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Model analyses of the contribution of in-channel processes to sediment concentration hysteresis loops

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SUMMARY

Sediment concentration (*SC*)–water discharge (*Q*) relations in rivers are typically governed by multiple and relatively complex processes. Due to hysteresis effects, sediment discharges can differ for similar or equivalent water discharges, which causes scatter in empirical datasets and may decrease the predictive power of *SC* rating curves. Such hysteresis effects must therefore be understood and accounted for to make dependable predictions for river system management. The overall objectives of this study are to develop modelling approaches suitable for reproducing and predicting hysteresis effects at larger scales and to investigate the possible contribution of in-channel processes (erosion and deposition) to sediment concentration hysteresis loops. To investigate relevant field-scale conditions, we develop a one-dimensional dynamic sediment transport model of the downstream Tuul River (northern Mongolia), investigating in-channel processes along a 141 km stretch during a hydrological year. The results show that the present modelling approach can reproduce both anti-clockwise and clockwise hysteresis effects. Importantly, in-channel processes alone can cause considerable anti-clockwise hysteresis effects without being reinforced by catchment processes such as hillslope erosion. Such specific contributions from in-channel processes introduced data scatter into the sediment rating curves, decreasing their R^2-values from unity to approximately 0.5 to 0.6. More generally, possible changes in the number or magnitude of high-flow events, caused by climatic or other anthropogenic factors, could influence total sediment deposition, which was primarily found to occur during relatively short high-flow events. Such potential changes also have important implications for the possible spreading of polluted sediments.

1. Introduction

Single hydrological flow events can substantially contribute to riverine sediment transport (Smith et al., 2003; López-Tarazón et al., 2009; Ollivier et al., 2010). Knowledge on the magnitude and variability of event-based sediment loads is essential for the protection planning and management of river systems, including their contaminants and ecosystems (Lisle, 1989; Graf, 1996; Törnqvist et al., 2011; Cofalla et al., 2012; Destouni et al., 2013). In natural river systems, sediment transport hysteresis can be observed to varying extents (Lawler et al., 2006; Fan et al., 2013); thus, sediment discharge is variable for similar or equivalent water discharges. Furthermore, sediment concentration (*SC*)–water discharge (*Q*) hysteresis loops can vary from clockwise to anti-clockwise. Clockwise hysteresis loops occur when the *SC* peak arrives before the *Q* peak. The *SC* is then generally greater during the rising limb of a flow hydrograph than during the falling limb. Clockwise hysteresis loops are often related to the depletion of readily available sediment sources and the associated dilution of suspended sediment concentrations (Bača, 2008). High *SC*–*Q* skewness can occur when the bed load constitutes a considerable portion (>30%) of the total sediment load (Alexeevsky, 1998), such as in the presence of large in-channel sediment sources (e.g., submerged bars). Anti-clockwise hysteresis loops occur when the sediment delivery to the river channel is limited at the beginning of an event. These loops can, for instance, be associated with catchment processes that delay the sediment delivery from the upper portions of a river basin (Hughes et al., 2012). Furthermore, anti-clockwise loops can be a result of the delivery of fine-grained material from disturbed floodplains, including mining sites (Chalov, 2014).

The *SC*–*Q* relations in rivers are typically governed by multiple and relatively complex processes (Hudson 2003; Lawler et al., 2006; Lefrançois et al., 2007), such as hillslope erosion within catchment areas (Nadal-Romero et al., 2008; Runkui et al., 2010), sediment wave dispersion (Bull, 1997), upstream floodplain

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sedimentation (Asselman and van Wijngaarden, 2002) or an abrupt erosion of river banks (Lefrançois et al., 2007). In many cases, the net effect of such varied processes is quantified empirically based on historical observation data. Commonly, these relations take the power law form: $SC = aQ^b$, where a and b are regression coefficients (Asselman, 2000). However, the above-mentioned hysteresis effects cause scatter in the empirical datasets, which must be understood and considered to enable dependable predictions for river system management. A primary challenge is therefore to identify key governing processes and their relative contribution to such hysteresis, particularly at large-catchment scales, where many of the processes are less well investigated or understood than at smaller scales (Williams, 1989; Alexeevsky, 1998; Jarsjö et al., 2012; Törnqvist et al., 2015).

For example, in addition to catchment and floodplain processes, spatiotemporal shifts in the channel characteristics, such as its cross-sectional shape, gradient and/or bed material conditions, can also potentially contribute to hysteresis in *SC*–*Q* relations (Kleinhans et al., 2007; El kadi Abderrezzak and Paquier, 2009). These in-channel changes are generally caused by natural processes, such as erosion and deposition, and reflect spatiotemporal sediment storage conditions. The exchange of sediments on a channel bed can be very dynamic under transient flow conditions (Ciszewski, 2001), particularly in relation to the longer timescales of floodplain storage (Walling et al., 1998). Although in-channel dynamics clearly contribute to the variability in sediment yield along rivers (Smith and Dragovich, 2008) through erosional/depositional processes that cause differences between upstream and downstream sediment loads (Owens et al., 1999; Smith et al., 2003), questions remain regarding whether and to what extent in-channel processes contribute to hysteresis effects.

