Hydrol. Earth Syst. Sci. Discuss., 12, 12615–12648, 2015
www.hydrol-earth-syst-sci-discuss.net/12/12615/2015/
doi:10.5194/hessd-12-12615-2015

Hydrology and Earth System Sciences Discussions
Open Access

Afforestation by natural regeneration or by tree planting: examples of opposite hydrological impacts evidenced by long-term field monitoring in the humid tropics

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Received: 30 October 2015 – Accepted: 16 November 2015 – Published: 4 December 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The humid tropics are exposed to an unprecedented modernization of agriculture involving rapid and highly-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 controlling 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 hydro-meteorological variables has been operating in several headwater catchments in tropical Southeast Asia since 2001. The GR2M water balance model repeatedly calibrated over successive 1 year periods, and used in simulation mode with specific 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 flows 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 flow patterns: pluri-annual flow cycles induced by the shifting system, on top of a gradual flow increase over years caused by the spread of the plantation. In Vietnam, the abandonment of continuously cropped areas mixed with patches of tree 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 or planting) led to opposite changes in flow 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 exhibits 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 plantations are being established for commercial and restoration purposes (Miura et al., 2015). Forest regrowth is either a cyclic phenomenon like in shifting cultivation systems (Ziegler et al., 2011) 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 recognized 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 flows (Brown et al., 2005; Calder, 2007), the opposite or no significant hydrologic changes are observed in some instances (Wilcox and Huang, 2009; Hawtree et al., 2015). The lack of an unequivocal hydrological response to afforestation feeds controversies around the role of forests in controlling river flows (Andreassian, 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 stream-flow 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 between two neighboring catchments idealy similar in geomorphology, area, land-use and climate. Following 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 occured. 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 observed hydrological changes (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 plantation in Laos, and one subject to natural forest regrowth following the abandonment of intensively cultivated hillslopes with cash crops and patches of tree plantations in Vietnam;

2. use a conceptual rainfall–runoff model, and apply correlation analyses and a non-parametric trend detection test, based on cross simulation matrices, to assess

how these land-use changes have modified the hydrological behaviour of the catchments;

3. compare the effects of forest plantations and natural forest regrowth on streamflows in the two studied catchments.

2 Materials and methods

2.1 Study sites

The two studied 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). 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 flow (Table 1). Both were cultivated by smallholder farmers when the monitoring network started operating in the early 2000s.

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 lacrima 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 10–15 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 low input and largely no-till.

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 this was upland rice, but more recently the hardier crops 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, the opportunity arose to introduce livestock, 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. Most of the Dong Cao catchment now consists of natural forest regenerating from abandoned farm land and neglected tree plantations, following the conversion of the main land owner to off-farm activities. 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 institutions involved in Laos and Vietnam from April 2001 to March 2014. They include records of daily rainfall, reference evapotranspiration, flow and annual land-use maps. Stream water level was measured at the outlet of each catchment with 1 mm vertical precision at 3 min time interval by a water level recorder (OTT, Thalimedes) equipped with a data logger within a V-notch weir. A control rating curve (the relationship between water level and discharge) was determined using the velocity area method at each station. In general, flow data quality is very good with rare interruptions in the measurements (August–November 2001 in Vietnam) caused by flood destruction of the measurement devices. This interruption explains why flow simulations were performed starting from 2002 in this country (cf. Sects. 2.3 and 3.3 and Fig. 7). 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 reference evapotranspiration (ET_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. Mean monthly variations of rainfall, runoff and ET_0 are displayed in Fig. 2.

Annual land use maps were prepared 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. In Laos, the unit annual crops includes rainfed upland rice, Job's tear 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 two years after planting (Teak + annual crops) and become a monoculture after canopy closure (Teak). In Vietnam, Forest communities combine 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 plantation 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 includes cassava and maize; Fodder corresponds to the planted exotic grass *Bracharia ruziziensis* mixed with local grasses. Temporal variations in the percentage area of each land-use unit are illustrated in Figs. 5c and 7c.

