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Impact of land-use change on the hydrology of North Lao PDR watersheds

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Abstract We investigated the impact of land-use change on the hydrology of different major Lao tributary watersheds of the Mekong River. The region is the North of Laos centred on Luang Prabang and the watersheds are the Nam Khan, Nam Ou, Nam Suong, Nam Lik and Nam Ngum. An additional small agricultural catchment called Houay Pano close to the Nam Khan, is also considered. We used the lumped rainfall–runoff conceptual models GR4J and GR2M, developed by Irstea in France, the Mekong River Commission hydro-meteorological database and the Japanese Aphrodite meteorological database. The objective was to detect in the hydrological regime of the watersheds any impact of de(re)forestation processes known to have occurred since the 1980s, but at a degree which has not been quantified. For this purpose we adopted the cross-simulation methodology developed by Irstea which has proved to be efficient to detect trends in long term watershed hydrology. The results did not show any significant hydrological change since 1960. On the other hand the application of the same methodology to the small catchment Houay Pano surveyed since 2001 proved to be convincing. We saw evidence of the impact of slash and burn practice, followed by a long fallow period, on a catchment's hydrology over a seven year period.

Key words Mekong tributaries; land-use change; conceptual models

HYDROLOGIC CONTEXT, OBJECTIVES AND MODELLING APPROACH

The Mekong is one of southeast Asia's rivers most vulnerable to global change (flooding, low flows and drought). Half of the Mekong River discharge originates from the mountainous areas of northern Laos, corresponding to about a quarter of the Mekong River basin. The impact of land use and climate change on the hydrology of the region is largely unknown, even if recent works began to address these issues (Costa-Cabral *et al.*, 2008; Kinouchi, 2010; Lacombe *et al.*, 2010).

It is now recognized that since the end of the 1980s the area of traditional upland agriculture (i.e. rotational shifting agriculture) has decreased, while permanent intensive agriculture has increased (Thongmanivong & Fujita, 2006). There is also some evidence that the relocation of upland population to riparian zones led to an increase of the forest cover, probably as a result of the reforestation of abandoned areas. Nevertheless the quality and the extent of this forest cover remains unclear.

In the framework of the Research Consortium Climate-Environment-Society (GIS Climat www.gisclimat.fr) the PASTEK project aimed to study the impact of land-use change on the discharge of five major north Lao Mekong tributaries and of a small agricultural catchment, Houay Pano, surveyed by IRD (Institut de Recherche pour le Développement, France) since 2001. The watersheds are the Nam Khan (7455 km^2), Nam Ou (20 087 km^2), Nam Suong (6578 km^2), Nam Lik (4795 km^2) and Nam Ngum (8430 km^2). Houay Pano (0.62 km^2) is located 10 km east of Luang Prabang (LP) city, in the central part of North Laos (Fig. 1). It is part of the farming land of Lak Sip village. It is mainly cultivated following an altered shifting cultivation system (slashing-burning-cropping) with short fallow periods (Ribolzi *et al.*, 2008).

The hydro-meteorological data (discharge and rainfall) is provided by the MRC (Mekong River Commission) for the five watersheds. The database is limited and many data are missing. The Nam Khan is the only watershed whose discharge is measured continuously and daily since

