Hydrol. Earth Syst. Sci., 20, 2691–2704, 2016
www.hydrol-earth-syst-sci.net/20/2691/2016/
doi:10.5194/hess-20-2691-2016

Hydrology and Earth System Sciences
Open Access

Contradictory hydrological impacts of afforestation in the humid tropics evidenced by long-term field monitoring and simulation modelling

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Received: 30 October 2015 – Published in Hydrol. Earth Syst. Sci. Discuss.: 4 December 2015
Revised: 29 April 2016 – Accepted: 7 June 2016 – Published: 8 July 2016

Abstract. The humid tropics are exposed to an unprecedented modernisation of agriculture involving rapid and mixed land-use changes with contrasted environmental impacts. Afforestation is often mentioned as an unambiguous solution for restoring ecosystem services and enhancing biodiversity. One consequence of afforestation is the alteration of streamflow variability which controls habitats, water resources, and flood risks. We demonstrate that afforestation by tree planting or by natural forest regeneration can induce opposite hydrological changes. An observatory including long-term field measurements of fine-scale land-use mosaics and of hydrometeorological variables has been operating in several headwater catchments in tropical southeast Asia since 2000. The GR2M water balance model, repeatedly calibrated over successive 1-year periods and used in simulation mode with the same year of rainfall input, allowed the hydrological effect of land-use change to be isolated from that of rainfall variability in two of these catchments in Laos and Vietnam. Visual inspection of hydrographs, correlation analyses, and trend detection tests allowed causality between land-use changes and changes in seasonal streamflow to be ascertained. In Laos, the combination of shifting cultivation system (alternation of rice and fallow) and the gradual increase of teak tree plantations replacing fallow led to intricate streamflow patterns: pluri-annual streamflow cycles induced by the shifting system, on top of a gradual streamflow increase over years caused by the spread of the plantations. In Vietnam, the abandonment of continuously cropped areas combined with patches of mix-trees plantations led to the natural re-growth of forest communities followed by a gradual drop in streamflow. Soil infiltrability controlled by surface crusting is the predominant process explaining why two modes of afforestation (natural regeneration vs. planting) led to opposite changes in streamflow regime. Given that commercial tree plantations will continue to expand in the humid

tropics, careful consideration is needed before attributing to them positive effects on water and soil conservation.

1 Introduction

Although the humid tropics exhibit the highest rate of deforestation and biodiversity losses globally (Keenan et al., 2015; Hansen et al., 2013; Bradshaw et al., 2009), new forests are regenerating on former agricultural and degraded lands, and tree plantations are being established for commercial and restoration purposes (Miura et al., 2015). Forest regrowth is either cyclic like in shifting cultivation systems (Ziegler et al., 2011; Hurni et al., 2013) or more permanent. The latter, afforestation, is the production of forest over an area of open land either by planting or by allowing natural regeneration. If appropriately managed, forest restoration, or afforestation, can lead to biodiversity enhancement (Chazdon, 2008), not only in the forested area but also farther downstream, in response to modified hydrological processes at the hillslope and catchment levels (Konar et al., 2013). Although important for a sustainable management of headwater catchments, the current understanding of hydrological processes altered by land-use changes remains limited in the tropics (Sidle et al., 2006). Reasons include the scarcity of long-term field monitoring (Douglas, 1999; Wohl et al., 2012) and several factors confounding causalities between land use and hydrological changes: mixed land-use patterns, climate variability, and catchment size (Beck et al., 2013; van Dijk et al., 2012). While it is widely and independently recognised that evapotranspiration is a central driver of basin annual water yield (Brown et al., 2005), changes in soil infiltrability also control groundwater recharge and water uptake by roots (Beck et al., 2013; Bruijnzeel, 2004). While in most cases, afforestation will reduce streamflow (Brown et al., 2005; Calder, 2007), the opposite or the absence of significant hydrologic changes are observed in some instances (Wilcox and Huang, 2010; Hawtree et al., 2015). The lack of an unequivocal hydrological response to afforestation feeds controversies around the role of forests in controlling river flows (Andréassian, 2004) and highlights the need for further research (Calder, 2007). A few studies have attempted to predict the catchment-scale hydrological effects of land-cover changes on streamflow in the humid tropics, mainly from model-based simulations of land-use change scenarios (Thanapakpawin et al., 2006; Guardiola-Claramonte et al., 2010; Homdee et al., 2011). Hydrological assessments based on actual data are rare in the humid tropics (Wohl et al., 2012) and often confined to the plot level (Ziegler et al., 2004; Podwojewski et al., 2008; Valentin et al., 2008a; Patin et al., 2012).

Two main approaches are usually deployed to assess how land-use changes alter hydrology. Paired catchment studies establish statistical relationships for outflow variables, during a calibration period, between two neighbouring catchments ideally similar in geomorphology, area, land use, and climate. Following this calibration, land-use treatments are applied to one catchment and changes in the statistical relationships are indicative of the land treatment effect on hydrology. Important limitations of this approach are the relatively few samples used for model development, and the spatial variability of rainfall events between the two catchments (Zégre et al., 2010). A second approach involves the calibration of a rainfall–runoff model in one single catchment. The model is first calibrated before a land-cover treatment occurred. The model is then used as a virtual control catchment along with rainfall observed after the land-cover treatment, in order to reconstitute runoff as if no change in the catchment had occurred. An underlying assumption for this approach is that the catchment behaviour is stationary in both the pre-treatment and post-treatment periods. This assumption is seldom tested. In addition, very few studies have tested the statistical significance of changes in the relationship between rainfall and runoff (Zégre et al., 2010).

The objectives of our research were to

1. Monitor inter-annual and long-term changes in land use and hydrology in two headwater catchments in tropical southeast Asia, one exposed to a gradual conversion of rainfed rice-based shifting cultivation to teak plantations in Laos, and one subject to natural forest regrowth following the abandonment of intensively cultivated hillslopes with cash crops and patches of mixed-trees plantations in Vietnam.

2. Use a conceptual monthly lumped water balance model repeatedly calibrated over successive 1-year periods and used in simulation mode with specific rainfall input to generate cross simulation matrices (Andréassian et al., 2003). These matrices are used to isolate the hydrological effect of rainfall variability from that of other environmental changes (e.g. land-use change, in this article) in each study catchment.

3. Apply correlation analyses and a non-parametric trend detection test to streamflow reported in the cross simulation matrices, to investigate and quantify causal relationships between land-use changes and changes in the hydrological behaviour of the study catchments, and assess whether the hydrological changes are statistically significant over the whole study period.

