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Model shows that rivers transmit high-frequency climate cycles to the sedimentary record

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ABSTRACT

Rivers are a major component of sediment routing systems that control the transfer of terrigenous sediments from source to sink. Although it is widely accepted that rivers are perturbed by millennial-scale climatic variability, the extent to which these signals are buffered or transferred down river systems to be recorded in sediments at or beyond the river mouth remains debated. Here, we employ a physically based numerical model to address this outstanding issue. Our model shows that river transport strongly amplifies high-frequency sediment flux variations arising from changing water discharge, due to positive feedback between discharge and the channel gradient. This behavior is distinctly different from short-period sediment flux signals (with constant water discharge) where the output sediment flux is strongly dampened within the river, due to negative feedback between the channel gradient and sediment concentration. We conclude that marine sedimentary basins may record sediment flux cycles resulting from discharge (and ultimately climate) variability, whereas they may be relatively insensitive to pure sediment flux perturbations (such as for example those induced by tectonics).

INTRODUCTION

The marine stratigraphic record contains evidence for changes in rates of sedimentation consistent with millennial-scale climate cycles (Van der Zwan, 2002; Covault et al., 2011). Although it is accepted that such stratigraphic cycles are governed by changes in the ratio between the rate of sediment supply and the space available for sedimentation (Shanley and McCabe, 1994), their origin is debated (Törnqvist, 2007). It is generally recognized that stratigraphic cyclicity with Milankovitch periodicities can be caused by glacio-eustatic sea level variations (Shanley and McCabe, 1994). However, climate change also influences rainfall and erosion rates in mountain catchments and therefore the rates at which clastic sediments are delivered to river systems (Bull, 1991; Thomas, 2003). A fundamental unknown is whether these variations in sediment flux can be transmitted through rivers to sedimentary basins, or whether intermediate mechanisms, such as floodplain storage, dampen or destroy sediment flux pulses to the extent that the sediment supply rate at the basin entrance is constant (Castelltort and Van Den Driessche, 2003; Métivier and Gaudemer, 1999; Jerolmack and Paola, 2010; Armitage et al., 2011; Wittmann et al., 2011). Estimations of the time required for long (>300 km) alluvial rivers to respond to external perturbations are on the order of 10^5 yr (Castelltort and Van Den Driessche, 2003), implying that it is unlikely that they are able to transmit large orbitally paced sediment flux pulses. These results are difficult to reconcile with evidence for abrupt millennial-scale changes in sediment flux, such as recorded in the shallow marine sediments near the mouth of major river systems (Goodbred and Kuehl, 2000; Clift et al., 2008).

Here we investigate the fate of sediment pulses in alluvial rivers using a physically based numerical model that treats nonlinear interactions between shallow water flow and sediment transport (Simpson and Castelltort, 2006). This model is based on the conservation of mass and momentum for water and sediment and makes no a priori assumption of diffusive behavior that could dampen sediment flux pulses (see the GSA Data Repository[1]). Like laboratory-scale flume experiments, our small-scale numerical simulations are a powerful tool for studying dynamic aspects of evolving river systems that are otherwise difficult to analyze over geological spatial and temporal scales.

NUMERICAL MODELING

In our simulations, after an initial period during which the river is left to attain a steady-state sediment flux at the outlet, a sinusoidal variation in water flux is applied (see the Data Repository). We find that during the times when the water flux decreases, progressive aggradation of a steep sediment wedge occurs in the upper reaches of the river while downstream portions are completely starved of sediment (Fig. 1A). This situation is reversed during the increasing portion of a water flux cycle, when the previously deposited sediment wedge is incised and flushed downstream. The sediment outflux record for this simulation is highly episodic in time, with large sediment outfluxes correlating with times of large water flux and sediment influx (Fig. 1B). This response is linked to the tendency for a river to evolve, by slope adjustment, toward an equilibrium state such that it is just able to transport its sediment flux without undergoing net aggradation or degradation (Mackin, 1948). Calculations here show that the equilibrium slope has a strong negative correlation with the water flux (Fig. 1C). Changes in water flux perturb the river by altering the equilibrium slope, requiring slope adjustment. This is achieved by either aggradation or downcutting, both of which alter the total mass of sediment stored in the river system and therefore the sediment flux delivered downstream. Channel slope adjustment in this case is a form of nonlinear feedback that amplifies the sediment outflux during phases when the water flux increases (due to downcutting), while the sediment outflux is reduced when the water flux decreases (due to upstream aggradation). Similar observations have been made in laboratory experiments (van den Berg van Saparoea and Postma, 2008).

