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Full title: Impact of armed conflict on broad-scale hydrology in the Mekong Basin - Investigations in data-scarce conditions

Short title: Impact of armed conflict on broad-scale hydrology in the Mekong Basin

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Abstract

The Vietnam War played a decisive role in the pre-1990s deforestation of the lower Mekong Basin, which in turn, likely influenced regional broad-scale hydrology. This note presents and discusses new analyses that strengthen this thesis. While concurrent overestimation of discharge and underestimation of rainfall, a couple of years after bombing climaxed in the early 1970s, could theoretically explain the sharp rise in water yield previously attributed to bomb-induced deforestation, new observations suggest that bombing has durably modified the landscape: by 2002, degraded forests still largely overlapped with areas heavily bombed 30 years earlier. This corroborates observed long-term hydrological changes and suggests that warfare-induced deforestation has more profound and durable hydrological effects than previously thought.

Keywords: hydrological change; deforestation; data scarcity; causal link; Vietnam War; Mekong

1- Introduction

It is known that, in small catchments, deforestation decreases evapotranspiration, hence increases annual basin water yield (Brown et al., 2005). The paucity of significant results at larger scale stems from factors like land cover heterogeneity, climate variability, or counteracting changes in vegetation covers (Bruijnzeel, 2004). Hydrological impacts of deforestation have rarely been detected in basins exceeding 10,000 km², e.g. Mahé et al. (2005); Descroix et al. (2009). In a 50,300 km² catchment of the Mekong Basin, runoff sharply rose after Vietnam War bombing climaxed in the early 1970s. Flows remained at higher than pre-war levels until the early 2000s. Lacombe et al. (2010) attributed these changes to bomb-induced deforestation followed by the regrowth of shallow-rooted sparse vegetation on degraded soil. While data scarcity prevented firm confirmation of this hypothesis, we present new analyses strengthening causalities.

2- Water level-discharge rating curves

Runoff in the area studied by Lacombe et al. (2010) was estimated by subtracting upstream discharge at Mukdahan (Mekong River) and Ubon Ratchathani (Mun River) from the Mekong discharge at Pakse (Fig. 1). At each gauging station, continuously recorded daily water levels (1960-2003) were converted to discharge using rating curves updated annually. Since discharge records at Pakse are incomplete, water-level-specific discharges available for this station were averaged to generate the rating curves missing for the 1974-75 period, during which runoff peaked, following bombing climax. To verify whether this approach could overestimate discharge, we designed dummy rating curves producing annual runoff

equivalent to that simulated by the GR2M model in 1974 and 1975, assuming pre-war catchment conditions (Lacombe et al., 2010). An order-2 polynomial accurately represents the water level - discharge relationship ($R^2=1.00$ for all measured rating curves). While the 1974 dummy rating curve falls about 2 standard deviations below the averaged rating curve, half of the error bars of both curves overlap and mean discharge values of this hypothetical rating curve are slightly higher than the lowest discharge on record (Fig. 2). Therefore, when using the averaged rating curve, we cannot dismiss the possibility that an unrecorded change in the Mekong River cross section in 1974 could have led to an artificial runoff peak. In contrast, the 1975 dummy rating curve falls about 5.4 standard deviations below the averaged curve, without overlap of error bars between curves, and includes discharge values far lower than the lowest values on record (Fig. 2). Since the 1975 dummy rating curve yields unrealistically low discharge, the runoff peak observed in 1975 is arguably not an artefact although its exact value cannot be ascertained. However, the sharp runoff peak recorded the same year in the Mukdahan-Kong Chiam sub catchment (Fig. 2 in Lacombe et al., 2010), an area more than 1.5 times more intensively bombed than the overall study area, concurs to confirm the causal link between hydrological change and a war-induced ecocide of unprecedented scale (Pralle, 1969; Seig, 1970) in this 50,300 km² catchment.

