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A spatially lumped model to investigate downstream sediment flux propagation within a fluvial catchment

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ABSTRACT

A spatially lumped process–response model, PaCMod, is presented, which calculates long time series (10^3–10^6 years) of fluvial water discharge and sediment load at the river catchment outlet, based on climatic data, drainage basin characteristics and user-defined parameters. Key aspects of the model are (i) the lumped approach, allowing for fast simulations and preserving the same resolution from palaeoclimatic conditions and geomorphological reconstructions; (ii) the parameterization of sediment routing and storage within the catchment. PaCMod was successfully tested on observed data from three present-day fluvial systems: the Meuse, the Waipaoa, and the Po Rivers. Moreover, the simulated sediment flux for the Meuse and for the Waipaoa Rivers in the late Quaternary is in agreement with published field and modelling work. PaCMod experiments show how the downstream propagation of the original climatic signal is hampered by sediment routing and storage within the catchment.

1. Introduction

Understanding the effects of palaeoclimate forcing on catchment sediment yield and on basin stratigraphy is still an outstanding research objective in sedimentary geology. Numerical simulations have shown that Quaternary climatic changes produced clear sediment flux pulses (e.g., Tucker and Slingerland, 1997; Tebbens et al., 2000a; Kettner et al., 2009; van Balen et al., 2010). Sediment budgeting works have indicated that, for certain source-to-sink systems, the sediment flux signal is preserved in the stratigraphic record (e.g., Busschers et al., 2007; Vis et al., 2008; Sømme et al., 2011), while for other systems it is lacking or strongly buffered (e.g., Trimble, 1977; Metivier and Gaudemer, 1999; Phillips, 2003; Brommer et al., 2009).

The role of sediment supply in basin stratigraphy has received more and more attention in the last decades because understanding the palaeo sediment supply fluxes can provide a better interpretation of the available core and seismic data and can help interpreting stratigraphy at the parasequence and event-bed scale (Blum and Törnqvist, 2000; Storms, 2003; Hampson and Storms, 2003; Blum and Aslan, 2006; Helland-Hansen and Hampson, 2009; Charvin et al., 2011; Holbrook and Bhattacharya, 2012). Numerical simulations of fluviodeltaic and shoreface–shelf systems have clearly shown a relation between sediment supply and stratal response (Hampson and Storms, 2003; Storms and Swift, 2003; Kubo et al., 2006; Charvin et al., 2011). This implies that we are able to detect a climatic signal in marine stratigraphy, but we still poorly understand the modification of such signal during its downstream propagation toward the marine domain.

The simplest approach to simulate catchment processes is a spatially lumped model, which is based on spatially averaged parameters representing the behaviour of the system in time (e.g. Leeder et al., 1998; Weltje et al., 1998; Bogaart and van Balen, 2000; Bogaart et al., 2003a,b; Syvitski and Milliman, 2007; Kettner and Syvitski, 2008). A more advanced and complex approach is a two-dimensional landscape evolution model (e.g., Tucker and Slingerland, 1997; Whipple and Tucker, 1999; Coulthard et al., 2002; Armitage et al., 2011) where all dependent variables are functions of time and spatial coordinates. These models include internal catchment dynamics, such as landscape thresholds, sedimentation and erosion wave propagation that contribute to the generation as well as intra catchment modification and dampening of a climatic or tectonic signal (Walling, 1983; Phillips and Slattery, 2006; Coulthard and Van De Wiel, 2007; Whittaker et al., 2010; Armitage et al., 2011).

The generally poor control on palaeoclimate and catchment morphology hampers the applicability of two-dimensional models, as they require a high level of input detail, which is usually unavailable the further we move back in time. Spatially lumped models produce results that have the same resolution as the input boundary conditions instead. As such, they could be used for palaeo settings for which catchment properties and climate reconstructions are poorly known. However, because of the spatial lumping, they do not simulate catchment memory, i.e. the inheritance of previous climatic and morphologic conditions, which is enhanced by sediment routing and storage.

We have developed a spatially lumped model, PaCMod, that simulates time series of fluvial water discharge and sediment load from

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any given catchment. It combines new modelling algorithms and parameterizations for environmental response to climatic changes, sediment routing, and storage (catchment memory) with existing and modified routines from Hydrotrend (Syvitski et al., 1998; Kettner and Syvitski, 2008) and PALAEOFLOW (Bogaart et al., 2003a). The aims of this paper are (i) to describe the new modelling technique, its potential and limitations; (ii) to test the model on real-world present-day and late Pleistocene–Holocene cases, and (iii) to investigate how the sediment flux signal is generated, transmitted, and buffered in a river drainage system.

2. PaCMod outline

A schematic overview of the PaCMod modelling approach is shown in Fig. 1. The main inputs are climatic conditions and catchment properties. We define the catchment as the upland, mainly erosional part of a drainage basin in which sedimentation occurs only temporarily, as alluvial fans, confined floodplains, and channel deposits. PaCMod consists of three connected routines operating at different timescales: the long-term routine, the epochs routine, and the yearly routine.

In the long-term routine, the long-term climatic and environmental boundary conditions are defined. We consider the long-term climate as a series of discrete points in time, which we call epochs. The spacing between epochs (typically 500–1000 years) is based on the discreteness of the palaeoclimatic proxy data and on computational demand. For each epoch (epochs routine), PaCMod performs short simulations (10–30 years) at a daily timescale, producing daily weather conditions (*weather module*) and river discharge values (*hydrological module*). In addition, erosion rates, long-term suspended load, and channel pattern are calculated for each epoch based on average environmental conditions (*erosion module and channel pattern module*).

