values and the observed values. This good similarity between observed and simulated flows is evidenced by the numerical results, which show a strong correlation of 0.94 and a Nash coefficient of 0.92 for the calibration period. Nash values are 0.95; 0.83 and correlation values are 0.97

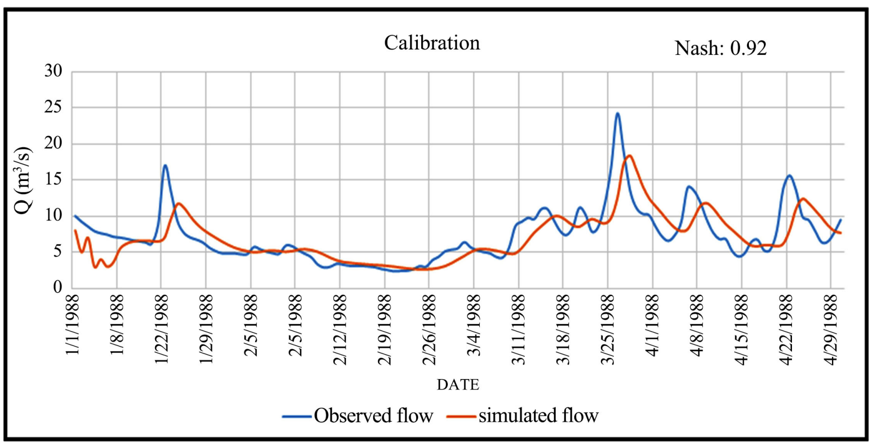

Figure 4. Comparison between observed and simulated flow rates after model calibration from 01 January to 30 April 1988.

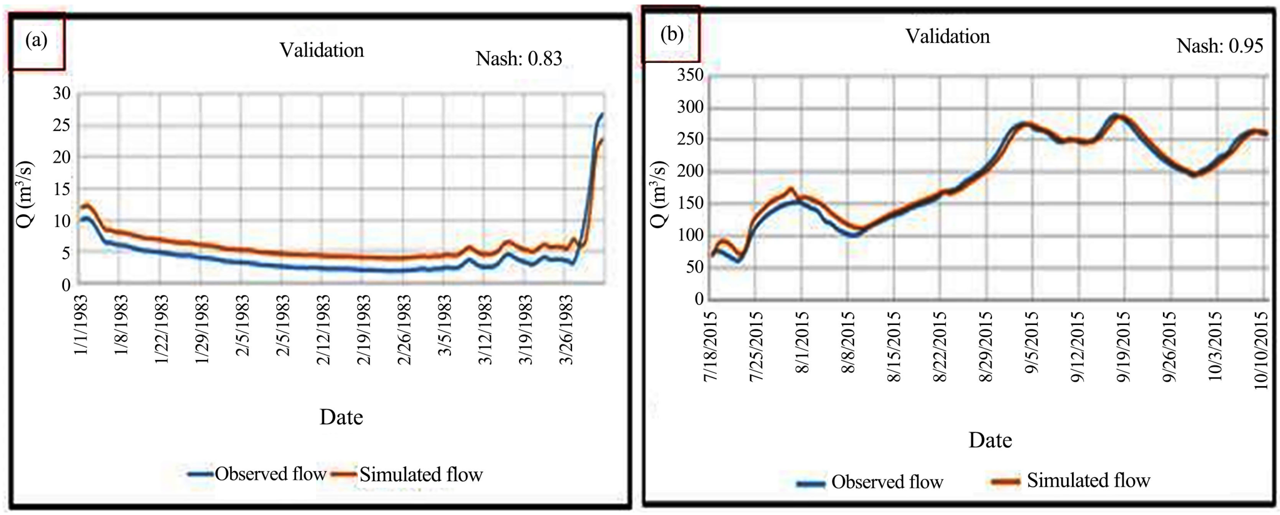

Figure 5. Comparison between flows observed and simulated after the model validation from January 1 to March 26, 1983(a) and from July 18 to October 10, 2015(b).

and 0.85 for validations periods. This good correlation between the simulated flow rates and observed flows shows that the hydraulic model reproduces well the dynamics of the flows of the watercourse.

3.1.3. Comparison of Cavally River Velocities before and after the Diversion Channel Completion

The velocities before and after the realization of the diversion channel are relatively low on the level of banks and high in the minor bed (Figure 6). These values in the same order of magnitude and lie between 0.10 and 1.6 m/s. Velocities decrease considerably by the upstream towards downstream. The highest velocities are in the zone of cut of the meander. It should be also noted that under the natural conditions there is an acceleration of the flow in concave banks at the entry of the meander.

