ຜົນກະທົບຂອງການຟື້ນຟູປ່າເຫຼົ່າ ຕໍ່ປະລິມານນໍ້າຫວ້ຍ ໃນເຂດອ່າງໂຕ່ງ ທີ່ມີການເຮັດໄຮ່ ຢູ່ ພາກເໜືອ ຂອງ ສ.ປ.ປ ລາວ

ໂອລີວິເອ ຣິໂບນຊີ, ຊັງປີແອ ທີໂບ, ເອມານູແອນ ບວກດົງ, ຊັງປີແອ ບຣີກເກ, ປີແອ ມາກຊັງ, ເອມານູເອນ ມູເຊີ, ອາແລງ ປີເອເຣ, ໂອລິດ ແສງຕາເຮືອງຮຸ່ງ, ຄຣິສຕຽນ ວາເລນຕິນ

ບົດຄັດຫຍໍ້

ແຫຼ່ງສາຍນໍ້າຫ້ວຍຈາກເຂດສູງ ຖືວ່າເປັນເຂດສຳຄັນໃນເຂດຍອດນໍ້າ. ຈຸດປະສົງຂອງບົດນີ້ແມ່ນເພື່ອສຶກສາຜົນກະທົບ ຂອງການຟື້ນຟູປ່າເຫຼົ່າຕໍ່ລະບົບນໍ້າໃນເຂດອ່າງໂຕ່ງທີ່ມີການເຮັດໄຮ່. ການຄົ້ນຄວ້າແມ່ນແນໃສ່ ວິໄຈໄລຍະຂອງກະແສນໍ້າໄຫຼລະດັບຕໍ່າສຸດ ໃນຊ່ວງລະດູແລ້ງ ແລະ ລະດູຝົນ. ຜ່ານການຄົ້ນຄວ້າເປັນເວລາ 6 ປີ (2000-2007) ສາມາດເວົ້າໄດ້ວ່າ ການຟື້ນຟູປ່າເຫຼົ່າແມ່ນມີຜົນກະທົບທາງບວກ ຕໍ່ລະບົບນໍ້າໃນເຂດອ່າງໂຕ່ງ ດັ່ງນີ້: 1) ການຟື້ນຟູປ່າເຫຼົ່າ ເຮັດໃຫ້ຄວາມສົມດູນຂອງລະບົບນໍ້າມີການປ່ຽນແປງ, ໂດຍສະເພາະ ການກະຈາຍຂອງນໍ້າຝົນ ຜ່ານການລະເຫີຍ ແລະ ການກຳບັງຂອງພຸ່ມໄມ້; 2) ການເກັບກັກນໍ້າໄວ້ດ້ວຍຮາກ ເພື່ອການຈະເລີນເຕີບໂຕຂອງລຳຕົ້ນ ແລະ ພາກສ່ວນອື່ນໆ ເຮັດໃຫ້ນໍ້າໃຕ້ດິນຫຼຸດລົງ; 3) ການສູນເສຍນໍ້າໃຕ້ດິນ ເຮັດໃຫ້ປະລິມານນໍ້າໃນຫ້ວຍໜ້ອຍລົງ ຍ້ອນການຫຼຸດລົງຂອງສາຍນໍ້າໄຫຼປົກກະຕິ ໃນລະດູຝົນ ແລະ ລະດູແລ້ງ; 4) ນໍ້າໃຕ້ດິນເປັນຕົວປະກອບທີ່ສຳຄັນ ພາໃຫ້ມີນໍ້າຖ້ວມ. ນໍ້າໄຫຼບ່າໜ້າດິນ ປະກອບສ່ວນການເພີ້ມຂຶ້ນຂອງນໍ້າ ໃນເວລາມີຝົນຕົກແຮງ.

Effect of fallow regrowth on stream water yield in a headwater catchment under shifting cultivation in northern Lao PDR

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Abstract

Low flow generation from the uplands of has been identified as the one of the most important watershed issues in Southeast Asia. The aim of this work was to examine the effect of fallow regrowth on the hydrological behaviour of a fragmented landscape, under shifting cultivation with short fallows, which is a system typical of the northern Lao P.D.R. uplands. The study focused specifically on analysing and understanding periods of low flow during the dry and wet seasons. After 6 years of hydrological and land use monitoring (2002-2007) in the Houay Pano headwater catchment, we can conclude that fallow regrowth significantly affects the hydrological regime of the catchment. The main results obtained can be summarised as follows: **(i)** Development of fallow vegetation induces remarkable changes in the annual water balance, in particular, it increases the fraction of incident rainfall redirected by transpiration and canopy interception; **(ii)** Increased root water uptake subsequent to perennial vegetation growth, reduces groundwater recharge and subsurface reserves; it also lowers the water table, hence limiting stream feeding by shallow groundwater; **(iii)** This groundwater depletion leads to a drop in the annual stream water yield due to a decrease in wet season inter-stormflow and dry season baseflow; **(iv)** Subsurface groundwater is the major contributor to floods. Overland flow (surface runoff) contributed most significantly to flood waters during rainfall events in the first two years of fallow regrowth.

