RESEARCH ARTICLE

Double Mass Plots reveal a marked decrease in the water yield of a Lower Mekong River watershed in 1985 from cutting the climax forest

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Key points:

1. Cumulative water yield over cumulative precipitation is shown to provide a sensitive method for detecting land use changes on water yield.
2. The water yield of a forested watershed in upper Laos to the Mekong River was shown to decrease by 42% (for cut area 50%) from 1985 for 10-12 years.
3. There is no public record of the event, but we calculate that 75-80% of the virgin forest on the watershed (about 60 million ha) was cut in one year.

ABSTRACT

In most, but not all of the scientific literature, cutting of forested watershed results in an increase in the water yield of a watershed. In this study, a double-mass plot of the cumulative monthly flow of water between 1961 and 2000, from a 79,000 km^2 (7.9 million ha) forested watershed feeding into the Mekong River, on cumulative monthly precipitation over the same period, was used to demonstrate a significant ***decrease*** in the water yield in 1985. For 10-12 years after 1985, the total water yield from the watershed decreased by 42% (256 mm) while the late (March and April) dry-season flow decreased by almost 80%. From the changes in water yield and an understanding of the local hydrology, we calculated that 75-80% of the forested area was cut, i.e. more than 6 million ha, implying that the decrease in total water yield from the area of the forest that was actually cut, was just over 50%, while the late dry-season flow from the same area was virtually eliminated. We consider that the main reason for the reduction in water yield, after the forest was cut was an immediate increase in dry-season transpiration by the remaining old forest, newly-exposed understorey and regrowth vegetation, all of which were considered to be accessing groundwater in the regolith. The amount of groundwater accessed was sufficient to allow the cut forest to lose water at the potential rate over the whole year. We conclude that restoration of the watershed water flows resulted mainly from forest regrowth.

Index terms. 1804, Hydrology; 1879, Watershed; 1860, Streamflow; 1829, Groundwater hydrology.

Keywords. Deforestation; groundwater; land use; Lao Peoples Democratic Republic; recharge; soil water storage.

1. Introduction

The Mekong River flows from its headwaters in the Tibetan mountains of China, through Myanmar, Laos, Thailand, Cambodia into Vietnam, where it flows into the South China Sea. It is the 10^{th} largest river in the world in terms of annual flow of about 15,000 km^3 (Hecht et al., 2019; Spruce et al., 2020). With a watershed of about 795,000 km^2, supporting a population of above 75 million that is expected to increase to over 100 million by 2050 (Varis et al., 2012), there is considerable interest in the efficient use of this water resource for hydropower, agriculture, fisheries, light industry and potable water. The development of dams, climate change and land-use change along the Mekong River has led to several attempts to determine the consequences of these interventions on the water yield and water flows of the river (Lyon et al., 2017: Li et al., 2017; Pokhrel et al., 2018; Hecht et al., 2019).

The flow of the Mekong River in the lower Mekong Basin is largely influenced by the South-east Asian Monsoon when the south-west monsoon brings a humid air mass from the Indian Ocean over the Basin. This results in a wet season of high river flows of more than 30,000 $m^3 s^{-1}$ near the mouth from June to October and low flows of less than 2000 $m^3 s^{-1}$ in the dry season from November to May (Pokhrel et al., 2018). A comparison by Pokhrel et al. (2018) of the monthly flows at five gauging stations along the Mekong River showed that the wet season flows increased between the decade from 1982-1992 to the decade from 1993-2004. However, Lyon et al. (2017) found no change on average in the water flows of 33 smaller watersheds or sub-watersheds in the lower Mekong Basin over the last 50 years, 64% showed no change in the water flow, while 21-24% showed an increasing trend and 12-15% showed a decreasing trend in water flow. It is not clear whether the observed changes arise from the variation in climate, particularly precipitation, or land use change.

Since the 1980s there have been a number of models developed to simulate and demonstrate an understanding of the hydrological processes involved in the flows and water yield of the Mekong River (Johnston and Kummu, 2012; Mouche et al., 2014; Lyon et al., 2017; Pokhrel et al., 2018). However, Pokrel et al. (2018) suggest that the paucity of observed data limits the calibration and evaluation of the models. While the role of climate change and diversion of flows for agricultural and industrial use are topical issues, in this paper we concentrate on the variation in water yield from 1961-2000 of a watershed of the lower Mekong River located primarily in the People's Democratic Republic of Laos. We use a simple measure, the cumulative water yield plotted on cumulative precipitation (Searcy and Hardison, 1960), to identify a large land-use change in 1985 that persisted for over a decade and occurred prior to the more recent development of several dams along the upper Mekong and before major changes in climate were observed.

Although the flow of the Mekong River has been recorded since 1913 to provide data to ensure the equitable sharing of this water resource between the countries through which it flows, there has been little success in formally determining the relationship between water yield and forest/land cover in the Mekong Basin (Mekong River Commission, 2005) because of the very large variation in the flow record arising from the variation in precipitation and the lack of knowledge on the water use of the various land covers across the basin. According to the Lao Ministry of Natural Resources and Environment, in the late 1960's the amount of evergreen forest in Laos was 17 million hectares, but by 2002 the area of evergreen forest had declined to 9.7 million hectares, a decrease of 7.3 million ha or 43% of the original forested area (Thomas, 2015). A land use map for 1997, near the end of the focus period of the present study, showed that the majority of the focus watershed in Laos was covered by evergreen forest, with small areas of shifting agriculture (also known as slash-and-burn agriculture and swidden agriculture), while lower areas in Thailand had been converted to permanent crops with remnants of shrub vegetation (Spruce et al., 2020). There are no public records of logging in Laos in the 1980s as far as we are aware. However, we consider that the marked land use change observed in 1985 must have been the result of logging of the evergreen climax forest.

The consensus of extensive research in controlled watershed studies is that harvesting trees causes an increase in total watershed water yield, with the greatest proportional increase occurring in low flow periods (Gilmour, 2014, quoting Bosch and Hewlett, 1982, Andréassian, 2004, Scott et al., 2005, Landsberg and Gower, 1996; Zhang et al., 1999). Contrary to this, Gilmour (2014) reported that there is widespread belief in South-East Asia that "harvesting timber from forested watersheds and clearing forests causes wells, springs and streams to cease flowing, and that, conversely, reforesting bare hillsides will cause water to reappear in wells, springs and streams (Hamilton, 1985)." This popular belief is based on an analogy of forests as "sponges" that soak up water during wet periods and release it slowly over the dry season. This implies that forested watersheds absorb virtually all the incipient precipitation and release it slowly into streams during the year (Gilmour, 2014). These regional beliefs are supported to some extent by studies that have shown that the water yield of *Eucalyptus* watersheds decreased after regrowth forest was established (Langford, 1976, Kuczera, 1987, Vertessy et al., 1998, Buckley et al., 2012). Thus, there is considerable uncertainty on the influence of forest management on the water yield of the Mekong River watersheds with climax evergreen forest cover.

This study is limited to the interpretation of hydrological flow data compiled by the Mekong River Commission between 1960 and 2000 for the watershed between Luang Prabang (LP) and Chiang Saen (CS), abbreviated to LP-CS watershed. The primary scientific objective of the study was to examine the extent to which changes in land use over time are detectable by double-mass plots of water yield on precipitation (Searcy and

Hardison, 1960) and to measure the associated changes in water yield flowing to the Mekong River. The second objective was to determine the proportion of the watershed over which the land-use change was observed. This is necessary to calculate the actual change in water yield from the particular land use change of interest.

We hypothesise: (1) that double-mass plots of water yield on precipitation can detect relatively small land-use and non-climate related changes in forested watersheds; (2) that as observed in many watersheds, cutting of climax forest increases the water yield of the watershed; and (3) the area of cut forest can be estimated from the changes in water yield and an understanding of the local hydrology.

2. Methods

2.1 Overview

The study focuses on the flow of water from the watershed bounded by smaller watersheds feeding into the Mekong River upstream of the monitoring station at Luang Prabang (LP) and downstream of the monitoring station of Chiang Saen (CS) in the People's Democratic Republic of Laos (Laos). This watershed, referred to as the LP-CS watershed, essentially covers the uplands of the Laos, while about 20% is largely upland terrain in Thailand (Figure 1). The watershed and its component sub-watersheds between Chiang Saen and Luang Prabang cover an area of 79,000 km^2 (7.9 million ha), and is generally mountainous. The soils are shallow, generally less than 0.5 m deep though there are some flat areas where the soil depth is about 0.75 m deep (Pelletier et al., 2016). The soil is underlain by a permeable regolith consisting of weathered rock. The data set published by Pelletier et al. (2016) provide "high-resolution estimates of the thickness of the permeable layers above bedrock (soil, regolith, and sedimentary deposits) within a global 30-arcsecond (~ 1 km) grid using the best available data for topography, climate, and geology as input." The dominant thickness of the regolith over the LP-CS watershed is 50 m. The FAO soil classification for the watershed is various types of Accrisol, implying the widespread existence of a well-defined *B* horizon. The *A* horizon soils consist of sandy to loamy silty clay soils overlying a *B* horizon of clay, with an available soil water content from 10% (sandy) to 20% by volume (Kramer, 1983). The average dry-season maximum soil moisture deficit for almost all the soils covering the watershed is estimated to be in the range of 50-100 mm.