3.1.4. Comparison of Water Levels before and after Diversion Channel Completion

The maps in Figure 7 show the difference in water level before and after the installation of the diversion channel. It can be noted that downstream of the canal the water levels remain almost in their natural state channel. On the other hand, just upstream of the canal, water levels have decreased by about 0.2 m, resulting in a slight increase in the Cavally River's hydraulic capacity at this location.

3.1.5. Flood Propagation Area Model before and after the Diversion Channel Construction

The maps in Figure 8 show the propagation area of the Cavally River before the construction of the bypass channel for floods with the 20- and 100-years return period. With reference to this figure, the water level varies from 262.1 to 262.4 m for the 20-year flood, and from 262.4 to 262.7 m for the 100-year flood in the meander cut-off zone (diversion channel).

Flooding areas changed slightly in the meander cutting zone and the water level decreased immediately downstream of the road by about 20 cm for both cases (**Figure 9**). In general, the difference in water levels of the floodplain is almost negligible.

With regard to the results of the flood propagation model the most important depths were observed at the upstream zone of the section of the watercourse. The water level increases of 20 cm upstream the channel (**Figure 10**).

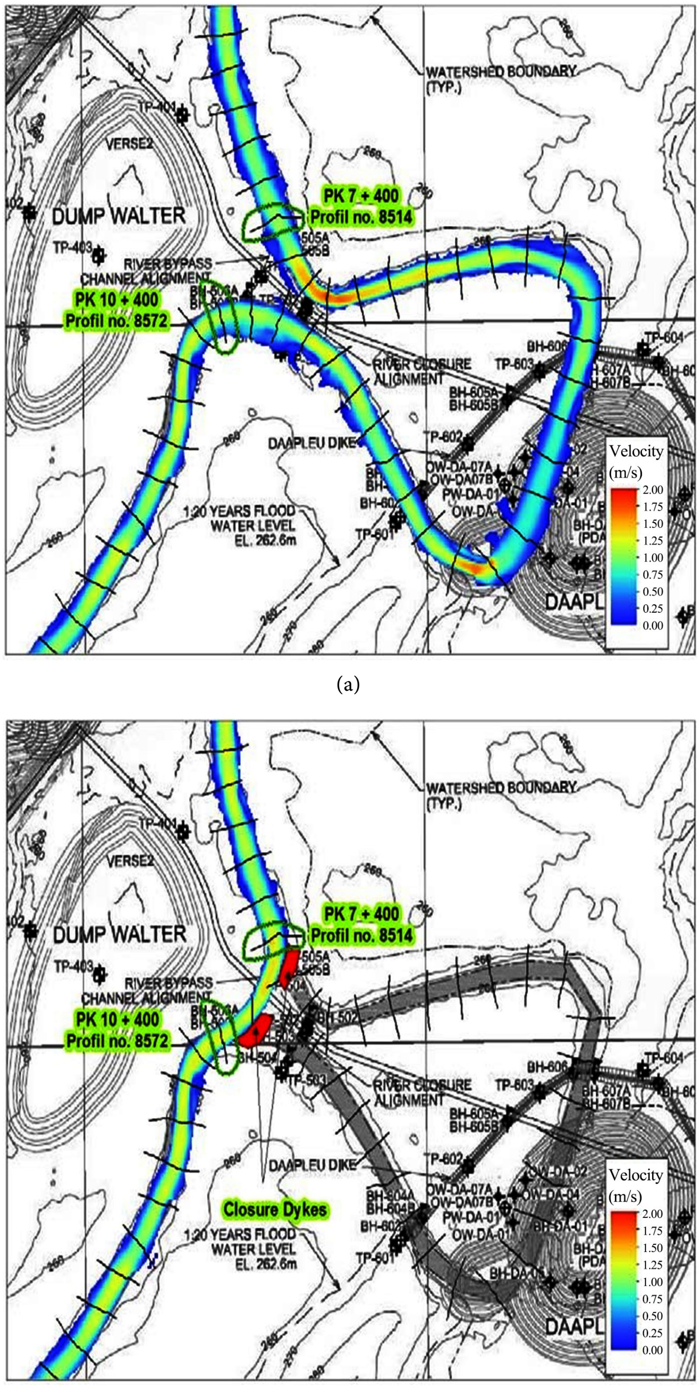

Figure 6. Velocities distribution before (a) and after (b) diversion channel.