We have performed a suite of simulations to investigate how the sediment outflux from rivers depends on the period of external forcing relative to the river response time, defined as the characteristic time required for a river to achieve equilibrium following a perturbation (Howard, 1982; Paola et al., 1992; see the Data Repository). We find that the sediment outflux is strongly amplified relative to the input sediment flux over a wide range of driving periodicities (Fig. 2). Remarkably, we observe resonance-type behavior: the largest sediment output amplitudes occur for intermediate input periods. Although the precise mechanism causing this behavior is unclear, these intermediate periods appear optimal with respect to generating large sediment outflux pulses. When the forcing period is far smaller (four orders of magnitude) than the response time, only a small aggradational wedge is accumulated in the time during which the water flux decreases, releasing a relatively small pulse when the wedge is eventually flushed downstream. Conversely, when the forcing period is larger than the response time, the entire river nearly attains its equilibrium slope in the time between cycles, enabling sediment to pass downstream in a more continuous, less pulsed manner. Importantly, even when the driving period is two orders of magnitude less than the river response time, the magnitude of sediment outflux pulses exceeds the input amplitude by a factor of almost ten. These results indicate

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[1] GSA Data Repository item 2012325, supplementary material, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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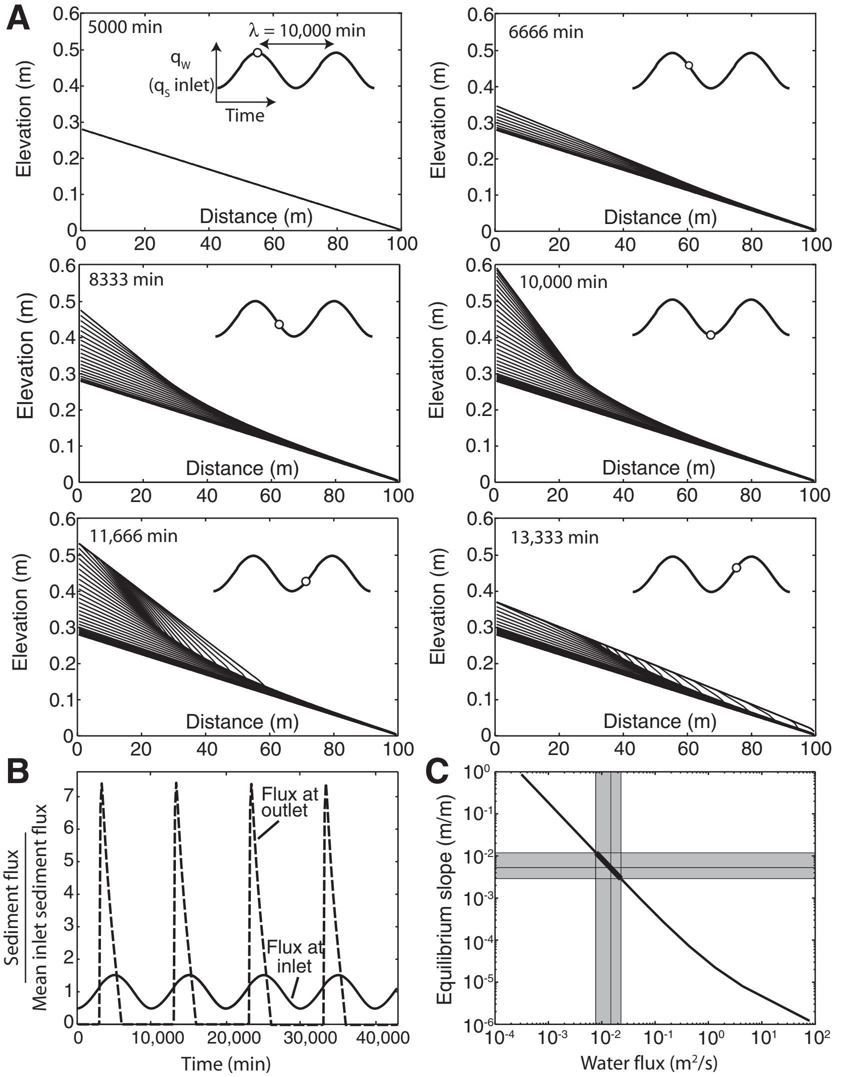

Figure 1. Response of model river to sinusoidal variations in water flux. The water flux (q_w) has a period of 10,000 min and varies by a factor of three. Inlet sediment flux (q_s) covaries with the water flux because the sediment concentration is held constant. A: Evolution of longitudinal river profiles and fluvial stratigraphy over one complete water flux cycle. Lines are plotted regularly every 166 min. Inset white circled dots show the current position relative to the water flux cycle. B: Sediment fluxes at the inlet (solid line) and outlet (dashed line) of the river, both normalized to the mean inlet sediment flux. C: Equilibrium slope of the river as a function of water flux (black line) showing the range of variability investigated in this simulation (bold segment).

