HYDROLOGICAL RESPONSE OF LAND USE CHANGE IN MOUNTAINOUS SUB-WATERSHEDS OF THE MEKONG RIVER BASIN

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ABSTRACT

In the Mekong River basin, Lao PDR, relocation of villages and governmental restriction to the slash and burn agriculture has been in operation since 1980s. These social and political backgrounds could possibly alter basin-wide land use and land cover status and cause adverse hydrological impacts. However, no analysis was conducted based on measurement data to reveal the land use change and relate it to watershed-scale hydrological responses. Thus, this study aims at revealing the hydrological impacts of land use changes in mountainous sub-watersheds of the Mekong River basin by analyzing rainfall-runoff response and trends of monthly rainfall and streamflow.

Out of the five sub-watersheds analyzed, the apparent land use change was found between 1993 and 1997 in Nam Khan, Nam Ou and Nam Suong watersheds, where shrub lands increased and upland agriculture conversely decreased. Corresponding to this change, annual runoff ratio increased by more than 10 points in Nam Khan and Nam Suong watersheds. On the other hand, none to slight changes in land use were found for Nam Lik and Nam Ngum watersheds, which correspond to relatively constant or even decreasing runoff ratios. The seasonal Kendall test revealed increasing trends of areal rainfall in May for four watersheds, and comparatively strong increasing trend of streamflow in July was found for watersheds where drastic land use change occurred in 1990s.

1. INTRODUCTION

In the Mekong River basin, Lao PDR, where slash and burn agriculture has long been managed, relocation of villages from highlands to riparian and roadside areas proceeded for economical development and restricting expansion of shifting cultivation (Thongmanivong *et al.*, 2006). In addition, governmental policy to restrict the slash and burn agriculture has been in operation since the 1990s for the conservation of forests. As a consequence, the land use has been reportedly changed, resulting in the shortened fallow periods and degraded fertility of agricultural lands. However, no analysis clearly revealed possible hydrological consequences of such a land use change. Thus, this study aims to analyze the impacts of land use changes on streamflow to provide scientific information for national policy makers by looking into meteorological and hydrological trends and rainfall-runoff relations for the tributary watersheds of the Mekong River basin using measurement data obtained in the past two decades.

2 STUDY AREA AND DATA

2.1 General characteristics of study area

This study focuses on the hydrological impact of land use and land cover changes in upland agricultural regions located in the northern Laos. Study areas are selected based on the data availability of rainfall, streamflow and land use change during a certain period of year. Sub-watersheds of the Mekong River basin selected for this study are Nam Ou, Nam Suong, Nam Khan, Nam Ngum and Nam Lik (Figure 1), which have catchment areas of 20,087km^2, 6,578km^2, 7,455km^2, 8,430km^2 and 4,795km^2, respectively. These watersheds are located in the altitude ranging from 250m to 2,160m above mean sea level (Figure 1).

2.2 Data source and availability

Hydrological and meteorological data such as daily streamflow and precipitation has been measured since 1920s and is available from the Mekong River Commission (MRC) and the Department of Meteorology and Hydrology of the LaoPDR (DMH), but includes discontinuities and missing data values (Table 1). Data measured in recent two decades are used in this study even these data includes missing values during a certain period and thus the number of measurement sites suit for trend analysis is limited. Figure 2 and 3 show the locations of streamflow and rainfall gauging sites, of which data obtained at stations listed in Table 1 is used for analysis. Data availability is summarized in Table 1, in which the number of month with missing data is specified. In addition, a gridded rainfall data (Yatagai *et al.*, 2008), which was interpolated from multiple-points rainfall data, is utilized to consider spatial variability of rainfall

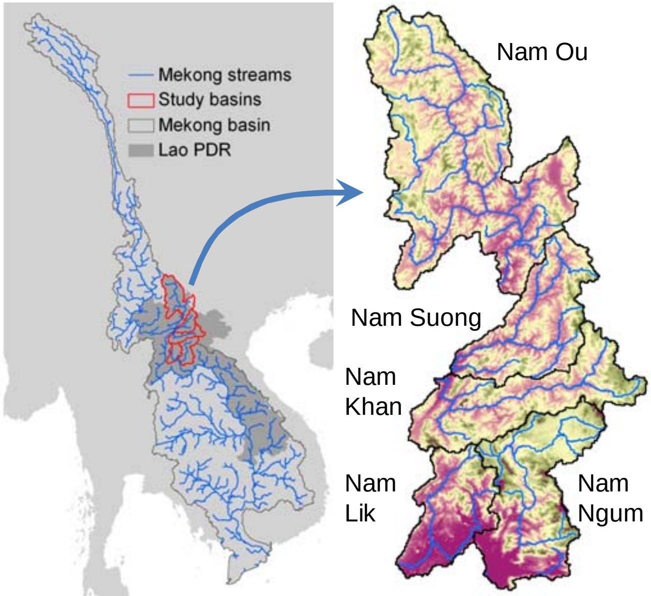


Figure 1. Location of five sub-watersheds.

