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27. EVALUATING THE POTENTIAL EFFECT OF LAND USE CHANGE ON DISCHARGE OF THE AMAZON BASIN THROUGH RESIDUAL ANALYSIS

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Land use change has raised concerns from society and scientific community due to its direct influence on rivers water quantity and quality. There is a common sense that land use change through deforestation increases the annual runoff. Most land use impact studies are based on satellite images, although, these images are scarce in representing past times in some locations. This study has the objective to implement a method to evaluate the potential effects of land use change on discharge through an application of the TOPMODEL with a multi-velocity approach. The method is based on an analysis of model residual (difference between observed and calculated discharges) regarding data error and model structure limitations. It consists of five steps: (1) model calibration against the entire time-series; (2) model calibration against a period of six years; (3) model validation, using the parameters determined in the previous step, against the entire time-series; (4) model residual computation for the steps 1 and 3 and (5) model residual trend analysis. The method was applied to the Humaita basin, sub-basin of the Amazon basin. The filtered model residual analysis shows a period of accentuated increase in discharges which matches with higher deforestation periods, therefore giving evidences that the method may be a key variable to isolate the effect of land use change on discharges.

Key Words : ***land use change, TOPMODEL, model residual, trend, the Humaita basin, the Amazon basin***

1. INTRODUCTION

Land use change has raised concerns from society and scientific community due to its direct influence on rivers water quantity and quality. Quilbé *et al.*[1]) stated that runnof and water quality are influenced by many natural and anthropogenic factors that occur at the watershed scale. It is well-known that land use constitutes one of these factors, and that deforestation of one piece of land for agricultural or urban development can affect locally water balance and pollutant fate. There is a common sense that land use change through deforestation increases the annual runoff [2]) and the increase depends on several factors such as forest type, soil type, soil depth and topography [3]).

According to Elfert *et al.* [4]), there are three different approaches to identify possible impacts of land use change on catchment hydrology: (1) if long-term data series and land use information are available, statistical analysis could be carried out; (2) paired catchment studies are often performed to reveal differences in the hydrological behavior of catchments with different land use; (3) hydrological models calibrated for the current and/or past land use are able to simulate future scenarios of land use and effects on discharges can be studied.

The first approach has issues concerning long-term data availability. Quite often long-term discharge data are not available and/or land use information, such as satellite images, covering the required period. The second approach relies on experimental catchments with similar topography and soil types, among other characteristics, although with different land use. Those catchments are quite complicated to find and set up.

Those difficulties in the first two approaches may explain the amount of studies applying hydrological models (*e.g.* Niehoff *et al.* [5]); Beighley *et al.* [6]);

Bettina and Uhlenbrook [7]; Tang *et al.* [8]; Lee and Chung [9]; Troy *et al.* [10]; Quilbé *et al.* [1]; Wang *et al.* [11]; Mao and Cherkauer [12]; Elfert and Bormann [4]; Chu *et al.* [13]; Petchprayoon *et al.* [14]; Ghaffari *et al.* [15]; Morán-Tejeda *et al.* [16]).

As pointed out by Elftert *et al.* [4], the use of hydrological models in order to evaluated land use change should be followed by a model sensitivity analysis with respect to land use change. Otherwise, effects on discharges would be an effect from the model approach and not from the land use change itself.

In addition, most of these studies are based on satellite images to characterize the land use. 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. Moreover, satellites images are scarce in representing past times in some locations. Steininger *et al.* [17] pointed out that estimates of deforestation that are based on survey questionnaires or limited samples of satellite observations, such as those provide by the Food and Agriculture Organization of the United Nations (FAO), have been subject to criticism and have failed to accurately document the distribution of deforested areas.

In order to avoid the lack of satellite images, a hydrological model can be applied to a long-term time-series. Once the model is calibrated for a specific period, its response is compared with the observed discharge over the entire time-series.

