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Research papers

Impacts of large dams on the complexity of suspended sediment dynamics in the Yangtze River

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ABSTRACT

The Yangtze River is one of the largest and most important rivers in the world. Over the past several decades, the natural sediment regime of the Yangtze River has been altered by the construction of dams. This paper uses multi-scale entropy analysis to ascertain the impacts of large dams on the complexity of high-frequency suspended sediment dynamics in the Yangtze River system, especially after impoundment of the Three Gorges Dam (TGD). In this study, the complexity of sediment dynamics is quantified by framing it within the context of entropy analysis of time series. Data on daily sediment loads for four stations located in the mainstem are analyzed for the past 60 years. The results indicate that dam construction has reduced the complexity of short-term (1–30 days) variation in sediment dynamics near the structures, but that complexity has actually increased farther downstream. This spatial pattern seems to reflect a filtering effect of the dams on the on the temporal pattern of sediment loads as well as decreased longitudinal connectivity of sediment transfer through the river system, resulting in downstream enhancement of the influence of local sediment inputs by tributaries on sediment dynamics. The TGD has had a substantial impact on the complexity of sediment series in the mainstem of the Yangtze River, especially after it became fully operational. This enhanced impact is attributed to the high trapping efficiency of this dam and its associated large reservoir. The sediment dynamics "signal" becomes more spatially variable after dam construction. This study demonstrates the spatial influence of dams on the high-frequency temporal complexity of sediment regimes and provides valuable information that can be used to guide environmental conservation of the Yangtze River.

1. Introduction

Rivers play a vital role in human society by providing water to support agriculture, municipal needs, power generation, navigation, and recreation. To help meet human demands, many rivers in the world are now regulated by dams. The negative environmental effects of dams and reservoirs on river systems have been well documented. These structures disrupt river continuity by altering flow regimes, sediment fluxes, and thermal characteristics (Yang et al., 2002; Nilsson et al., 2005; Syvitski et al., 2005; Graf, 2006; Wang et al., 2007; Li et al., 2011; Yang et al., 2014, 2015). The impact on sediment fluxes can be especially pronounced because large dams impede the movement of transported material, which becomes deposited in reservoirs. In China, the annual sediment loads of large dammed rivers, such as the Yangtze River and the Yellow River, have declined markedly due to human activities (Li et al., 2011; Walling, 2006; Wang et al., 2007). Altered sediment regimes induced by dam construction often result in changes in the geomorphology, physical habitat and biodiversity of river channels downstream from dams (Rossi et al., 2009; Wang et al., 2011, 2012).

The Yangtze (Changjiang) is the longest river in Asia and one of the largest in the world. A large number of dams have been built in the Yangtze River basin in the last few decades. Most major and medium-size dams have been constructed on the mainstem and tributaries in the upstream portion of the basin. The largest dam in the world, the Three Gorges Dam (TGD), is located in the upper reaches of Yangtze River. Since impoundment of water began in 2003, the Three Gorges Dam and its associated reservoir, which has a storage capacity 3.93×10^{10} m^3, have dramatically altered sediment fluxes in the middle and lower reaches of the river

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(Dai and Liu, 2013). Ten years after the dam became operational, the sediment flux declined dramatically, but now appears to be stabilizing at a new long-term average (Dai and Liu, 2013). Considerable attention has been focused on how reductions in sediment load have affected the sedimentology and geomorphology of the river channel and floodplain (Chen et al. 2010), the stability of sediment rating curves (Hu et al. 2011), and patterns of sedimentation and erosion within the river (Yuan et al., 2012, 2014). Constructions of dams, along with soil conservation measures and bank protection, have reduced the flux of sediment from the Yangtze River to the East China Sea (Dai et al., 2016). Many studies have examined the consequences of dam construction along the Yangtze River on seasonal or annual variations in sediment loads (Yang et al., 2006a, Zhang et al., 2009, 2012, Li et al., 2011, Luo et al., 2012, Dai and Lu, 2014, Yang and Yang, 2015, Yang et al., 2007, 2015), but no investigation to date has examined how dams have influenced high-frequency suspended sediment dynamics over time scales of days to weeks.