3- Rainfall spatial variability

Because of data scarcity, Lacombe et al. (2010) used a 3-station average (Mukdahan, Ubon Ratchathani and Pakse, cf. Fig. 1) to investigate temporal changes in the rainfall-runoff relationship. It can be argued that extreme rainfall in the un-gauged eastern mountainous and heavily bombed side of the study area could have contributed to the extreme runoff peak of 1975. To investigate this, we split the study area into a western part, covering about 60% of the catchment's overall surface area and including 8 rain gauges operated since 1966 (Fig. 1), and the remaining eastern part, where 3 rain gauges started being operated in 1985. Using the uninterrupted rainfall records of the western part and a range of mean annual runoff coefficients, we estimated annual rainfall depths in the eastern part yielding the 1975 runoff peak observed by Lacombe et al. (2010). The same procedure was performed using a rating curve at Pakse yielding 5% lower Mekong River discharge, similar to the 1974 hypothetical rating curve presented in section 2, and inducing a 20% reduction of runoff over the study area (Fig. 3a). The Gumbel distribution model adjusted to observations from the 3 rain gauges in the eastern part between 1985 and 2003 was used to estimate the return period of the annual rainfall depths (Fig. 3b). This analysis shows that, over the eastern part, rainfall depths corresponding to reasonable return periods (i.e. < 200 years) imply dubious runoff coefficients of 70%. Further, assuming pre-war mean runoff coefficients of 45%, rainfall alone could not explain the 1975 runoff peak unless we consider that it was caused by unrecorded event(s) with a >1,000 year return period. In contrast, rainfall depths corresponding to the rating curve yielding reduced discharge at Pakse have return periods of 6 to 160 years and imply runoff coefficients of 50-60%, reconcilable with runoff observed during wet, pre-war years in the study area (e.g. years 1961 and 1962; Fig. 2, Lacombe et al., 2010).

4- Land cover

Lacombe et al. (2010) assumed a relationship between tonnages of explosive ordnance and deforested area, based on published bomb damage assessment (BDA) (Seig, 1970). Yet, without ground truth assessment, it is debatable to what extent BDA can be used to infer changes in catchment hydrology. SPOT satellite images from 2001 and 2002 (scales 1:50,000 and 1:100,000) combined with field verifications were used by the Ministry of Agriculture and Forestry of Laos (MAF, 2005) to produce a countrywide land-cover map. We merged the

15 land-cover types of this map into 3 categories, namely: “Forest” (evergreen and deciduous forest, dipterocarp and coniferous); “Degraded forest” (sparsely forested areas with very low crown density, bamboo, savannah, scrub and barren land often exhibiting a high density of bomb craters in the study area); and “Agricultural land” (rice paddy, agricultural plantations and other agricultural lands). Overlaying the distribution of locations that received > 3 tons.km⁻² of explosive ordnance to this map reveals that, by 2002, the most heavily bombed areas of the studied catchment were classified as degraded forest (82%), agricultural land (12%) and forest (6%) and 70% of degraded forest corresponds to heavily bombed areas (Fig. 1). Pre-bombing land-cover maps confirm that the catchment was covered by rain forest before the war (Seig, 1970), consistent with the fact that one of the main objectives of the bombing missions was to clear the forest to unmask enemies.

5- Conclusions

An overestimation of discharge combined to an underestimation of rainfall, although unlikely, could theoretically explain the 1975 water yield peak attributed by Lacombe et al. (2010) to bomb-induced forest removal. But, the temporal co-occurrence of runoff peak in the most intensively bombed Mukdahan-Kong Chiam sub catchment together with the spatial co-occurrence of heavily bombed areas and degraded forest strengthen the hypothesis of a causal link between bombing, long-term soil and forest degradation and altered hydrology.