Lørup *et al.* [18] applied a modified approach combining statistical analysis and a hydrological model application. They used the model residual (difference between observed and calculated discharges) to analyze the effect of land use change on discharges. They concluded that the model residual was the key variable for testing the effects of land use change in the statistical analysis. Misinterpretation of the test results, for instance caused by changes in the rainfall regime, was avoided. In their study, they used the hydrological model to reduce the noise on discharges generated by climate variability. However, they took into account no effect of data error or model limitation on the results.

This study has the objective to implement a method to evaluate the potential effects of land use change on discharge through an application of the TOPMODEL with a multi-velocity approach. The method is based on an analysis of model residual (difference between observed and calculated discharges) regarding data error and model structure limitations. The method was applied to the Humaita basin, sub-basin of the Amazon basin.

2. METHODOLOGY

(1) Study area and data

For this study the Humaita basin was chosen (**Fig. 1**). This basin is a sub-basin of the Amazon basin and has roughly one million km^2. It is located in the southwestern part of the Amazon basin. This basin has nearly all of its area inserted in the Bolivian territory. Near its outlet is the city of Porto Velho which 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).

Meteorological data (precipitation, radiation and temperature) were extracted from Hirabayashi *et al.* [19] 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 [20]. This method is a good alternative when all the necessary data for the Penamn-Monteith method [21] 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.

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

Fig. 1 Location of the Humaita basin (brown area) and the Amazon basin (black line) in the South America. Elevations in meters from ETOPO1.

and minimum value of 2.36 mm. The precipitation time-series has a significant downward trend at $p \leq 0.05$ according to the Mann-Kendal test, as well as the evapotranspiration time-series.

The daily observed discharge 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. The daily observed discharges time-series has a significant downward trend at $p \leq 0.05$.

(2) Hydrological model

In this study TOPMODEL [22] with a multi-velocity approach [23,24] 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:

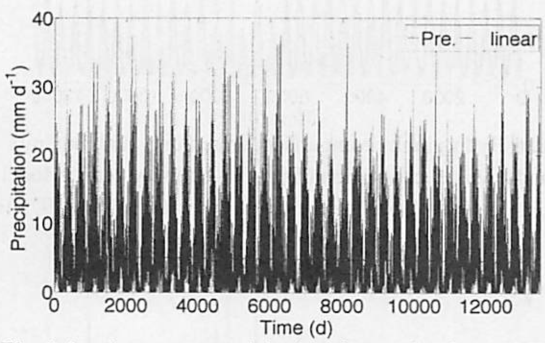

Fig. 2 Areal average precipitation time-series from 1972 to 2006. Significant downward trend at $p \leq 0.05$.

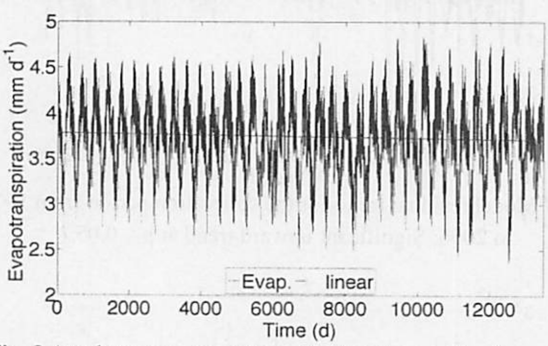

Fig. 3 Areal average evapotranspiration time-series from 1972 to 2006. Significant downward trend at $p \leq 0.05$.

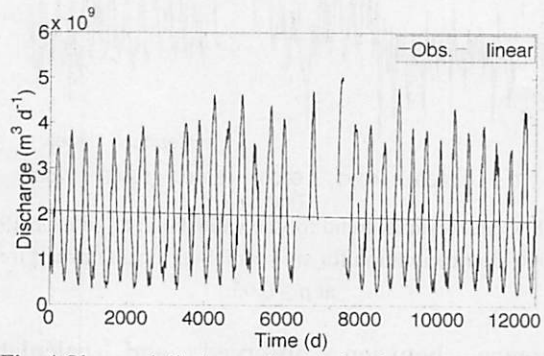

Fig. 4 Observed discharge time-series from 1972 to 2006. Significant downward trend at $p \leq 0.05$.