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. The model estimates monthly stream-flow from monthly areal rainfall and monthly ET_0. 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 water levels in the model reservoirs at the beginning of each hydrological year were found to vary within a range of values with no influence on simulated wet and dry season flows, hence the absence of specific initial period to initialize the reservoir water levels prior the model calibration. These initial water levels were set to the inter-annual averages of values observed at the beginning of each hydrological year. The model was repeatedly calibrated over successive 1 year periods (13 years in Laos from April 2001 to March 2014 and 12 years in Vietnam from April 2002 to March 2014) by maximizing two efficiency criteria. 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 flow simulations, respectively. The former and the later are suitable for evaluating high and low flows simulations, respectively (Pushpalatha et al., 2012). The constraint of a less than 10 % bias on annual flow over each year was applied to all calibrations. For each of the two calibration methods, each of the 13 (12) sets of model parameters were used to perform simulations over the other 12 (11) 1 year periods in Laos (Vietnam) (cf. generalized split-sample test from Coron et al., 2012). The annual variables “wet season flow” and “dry season flow” were defined as the sum of monthly simulated flows over the wet and the dry season, respectively. This procedure resulted in two n-by-n cross-simulation matrices of hydrological variables q_{ij} where $n = 13$ for Laos and $n = 12$ for Vietnam (Fig. 3).

In a given matrix, each column j ($j \in N|1 \leq j \leq n$) 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 ($i \in N|1 \leq i \leq n$), flow was simulated with rainfall from year i. Flow variations between columns are not rainfall-related and reflect other environmental changes (e.g. land-use change). Flow variations between rows result from inter-annual rainfall variability. The possible underestimation (overestimation) of flow simulated with rainfall lower (higher) than that used for model calibration (Coron et al., 2012) was accounted by multiplying simulated flows values by the coefficient $\alpha = (R_\mathrm{c} + a(R_\mathrm{s} - R_\mathrm{c}))/R_\mathrm{s}$ where R_c and R_s are annual rainfall depths during calibration and simulation years, respectively, and a is a coefficient varying between 0 (high influence of rainfall on simulation accuracy) and 1 (no influence of rainfall on simulation accuracy) to generate an error interval around simulated flows. Variations in simulated flow between the columns of the matrices were plotted against time to illustrate temporal changes in hydrological behaviour in Laos (Fig. 5a and b) and Vietnam (Fig. 7a and b). 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 studied period (years 2004 in Laos and year 2012 in Vietnam, cf. Fig. 4).

Following the approach proposed by Andreassian et al. (2003), the calculation of the statistical significance of gradual changes in catchment behaviour was based on cross-simulation matrices similar to the one illustrated in Fig. 3. Each of the two original n-by-n matrices was resampled 10 000 times by permuting columns. For each original and permuted matrix, the statistic S was calculated using Eq. (1).

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

where q_{ij} is the flow 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 (resp., positive) S values correspond to a decrease (resp., increase) trend in basin water yield. The p value of a negative (resp., positive) trend is equivalent to the non-exceedence (resp., exceedence) frequency of the original S values compared to the range of S values derived from the permuted matrices.

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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 increase 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 46.8 % over the years 2002 and 2003 to 18.1 % over the years 2012 and 2013 (Fig. 4). Consistently, the non-parametric cross-simulation test applied to wet and dry season flows did not reveal any significant trend in catchment behaviour in Laos over the period 2001–2013: p values = 0.50 and 0.49 for the wet and dry season flows, respectively. In contrast, a highly significant reduction of the basin water yield was observed in Vietnam over the period 2002–2013: p values = 0.03 and 0.01 for the wet and dry season flows, respectively.