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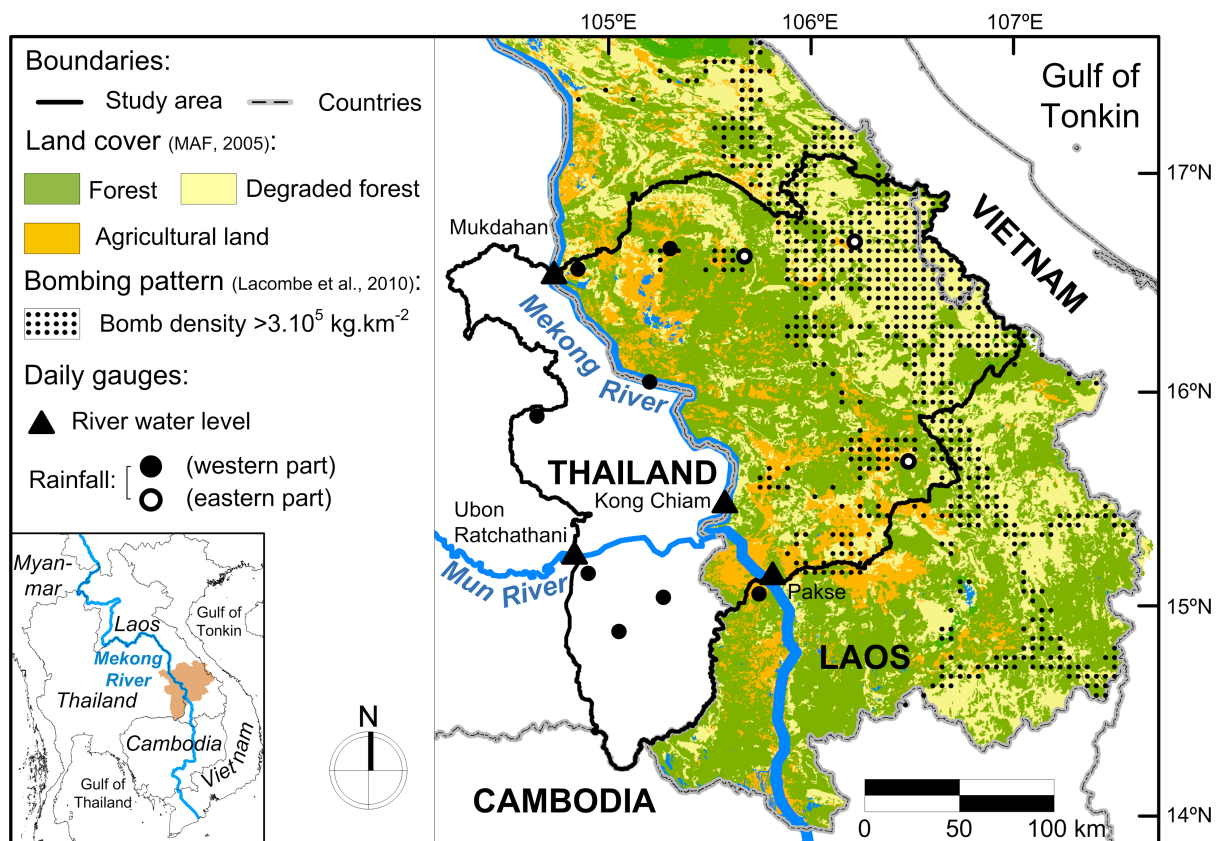


Figure 1 Hydro-meteorological stations, land-cover and heavily bombed area in the studied catchment