[Figure 1 about here]

The vegetation at the beginning of the study period (1960) was assumed to be largely evergreen climax forest with small areas cleared for shifting agriculture. In 1997 this was still the case in Laos, but approximately 50% of the watershed in Thailand had been cleared and converted to permanent crop land (Spruce et al., 2020). However, in the subsequent thirteen years to 2010, almost all of the watershed in Thailand had been converted to permanent cropland, while further clearing had occurred in Laos and resulted in a conversion to slash-and-burn croplands and shrubland (MRC website seminar accessed in 2008; Spruce et al., 2020). Today about half the area in Thailand is agricultural land, while the remainder including the rest of the watershed in Laos is mainly covered by degraded forest/shrubs and shifting agriculture (Google Earth).

The double-mass plot of cumulative river flow over a fixed period (1960 to 2000) against cumulative precipitation over the same period was used to assess whether land use changes over that period could be detected and whether they affected the water yield of the LP-CS watershed (Searcy and Hardison, 1960). A straight line of constant slope indicates a constant land use despite the variability in annual precipitation and river flow. The slope of this regression multiplied by mean annual precipitation gives the average water yield of the landscape. A change in slope of such a plot may indicate (1) a change in land use, (2) a variation in the exposure of the rain gauge, (3) a change in the calibration of the river gauges used to obtain the flow record, or (4) the capture of water in a reservoir for other use such as irrigation or reticulation outside the watershed (Searcy and Hardison, 1960). Based on the tests for homogeneity of the Lao precipitation record, enquiries of the Mekong River Commission from whom the data was obtained, and an aerial "Google Earth" survey of the watershed, we conclude that any changes in slope observed in this study were the result of land-use change and not any of the other factors. As far as is known, there are no public records of logging over the study period, but we conclude that changes in the slope of the relationship between cumulative water yield and cumulative precipitation are the result primarily of logging of the forest and, to a much smaller extent, due to partial clearing of small areas of forest for shifting cultivation. Moreover, there is no extensive land conversion, other than logging, that could possibly be detected in a double mass plot over the small time scale of a year observed after 1985.

2.2 Data

The continuous daily flow records of the Mekong River at the monitoring stations of Chiang Saen (1961-2000) and Luang Prabang (1950-2000) and daily evaporation (1989-2000) were obtained from the Lao National Mekong Committee in 2003 and are now available from the Mekong River Commission data portal (https://portal.mrcmekong.org/home (accessed in July 2020). To obtain the flow for the LP-CS watershed, monthly values of the flow recorded at Chiang Saen were subtracted directly from the monthly Luang Prabang flow record and accumulated to give the annual values. Dry-season flow, referred to as baseflow and defined by the Mekong River Commission as flows from November to May inclusive, and late dry-season flow, the sum of flows for March and April, were also calculated.

Daily Precipitation records from Chiang Rae (1913-2000) and Luang Prabang (1950-2000) were downloaded from the US "Climate Data Online" repository of the US National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/search accessed in July 2020). Daily precipitation at Luang Prabang was recorded and summed to give monthly and annual precipitation. To test the homogeneity and accuracy of the precipitation record for Luang Prabang, double-mass plots of cumulative precipitation at Luang Prabang were compared against the downloaded records of precipitation at Chiang Rae, Vientiane and Udon Thani located 50 km SE of Vientiane. In all the tests, the double-mass plots were linear indicating that the precipitation record at Luang Prabang can be assumed to be accurate and homogenous (Searcy and Hardison, 1960). The average annual precipitation at Luang Prabang (1950-2000), located on the southern boundary and at a low altitude relative to the elevation of the majority of the watershed, was 1263 mm (Table 1). The precipitation (exclusively rainfall) isohyets in Figure 1, taken from Basanayake et al. (2006), indicate that the annual average precipitation over the watershed varied between 1400 and 2000 mm.

As a check on the veracity of the data, monthly pan evaporation data was also obtained from the Lao Department of Hydrology and Meteorology. Annual potential evaporation (PET), the same as the Penman-Monteith Reference Evaporation (Penman, 1954, Monteith, 1965), was obtained from the Global Potential Evapotranspiration (Global-PET) dataset of the CGIAR Consortium for Spatial Information (https://www.nature.com/articles/s41597-022-01493-1) accessed in July 2022). Annual PET ranged between 1360 and 1720 mm over the watershed with an average annual value 0.98 times the annual pan evaporation recorded at Luang Prabang.

Pan evaporation is normally about 80% of the Reference Evaporation (Allen et al., 1998), but the albedo of forest is generally 10-15% less than for the reference surface of well-watered grass (Betts et al., 1997), increasing the available energy over the forest by about 15%. Therefore, monthly pan evaporation at Luang Prabang was used as the measure of potential evaporation of the forest covering the LP-CS watershed.

2.2 Theory

In this section we describe the processes that determine the water loss from forests in the region and quantify them in terms of equations that we can use to estimate the fraction of the forest that was cut and the evapotranspiration from cut forest over the dry season. We need to write and derive these equations in terms of variables that we can either obtain from the available data or that we can estimate. We pre-empt the development of the theory below, with the fact that the double-mass plots indicated that the water yield from the cut forest was less than from the virgin forest.

The flows into the Mekong River, from the watershed of interest, reflect the input of precipitation and losses by transpiration. interception and subsequent evaporation, water entering and leaving the soil profile, and changes in groundwater storage on the watershed. These components can be combined into a water budget for an area of watershed discharging water into a river over a certain time:

$$P = F + ET + \Delta S + G \qquad (1).$$

where, P is precipitation, F is the flow into the river, ET is the evapotranspiration, ΔS and G are changes in soil water content and groundwater storage on the watershed, respectively. The driving force for these water flows is the radiant energy impinging on the watershed. We have no data on the partitioning of this radiant energy into sensible heat, evapotranspiration and thermal energy absorbed by the vegetation and soil except that we can assume that in the wet season, with temperatures in excess of 30 ^{o}C (see Penman-Monteith equation for evaporation) and for a time scale in months, sensible heat losses are very small, especially when the canopy is wet and the surface resistance to vapor transfer into the atmosphere becomes negligible (Waggoner et al., 1969). This is confirmed by Kumagai et al. (2005) who measured evapotranspiration from a Bornean tropical rainforest during the wet season using eddy correlation techniques and obtained daily energy budgets that demonstrated that in wet periods the daily latent heat flux (evapotranspiration) averaged in excess of 90% of the net radiation. Thus, under wet conditions we assume that most of the net radiant energy was partitioned into evapotranspiration.

Both land surfaces before and after cutting would have been essentially saturated during the wet season, and freely transpiring and evaporating, but we observed that annually the cut forest used more water than the virgin forest and so the question arises whether the cut forest was receiving advected energy from the SW monsoon during the wet season in particular? However, both surfaces were very extensive (300 km across) compared with the thickness of the atmospheric boundary layer. Lateral advection of energy into forests, though it occurs in less extensive forests is not expected over such an extensive area as the LP-CS watershed (Morton, 1984). However even if it did exist at this scale, it is difficult to explain why the cut forest would interact more intimately with the atmosphere, drawing more energy from the atmosphere, than a tall virgin forest. We would expect the opposite. Thus, we can assume that over the wet season, the potential evaporation for the cut forest was the same as that for the virgin forest.

2.3. Estimate of watershed area subjected to land-use change (cutting of the forest)

If the land use of a unit area of forest with an initial annual flow rate of F_1 is changed by the fraction "*a*" to another land use (cut forest) from which the flow rate is F_c, the water yield from the cut area is aF_c. Similarly, that from the uncut area is $(1-a)\,F_1$. Adding the two partial flows together and dividing by the unit area, gives the flow rate from the original unit area that was partially cut, namely F_2. That is:

$$F_2 = (1- a)\, F_1 + aF_c \qquad (2)$$

where F_c is the flow rate from the partially cut forest. Rearranging this equation yields:

$$a = (F_1 - F_2)/(F_1 - F_c) \qquad (3)$$

Equation 3 applies to annual and seasonal flows (after changing the variable names) and allows the estimation of "*a*" from an estimate of flow rate from a cut area F_c, as F_1 and F_2 are already known.