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

Annual values of N_{SEQ} and N_{SElnQ} averaged over the whole studied periods are high: 90.0 and 87.2 %, respectively. The lowest annual values were obtained in 2008 ($N_{\mathrm{SElnQ}} = 74.0$) and 2009 ($N_{\mathrm{SEQ}} = 69.1$). Figure 5a and b show inter-annual variations in simulated wet and dry season flows. Figure 5c depicts temporal variations in the percentages of surface area of each land-use unit in the catchment. The black bold solid curve indicates the cumulated percentage of surface area under annual crops, 1 year fallow and teak plantations. The inter-annual variations of this curve are correlated to the variations in simulated wet and dry season flows ($r = 0.45$, F test p value $= 0.12$ and $r = 0.63$, F test p value $= 0.02$, respectively). Any other combinations of land-use units led to lower correlation between cumulated percentages of surface area and seasonal simulated flows. Quantitatively, between 2001 and 2003, simulated wet and dry season flows increased by 174 and 37 mm, respectively. Over the same period, the cumulated surface area of annual crop, 1 year fallow and teak plantation increased from 26.5 to 61.7 % of the catchment area. From 2003 to 2006, the cumulated percentage area of annual crops, 1 year fallow and teak plantations decreased to 18.3 % while simulated wet and dry season flows decreased by 135 and 71 mm, respectively. The main land-use changes that occurred during this first sub-period (2001–2006) 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 the 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 cumulated percentage area of annual crops, 1 year fallow and teak plantation increased from 18.3 to 54.0 % while simulated wet and dry season flows increased by 122 and 40 mm respectively. Hydrological changes observed between 2008 and 2009 are difficult to quantify because of the relatively high uncertainty in simulated flow in 2009. But consistently, from 2010 to 2011, the cumulated percentage of areas under annual crops, 1 year fallow and teak plantations increased from 51.0 to 67.6 % while simulated wet and dry season flows increased by 401 and 66 mm, respectively. Conversely, from 2011 to 2013, the same cumulated percentage decreased to 54.5 % while wet and dry season flows decreased by 352 and 50 mm, respectively.

Over the first sub-period (2001–2006), on average, an increase (decrease) of x in the cumulated percentage of area under annual crop and 1 year fallow induces an increase (decrease) of $2.59x$ and $1.19x$ mm in wet and dry season flows, 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 crop, 1 year fallow and teak plantation is greater: $11.72x$ and $2.89x$ mm in wet and dry season flows, respectively (Fig. 6a and b).

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

Annual values of N_{SEQ} and N_{SElnQ} averaged over the whole studied periods are high: 89.0 and 88.0 %, respectively. The lowest annual values were obtained in 2008 ($N_{\mathrm{SEQ}} = 57.2$) and 2010 ($N_{\mathrm{SElnQ}} = 69.3$). Figure 7a and b displays inter-annual variations in simulated wet and dry season flows. Figure 7c depicts temporal variations in the percentages of surface area of each land-use unit in the catchment. The black bold solid curve indicates the cumulated percentage of surface area under annual crops, forbs and fodder, which are all herbaceous covers, in contrast with the woody land-use units mixed-trees plantation and forest communities. The inter-annual variations of this curve are correlated to the variations in simulated wet and dry season flows time-lagged by one year ($r = 0.61$, F test p value = 0.034 and $r = 0.82$, F test p value = 0.001, respectively) (Fig. 6c and d). Quantitatively, Fig. 7a and b shows an overall reduction of simulated wet and dry season flow from 2002 to 2013 (−332 and −61 mm, respectively). From 2002 to 2004, simulated wet and dry season flows reduced by 299 and 47 mm, respectively, following the reduction of non-woody vegetation cover from 40 to 29 % between 2001 and 2003. From 2004 to 2006, simulated flows are relatively stable, in accordance with the relative stability in the percentage of areas under non-woody cover over the period (2003–2005). The drop in simulated wet and dry flows in 2007 (down to 276 and 15 mm, respectively) follows a drop in the percentage of areas under non-woody cover to 11 % in 2006. The period (2008–2010), exhibiting slightly greater simulated wet and dry season flows, up to 505 and 32 mm, respectively, follows a period (2007–2009) with a greater percentage of areas under non-woody cover (up to 24 %). Afterwards, the percentage of area under non-woody cover and simulated wet and dry season flows decline again, to 11 %, and 161 and 8 mm, respectively. Over the studied period, the year 2009 exhibits the lowest annual rainfall depths in the two catchments (Fig. 4), with high levels of uncertainties in simulated flows (Fig. 7a and b), possibly explaining the discordance between land-uses changes and simulated wet season flow in this particular year.

4 Discussion

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

Figures 5 and 6a and b indicate that catchment flows are 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 flow production. In agreement with these observations, Ribolzi et al. (2008) determined a negative correlation between the percentage of area under 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 flows was not isolated from that of land-use change (gradual decline of total fallow areas from 2002 to 2006, cf. Fig. 5c).