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

where tc_k [T] is the time of concentration of a 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. **Equation 1** tries to take into account the spatial variability of velocities in a basin, instead of the lumped velocity in the original TOPMODEL approach.

(3) Model performance

In order to evaluate the model performance, Nash coefficient [25] and log Nash coefficient were chosen, as follows:

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

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

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 **Equations 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.

(4) Analysis of the effects of land use change on discharges

The method consists of the following steps: (1) model calibration against the entire time-series;(2) model calibration against a period of six years; (3) model validation, using the parameters determined in the previous step, against the entire time-series; (4) model residual computation for the steps 1 and 3 and (5) model residual trend analysis.

The model residual trend analysis is computed through the difference between the model residual from the model calibration for the entire time-series and model validation. Thereby, reducing the effect of model structure limitations and data error on the model residual. This new model residual is called filtered model residual.

Furthermore, the filtered model residual is analyzed in order to identify a possible relationship with the deforestation process in the basin.

3. RESULTS AND DISCUSSION

The model was calibrated for the entire time-series obtaining a performance *Eff* of 0.66. It is considered a rather efficiency. **Fig. 5** shows the hydrographs comparison for this calibration. It can be noticed a model overestimation during the first ten years. This overestimation is noticeable through the calculated total discharge, uncertainty and max/min bounds as well. The overestimation may be associated to data error (for instance the areal average precipitation) and/or model structure limitations.

In the calibration period for six years, the model obtained a performance coefficient *Eff* of 0.80 and in the validation period, *Eff* was equal to 0.61. Through the **Fig. 6** is possible to see that most observed discharges lay inside the uncertainty and max/min bounds. Therefore, the model was validated for the entire time series. As expected, the model performed better the first ten years (such years nearly coincide with the calibration years), however, it underestimated the last years.

It was confirmed, by means of the model residuals analysis (**Figs. 7** and **8**), an upward trend in the discharges. **Fig. 7** shows the model residual for a model calibration against the whole time-series. It would be expected no trend in this analysis. Therefore, this trend can be associated to data error and/or model structure limitations. **Fig. 8** shows the model residual for the model validation after calibration for six years. The upward trend seen in this analysis can be associated to land use change, data error and model structure limitations. Considering these two trends, the hypothesis of this work is the possibility to filter the data error and model structure limitations taking the difference between the two model residuals.

Fig. 9 shows the filtered model residual (model residual from **Fig.7** minus model residual from **Fig. 8**). There still is a remaining upward trend. This trend is statistical significant according to the Mann-Kendall test at a significant level of 0.05. This trend is hidden in the original discharge data, which has a downward trend. This upward trend means that the difference between observed and calculated discharge increased along the time and it may be an

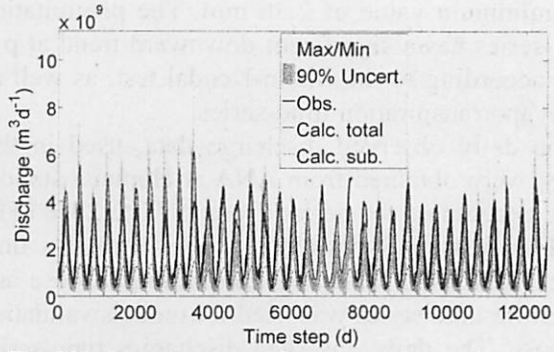

Fig. 5 Hydrographs comparison, uncertainty and max/min bounds. Model calibration (*Eff* = 0.66) for the entire time-series from 1972 to 2006.