4. Compare the effects of forest plantations and natural forest regrowth on streamflow in the two study catchments.

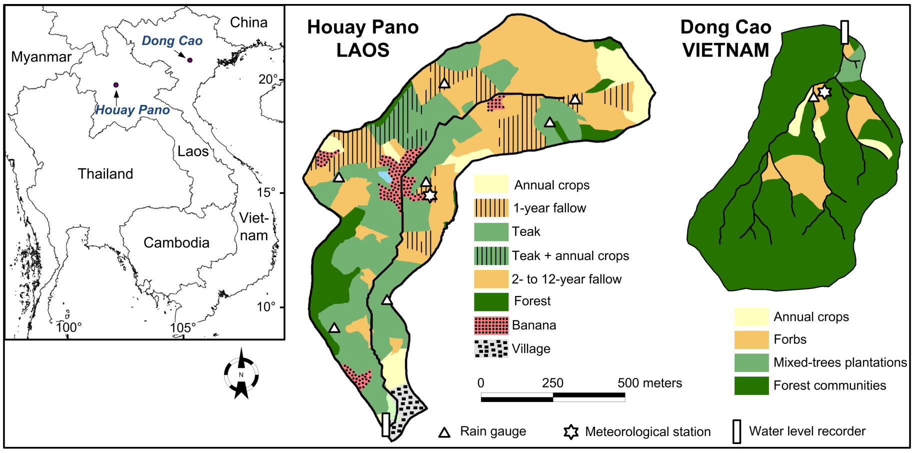

Figure 1. The two study catchments of the MSEC network and their land use in 2013.

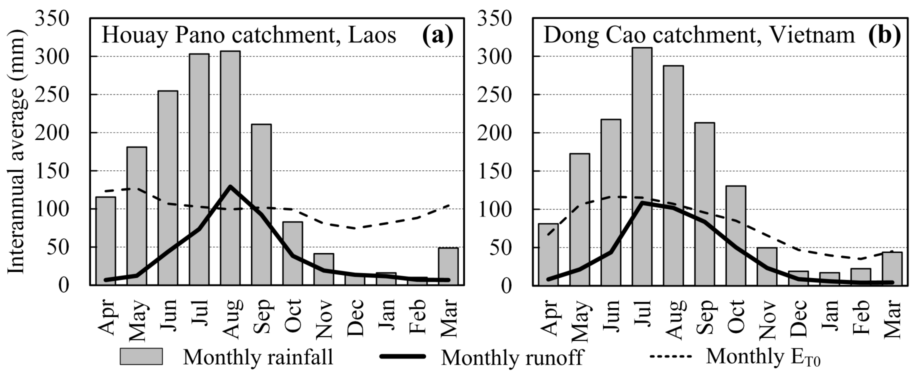

Figure 2. Monthly rainfall, runoff, and E_{T0} averaged over the study periods in Laos and Vietnam.

2 Materials and methods

2.1 Study sites

The two study catchments (Fig. 1) are part of a regional monitoring network named "Multi-Scale Environmental Change" (MSEC, http://msec.obs-mip.fr/), located in southeast Asia (Valentin et al., 2008b). They are exposed to a tropical climate influenced by the southwest monsoon bringing warm and humid air masses during the wet season (April–September), and by the northeast monsoon bringing colder dry air during the dry season (October–March). Rainfall is highly seasonal with more than 80 % of annual rainfall occurring during the wet season (Fig. 2). Averaged throughout the period (April 2001–March 2014), annual runoff amounts to about 26–27 % of annual rainfall in both catchments. The two catchments, located in upland rural areas, have similar size, elevations ranges, mean slopes, mean annual rainfall, and mean annual streamflow (Table 1). Both were cultivated by smallholder farmers when the monitoring network started operating in the early 2000s.

Table 1. Catchments characteristics.

Country	Laos	Vietnam
Catchment name	Houay Pano	Dong Cao
Province	Luang Prabang	Hoa Binh
Latitude	19°51′10″ N	20°57′40″ N
Longitude	102°10′45″ E	105°29′10″ E
Catchment size	60.2 ha	49.7 ha
Elevation range	430–718 m	130–482 m
Mean slope	48 %	40 %
Mean annual rainfall	1585 mm	1556 mm
Mean annual streamflow	418 mm	415 mm
Geology	Shale, schist	Schist
Soils	Alfisol, Entisol, Ultisol	Ultisol

The Houay Pano catchment in Laos is located about 10 km south of Luang Prabang city. It is representative of a landscape dominated by shifting cultivation, the principal activity in the uplands of northern Laos. The catchment was first cleared of semi-deciduous forest in the late 1960s (Huon et al., 2013) and used for shifting cultivation (crop–fallow rotation). In this system, one annual crop comprising mainly rainfed rice (*Oryza sativa*) with Job's tears (*Coix lacryma-*

Jobi) and maize (*Zea mays*) as secondary crops, is followed by several years of natural vegetation regrowth (woody fallow). On average, about 30 % of the land is cropped in a given year in this shifting system. The duration of the fallow period has declined from an average of 8.6 years in 1970 to 3.2 years in 2003 (de Rouw et al., 2015). At the onset of the land-use monitoring, the shifting cultivation system expanded over about 80 % of the catchment area. Non-farmed areas, about 15 % of the catchment surface area, were split between patches of mixed deciduous and dry Dipterocarp forest, paths, and the village. About 5 % were occupied by banana trees (*Musa spp.*) and teak tree plantations (*Tectona grandis L.*). *Tectona grandis L.* is an endemic species planted with an average density of 1500 trees ha^{-1} and a typical rotation length of 25–30 years. It is fully deciduous with total defoliation lasting 2–3 months during the dry season. Canopy typically closes after 3–5 years depending on the plantation density. In northern Laos, teak plantations have expanded quickly over the last decade (Newby et al., 2014), and specifically from 3 to 35 % of the catchment area in Houay Pano between 2006 and 2013, encroaching into the area used for shifting cultivation. In this catchment, agriculture has remained largely no-till with very limited external inputs such as fertilisers and pesticides.

The Dong Cao catchment is located in northern Vietnam, about 50 km southwest of Hanoi, along the eastern side of the Annamite Mountain range. The catchment was covered by lowland primary forest prior to 1970. Paddy rice and arrowroot (*Colocasia esculenta*) were cultivated only on the foothills and along the main stream. After 1970, because of population growth, greater food demand, and market demand, the forest was cut on the slopes and replaced by continuous cropping of annual crops without external inputs: initially upland rice, and more recently maize and cassava (*Manihot esculenta*). By 1980, all remaining forest had been cut. After 2000, due to soil exhaustion and erosion, declining yields, and governmental incentives, cassava on the steep slopes was rapidly replaced by evergreen tree plantations (with an average density of about 1600 trees ha^{-1}), including acacia (*Acacia mangium*) (Clément et al., 2007, 2009), eucalyptus (several species), Cinnamomum (several species), and fruit trees (Podwojewski et al., 2008). On less steep slopes, livestock was introduced, replacing cassava. Available land was used either for pasture and partly planted with grass fodder (*Bracharia ruziziensis*) (Podwojewski et al., 2008), or for expanding existing tree plantations in low densities. Following the recent conversion of the main land owner to off-farm activities, most of the tree plantations and annual crops were finally abandoned, leading to the natural re-growth of forest communities whose percentage area over the Dong Cao catchment nearly doubled between 2001 (45 %) and 2013 (84 %). Grazing and other activities linked to husbandry continue on a small area in the catchment. Water discharged from the main stream irrigates about 10 ha of paddy rice located downstream of the catchment.

