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Characterization of alluvial formation by stochastic modelling of paleo-fluvial processes: The concept and method

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SUMMARY

Modelling fluvial processes is an effective way to reproduce basin evolution and to recreate riverbed morphology. However, due to the complexity of alluvial environments, deterministic modelling of fluvial processes is often impossible. To address the related uncertainties, we derive a stochastic fluvial process model on the basis of the convective Exner equation that uses the statistics (mean and variance) of river velocity as input parameters. These statistics allow for quantifying the uncertainty in riverbed topography, river discharge and position of the river channel. In order to couple the velocity statistics and the fluvial process model, the perturbation method is employed with a non-stationary spectral approach to develop the Exner equation as two separate equations: the first one is the mean equation, which yields the mean sediment thickness, and the second one is the perturbation equation, which yields the variance of sediment thickness. The resulting solutions offer an effective tool to characterize alluvial aquifers resulting from fluvial processes, which allows incorporating the stochasticity of the paleoflow velocity.

1. Introduction

Rivers are one of the most dynamic external forces interacting with and modifying the Earth's surface. Sediment erosion and deposition in rivers (fluvial processes) affect the geomorphic evolution of land surface and basin stratigraphy. Various models have been developed over the past decades to quantitatively describe fluvial processes, including geostatistical models that mimic the final results of fluvial processes statistically, and process-based models that quantify the physics of fluid and sediment transport (e.g. Koltermann and Gorelick, 1996; Paola, 2000; Van De Wiel et al., 2011). Geostatistical methods predict unknown data by interpolation based on probabilistic models inferred from measured data. These methods can be conditioned to the measured information, but their applicability is often limited due to sparse data. In contrast, process-based models which describe the mechanics of fluvial processes can be used to simulate the lithology distribution in the absence of measurements (Li et al., 2004; Tetzlaff, 1990).

The Exner model is a classical process-based description of fluvial processes, which is based on a mass balance of sediment transport in the river and sediment accumulation on the riverbed (Exner, 1925; Leliavsky, 1955). It was generalized by Paola and Voller (2005) to consider the influence of tectonic uplift and subsidence, soil formation and creep, compaction and chemical precipitation and dissolution. For a wide range of specific problems, such as short- or long-term riverbed evolution, a mass balance equation can be extracted from the general Exner equation by combining and dropping negligible terms.

Fluvial process models based on the general Exner equation are widely used. Several types of such models are available. In the convective model (Davy and Lague, 2009; Paola and Voller, 2005), the sediment flux and accumulation at the position of interest is assumed to be controlled by the upstream landscape features and sediment input. The diffusion model (Paola et al., 1992; Paola and Voller, 2005) simulates influences of both upstream and downstream locations on the target positions. In addition, the fractional model (Voller et al., 2012) accounts for non-local upstream and downstream influences.

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Nomenclature

Symbol	Definition		
β	deposition coefficient, L/T	ϕ^*	conjunction of ϕ
C_d	dimensionless drag coefficient	φ	porosity of deposited sediment
D	deposition rate of sediment, L/T	$q_s(t)$	sediment input from the river source, L
$dZ_v(\kappa)$	complex Fourier amplitude of flow velocity	ρ_f	density of water, M/L^3
Δt	time step, T	$s_{vv}(\kappa)$	spectral density function of flow velocity
Δx	length of discretized segment, L	t	time, T
E	erosion rate of sediment, L/T	v	stream velocity, L/T
γ	erosion efficiency coefficient, L$^{2.5}$ T^2/M$^{1.5}$	W_f	width of fluvial trace, L
H	river depth, L	W_c	width of river channel, L
κ	magnitude of the wave number vector	x	distance along the stream from its origin, L
λ	correlation scale of the flow velocity, L	η	sediment load in the river, L^3/L^2
p	probability of the channel occurrence	σ_M^2	variance of the quantity M
ϕ	transfer function between v and η	z	sediment thickness, L

In these fluvial process models (FPM), the flow velocity is the key input parameter. The velocity can be resolved by a fluid dynamics model (FDM) based on the Navier–Stokes equations (e.g. Gonzalez-Juez et al., 2009; Necker et al., 2005). Approaches that couple FPM and FDM can yield a detailed description of fluvial processes and channel evolution. However, these are mostly limited to controlled laboratory settings. At the catchment scale, a coupled FPM–FDM has been applied in two-dimensional planes where the vertical velocity variation has been neglected (Koltermann and Gorelick, 1992). Fully-coupled modelling of the fluvial processes and fluid dynamics, however, is still a challenge, because applying the FDM requires precise knowledge of the initial and flow boundary conditions, which are generally not available (e.g. Koltermann and Gorelick, 1992; Lesshafft et al., 2011; Simpson and Castelltort, 2006).

