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Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia

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Abstract

Studies that relate changes in land cover with changes in river discharge at the small scale (<1 km^2) are abundant. These studies generally indicate that deforestation causes an increase in the annual mean discharge. However, previous studies that evaluated the effects of changes in land cover in larger river basins (>100 km^2) usually have not found similar relationships. Here we analyse a 50-year long time series of discharge of a tropical river, the Tocantins River at Porto Nacional (175,360 km^2), as well as precipitation over this drainage area, during a period where substantial changes in land cover occurred in the basin (1949–1998). Based on agricultural census data, we estimate that, in 1960, about 30% of the basin was used for agriculture. Previous work indicates that by 1995, agriculture had increased substantially, with about 49% of the basin land used as cropland and pastures. Initially, we compare one period with little changes in land cover (period 1-1949–1968) with another with more intense changes in land cover (period 2-1979–1998). Our analysis indicates that, while precipitation over the basin is not statistically different between period 1 and period 2 ($\alpha = 0.05$), annual mean discharge in period 2 is 24% greater than in period 1 ($P < 0.02$), and the high-flow season discharge is greater by 28% ($P < 0.01$). Further analyses present additional evidence that the change in vegetation cover altered the hydrological response of this region. As the pressure for changes in land cover in that region continue to increase, one can expect important further changes in the hydrological regime of the Tocantins River.

Keywords: Large-scale hydrology; Change in land cover; Climate variability; Hydroclimatology

1. Introduction

Modifications in the long-term discharge of a river can be caused by decadal or interdecadal climate variability, by changes in land use and land cover in the upstream basin, by the construction of large artificial lakes, and by diversion of water for irrigation. In a large river basin, the two most likely drivers of long-term discharge modifications are precipitation variability and changes in land use and land cover in the upstream basin.

In many tropical regions, large-scale changes in land cover involve the replacement of the natural vegetation by crops or pastures. In non-arid tropical

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regions of South America, the natural vegetation is, depending on the seasonal water deficit, either a tropical forest (evergreen or deciduous), or a cerrado, a savanna-like vegetation. The conversion of tropical forest or cerrado to grassland disrupts the hydrological cycle of a drainage basin, by altering the water yield of the area. Although studies that relate small scale ($< 1\ \mathrm{km}^2$) changes in land cover with changes in river discharge generally indicate that deforestation causes an increase in the annual mean discharge, the few studies that evaluated the effects of changes in land cover in tropical meso- or large-scale river basins ($> 100\ \mathrm{km}^2$) usually could not find similar relationships (Bruijnzeel, 1990).

The Tocantins basin, in central Brazil (Fig. 1), is a region where the hydrological impacts of large-scale conversion of the natural vegetation are still to be determined. Before the construction of Brasilia started, in 1956, the population density of that region was low. Since then, it has increased more than ten-fold (Fig. 2), and the region has undergone remarkable changes in land use and land cover.

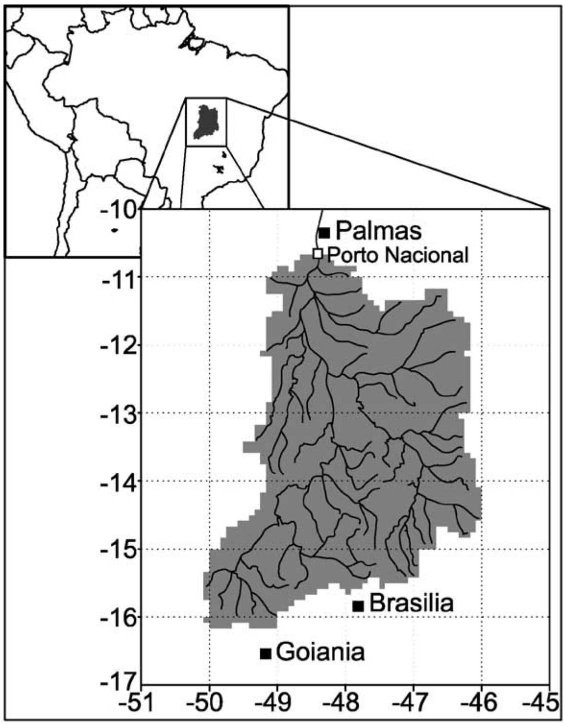

Fig. 1. Orientation map. The grey area represents the region under study.