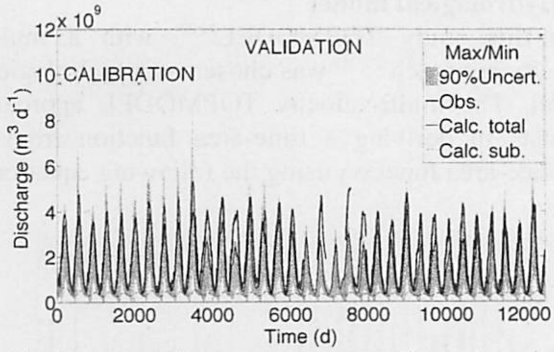

Fig. 6 Hydrographs comparison, uncertainty and max/min bounds. Model calibration (*Eff* = 0.80) for six years. Model validation (*Eff* = 0.61) for the entire time-series from 1972 to 2006.

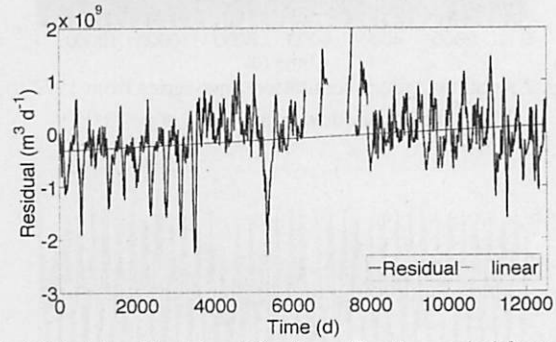

Fig. 7 Model residual trend for the calibration period from 1972 to 2006. Significant upward trend at $p \leq 0.05$.

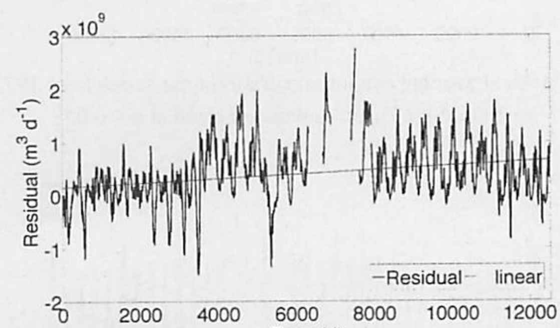

Fig. 8 Model residual trend for the validation period from 1972 to 2006 after calibration for six years. Significant upward trend at $p \leq 0.05$.

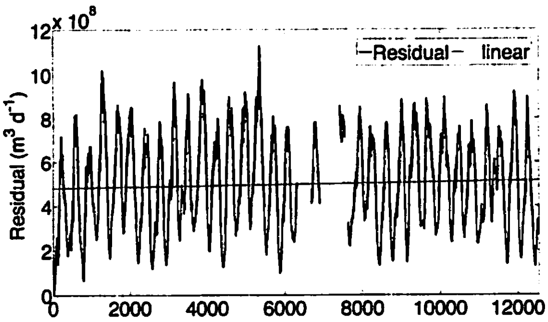

Fig. 9 Filtered model residual trend from 1972 to 2006. Significant upward trend at $p \leq 0.05$.

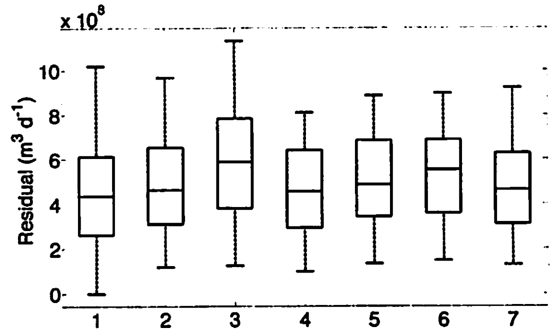

Fig. 10 Frequency distribution of the filtered model residual. Groups: 1 (1972-1976), 2 (1977-1981), 3 (1982-1986), 4 (1987-1991), 5 (1992-1996), 6 (1997-2001) and 7 (2002-2006).

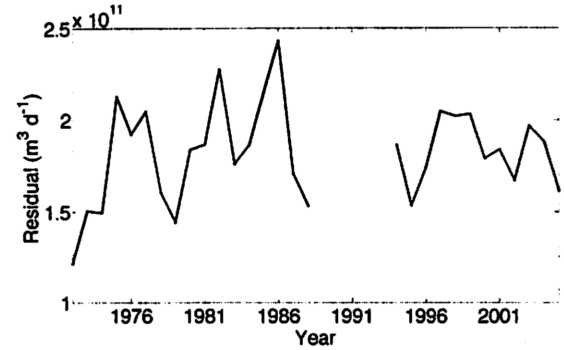

Fig. 11 Filtered model residual cumulated annually from 1972 to 2006.