This study showed that water resources in the uplands of northern Laos are sensitive to land use and hence potentially vulnerable to inappropriate management. The conclusions made in this paper go a step towards predicting the likely consequences of the Government's current effort to eradicate shifting cultivation and replace it with perennial crops such as teak plantations.

Key words: *Runoff; Low flow; Stromflow generation; Water balance; Fallow regrowth; Uplands of Lao P.D.R*

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Introduction

The role of forest and trees in watershed hydrology and the impact of deforestation on hydrological regimes has been widely studied (e.g. Calder, 1998). Generally, although responses vary widely between sites and situations, the removal of forest cover leads to higher water yields. Many studies on evapotranspiration indicate that in both very wet and very dry climates, evapotranspiration from forests is likely to be higher than that from shorter crops and consequently less runoff is generated from forested areas. However, little is known about the hydrological response of headwater catchments following land use and land cover changes that occur during rotational shifting cultivation cycles, which include several years of fallow followed by a one year clearing-burning and cropping phase (Gafur et al., 2003).

In northern Lao PDR, the traditional shifting cultivation system has been evolving over the decades in response to population pressure (Lestrelin et al., 2005). The cultivation cycle, i.e. the time period between two successive clearing/cropping operations on the same site, has been shortened to 2-5 years, whereas ecological sustainability may require a minimum fallow period of at least 10 years (de Rouw et al., 2005). In this agro-ecosystem, the hydrological regime may be changing with potentially increasing negative downstream effects. A few studies reported the consequences of fallow shortening on soil erosion (e.g. Valentin et al., this issue). However, as mentioned by Bruijnzeel (2004) in a review paper, further research is required on the baseflow regime of streams and rivers. The problem of "low flow" generation from the uplands has been identified as the one of the most important watershed issues in Southeast Asia, with numerous human activities, e.g. hydropower production, paddy rice sustainability in the lowlands, depending on this crucial environmental service.

The effect of land use changes on low flow production, dry-season flow in particular, depends on competing processes (e.g. evapotranspiration and infiltration) and is likely to be highly site specific (Calder, 1998). In tropical areas, afforestation can lead to decreased dry-season flows due to increased evapotranspiration, putting hydroelectric plan operations and drinking water supplies at risk (FAO, 1987). In the Mae Thang watershed (Thailand), afforestation programmes led to water shortages downstream, which resulted in reduced water availability for irrigation (Chomitz and Kumari, 1996).

This paper focuses on the effect of fallow regrowth on total annual stream water yield in a fragmented landscape under shifting cultivation with short fallow. Several questions arise in this context. Does the crop/fallow ratio influence rainfall infiltration opportunities and hence groundwater reserves? Are the groundwater reserves replenished sufficiently during the rainy season to sustain the dry season baseflow? The overall objective is to provide information on inter-annual runoff variability at the scale at which farmers operate and at which downstream impacts can be assessed. Special attention was paid to the analysis and understanding of baseflow (low flows) behaviour during the dry and wet seasons compared with land cover and land use dynamics.

We investigated baseflow generation for six years (2002-2007), which corresponded to an entire crop-fallow cycle within the Houay Pano catchment. We surveyed land use (mainly crop/fallow evolution) and quantified stream water yields at the catchment outlet.

Materials and methods

The biophysical and socio-economic characteristics of the study site (a headwater catchment in northern Lao PDR) are described by Valentin et al. (this issue).

Land use mapping and topography

Annual land use maps were prepared for seven years (2001-2007) from detailed field surveys. Observed land uses included fallow, degraded secondary forest, teak plantation, banana, upland rice, Job's tears (Coix lacryma-jobi L.), sesame, and maize. The percentage of catchment occupied by each type of land use or land cover was derived from land use maps established each year. The boundaries between land use units were mapped in the field using a combination of GPS and theodolite survey points. The mapping accuracy of land use boundaries is estimated to be within ± 2.5 m (Chaplot et al., 2005). The proportion of each land use was estimated using Arc-View software (ESRI, 1997).

