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Suspended sediment source and propagation during monsoon events across nested sub-catchments with contrasted land uses in Laos

Sylvain Huon[a,*], Olivier Evrard[b], Elian Gourdin[b], Irène Lefèvre[b], Thierry Bariac[c], Jean-Louis Reyss[b], Thierry Henry des Tureaux[d], Oloth Sengtaheuanghoung[e], Sophie Ayrault[b], Olivier Ribolzi[f]

[a] Sorbonne Université UPMC Univ Paris 06, Institut d'Ecologie et des Sciences de l'Environnement de Paris (IEES Paris), Case 120, 4 Place Jussieu, 75252 Paris, Cedex 05, France
[b] Laboratoire des Sciences du Climat et de l'Environnement (LSCE), UMR 8212 (CEA-CNRS-UVSQ), Université Paris-Saclay, Domaine du CNRS, Avenue de la Terrasse, 91198 Gif-sur-Yvette Cedex, France
[c] Sorbonne Université UPMC Univ Paris 06, Institut d'Ecologie et des Sciences de l'Environnement de Paris (IEES Paris), CNRS, Campus INRA, AgroParisTech, Bâtiment EGER, 78550 Thiverval-Grignon, France
[d] IRD, National Agriculture and Forestry Research Institute (NAFRI), P.O. Box 4199, Ban Nogviengkham, Xaythany District, Vientiane, Lao Democratic People's Republic
[e] Department of Agricultural Land Management (DALaM), P.O. Box 4199, Ban Nogviengkham, Xaythany District, Vientiane, Lao Democratic People's Republic
[f] Géosciences Environnement Toulouse (GET), UMR 5563 (CNRS-UPS-IRD), 14 Avenue Edouard Belin, 31400 Toulouse, France

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ABSTRACT

Study region: Houay Xon catchment in northern Laos.
Study focus: Because agricultural headwater catchments of SE Asia are prone to erosion and deliver a significant proportion of the total suspended sediment supply to major rivers and floodplains, the potential sources of sediments and their dynamics were studied for two successive storm flow events in June 2013. Characterization of suspended sediment loads was carried out along a continuum of 7 monitoring stations, combining analyses of fallout radionuclides, particle borne organic matter and stream water properties.
New hydrological insights: Radionuclide activities showed that remobilization of soil particles deposited during the previous rainy season or supplied by riverbank erosion is the dominant process, although pulses of surface-soil derived sediments also propagate downstream. This interpretation is supported by suspended organic matter data that also fingerprints the mixing of surface soil *vs.* subsurface particles. The study moreover highlights the advantages and the drawbacks of combining fallout radionuclides, particle borne organic matter composition and stream water characteristics to discriminate and quantify sediment sources and dynamics in rural areas undergoing urban sprawl.

* Corresponding author at: Sorbonne Université UPMC Univ Paris 06, Institut d'Ecologie et des Sciences de l'Environnement de Paris (IEES Paris), Case 120, 4 Place Jussieu, Paris, Cedex 05, 75252, France.
E-mail address: sylvain.huon@upmc.fr (S. Huon).

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1. Introduction

Intense monsoon rainfalls may trigger severe erosion on cultivated or afforested hillslopes in small tropical mountainous catchments of SE Asia (Sidle et al., 2006; Valentin et al., 2008). Headwater catchments are characterized by high specific water discharges and sediment loads (Milliman and Syvitski, 1992) and may be considered as important sources of sediments to the floodplains of large rivers draining the region, such as the Mekong River (Lacombe et al., 2016). Furthermore, Southeast Asian rivers were also identified as major contributors of terrestrial organic matter supply to the ocean (Ludwig et al., 1996; Huang et al., 2012) and play a significant role in the global carbon cycle (Lal, 2003).