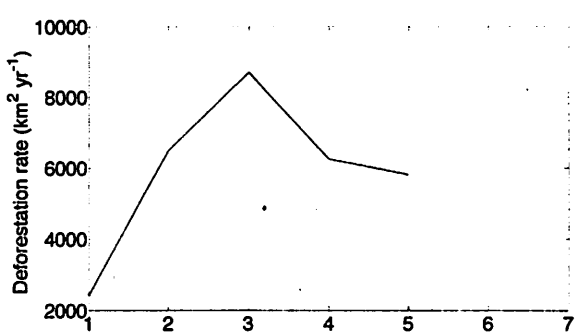

Fig. 12 Deforestation rates in Bolivia. Groups: 1 (1970-1975), 2 (1976-1980), 3 (1981-1985), 4 (1986-1990), 5 (1991-1995), 6 (1996-2000) and 7 (2001-2006).

evidence that the discharges in the basin increased during the analyzed period due mostly to alterations in the basin, such as land use change.

Fig. 10 shows the frequency distributions of the filtered model residual grouped in seven temporal classes. Each class corresponds to a period of five years. Thereby, the seven classes corresponds to the periods of 1972-1976, 1977-1981, 1982-1986, 1987-1991, 1992-1996, 1997-2001 and 2002-2006.

Through **Fig. 10** is possible to notice that between the periods 2 and 3 (1977-1981 and 1982-1986) there was an accentuate increase in discharges, mainly in the low discharges. After these period the increase in discharge remained constant until the end of time-series.

Nearly the same period was verified when analyzing the filtered model residual cumulated annually (**Fig. 11**). There is a steep upward trend until 1985. This may indicate an accentuated process of deforestation in the basin.

Steininger *et al.* [17] analyzed the deforestation processes in the Bolivian Amazon. Despite some criticism about the values of rate of deforestation, they included the FAO analysis in their work. **Fig. 12** shows the deforestation rates for every five years from 1970 to 1995. In order to improve the comparison, it was added two null data related to the periods of 1996-2000 and 2001-2006. The period from 1970 to 1985 was the noticeable deforestation rates.

The analysis using the filtered model residual matches with the deforestation rates estimated by FAO and cited by Steininger *et al.* [17], taking into account that the Humaita basin is nearly totally inserted in the Bolivian territory. Therefore, the analysis gives evidences that the filtered model residual may be a key variable to isolate the effect of land use on discharge of the Humaita basin.

4. CONCLUSIONS

The present work introduced a method to evaluate the potential effects of land use change on discharge. The method consists of analyzing the model residual from calibration and validations processes. The method tries to take into account the data error and model structure limitations. Model residuals from a model calibration for the entire time-series and from a validation process (using parameters calibrated against six years) were subtracted. The remaining model residual (filtered model residual) was analyzed in terms of its frequency distribution (for every five years) and annual cumulated distribution. Afterwards, the results were compared with deforestation data surveyed in the basin.

The TOPMODEL multi-velocity approach was chosen as a hydrological model and it was applied to the Humaita basin. A period of 35 years (1972 – 2006) was selected to carry out the simulations.

The frequency distribution analysis and annual cumulative analysis of the filtered model residual show a period (1977 – 1985) of accentuate increase in discharges. This period is consistent with deforestation data and gives evidence that the method can isolate the effect of land use change on discharge. However, it is necessary to bear in mind that climate variables, by means of evapotranspiration, for instance, may also affect the residual, although in a less likely way.

The filtered model residual may be considered as a key variable to analyze the potential effect of land use in the Humaita basin and further studies should be carried out in other basins in order to thoroughly validate the method.

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