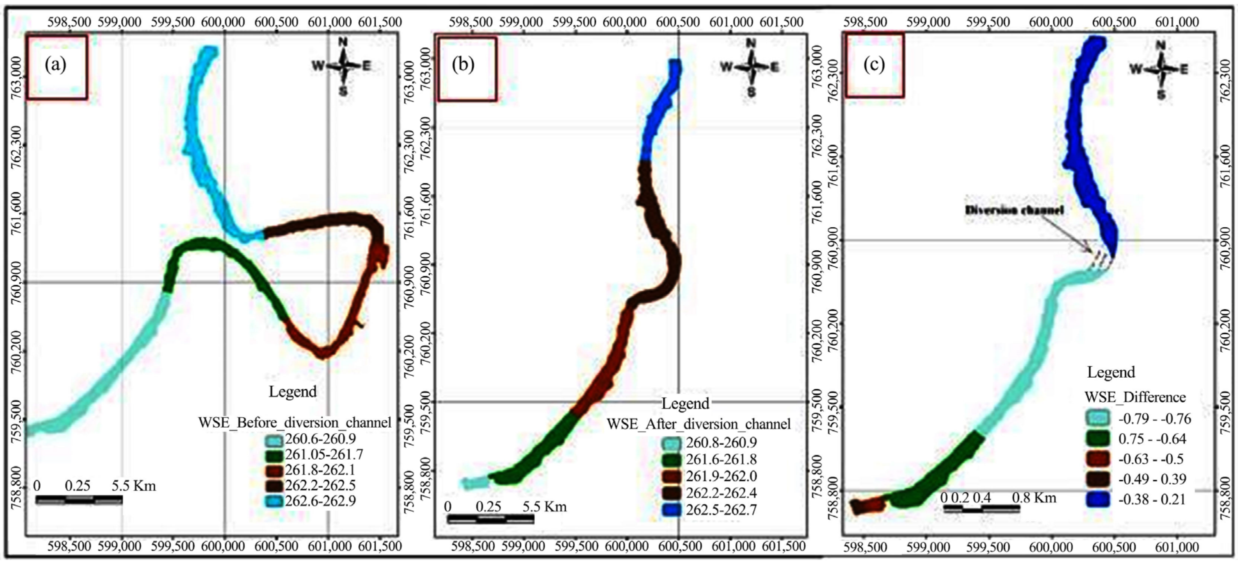

Figure 7. Difference in water surface elevation (c) between existing conditions (a) and future conditions (b).

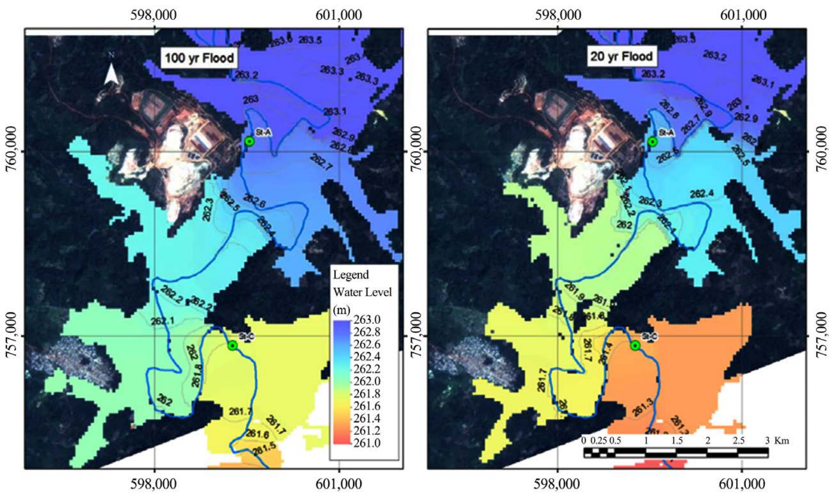

Figure 8. Flood propagation area before the diversion channel construction: 100 years (a) and 20 years (b).

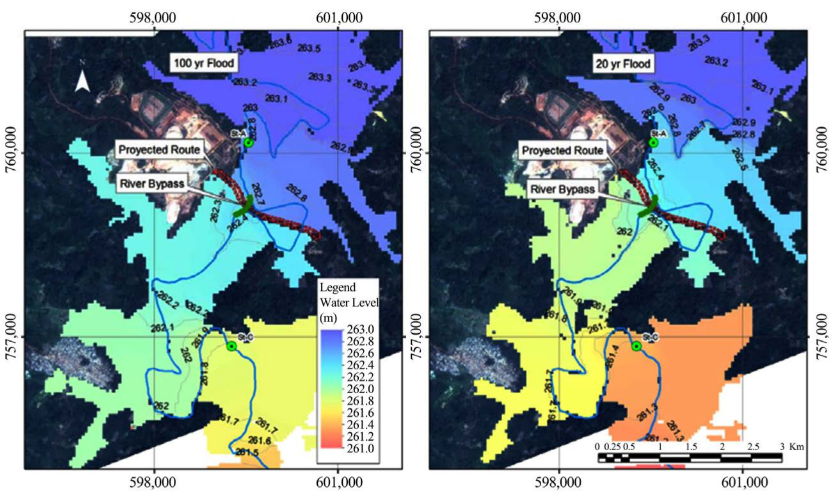

Figure 9. Flood propagation area after the diversion channel construction: 100 years (a) and 20 years (b).