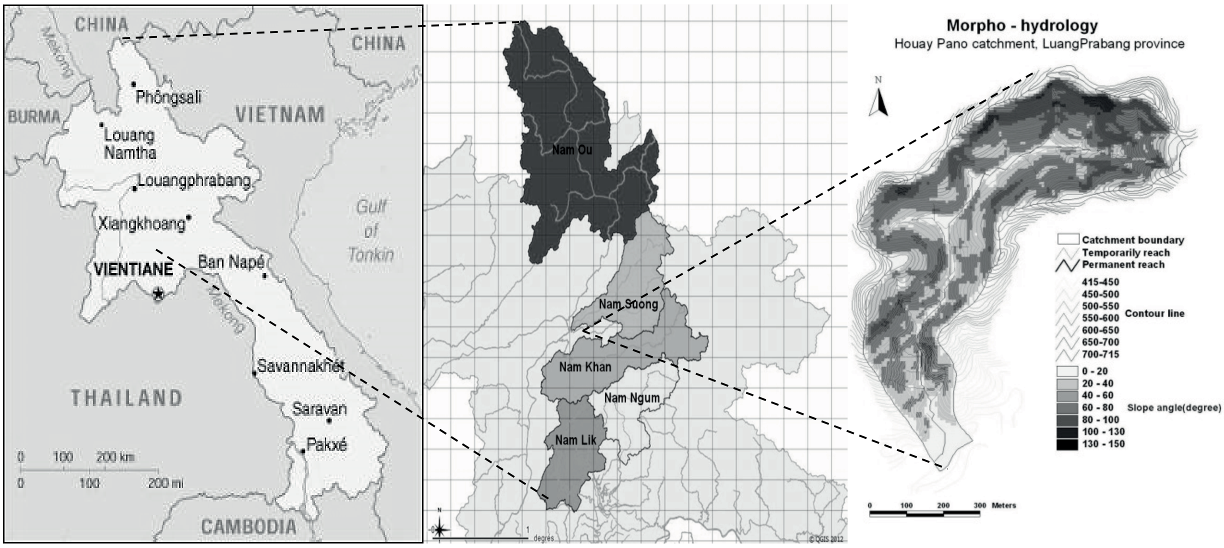

Fig. 1 Lao PDR (left), the five watersheds of North Laos (centre) and Houay Pano catchment close to Nam Khan watershed (right).

1960. Rainfall is measured at the meteorological station of LP, located at the western end of the watershed. For these reasons the Nam Khan can be considered by hydrologists to be a reference watershed in North Laos. Houay Pano mobilizes a large array of disciplines including catchment hydrology, hydrologic modelling, geochemistry, microbiology, soil science, agronomy, geography and environmental policy. Rainfall is monitored with seven raingauges and one meteorological station, and the discharge of the permanent stream is measured at the outlet of four nested catchments. The overall objective of these studies is to assess land use and slope effects on the catchment hydrology and erosion.

To model the hydrology of the large watersheds and small catchment we adopted a conceptual modelling approach. Indeed, this approach is more suited to this type of insufficiently gauged watersheds than the distributed modelling approach. The conceptual models are the GR2M and GR4J models developed at Irstea in France. These models are reliable, continuous lumped rainfall–runoff models functioning at a daily (GR4J) or monthly time step (GR2M) (Perrin *et al.*, 2003). GR4J depends on four calibrated parameters, which account for water balance (X_1, capacity of production store; X_2, water exchange coefficient) and water transfer (X_3, capacity of the nonlinear routing store; X_4, unit hydrograph time base), and GR2M on two parameters (X_1, capacity of production store, and X_2, capacity of the routing store).

To assess the impact of land-use and land-cover changes we followed the cross-simulation methodology developed by Andréassian *et al.* (2003). The principle of the method is the following. The period of study (N years) is divided into n sub-periods P_i (i = 1,n) of equal length (p years, N = np). To each sub-period P_i corresponds a precipitation time series, denoted also P_i. Calibration of GR4J for each P_i yields n successive models of catchment behaviour (defined by n different X_i parameter sets), called M_1, M_2, …M_n. M_i is the model for sub-period P_i calibrated with precipitation series P_i. The next step is to simulate the response of each hydrologic model M_j to a given rainfall series P_i. If this response is the total flow, Q_{ij}, the result can be displayed in matrix form, called cross-simulation matrix. If for a given period P_i, $Q_{ij} < Q_{ii}$ for any $j < i$ and $Q_{ij} > Q_{ii}$ for any $j > i$, there is a clear trend showing that the capacity of the catchment to produce flow increased along the whole period. This can be a sign of a deforestation process. In the contrasting case, $Q_{ij} > Q_{ii}$ for any $j < i$ and $Q_{ij} < Q_{ii}$ for any $j > i$ the situation is reversed and this can be the sign of reforestation. The matrix ($P_i \times M_j$) can be recoded with plus and minus signs. In the first case when Q_{ij} increases with the period, Q_{ij} is replaced by a plus and in the second case by a minus. In the intermediate case the number of pluses equals the number of minuses and nothing can be said about the hydrological impact of land-use evolution. Andréassian *et al.* (2003)

illustrate the method on three types of watersheds (afforested agricultural and burnt-over forested watersheds, and a watershed covered by old-growth forest).

NAM KHAN, NAM OU, NAM SUONG, NAM LIK, NAM NGUM WATERSHEDS

Kinouchi (2010) studied the hydrology of different North Laos watersheds, including the Nam Khan. He showed that the Aphrodite meteorological database produced reliable results. This database has been built by the Japanese Meteorological Research Institute and covers southeast Asia with a grid mesh of 0.25° at a daily time step since 1960 (Yatagai *et al.*, 2009). The Nam Khan domain is covered by 23 cells of the gridded rainfall data. Simulations performed with GR4J showed that better results are obtained with Aphrodite (Nash = 0.66) than with MRC rainfall data (Nash = 0.5). Figure 2 shows that rainfall provided by the Aphrodite database is notably different from that provided by the MRC database (rainfall measured at LP), especially during the 1982–1987 period. We adopted the Aphrodite database. In our simulations rainfall has been averaged over the 23 Aphrodite cells.