Rivers can be viewed as complex nonlinear dynamic systems. The nonlinear dynamics of these systems result in deterministic uncertainty of characteristics of river hydrology, including temporal variations in flow or sediment concentration. Sediment dynamics refers to the temporal variability in the transport of sediment within river systems. Entropy provides a measure of the complexity of dynamical systems, where complexity is associated with the degree of uncertainty (i.e., disorderliness, randomness, or irregularity) of temporal signals generated by system dynamics. A highly irregular signal, like white noise, will have high entropy, whereas a highly regular signal, like a sine wave, will have low entropy (Li and Zhang, 2008; Sang et al., 2015). Traditional entropy theory has been widely used in hydrological analysis (Mays et al., 2002; Maruyama et al., 2005; Ozkul et al., 2000; Wang et al., 2004; Liu et al., 2016). Traditional methods yield entropy measures at a single time scale, rather than characterizing the underlying dynamics of the system over multiple time scales. Multi-scale entropy analysis of biological phenomena (Costa et al., 2002) has been used to evaluate system complexity at multiple scales. Subsequently, hydrologists have used multi-scale methods to examine the complexity of time series of discharge, including the influence of dam construction on hydrological complexity (Li and Zhang, 2008; Zhou et al., 2012). These developments suggest that multi-scale entropy analysis is a useful tool for examining the complexity of sediment dynamics in river systems, particularly systems that have been altered by the construction of dams, such as the Yangtze River system.

This study uses multi-scale entropy analysis to examine how the construction of dams within the Yangtze River basin has affected the complexity of sediment dynamics of this river system. The objectives of the paper are: (1) to determine the multi-scale entropy of daily sediment load time series prior to and after the construction of dams and (2) to assess how dams influence the complexity of sediment along the river, especially after the TGD started impounding water. Changes in multi-scale entropy provide insight into how dam construction has altered the complexity, and therefore uncertainty, of fluvial sediment dynamics.

2. Conceptual and methodological framework

2.1. Conceptual framework

Sediment dynamics refers to the temporal variability in the transport of sediment load within river systems. Temporal variation in sediment loads over time provides information on sediment dynamics. The complexity of sediment dynamics within a river system is determined by interaction among sediment availability, hydrological variability, and other factors, such as human modification of watershed processes, that influence temporal variation in sediment transport. The problem of human impact on high-frequency components of temporal variation in sediment load through the construction of large dams, the focus of this study, can be conceptualized as a filtering process (Fig. 1). Large dams, by trapping and storing sediment transported by the river (Nilsson et al., 2005), should fundamentally alter the sediment signal, not only by reducing the amount of sediment, but also by changing temporal variation in the signal. In particular, the trapping and storage effect of dams should act like a low-pass filter that smooths the signal, thereby reducing the irregularity or complexity of high-frequency components of the signal compared to conditions prior to dam construction. Large-scale seasonal or interannual variations of the signal associated with watershed-scale changes in sediment delivery remain distinct, but short-term daily to weekly variations become muted. This filtering effect should be most pronounced immediately downstream of the dams. Farther downstream, as distance from the dam increases, local relative contributions of sediment to the main stem from tributaries will increase, thereby progressively increasing the high-frequency complexity of the sediment signal relative to the characteristics of the signal immediately downstream of the dam. Therefore, complexity should increase with increasing distance from a dam. The extent to which complexity increases depends on the nature of sediment contributions from tributaries downstream of the dam. If the high-frequency complexity of these contributions exceeds that of upstream contributions that are now filtered by the dam, irregularity of the sediment signal following dam construction at river locations far from the dam may actually be greater than the irregularity of this signal prior to dam construction. The result would be an increase in signal complexity relative to predam conditions.

2.2. Methodological framework: Entropy theory and analysis

Entropy theory and analysis provides a tool for exploring the impact of dams on the high-frequency complexity of sediment

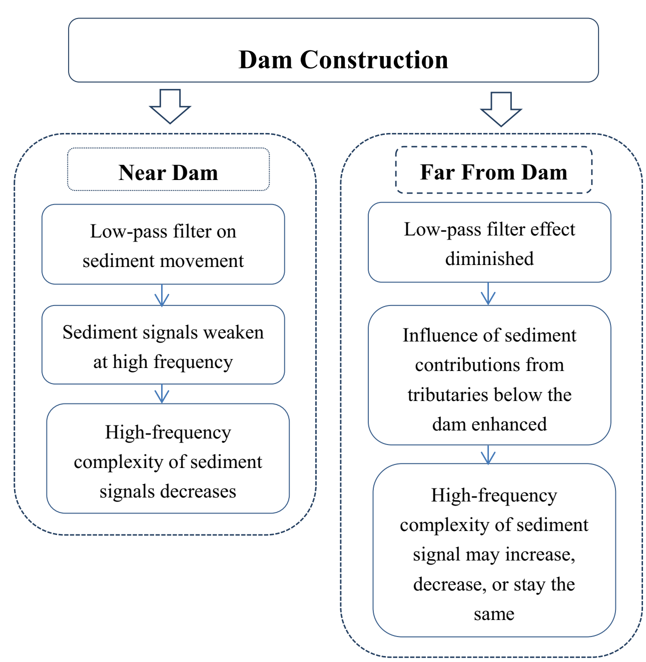

Fig. 1. Conceptual framework illustrating the influence of dam construction on the complexity of river sediment dynamics.