We consider now how to estimate F_c. With reference to Equation 1, the annual water budget for the cut area is:

$$F_c = P - (ET_c + \Delta S_c) \qquad (4)$$

where P is the annual precipitation, ET_c is the annual evapotranspiration from the cut area and ΔS_c is the total change in stored water (soil moisture and groundwater) over the dry season for the cut forest. The energy budget for the surface implies that the term in brackets will be less than the annual potential evaporation. We obtain a maximum estimate of this bracketed term by putting it equal to the annual potential evaporation E_p. which we know (Table 1), giving us a minimum value for F_c.

To obtain this minimum estimate of F_c for the cut area from Equation 4, we also need an accurate estimate of P *for the whole watershed* as we know that the isohyets in Figure 1 are only indicative because there are so few rain gauge stations in Northern Laos. To obtain an estimate of P from the water budget for the forest *before* cutting we assume that during the wet season evapotranspiration from the wet forest was equal to pan evaporation. Note that pan evaporation for any given period varies much more conservatively across the landscape under consideration than precipitation in the region under study. Therefore, we can say that before cutting the annual water budget for the uncut area is:

$$P = F_1 + E_{pw} + P_d + \Delta S \qquad (5)$$

where E_{pw} is pan evapotranspiration (≅PET) over the wet season and P_d is the precipitation over the dry season.

Substituting $P_d = kP$ into Equation 5 where k is the ratio of the dry-season to total annual precipitation for the whole watershed, assumed to be equal to k at Luang Prabang, and rearranging the terms, we get annual precipitation expressed in terms of data (except for ΔS) that can be obtained from the weather station and flow gauge at Luang Prabang. i.e.

$$P = (F_1 + E_{pw} + \Delta S)/(1 - k) \qquad (6)$$

Having derived P we can now substitute its value into Equation 4 to obtain a minimum estimate of F_c and thence into Equation 3 to obtain a minimum estimate for "a". We assume that the factors controlling the soil moisture deficit before and after cutting the forest remain the same and thus ΔS does not change after cutting. The additional water uptake from the cut forest must then be given by G_c/a mm, where G_c, the total groundwater uptake,, equal to the difference in measured flows. (Note that it does not matter here if part of the groundwater uptake is actually from the unsaturated zone). The total dry season evaporation E_{dc}, for the cut area is then:

$$E_{dc} = P_d + \Delta S + G_c/a \qquad (7)$$

from which we obtain on substituting $E_{pd} \geq E_{dc}$ into Equation 7, a second estimate of "a":

$$a \geq G_c/(E_{pd} - \Delta S - P_d) \qquad (8)$$

3. Results

The mean annual precipitation at Luang Prabang for the 40 years between 1961 and 2000 was 1263 mm while the mean annual pan evaporation (1984-2000) was 1562 mm (Table 1). The wet-season (June to October, as defined by the Mekong River Commission) precipitation of 923 mm was much higher than the dry-season (November to May) precipitation of 341 mm, while the reverse was true for pan evaporation with the dry-season evaporation of 909 mm compared with the wet-season evaporation of 653 mm (Table 1).

[Table 1 about here]

The double-mass plot of cumulative flow versus cumulative precipitation for the LP-CS watershed (Figure 2) showed minor variations in slope over the period from 1960 to 1975, a steady linear increase between 1976 and 1985, and a significant and sudden change in the slope of the relationship between cumulative water flow or water yield and cumulative precipitation from 1986 to 1995. From 1995 to 2000 the trend depicts a gradual return to the rate of increase that was measured from 1976 to 1985 (Figure 2). The slope of the LP-CS double-mass plot over the 10-year span from 1976 to 1985 (S_1) was 0.44 ± 0.005 and that for 1986-1995 (S_2) was 0.29 ± 0.006, where the errors are one standard deviation of the mean slope. The relative errors observed, implies that we can estimate the flow from the LP-CS watershed over a decade, using a linear double mass plot, to 95% precision of about ±3%. Mean annual precipitation at Luang Prabang over this 20-year interval was 1390 mm, 127 mm higher than the 40-year mean in Table 1. The mean annual flow from 1976-1985 was 607 ± 7 mm and from 1986-1995 was 351 ± 8 mm, a reduction in flow of 42% or 256 mm

(Table 1). The 1996-2000 record shows a recovery in flow so that the average flow for that period was only 9% lower than for the period from 1975 to 1985 (Figure 2).

[Figure 2 about here]

The seasonal variation in the mean monthly precipitation and river flow for the period from 1976 to 1995 reached a maximum in August in the middle of the wet season (Figure 3; Table 1). However, the onset of the wet season flow lagged the increase in precipitation by about 4 months both before and after the change observed in 1985, implying that both before and after 1985, the higher precipitation late in the dry season and the precipitation early in the wet season was being used to relieve water deficits in the watershed generated over the previous dry season before significant flow into the Mekong could occur. However, after 1985 the delay later in the wet season flow was even greater and the flow into the Mekong was less.

After 1985, the large absolute reductions in flow into the Mekong River occurred primarily from August to October (Figure 3) when the watershed soils were likely saturated and also, throughout the dry season (November to May). The relative decrease in the dry-season flows of 49% from 148 mm down to 76 mm (Table 1) was greater than the 42% decrease in total flow (Table 1, Figure 3). Furthermore, the relative reduction in the late dry-season flow (March and April) of 77% was even greater following the change in land use in 1985 (Figure 4). However, the recovery in the late dry-season flow occurred much earlier, within about 5 years (Figure 4), compared with more than 12 years required for the recovery of the total flow (Figure 2).

Plotting the cumulative wet season (June-October) flow and the April (late-season) flow, normalised with respect to the sum of the cumulative flows between 1976 and 1985, on cumulative precipitation for the appropriate months (Figure 5) shows their relative responses (as determined from the slopes of these curves). The greater reduction in late-season flow than wet-season flow was evident in 1986, indicating that the land use changed within a single year.

[Figure 3 about here]

[Figure 4 about here]

[Figure 5 about here]

The annual flows into the Mekong River, both pre- and post-1985, are considerably lower than the annual precipitation (Table 1). This is also true of flows in the wet season (Figure 3). They reflect losses by transpiration, interception and subsequent evaporation, and water entering and leaving the soil. To maintain a constant energy use over the wet season before and after 1985, we consider that the observed reduction in wet-season flow after 1985 (Figure 3) was primarily due to groundwater storage, or possibly an increase in unsaturated soil water storage above ΔS, that was depleted over the following dry season. Note that the magnitude of this annual change of water in storage for the *area of the forest actually cut* is the total reduction in observed flow of 256 mm (Table1) divided by "*a*" mm.

It is in the saprolite or similar of the weathered zone just below the soil layer that we propose the bulk of groundwater accessed by the cut forest, is stored. Assuming that groundwater uptake by the vegetation after cutting removes all the moisture from the capillary fringe of the groundwater held there by matric suction, the minimum change in depth of this lowered groundwater surface in *the cut area* is given by the change in stored precipitation (256/*a* mm) divided by the porosity of the aquifer. In a mature weathered profile of mountainous terrain in the tropics the expected bulk densities in the soil horizons are in the range of 1-1.2 g/cm^3, grading with depth into saprolite, or similar (Hayes et al., 2019) of bulk density in the range of 1.5-1.7 g/cm^3, equivalent to a porosity of about 0.4 (Anderson et al., 2002: Morris et al., 1967). Thus, the minimum seasonal change in the average level of the groundwater in the cut area as a result of the uptake of groundwater, as distinct from lateral drainage to supply the dry-season flow, which must also be superimposed on it, is about 0.8 m. Adding to this, the fall in levels due to the dry-season discharge of about 80 mm gives a total minimum predicted average fall in groundwater level in the cut forest over the dry season of about 1.0 m for the cut forest compared with a fall of only 0.4 m for the virgin forest.