2.2 Data collection

Data were collected by IRD (Institut de Recherche pour le Développement) and the national agricultural research institutions from April 2001 to March 2014 in Laos, and from April 2000 to March 2014 in Vietnam. They include records of daily rainfall, reference evapotranspiration (E_{T_0}), streamflow, and annual land-use maps. Stream water level was measured at the outlet of each catchment within a V-notch weir, by a water level recorder (OTT, Thalimedes) equipped with a data logger, with 1 mm vertical precision at 3 min time interval. A control rating curve (the relationship between water level and discharge) was determined using the velocity–area method at each station. In general, streamflow data quality is very good with rare interruptions in the measurements (August–November 2001 in Vietnam) caused by flood destruction of the measurement devices. Daily areal rainfall was computed using data collected by manual rain gauges (one in Vietnam, seven in Laos). Catchment-scale daily areal rainfall was derived from the point measurements using the Thiessen polygons method. Daily E_{T_0} was estimated following the Penman–Monteith FAO method applied to meteorological variables (air temperature, 2 m high wind speed, relative air humidity, and global solar radiation) collected by a weather station (CIMEL, ENERCO 404) installed at mid-hillslope in each catchment (Fig. 1). Mean monthly rainfall, runoff, and E_{T0}, averaged over the study period, are displayed in Fig. 2.

Land use was mapped annually for 13 years (April 2001–March 2014) from detailed field surveys undertaken each year in October–November, after the harvests of annual crops, when fields are clearly marked and easily accessible without damaging crops. A combination of GPS and theodolite survey points were used in the field to map boundaries between land-use units. ArcMap 10.0 was used to estimate the proportion of each land-use unit in each catchment. The mapping accuracy of land-use boundaries is estimated to be within ± 2.5 m (Chaplot et al., 2005). Land-use units covering less than 1 % of the catchment areas are not reported here. In the Houay Pano catchment in Laos, distinction was made between fallow of different ages varying between 1 and 12 years. Some of the land-use units correspond to the aggregation of several land uses observed in the field, as detailed thereafter.

In Laos, the unit "Annual crops" includes rainfed upland rice, Job's tears and maize; "Forest" includes patches of remaining forest, either mixed deciduous or dry Dipterocarp; "1-year fallow" and "2- to 12-year fallow" form two distinct land-use units due to differences in soil surface crusting rates and associated hydrodynamic conductivity (Ziegler et al., 2004); Teak plantations are often associated with annual crops during the first 2 years after planting ("Teak + annual crops") and become a monoculture after canopy closure ("Teak"). "Banana" corresponds to small banana plantations.

In Vietnam, the unit "Forest communities" combines abandoned farmland that has developed into an open forest, usually after 5 years of undisturbed growth, and patches of more developed secondary forest; "Mixed-trees plantations" includes acacia, eucalyptus, cinnamon, and fruit trees, both young and mature. These plantations have developed an understorey of natural vegetation; "Forbs" are abandoned farm lands covered by a dense herbaceous cover of perennial dicots and grasses, usually developed within 5 years since the last cropping; "Annual crops" include cassava and maize; "Fodder" corresponds to the planted exotic grass *Bracharia ruziziensis* mixed with local grasses.

2.3 Assessment of hydrological changes

The two-parameter monthly lumped water balance model GR2M was used to investigate changes in the hydrological behaviour of the two study catchments. This model was empirically developed by Mouelhi et al. (2006) using a sample of 410 basins under a wide range of climate conditions. GR2M includes a production store and a routing store. The model estimates monthly streamflow from monthly areal rainfall and monthly E_{T0}. The two parameters of the model determine the capacity of the production store and the flow of underground water exchange. Compared with several widely used models, GR2M ranks amongst the most reliable and robust monthly lumped water balance models (Mouelhi et al., 2006). For this analysis, like in most hydrological analyses performed in the Mekong Basin, each hydrological year n starts in April of year n and ends in March of year $n+1$ (Lacombe et al., 2010). The model was repeatedly calibrated over 12 successive 1-year periods from April 2002 to March 2014, thus allowing an initial warm-up period for the initiation of the water level in the two model reservoirs of at least 1 year. The Nash–Sutcliffe efficiency criteria calculated on flow (N_{SEQ}) and calculated on the logarithm of flow (N_{SElnQ}) were used for the evaluation of wet and dry season streamflow simulations, respectively. While each of these two efficiency criteria are calculated with the 12 monthly flow values of each 1-year calibration period (including wet and dry season streamflow), N_{SEQ} and N_{SElnQ} give more weight to high- and low-flow values, respectively. Therefore, the former and the latter are suitable for evaluating high- and low-flow simulations, respectively (Pushpalatha et al., 2012). The nonlinear generalized reduced gradient (GRG) method (Lasdon and Warren, 1979) was used to determine the values of the two model parameters that maximise the efficiency criteria. A constraint of a less than 10 % bias on annual streamflow over each year was applied to all calibrations using a branch-and-bound method that runs the GRG method on a series of subproblems. This constraint was achieved for all calibrations. For each of the two objective functions, each of the 12 sets of model parameters were used to perform simulations over the other 11 1-year periods (cf. generalized split-sample test from Coron et al., 2012). The annual variables

$$
\begin{array}{c|ccccc|}
 & \mathrm{M}_1 & \cdots & \mathrm{M}_j & \cdots & \mathrm{M}_n \\
\hline
\mathrm{R}_1 & q_{11} & \cdots & q_{1j} & \cdots & q_{1n} \\
\vdots & \vdots & & \vdots & & \vdots \\
\mathrm{R}_i & q_{i1} & \cdots & q_{ij} & \cdots & q_{in} \\
\vdots & \vdots & & \vdots & & \vdots \\
\mathrm{R}_n & q_{n1} & \cdots & q_{nj} & \cdots & q_{nn} \\
\hline
\end{array}
$$

Figure 3. Cross-simulation matrix. Here, i is the row index and j is the column index; $M_j (j \in N|1 \leq j \leq n)$ defines the set of model parameters calibrated over year j using R_j as input; and R_i $(i \in N|1 \leq i \leq n)$ defines the rainfall that occurred over year i.

"wet season streamflow" and "dry season streamflow" were defined as the sum of monthly simulated streamflow over the wet and the dry season, respectively. This procedure resulted in two 12-by-12 cross-simulation matrices of hydrological variables q_{ij} for each study catchment (Fig. 3).

In a given matrix, each column j $(j \in N|1 \leq j \leq 12)$ corresponds to a set of model parameters M_j capturing the hydrological conditions of the catchment that prevailed during year j. In each row i $(i \in N|1 \leq i \leq 12)$, streamflow was simulated with rainfall from year i. Flow variations between columns for a given row are not rainfall-related and reflect other environmental changes (e.g. land-use change). Flow variations between rows for a given column result from inter-annual rainfall variability. Variations in simulated streamflow between the columns of the matrices were plotted against time. In these simulations, rainfall input to the model is similar each year and corresponds to the year with actual rainfall exhibiting median annual depth over the study period (year 2004 in Laos and year 2012 in Vietnam, cf. Fig. 4). The inter-annual variations in simulated streamflow illustrate changes in the hydrological behaviour of the study catchments under stable rainfall conditions (Houay Pano catchment in Fig. 5a, b and Dong Cao catchment in Fig. 6a, b). The objective of this simulation framework is to isolate the hydrological effect of rainfall variability from that of other environmental disturbances and verify the hydrological influence of actual land-use changes by comparing Figs. 5a, b, and 6a, b with Figs. 5c and 6c, respectively, showing inter-annual variations in the cumulative percentage areas of the land-use units.