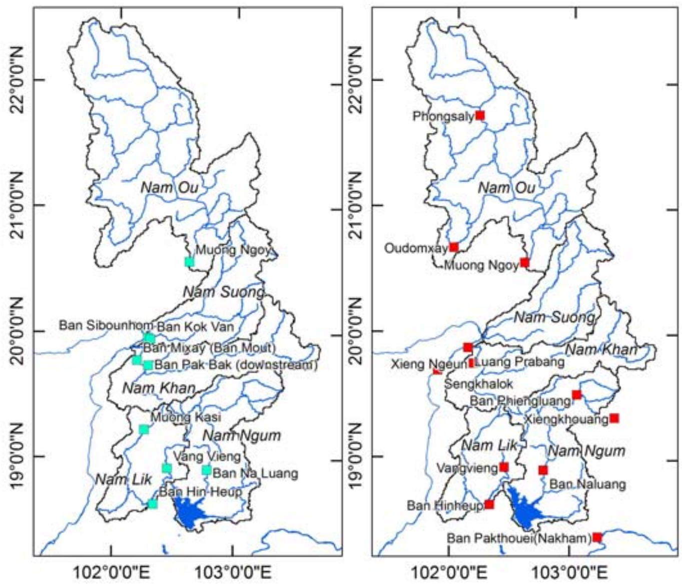


Figure 2. Location of gauging stations. (Left: streamflow, right: rainfall)

Table 1. Number of month with missing data. (up: streamflow, bottom: rainfall)

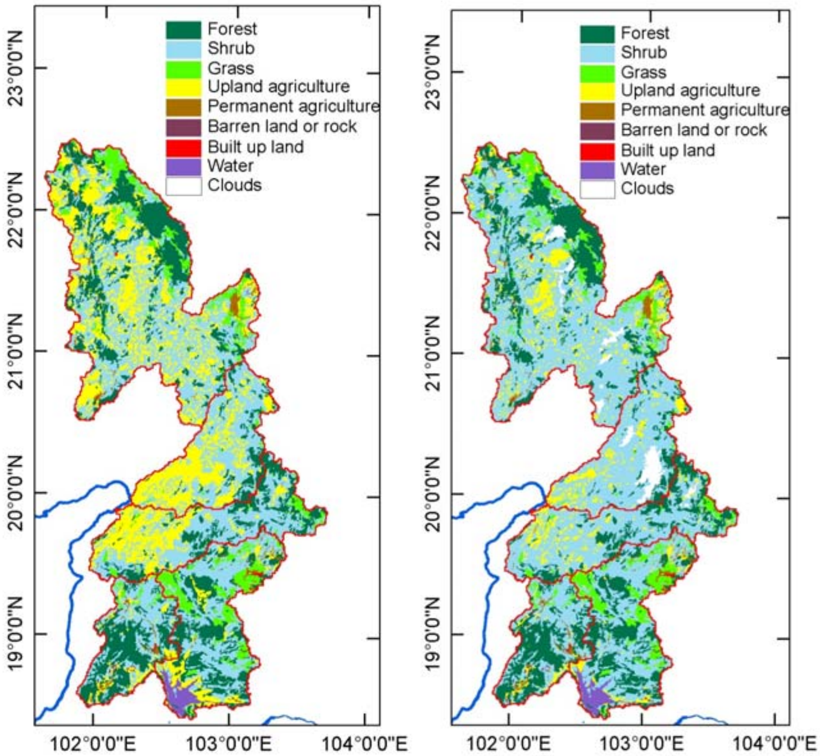
Station / Year	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06
Ban Mixay	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	12	12
Ban Naluang	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ban Hin Heup	10	12	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
Ban Sibounhom	12	12	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	12	12
Muong Ngoy	12	12	3	4	3	0	0	0	10	6	1	0	0	0	0	0	0	1	0	12	12	12

Station / Year	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06
Ban Hinheup	12	12	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	12
Vang Vieng	12	12	0	7	0	0	0	0	0	0	1	0	1	4	0	0	0	0	0	0	0	0
Sengkhalok	12	12	12	8	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	12
Luang Prabang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ban Naluang	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Xiengkhouang	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Muong Ngoy	12	12	12	12	12	12	12	12	0	12	0	12	0	0	0	0	0	0	0	0	0	0
Oudomxay	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
Phongsaly	12	12	12	0	12	0	0	0	8	0	1	4	0	0	0	0	0	0	0	0	0	12

over large mountainous areas.