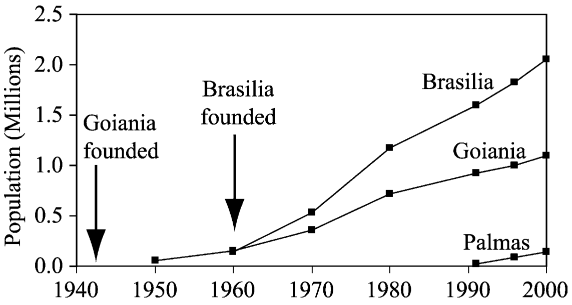

Fig. 2. Population trends in the main cities near the area of study. Goiânia was founded in 1942 to be the new capital of the state of Goiás. Brasília was founded in 1960 to be the new capital of Brazil. Palmas was founded in 1989, to be the capital of the new state of Tocantins. Data are from IBGE (1950, 1960a, 1970, 1980, 1991 and 2000) demographic censuses and one IBGE population count (1996). Data for 1991, 1996 and 2000 were downloaded from http://www.ibge.gov.br.

In the absence of observation studies in the region, Costa and Foley (1997) used modelling to evaluate the effects of changes in land cover (notably the conversion of rainforest/cerrado to pasture) on the hydrology of the Amazon basin as a whole. For the sub-humid Tocantins River basin, in the southeastern part of the Amazon basin, their simulation results indicated that a complete deforestation would increase the simulated annual mean discharge by 16%.

In this paper, we use observations to determine the effects of large-scale changes in land cover on the discharge of the Tocantins River. Section 2 reviews the vegetation-related hydrological processes and the field experiments that have been used to evaluate the effects of changes in land cover on the hydrological response of an area. Section 3 describes the Tocantins River basin, including its historical changes in land use. Section 4 describes the hydrometeorological data used in the analysis, while Section 5 evaluates the effects of changes in land cover on the discharge of the Tocantins River.

2. Effects of changes in land cover on catchment discharge

The conversion of vegetation such as tropical forest or savanna to grassland disrupts the hydrological cycle of a drainage basin by altering the balance between rainfall and evaporation and, consequently, the runoff response of the area. The higher surface albedo, the lower surface aerodynamic roughness, the lower leaf area and the shallower rooting depth of pasture compared with forest/cerrado all contribute to reduce evapotranspiration (ET) and increase the long-term discharge (Costa and Foley, 1997; Zhang et al., 2001; Costa, 2003). In addition, low-productivity grasses, like natural grassland pasture, have lower leaf area and produce less litter than the original vegetation. With a lower leaf area, the pasture does not intercept as much rainfall as the forest/cerrado does, and a higher fraction reaches the ground. With less litter, the capacity of surface detention is decreased, and a greater proportion of the rainfall runs off as overland flow. If surface runoff increases substantially and infiltration is critically reduced, soil moisture may also decrease, contributing to a further reduction in the ET.

In summary, one should expect that the replacement of natural tropical vegetation (such as tropical forest or cerrado) with grassland, would cause a decrease in the ET and an associated increase in the average annual long-term discharge. In addition, the shift from sub-surface flow to overland storm flows that often accompanies deforestation followed by adverse land use may produce rather dramatic changes in the catchment peak flows as well. Furthermore, if the change in infiltration associated with the land use change overrides the effect of reduced evaporation, then a shift in the river's flow regime may be expected with increased peaks during the rainy season and lowered flows during the dry season (Bruijnzeel, 1990).

Bosch and Hewlett (1982) reviewed the results of 94 (mostly paired) catchment experiments throughout the world and concluded that removal of forest almost invariably leads to higher stream flow, and reforestation of open lands generally leads to a decline in the overall stream flow. Bruijnzeel (1990, 1996) reviewed the hydrological effects of land cover transformation in the humid tropics, and concluded that: (a) carefully executed light selective harvesting of trees (up to 20% removal of biomass) has little (if any) effect on stream flow; (b) removal of the natural forest cover may result in a considerable increase in water yield (up to 800 mm yr^{-1}), depending on the amount of rainfall received and the degree of surface disturbance; and (c) there is a decline in stream flow with time associated with a reforestation. Sahin and Hall (1996) used regression analysis and data from 145 experiments to study the effects of land use change on water yields. Their analysis of the tropical forest data (only five experiments were included) suggests that runoff increased on average by 10 mm yr^{-1} after a 10% deforestation and by 213 mm yr^{-1} after a total (100%) deforestation.

Nearly all the results presented in the literature were obtained for relatively small catchment areas (<1 km^2), where most experimental conditions can be tightly controlled. Such experiments usually evaluate the effects of either deforestation or reforestation on the catchment hydrology. Some deforestation experiments consider the subsequent regeneration of the forest, and therefore become a reforestation experiment later (Malmer, 1992). However, these are controlled experiments, when deforestation and reforestation usually do not happen at the same time in the experimental area.