With reference to Equation 6, the estimate of precipitation for the watershed, by taking $k = P_d/P = 0.27$ (Table 1) and setting the soil water deficit initially $\Delta S = 100$ mm, gives an estimate of the annual average precipitation (P) for the watershed of 1862 mm. If $\Delta S = 50$ mm, then the annual precipitation for the watershed is 1794 mm. Thus, the average annual precipitation for the whole watershed is estimated from our two assumed values of ΔS, to be slightly more than 1800 mm which is broadly consistent with the isohyets given in Figure 1. From the estimate of P for the whole watershed we can now use Equation 4 to estimate the flow from the cut area F_c and then the value of cut area "*a*" from Equation 3. A minimum value of "*a*" is obtained using a minimum estimate of the flow from the cut forest, F_c. The minimum value for F_c, in turn, is obtained from Equation 4, assuming the total annual evapotranspiration from the cut forest ET_c is equal to the annual pan evaporation (i.e., the available energy for evaporation over the whole year = pan evaporation = 1562 mm). Using the above substitutions gives minimum values of F_c of 300 mm for $\Delta S = 100$ mm and a F_c of 232 mm for $\Delta S = 50$ mm. Therefore, from Equation 3, the minimum estimate for the fraction of the watershed that was cut "a" was **0.83** if $\Delta S = 100$ and 0.**68** if $\Delta S = 50$.

Assuming the whole LP-CS watershed was cut (i.e. ”a" = 1.0), substitution in Equation 7 yields a minimum estimate of the pan factor (evapotranspiration from the forest/pan evaporation) for the cut forest of 0.95 if ΔS = 100 and 0.87 if ΔS = 50, implying that the cut forest was losing water over the dry season at the potential rate. Substituting the known values into Equation 8 and assuming the dry season evapotranspiration was at the potential rate and that all the dry-season precipitation was evaporated and does not appear as flow, the estimated “*a*” from the dry season water budget was >0.79 if ΔS = 100 and >0.69 if ΔS = 50. These values of “*a*” imply that while the double mass plots showed 42% decrease in total flow, the decrease for the area actually cut was ***about 50%*** while the decrease for the late dry-season flow (March + April) was 96% (i.e. essentially no flow). Reducing “*a*” yields an even higher percentage reduction in flows (>100%, for the late dry-season flow), so we conclude again that our estimate of “$a \cong 0.8$” is about right.

Finally, if the late dry-season (March + April) flow after logging (F_c), is set to zero in Equation 2 and values of F_1 and F_2 are obtained from the slopes of the late dry-season flow record before and after logging (Figure 4), then Equation 2 implies that the minimum area logged is “*a*” = 0.75, similar to the other estimates of “*a*” Thus, we consider that the estimate of “*a*” = 0.8 (that is 80% of the forested watershed was cut/logged) for ΔS = 100 mm is probably closest to reality because (i) it is consistent with the dry-season water budget estimate, (ii) the soils over a large part of the watershed are at least 500 mm thick with soil particles finer than sand, and therefore are expected to have a deficit closer to 100 mm than 50 mm (Kramer, 1983), and (iii) it gives a realistic estimates of the reduction in total flow and late dry-season flow following cutting.

4. Discussion

Between 1960 and 1975 there were minor fluctuations in the slope of the double mass plots that were within the estimated 3% accuracy from the measured error term of the slope of LP-CS watershed double mass plots. We attribute these small fluctuations in flow to small logging operations and/or to a much lesser extent, the clearing of portions of the forest for slash-and-burn agriculture. However, in 1985, there was a major change in the slope of the double-mass plot of cumulative flow versus cumulative precipitation of the watershed that occurred over the short term of a year and then persisted for about 10 years before a gradual return to the original slope of the relationship. We conclude that these changes in slope of the cumulative flow versus cumulative precipitation are evidence of a major logging event covering a significant fraction of the LP-CS watershed and causing a 50% reduction in water yield from the area actually cut.

In agreement with Searcy and Hardison (1960), we conclude that the double-mass plots of flow against precipitation of a watershed are a useful method of detecting changes in the land response of watersheds, confirming Hypothesis 1 “that double-mass plots of water yield on precipitation can detect relatively small land-use and non-climate related changes in forested watersheds”. The sensitivity of the double-mass plot of cumulative flow against cumulative precipitation was sufficient to reveal that the largest relative reduction in flow was in the late dry-season (March-April) flow. Further, we conclude that if the average water-holding capacity of the soil over the watershed is 100 mm, then the forest operation affected about 80% of the watershed area, whereas if the average water-holding capacity of the soil over the watershed is 50 mm the proportion of the watershed cleared was about 70% of the area of the watershed. In either case, this suggests a large proportion of the watershed was affected by the logging/thinning. The study also showed that the logging event resulted in a decrease in the water yield of the watershed which was unexpected and that the storage of water in the soil as groundwater played an important role in the delay of the release of water into the Mekong River.

Like most of Indochina the meteorological conditions of the LP-CS watershed consist of a high summer incidence of rainfall during the wet season, which generates a high wet season flow (June to October), followed by a dry-season flow (November to May) amounting to about 25% of the total flow. Potential evaporation over the dry season in the region is the order of 1000 mm, about 75% of the annual potential evapotranspiration (Table 1; Lyon et al., 2017), while precipitation over the dry-season is 340 mm of which 36% or 125 mm occurs in the last two months of the dry season (Table 1), indicating that dry-season precipitation contributes little, if anything, to the dry-season water flow. Also, daily flow data into the Mekong shows no change with precipitation events in the watershed confirming precipitation in the dry season has negligible influence on dry-season water flows. This flow distribution implies that there is a significant and widespread aquifer storing water across the watershed during the wet season that drains and releases water in the dry season. The most likely candidate for this aquifer is the weathered rock of the deep regolith covering most of the uplands in the region (Anderson et al. 2002; Pelletier et al. 2016). While the soil and groundwater storage capacity in the LP-CS watershed is small compared with the groundwater in the Lower Mekong Basin as a whole that provides a critical resource of potable water and water for irrigation of rice and other food crops (Pokhrel et al., 2018), it provides a steady dry-season flow into the Mekong River (Figure 3). Indeed, Evaristo and McDonnell (2019) concluded that the amount of water stored in a landscape is one of the most important factors in predicting streamflow response to forest removal.

4.1 Reduction in water yield after clearing

The double-mass plot of flow against precipitation clearly showed that there was a *reduction,* not an increase, in the water flow or yield of the forested watershed that we conclude was the result of a logging event in 1985. Thus, Hypothesis 2 “that as observed in many watersheds, cutting of climax forest increases the water yield of the watershed” was not confirmed and raises the question of how logging induced a 50% reduction in water yield in the area actually cut, rather than an increase in yield as frequently observed and predicted (Landsberg and Gower, 1996). This result was unexpected as a review of 94 watershed experiments showed that a reduction of the cover (conifer, deciduous hardwood or shrub vegetation) by 15-90% increased the annual streamflow, while none decreased the streamflow (Bosch and Hewlett, 1982). Further, Evaristo and McDonnell (2019) showed that the water yield from deforestation varied markedly with the water yield increasing by 58±8.6% with only four or five of the 251 paired watershed showing a decrease in water yield. Mouche et al. (2014) who studied 5 small forested watersheds of Mekong River tributaries in Northern Laos around Luang Prabang between 1960 and 2004 could not decide, using two conceptual models, “whether land-use change impacted the hydrological regime of the watersheds or not.” They attribute this to the unreliability of the water yield and rainfall data, the method of use of the rainfall data in the models and because small changes on forest cover (less than 20-30%) may not be detectable (Andréassian, 2004; Mouche et al., 2014). However, Langford (1976), Kuczera (1987) and Cornish (1993) all showed decreases in water yield in the first decade after bushfires, or patch-cutting of 22% of a forested watershed (Lane and Mackay, 2001). The observed large reduction in water yield for the decade after 1985, therefore, was unusual and requires explanation.

The observed 42% reduction in water yield into the Mekong River occurred as a result of the felling of the native forest. It cannot be explained by a change in the calibration of the Luang Prabang flow gauging station as a similar result was obtained for the Vientiane-Chiang

Saen watershed flow data using the precipitation records from Chiang Rae just north-west of the LP-CS watershed. Further, we dismiss the possibility that changes to the monitoring of precipitation or river flows could result in an abrupt change in either the measured precipitation or flows because the reduction in flows began to increase again and 10-12 years later were only about 10% lower than those before the major change in 1985. In fact, the dry-season flow increased in about 5 years, but it took 10-15 years for the total flow to increase to that observed before the logging event. Similarly, the interception of water by the building and filling of a large reservoir for the use of water outside the watershed would reduce the flow and, while there may be some recovery after the reservoir fills to capacity, there is no evidence of such construction on the watershed at the time and the few hydropower dams built in the watershed were developed after the period of this study (Hecht et al., 2019). Finally, climate change has resulted in about a 0.5°C rise in temperatures since 1970, but with no change in precipitation, but both temperature and precipitation are predicted to increase with increased intensity of precipitation, flooding and droughts by the middle of the present century (Pokhrel et al., 2018). However, there is no evidence in the climate data that climate change was affecting the temperatures and precipitation in 1985 in a way that would cause a sudden and large reduction in water yield (Li et al., 2017; Pokhrel et al., 2018; Hecht et al., 2019). Therefore, we conclude that the sudden change in land use across the watershed in 1985 must have been the result of a significant logging event with on-site stockpiling and eventual transport of logs out of the LP-CS watershed possibly taking years after the felling operation.