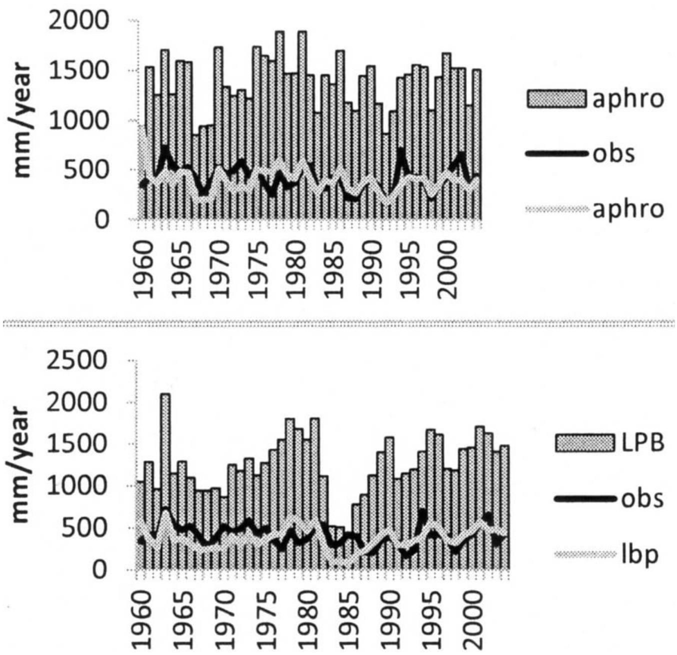

Fig. 2 Hyetograms (bars), simulated (grey solid line) and measured (black solid line) hydrograms (Nam Khan). Upper figure : Aphrodite database and lower figure Luang Prabang rainfall data.

A first series of simulations has been performed following the "split sample test" strategy (Perrin *et al.*, 2003). The 1960–2004 period is divided into three 15-year periods (1960–1975, 1976–1988, 1989–2004) and GR4J is calibrated on each of these periods and applied to the two others. A satisfactory Nash coefficient is obtained for each calibration period (0.64, 0.66, 0.75) but the application of the 1976–1988 model to the two other periods leads to poor Nash values, and the same when 1960–1975 and 1989–2004 models are applied to the 1976–1988 period, indicating that this 1976–1988 period is problematic. This observation is also confirmed by the application of GR2M. The set of calibrated GR4J X_i parameters is almost the same for the periods 1960–1975 and 1989–2004, but differs notably in 1976–1988, which would indicate a change of hydrologic regime during this period. We attribute this to a questionable measure of the discharge during this period. According to IRD hydrologists working in Laos the same rating curve has been used during all this period. To examine more precisely this period we divided the 1960–2004 period into 14 three years periods. Nash coefficients obtained for each calibration period were still good (0.64 < Nash < 0.85) and the analysis of the X_1 parameter in the central period 1976–1988 showed that this coefficient has to drop to a negative value indicating an absence of a production store.

The cross-simulation methodology presented in the previous section helps to identify changes in the hydrologic regime of a watershed related to the change of land-use. The cross-simulation matrix is given in Fig. 3. It has been recoded with plus and minus signs. We see that the matrix is divided into two distinct blocks: one with a majority of minus signs and the other one with a majority of plus signs. The interpretation is not straightforward. The two blocks of minus correspond to the period (P16–P31), i.e. (1976–1988). Again, this period seems to be particular and seems to show a decrease of the Nam Khan discharge. The analysis of the evolution of the X_i parameters did not bring any new insight into the matrix structure.

	M1	**M4**	**M7**	**M10**	**M13**	**M16**	**M19**	**M22**	**M25**	**M28**	**M31**	**M34**	**M37**	**M40**
P1	**o**	=	+	=	+	-	-	=	-	-	=	=	-	=
P4	=	**o**	+	-	=	-	-	-	-	-	-	=	-	=
P7	+	+	**o**	-	-	-	-	-	-	-	-	-	-	-
P10	=	-	-	**o**	+	-	-	=	-	-	=	=	-	+
P13	+	=	-	+	**o**	-	-	-	-	-	-	-	-	=
P16	-	-	-	-	-	**o**	+	+	+	+	+	+	+	+
P19	-	-	-	-	-	+	**o**	+	+	+	+	+	+	+
P22	-	-	-	=	-	+	+	**o**	-	-	=	=	-	+
P25	-	-	-	-	-	+	=	-	**o**	+	+	+	=	+
P28	-	-	-	-	-	+	+	-	+	**o**	+	+	=	+
P31	-	-	-	-	-	+	+	-	+	+	**o**	=	-	+
P34	=	=	-	+	-	+	+	=	+	+	=	**o**	-	=
P37	-	-	-	-	-	+	+	-	=	=	-	-	**o**	+
P40	=	=	-	+	=	+	+	+	+	+	=	=	+	**o**