Hydrological effects of changes in land cover may be difficult to discern in the case of large-scale basins that have a variety of land use classes, and vegetation in various stages of regeneration. In addition, important spatial and temporal variations in rainfall may exist across decades. In his review, Bruijnzeel (1990) cited a few studies that evaluated the effects of meso- or large-scale tropical deforestation, but could not arrive at consistent conclusions: Qian (1983) was unable to detect systematic changes in streamflow patterns of basins ranging in size from 7 to 727 km^2 on the island of Hainan, China, during the 1960s and 1970s, despite extensive deforestation (~30% loss of tall forest between 1950 and 1980); Dyhr-Nielsen (1986) arrived at the same conclusion after studying rainfall and runoff data over the period 1955–1980 for the 14,500 km^2 Pasak River basin in northern Thailand, which lost up to 50 percent of its tall forest cover during this period.

More recently, Wilk et al. (2001) studied the 12,100 km^2 Nam Pong catchment in northeast Thailand, where the area classified as forest decreased from 80 to 27% between 1957 and 1995. They could not detect changes in the rainfall totals and patterns, in any other water balance terms, or in the dynamics of the recession of the hydrograph at the end of the rainy season. The authors believe that a number of abandoned areas, where secondary growth can be expected, account for the results.

However, detectable changes in streamflow may be expected where large tracts of forest vegetation have been replaced by annual cropping rather than left to regenerate. Madduma-Bandara and Kuruppuarachchi (1988), also cited by Bruijnzeel (1990), reported an increase in mean annual flow for the 1108 km^2 Mahaweli basin in Sri Lanka, despite a weak negative trend in rainfall over the same period (1944–81). Although both trends were not statistically significant at the 5% significance level, the increase in the annual runoff ratio was highly significant.

Bruijnzeel (2003) highlights the importance of considering the rates and extent of urbanization in the analysis. For example, Van der Weert (1994) compared streamflow totals for the 4133 km^2 Citarum river basin in West Java, Indonesia, for the periods 1922–1929 and 1979–1986. Average annual rainfall totals for the two periods were very similar at 2454 and 2470 mm, respectively. The corresponding average streamflow totals were 1137 and 1261 mm (an increase of 11%), suggesting a decrease in catchment ET of about 110 mm yr^{-1}. Little forest clearance was reported for the former period, although in 1985 almost 50% of the catchment was covered by forest, plantations or mixed gardens, whereas settlements and irrigated rice fields occupied 7 and 34%, respectively, with rainfed fields making up the remainder (Van der Weert, 1994). Despite the conversions from forest to agriculture, Bruijnzeel (2003) argues that the increase in water yield must be attributed primarily to the increase in areas with compacted surfaces, such as roads and settlements. In another study, Cheng (1999) claims that increased annual discharge on several large river basins (25,500–66,625 km^2) in the upper Yangtze valley in Southwest China is due to afforestation, whereas Bruijnzeel (2003) ascribed the effect to increased urbanization instead.

Observational studies of the effects of land cover conversions on the hydrology of very large basins ($>100{,}000$ km^2) are scarce, especially in the tropics. In one of the few studies available, Gentry and Lopez-Parodi (1980) proposed that an increase in the discharge of the Amazon River at Iquitos was caused by deforestation in the upstream Andes, although Richey et al. (1989) suggested that the increase in discharge they observed was actually caused by climate variability.

The few large-scale catchment studies reviewed above have not found a consistent pattern of hydrological response to large-scale changes in land cover. The lack of studies of very large and persistent land cover conversions suggests that if appropriate land cover, precipitation, and discharge data were available, it would be possible to determine whether the impact of land cover change across very large catchments is similar to that observed in smaller watersheds. In the remainder of this paper, we evaluate such impacts on a 175,360 km^2 catchment on the Tocantins River.

3. The Tocantins River basin

The Tocantins River has a total drainage area of 767,000 km^2, with an average annual mean discharge of about 11,000 m^3 s^{-1} at its mouth. With a high hydroelectric potential, the basin water resources have been monitored for a long time, and there are a few discharge time series long enough to evaluate the long-term hydrological impacts of large-scale tropical forest conversion.

We have selected for study the fluviometric station of Porto Nacional (Fig. 1), because it has a long time series (1949–1998) of daily discharge measurements with few gaps. Also, the upstream basin has undergone significant changes in land cover in recent decades, but it has not been regulated by significant dams yet. In addition, although several cities were constructed in the vicinities of the basin (Fig. 1), urbanization and construction of roads inside the basin are considered negligible. The area of study upstream of Porto Nacional has a drainage area of 175,360 km^2. Annual mean precipitation over the region of study is about 1600 mm yr^{-1}. The strongly seasonal rainfall regime has two distinct seasons, with the rainy season peaking in December–January–February, while the dry season extends for several months, with the driest months being June–July–August (Fig. 3), period when precipitation totals over the area of study are usually below 10 mm/month. The high-flow season is January–February–March, and the low-flow season is August–September–October (Fig. 3). The one-month lag between the rainy season