Due to these difficulties, the determination of flow velocity is often uncertain. Therefore, a trend in the past decades has been to develop stochastic fluvial process models that account for the stochasticity in the river discharge (e.g. Lague, 2014; Molnar et al., 2006; Tucker and Bras, 2000), and the stochasticity of particle motion (e.g. Furbish et al., 2012; Roseberry et al., 2012).

In this paper, we pursue a similar stochastic approach by developing the convective FPM (Davy and Lague, 2009), to account for the uncertainties in factors that can be represented by the statistics of flow velocity. These factors include riverbed topography, river discharge and river channel position in the fluvial trace. The velocity in the model is characterized by a stochastic description consisting of an ensemble mean component and a perturbation component. The model relates the statistics of the velocity with the statistics of sediment load in the river and of sediment thickness on the riverbed.

This study is organized as follows: Section 2 introduces the convective FPM and the stochastic formulation employing the perturbation method. Section 3 derives the analytical solutions for the sediment load and sediment thickness. The algorithmic implementation is summarized in Section 4 and Section 5 applies the stochastic model to a synthetic case.

2. Governing equations

2.1. Mass balance equation

The mass balance describing fluvial processes is expressed as two separate equations (Davy and Lague, 2009; Paola and Voller, 2005). The first one describes sediment transport in the river:

$$\frac{\partial \eta(x,t)}{\partial t} + \frac{\partial v(x,t)\eta(x,t)}{\partial x} - E(x,t) + D(x,t) = 0, \tag{1}$$

and the second one describes sediment accumulation on the riverbed:

$$\frac{\partial z(x,t)}{\partial t} = \frac{1}{1-\varphi}[D(x,t) - E(x,t)]. \tag{2}$$

Expressions for E (erosion rate) and D (deposition rate) are given in Appendix B. A list of notation is available at the end.

The flow velocity (v) is one of the key parameters in Eqs. (1) and (2), which can be modelled by Navier–Stokes equation (Necker et al., 2005) or simply described by the Manning formula (e.g. Lague, 2010; Le Méhauté, 1976) (Appendix A). However, the application of Eqs. (1) and (2) to reproduce a geological formation often presents uncertainties, because the factors influencing v such as paleotopography and paleohydrology are difficult to determine. It is therefore necessary to develop Eqs. (1) and (2) as stochastic equations that contains the information on the uncertainty of v. Due to the complexity of the factors influencing alluvial sedimentary processes, we deliberately chose to make the following simplifying assumptions:

(1) Chemical precipitation and dissolution, and the abrasion of the sediment particles are not considered.
(2) One-dimensional convective Exner model in Eqs. (1) and (2) is flexible for the modelling river morphodynamics in an inland sedimentary basin. The influences of sediment particle diffusion and the downstream boundary on sediment transport and accumulation are neglected (Zolezzi and Seminara, 2001). In the near-shore environment, where the downstream boundary has significant influence on the sedimentary processes, it would be worthwhile to use the diffusive Exner equation, which is not discussed in this study.
(3) We focus on the uncertainty in sediment transport and accumulation induced by the velocity fluctuation, but the uncertainty relating to the sediment load fluctuation attributed, for example, to the tributaries, is beyond the scope of this study.

2.2. Mass balance equation revisited

Eqs. (1) and (2) are nonlinear partial differential equations, which are solved numerically. River channels are discretised into N segments with $N+1$ nodes, and v is assumed to be constant within each segment (Lanzoni and Seminara, 2002). Eqs. (1) and (2) are then rewritten as:

$$\frac{\partial \eta(x_k,t)}{\partial t} + v_k\frac{\partial \eta(x_k,t)}{\partial x_k} - E_k + D_k = 0, \tag{3}$$