3 LAND USE CHANGE

In 1980s, the relocation of the upland population to lower elevations and roadside areas began aiming at restricting expansion of shifting cultivation while extending government services to rural villages (Thongmanivong *et al.*, 2006). Since then, Lao PDR has undergone a rapid economic transformation toward a market economy (Fujita and Phanvilay, 2008). Providing secure resource and property rights particularly became an important issue in the early 1990s as a way to promote investment and efficient use of land, thus the Land and Forest Allocation (LFA) Policy was introduced in the early 1990s as a means of legitimately recognizing the customary rights of local communities to use and manage land and forest resources and it was proclaimed in 1996 (Fujita and Phanvilay, 2008). LFA policy regulated household access to upland swidden and fallow lands, by limiting householders' access to three or four plots, which resulted in shortening of the fallow period from the traditional interval, which generally extends 7 to 15 years (Fujita and Phanvilay, 2008). The substantial impact of LFA policy enforcement can be found in national statistics that shows a large area of upland agriculture has declined even during the short period of years between 1995 and 2000.



<1993> <1997>

Figure 3. Land use distribution in five sub-watersheds.

To investigate the hydrological impacts of recent land use changes in the Northern Laos, the land use and land cover status was analyzed for five sub-watersheds shown in Figure 1. Land use data obtained from MRC, which is originally produced from Landsat ETM, was used. Original land use types are reclassified after Thongmanivong and Fujita (2006) as shown in the legend of Figure 3. It is clearly seen that the areas of upland agriculture significantly reduced and conversely turned into shrub lands, especially in the downstream area of Nam Suong and Nam Khan watersheds, and the upstream area of Nam Ou watershed. The land use ratios in each watershed are summarized in Figure 4. The ratio of forest shows no substantial change between 1993 and 1997 for all watersheds, although its magnitude is quite different from each other. Nam Suong and Nam Lik watersheds have the lowest and the highest forest ratios, respectively. The ratio of Shrubs increased in Nam Ou, Nam Khan and Nam Suong watersheds by 18%, 17% and 25%, respectively, while the ratio of upland agriculture decreased by almost the same amounts in each watershed. The increase of shrubs and grassland occurred probably as a result of the

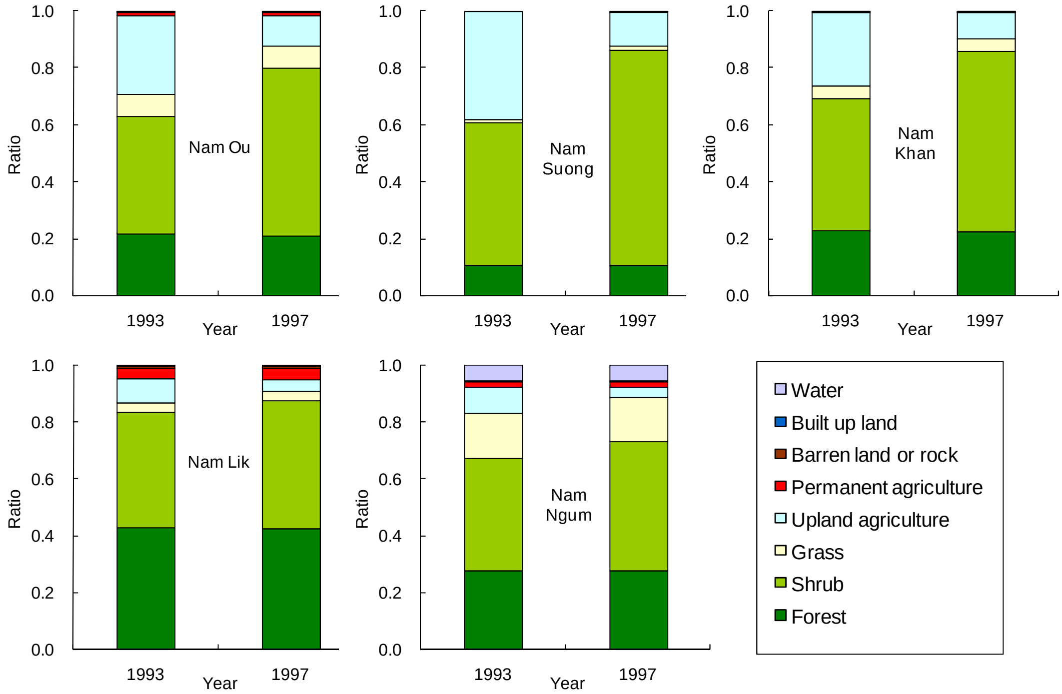


Figure 4. Land-use change between 1993 and 1997.