Following the approach proposed by Andréassian et al. (2003), the statistical significance of gradual changes in catchment behaviour was calculated using cross-simulation matrices similar to the one illustrated in Fig. 3. Each of the

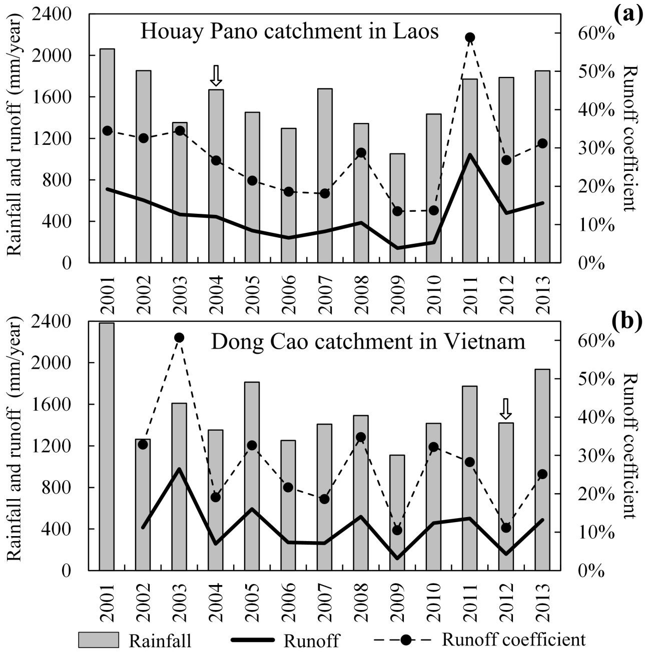

Figure 4. Annual rainfall, runoff, and runoff coefficient measured in Houay Pano **(a)** and Dong Cao **(b)** catchments. Runoff values are not available in Vietnam in 2001 (cf. Sect. 2.2). Arrows point to rainfall years used in model simulations displayed in Figs. 5 and 6.

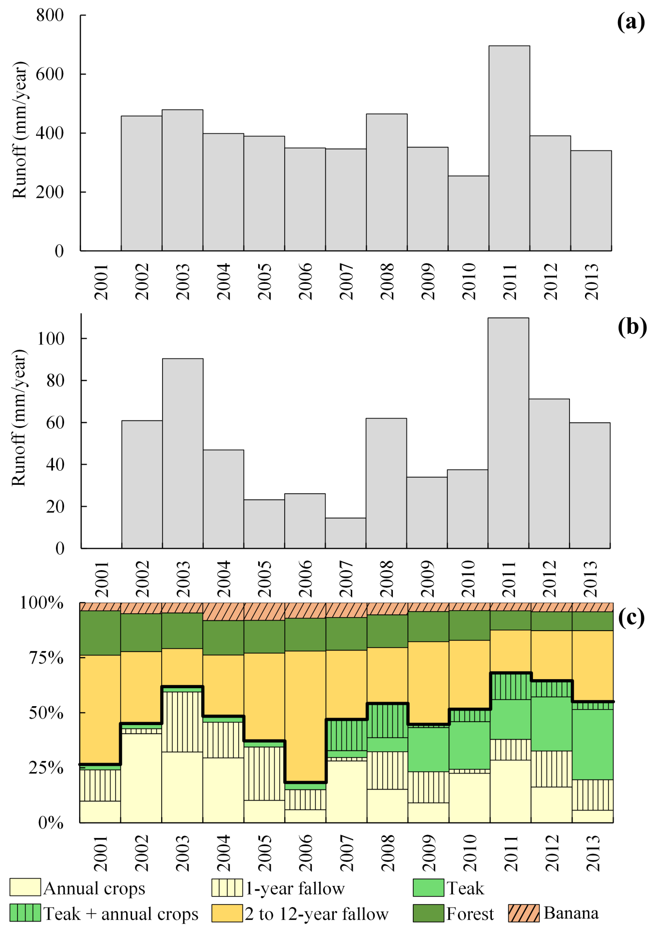

Figure 5. Houay Pano catchment, Laos. Wet season **(a)** and dry season **(b)** streamflow simulated with GR2M calibrated each year (indicated on x axis) and ran with the same rainfall input. Cumulative percentage area of the land-use units **(c)**.

two original matrices was resampled 10 000 times by permuting columns. For each original and permuted matrix, the statistic S was calculated using Eq. (1).

$$S = \sum_{i=1}^{n} \left[\sum_{j=1}^{i-1} (q_{ii} - q_{ij}) + \sum_{j=i+1}^{n} (q_{ij} - q_{ii}) \right], \quad (1)$$

where q_{ij} is the streamflow value found in the ith row and the jth column of the matrix. Under the null hypothesis H_0 of absence of unidirectional trend in the hydrological behaviour of the catchment, the value of S associated to the original matrix should be close to zero. A negative (respectively, positive) S value corresponds to a decrease (respectively, increase) trend in basin water yield. The p value of a negative (respectively, positive) trend is equivalent to the non-exceedance (respectively, exceedance) frequency of the original S value compared to the range of S values derived from the permuted matrices.

3 Results

3.1 Hydrological changes according to measured variables and cross-simulation test

Annual rainfall and runoff variations are consistently correlated in Laos ($r = 0.71$, F test p value $= 0.001$) and Vietnam ($r = 0.59$, F test p value $= 0.04$). Rainfall and runoff tend to decrease from 2001 to 2009 and to increase from 2009 to 2013 in the two catchments, with a few singular years (e.g. lower rainfall and runoff in Vietnam in 2002; higher runoff in Laos in 2011) (Fig. 4). In Laos, the annual runoff coefficient C (C =annual runoff/annual rainfall) gradually declines from 2001 (34.5 %) to 2009 (13.5 %) and then increases until 2013 (31.1 %), with local peaks in 2003 (34.5 %), 2008 (28.8 %), and 2011 (58.9 %). In Vietnam, C exhibits greater inter-annual variability than in Laos with an overall declining trend, from about 48.5 % over the years 2002 and 2003 to 19.2 % over the years 2012 and 2013 (Fig. 4). Consistently, the non-parametric cross-simulation test applied to wet and dry season streamflow did not reveal any significant trend in catchment behaviour in Laos over the simulation period 2002–2013: p values were 0.48 and 0.33 for the wet and dry season streamflow, respectively. In contrast, a highly significant reduction of the basin water yield was observed in Vietnam over the same period: p values were 0.03 and 0.01 for the wet and dry season streamflow, respectively.