The contrasting hydrological behavior between 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 surface area) than those observed under old fallow (about 10 % of the microplot surface area). The authors showed that soil infiltrability decreases as the soil surface crusting rate increases, thus explaining the lower flow productivity of 2–12 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 flows 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 fallow during the wet season. However, the facts that (1) under young teak trees, the understorey is cropped annually 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, 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 four 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 flows. The low infiltrability and limited root water uptake during the dry season explains the increasing wet and dry season flows as teak plantations expanded over the catchment between 2006 and 2013 (Figs. 5 and 6a, b).

No local measurement of infiltrability and soil surface crust was performed under the natural forest areas 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 bold solid curve in Fig. 5c). This is in accordance with Brown et al. (2005) and with our findings in Vietnam (cf. Sect. 4.2, Figs. 6c and d and 7), showing that sparcer (denser) natural vegetation cover increases (reduces) streamflows. Finally, it should be noted that the area covered with banana trees remained stable over the studied period and had no discernable effect on flow variations.

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

Figures 6c and d and 7 indicate that catchment flows are predominantly produced over herbaceous land-use units (Annual crops, Forbs and Fodder), while tree-based land-use units (Mixed-trees plantation and Forest communities) make a comparatively lower contribution to flow (cf. the location of these land-use units above or below the black bold solid curve in Fig. 7c). These differences are consistent with local observations. Deploying several 1 m^2 microplots 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 plantation 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; (ii) from mixed-trees plantations to forest communities (Fig. 7c). 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 system and denser tree canopy (Dunin et al., 2007; Ribolzi et al., 2008). This explains the decrease in simulated wet and dry season flows at the catchment level (Fig. 7a and b) from 2002 to 2013. The visual comparison of the simulated flow time series (Fig. 7a and b) with the time series of land-use (Fig. 7c) indicates a 1 year delay in the response of seasonal flow to land-use changes, which is confirmed by correlation analyses (Fig. 6c and 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 flow (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 Don Cao catchment water yield over the full study period is equivalent to a reduction of 165 004 m^3 (332 mm) during the wet season and 30 317 m^3

(61 mm) during the dry season. While the dry season flow reduction may have negative consequence on irrigated rice located downstream of the catchment, the reduction in wet season flow is expected to contribute to decreased flood risk. The overall reduction in streamflow could be interpreted as a serious threat to river ecosystems. While this statement is true, it ignores the fact that the catchment was covered by lowland primary forest prior to 1970 with likely evapotranspiration greater and flow production 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 studied 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 = 0.5, cf. Sect. 3.1), as it is often done in hydrological impact assessments. In contrast, the same test has resulted in highly significant changes in the Dong Cao catchment, Vietnam, (p values < 0.03) because the land-use change was unidirectional over the whole studied period. These results highlight the need to measure and assess the inter-annual co-variability of land-uses and flows at the finest temporal scale when assessing changes in catchment behaviour.

Two main types of land-use change in the Houay Pano catchment, Laos, had different hydrological impacts: (i) the transition from 2 to 12 year fallow + forest to annual crops +1 year fallow; (ii) the transition from 2 to 12 year fallow + forest to annual crops +1 year fallow + teak plantations. The first (observed over 2001–2006) induced increases in simulated seasonal flow lower than those induced by the second (observed over 2006–2013) (Fig. 6a and 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 flow 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 young herbaceous cover (annual crops, forbs and fodder) to naturally regenerating tree-based covers in Vietnam (mixed-trees plantation and forest communities). In the two countries, the conversion of young herbaceous cover (including teak plantations in Laos) over 1 % of the catchment induced wet and dry seasons flow reductions of about 11.5 and 2 mm, respectively (cf. the coefficients of the linear regressions in Fig. 6a and c and b and d, respectively). Assuming the linearity of these relationships, the average difference between actual annual evapotranspiration of the two land-uses (pre- and post-conversion) is about $100 \times (11.5 + 2) = 1350$ mm, which is of the main order of magnitude as typical evapotranspiration of tropical forest in continental Southeast Asia (Tanaka et al., 2008). This comparison indicates that the evapotranspiration of the young herbaceous cover (including teak plantations in Laos) is likely limited by the soil water availability in accordance with the low infiltrability rates previoulsy measured at the microplot level.