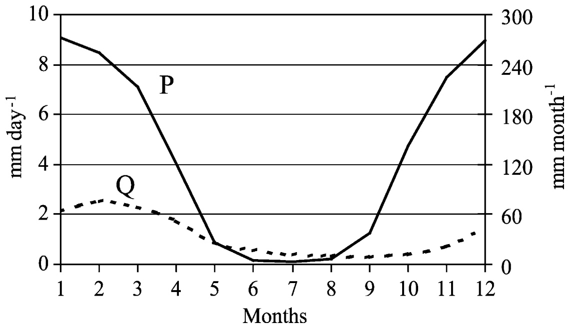

Fig. 3. Climatology of precipitation (*P*) and annual long-term hydrograph (*Q*) of the Tocantins River at Porto Nacional (latitude 10°42′S; longitude 48°25′W; altitude 195 m; drainage area 175,360 km^2; time period 1949–1998).

and high-flow season is consistent with the size of the catchment.

The dominant natural vegetation is the cerrado, which is characterized by grasses, small palms, shrubs and twisted or leaning trees. Although this definition fits several floristic physiognomic forms, from grassland to open forest, our study area was most likely previously covered by a specific type of cerrado called cerrado sensu stricto, which is dominated by closed shrubs, with scattered trees. Total leaf area index varies between 0.7 and 1.5 according to the season (of which 50–70% is tree LAI), and canopy height is around 8–10 m (Miranda et al., 1996).

Since the 1960s, cerrado has been one of the preferred agricultural frontiers in Brazil. Most of the land that was originally covered by cerrado is now used for crops and pastures (Mittermeier et al., 1999), and an extrapolation of the population curves in Fig. 2 suggests that both types of land use in this region will continue to increase in the next decades. The pasture replacing natural vegetation is termed either natural or planted, although both forms differ substantially from the pre-existing vegetation. Natural pasture is usually originated from a cerrado that had its trees and shrubs cleared, leaving only the natural grassland. Planted pasture, on the other hand, is formed by the introduction of non-native, high-productivity grasses, through agricultural processes such as land clearing (including burning), plowing, fertilization and planting. Using agricultural census data (IBGE, 1960b), we estimate that 30.2% of the area of study was used for agricultural purposes in 1960, with most of that land use in the form of natural pasture (Table 1). Cardille et al. (2002) merged satellite imagery and agricultural censuses to provide a geographically explicit description of land cover and land use practices in the Amazon and Tocantins basins. The resultant data set depicts the fraction of each 5-min (9 km × 9 km) grid cell that was devoted to agricultural activity during the mid-1990s. We have used this data set to estimate that 49.2% of the area of study was used for agriculture in 1995, with planted pasture covering most of the additional area in use since 1960 (Table 1). Fig. 4 shows the Cardille et al., estimates for total land use for the area under study.

Table 1
Estimates of land used for agricultural purposes in the study area in 1960 and 1995, as a percent of the total study area

	1960	1995
Planted pastures (%)	4.6	22.8
Natural pastures (%)	24.1	22.9
Crops (%)	1.5	3.5
Total land use (%)	30.2	49.2

1960 data are from IBGE (1960b), 1995 data are from Cardille et al. (2002).

4. Hydrometeorological data

To determine the hydrological effects of tropical vegetation conversion over large areas, the paired-basin methodology is not appropriate. Instead, it is a more tractable problem to study the same basin over different periods of time. These periods should be long enough to include a representative sample of climate, while having considerable changes in land cover between them.

We used the daily records of discharge of the Tocantins River at the station of Porto Nacional (latitude 10°42′S; longitude 48°25′W; altitude 195 m; drainage area 175,360 km^2), which are available for the period 1949–1998 (Fig. 3) (Discharge data were downloaded from http://hidroweb.aneel.gov.br). The daily data were grouped into monthly data, and months that had less than 25 days of data were eliminated (3% of the series).

The daily discharge is calculated from the daily stage average using a rating curve. The daily stage is an average from manual stage measurements taken