3.2 Simulated streamflow and land-use changes in the Houay Pano catchment, Laos

Annual values of N_{SEQ} and N_{SElnQ} averaged over the whole study periods are high: 89.9 % and 86.6 %, respectively. The lowest annual values were obtained in 2008 ($N_{SElnQ} = 74.0$) and 2009 ($N_{SEQ} = 69.1$). Figure 5 shows that the cumulative percentage area including annual crops, 1-year fallow, and teak plantations (materialised by the black solid-bold curve) is positively correlated to the variations in simulated wet and dry season streamflow ($r = 0.49$, F test p value = 0.09 and $r = 0.77$, F test p value = 0.00, respectively). Any other combinations of land-use units led to lower correlation between the corresponding cumulative percentage areas and seasonal simulated streamflow. Quantitatively, between 2002 and 2003, simulated wet and dry season streamflow increased by 21 and 29 mm, respectively. Over the same period, the cumulative percentage area including annual crops, 1-year fallow, and teak plantations increased from 45.2 to 61.7 % of the catchment area. From 2003 to 2006, the cumulative percentage area including annual crops, 1-year fallow, and teak plantations decreased to 18.3 % while simulated wet and dry season streamflow decreased by 129 and 64 mm, respectively. The main land-use changes that occurred during the first sub-period (2002–2006) involve cyclic alternations between rainfed rice that is cropped one year, and fallow (up to 6 consecutive years), which are typical land uses of the shifting cultivation system that prevails in the uplands of Laos. The second sub-period (2006–2013) is characterized by a continuation of the same shifting cultivation dynamic, yet with cycles of slightly lower magnitude. The main change observed over this second sub-period is a gradual spread of teak plantations, with their total surface area increasing from 3.3 to 35.1 % of the catchment, with a corresponding decline in the area of shifting cultivation. From 2006 to 2008, the cumulative percentage area including annual crops, 1-year fallow, and teak plantations increased from 18.3 to 54.0 % while simulated wet and dry season streamflow increased by 115 and 36 mm, respectively. Between 2008 and 2009, the cumulative percentage area including annual crops, 1-year fallow, and teak plantations decreased from 54.0 to 44.2 % while simulated wet and dry season streamflow decreased by 113 and 28 mm, respectively. Consistently, from 2010 to 2011, the cumulative percentage area including the same land-use units increased from 51.0 to 67.6 % while simulated wet and dry season streamflow increased by 442 and 72 mm, respectively. Conversely, from 2011 to 2013, this cumulative percentage area decreased to 54.5 % while wet and dry season streamflow decreased by 356 and 50 mm, respectively (Fig. 5).

Over the first sub-period (2002–2006), on average, an increase (decrease) of x in the cumulative percentage area including annual crops and 1-year fallow induces an increase (decrease) of 2.90x mm and 1.48x mm in wet and dry season streamflow, respectively. Over the second sub-period (2007–2013), on average, the magnitude of the flow response to an increase (decrease) of x in the cumulate percentage of area under annual crops, 1-year fallow, and teak plantations is greater: 11.72x mm and 3.31x mm in wet and dry season streamflow, respectively (Fig. 7a, b).

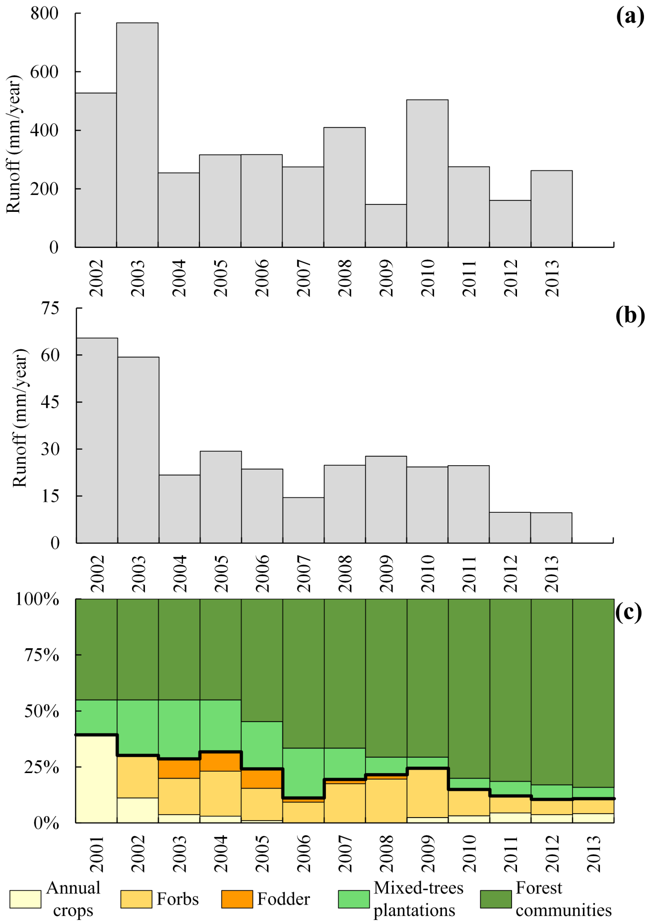

Figure 6. Dong Cao catchment, Vietnam. Wet season **(a)** and dry season **(b)** streamflow simulated with GR2M calibrated each year (indicated on x axis) and ran with the same rainfall input. Cumulative percentage area of the land-use units **(c)**.

3.3 Simulated streamflow and land-use changes in the Dong Cao catchment, Vietnam

Annual values of N_{SEQ} and N_{SElnQ} averaged over the whole study periods are high: 89.0 and 88.0 %, respectively. The lowest annual values were obtained in 2008 ($N_{SEQ} = 57.2$) and 2010 ($N_{SElnQ} = 69.3$). Figure 6 shows that the cumulative percentage area including annual crops, forbs, and fodder (materialised by the black solid-bold curve) is positively correlated to the variations in simulated wet and dry season streamflow time-lagged by 1 year ($r = 0.56$, F test p value = 0.06 and $r = 0.82$, F test p value = 0.00, respectively) (Fig. 7c, d). Like in Laos, any other combinations of land-use units led to lower correlation between the corresponding cumulative percentage areas and seasonal sim-