The decrease in water yield suggests that the evapotranspiration of the understorey vegetation remaining after the overstorey trees were cut down was higher than when the overstorey vegetation was in place. This is possible as the evapotranspiration of climax vegetation can be lower than young vigorously-growing vegetation due to lower stomatal conductance and lower green leaf area (Waggoner and Turner, 1971; Murakami et al., 2000; Sun et al., 2016). The opening up of the forest canopy by thinning or logging will enable the understorey to maximise its rate of transpiration to its full potential.

Evaristo and McDonnell (2019) indicated that to understand the influence of deforestation on the water yield of forest watersheds requires consideration of the storage of water in the soil between the surface and unweathered bedrock. The reduction in flow after cutting, indicates that over the dry season while the cut forest was losing water, it was also accessing a water store that was over and above that accessed by the virgin forest. Though it is possible that the cut area of the forest was using more water from the unsaturated zone, the extra amount extracted, equal to about 320mm from the area actually cut, is higher than can be readily explained. To explain it, we propose that this additional water was obtained by the regenerating forest accessing shallow groundwater that exists in the regolith and provides the dry-season flow.

Considering that evapotranspiration is determined to a significant extent by the net radiation the question also arises "Could the net radiation of the cut forest have been greater because its albedo was less?" - might this explain its higher water use?" However, this is unlikely given that the drying of the foliage of the cut trees will increase the albedo of the cut forest as dry vegetation is more reflective. Moreover, paths cut in a jungle in one dry season are generally impenetrable the next, indicating that the regrowth vegetation would have quickly overtaken the disturbance caused by felling of the trees. Therefore, we discount changes in the albedo of the cut forest as a factor influencing the relative water use of the virgin and cut forest because of the speed at which disturbed forest and jungle understorey rebounds. Whether the albedo of the understorey differs significantly from the overstorey depends on the extent to which young trees dominate it. This is a matter for further investigation. Accordingly, based on the available information, we believe that we can assume, conservatively, that during the wet season, both surfaces (before and after the felling operation) equally used almost all the available radiant energy for evaporation and transpiration at a rate comparable to pan evaporation. This implies that the reduction in the flow into the Mekong after cutting must have been caused only by differences in evapotranspiration over the dry season (see Equation 1).

The limit on evapotranspiration over the dry season is generally the soil moisture deficit plus a portion of the of the dry-season precipitation. In the case of the soil moisture deficit for both the cut and uncut forest, we estimate that because sandy soils are not prevalent, it is towards the upper end of the range of 50-100 mm. Precipitation during the dry season is highly dispersed and small relative to the evaporative demand. We observed that in high resolution (daily) flow records, the dry-season flow is smooth with no significant spikes in flow due to rainfall. Thus, moisture from these dry-season precipitation events must be lost as interception and evaporation or, if not completely lost this way, percolate downwards through the canopy, relieving the soil moisture deficit slightly to be quickly lost as soil evaporation or a short-term increase in evapotranspiration. Therefore, we consider that before and after a portion of the forest was cut, all the dry-season precipitation was lost to evapotranspiration.

4.2 Area of watershed subjected to the land-use change (logging)

Based on the potential evaporation of the whole watershed, the change in water yield from cutting, relative to precipitation, the late dry-season flows and knowledge of the water-holding capacity of the soil, we calculated that in 1985, 70-80% of the watershed covered by virgin forest was cut. The lower value (70%) was calculated assuming that the soil water deficit in the upper 0.5 m of soil was 50 mm, while the upper value (80%) was calculated assuming that the water-holding capacity of the upper 0.5 m of soil was 100 mm. Thus, we conclude that Hypothesis 3 that “the area of cut forest can be estimated from the changes in water yield and an understanding of the local hydrology” was confirmed.

Finally, the results of this analysis are broadly consistent with the general belief of communities in South-East Asia that harvesting timber from forested watersheds and clearing forests causes wells, springs and streams to cease flowing, but reforesting bare hillsides will cause water to reappear in wells, springs and streams, as outlined by Gilmour (2014). To this extent the uncut forest acts as a “sponge” and logging the forest will reduce the water yield overall. We consider that the reason for the reduction in water yield after logging is that harvesting mature trees from forested watersheds, using conventional truck/cable-based logging systems, minimizes damage to the understory vegetation and increases the dry-season transpiration rate due to an increased exposure of the understory to light and the net radiation.

5. Conclusions

- In the context of Mekong flow and precipitation patterns, flows spanning a decade were measured with about 3% accuracy. Thus, the double-mass plots of flow against precipitation of a watershed are a moderately sensitive method of detecting changes in the land response of watersheds.
- The changes in the water budget of a forested watershed can be used to estimate the area of the watershed affected by a land-use change such as that caused by logging.
- Of the 7.9 million ha reportedly logged between the late 1960’s and 2002 throughout Laos, we calculate that more than 6.3 million ha was felled in northern Laos in a single operation over one dry season in 1985. Stockpiling and transport of the logs

off site should have no observable effect on water yield and may have been conducted over an extended period of time after logging.

- As re-growth forest can lose water during the dry season at close to the potential rate providing groundwater is available, we conclude that the inferred 50% reduction in the water yield of the cut area of the LP-CS watershed for up to 12 years resulted from the felling of the virgin forest in Laos. However, whether logging results in an increase or decrease in water yield will be dependent on the subsequent land use. If the understory vegetation containing regrowth forest is left to grow, as in the present study, then it likely to result in at least an initial decrease in water yield, but clearing of the regrowth forest is likely to increase the water yield as observed in other studies.
- Mature trees in the tropics, older than 15 years, with superficial groundwater resources available, are conservative users of water compared with the understory and appear to protect the water resource from a potentially higher water use by the understory and regrowth forest.

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Conflict of Interest.

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement.

Daily flow records of the Mekong River at the monitoring stations of Chiang Saen and Luang Prabang, and daily evaporation (1989-2000) are available from the Mekong River Commission data portal (https://portal.mrcmekong.org/home). Daily precipitation records from Chiang Rae and Luang Prabang are available from the US "Climate Data Online" repository of the US National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/search).

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Data curation: Edward B Wronski
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References

Allen, R. G., Pereira, L. S., Reas, D., & Smith, M. (1998). *Crop Evapotranspiration*. FAO Irrigation and Drainage Paper No. 56, FAO, Rome. 290 pp.

Anderson, S.P, Dietrich, W.E., & Brimhall, G.H., (2002). Weathering profiles, mass-balance analysis, and rates of solute loss: Linkages between weathering and erosion in a small, steep catchment. *Geolological Society of America,* 114(9), 1143-1158.

Andréassian, V. (2004). Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology,* 291, 1–27. https://doi.org/10.1016/j.jhydrol.2003.12.015.

Basnayake, J., Inthavong, T., Kam, S.P., Fukai, S., Schiller, J.M., & Chanphengxay, M. (2006). Climatic diversity within the rice environments in Laos. In: J.M Schiller, (Ed.). *Rice in Laos* (Chapter 4, pp. 47-65). International Rice Research Institute, Los Baños.

Betts, A. K., and Ball, J.H. 1997. Albedo over the boreal forest, *Journal of Geophysical Research,* 102(D24), 28901–28909. https://doi.org/10.1029/96JD03876.

Bosch, J.M., & Hewlett, J.D. (1982). A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55, 3-23. https://doi.org/10.1016/0022-1694(82)90117-2.

Buckley, T.N., Turnbull, T.L., Pfautsch, S., Gharun, M, & Adams, M.A., 2012. Differences in water use between mature and post-fire regrowth stands of subalpine *Eucalyptus delegatensis*. *Forest Ecology and Management*, 270, 1–10. https://doi.org/10.1016/j.foreco.2012.01.008.

Cornish, P.M. (1993). The effects of logging and forest regeneration on water yield in a moist eucalypt forest in New South Wales, Australia. *Journal of Hydrology*, 150, 301- 322. https://doi.org/10.1016/0022-1694(93)90114-O.

Evaristo, J., & McDonnell, J.J, (2019). Global analysis of streamflow response to forest management. *Nature,* 570, 455-458. https://doi.org/10.1038/s41586-019-1306-0

Gilmour, D. (2014). Forests and water: A synthesis of the contemporary science and its relevance for community forestry in the Asia–Pacific region. RECOFTC Issue Paper No.3. RECOFTC - The Center for People and Forests, Bangkok, Thailand.