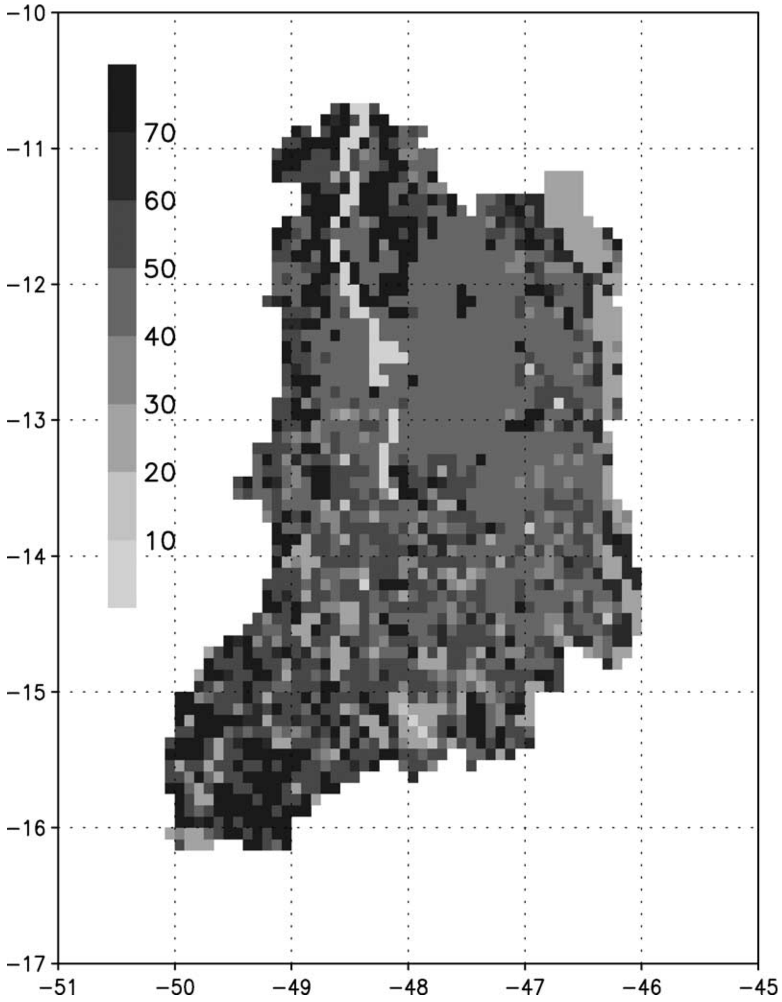

Fig. 4. Mid-1990s agricultural land use map of the region in study (from Cardille et al., 2002), with intensity expressed as percentage of each grid cell.

twice a day. The rating curve is determined from measurements of stage, cross-section area and flow velocity, which are usually taken every three months. Rating curves are frequently updated to account for changes in the cross-section of the river.

We spatially average the precipitation upstream of Porto Nacional for every month in the period 1949–1998, building the time series used. We use the CRU dataset (New et al., 2000), which is a gridded global dataset ($0.5 \times 0.5°$ resolution) of climate variables for the period 1901–1998. New et al. interpolated nearby rain gauge stations using a cubic spline to produce the gridded precipitation data. However, the density of rainfall stations in the area is low (1 station per 2900 km^2 or less, depending on the number of stations available each month of the series), prompting us to ensure the quality of the precipitation dataset.

Two initial tests were made to assess the quality of the precipitation dataset for the study area. First, we calculate the local annual mean ET by subtracting the 50-year mean discharge (2314 $m^3 s^{-1}$, or 1.14 mm day^{-1} over 175,360 km^2) from the 50-year average rainfall reported by the CRU dataset (4.29 mm day^{-1} or 1566 mm yr^{-1}). The resulting ET (3.15 mm day^{-1}, or 1150 mm yr^{-1}) is consistent with other estimates of the annual mean ET of cerrado

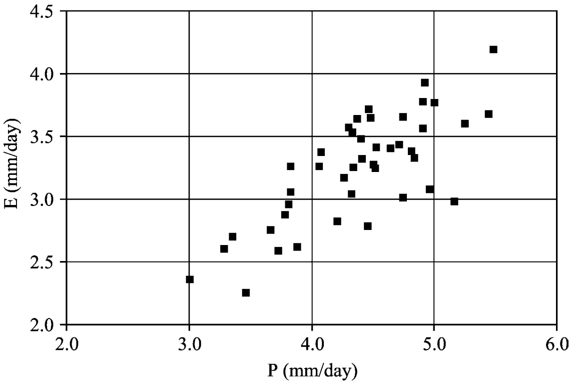

Fig. 5. Relationship between annual-mean evapotranspiration (ET) and annual-mean precipitation (P) for the region in study. The linear relationship indicates a water-stressed region.

Table 2
Long term mean of hydrological variables in the Tocantins River basin upstream of Porto Nacional

Period	P (mm/day)	Q (m^3/s)	Q (mm/day)	ET (mm/day)	C
1949–1968	4.22	2055.6	1.00	3.22	0.237
1979–1998	4.35	2532.3	1.24	3.11	0.285

P is precipitation (calculated from the CRU dataset), Q is discharge (from the ANEEL records), ET is evapotranspiration ($P - Q$), and C is the runoff coefficient (Q/P).

(3.62 mm day^{-1}, or 1321 mm yr^{-1}) (Costa and Foley, 1997). See also Section 5 for further discussion on the ET.