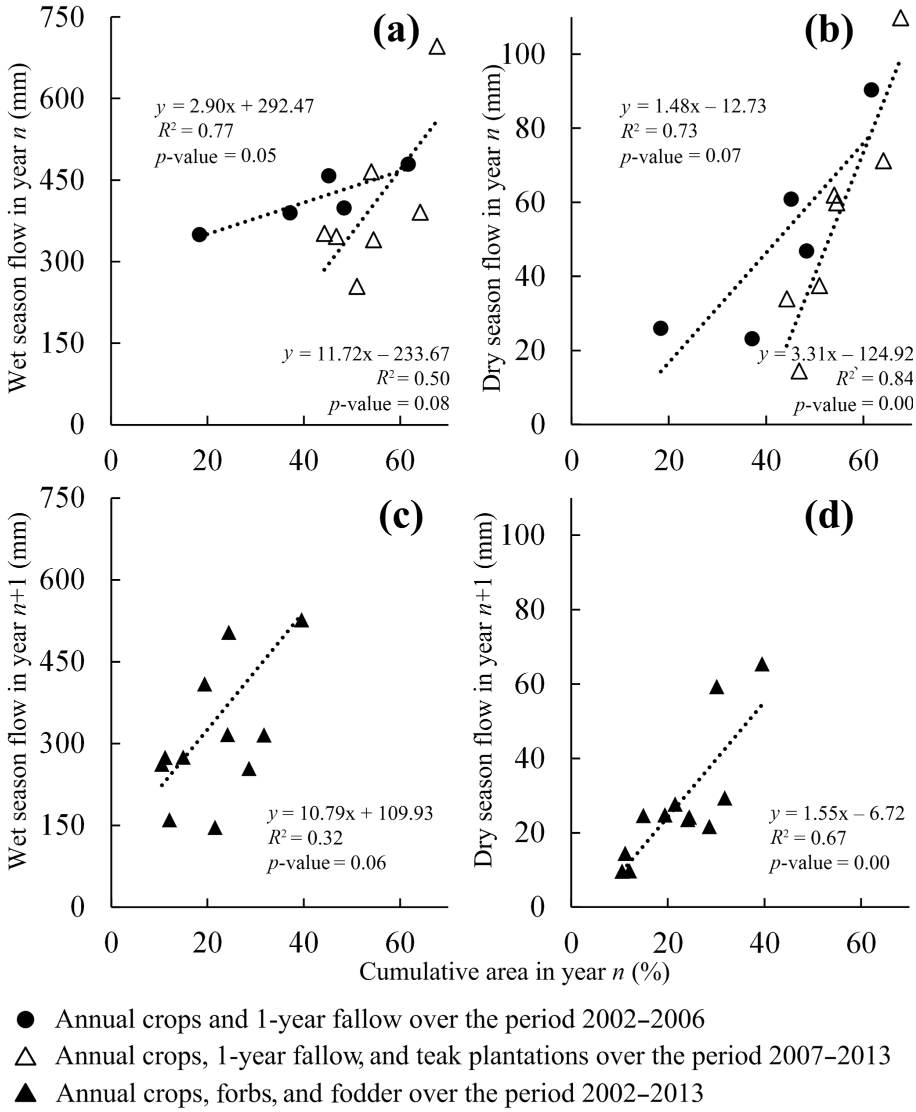

Figure 7. Correlations between simulated streamflow and land-use types. Panels **(a)** and **(b)** show the Houay Pano catchment, Laos. Panels **(c)** and **(d)** show the Dong Cao catchment, Vietnam. Percentage areas of year n ($n \in N\,|2001 \leq n \leq 2012$) are correlated to seasonal streamflow of year $n+1$ in Vietnam.

ulated streamflow. It is interesting to note that these land-use units are all herbaceous covers, in contrast with the tree-based land-use units "Mixed-trees plantations" and "Forest communities" appearing above the black solid-bold curve in Fig. 6c. Quantitatively, Fig. 6a, b show an overall reduction of simulated wet and dry season streamflow from 2002–2003 to 2012–2013 (−435 and −53 mm, respectively). From 2002 to 2004, simulated wet and dry season streamflow reduced by 272 and 44 mm, respectively, following the reduction of herbaceous vegetation cover from 40 to 29 % between 2001 and 2003. From 2004 to 2006, simulated streamflow is relatively stable, in accordance with the relative stability in the percentage area of herbaceous cover over the period (2003–2005). The drop in simulated wet and dry streamflow in 2007 (down to 275 and 15 mm, respectively) follows a drop in the percentage area of herbaceous cover to 11 % in 2006. The period (2008–2010), exhibiting slightly greater simulated wet and dry season streamflow, up to 504 and 28 mm, respectively, follows a period (2007–2009) with a greater percentage area of herbaceous cover (up to 24 %). Afterwards, the percentage area of herbaceous cover and simulated wet and dry season streamflow decline again, to 11 %, and 161 and 10 mm, respectively. Over the study period, the year 2009 exhibits the lowest annual rainfall depths (Fig. 4), possibly explaining the discordance between land-uses changes and simulated wet season streamflow in this particular year (cf. Fig. 6 and Sect. 4.4).

4 Discussion

4.1 Land-use changes and hydrological processes in the Houay Pano catchment, Laos

Figures 5 and 7a, b indicate that catchment streamflow is predominantly produced by the following land-use units: annual crops, 1-year fallow, and teak plantations while 2- to 12-year fallow, forest, and banana plantations make a comparatively lower contribution to annual streamflow production. In agreement with these observations, Ribolzi et al. (2008) determined a negative correlation between the percentage area of total fallow and annual runoff coefficients in the same catchment over the period 2002–2006. However, the authors could not ascertain the causality between these two variables because the possible effect of rainfall variability (gradual decline of annual rainfall from 2002 to 2006, cf. Fig. 4a) on streamflow was not isolated from that of land-use change (gradual increase of total fallow areas from 2002 to 2006, cf. Fig. 5c).

The contrasting hydrological behaviour of areas under annual crops and 1-year fallow, on the one hand, and areas under 2- to 12-year fallow, on the other hand, observed at the catchment level, are consistent with local observations. Using several 1 m^2 microplot experiments in the Houay Pano catchment, Patin et al. (2012) showed that soil under annual crops (rice) exhibit rates of soil surface crusting that are much higher (about 50 % of the microplot area) than those observed under old fallow (about 10 % of the microplot area). The authors showed that soil infiltrability decreases as the soil surface crusting rate increases, thus explaining the lower overland flow productivity of 2- to 12-year fallow, compared to that of annual crops. Due to the low faunal activity and the absence of tillage in the upland rice-based cultivation systems, the high rates of crusting rate persist during the first year of fallow (Ziegler et al., 2004), thus explaining similar hydrological behaviours of annual crops and 1-year fallow. While infiltrability increased as fallow aged, its developing leaf area and root system also contributed to lower streamflow at the catchment outlet (cf. period 2003–2006 in Fig. 5). The fraction of incident rainfall intercepted by the canopy and subsequently evaporated increased while larger volumes of infiltrated water were redirected by transpiration. The increased root water uptake reduced groundwater recharge and subsurface water reserves; it also lowered the water table, hence limiting stream feeding by shallow groundwater. This groundwater depletion led to a drop in the annual stream water yield due to a decrease in wet season inter-storm flow and dry season base flow (Ribolzi et al., 2008).