Hydro-meteorological measurements

Rainfall was monitored using a network of six manual rain gauges (see Valentin et al., this issue) and an automatic rainfall recorder with 0.5 mm capacity tipping-buckets. Annual reference evapotranspiration (ETo) was estimated following the Penman-Monteith FAO method (http://www.fao.org/docrep/X0490E/x0490e0k.htm#TopOfPage) with the program CropWat4 windows (version 4.3), and using monthly mean meteorological parameters (air temperature, wind speed at 2 m height, relative air humidity, and global solar radiation) collected with a weather station (CIMEL, EMERCO 404) installed at mid-hillslope in the catchment.

The discharge of the permanent stream was measured at the outlet of four nested catchments (S1, S2, S3 and S4) from March 2001 using automatic recording stations consisting of a water level recorder (OTT, Thalimedes) and a V-nor weir. A control rating curve (the relationship between water level and discharge) was determined using the velocity area method at each station. Water-level data were downloaded every week. Among the four weirs monitored along the Houay Pano stream, S3 was installed on the bedrock in a steep-sided reach, and thus may guarantee the control of total outflow and hence will be considered in this study for the stream flow deficit (SFD) estimate (see below).

The water table level was monitored from June 2002 using a network of 12 piezometers (0.055 m internal diameter PVC tubes; screen height = 0.5 m) positioned at a depth between 1 and 6 meters and distributed along three transects (T1, T2 and T3), each including four piezometers .T1 and T3 were settled near the permanent stream in the main valley, while T2 was installed across an ephemeral first-order stream in a lateral sub-valley. The results presented here are for one piezometer (T1-A3) which was representative of the downstream groundwater system.

Estimate of actual evapotranspiration

The impact of land use on total annual runoff is a function of many variables. Actual evapotranspiration (ET) (i.e. evaporation of soil water and transpiration by plants) and interception (I) of rainwater by plant cover are the most important factors in most tropical environments. The estimate of these two variables using classical measurement techniques (e.g. lysimeters, rain gauges) based on local observations is technically complicated to implement and extremely difficult to upscale at the catchment level, especially in heterogeneous upland environments. We preferred to estimate

ET+I indirectly by the "stream flow deficit" (SFD) method with the following water balance equation:

$$SFD = P - (R + \Delta S) \quad (1)$$

Where P is the total annual rainfall, R is the total annual runoff (i.e. stormflow and inter-stormflow) and ΔS is the change in water storage at the surface and/or the subsurface within the catchment (i.e. the amount of water that is being added to or removed from water stored within the catchment). All the terms of this equation are expressed in mm. We hypothesised that the inter-annual changes in soil water storage (i.e. the unsatured zone) were negligible and that only the annual dynamical groundwater volume of storage (S_y) may vary, hence ΔS was estimated as follow:

$$\Delta S = S_{y+1} - S_y \quad (2)$$

while S_y and S_{y+1} were approximated at the end of each year with the following equation:

$$S_y = Q_0 / \alpha \quad (3)$$

Where Q_0 is the stream base flow discharge at time t_0 (31 December) and α is the depletion coefficient, characteristic of the groundwater reservoir, estimated by fitting an exponential decay curve (Maillet, 1905) to observed stream discharge values during a low flow period without any flood disturbances.

Storm-hydrograph separation

In order to estimate the contributions of surface (i.e. rainfall water that fell during the rain event) and subsurface (i.e. water in the ground before the rain event) flows during floods, storm hydrographs were separated using a tracer-based mixing model approach (e.g. Collins and Neal, 1998). In the case of Houay Pano, a strong linear relationship was established between residual alkalinity, a conservative natural tracer (Ribolzi et al., 1996), measured from numerous spot water samples, and electrical conductivity. Electrical conductivity is easy to monitor and inexpensive so it was used as the hydrological tracer for storm hydrograph separation.

Results

Land cover changes

The Houay Pano catchment is part of the farming land of Lak Sip village. It is mainly cultivated following an altered shifting cultivation system with short fallow periods (Figure 1). Annual crops and fallows were the main land cover changes throughout the survey period.

The proportion of other land use types (secondary forest, permanent crops) also varied but within a narrow range. Figure 2 shows the mean 5-year periodicity of the rotational farming system: i.e. one year of slashing-burning-cropping followed by a fallow period of four years. The highest proportion of annual crops, about 51 % of the total catchment area, was observed in 2007. It was a bit more than in 2002 (46%). This percentage decreased regularly the four following years (2003-2006) as almost all the fields of annual crops were left as fallow areas. In 2006, only 6% of the catchment area was allocated to annual crops. Fallow areas evolved with in a converse trend: they decreased first from 66% in 2001 to 33% in 2002 and then increased to reach a maximum of 71% in 2006. Figure 2 also shows the ratio of crop/fallow areas. It increased steeply from 2001 to 2002, then decreased more gradually from 2002 to 2006, and at last increased again sharply from 2006 to 2007. This periodic behaviour indicated that almost all the Lak Sip farmers follow the same rotational cycle. However, this global observation at the catchment scale masks heterogeneities: some of the fields were cultivated more intensively with only two years of fallow (de Rouw et al., 2005), whereas for a low percentage of others (<1.5 %) the period exceeded five years.