Fig. 3 Cross-simulation matrix, Nam Khan watershed. P stands for period and M for model. P1 is the first period (1961–1963), P4 the second (1964–1966), … and M1, M4, … are the corresponding models.

In order to qualify the results obtained on the Nam Khan watershed and test the hypothesis of a hydrologic impact of land-use change in North Laos we applied the same methodology to the four other watersheds: Nam Ou, Nam Suong, Nam Lik and Nam Ngum (Fig. 1). These watersheds are located in North Laos, close to the Nam Khan, on the left bank of the Mekong River. Data are provided by the MRC for the period 1987–2004 (18 years). We followed the same line as Kinouchi (2010) but with a different modelling approach. Kinouchi investigated the evolution of the yearly averaged runoff coefficient of each watershed. Based on two land-use maps provided by MRC he showed that the observed evolution (diminution of upland agriculture and conversely increase of shrublands, but with no change in forest cover), is correlated with an increase of the runoff coefficient (10% for the Nam Khan and Nam Suong where the land-use change concerns less than 20% of the watershed areas).

The followed methodology is the same as for the Nam Khan (split sample test with two periods of eight years and a resampling approach with five periods of three years). Globally, the split sample test results show that GR4J performs well for all the watersheds (Nash = 0.7–0.9) and GR2M performs better: results for the calibration period are as good as those obtained for the other period. The X_1 and X_2 parameters of GR2M do not change. The resampling approach did not allow us to identify any impact of the land-use change on the hydrology of the watersheds. No trends in the matrix have been detected and the X_i parameters appeared to be rather independent of the period considered.

In conclusion we observed that the conceptual models perform well, the monthly time step model better than the daily. We could not decide whether land-use change impacts the hydrological regime of these watersheds or not. This can be explained by the reliability of the discharge measurements, especially during the period 1976–1988, and by the rainfall data. Figure 2 shows clearly how large the difference can be between the rainfall measured at LP, located at the western extremity of the Nam Khan watershed, and that of the Aphrodite database. Many authors have pointed out that the detection of an impact of land-use change on watershed hydrology is a very complex task, even impossible in many cases. Andréassian (2004) showed that in some cases a few percent change in land-use may be detected and in some others a radical change of land use may not.

HOUAY PANO CATCHMENT

Houay Pano is a small agricultural catchment (0.62 km^2) located near Luang Prabang and surveyed over more than 10 years by IRD (Fig. 1) (Ribolzi *et al.*, 2008). The catchment is representative of southeast Asian catchments with a typical slash and burn cropping system without industrial inputs. Approximately 80% of the land use is rotating land. Annual crops, mainly upland rice (*Oryza sativa*) or Job's tears (*Coix lacrima-jobi*) are cultivated for 1 year, followed by a fallow period during which secondary vegetation covers the fields. The hydrological monitoring showed that the fallow regrowth has an important impact on annual water budget: it increases the canopy interception, the evapotranspiration process and root water uptake subsequent to perennial vegetation growth. As a result it reduces groundwater recharge and subsurface reserves. 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. Figure 4 shows the evolution of the proportion of fallow and crop from 2001 to 2007 and its impact on the main streamflow components during 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. the ratio streamflow depth/rainfall depth) (Ribolzi *et al.*, 2008).