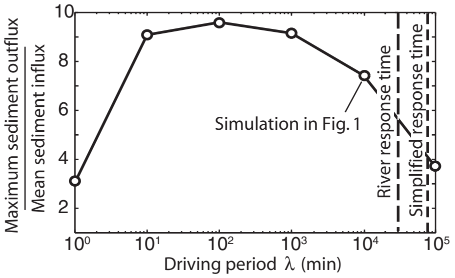

Figure 2. Sediment outflux amplitude response for six simulations driven with water flux cyclicity with different periods. Except for the driving period, all other parameters are held constant. The sediment outflux is strongly amplified, even though most periods investigated are significantly shorter than the characteristic time required for a river to recover from a perturbation (river response time), calculated from Equation DR1 in the Data Repository (see footnote 1) using φ = 0.4, S^e = 0.012, S^o = 0.0028, L = 100 m, q_s = 0.0000156 m²/s. For comparison, we also show a simplified river response time based on the widely applied relation $\tau = \frac{\langle S \rangle L^2}{q_s}$ where ⟨S⟩ is the mean slope (Métivier and Gaudemer, 1999).

that millennial-scale variations in water flux will have a major impact on the supply rate of sediments from major river systems, even when system response times exceed 10^5 yr.

Model rivers forced with sediment flux cycles, introduced via a sinusoidal variation in the input sediment concentration while the water flux is held constant, exhibit markedly different behavior (see also van den Berg van Saparoea and Postma, 2008). We find that during the times when the sediment influx is increasing, the river is forced to increase its equilibrium slope, resulting in aggradation (Figs. 3A and 3B). This additional storage of sediment in the river system reduces the amount of sediment passing downstream and therefore decreases the amplitude of the sediment outflux relative to the influx (Fig. 3C). Conversely, when the inlet sediment flux decreases, the river is forced to reduce its equilibrium slope by downcutting. This liberates mass stored in the river system, leading to an increased sediment outflux. In both cases, the change in sediment flux with time at the outlet has the opposite sign to that at the inlet, so the system response is one of negative feedback and dampening, though no diffusion or period attenuation is observed. This behavior is related to the weak positive correlation between the sediment concentration and the equilibrium river slope (Fig. 3B). For this scenario, the amount of dampening increases strongly when the driving frequency approaches the system response time (Fig. 3D). We conclude that sediment pulses originating from multimillennial-scale variations in sediment concentration (e.g., with a period $\geq 10^4$ yr) are unlikely to be transmitted through large river systems (e.g., >300 km long with response times of $\geq 10^5$ yr) to the downstream sedimentary record.

DISCUSSION

Previous studies have highlighted the importance of floodplain processes in modulating the sediment outflux of river systems (Castelltort and Van Den Driessche, 2003; Métivier and Gaudemer, 1999; Allen, 2008). Our simulations confirm the notion that alluvial channels provide a temporary sink for sediments during periods of aggradation, something which decreases the amplitude of sediment pulses passing downstream. However, equally important is the possibility that channels provide a source of sediments that can become liberated during phases of downcutting, resulting in the release of large sediment flux pulses downstream (Goodbred, 2003; van den Berg van Saparoea and Postma, 2008). Both scenarios imply that during phases of rapid climate change, at any one time there will normally be disparity between the amount of sediment supplied from upstream catchments and that delivered farther downstream. This disequilibrium between input and output fluxes is recorded in fluvial terrace successions. For example, field data from the Rhine and Meuse Rivers (northwest Europe) indicate that the slope of aggradational terraces decreased from 0.00028 to 0.00013, while the fluvial style