Rainfall characteristics

The rainfall distribution during the study period followed the normal rainfall pattern for Luang Prabang, with the rainy season extending from mid-May to mid-October. Annual rainfall was rather stable from 2002 to 2006 (Figure 3), with a low variation coefficient~5% (SD=67 mm). However the annual rainfall values measured in 2001 and 2007 (1738 and 1139 mm, respectively) differed significantly from that of the 2002-2006 period (mean value=1343 mm). Therefore, in order to better discriminate the effect of land cover changes on stream yield from that of annual rainfall variations, the following hydrological analysis focused on the 2002-2006 period.

Variations in the water table level and groundwater reserves

Figure 4 shows the water table level variations over the study period in piezometer T1-A3. It appears extremely variable, especially during the wet season when extremely sharp fluctuations were observed. The minimum and maximum values measured were 319 cm and 102 cm respectively that is, a range of

217 cm. The water table level began to rise mostly in May with the return of the first rainfall events, and the highest values were observed during the climax of the rainy season, i.e. between July and September. The steepest change measured was 165 cm in less than five days in July 2002. Figure 4 also shows the mean overall trend since monitoring began. It clearly indicates a decrease corresponding to a fall in the mean water table level of 39 cm in five years (from May 2002 to May 2007).

In headwater catchments, the range and dynamics of water table variations can vary tremendously from station to station depending on local conditions (e.g. distance to the stream, transmissivity of soil layers). In view of this variability, direct water table monitoring using a limited number of piezometers is difficult to upscale. Because we were aware of this limitation, we estimated the dynamic-groundwater-stock (S_y) that can potentially sustain streamflow during the dry season using equation (3). Figure 4 shows annual ΔS values. The variation was positive in 2002 (+82 mm), meaning that the groundwater stock increased throughout the year which had the highest annual cropping rate during the study period. Then, it decreased (130 mm) in 2003, the year with the highest percentage of one year fallow cover. Finally, the variations remained close to zero for the three following years.

Behaviour of streamflow components

Figure 5 shows the inter-annual variations in the main streamflow components (i.e. surface and subsurface contributions during floods, and inter-stormflow during the wet and dry seasons) and the annual runoff ratio (i.e. streamflow depth/rainfall depth). The annual runoff ratio decreased regularly from 43% in 2002 down to 26% in 2006. As year-to-year annual rainfall variations were very little, the annual streamflow behaved in the same way as the annual runoff ratio: it decreased from 598 mm (i.e. 5976 m3/ha) in 2002 to 325 mm (i.e. 3251 m3/ha) in 2006. This decreasing trend was clearly due to baseflow changes, and in particular the wet season baseflow. Mean values of overland flow, subsurface stormflow, dry season baseflow and wet season baseflow were 17 mm (STD = 13 mm, VC=80%), 133 mm (STD = 25 mm, VC=19%), 96 mm (STD = 18 mm, VC=19%) and 198 mm (STD = 89 mm, VC=45%), respectively. Baseflow was the main component of streamwater yield; it represented 66% of total streamflow for the study period. Subsurface flow (i.e. pre-event soil and ground water) widely dominated stormflow (89±9%). It remained extremely high (>90%) except in 2003 and 2004, the two first years of the fallow regrowth period (~80%).

Discussion

Groundwater recharge and streamflow decline vs fallow regrowth

A significant negative correlation was found between the annual stream flow coefficient and total fallow percentage (r=-0.94, P<0.001). As shown by Figure 6, the data fitted well with a linear regression (R^2=0.87). Hence our findings suggest that annual streamflow changes are the consequence of vegetation changes: annual streamflow decreased as plant growth in the fallow plots increased. This observation is consistent with the main conclusion of most studies of the impact of afforestation on the hydrological regime in headwater catchments that is, a change of land cover from lower to higher-ET leads to a decrease in annual stream flow (e.g. Bosch and Hewlett, 1982). Leaf area index increased during the fallow regrowth period (e.g. Dunin et al., 2007), hence interception and transpiration also increased. In particular, groundwater extraction due to transpiration increased with the growth of root systems, which were deep rooting for fallow plants. As a consequence, by extracting water from the unsaturated zone, root systems decreased groundwater recharge. Reduced recharge led to groundwater table depletion and hence affected baseflow and finally annual streamwater yield (Le Maitre et al., 1999).