4.4 Concluding remarks

A simple lumped model was used to investigate the relationship between land-use and catchment hydrology. This approach presents some limitations. For instance, land-uses changes occurring within or outside of the riparian area and their hydrological effects are not differentiated. While this simplification limits our understanding of the processes underlying the rainfall–runoff transformation, the high performance of the model in the two studied catchments evidences its efficiency for the analysis of hydrological changes. The model simulations showed that the land-use effects on soil surface properties and infiltrability, previously quantified in 1 m^2 micro-plots, are reconcilable with the hydrological behaviour of the catchments, at a scale six orders of magnitude larger. These results show that land-use – i.e. the way the vegetation cover is managed (e.g. recurrent burning of teak understorey and soil alteration) – exerts a control on flow 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 indicates that this other category of models would successfully simulate the effects of land-use changes only if they account for changes in soil properties following land conversions.

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 ecosystems, 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 flows. The conversion of annual crops and mixed-trees plantations to naturally re-growing forest in Vietnam led to decreased seasonal flows. 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.

Acknowledgements. This work was funded by the French watershed network (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).

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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 flow	418 mm	415 mm
Geology	Shale, schist	Schist
Soils	Alfisol, Entisol Ultisol	Ultisol

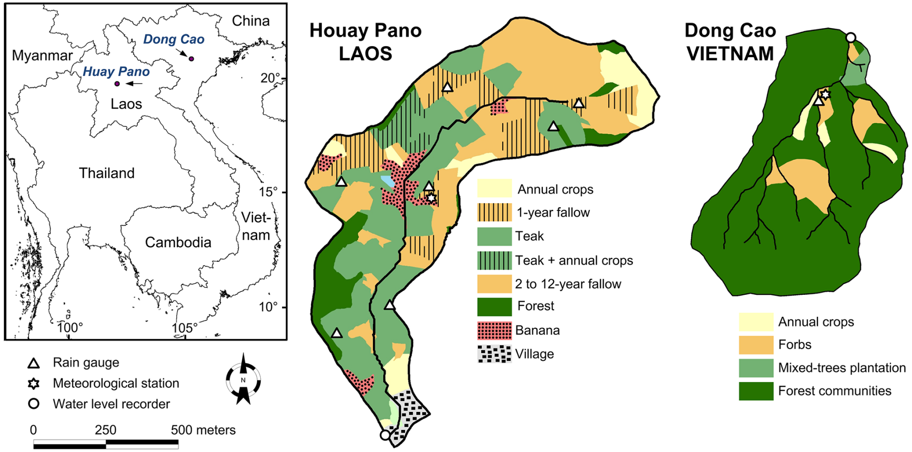

Figure 1. The two studied catchments of the MSEC network and their land-use in 2013.

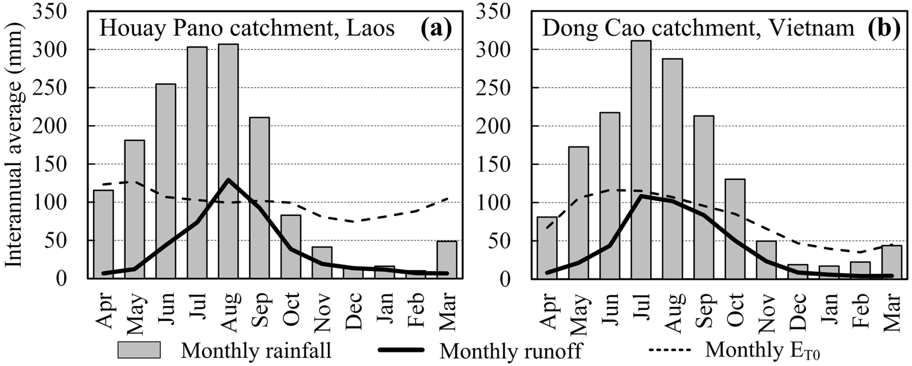

Figure 2. Monthly rainfall, runoff and ET$_0$ averaged over the studied periods in Laos and Vietnam.

