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# Assessing the Effect of Land Use Change on the Amazon Basin River Discharge

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## Synopsis

The objective of this study is to assess the effect of land use on discharge in a sub-basin of the Amazon basin, Brazil. This sub-basin is called Humaita and has roughly 1 million km$^2$. The data set for this study consists of precipitation and climate variables derived from a global re-analysis with a resolution of 50 km. Discharges data were acquired from the Brazilian water resources agency (ANA). The daily data set encompasses a period of 35 years (1972 – 2006). TOPMODEL with a multi-velocity approach was chosen as a hydrological model due to its simplicity and efficiency. The methodology consists basically of: (1) model calibration against a period of six years; (2) model validation and effect of land use identification against the entire time-series. The effect of land use was analyzed using the model efficiency to simulate the discharges for each year during the period of validation and re-calibrating the model for each year. After the re-calibration, the temporal variation of the model parameters values was analyzed. It was observed variations in model parameterization and this may be associated to land use change.

**Keywords**: Land use, TOPMODEL, multi-velocity, the Humaita basin, the Amazon basin.

## 1. Introduction

Land use change has received attention from society due to its direct influence on rivers water quantity and quality. Recent studies on this theme have focused on analyzing the effect of land use change by means of distributed hydrological models application. Various land use scenarios, usually based on satellites images and future projections according to the land use evolution in the watershed, are simulated in the model. Although satellites images are a powerful tool with spacial resolutions increasing day by day, they fail to represent a satisfactory temporal resolution when compared to the temporal resolution of discharge and other model inputs. In addition, satellites images are scarce in representing of past times in some locations. Few studies have focused on analyzing the effect of land used using only the observed discharges. This fact can be explained through poor and/or scarce data and difficulties to implement experimental catchments. A hydrological model can be used in order to compare observed discharge with calculated discharges. Through this comparison is possible to find evidences about the effect of land use change.

Leopold *et al.* (1964) carried out field surveys and shown that, in general, mean velocity tends to increase slightly downstream in most rivers. According to them, the relationship between velocity and discharge usually assumes a simple power function with an exponent of 0.34 at-a-station (stream channel geometry) and the same relationship can be used downstream. In other words, as the discharges increase downstream, the velocities increase following a power law relationship with exponent of 0.34. In addition, Leopold *et al.* (1964)

pointed out that in most basins a regular factor between cumulative area and discharge is a power law relationship with exponent of 0.75.

TOPMODEL (Beven e*t al.,* 1995) is a hydrological model based on variable source area assumption. TOPMODEL framework has two components: (1) the storage component, which is represented by three reservoirs and (2) the routing component, which is derived from a distance-area function and two velocities parameters. Its main parameter is the topography index derived from a digital elevation model. This index represents the propensity of a cell or region to become saturated.

This study aims to assess the effect of land use on discharge in a sub-basin of the Amazon basin, Brazil. through the application of a TOPMODEL with a multi-velocity approach.

## 2. Methodology

### Study areas and data series

For this study the Humaita basin was chosen (Fig. 1). This basin is a sub-basin of the Amazon basin and has roughly 1 million km$^2$. It is located in the southwestern part of the Amazon basin. The city of Porto Velho is inserted in this basin and it is one of the most important cities in the north of Brazil.

The topographic data were extracted using ETOPO1 elevations global data. ETOPO1 has a spatial resolution of one minute and has been available from National Geophysical Data Center (NGDC), National Oceanic and Atmospheric Administration (NOAA). The topographic data were composed by basin boundary, slopes, cells distances (distance to the next downward cell), cells areas and cumulative areas. As the ETOPO1 delivers information in degrees, it was necessary to implement a GRASS routine to derive and adjust the information in meters. Cells areas change according to their spatial position (latitude and longitude). Taking into account this difference, the total cell area varied from 3.20 km$^2$ to 3.42 km$^2$ with an average value of 3.38 km$^2$. The same approach was carried out to derived corrected distances and slopes.

Meteorological data (precipitation, radiation and temperature) were extracted from Hirabayashi *et al.* (2008) re-analysis. They developed and assessed a global 0.5 degree near-surface atmospheric data from 1948 to 2006 at daily (for precipitation, snowfall, and specific humidity) and 3-hourly (for temperature, short- wave radiation, and longwave radiation) time scales.

Potential evapotranspiration was estimated through the Priestley-Taylor radiation method (Priestley & Taylor, 1972). This method delivered good estimates of actual evapotranspiration in a small forest clearcut. Lu *et al.* (2005) compared six potential evapotranspiration methods and concluded that radiation based methods performed better than temperature based methods. Furthermore, this method is a good alternative when all the necessary data for the Penamn-Monteith (Doorenbos & Pruit, 1992) method are not available.

Priestley-Taylor radiation method uses radiation data, average daily temperature, air pressure and an empirical constant. Air pressure values were derived from the elevation data and the empirical constant was set to the unit. Literature review presented on Flint & Childs (1991) work shows values of the empirical constant varying from 0.72 to 1.