succession of abandoned swidden areas to secondary forest due to the implementation of LFA policy (Thongmanivong and Fujita, 2006). Opposed to extensively performed upland shifting cultivation in those watersheds, Nam Ngum and Nam Lik watersheds show a little change of ratio in each land use type, probably due to relatively low land use ratio of the shifting cultivation.

4 HYDROLOGICAL RESPONSE CHARACTERISTICS

4.1 Monthly rainfall and stream discharge

The mean monthly rainfalls measured at 9 gauging stations in recent years (1999 - 2005) are shown in Figure 5. Monthly rainfall during the wet season (May to September) varies much depending on the location of gauging station. Vangvieng and Ban Naluang, where elevations are below 300m, recorded larger magnitudes compared with other stations located in higher altitude such as Xiengkhouang (1,060m) and Oudomxay (550m). Vangvieng and Ban Naluang are both located at the outlet of valleys, which connect northern uplands and southern flat plains with an abrupt change in elevation. The reason of larger rainfall recorded at these stations would be that the vapor transported from the south is urged to converge and form the clouds over the areas. As the streamflow in the watersheds of this study is emerged mainly from the rainfall during the wet season, the spatial variability of the rainfall during the wet season poses great uncertainties in separating the hydrological impact of land use change on streamflow.

To understand hydrological behaviors of watersheds under the circumstances of meteorological variability and the land use change, the monthly areal rainfall (R) and monthly discharge (Q) are drawn in Figure 6 for three separate periods during 1987 - 2002. Areal rainfall is calculated using a product called APHRO_EA_V0804 (Yatagai *et al.*, 2008) to average the spatial variability. The mean areal rainfall of Nam Suong watershed is less during 1997-2002 than that during 1987-1992, but the mean monthly streamflow is higher in 1997-2002 than in 1987-1992. In contrast, mean monthly streamflow at Ban Naluang located in Nam Ngum watershed shows little difference between the same two periods, although the mean areal rainfall is larger during 1997-2002. The different behavior of two watersheds in the rainfall-runoff response is possibly explained by land use changes enhanced by the LFA policy started in 1990s as well as the uncertainty in estimating the areal rainfall and other factors such as the soil condition and rainfall intensity.

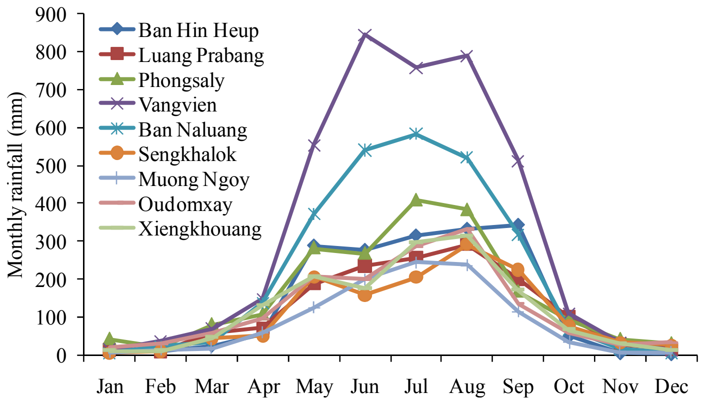


Figure 5. Monthly rainfall for the period 1999 – 2005.