Estimating real annual evaporation using the streamwater deficit approach

The strong linear correlation between the percentage of fallow regrowth and streamwater yield (Figure 6) is evidence that real annual evaporation (i.e. soil evaporation + interception + transpiration) can be accurately estimated using the streamflow deficit approach (Equation 1). Figure 3 shows the evolution with time of SFD/ETo (annual streamflow deficit / reference evapotranspiration). This ratio remained lower than 1 suggesting that, within a yearly timeframe the annual rainfall input and groundwater stocks were sufficient to satisfy the climatic demand so that the system was not under water stress. However, this ratio increased from 0.65 in 2002 up to 0.90 in 2006. Assuming that this trend continued, due to the Lak Sip village farmers deciding to continue fallow regeneration for one more year, our results suggest that the stream would have dried up during the following dry season.

Synchronised rotational shifting cultivation

Secondary forest and regrowth fallow fields are favourable habitats for wild fauna (e.g. birds, rodents) and straying livestock (pigs, goat). Because these animals can cause severe crop losses, farmers avoid cultivating paddy rice or any other food crops (corn, Job's tears) in the direct vicinity of fallow lands. A direct consequence of this practice is that farmers of the same village cultivate their land simultaneously and follow their rotational shifting cultivation cycles in phase. The Lak Sip village illustrates well this type of dynamic (Figure 1). Most of the fields were cultivated in the same year (i.e. 2002 and 2007 over the study period) and fallow vegetation re-grew continuously, at the catchment scale, until a maximum of about 71% of the catchment area was fallow in 2006 (Figure 2). This cyclic land use caused a periodic behaviour of the annual streamflow yields. Considering stable inter annual rainfall inputs, the lowest stream discharge was observed when the highest percentage of fallow was seen (i.e. when the real evapo-transpiration is maximal). Thus while the strategy adopted by the farmers does limits crop damage by animals and hence the risk of reduced crop yields, the water yield becomes uncertain. If the year preceding cultivation coincided with an exceptionally low annual rainfall input, stream flow may be extremely vulnerable.

Conclusions and recommendations

The aim of this study was to analyse the effect of fallow regrowth on the hydrological behaviour of a fragmented landscape under shifting cultivation with short fallow, a system typical of the northern Lao P.D.R. uplands. A specific focus of the study was to analyse and understand low flow during the dry and wet seasons. After 6 years of hydrological and land use monitoring in a headwater catchment, we can conclude that fallow regrowth significantly affected the catchment's hydrological regime. The main results obtained can be summarised in four points:

1) Development of fallow vegetation induced remarkable changes in the annual water balance, in particular, it

increased the fraction of the incident rainfall redirected by transpiration and canopy interception;

2) Increased root water uptake subsequent to perennial vegetation growth, reduced groundwater recharge and subsurface reserves; it also lowered the water table, hence limiting stream feeding by shallow groundwater;

3) This groundwater depletion caused a drop in the annual stream water yield due to a decrease in wet season inter-stormflow and dry season baseflow;

4) Subsurface groundwater was the major contributor to floods. The highest contribution by overland flow (surface runoff) to floods during rainfall events was observed for the first two years of the fallow regrowth.

This paper has demonstrated that water resources in the uplands of northern Laos are sensitive to land use and hence potentially vulnerable to inappropriate management. Based on our findings we can predict the likely consequences of the government's current effort to eradicate shifting cultivation and replace it with perennial crops such as teak plantations. These changes, in the context of soaring food prices, may put food production and security at risk. It could also negatively and strongly affect the sustainability of land and water eco-services in the uplands and endanger downstream areas for two main reasons:

1) Some tree canopies are known to enhance splash–induced erosion and modify soil surface features because rain drop size is increased when rain drops merge on leaf surfaces (Hall and Calder, 1993). Species such as Tectona grandis (teak) whose large leaves concentrate rainfall drops may thus cause severe erosion and soil surface crusting.

2) Concurrently, increased root water uptake as plantation trees grow, together with reduced infiltration due to soil surface crusting, will most probably reduce groundwater recharge and limit low flows.