As TOPMODEL is a lumped hydrological model, an areal average daily precipitation (Fig. 2) and evapotranspiration (Fig. 3) data were used. For this period (thirty five years) the mean precipitation value was 4.86 mm with a maximum value of 39.91 mm, whereas the mean evapotranspiration value was 3.74 mm with a maximum value of 4.87 mm and minimum value of 2.36 mm.

Daily discharges data, used in this study, were obtained from ANA at Humaita station. They encompass the period from 1972 to 2006 (Fig. 4). The first six years (1972 – 1977) of this time series were used for model calibration purpose and the entire time series was used for models validation purpose.

### Model approach modification

In this study TOPMODEL with a multi-velocity approach was chosen as a hydrological model. The multi-velocity TOPMODEL approach consists in deriving a time-area function from a distance-area function using the following equation:

$$tc_k = \sum_{k=1}^{N} \frac{l_k}{V'_{CH} A_k^{V'_R}} \tag{1}$$

where $tc_k$ [T] is the time of concentration of a

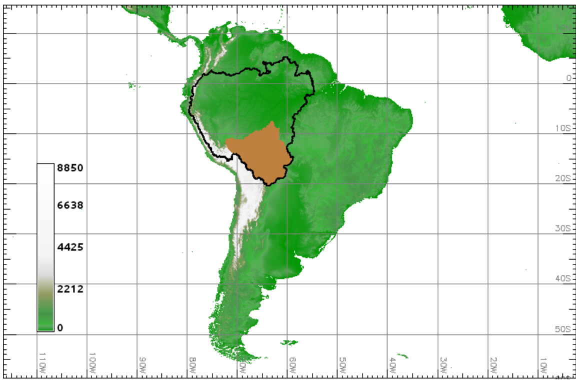

Fig. 1 Location of the Humaita basin (brown color) in the Amazon basin (black line) and South America. Topographic data from ETOPO1, elevations in meters.

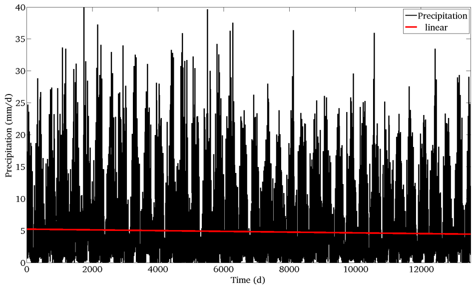

Fig. 2 Areal average precipitation time series (1972 – 2006).

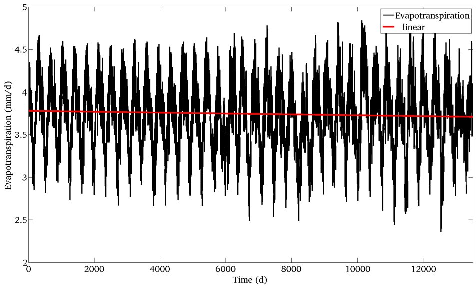

Fig. 3 Areal average evapotranspiration time series calculated with Priestley-Taylor method (1972 – 2006).

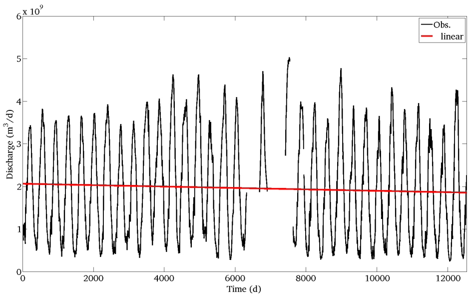

Fig. 4 Discharge time series at Humaita station (1972 – 2006).

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determined distance-area function class $k$; $V'_{CH}$ is a proportionality constant [$L^{-1}T^{-1}$]; $V'_R$ is a power law exponent [-]; $l_k$ is the plan flow path length from a class area $k$ to the basin outlet; $A_k$ [$L^2$] is the cumulative area of the class $k$ and $N$ is the total number of classes which the distance-area function is composed. As the cumulative area increases the velocity increases following a power law relationship. Eq. 1 tries to take into account the spatial variability of velocities in a basin, instead of the lumped velocity in the original TOPMODEL approach. More information about the multi-velocity approach can be found in Silva *et al.* (2010) and Silva *et al.* (2011).

## Model performance

In order to evaluate the model performance, Nash coefficient (Nash & Sutcliffe, 1970) and log Nash coefficient were chosen.

$$NSE(\Theta)=1-\frac{\sum_{t=1}^{N}\left(o(t)-\hat{o}(t|\Theta)\right)^2}{\sum_{t=1}^{N}\left(o(t)-\bar{o}\right)^2} \qquad (2)$$

$$NSE_{\log}(\Theta)=1-\frac{\sum_{t=1}^{N}\left(\ln(o(t))-\ln(\hat{o}(t|\Theta))\right)^2}{\sum_{t=1}^{N}\left(\ln(o(t))-\ln(\bar{o})\right)^2} \qquad (3)$$

where $o(t)$ is the observed discharge at the time $t$, $\hat{o}(t|\Theta)$ is the calculated discharge at the time $t$ given the parameter set Θ, $\bar{o}$ is the observed discharge average and $N$ is the number of time steps. Thereby, the model performance (*Eff*) is determined by the product of these two coefficients, *i.e.*, by the product of the Eqs. 2 and 3. The combination of these two objective functions is an attempt to search for simulations which try to fit the observed discharge data at high and low discharges simultaneously. Missing observed discharge data were excluded from the *Eff* computation.