The hydrological processes involved in the conversion of the rice-based shifting cultivation system to teak plantations are less intuitive. Teak trees can develop relatively high leaf area index (Vyas et al., 2010), deep and dense root systems (Calder et al., 1997; Maeght, 2014), i.e. traits consistent with a high water uptake by evapotranspiration. To that extent, their hydrological impact should be similar to that of 2- to 12-year fallow during the wet season. However, (1) under young teak trees, the inter-row area is cultivated with annual crops with high rate of soil surface crusting; (2) the large leaves of mature teak trees concentrate rainfall into big drops that hit the soil with increased kinetic energy hence forming surface crusts; and (3) most farmers intentionally keep the soil bare under mature teak trees by recurrent burning of the understorey. These three facts create the conditions for intense erosion that induces features such as gullies, raised pedestals, and root exposure. Suppression of the understorey led to the formation of impervious crusts that limited infiltration and in turn increased Hortonian overland flow and erosion, as typically observed in teak plantations where fires are a common phenomenon (Fernández-Moya et al., 2014). These processes were quantified at the 1 m^2 microplot level by Patin et al. (2012) in the Houay Pano catchment. Median infiltrability measured in teak plantations (18 $mm\,h^{-1}$) was nearly 4 times lower than that measured in fallow (74 $mm\,h^{-1}$), and equivalent to that measured in rice fields (19 $mm\,h^{-1}$). Compared to the dense fallow vegetation that remains green during the dry season, teak trees shed their leaves during the dry season, primarily in response to the gradual drop in precipitations and temperature (Abramoff and Finzi, 2015), thus reducing transpiration and increasing dry season streamflow. The low infiltrability throughout the year and the limited root water uptake during the dry season both explain the increasing wet and dry season streamflow as teak plantations expanded over the catchment between 2006 and 2013 (Figs. 5 and 7a, b).

No local measurement of infiltrability and soil surface crust was performed under the natural forest in the Houay Pano catchment. Therefore, it is not possible to conclusively prove their contribution to the catchment outflows. However, correlation analyses showed that this land-use unit behaves hydrologically like 2- to 12-year fallow (cf. the position of this land-use unit above the black solid-bold curve in Fig. 5c). This is in accordance with Brown et al. (2005) and with our findings in Vietnam (cf. Sect. 4.2, Figs. 6 and 7c, d), showing that sparser (denser) natural vegetation cover increases (reduces) streamflow. Finally, it should be noted that the area covered with banana trees remained stable over the study period and had no discernable effect on streamflow variations.

4.2 Land-use changes and hydrological processes in the Dong Cao catchment, Vietnam

Figures 6 and 7c, d indicate that catchment streamflow is predominantly produced over herbaceous land-use units (annual crops, forbs, and fodder), while tree-based land-use units (mixed-trees plantations and forest communities) make a comparatively lower contribution to streamflow (cf. the location of these groups of land-use units below and above the black solid-bold curve in Fig. 6c, respectively). These differences are consistent with local observations. Deploying several 1 m^2 microplot experiments in the Dong Cao catchment in 2004 and 2005, Podwojewski et al. (2008) showed that mean annual surface runoff coefficients under annual crops (10.8 %), fodder (5.9 %), and forbs (referred to as "fallow" in Podwojewski et al., 2008) (5.1 %), were higher than those of eucalyptus (2.0 %) and other tree-based covers (1.4 %) including mixed-trees plantations and forest communities. Applying controlled artificial rainfall (two events of 90 mm h^{-1} over 40 min each) on several 1 m^2 microplots in the Dong Cao catchment, Janeau et al. (2014) showed that the accumulation of litter under an *Acacia mangium* planted forest cover decreased the runoff coefficient by 50 %.

Two types of land-use successions occurred in the Dong Cao catchment: (i) from annual crops and fodder to forbs and finally to forest communities and (ii) from mixed-trees plantations to forest communities (Fig. 6c). These land-use changes are the result of afforestation by natural regeneration in both abandoned fields and neglected tree plantations, respectively. As indicated in Podwojewski et al. (2008), these natural successions are converging on lower surface runoff coefficients caused by increased infiltrability, allowing the evapotranspiration of larger volumes of sub-surface and ground water through denser and deeper root systems and denser tree canopy (Dunin et al., 2007; Ribolzi et al., 2008). This explains the decrease in simulated wet and dry season streamflow at the catchment level (Fig. 6a, b) from 2002 to 2013. The visual comparison of the simulated streamflow time series (Fig. 6a, b) with the time series of the cumulative percentage area of the herbaceous land-use units (e.g. the black solid-bold curve in Fig. 6c) indicates a 1-year delay in the response of seasonal streamflow to land-use changes, which is confirmed by correlation analyses (Fig. 7c, d). This delay is already known from a number of catchment experiments globally. Brown et al. (2005) showed that annual water yield altered by forest regrowth experiments takes more time to reach a new equilibrium, compared to deforestation experiments that usually induce quicker hydrological responses. In Laos, no time lag was observed between land-use changes and changes in simulated streamflow (Fig. 5) because this temporality was already accounted for in the difference made between 1-year fallow and 2- to 12-year fallow exhibiting contrasting soil surface crusting rates and infiltrability.

The reduction of the Dong Cao catchment water yield over the full study period is equivalent to a reduction of about 165 000 m^3 (330 mm) during the wet season and 30 300 m^3 (60 mm) during the dry season. While the dry season streamflow reduction may have negative consequences on irrigated rice located downstream of the catchment, the reduction in wet season streamflow is expected to contribute to decreased flood risk. The overall reduction in streamflow over the study period could be interpreted as a recovery of hydrological status prevailing prior to 1970 when the catchment was covered by lowland primary forest with evapotranspiration likely greater and streamflow production likely lower than that observed in the early 2000s.

4.3 Comparison of the relationships between land-use changes and changes in hydrological behaviour in the two study catchments

The dynamics of land-use changes in the Houay Pano catchment, Laos, involved cyclic patterns (landscape dominated by shifting cultivation and teak plantation expansion) whose hydrological effects would remain undetected if we had restricted our analysis to the statistical detection of gradual and unidirectional change in the rainfall–runoff relationship (p values > 0.3, cf. Sect. 3.1) over the whole study period, as it is often done in hydrological impact assessments. In contrast, the same test applied over the same period has resulted in highly significant changes in the Dong Cao catchment, Vietnam (p values < 0.03) because the land-use transition to forest was unidirectional over the whole study period. These results highlight the need to measure and assess the inter-annual co-variability of land use and streamflow at the finest temporal scale when assessing changes in catchment behaviour.

Two main types of land-use change at the scale of the Houay Pano catchment had different hydrological impacts: (i) the transition from (2- to 12-year fallow and forest) to (annual crops and 1-year fallow); (ii) the transition from (2- to 12-year fallow and forest) to (annual crops, 1-year fallow, and teak plantations). The first (observed over 2001–2006) induced increases in simulated seasonal streamflow lower than those induced by the second (observed over 2006–2013), as illustrated by the different slopes of the regression lines in Fig. 7a, b. Thus, teak plantations, recently introduced to replace traditional rice-based shifting cultivation systems, are generating more runoff than was generated by annual crops and 1-year fallow. This difference did not appear in the average values of infiltrability obtained by Patin et al. (2012) at the microplot level: 18 and 19 mm h^{-1} for teak plantations and rice fields, respectively. The microplot measurements were performed before 2010, while the major catchment-wide hydrological effects of the spread of teak plantations occurred in 2011 (Fig. 5), suggesting that Hortonian overland flow has increased over recent years in the teak plantations, in response to increased erosion processes and soil losses caused by the recurrent burning and clearing of the plantation understorey. This effect of land-use conversion on the hydrology of headwater catchment is expected to have detrimental effects on downstream river ecosystems and related biodiversity, not only through a change in streamflow variability but also with the enhanced erosion and flow sediment transport.