Next, to evaluate the quality of the interannual variability of the rainfall record, we calculated the annual ET, and plotted it against the annual rainfall (Fig. 5). The linear dependence of the annual ET on the annual rainfall is characteristic of a water stressed region, consistent with the cerrado vegetation cover of the study area. We believe that, if important biases existed in the precipitation dataset, there would not be a linear relationship between precipitation and ET. These two simple tests indicate that the precipitation data set has acceptable quality, and is suitable to be used in this study.

Both precipitation and discharge time series were divided in two 20-year long periods (1949–1968 and 1979–1998). The interval 1969–1978 was discarded, to allow for a larger difference in land use between the two periods. All samples used in the subsequent analyses passed the Lilliefors test for normality (Lilliefors, 1967; Conover, 1980).

5. Effects of changes in land cover on the discharge of the Tocantins River

Table 2 summarizes the long-term means of the main surface hydrological components of the Tocantins River basin upstream of Porto Nacional, for the two periods considered. The long-term ET is calculated by the difference between precipitation and discharge. An initial comparison of period 1 and period 2 shows an increase in precipitation of the order of 0.13 mm day^{-1} (47 mm yr^{-1}, or 3%), an increase in discharge of 0.24 mm day^{-1} (88 mm yr^{-1}, or 24%), a decrease in ET of 0.11 mm day^{-1} (40 mm yr^{-1}, or 3.4%) and an increase in the runoff coefficient from 0.237 to 0.285. From a hydrological point of view, the most important is the 24% increase in discharge. The higher long-term discharge, the lower ET and the higher runoff coefficient are all consistent with the changes in land cover, although the decrease in ET is within the uncertainty of the precipitation and discharge data.

Although about half of the increment in discharge can be explained by the increase in precipitation, the decrease in ET can be linked to a mechanism other than climate variability. As shown in Fig. 5, annual mean ET tends to increase with the annual mean precipitation. However, the fact that precipitation increases from period 1 to period 2, at the same time when ET goes in the opposite direction, indicates that there was a modification in other mechanisms that control ET, possibly a change in vegetation itself. Further statistical analyses, presented below, better elucidate the mechanisms driving the increase in discharge.

Classical statistical tools to examine difference in means are the t-test and the z-test. The t-test is used when the size of the sample is small (say, $n < 30$), and the z-test is used when the sample size is large. Table 3 shows z-tests for the comparison of means of monthly precipitation and discharge, and a t-test for the comparison of means of the annual runoff coefficient, demonstrating that: (a) precipitation means are not different at the 0.05 significance level; (b) the mean

Table 3
z-Test for means of long-term precipitation and discharge, and *t*-test for means of runoff coefficient

	Precipitation (mm day^{-1})		Discharge (m^3 s^{-1})		Runoff coefficient	
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2
Mean	4.22	4.35	2037.7	2505.5	0.233	0.288
Variance	17.48	16.70	3839608.5	6482160.9	0.002833	0.005383
Observations	239	239	239	227	19	12
Hypothesized mean difference	0		0		0	
Degrees of freedom					18	
t statistic					−2.261	
$P(T \leq t)$ one-tail					0.018	
z statistic	−0.358		−2.215			
$P(Z \leq z)$ one-tail			0.013			
$P(Z \leq z)$ two-tail	0.720					

Period 1 is 1949–1968. Period 2 is 1979–1998.

discharge of period 2 (1979–1998) is greater than the mean discharge of period 1 (1949–1968) at the 0.013 significance level; (c) the mean runoff coefficient of period 2 is greater than the mean runoff coefficient of period 1 at the 0.018 significance level. That is, although precipitation did not change significantly between the two periods, the discharge from the Tocantins basin and the runoff ratio increased between the earlier and later time periods.

From the analysis in Section 2, we expect that the hydrological effects of changes in land use would be especially evident in the rainy season, resulting in substantially higher discharge in the intense land use period than in the previous one. To test the hypothesis that land use change between these two periods affects peak discharge, we test the differences in the means of precipitation and discharge in rainy and high-flow seasons (defined in Section 3). Although the difference in rainy season precipitation is negligible, the mean discharge of the high-flow months of period 2 is 28% greater than mean discharge of the same season in period 1 ($P < 0.01$, Table 4). The significant increment in discharge during the high-flow season can also be observed in Fig. 6.

Although it can be argued that the 0.24 mm day^{-1} (88 mm yr^{-1}) increase in the annual mean discharge from period 1 to 2 could be partially explained by the 0.13 mm day^{-1} (47 mm yr^{-1}) increase in the annual mean precipitation in the same period, the same argument cannot be used during the rainy season, when the discharge at the high-flow season increased by 1195 m^3 s^{-1} (0.58 mm day^{-1}, or 212 mm yr^{-1}, $P < 0.01$), whilst the change in precipitation is negligible.