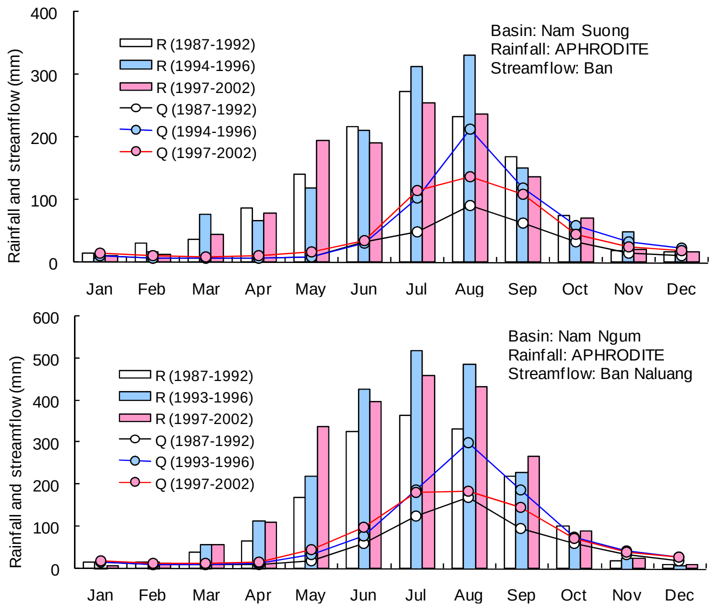


Figure 6. Monthly rainfall and discharge for different periods (up: Nam Suong, bottom: Nam Ngum).

4.2 Runoff ratio

The rate of precipitation that emerged as runoff from a watershed in each year, namely the annual runoff ratio, was quantified to extract the impact of land use change in the five sub-watersheds (Figure 7). Two types of rainfall data are used for each watershed, i.e., data obtained at a single gauging station and areal rainfall estimated from APHRO_EA_V0804 (shown by APHRODITE in Figures 6 and 7). The runoff ratio of Nam Suong watershed, when areal rainfall was applied, shows a strong increasing trend over the studied period. Nam Khan and Nam Ou show slight to moderate increasing trends of annual runoff ratio, but no distinct trend was observed for Nam Ngum watershed. Extremely large runoff ratio is calculated for Nam Lik watershed when areal rainfall is applied. This is probably due to the underestimation of areal rainfall caused by limited data availability. Although it is uncertain if a single gauging station represents the areal rainfall magnitude, using rainfall data observed at Vangvieng gives reasonable values of runoff ratio probably due to that Nam Lik watershed is relatively small and most part of the watershed lies under the topographic condition similar to Vangvieng. Mean annual runoff ratios in two separated periods are summarized in Figure 8. It must be noted that the different averaging period is used in each watershed depending on the data availability of streamflow, and the mean runoff ratios for Nam

Lik are calculated using point rainfall at Vangvieng. Figure 8 clearly shows that the runoff ratio increased in watersheds where a significant land use change was detected (Figure 4).

5 TREND OF RAINFALL AND STREAMFLOW

Rainfall and streamflow are interrelated by watershed-scale physical and biological processes such as evapo-transpiration, infiltration and groundwater outflows. In addition, land use change due to the restricted shifting cultivation and more commercialized agriculture would affect the interrelation by increasing the surface runoff and reducing the water storage in the surface soil layers. To estimate the change of hydrological system response incurred by the land use and land cover change, a statistical trend analysis was applied. If a significant trend in streamflow is found, that should be a composite impact of system's inputs, i.e., rainfall and land use change in each watershed. Negative trend in one input variable and positive trend in the other input variables can cancel out the trend of output. Thus, to understand the trend of rainfall and streamflow and relate them to the land use change would give some information about the possible change in the watershed-scale hydrological system response.

5.1 Trend test

Trends of monthly rainfall and streamflow are analyzed by the seasonal Kendall Test (Hirsch *et al.*, 1982). The null hypothesis H_o is that the data (X_i, i=1,2, $\cdots$, n) are a sample of independent and identically distributed random variables. The test statistic S is defined with the mean $E(S)$ and the variance $V(S)$ as follows.