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

Figure 3. Cross simulation matrix. i: row index. j: column index. M_j ($j \in N|1 \le j \le n$) defines the set of model parameters calibrated over year j using P_j as input. P_i ($i \in N|1 \le i \le n$) defines the rainfall that occurred over year i.

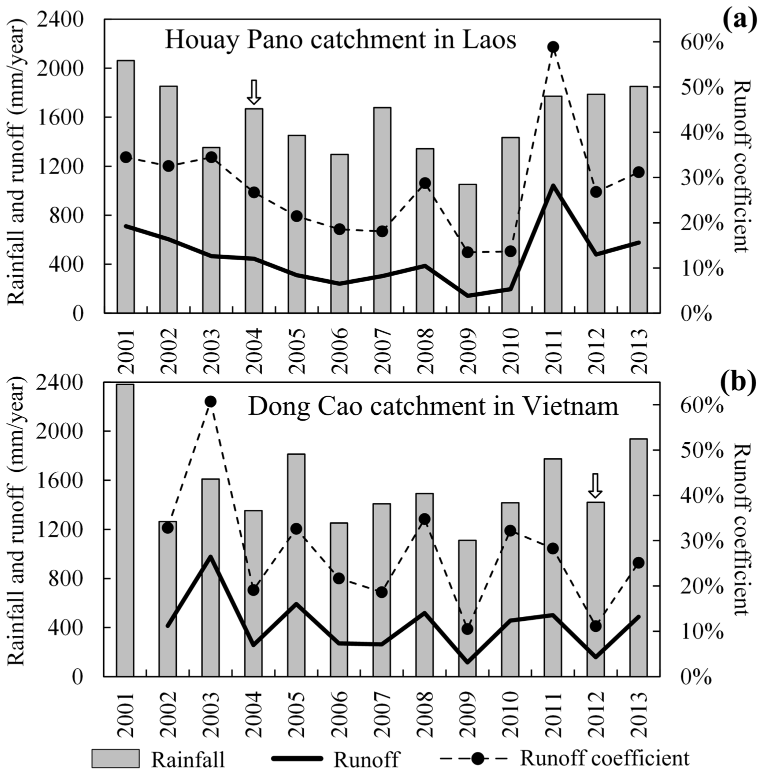

Figure 4. Annual rainfall, runoff and runoff coefficient measured in Houay Pano **(a)** and Dong Cao **(b)** catchments. Runoff values are not available in Vietnam in 2001 (cf. Sect. 2.2). Arrows point to rainfall years used in model simulations displayed in Figs. 5 and 7.

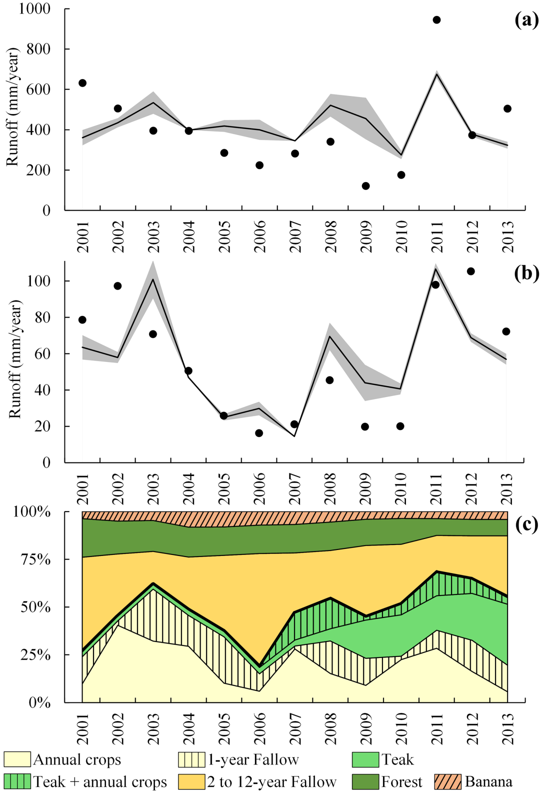

Figure 5. Wet season **(a)** and dry season **(b)** flow in Houay Pano catchment, Laos. Solid curve: flow simulated with GR2M re-calibrated each year and ran with same rainfall input. Shaded area: error interval for simulated flow. Black dots: measured flow. **(c)** Cumulative percentages of surface area of each land-use unit.