The overall objectives of this study are to develop modelling approaches suitable for reproducing and predicting hysteresis effects at larger scales and to investigate the possible contribution of in-channel processes to sediment concentration hysteresis loops. These aims also include more detailed assessments of the dynamics of in-channel sediment bed storage and gradation changes throughout a hydrological season and within single hydrological events. To this end, we use a one-dimensional dynamic sediment transport model supported by field observations in the Tuul River (northern Mongolia), which is characterised by a natural hydrological regime unaffected by engineered structures.

2. Materials and methods

2.1. Site description

The Tuul River is located in the Mongolian (upper) portion of the Selenga River Basin, which collects the majority of the runoff within the Lake Baikal Basin (Fig. 1a), located in southern Siberia (Russian Federation). The Tuul River flows from the Khetei mountain range to the Orkhon River, passing through the most populated area in Mongolia, the city of Ulan Bator, in its upstream portion. The area of the Tuul River Basin is approximately 50,000 km^2. The annual average air temperature at the Ulan Bator station is −0.8 °C, and the monthly means vary between −21.5 °C in January and 17.1 °C in July. The annual precipitation of the basin varies between 275 mm in its middle reaches and over 400 mm in the most upstream and downstream reaches of the river. The precipitation in the basin occurs mainly as rainfall in the warm May–August period. The annual mean discharge of the Tuul River at the Ulan Bator gauging station is 27 m^3/s, and the maximum recorded discharge since 1945 is 1580 m^3/s (Davaa and Odgarav, 2012).

During winter (November–March), the Tuul River channel is covered with thick ice, and its discharge is negligible. However, recent observations indicate a decreasing duration and thickness of the ice cover (Punsalmaa et al., 2004), which may reflect climatic changes in the region. Other indicators of climate change in the region include extended low-water periods in the lower (Russian) part of the Selenga River in recent decades (1976–1982 and 1996–2011; Chalov et al., 2015; Berezhnykh et al., 2012; Shimarayev and Starygina, 2010). Such hydrological changes have also been observed in the upper (Mongolian) portion of the Selenga River (Garmaev and Khristovorov, 2010; Davaa and Odgarav, 2012). Long-term hydrological data (1945–2012) for the Tuul River and the downstream sections of the river network (Orkhon River) demonstrate a low-water period since 1996 (Fig. 2a). However, in the Tuul River Basin, higher discharge conditions were observed during the most recent hydrological years (2012 and 2013; Centre of Register of Hydrotechnical Constructions, 2014). In addition, the annual maximum discharges have decreased since the mid 1990s (Fig. 2b). This is consistent with the observed pattern in the Selenga River Basin, where the maximum discharges have decreased and the minimum discharges have increased, which may reflect permafrost thaw in the basin (Törnqvist et al., 2014).

This study focuses on a 14 km long reach (called the focus reach) located approximately 104 km from the confluence of the Tuul and Orkhon rivers (Fig. 1c). The modelled reach of the river was much longer (Fig. 1b) than that to sufficiently separate the focus reach from the model boundaries and their influences (see also Section 2.2.4). The entire modelled reach of the Tuul River extends 245 km upstream of the confluence with the Orkhon River (Fig. 1b).

The geomorphology of the valley of the downstream Tuul River varies from quite wide with relatively flat floodplains (especially in the upper part) to narrow and more v-shaped in hilly areas. The average slope of the focus reach is 0.0004 (m/m), which is preceded by a long reach with an average slope of approximately 0.001 (see the Supplementary Information for a more detailed description). The channel of the focus reach is meandering, which is also the case for approximately 68% of the modelled reach of the Tuul River. This channel pattern is associated with abundant horizontal and vertical channel changes (Alexeevsky et al., 2013). In its most downstream reaches, the Tuul River crosses a mountainous area. This portion of the river has an incised channel containing extended straight reaches, which indicate stable channel conditions. The topography and vegetation of the Tuul River Basin is typical for a grassland steppe, with occasional shrub cover in the vicinity of water bodies. The natural steppe ecosystem and landscape of the downstream Tuul River valley, however, is disturbed by expanding placer gold mining. As shown in Fig. 1b, the mines are distributed over a large distance beginning just upstream of the focus reach. Previous studies of the mining activity indicate severe environmental impacts on the bodies of water downstream of the Tuul River and on Lake Baikal (Ferrington, 2000; Stubblefield et al., 2005; Byambaa and Todo, 2011; Thorslund et al., 2012).

2.2. Numerical modelling

HEC-RAS 4.1 is a one-dimensional modelling software package that allows the performance of four different river analyses: (1) steady flow, (2) unsteady flow, (3) water quality (organic matter) and (4) movable boundary sediment transport computation, which is used in this study. All four components of the model use common geometric data and common geometric and hydraulic computation routines (USACE, 2010a). The HEC-RAS sediment transport module has been successfully implemented in studying both relatively short (Zhang and Duan, 2011) and long, exceeding 300 km,