We conclude that the generalized introduction of monocultures over large areas of biophysically and geomorphologically diverse landscapes, including functionally sensitive areas such as riparian areas (Vigiak et al., 2008), although technically simple, will most likely result in vulnerable systems in which water flows, soil stability and crop yields will be highly unpredictable. Therefore it seems vital to allocate increased effort and resources to designing specific policies which will guide the introduction of perennial monocultures without threatening natural resource availability. This will require the informed design and implementation of diversified agro-systems, structured in both space and time, so that the impact of biophysical (e.g. climate variability) and economic (e.g. change in market demand) constraints can be optimally buffered at the scale of smallholder operations.

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a

b

Figure 1 – *Pictures showing the Houay Pano catchment **(a)** almost entirely covered with fallow (2001) and **(b)** after slash and burn (2007).*

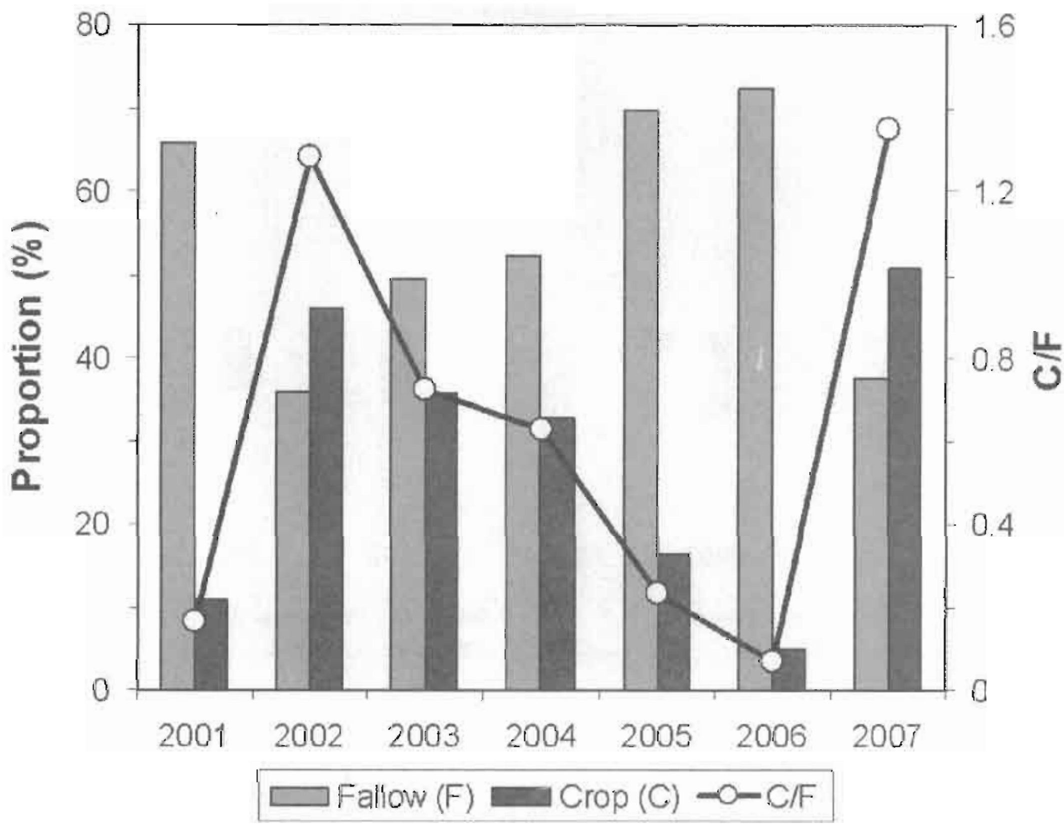

Figure 2 – *Evolution of total fallow and annual crop percentages and the ratio between the two (C/F) areas in the Houay Pano catchment.*