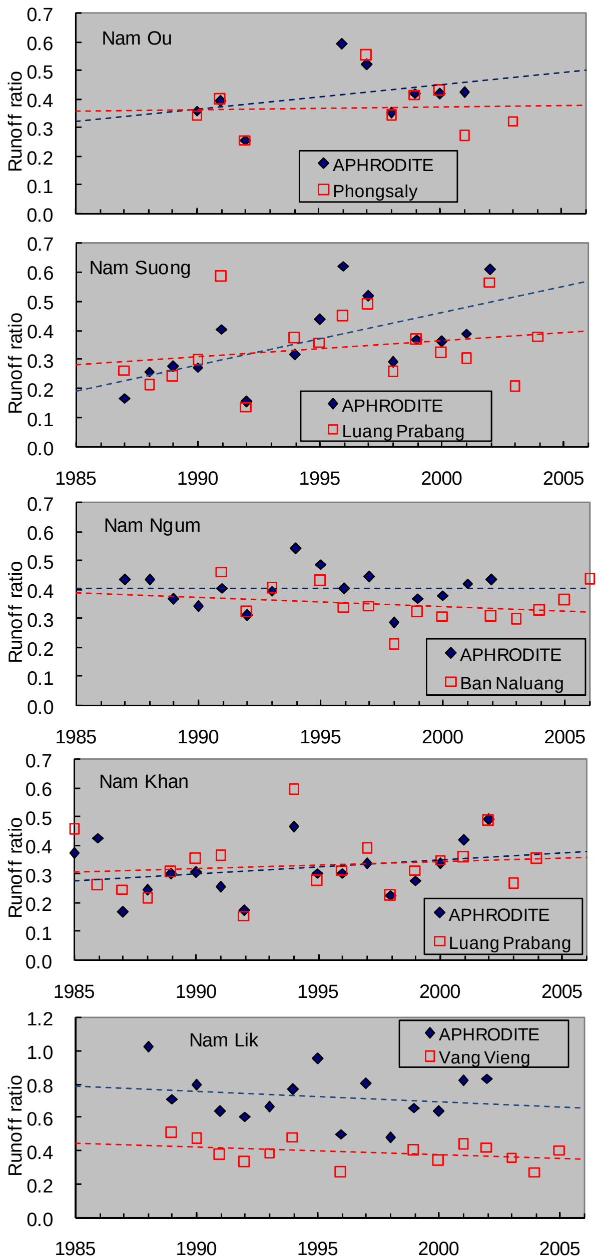


Figure 7. Runoff ratio derived using areal rainfall (APHRODITE) and point rainfall.

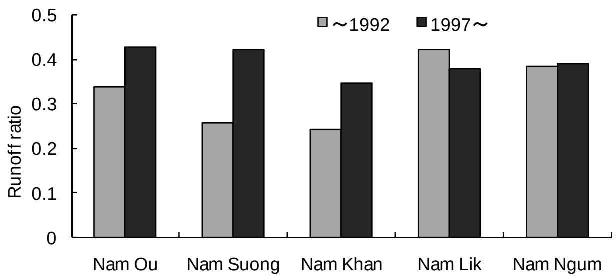


Figure 8. Mean runoff ratio in two periods.

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\operatorname{sgn}(X_j-X_i) \quad (1)$$

$$\operatorname{sgn}(\theta)=\begin{cases}1 & if\ \theta>0\\ 0 & if\ \theta=0\\ -1 & if\ \theta<0\end{cases} \quad (2)$$

$$E(S)=0 \quad (3)$$

$$V(S)=\left\{n(n-1)(2n+5)-\sum_{m=1}^{n}t_m m(m-1)(2m+5)\right\}\Big/18 \quad (4)$$

where t_m is the number of ties of extent m. The standardized statistic Z follows the standard normal distribution. In a two-sided test for trend, the hypothesis H_o should be accepted if $|Z| \leqq z_{\alpha/2}$, where $F_N(z_{\alpha/2}) = \alpha/2$, F_N and α being the standard normal cumulative distribution function and the significance level, respectively.

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{V(S)}} & S>0\\ 0 & S=0\\ \dfrac{S+1}{\sqrt{V(S)}} & S<0\end{cases} \quad (5)$$

The Seasonal Kendall slope estimator B was used to quantify the trend magnitude. In addition, the normalized Seasonal Kendall slope estimator B' was introduced to quantify the relative magnitude of trends against the monthly average of streamflow.

$$B=\overline{\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\frac{X_j-X_k}{j-k}} \quad (6), \quad B'=B/Q \quad (7)$$

where B is the Seasonal Kendall slope estimator of each month and Q is the mean monthly streamflow.

5.2 Trend of precipitation and streamflow

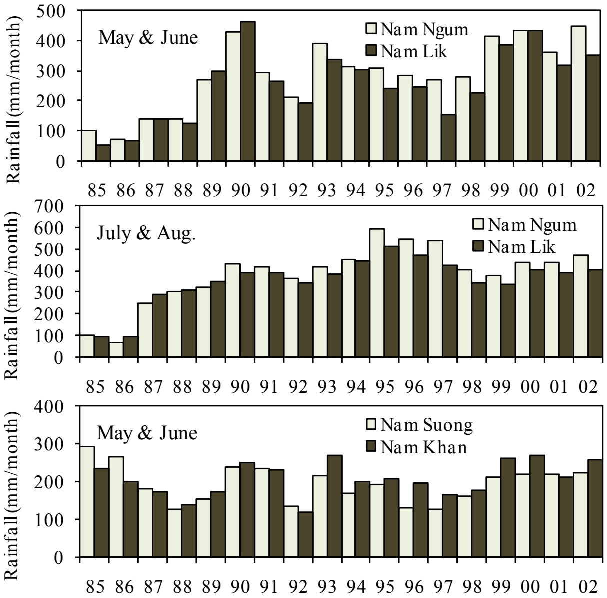


Figure 9. Monthly areal rainfall in two months.