The hydrological effect of this modern land conversion in Laos is of the same magnitude (but in the opposite direction) as that caused by the conversion of herbaceous cover (annual crops, forbs, and fodder) to naturally regenerating tree-based covers in Vietnam (mixed-trees plantations and forest communities). In the two countries, the switch from herbaceous cover (including teak tree plantations in Laos) to old fallow and/or forest over 1 % of the catchment area translates into reductions of wet and dry seasons' streamflow of about 10–12 mm and 1.5–3.5 mm, respectively (cf. the coefficients of the linear regressions in Fig. 7a, c and b, d, respectively). Assuming the linearity of these relationships, the average difference between actual annual evapotranspiration of the herbaceous cover (including teak trees in Laos) and natural tree-based cover ranges between $100 \cdot (10 + 1.5)$ and $100 \cdot (12 + 3.5)$ mm, i.e. 1150–1550 mm, which is of the same order of magnitude as typical evapotranspiration of tropical forests in continental southeast Asia (Tanaka et al., 2008). This comparison indicates that the evapotranspiration of the studied teak tree plantations in Laos (which could theoretically surpass that of the herbaceous cover because of potentially deeper root system and denser leaf area index) is likely limited by the soil water availability in accordance with the low infiltrability rates previously measured at the microplot level.

4.4 Reliability of the results

A two-parameter monthly lumped water balance model was used to investigate the relationship between land use and catchment hydrology. This approach presents some limitations. For instance, land-use changes occurring within or outside of the riparian area and their hydrological effects were not differentiated. The spatial patterns of the land-use mosaics (e.g. area, layout, and connectivity of the patches) were not accounted. This simplification limits our understanding of the processes underlying the rainfall–runoff transformation. However, the model efficiently captured the gradual changes in the catchments' behaviour (mean values of N_{SEQ} and $N_{\mathrm{SElnQ}} > 86\,\%$) which proved to be significantly ($0.00 < p$ values < 0.08) and consistently correlated to highly variable land-use patterns.

It could be argued that 1-year calibrations are too short for the model to accurately capture the hydrological behaviour of the catchment. This statement would be valid in the context of a more classical split-sample test including a calibration and a validation period where the model is used as a predictor. This procedure assumes that the catchment is hydrologically stable over these two sub-periods. In our approach, the water balance model was used to capture gradual changes in hydrological behaviour in order to verify if these changes are caused by actual changes in land-use conditions. With this aim, minimising the duration of the calibration periods to 1 year allowed maximising the dependency between the model parameters and the corresponding land-use patterns mapped annually. This approach proved to be appropriate given the high inter-annual variability of land use (Figs. 5c and 6c), and the significance of the correlations between land use and streamflow simulated with the different calibrated models (Figs. 5, 6, and 7). However, a 1-year calibration may result in a model that performs well under the specific climate conditions of the calibration year only. Simulation biases usually increase when the model is run under climate conditions different from calibration conditions (Coron et al. 2012), thus possibly hampering the detection of the hydrological changes illustrated in Figs. 5 and 6. To quantify this bias, GR2M was calibrated over the 2-year period (2012–2013) in the Dong Cao catchment where land use remained relatively stable between 2011 and 2013 (Fig. 6c). The rainfall years 2012 and 2013 correspond to the median (1421 mm) and the wettest (1938 mm) years, respectively, of the study period (2002–2013) (Fig. 4). Therefore, this two-year period exhibiting stable land use but contrasting rainfall conditions is well suited to investigate the effect of rainfall variability and calibration duration on model efficiency. The mean relative difference between streamflow simulated by this model and by the models calibrated over the 1-year periods 2012 and 2013 (the three models use the same 2012 year as rainfall input) approximates this simulation bias which was found to be higher for the wet season (20 %) than for the dry season (2 %). Overall, these biases are negligible compared to the major hydrological changes observed in the two study catchments: 67 % wet season streamflow reduction and 84 % dry season streamflow reduction over the study period in the Dong Cao catchment; 100 % wet season streamflow increase and 650 % dry season streamflow increase in the Houay Pano catchment between 2007 and 2011. In contrast, wet season streamflow over the period 2002–2006 in the Houay Pano catchment (Fig. 5a) exhibits the lowest inter-annual variations for a 5-year period in the study catchments, with a coefficient of variation (11 %) lower than the 20 % bias estimated for the wet season simulations, indicating a possibly significant modelling artefact. However, these streamflow variations are significantly and consistently correlated to land-use change over this short period (Fig. 7a), suggesting negligible biases even for these slightest streamflow variations. The main discrepancy between simulated streamflow and land use was observed during the 2009 wet season in the Dong Cao catchment (Fig. 6). In 2009, simulated streamflow is equivalent to about one-third of that in 2008 and 2010, while no major change in land use apparently explains this drop. This discrepancy could originate from a simulation bias because 2009 was the driest year of the study period (Fig. 4).

5 Conclusion

Our results show that the land-use effects on soil surface properties and infiltrability, previously quantified in 1 m^2 microplots, are reconcilable with the hydrological behaviour of the study catchments, at a scale 6 orders of magnitude larger. These findings indicate that land use – i.e. the way the vegetation cover is managed (e.g. recurrent burning of the understorey of teak tree plantations) – exerts a control on streamflow production greater than land cover (i.e. theoretical evapotranspiration characteristics of the vegetation). Another approach to assess the hydrological impacts of land-use changes typically involves physically based and distributed hydrologic models. Our analysis demonstrates that this other category of models necessarily needs to account for changes in soil properties following land conversions in order to efficiently simulate the hydrological effects of land-use changes.

According to the most recent Global Forest Resources Assessment (FAO, 2015), Laos and Vietnam are listed among the 13 countries globally which were likely to have passed through a national forest transition between 1990 and 2015, with a switch from net forest loss to net forest expansion (Keenan et al., 2015). Our analysis exemplifies the diverse impacts this forest expansion can have on streamflow, and how it can lead to extreme, yet opposite, hydrological changes, depending on how the newly established tree-based cover is managed. The conversion of rice-based shifting cultivation to teak plantations in Laos led to increased seasonal streamflow. The conversion of annual crops and mixed-trees plantations to naturally re-growing forest in Vietnam led to decreased seasonal streamflow. Considering that commercial tree plantations will continue to expand in the humid tropics, careful consideration is needed before attributing to them positive effects on water and soil conservation.

6 Data availability

The data set used in this analysis, including hydrometeorological records and land-use maps, is available at http://msec.obs-mip.fr/.

Acknowledgements. This work was funded by the French watershed network SOERE-RBV (réseau des bassins versants), the French Observatory for Sciences of Universe (Observatoire des Sciences de l'Univers), the CGIAR research program on Integrated Systems for the Humid Tropics, and the French ANR TECITEASY (ANR-13-AGRO-0007). The authors gratefully acknowledge the Institute of Research for Development, the International Water Management Institute, the Soils and Fertilizers Research Institute (Vietnam), and the Agriculture Land-Use Planning Center (Laos).

Edited by: G. Jewitt

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