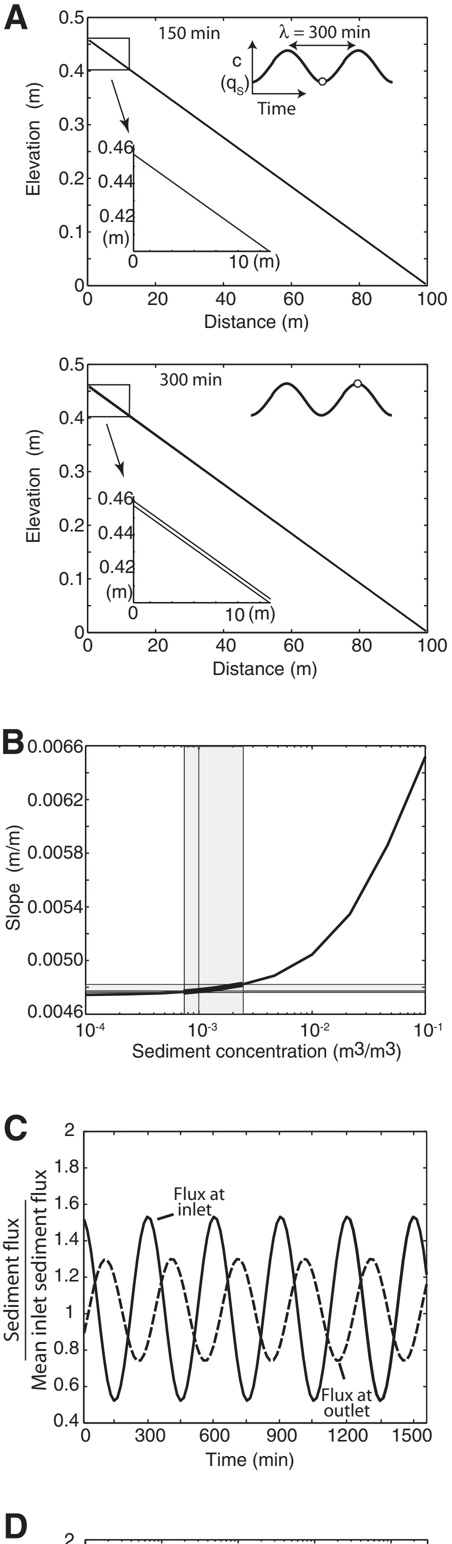

Figure 3. Response of model rivers to sinusoidal variations in sediment concentration. A: Evolution of longitudinal river profiles and fluvial stratigraphy over half of one sediment concentration cycle with a period of 300 min. The input sediment concentration and sediment flux (q_s) vary by a factor of three. Inset plots show zoom of the highest and lowest stratigraphic profiles. Minor aggradation occurs as the sediment influx increases, and minor downcutting takes place as the sediment influx decreases, neither of which is easily observed at this scale. This is due to the weak dependency of the equilibrium slope on sediment concentration, as shown in B. B: Equilibrium river slope versus sediment concentration. Bold segment shows the range of variability investigated in this simulation. Note that vertical scale is linear, whereas it was logarithmic in Figure 1C. C: Sediment fluxes at the inlet (solid line) and outlet (dashed line) of the river, both normalized to the mean inlet sediment flux. D: Sediment outflux amplitude response for eight simulations driven with sediment concentration cycles with different periods, all other parameters held constant. River response time was calculated with Equation DR1 in the Data Repository (see footnote 1) using $\varphi = 0.4$, $S^e = 0.004789$, $S^o = 0.004757$, $L = 100$ m, $q_s = 0.0000156\ \mathrm{m^2/s}$. Note that the sediment outflux is always dampened with respect to the input signal, whereas the opposite behavior is observed with water flux cycles shown in Figures 1 and 2.

changed from braided to meandering, between late Pleistocene and Holocene times (Huisink, 1997; Berendsen and Stouthamer, 2002). If it is assumed that this slope change occurred over the entire length of the Rhine River (1200 km), it would generate a Holocene-averaged sediment flux pulse of ~5700 m^2/yr, more than six times the current mean annual sediment flux (estimated to be ~880 m^2/yr). This possibility is consistent with a rapid increase in the sediment load recorded in the Rhine-Meuse delta over the latter half of the Holocene (Erkens et al., 2006). Our calculations show that this significant decrease in slope could be the result of a very modest increase in mean water flux from 3.7 to 5.7 m^2/s. A slope decrease of this magnitude cannot be explained by decreasing the sediment concentration, though it could be influenced by other factors such as varying the sediment grain size. Nevertheless, because the slope of a river system is highly sensitive to the water flux (Fig. 1C), small changes can have a major impact on the amount of sediment stored in river valleys, when they are sustained for millennial timescales. Many other large river systems show similar evidence for disequilibrium between modern and time-averaged post–Last Glacial Maximum sediment loads (Fig. 4A), which we interpret as further evidence for phases of temporary floodplain storage and release. These data differ markedly from flux estimates based on sediment volumes integrated over multiple climate cycles (Métivier and Gaudemer, 1999) or cosmogenic-derived sediment loads (e.g., Wittmann et al., 2011) that show apparent consistency between modern sediment fluxes and time-averaged values. Although this relationship has been suggested to indicate that sediment fluxes have remained constant through time despite major variations in the rate of sediment supply to rivers (for example, due to diffusive floodplain buffering), our simulations

