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Evaluating a spatially-explicit and stream power-driven erosion and sediment deposition model in Northern Vietnam

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ABSTRACT

Land use change and unsustainable farm management practises have led to increased soil erosion with severe consequences on the natural resource base in mountainous Northern Vietnam. Given the often prevailing data-limited situations in these regions, simulation models can be used to evaluate alternative land use trajectories or provide decision support for soil conservation planning. In this study, we present a newly developed dynamic and spatially-explicit **ERO**sion and sediment **DEP**osition model (ERODEP), which simulates soil erosion by stream power principles, sediment deposition based on texture-specific settling velocity classes, and sediment re-entrainment to move previously deposited particles back into runoff flow. ERODEP runs on a daily basis and was linked with the **L**and **U**se **C**hange **I**mpact **A**ssessment model (LUCIA) building on its hydrological and vegetation growth routines. The combined modelling framework was employed for a period of four years using field datasets of a small case study watershed. ERODEP-LUCIA simulated reasonably well soil erosion and sediment deposition patterns following the annual variations in land use and rainfall regimes. Output validation (i.e. modelling efficiency = EF) revealed satisfying to good simulation results, i.e. plot-scale soil loss under upland swiddening (EF: 0.60–0.86) and sediment delivery rates in monitored streamflow (EF: 0.44–0.93). Cumulative sediment deposition patterns in lowland paddy fields were simulated fairly well (EF: 0.66), but showed limitations in adequately predicting silt fractions along a spatial gradient in a lowland monitoring site. Findings of a sensitivity analysis demonstrated the interplay of soil erosion and sediment deposition by superimposed variations in stream power, sediment velocity and vegetation related parameters. Results highlighted the potential of ERODEP-LUCIA as an integrated biophysical assessment tool for mountainous ecosystems with moderate data availability.

1. Introduction

In mountainous Northern Vietnam, population pressure and market-driven forces have fostered the expansion of farming areas into steep sloping environments (Lippe et al., 2011; Saint-Macary et al., 2010; Sikor and Truong, 2002; Valentin et al., 2008). These dynamics led in combination with the locally prevailing rainfall patterns to an increase of runoff-driven soil erosion with detrimental effects on agricultural production and ecosystem functions (Chaplot and Poesen, 2012; Wezel et al., 2004; Ziegler et al., 2004).

Water-borne erosion is a complex and dynamic process at the landscape-scale. It involves detachment, transport and deposition of soil particles whose spatial and temporal distribution is intimately driven by the interplay of land use, soil and topography (Chaplot and Poesen, 2012). On-site effects influence agricultural productivity by the loss of nutrient-rich topsoil particles, reducing crop yields in the short- and soil fertility in the long-run (Blanco and Lal, 2008; Fiener et al., 2008). Off-site effects can comprise the pollution of surface water bodies by high loads of dissolved sediments or colloid substances such as pesticides (Ciglasch et al., 2005; Kahl et al., 2008). Soil cover by vegetation or surface litter plays a crucial role in this context. It reduces the erosive force of runoff flow by an increase in surface roughness and simultaneously enhances sediment deposition by a decrease in flow velocity (Blanco and Lal, 2008; Boardman, 2006; Podwojewksi et al., 2008; Rose, 1993). Sediment deposition often results in the accumulation of nutrient-rich soil particles on foot slopes or plain areas (Schmitter et al., 2010, 2011). Drawbacks need to be considered, as sediment deposition is a size-selective process where fine particles settle more slowly than coarser material forming enrichment areas of different soil quality (Beuselinck et al., 1999; Hairsine et al., 2002; Jetten et al., 1999).

The assessment of soil erosion and sediment deposition with conventional methods is laborious and expensive. Especially in a transient environment such as Northern Vietnam, tools are desirable that can offer implications for soil conservation planning by preferably relying only on a minimum set of information. Such tools should be able to

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quantify the magnitude and the locality of soil loss and sediment deposition which is important for erosion risk assessment and evaluating the effects of land use change. With the rise of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), modelling approaches emerged as important assessment tools in this context. ULSE draws in principle on a statistical analysis of spatially-lumped elements, and shows constraints when extrapolated beyond the limits of the corresponding dataset (Ciesiolka et al., 1995; Meritt et al., 2003; Siepel et al., 2002). Based on these conceptual limitations, a new generation of process-based models were developed, with GUEST (Griffith University Soil Erosion Template; Misra and Rose, 1996), LISEM (Limburg Soil Erosion Model; de Roo et al., 1996) and WEPP (Water Erosion Prediction Project; Nearing et al., 1989) as prominent examples. These models aim to mimic the spatial and temporal variation of soil erosion and sediment deposition by a detailed representation of the geophysical environment compared to USLE. In case of LISEM and WEPP, model algorithms were coupled with GIS systems disclosing new opportunities for environmental planning.

Nevertheless, a trade-off exists between model complexity, functionality and predictive power (Fiener et al., 2008). LISEM requires more than ten input maps and similarly to WEPP draws on temporally fine-scaled input data which are not always available in data-limited environments such as Northern Vietnam. WEPP has been further criticised by segmenting a watershed into spatially-clustered elements raising questions of its applicability as decision support tool for soil conservation planning (Boardman, 2006; Meritt et al., 2003). GUEST has proven its validity in a number of plot-based studies (Ciesiolka et al., 1995; van Dijk and Bruijnzeel, 2004; Yu, 2005; Yu and Rose, 1999). It was recently also employed at watershed-scale, however, without considering sediment deposition and sediment re-entrainment processes (Bui et al., 2013).