Hamilton, L.S. (1985). Overcoming myths about soil and water impacts of tropical forest land uses. In: S.A. El-Swaify, & L.A. Moldenhauer (Eds). *Soil Erosion and Conservation* (pp. 680-690).Soil Conservation Society of America, Ankeny, IA.

Hayes J. L., Riebe, C.S., Holbrook, W.S., Flinchum, B.A., & Hartsough, P. C. (2019). Porosity production in weathered rock: Where volumetric strain dominates over chemical mass loss. *Science Advances*. 5(9), eaao0834. https://doi.org/10.1126/sciadv.eaao0834

Hecht, J.S., Lacombe, G., Arias, M.E., Dang, T.D., & Piman, T. (2019). Hydropower dams of the Mekong River basin: A review of their hydrological impacts. *Journal of Hydrology*, 568, 285-300. https://doi.org/10.1016/j.jhydrol.2018.10.045

Johnston, R., & Kummu, M. (2012). Water resources models in the Mekong basin: A review. *Water Resources Management*, 26, 429-455. https://doi.org/10.1007/s11269-011-9925-8

Kramer, P.J. (1983). *Water Relations of Plants*. Academic Press. New York.

Kuczera, G. (1987). Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *Journal of Hydrology*, 94, 215–236. https://doi.org/10.1016/0022-1694(87)90054-0

Kumagai T., Saitoh, T.M., Sato, Y., Takahashi, H., Manfroi, O.J., Morooka, T., et al. (2005). Annual water balance and seasonality of evapotranspiration in a Bornean tropical rainforest. *Agricultural and Forest Meteorology*, 128, 81–92. https://doi.org/10.1016/j.agrformet.2004.08.006

Langford, K.J. (1976). Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. *Journal of Hydrology*, 29, 87-114. https://doi.org/10.1016/0022-1694(76)90007-X

Landsberg, J., Gower, S. (1996). *Applications of Physiological Ecology to Forest Management*. Academic Press, New York and London.

Lane, P.N.J., & Mackay, S.M. (2001). Streamflow response of mixed-species eucalypt forests to patch cutting and thinning treatments. *Forest Ecology and Management*, 143, 131-142. https://doi.org/10.1016/s0378-1127(00)00512-0

Li, D., Long, D., Zhao, J., Lu, H., & Hong, Y. (2017). Observed changes in flow regimes in the Mekong River basin. *Journal of Hydrology*, 551, 217-232. https://doi.org/10.1016/j.jhydrol.2017.05.061

Lyon, S.W., King, K., Polpanich, O., & Lacombe, G. (2017). Assessing hydrologic changes across the Lower Mekong Basin. *Journal of Hydrology, Regional Studies*. 12, 303-314. http://dx.doi.org/10.1016/j.ejrh.2017.06.007

Mekong River Commission. (2005). *Overview of the Hydrology of the Mekong Basin*. Mekong River Commission, Vientiane, Laos. 73pp.

Monteith, J.L. (1965). Evaporation and environment. *Symposium of the Society of Experimental Biology*, 19, 205-234.

Mouche, E., Moussu, F., Mügler, C., Ribolzi, O., Valentin, C., Sengtahevanghoung, O., et al. (2014). Impact of land-use change on the hydrology of North Lao PDR watersheds. In: *Hydrology in a Changing World: Environmental and Human Dimensions*. International Association of Hydrological Sciences Publication 363, 84-89.

Morris, D.A., & Johnson, A.I. (1967). *Summary of Hydrologic and Physical Properties of Rock and Soil Materials as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey*, U.S. Geological Survey Water-Supply Paper 1839-D, 42pp.

Morton, F.I. (1984). What are the limits on forest evaporation? Journal of Hydrology, 74, 373-398. https://doi.org/10.1016/0022-1694(84)90025-8

Murakami, S., Tsuboyama, Y., Shimizu, T., Fujieda, M., & Noguchi, S. (2000). Variation of evapotranspiration with stand age and climate in a small Japanese forested catchment. *Journal of Hydrology*, 227, 114–127. https://doi.org/10.1016/S0022-1694(99)00175-4

Pelletier, J.D., Broxton, P.D., Hazenberg, P., Zeng, X., Troch, P.A., Niu, G., et al. (2016). *Global 1-km Gridded Thickness of Soil, Regolith, and Sedimentary Deposit Layers*. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1304

Penman, H.L. (1954). *Evaporation over Parts of Europe*. *Proceedings of the General Assembly of Rome*, 3, 168-176.

Pokhrel, Y., Burbano, M., Roush, J., Kang, H., Sridhar, V., & Hyndman, D.W. (2018). A review of the integrated effects of changing climate, land use, and dams on Mekong River hydrology. *Water* 10, 266. https://doi.org/10.3390/w10030266

Scott, D. F., Bruijnzeel, A., & Vrije, L. (2005). Forests, water and people in the humid tropics, In: (Eds), M. Bonell, & L.A. Bruijnzeel, *The Hydrological and Soil Impacts of Forestation in the Tropics*. UNESCO and Cambridge University Press, Cambridge, UK.

Searcy, J.K. & Hardison, C.H., (1960). *Double-Mass Curves*. U.S. Geological Survey Water-Supply Paper. 1541-B.

Sun, G., Domec, J-C., & Amatya, D.M. (2016). Forest evapotranspiration: measurement and modelling at multiple scales. In: (Eds). D.M. Amatya, T.M. Williams, L. Bren, & C. de Jong. *Forest Hydrology: Processes, Management and Assessment* (pp.32-50). CABI, Wallingford, U.K..

Spruce, J., Bolton, J., Mohammed, I.N., Srinivasan, R., & Lakshmi, V. (2020). Mapping land use cover change in the Lower Mekong Basin from 1997 to 2010. *Frontiers of Environmental Science*. 8, 18pp. https://doi.org/10.3389/fenvs.2020.00021

Thomas, I.L. (2015). *USAID Lowering Emissions in Asia's Forests (USAID LEAF): Drivers of Forest Change in the Greater Mekong Subregion – Lao PDR Country Report*. 33pp. https://data.opendevelopmentmekong.net/dataset/a7319336-89bb-4511-9c81-e5441c61f877/resource/8fe5a029-4b36-47e9-a0cc-6bef0e0f0bb2/download/lao-pdr-final-revised-nov2015.pdf

Varis, O., Kummu, M., & Salmivaara, A.(2012). Ten major rivers in monsoon Asia Pacific: An assessment of vulnerability. *Applied Geography*, 32, 441-454. https://doi.org/10.1016/j.apgeog.2011.05.003

Vertessy, R., Watson, F., O'Sullivan, S., Davis, S., Campbell, R., Benyon, R., et al. (1998). *Predicting Water Yield from Mountain Ash Forest Catchments*. Cooperative Research Centre for Catchment Hydrology, Australia, Industry Report 98/4.

Waggoner, P.E. & Turner, N.C. (1971). Transpiration and its control by stomata in a pine forest. Connecticut Agricultural Experiment Station Bulletin No. 726. 87pp.

Waggoner, P.E., Begg, J.E. & Turner, N.C. (1969). Evaporation of dew. Agricultural and Forest Meteorolology, 6, 227-230. https://doi.org/10.1016/0002-1571(69)90007-7

Zhang, L., Dawes, W.R., & Walker G.R. (1999). Predicting the effect of vegetation changes on catchment average water balance. Cooperative Research Centre for Catchment Hydrology, Technical Report 99/12, 35pp.

TABLE LEGEND

Table 1. Long-term (1961-2000) monthly pan evaporation (*E*pan) and precipitation (*P*) for Luang Prabang and the average monthly flow recorded at Luang Prabang less that upstream at Chiang Saen for ten years from 1976 to 1985 (F_1) and from 1986 to 1995 (F_2).

FIGURE LEGENDS

Figure 1. Map of the Lao Peoples Democratic Republic (light yellow) showing the location of the Luang Prabang–Chiang Saen (LP-CS) watershed (green) in Laos and Thailand with the hydrological monitoring stations at Chiang Saen and Luang Prabang on the Mekong River (thick blue line) along with the capital city of Laos, Vientiane, and the major cities of Chiang Rai and Udon Thani in Thailand. The precipitation (rainfall) isohyets for the country were obtained from Figure 6 of Basanayake et al. (2006).

Figure 2. Double-mass plot of cumulative flow (*F*) recorded at Luang Prabang, less that upstream at Chiang Saen, on cumulative precipitation (*P*) recorded at Luang Prabang. The data for 1961-1975 are the square red symbols, data for 1976-1985 are the green triangles and data for 1986-2000 are the blue circles. The straight line is the fitted linear regression ($F = 0.44P - 1152$) to the data between 1976 and 1985 (green triangles). Note the significant deviation from the fitted linear regression beginning in 1986.