Table 4
Paired *t*-test for means of all rainy seasons precipitation (December–January–February) and all high-flow seasons discharge (January–February–March)

	Precipitation (mm day^{-1})		Discharge (m^3 s^{-1})	
	Period 1 (1949–1968)	Period 2 (1979–1998)	Period 1 (1949–1968)	Period 2 (1979–1998)
Mean	8.80	8.80	4244.3	5439.2
Variance	2.03	3.86	2763200.8	5466112.9
Observations	20	20	19	
Hypothesized mean difference	0		0	
Degrees of freedom	19		18	
t Statistic	-2.644×10^{-5}		−3.056	
$P(T \leq t)$ one-tail			0.003	
$P(T \leq t)$ two-tail	0.9999			

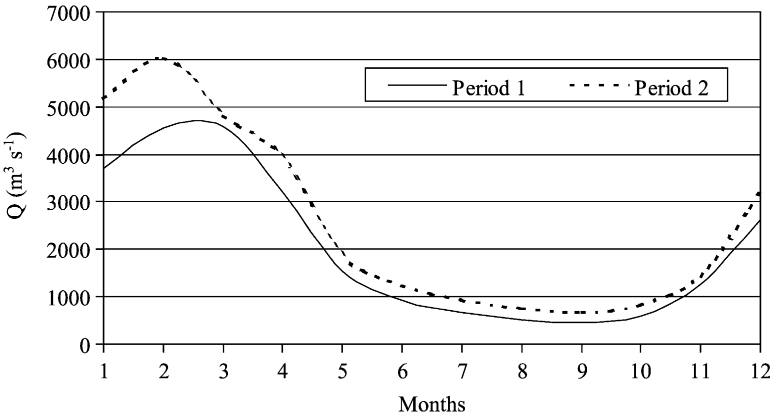

Fig. 6. Average river discharge (Q), for periods 1 and 2, for the Tocantins River at Porto Nacional. Period 2 peak is one month ahead of period 1 peak, consistent with a less protected surface.

The increase in surface flow during the rainy season is mainly related to reduced infiltration after the changes in land cover. This reduction is not large enough to produce a reduction in dry season flow, suggesting that changes in infiltration characteristics have been modest (Fig. 6).

If the changes in land cover are responsible for the increase in discharge, then one can also expect that the precipitation variability interacts with the changes in land cover, i.e. the increases in the discharge from period 1 to period 2 should be greater during the rainiest than during the driest years. To test this hypothesis, we did a classical two-way analysis of variance, which evaluates the strength of the interaction between precipitation variability and changes in land cover exist. To represent the precipitation variability, the rainy season precipitation and the high-flow season discharge of the five rainiest and five driest years in each 20-year period were sampled (top and bottom 25% years— Table 5). The ANOVA (Table 6) confirms that both precipitation variability and land cover change are sources of variation of discharge ($P < 1 \times 10^{-5}$ and $P < 0.05$, respectively), but also demonstrates that the interaction between climate variability and land cover change is also a source of variation of discharge ($P < 0.01$). In other words, the impact of the precipitation variability in the discharge is amplified by the changes in land cover.

There is additional evidence that the change in vegetation cover is responsible for the changes in the hydrograph between the two periods. The first evidence is that the mean amplitude of the hydrograph increases from period 1 to period 2 (Table 7). In addition, the peak of the hydrograph in period 2 is one month in advance of the peak of hydrograph in period 1 (Fig. 6), while the precipitation peak is the same in both periods, suggesting that a higher fraction of rain runs off as the faster overland runoff, which is also consistent with a surface less protected by vegetation. Furthermore, the increase in discharge during the dry

Table 5
Rainy season mean precipitation (and confidence interval) in the five rainiest and five driest years in each 20-year period, and the high-flow mean discharge in the same years

	Precipitation (mm day^{-1})		Discharge (m^3 s^{-1})	
	Period 1	Period 2	Period 1	Period 2
Rainiest	10.58 ± 1.29	11.46 ± 2.21	4897.3 ± 1499.4	7447.8 ± 1611.4
Driest	7.10 ± 1.06	7.03 ± 0.92	2758.4 ± 1441.9	2392.3 ± 791.6

The confidence interval is calculated at the 5% level of significance ($t_{0.05,4} = 2.78$).

Table 6
Analysis of variance of annual mean discharge of the Tocantins River at Porto Nacional

Source of variation	SS	df	MS	*F*	*P*
Climate variability	64700246	1	64700246	52.97705	1.85×10^{-6}
Land cover change	5964165	1	5964165	4.883503	0.042
Interaction	10633606	1	10633606	8.706877	0.009
Within	19540612	16	1221288		
Total	1.01×10^8	19			

SS: sum of squares; df: degrees of freedom; MS: mean square; *F*: *F* statistic; *P*: probability that the *F* statistic is exceeded in the *F* distribution.

season (220 $m^3\,s^{-1}$ on average— Table 7, or 0.11 mm day^{-1}) is consistent with the decrease of ET (0.11 mm day^{-1}, long-term average).