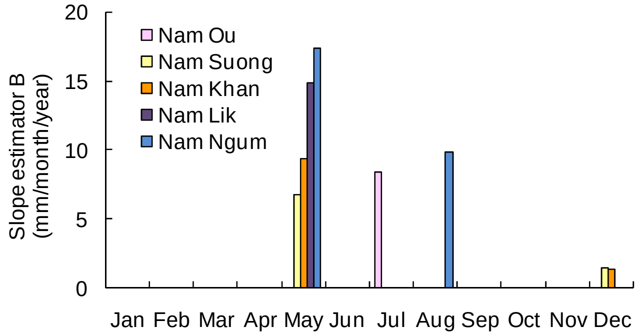


Figure 10. Seasonal Kendall slope estimator for areal rainfall during 1987-2002.

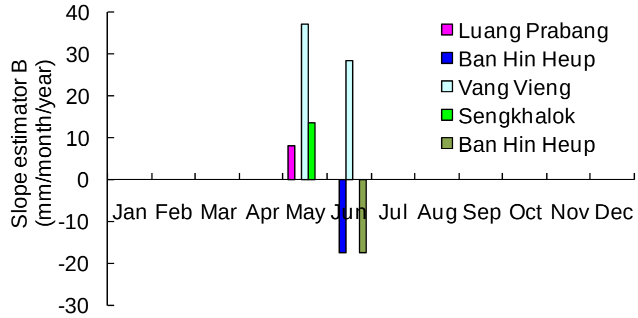


Figure 11. Seasonal Kendall slope estimator for point rainfall during 1987-2002.

Figure 9 shows examples of areal rainfall derived from APHRO_EA_V0804. During May and June, monthly rainfall is increasing for both Nam Lik and Nam Ngum watersheds, while such a trend is not seen for Nam Khan and Nam Suong watersheds. Part of the reason for the increase can be attributable to the underestimation of areal rainfall in 1985 and 1986, when the gauging data is only available at Luang Prabang (Table 1). For this reason, the seasonal Kendall Test of the monthly areal rainfall was applied to the five watersheds during the period 1987 - 2002. The slope estimator *B* for data representing a trend with the significance level of 5% was shown in Figure 10. All the watersheds except for Nam Ou watershed showed increasing trends in May with the significance level of 5%, while Nam Ou and Nam Ngum watersheds showed distinct trends in July and August, respectively (Figure 10). The increasing trend in May is consistent with the earlier onset of wet season alleged from local people. Trends of monthly point rainfalls were also analyzed with the same significance level for the same period (actual period of analysis depends on the data availability shown in Table 1). In this case, significant increasing trend was found at Vang vieng for May and June, and two other points also showed positive trends in May. Trends of monthly areal rainfall during the wet season are likely due to a composite result of point rainfall with different trend characteristics.

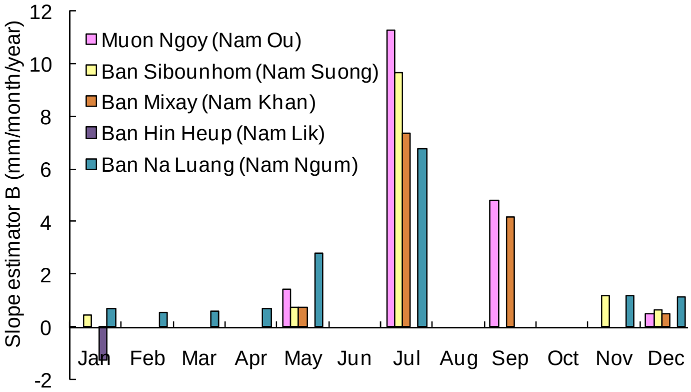


Figure 12. Seasonal Kendall slope estimator for monthly flow depth during 1987-2002.