Figure 3. Hydrographs for the Luang Prabang–Chiang Saen (LP-CS) watershed for the ten year periods 1976-1985 (green line) and 1986-1995 (blue line) showing the difference in

water yield (black line) relative to 50% of the average monthly precipitation at Luang Prabang (red line).

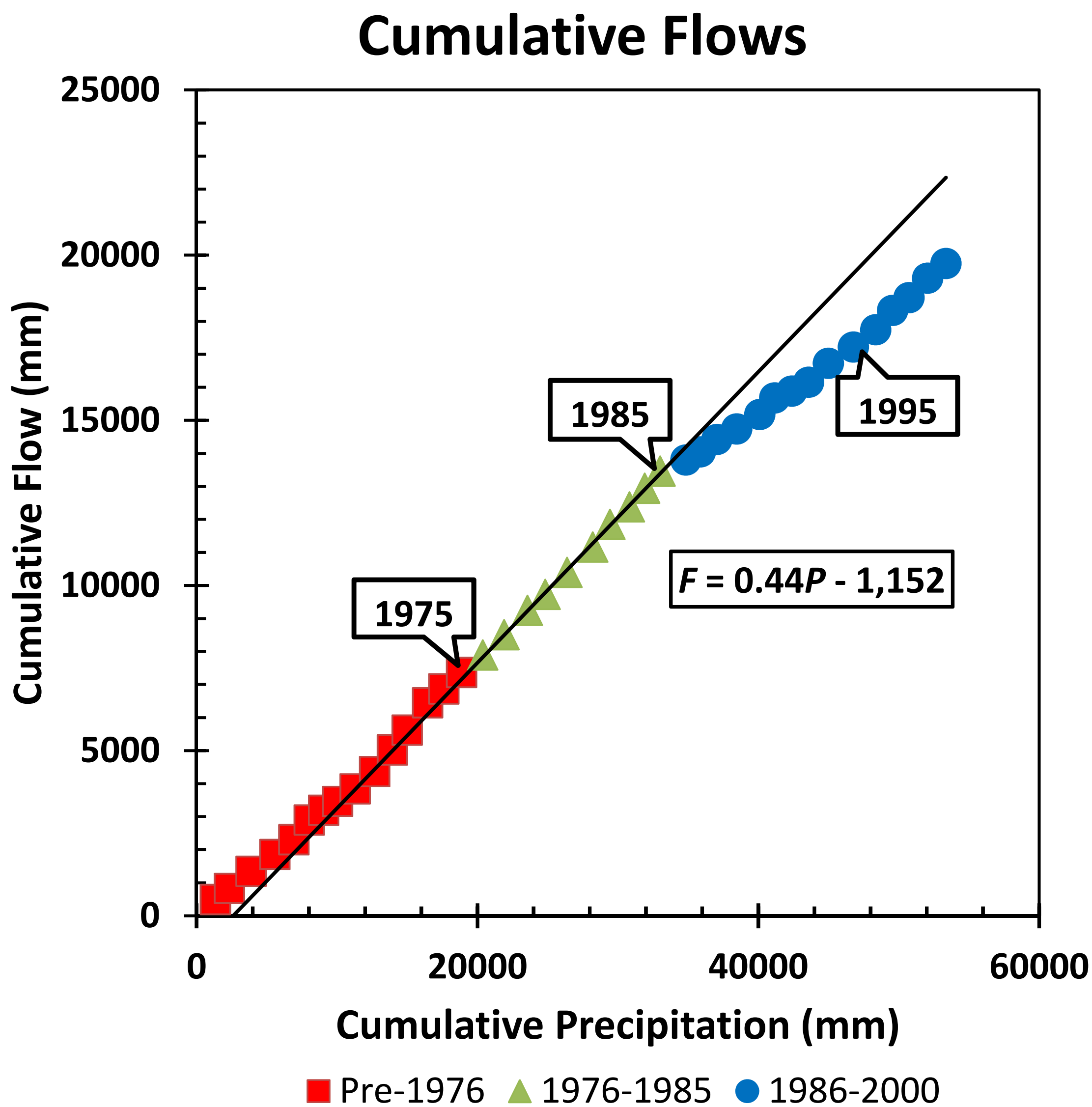
Figure 4. Double-mass plot of cumulative late dry-season flow (March-April) (F) from the Luang Prabang–Chiang Saen (LP-CS) watershed on cumulative precipitation (P) recorded at Luang Prabang for the period from 1975-1996. The data for 1975-1985 are the red diamonds, data for 1986-1990 are the green circles and data for 1991-1996 are the blue triangles. The fitted linear regression to the data from 1975 to 1986 ($F = 0.014P - 21.5$) is similar the fitted linear regression to the data from 1991-1995 ($F = 0.010P - 51.0$), but very different from the fitted linear regression for the data from 1986-1990 ($F = 0.004P + 146$).

Figure 5. Scaled up and normalised double-mass plot of cumulative wet-season (June-October) flow and late dry-season (April) flow (F) from the Luang Prabang–Chiang Saen (LP-CS) watershed on cumulative precipitation (P) recorded at Luang Prabang for the period from 1980-1990. The data for wet-season (June to October) flow are the green symbols and the April flow data are the red symbols (squares 1981 -1985 and triangles 1986 - 1991). The lines are the fitted linear regressions.

Table 1. Long-term (1961-2000) monthly pan evaporation (*E*pan) and precipitation (*P*) for Luang Prabang, and the average monthly flow recorded at Luang Prabang less that upstream at Chiang Saen for ten years from 1976 to 1985 (F_1) and from 1986 to 1995 (F_2).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Season	Dry Season					Wet Season					Dry Season		
*E*pan (mm)	104	119	161	168	162	140	135	132	127	119	100	95	1562
P (mm)	14	19	33	91	143	173	219	261	163	107	28	13	1263
F_1 (mm)	22.6	12.1	8.0	6.6	11.0	27.9	69.0	139	133	90.5	54.2	33.0	607
F_2 (mm)	13.3	6.5	3.3	0.6	6.0	20.5	44.5	87.8	70.2	52.0	30.2	15.9	351

Figure 1. Map of the Lao Peoples Democratic Republic (light yellow) showing the location of the Luang Prabang–Chiang Saen (LP-CS) watershed (green) in Laos and Thailand with the hydrological monitoring stations at Chiang Saen and Luang Prabang on the Mekong River (thick blue line) along with the capital city of Laos, Vientiane, and the major cities of Chiang Rai and Udon Thani in Thailand. The precipitation (rainfall) isohyets for the country were obtained from Figure 6 of Basanayake et al. (2006).



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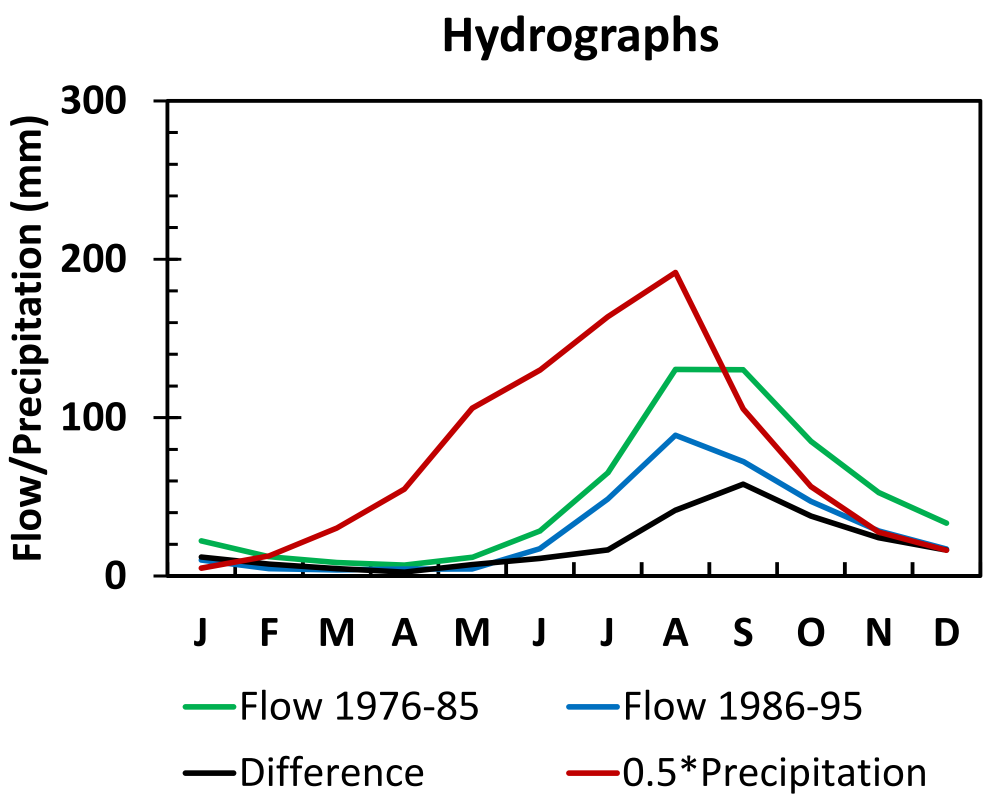

Figure 3. Hydrographs for the Luang Prabang–Chiang Saen (LP-CS) watershed for the ten year periods 1976-1985 (green line) and 1986-1995 (blue line) showing the difference in water yield (black line) relative to 50% of the average monthly precipitation at Luang Prabang (red line).