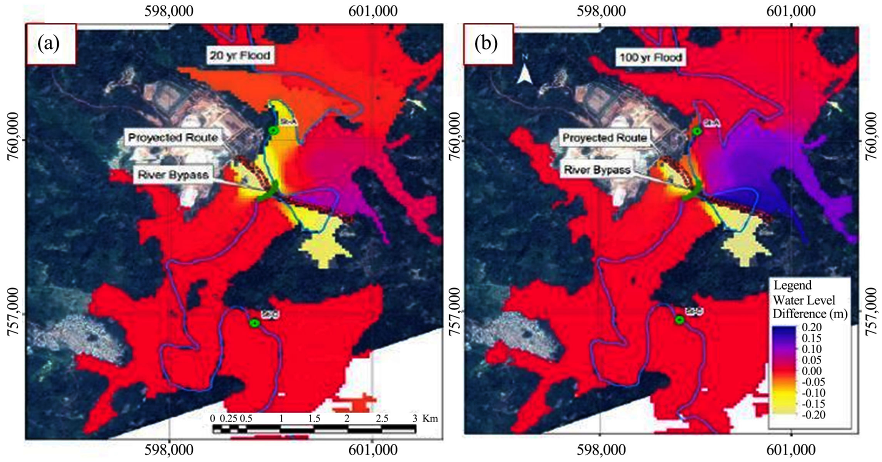

Figure 10. Water level difference after the diversion channel construction20 years (a) and 100 years (b).

3.2. Discussion

As part of the design of the Cavally River diversion channel using a 1D-2D hydraulic model, studies were carried out to impose flow conditions like the watercourse. The geometric characteristics of the bypass channel are justified by the iteration method. The two-year return period estimated for the sizing of the diversion channel is between the maximum flood interval (238 - 300 m^3/s) recorded on the catchment and respects the initial conditions of the flows of Cavally River. Wang *et al.* (2010) [15] showedthat the design flow must be estimated with the largest flood in the watershed in order to ensurebetter flow conditions.

The results obtained by the HEC-RAS model showed in general that the model reproduces well the conditions of flow of the river according to Nash coefficients which vary from 0.83 to 0.95 [6] [16].

The Manning coefficient used for the calibration and validation of the hydraulic model is 0.052 $m^{1/3}\cdot s^{-1}$ for the minor bed and 0.06 $m^{1/3}.s^{-1}$ for the major bed. This value is high, but this is quite acceptable considering the composition of the soils, gold panning activities in the stream bed as well as the nature of the existing vegetation at the level of Cavally River. The roughness of the watercourse is a highly variable parameter that depends on the number of factors such as surface roughness, vegetation cover, channel irregularities, channel alignment [17]. The values obtained in this study confirm those of many authors who indicate that the Manning-Strickler coefficient is generally high for highly anthropogenic streams through material extraction activities [18] [19].

The velocities before and after the derivation of the diversion channel are relatively low at the banks and high in the minor bed. It is important to note that under natural conditions there is an acceleration of the flow in the concave bank at the entrance of the meander. After completion of the bypass channel speeds become slightly high. This could be due to layer gradients that increase velocity vectors due to shape profiles and non-uniform velocity distribution at depth [20] [21].

Comparison of the water levels before and after the diversion of the river at Ity station showed that the Cavally River will not be really disturbed by this channel because the reduction of the water level by 0.2 m will cause an increase practically negligible flow velocity. Moreover the decrease in the water level (0.2 m) will be insignificant compared to the total fluctuations of the river which vary in a year from 6 to 7 m. The reduction of the water level is due to the diversion channel which contributes to a reduction of the fluctuations of water levels by minimizing the phenomena of flooding [22] [23] [24]. Therefore, the hydraulic conditions upstream and downstream of the diversion channel would not be significantly different from the existing natural conditions.

4. Conclusion

The work presented in this article focuses on the realization of a hydraulic model to design a diversion channel capable of ensuring a hydraulic operation like the initial conditions (water levels, flow and speed) of the Cavally River. About the diversion channel, it has a length of 280 m and to avoid an oversize of it, it has been dimensioned for a return period of 2 years with a flow rate of 240 m^3/s, an average speed of 1.1 m/s and a slope of 0.0036 m/m. Flow velocities in the Cavally River range from 0.1 to 1.6 m/s from upstream to downstream. Hydraulic conditions (water levels, flow and velocity) in the channel after diversion will remain substantially like the natural state of the watercourse. The diversion channel will therefore have no significant impact on the hydraulic operation of the Cavally River.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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