## Land use effect evaluation

The methodology consists basically of: (1) model calibration against a period of six years; (2) model validation over thirty five years; (3) model residual trend analysis and (4) calibration for every year of the time series, varying only the saturated hydraulic transmissivity parameter ($T_0$) and the temporal distribution of $T_0$ analysis.

## 3. Results and discussion

In the calibration period, the model obtained a performance coefficient *Eff* of 0.80 (6 years) and in the validation period, *Eff* was equal to 0.61. Through Fig. 5 is possible to see that most observed discharges lay inside the uncertainty bounds of 90 % and inside the max/min interval. Therefore, the model was validated for the entire time series.

It was confirmed, by means of the model residuals analysis (Fig. 6), a trend in the discharges. This means that the difference between observed and calculated discharge increased along the time and it is a evidence that the discharges in the basin increased during the analyzed period due to alterations in the basin (land use) and not due to input climate data.

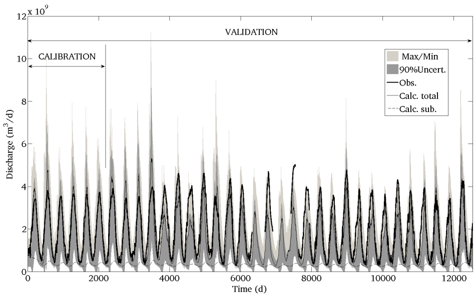

Fig. 5 Model calibration (*Eff* = 0.80), 1972 - 1977 and validation (*Eff* = 0.61), 1972 – 2006.

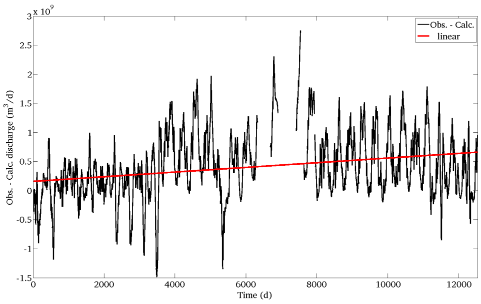

Fig. 6 Model residuals (Observed – calculated discharges) time series (1972 – 2006).

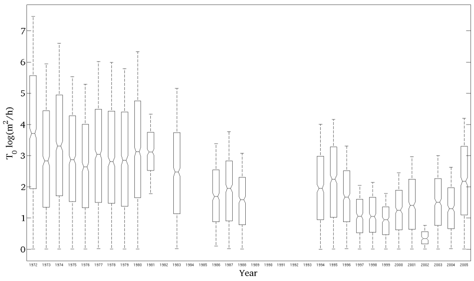

Fig. 7 Temporal frequency distribution of calibrated $T_0$ parameter (*Eff* ≥ 0.5) for every year (1972 – 2006).

The model was calibrated for every year in the time series and the temporal frequency distribution of parameter $T_0$ was analyzed for simulations with *Eff* equal or greater than 0.5 (Fig. 7). Through this analysis, it is possible to notice that there was a negative trend in $T_0$ values. This is in accordance to the effect of deforestation process on $T_0$ values.

## 4. Conclusions

The TOPMODEL multi-velocity approach was applied to the Humaita basin in order to assess the effect of land use change on discharges. Through the model residuals analysis was possible to state that the discharges increased due to land use change. In addition, the temporal frequency distribution of $T_0$ show a negative trend in $T_0$ values. This is consistent with the effect of deforestation. Further studies should be carried out in other basins in order to validate the methodology.

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## アマゾン流域の河川流量の土地利用変化の影響の評価

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### 要　旨

本研究の目的は，約1000000平方キロメートルとウマイタ流域における放電の土地利用の影響を評価することです。この研究のためのデータセットが50キロの解像度を持つ世界的な再分析から派生した降水量と気候変動の変数で構成されています。放電データは，ブラジルの水資源庁（ANA）から取得した。毎日のデータセットは，34年の期間を網羅しています。マルチ速度アプローチ　TOPMODELは，そのシンプルさと効率のために水文モデルとして選ばれた。方法論は,基本的に2つのステップで構成されています：6年,モデルの検証と全体の時系列の土地利用の識別の効果の持続期間のためのモデル校正を。土地利用の効果が検証して，再度各年のモデルを校正期間中の各年分の放電をシミュレートするモデルの効率化を用いて分析した。再校正後，モデルのパラメータ値の時間変化を解析した。これは,モデルパラメータの変化を観察されましたが，　これは利用の変化，土地に関連付けることができます。

**キーワード**: 土地利用，　TOPMODEL，マルチ速度，ウマイタ流域，アマゾン川流域