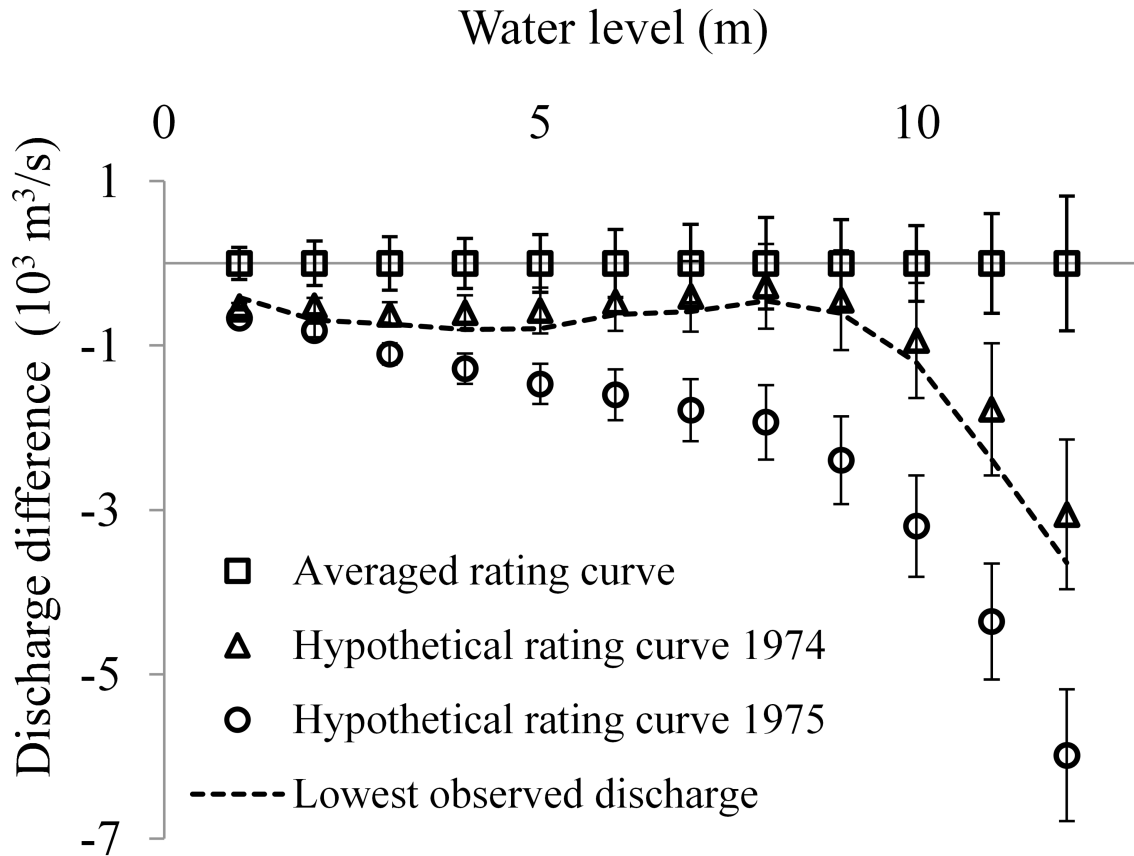


Figure 2 Centered discharge variables (corresponding to 4 curves named in the legend), using averaged discharge values. Error bars on averaged rating curve: inter-annual standard deviation of measured discharges. Error bars on dummy rating curves reflect standard error between observed and simulated runoff over model adjustment period (Lacombe et al. 2010)

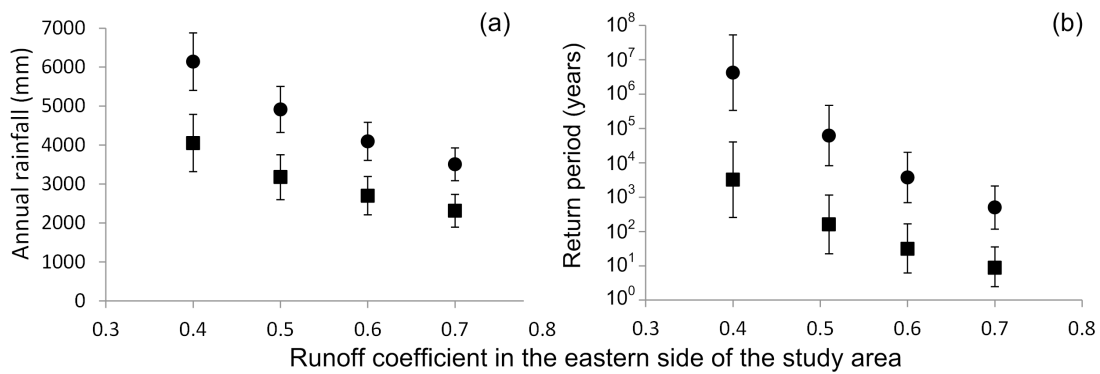


Figure 3 Expected rainfall in eastern side of study area (a) and associated return period (b) yielding the 1975 study area runoff depth estimated by Lacombe et al. (2010) using the averaged rating curve (circles) and 5% lower Mekong River discharge values (squares) at Pakse. Error bars reflect inter-annual variations of runoff coefficients measured in the study area (1960-2003), varying between 40% and 60% and used to compute runoff in the western side of the study area