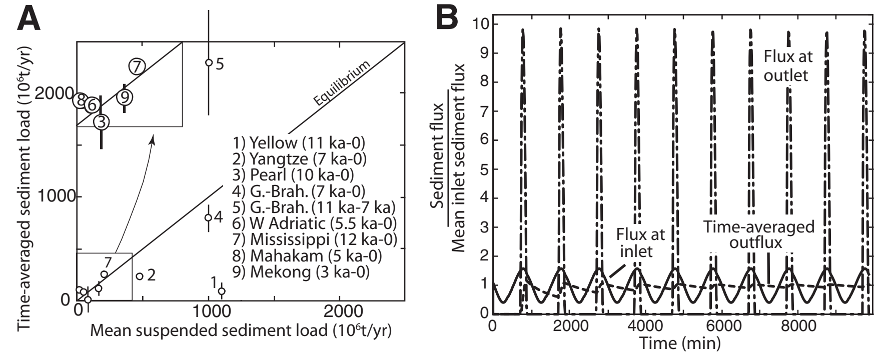

Figure 4. Disequilibrium sediment fluxes in natural and model rivers. A: Mean actual suspended sediment loads compared with time-averaged total sediment loads for several large modern river systems since the Last Glacial Maximum. Inset legend refers to the river, averaging time interval, and data source (1—Liu et al., 2001; 2—Yang and Liu, 2007; 3—Liu et al., 2009; 4–5—G.-Brah. (Ganges-Brahmaputra), Goodbred and Kuehl, 2000; 6—Cattaneo et al., 2003; 7—Blum and Roberts, 2009; 8—Storms et al., 2005; 9—Xue et al., 2010). Vertical lines show errors estimated on the basis of age and volume uncertainties (only shown when data are available). Upper left inset shows a blowup of data points in the lower left part of the diagram. Rivers with sediment loads that have remained constant since the late Pleistocene are expected to fall on the diagonal "equilibrium" line. B: Sediment fluxes in a numerical simulation where the water flux varies by a factor of three and has a cyclic periodicity of 1000 min. Note that, although the output sediment flux (dashed-dotted line) is highly episodic and amplified relative to the input flux (solid line), the time-averaged sediment outflux (dashed line) smoothes the true variability, even for timescales of less than one cycle period. This apparent smoothing of the output signal is clearly methodological rather than physical in origin.

show that estimations of the sediment outflux based on time-averaged data are a poor recorder of the true sediment outflux variability, reflecting instead the mean sediment outflux (Fig. 4B). Thus, we interpret the apparent constancy of sediment flux over million-year timescales to be an artifact caused by the inability to invert highly episodic sediment flux records from time-averaged sediment volume data.

Our study shows that whether sedimentary signals are faithfully transmitted to downstream archives depends fundamentally on the nature of the external perturbations. For example, sediment flux signals resulting from variations in sediment concentration for a constant water discharge will tend to be strongly buffered, while those arising from variations in water discharge are more likely to be transmitted and potentially even amplified (see also van den Berg van Saparoea and Postma, 2008). This difference in behavior could mean that climatic cycles involving changes in water discharge are more likely to be registered in the sedimentary record than perturbations that influence only the sediment flux (for example, change in the slip rate on a fault). Other studies have shown that downstream transmission of environmental signals also depends on the relative frequency and amplitude of perturbations compared to that of the inherent (autocyclic) variability of sediment transport (Jerolmack and Paola, 2010). Although the subcritical flow regime (Froude number less than 1) of the simulations presented here precludes autocyclic behavior, self-propagating cyclic steps and associated autogenic sediment outflux cycles are observed with our model when Froude numbers exceed 1 (see also Fagherazzi and Sun, 2003). Further research will determine the extent to which such autocyclicity is capable of filtering environmental signals in river models.

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