The variations in annual mean discharge, the timing and the amplitude of the peak flow are consistent with changes in the vegetation cover witnessed in the Tocantins basin between the two periods. The causes of such variations can be attributed both to reduced ET and reduced infiltration during the rainy season.

The analyses above demonstrate the effects that the actual changes in land use and land cover had in the catchment hydrology. These results can be used to estimate what would be the long-term effects of an extreme deforestation, i.e. from 100% of cerrado cover to 100% of agriculture land use, if the change in ET due to the land cover change is known. To estimate that, first we assume that the long-term ET of the cerrado and of the agricultural lands, although different between themselves, do not differ between periods 1 and 2. We also assume that the rate of change from natural vegetation to agricultural land use between 1960 and 1995 was constant in the period 1949–1998, and then calculate the fraction of land use in the basin for all years in the period (29% in period 1; 46% in period 2). We then define that the total study area ET in each period (Table 2) is equal to the weighted sum of each land cover ET. Finally, we solve a system of two equations (one equation for each 20-year period). Using this approach, we estimate that the average cerrado ET is 3.42 mm day^{-1} (1248 mm yr^{-1}), while the agriculture ET (a combination of planted pastures, natural pastures and crops ET) is 2.74 mm day^{-1} (1000 mm yr^{-1}).

Table 7
Summary of the changes in the main characteristics of the annual hydrograph of the Tocantins River at Porto Nacional

Discharge ($m^3\,s^{-1}$)	Period 1 (1949–1968)	Period 2 (1979–1998)
Annual mean	2055.6	2532.3
Mean high season (January, February, March)	4168.7	5295.0
Mean low season (August, September, October)	525.3	745.2
Mean amplitude	4130.0	5340.0

The mean amplitude is calculated as the difference between the mean discharge of highest flow month and the mean discharge of the lowest flow month.

This estimated drop in ET (0.68 mm day^{-1}, or 248 mm yr^{-1}) is considerably larger than the results found by Costa and Foley (1997), who simulated that the ET would drop from 3.62 to 3.54 mm day^{-1}, if the cerrado was replaced by grasslands. One of the reasons why the grasslands ET of Costa and Foley was greater is because they assumed grasses had a leaf area index (LAI) equal to 5.0, a value too high compared to the range of 0.5–4.0 measured at planted pastures in Amazonia by Roberts et al. (1996), and probably even higher than the LAI of natural pastures found in the region of study.

6. Summary and conclusions

In this paper, we evaluate how increases in land use in the upper Tocantins basin affect its discharge. Initially, we estimate that the agricultural land use of the basin increased from 30.2% in 1960 to 49.2% in 1995. We divide the period of study (1949–1998) in two 20-year long periods, one with less land use (1949–1968), and another with more land use (1979–1998). Our analysis indicates that, although precipitation did not change significantly from period 1 to period 2, the annual mean discharge increased by 24% ($P < 0.02$), while the rainy season discharge increased by 28% ($P < 0.01$) and seasonal peaks occurred about one month earlier. Such variations can be ascribed both to reduced ET and reduced infiltration during the rainy season. Our results agree with what is expected from small-scale deforestation experiments (Bosch and Hewlett, 1982; Bruijnzeel, 1990; Sahin and Hall, 1996), from theoretical analysis (see Section 2), and from large-scale hydrological modelling (i.e. Costa and Foley, 1997; Matheussen et al., 2000; Cognard-Plancq et al., 2001).

We conclude that the reduced infiltration after the changes in land cover causes an increase in surface flow during the rainy season. This reduction is not large enough to produce a reduction in dry season flow, suggesting that changes in infiltration characteristics have been modest. On the other hand, the reduction in ET after the change in land cover causes a consistent increase in discharge throughout the year.

Most previous large-scale deforestation studies and reviews (Bruijnzeel, 1990; Wilk et al., 2001) presented results that do not agree with the results from small-scale deforestation experiments. This is usually attributed to the possibility that, while part of the basin in study is being cleared, other parts, previously abandoned, may be regenerating, and therefore counterbalancing each other. Given the results of the Tocantins basin upstream of Porto Nacional, we suggest that the rate of conversion from cerrado to agricultural use is considerably higher than the rate of abandonment of land to regeneration.

In the last 50 years, large changes in land cover for agriculture have already affected the discharge of the Tocantins River at seasonal and long-term time scales. As the pressure for changes in land cover in that region continue to increase, one can expect further significant changes in the future hydrological regime of the Tocantins River.

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