Fallout radionuclides can be used to understand the dynamics of suspended matter and sediment deposits in riverine environments (e.g., Matisoff et al., 2005; Olley et al., 2012, 2013). Beryllium-7 (^{7}Be; produced in the upper atmosphere) and unsupported lead-210 ($^{210}Pb_{xs}$; produced by the decay of radon-222 emitted by continental surfaces) are both mainly supplied to the soil surface by wet deposition (e.g., Caillet et al., 2001; Ioannidou and Papastefanou, 2006; Conaway et al., 2013). They are characterized by contrasted half-lives, 53.2 days and 22.3 years for ^{7}Be and ^{210}Pb, respectively, and by high solid – dissolved distribution coefficients (Olsen et al., 1985; Taylor et al., 2012). As they both bind strongly and rapidly to particles, they may be used to trace, during flood events, the source of fine suspended sediments from soils to deposition areas (Dominik et al., 1987; Bonniwell et al., 1999; Matisoff et al., 2002; Evrard et al., 2010; Saari et al., 2010). Furthermore, in tropical catchments where the summer monsoon is followed by a long dry period, the complete decay of ^{7}Be deposits occurs every year after the rainy season. It can then be assumed that most of the particles tagged with ^{7}Be at the onset of the monsoon are supplied to the rivers during the first storms of the rainy season. Discrimination between particles originating from surface soil and subsurface sources (gullies and riverbanks) can be achieved by comparing their activities in fallout cesium-137 (^{137}Cs) that was delivered by atmospheric nuclear bomb tests in the 1960s (Ritchie and McHenry, 1990). Measurable activities of ^{137}Cs (half-life of 30.2 years) are still found in surface soils whereas soil particles originating from gullies or riverbank collapses, sheltered from fallout radionuclides, are depleted in this radioisotope (Olley et al., 1993; Evrard et al., 2013; Hancock et al., 2014). In addition the composition of total organic matter (Kao and Liu, 2000; Masiello and Druffel, 2001; Bellanger et al., 2004; Huon et al., 2006; Hilton et al., 2010; Smith et al., 2013; Laceby et al., 2014) can also be used to trace changes in sources and pathways of particle borne organic matter across catchments (Ritchie and McCarty, 2003; Ellis et al., 2012; Schindler Wildhaber et al., 2012; Ben Slimane et al., 2013; Koiter et al., 2013; Laceby et al., 2016). To relate water flow to sediment transport, water characteristics such as its electric conductivity and ^{18}O content (δ^{18}O) can also provide useful information on the contribution of overland flow and groundwater to river discharge (Nakamura, 1971; Pilgrim et al., 1979; Sklash and Farvolden, 1979; Ribolzi et al., 1996; Collins and Neal, 1998; Klaus and McDonnell, 2013).

Relevant information on soil sources of sediments in upstream catchments can be inferred from the study of suspended and dissolved load characteristics (Gourdin et al., 2014a, 2014b; Gourdin et al., 2015; Evrard et al., 2016). However, the nature of particulate matter may change further downstream, in particular, when land use involves areas affected by urban sprawl. Moreover linking soil sources to sediment delivery is not straightforward as deposition and remobilization processes take place, in particular, in lower parts of hillslopes (Chaplot and Poesen, 2012) and in ephemeral riverine depositional areas. The main objective of this study was to determine the contribution of cultivated soil surface and in-channel (subsurface) sources of particles in suspended sediment loads using a multi-tracer approach that combines fallout radionuclide activity measurements (^{137}Cs, $^{210}Pb_{xs}$ and ^{7}Be), total organic matter analyses (total organic carbon and total nitrogen concentrations, δ^{13}C and δ^{15}N) and water flow characteristics (electrical conductivity and δ^{18}O). These investigations were carried out in June 2013 for two successive storm flow events along the course of the Houay Xon river, flowing into the Mekong at Luang Prabang in Laos.

2. Study site

With an extension of 22 km^2 the Houay Xon (HX) catchment is located 10 km SE of Luang Prabang in northern Laos (Fig. 1). Its permanent stream is a tributary of the Nam Dong River, flowing into the Mekong River in Luang Prabang (Ribolzi et al., 2010). Its upstream basin, the Houay Pano (HP) catchment, is part of the MSEC (Monitoring Soil Erosion Consortium) network since 1998 (Valentin et al., 2008; Lacombe et al., 2016). The tropical monsoon climate of the region is characterized by the succession of dry and wet seasons, *ca.* 80% of annual rainfall (1302 ± 364 mm yr^{-1} on average between 1960 and 2013; Gourdin et al., 2014a) occurring during the rainy season from May to October (Ribolzi et al., 2008). The stream has an average base flow of 0.4 ± 0.1 L s^{-1} that may exceed 150 L s^{-1} at S4 during important flood events and flows into the Houay Xon (22.4 km^2 catchment) in the village of Ban Lak Sip (BLS).

The HX River is continuously monitored at station S10 (11.6 km^2 catchment), located 2.5 km downstream of the village. Additional sampling stations were installed, one within the BLS village (HP1; Fig. 1) and two further downstream along the HX River (HX2 and HX3 on Fig. 1). Another station, HT1, was added to monitor the Houay Thong (HT) tributary before its junction with the HX River, upstream of HX3 (Fig. 1). The characteristics of all the sampling stations and collection points are summarized in Table 1.

The geological basement of the Houay Xon catchment is composed at 95% by rocks of the lower Indonisian series (greywackes, pelites and quartzites; VKL, 1971), overlaid in the uppermost part of the catchment by Carboniferous – Permian limestone cliffs. Altitude ranges between 272 and 1300 m a.s.l. (Fig. 1). Soils consist of deep (> 2 m) and moderately deep (>0.5 m) Alfisols (UNESCO, 1974), except along crests and ridges where Inceptisols can be also found (Chaplot et al.,