Given the global challenges of climate and land use change, new conceptual soil erosion and sediment deposition models are required (Blanco and Lal, 2008; Boardman, 2006; Nearing and Hairsine, 2011) and these need to be coupled with corresponding mechanistic, spatially-explicit vegetation and land use change models. Compared to existing modelling approaches, the added-value of such a tool lies in its integrated representation of hydrological, geophysical and vegetation factors in a dynamic and spatially-explicit environment. However, caution has to be taken, as an increase in model complexity should not necessarily lead to an increase in data demand, and preferably rely only on a minimum set of input maps such as land use, soil and topography. Drawing on such a modelling framework would not only allow a wider application in regions such as Northern Vietnam, but could also support the urgent need to establish sustainable soil conservation strategies in these vulnerable landscapes. Following these premises, we developed the **ERO**sion and sediment **DEP**osition model (ERODEP) which draws on principles of the GUEST model as presented in Yu et al. (1997) and a size-specific sediment deposition algorithm developed by Hairsine and Rose (1992). ERODEP was coupled with the **L**and **U**se **C**hange **I**mpact **A**ssessment model (LUCIA) version 1.0 (Marohn, 2009) building on its runoff and surface cover routines. LUCIA is a dynamic and spatially-explicit landscape model for tropical watersheds of up to a size of 30 km^2. LUCIA integrates hydrological, geophysical, soil organic matter, and vegetation growth routines in a single framework. LUCIA runs on a daily time step and was encoded in the environmental software language PCRaster (http://pcraster.geo.uu.nl/) to make use of its embedded hydrological routing functionality.

Consequently, the main objective of this study was to evaluate the predictive power of the coupled ERODEP-LUCIA model using available datasets of a small watershed in Northern Vietnam. In particular, we assessed (i) if ERODEP-LUCIA could be calibrated with a minimum input dataset of only one rainy season, (ii) if the coupled model would be able to predict the quantity of soil loss and sediment delivery at an annual and event-based resolution, (iii) whether modelling outputs could adequately mimic texture-specific sediment deposition patterns as observed along a spatial gradient in the lowland watershed part, and (iv) if the simulated spatial distribution of soil erosion and sediment deposition patterns can be used as decision support for soil conservation planning. By presenting the results of the four goals presented above, we discuss the lessons learned and opportunities of the coupled ERODEP-LUCIA approach as soil erosion risk assessment approach for study areas in Northern Vietnam in particular, and as decision support tool for tropical environments under transition in general.

2. The ERODEP model

The **ERO**sion and sediment **DEP**osition model (ERODEP) follows the basic assumption that runoff-driven soil erosion, hereafter called 'sediment entrainment' (Hairsine and Rose, 1992), dominates over rainfall-induced soil detachment. This assumption is particularly evident in sloping environments where runoff often functions as main driver of soil erosion combining sediment entrainment and sediment transport simultaneously (Yu and Rose, 1999). ERODEP considers cohesive strength as a property of the soil matrix regulating soil removal by entrainment as non-selective process. In contrast, sediment deposition is viewed as a site-selective process where the rate of sediment settling is the product of sediment concentration in water flow and a size-specific sediment settling velocity. Fig. 1 provides an overview of the basic principles employed in ERODEP simulated at an individual grid cell element (pixel). The model runs on a daily time step to reduce the commonly high input demands of temporally fine-scaled hydrological models which operate on a minute or second basis. Instead, ERODEP employs hydrological downscaling techniques and assumes that due to this adjusted functionality the simulated soil erosion and sediment deposition rates are representing average daily flow conditions. Over the next section we present the guiding algorithms which together form the newly developed simulation approach. Where necessary, inputs provided by the LUCIA model are described together with underlying model assumptions and functionality. Further information on the LUCIA model version 1.0 can be found in Marohn (2009) and an updated version in Marohn and Cadisch (https://lucia.uni-hohenheim.de/).

2.1. Hydrological functionality

With the focus to develop a simplified process-based simulation approach, ERODEP builds on the hydrological module of LUCIA to simulate a steady-state discharge rate. The model initiates its sub-routines by calculating Q_{rate} as an hourly runoff rate (mm h^{-1}) based on a scaling technique of Yu et al. (1997):

$$Q_{\mathrm{rate}} = \left(\frac{Q_{\mathrm{tot}}}{R_{\mathrm{tot}}}\right) \cdot R_{\mathrm{int}} \tag{1}$$

with Q_{tot} the daily runoff (mm d^{-1}), R_{tot} daily rainfall (mm d^{-1}), and R_{int} rainfall intensity (mm h^{-1}). Data of R_{tot} have to be given as input to ERODEP whereas Q_{tot} is simulated by LUCIA as the remainder of daily rainfall minus interception and water that can infiltrate into unsaturated soil in time. When data on rainfall intensity are absent, as in the case of this study, an idealised exponential rainfall depth-intensity distribution can be assumed (van Dijk and Bruijnzeel, 2003). The distribution should preferably rely on local datasets holding similar features as the original case study area. We used a dataset by Ziegler et al. (2004) with the empirical function ($R^2 = 0.75$):

$$R_{\mathrm{int}} = 0.09871 \cdot {R_{\mathrm{tot}}}^{0.8851} \tag{2}$$