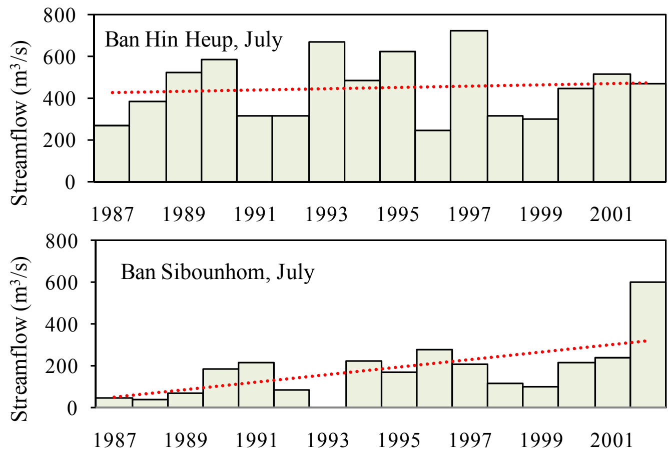


Figure 13. Monthly mean streamflows of Nam Lik (Ban HinHeup) and Nam Suong (Ban Sibounhom) during 1987-2002.

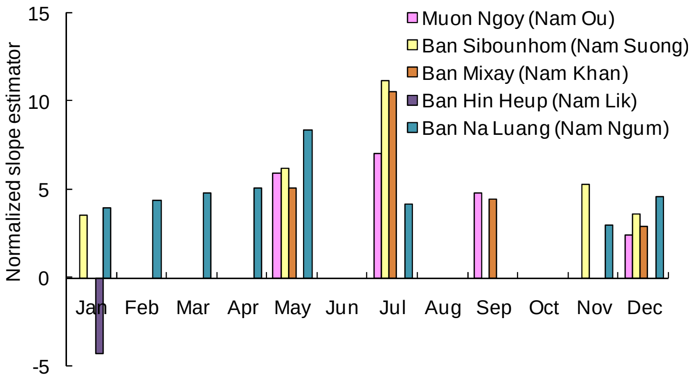


Figure 14. Normalized slope estimator for monthly mean streamflow during 1987-2002.

The result of trend test for the monthly streamflow was shown in Figure 12, in which streamflow was converted to the flow depth by considering the catchment area of each watershed. In contrast to the areal rainfall trends (Figure 10), a strong increasing trend of the flow depth was found for July, except for the Nam Lik watershed. In principle, runoff is generated with some delay due to the water storage in relatively dry watersheds (Figure 6), thus the trend detected for the streamflow in July is possibly corresponds to the increasing trends of rainfall in May. However, areal rainfall of Nam Suong and Nam Ou watersheds shows smaller or even no trend in May, while the increasing trend of streamflow in July is larger for the Nam Ou river (Muon Ngoy station) and the Nam Suong river (Ban Sibounhom station, see also Figure 13). These results indicate that drastic land use changes due to the abandoned swidden and increased shrub over the northern part of the Mekong basin can be related not only to the increasing runoff ratio but also to the increasing trends of streamflow. These hydrological impacts can be explained by some reasons such as reduced evapo-transpiration and soil permeability. For Nam Lik watershed, where no trend of streamflow was found for July (Figure 13), it is considered that the impact of increasing areal rainfall is alleviated by the forest that covers more than 40% of the watershed. It is interesting to note that the normalized slope estimator shows increasing trends of streamflow even in the dry season (from October to April), especially for Ban Na Luang in Nam Ngum watershed (Figure 14). As indicated in Figure 9, a strong increasing trend of areal rainfall in May is followed by a moderate trend in August for Nam Ngum watershed. This implies that the larger amount of rainfall during the wet season, especially in May and August, contributed to the increased streamflow in the subsequent periods including the dry season.

6 CONCLUSIONS

This study aimed to better understand the hydrological response of the land use and land cover change in the upper Mekong River basin located in LaoPDR. Under limited hydrological and meteorological data availability, annual runoff ratio estimated for five sub-watersheds for the period since the middle of 1980s showed increases by more than 10 points in Nam Khan and Nam Suong watersheds, where a drastic change in the land use and land cover was found. This is likely due to the introduction of the National Land Allocation policy and the relocation of villages to the lowland areas. On the other hand, none to slight changes in land use were found for Nam Lik and Nam Ngum watersheds, which correspond to relatively constant or even decreasing runoff ratios. The seasonal Kendall test showed increasing trends of areal rainfall in May for four watersheds, which support alleged early onset of the wet season. Increasing trends of Streamflow in July is partly due to the increased rainfall in May, but the streamflow trend was significant for watersheds where drastic land use change occurred in the 1990s.

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