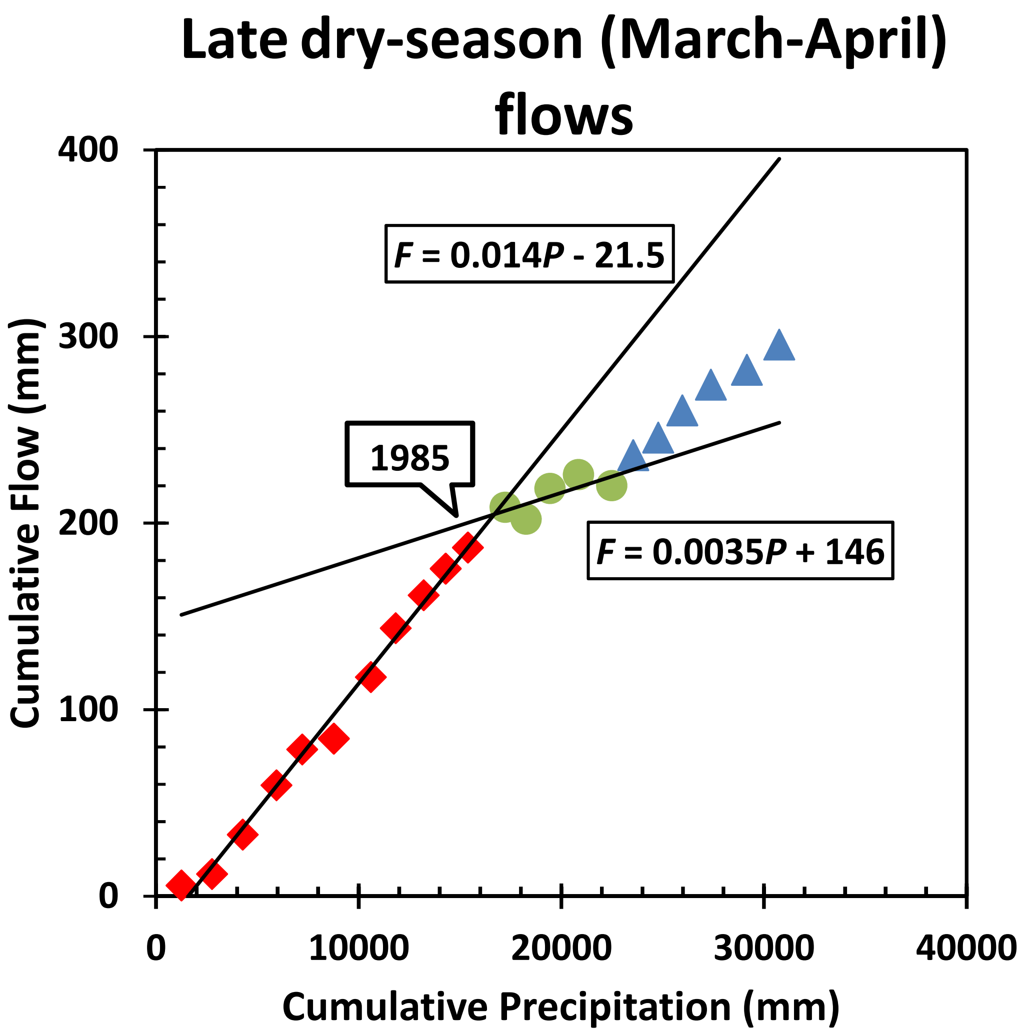

Figure 4. Double-mass plot of cumulative late dry-season (March-April) flow (*F*) from the Luang Prabang–Chiang Saen (LP-CS) watershed on cumulative precipitation (*P*) recorded at Luang Prabang for the period from 1975-1995. The data for 1975-1985 are the red diamonds, the data for 1986-1990 are the green circles and the data for 1991-1996 are the blue triangles. The fitted linear regression to the data from 1975 to 1985 ($F = 0.014P - 21.5$) is similar the fitted linear regression to the data from 1991-1996 ($F = 0.010P - 51.0$), but very different from the fitted linear regression for the data from 1986-1990 ($F = 0.004P + 146$).

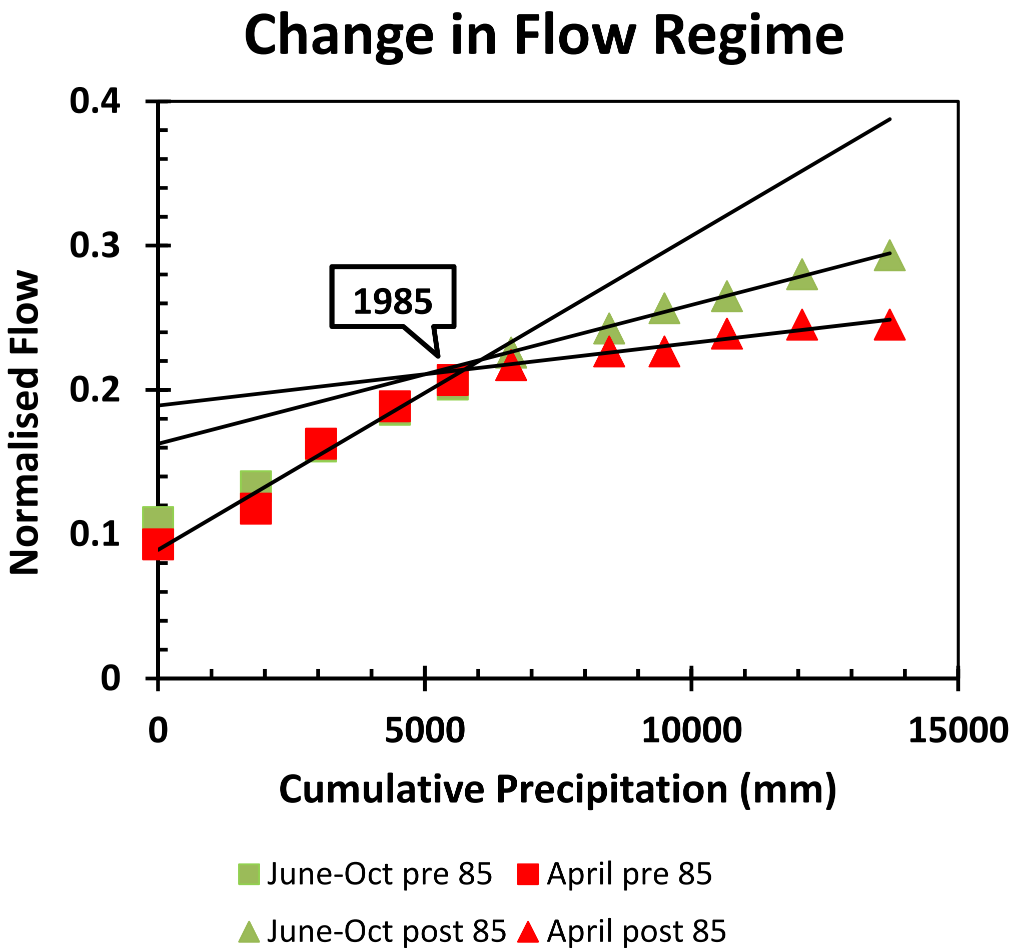

Figure 5. Scaled up and normalised double-mass plots of cumulative wet-season (June-October) flow and late dry-season (April) flow (*F*) from the Luang Prabang–Chiang Saen (LP-CS) watershed on cumulative precipitation (*P*) recorded at Luang Prabang for the period from 1980-1990. The data for wet-season (June to October) flow are the green symbols and the April flow data are the red symbols (squares 1981 -1985 and triangles 1986 - 1991). The lines are the fitted linear regressions.