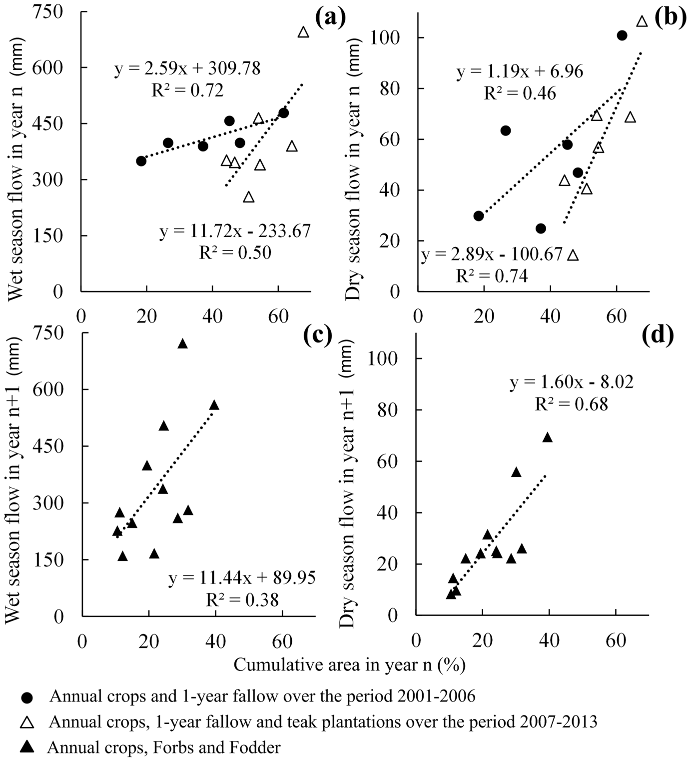

Figure 6. Correlations between simulated flow and land-uses types. **(a, b)** Houay Pano catchment, Laos. **(c, d)** Dong Cao catchment, Vietnam. Percentage areas of year *n* ($n \in N|2001 \leq n \leq 2012$) are correlated to seasonal flows of year *n*+1 in Vietnam.

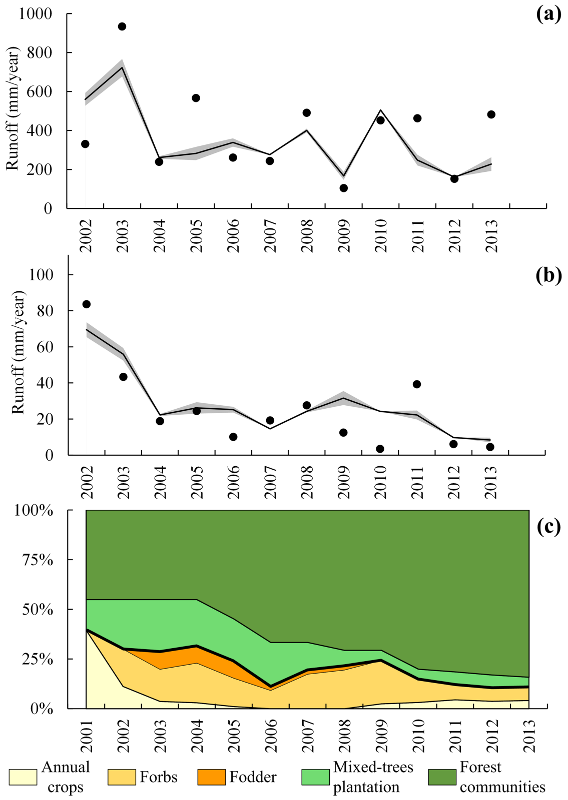

Figure 7. Wet season **(a)** and dry season **(b)** flow in Dong Cao catchment, Vietnam. Solid curve: flow simulated with GR2M re-calibrated each year and ran with same rainfall input. Shaded area: error interval for simulated flow. Black dots: measured flow. **(c)** Cumulative percentages of surface area of each land-use unit.