Finally, the yearly routine interpolates the daily values obtained from the epochs routine over the whole simulation timespan on a yearly scale. A long time series of fluvial water discharge is generated, and the bedload transport capacity is calculated for each time step (*discharge and transport capacity module*). The sediment supply from hillslopes, the suspended sediment load, and the bedload transport capacity are eventually balanced in a global sediment transport module (*sediment balance module*).

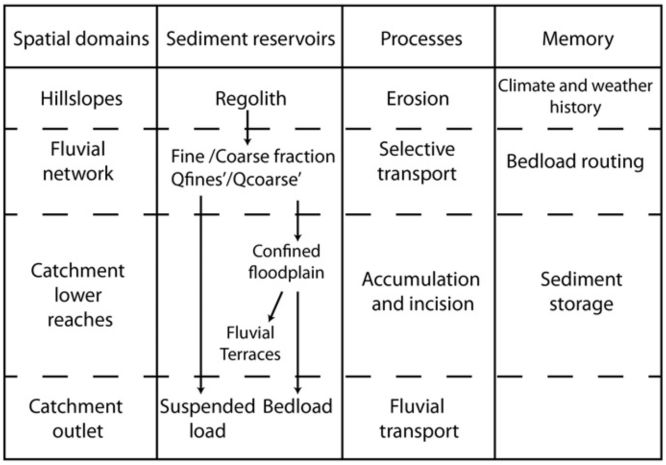

Fig. 1. Schematic overview of PaCMod modelling approach. The three-dimensional morphology of a real catchment is collapsed into four spatial domains where different processes occur and sediment is routed and temporary stored. The processes occurring in the catchment operate simultaneously but at different time scales (e.g., decennia to millennia for hillslope erosion and days for fluvial transport). Therefore the model structure is composed of three different routines working at different timescales.

2.1. Long-term routine

In the long-term routine, the climatic boundary conditions (temperature and precipitation), derived from palaeoclimate proxies, are related to three environmental parameters: vegetation cover *Veg*, soil holding capacity H_c, and runoff/infiltration coefficient R/I. We define *Veg* as the area of the catchment covered by arboreal species (0–1); H_c is defined as the amount of water that can be hold by soils (mm); and R/I is defined as the ratio (0–1) between overland flow and water that infiltrates under the surface (Bogaart et al., 2003a). The relation between total annual precipitation P_a (mm/y) and *Veg* is modelled as a logarithmic function, with the constant of proportionality set by the coefficient $v1$. The relation between mean annual temperature T_a (°C) and *Veg* is treated as a Gaussian function (Eq. (1)), similar to Weltje et al. (1998), with a thermal optimum set by the coefficient $v2$ (Fig. 2A).

$$Veg = \left(-\frac{1}{e^{(v1\cdot P_a)}}+1\right)\cdot\left(\frac{e^{-(T_a-v2)^2}}{2\cdot v3^2}\right). \tag{1}$$

H_c is assumed to be directly related to vegetation cover (Weltje et al., 1998) with a range of 0–100 mm (Bogaart et al., 2003a). The R/I is modelled as inversely proportional to vegetation cover (Eq. (2)) and directly proportional to temperature, when $T_a > 0$ °C. For $T_a < 0$ °C we assumed a value of 0.9 for R/I based on Bogaart et al. (2003a). In this way we simulate the effect of permafrost (or soil frost), which inhibits the infiltration capacity (Fig. 2B) (Couture and Pollard, 2007).

$$R/I = x1 - Veg^{x2} + x3^{x4\cdot T_a} \quad \text{for } T_a > 0\,^\circ\text{C} \tag{2}$$

where $v3$, $x1$, $x2$, $x3$, and $x4$ are user-defined coefficients.

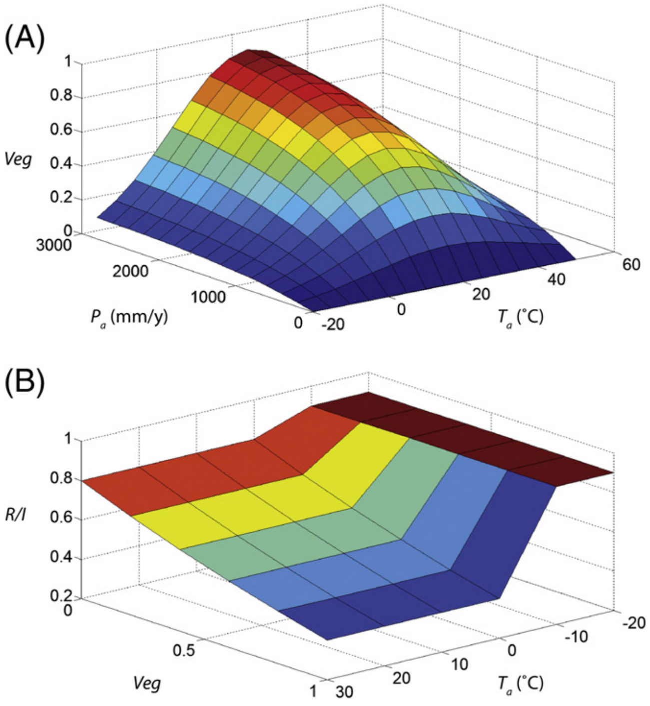

Fig. 2. (A) Vegetation cover as a function of temperature (°C) and annual precipitation (mm/y); (B) R/I coefficient as a function of temperature and vegetation cover (0–1). The values of the user-defined coefficients are: $v1$ (0.001), $v2$ (20), $v3$ (20), $x1$ (0.5), $x2$ (0.2), $x3$ (0.01), and $x4$ (0.03).