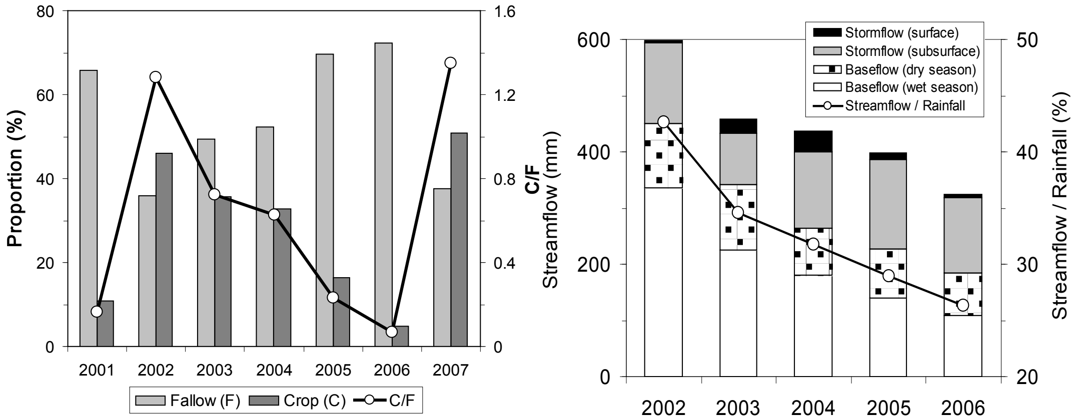

Fig. 4 Evolution of total fallow and annual crop percentages and the ratio between the two (C/F) areas in the Houay Pano catchment (left); total annual streamflow components and ratio between total annual streamflow and rainfall (right) (Ribolzi *et al.*, 2008).

We modelled Houay Pano hydrology with GR4J and verified whether the cross-simulation methodology could account for land-use change (i.e. fallow regrowth). The cross-simulation matrix has been computed for each of the four monitored sub-catchments and for the period 2003–2008. Results for the catchment outlet are given in Fig. 5. The 2002 and 2003 hydro-meteorological data were used to initialize the X_i parameters of GR4J and each year was considered as a sub-period, which is not satisfactory from a statistical point of view. Nash coefficients are lying between 0.7 and 0.9, whatever the sub-catchment and the year. We observed for each year the same model ranking in the capacity to produce flow: M04 > M05 > M06, M06 < M07 and M07 > M08 where M0i is the model of year 200i (2008 is not represented in Fig. 4). We observed M04 > M05 > M06 when F04 < F05 < F06, where F0i is the fallow percentage for the year 200i. Model M07 produced more water than models M04, M05 and M06, and model M08 less water than M07. This is completely coherent with the evolution of the fallow percentage F07 < F04, F05, F06, F08. Nevertheless M08 produced more water than M04 though the percentage of fallow is nearly the same. This is explained by the fact that in 2008 a fraction of the fallow area has been replaced by a teak plantation. The dependency of the models hydrologic responses with respect to the fallow percentage is illustrated in Fig. 5, which represents the mean annual runoff coefficient as a function of the fallow percentage for each precipitation series (i.e. each mean annual flow Q_{ij} divided by the annual precipitation P_i as a function of model M_j, or fallow percentage F_j). The correlation between flow and fallow percentage is obvious whatever the precipitation.

	M04	M05	M06	M07	M08
P04	478	398	366	586	564
P05	496	406	376	613	607
P06	442	364	336	544	527
P07	318	262	239	397	384
P08	319	257	235	404	390

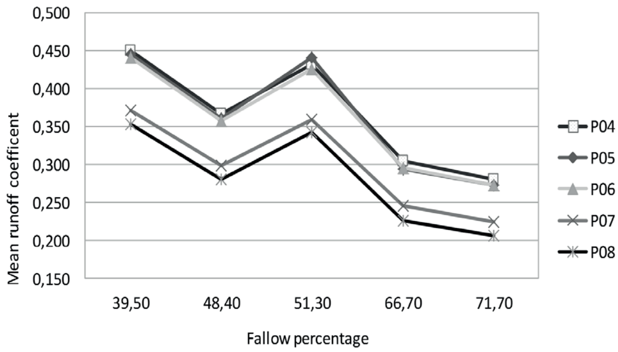

Fig. 5 Houay Pano catchment. Cross-simulation matrix (in mm) (left) and mean annual runoff coefficient as a function of fallow percentage for each precipitation series.

CONCLUSION

The application of the conceptual hydrologic models GR4J and GR2M to North Lao watersheds led to satisfactory Nash coefficients. As expected the monthly time step GR2M performs better than the daily time step model GR4J. We could not detect any impact of land-use evolution on the hydrologic regime of the Mekong tributaries. On one hand the reliability of discharge and rainfall data, but also the representativeness of a single rainfall rate value for the conceptual modelling of large watersheds such as the Nam Khan, has to be questioned. On the other hand, according to Andréassian (2004), when the percentage of the watershed area affected by de- or re-forestation is less than ~20–30% the impact on the discharge may be hard to detect. On the other side the impact of agricultural practice on the discharge of a small agricultural catchment monitored since 2001 was clearly evidenced, thanks to the reliability and density of the data. These results show that the reliability of hydro-meteorological data is of primary importance to assess the impact of land-use change, particularly at large watershed scales.

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