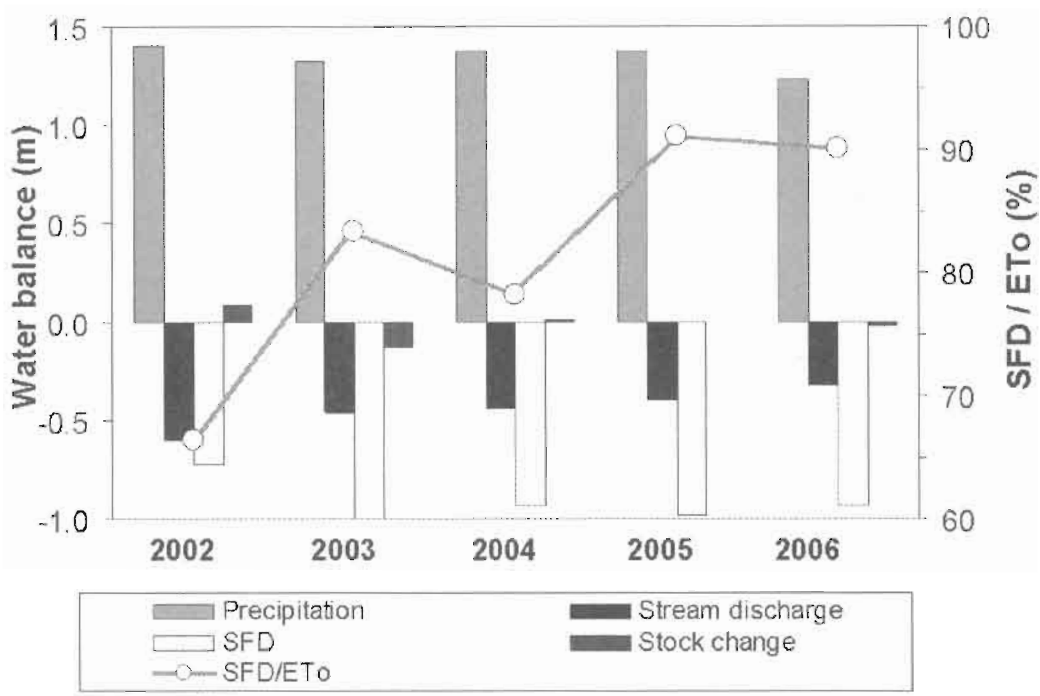

Figure 3 – *Terms of the annual water balance (i.e. precipitation, stream discharge, streamflow "deficit" (SFD) and water stock change) and the ratio between SFD (i.e. estimate of actual evapotranspiration + canopy interception) and reference evapotranspiration (ETo) calculated using the FAO Penman-Monteith method.*

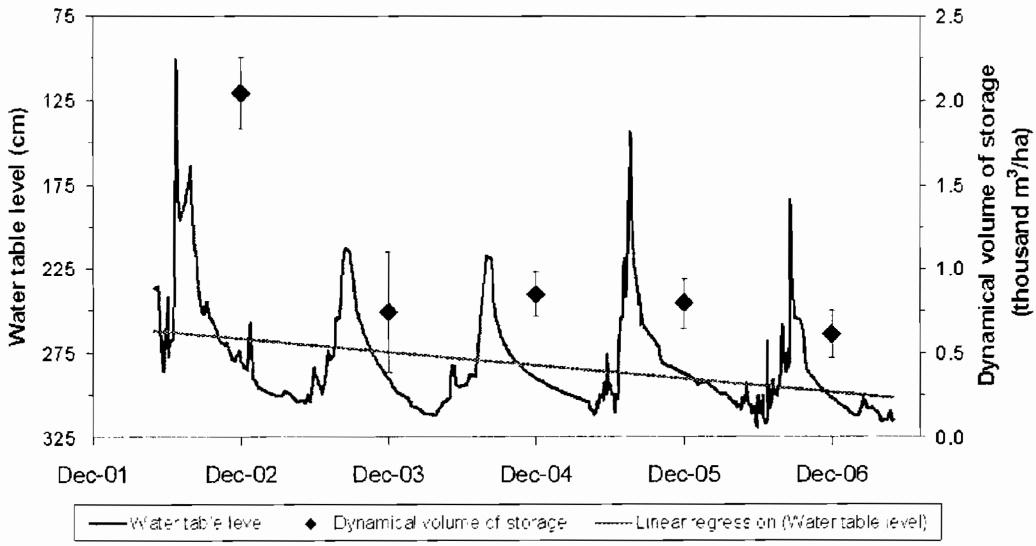

Figure 4 – *Water table level measured in a piezometer (T1-A3) positioned in the downstream part of the catchment with its trend line (linear regression) and estimated dynamical volume of storage (water in the saturated zone) at the end of each year.*

