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Suspended sediment dynamics in a Southeast Asian mountainous catchment: Combining river monitoring and fallout radionuclide tracers

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SUMMARY

Soil erosion is intense in mountainous tropical regions where heavy storms result in the supply of large quantities of sediment to rivers. The origin and dynamics of suspended sediment were analysed in a catchment located in northern Laos during the first erosive flood of the rainy season in May 2012. The catchment was equipped with 4 successive gauging stations (draining areas ranging 0.2–11.6 km^2). Fallout radionuclides (Beryllium-7 – ^{7}Be, unsupported Pb-210 –^{210}Pb$_{xs}$, and Cesium-137 – ^{137}Cs) were determined on rainfall, overland flow, stream water, suspended sediment, soil surface and subsurface samples (with $n = 3, 19, 75, 75, 65$ and 14 respectively). Assumptions underpinning the ^{7}Be-labelling method were validated by implementing experiments in the laboratory (i.e., rainwater ^{7}Be sorption to soil particles) and in the field (i.e., ^{7}Be:^{210}Pb$_{xs}$ activity ratio evolution in rainwater and related overland flow during a natural storm event). Radionuclide analyses provided a way to quantify variations in sediment dynamics and origin throughout the flood: (1) a proportion of recently eroded sediment (labelled by ^{7}Be, and referred to as "fresh sediment") ranging between *ca.* 8–35% in suspended loads; (2) higher contributions of fresh sediment at the beginning of the flood rising stage; (3) a progressive dilution of fresh sediment by particles remobilised from the riverbed/channel; (4) the dominance of particles originating from the soil surface (*ca.* 70–80% of total sediment load) in upper parts and a much larger contribution of subsurface material (*ca.* 64%) at the downstream station. The original contribution of ^{7}Be-labelled particles derived from collapsed riverbanks to sediment export was also demonstrated. This pilot study supports the use of fallout ^{7}Be and ^{210}Pb$_{xs}$ in tropical catchments to constrain sediment dynamics. It also puts forward the need to better characterize the sources of sediment in order to avoid possible misinterpretations.

1. Introduction

Soil erosion is particularly intense in mountainous subtropical regions where heavy storms may result in the supply of large quantities of suspended sediment to streams (Descroix et al., 2008; Valentin et al., 2008). Large exports of suspended matter by mountain rivers lead to numerous problems downstream (Syvitski et al., 2005). Sediments can accumulate behind dams, which results in the siltation of water reservoirs (Downing et al., 2008; Thothong et al., 2011). Suspended matter also contributes to water quality degradation (Tanik et al., 1999) and conveys biological compounds, playing thereby a major role in global nutrient biogeochemical cycles (Quinton et al., 2010). It also constitutes a potential vector for various pollutants such as metals, polycyclic aromatic hydrocarbons or faecal bacteria (Ribolzi et al., 2010; Gateuille et al., 2014).

In order to limit those negative impacts, sediment supply to rivers needs to be controlled. Design and implementation of appropriate management procedures require a better understanding of suspended matter dynamics in mountainous catchments. Their behaviour should be better constrained in time, and particularly during floods, as most riverine sediments are exported during those short periods (Meybeck et al., 2003; Mano et al., 2009). To this end, tracers that are preferentially sorbed or contained in the fine mineral and organic suspended fractions (i.e., clays and fine silts, He and Walling, 1996) may be used to follow sediment pathways across catchments (Koiter et al., 2013).

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Radionuclides that are supplied to the soil surface by rainfall, i.e. beryllium-7 (^{7}Be) and unsupported or excess lead-210 (^{210}Pb$_{xs}$) are used to estimate soil erosion rates at the hillslope scale (Schuller et al., 2006; Sepulveda et al., 2008), or to characterize the temporal transfer of sediment in larger river systems (Bonniwell et al., 1999). Their different half-lives ($T_{1/2} = 53$ days for ^{7}Be and $T_{1/2} = 22.3$ years for ^{210}Pb$_{xs}$) are particularly relevant to differentiate between fresh sediment tagged with ^{7}Be and older remobilized sediment depleted in ^{7}Be. Based on this simple principle, Matisoff et al. (2005) proposed to calculate the ^{7}Be:^{210}Pb$_{xs}$ activity ratio (^{7}Be/^{210}Pb$_{xs}$) in both rainwater and riverine sediment to estimate fresh sediment percentages in rivers and infer transfer times or transport distances. Alternative approaches used radionuclide mass-balance models such as the one proposed by Dominik et al. (1987) and improved by Le Cloarec et al. (2007), or associated both methods (Evrard et al., 2010). However, several limitations may arise regarding the assumptions underpinning those methods. The validity of radionuclides as tracers of sediment fluxes in large rivers has been recently questioned (Walling, 2012; Taylor et al., 2013). The main criticism focussed on the potential difference of ^{7}Be/^{210}Pb$_{xs}$ activity ratio value in rainwater and in fresh sediment. This may occur when particles are tagged with radionuclides from successive storms and not with the event of investigation alone. Another concern arises from a possible misinterpretation of ^{7}Be/^{210}Pb$_{xs}$ variations measured in sediment, as low values may result from various processes: radionuclide decay; desorption (when sediment remained buried in the riverbed) or changes in the source of sediment with the supply of subsurface particles (depleted in fallout radionuclides; e.g., Whiting et al., 2005). In order to reduce those uncertainties, a third fallout radionuclide, cesium-137 (^{137}Cs; $T_{1/2} = 30.2$ years) proved to be useful to distinguish between particles originating from soil surface and exposed to atmospheric fallout of bomb tests during the second half of the 20th century (Ritchie and McHenry, 1990) and particles from the subsurface (below *ca.* 30 cm depth), protected from ^{137}Cs and ^{7}Be fallout (e.g. Olley et al., 1993; Ben Slimane et al., 2013; Evrard et al., 2013; Hancock et al., 2014).

In this study, experiments were carried out in the Houay Pano – Houay Xon nested catchments located in Laos and exposed to summer monsoon, to quantify the respective contributions of surface and subsurface soil to suspended sediment loads during an erosive flood event that took place at the beginning of the rainy season in May 2012. The fallout ^{7}Be activity of the previous rainy season should have sufficiently decayed during the 6-months dry period to become negligible compared to their recent supply at the onset of the wet season. Every compartment of the erosional system, from rainwater to stream sediment, was sampled for fallout radionuclide analyses. Adsorption experiments were also conducted for ^{7}Be at the microplot's scale under natural rainfall and in the laboratory.

2. Study site

The Houay Pano catchment, located 10 km south of Luang Prabang in northern Laos (Fig. 1), has been part of the MSEC (Monitoring Soil Erosion Consortium) network since 1998 (Valentin et al., 2008). The tropical monsoon climate of the region is characterized by the succession of dry and wet seasons with *ca.* 80% of rainfall occurring during the rainy season from May to October (Ribolzi et al., 2008). The Houay Pano stream has an average base flow of 0.4 ± 0.1 L s^{-1} and is equipped with 2 gauging stations that subdivide the catchment into nested subcatchments. These stations, S1 and S4, draining 20 ha and 60 ha respectively, are located along the main stem of the stream. Between S1 and S4 stations, water flows through a swamp (0.19 ha), supplied with water by a permanent groundwater table (Fig. 1). Only temporary footslope and flood deposits can be found along this narrow section of the stream and the swamp represents the major sediment accumulation zone in the Houay Pano catchment. The Houay Pano stream flows into the Houay Xon River (22.4 km^{2} catchment) and is continuously monitored at S10 (draining a 11.6 km^{2} catchment), located 2.8 km downstream of S4. The Houay Xon is a tributary of the Nam Dong River, flowing into the Mekong River within the city of Luang Prabang (Ribolzi et al., 2010).

The geological basement of the Houay Pano catchment is mainly composed of pelites, sandstones and greywackes, overlaid in its uppermost part by Carboniferous to Permian limestone cliffs. Soils consist of deep (>2 m) and moderately deep (>0.5 m) Alfisols (UNESCO, 1974), except along crests and ridges where Inceptisols can be found (Chaplot et al., 2009). Soils have a low cation exchange capacity and a low pH ranging between 4.9 and 5.5 across the catchment. Native vegetation consisted of lowland forest dominated by bamboos that were first cleared to implement shifting cultivation of upland rice at the end of the 1960s (Huon et al., 2013). Elevation across the catchment ranges *ca.* 272–1300 m.a.s.l. As cultivation takes place on steep slopes (ranging between 3% and 150%), the catchment is prone to soil erosion (Chaplot et al., 2005; Ribolzi et al., 2011). Due to the decline of soil productivity triggered by soil erosion over the years (Patin et al., 2012) and to an increasing labour need to control weed invasion (Dupin et al., 2009), farmers progressively replaced rice fields by teak plantations in the catchment (Fig. 1). During the present study, main land uses in the Houay Pano catchment were teak plantations (36% of total area), rotating cropping land (35%), Job's tears (10%), banana plantations (4%) and upland rice fields (3%); the forest covering less than 9% of the area. The land use was different in the larger area drained by S10, with 56% of the surface covered with forests, 15% under teak plantations and 23% under cropland.

3. Materials and methods

3.1. Sample and data collection

Rainfall, stream and overland flow waters were sampled during the May 23 flood in 2012. Rainfall intensity was monitored with an automatic weather station (elevation: 536 m.a.s.l.) and stream discharge was calculated from water level continuous recording and rating curves. Rainfall was sampled with three cumulative collectors, located in the village near the confluence between Houay Pano and Houay Xon streams, near a teak plantation on the hillslopes located just upstream of the village and within the Houay Pano catchment. Overland flow was collected at the outlet of 1-m^{2} experimental plots. Stream water was collected in plastic bottles after each 20-mm water level change by automatic samplers installed at each gauging station. Fifty-six total suspended sediment (TSS) samples were collected at the three stations (S1, S4, S10). Samples were dried shortly after collection in an oven ($t \approx 100$ °C) for 12–48 h. In addition, sediment deposited upstream of S4 in the river channel (top 0–1 cm of in-channel deposits collected using a plastic trowel) was sampled the day before the May 23 flood to document the initial radionuclide activity. Surface soil samples (top 0–5 cm; $n = 65$) were collected using plastic trowels on the hillslopes connected to the Houay Pano Stream and the Houay Xon River (Fig. 1) during three campaigns conducted in July 2002 (Huon et al., 2013), May 2012 and December 2012. Additional gully ($n = 6$) and riverbank ($n = 8$) samples were also collected in December 2012 to document the characteristics of the potential subsurface sources of sediment to the river.