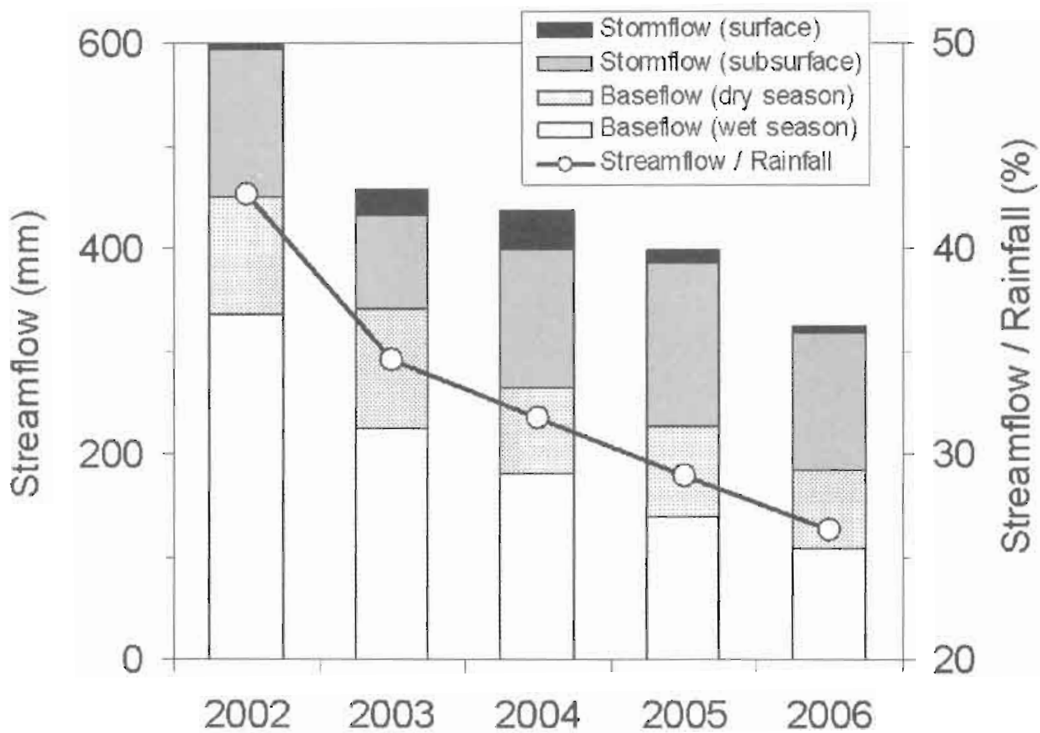

Figure 5 – *Total annual streamflow components (surface and subsurface stormflows, baseflow during the dry and wet seasons) and ratio between total annual streamflow and rainfall in the Houay Pano catchment.*

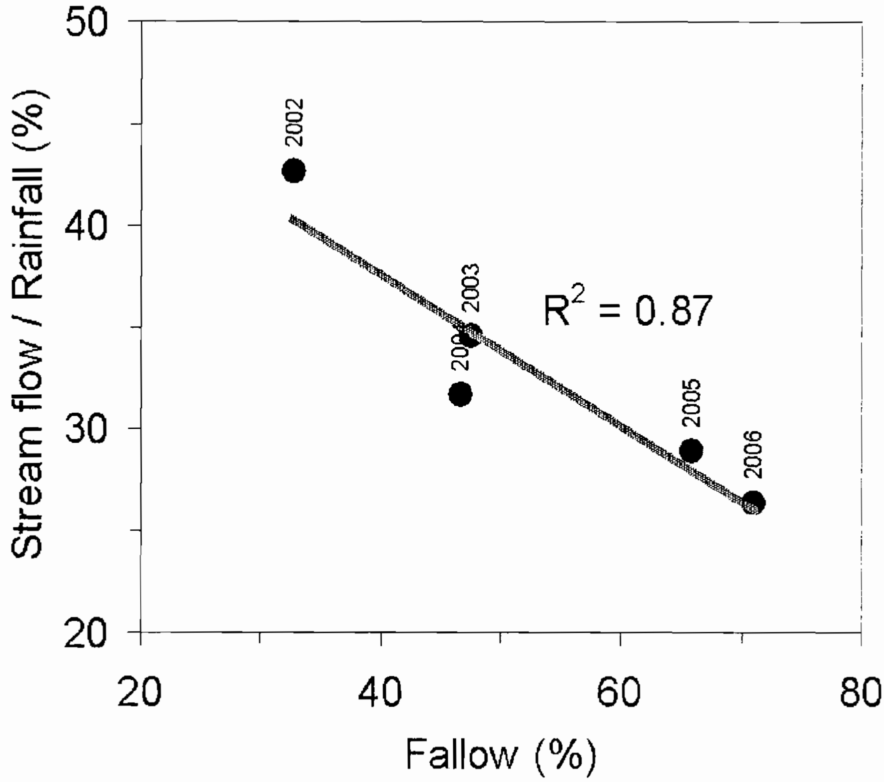

Figure 6 – *The annual stream flow coefficient (Stream flow / Rainfall) as a function of total fallow percentage.*

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IRD Institut de recherche pour le développement

IWMI International Water Management Institute

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ອອກແບບ ແລະ ຈັດໜ້າ ໂດຍ: ຂັນຄຳ ອ້ວນອຸດົມ, ສູນຂໍ້ມູນຂ່າວສານ, ສຄກປ