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Original Research

Simulating bed evolution following the Barlin Dam (Taiwan) failure with implications for sediment dynamics modeling of dam removal

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A B S T R A C T

The failure of the Barlin Dam in Taiwan offers an important case study for evaluating concepts in modeling the rapid erosion and channel recovery following intentional and unplanned dam removals. We present a modeling effort that applied a 1D and quasi-2D uncoupled hydraulics and sediment model (NETSTARS) to evaluate how discretization and parameterization influence thefitofbed elevationpredictions to observations following dam failure. Our analysis evaluated the model sensitivity to sediment transport function, active layer thickness, and number of stream tubes used to define the cross-section. Results indicate that a) the model is more sensitive to active layer thickness and sediment transport function than to the number of stream tubes, b) development of dam removal models are likely to benefit from varying the active layer thickness in time, and c) increased lateral discretization does not appear to improve model fit in the steep and rapidly changing river environment at our site. We conclude with discussion on differences between, identifying the need for, and general use of 1D, quasi-2D, and fully 2D models in dam removal and failure analysis.

1. Introduction

The fate of sediment released following dam removals has been the focus of increasing study as dams reach the end of their working life and connectivity is increasingly prioritized for river restoration purposes. Much of this research has emphasized field monitoring (e.g. Doyle et al., 2002; Major et al., 2012; Kibler et al., 2011) of the rates of and patterns in erosion and deposition following the pulse release of sediment with dam removal. Numerical and physical modeling studies are also increasing undertaken (Cui et al., 2006; Cantelli et al., 2007; Wells et al., 2007; Cui & Wilcox, 2008; Downs et al., 2009; Konrad, 2009) in an effort to advance understanding on dam removal impacts and the sediment dynamics of sediment pulses. These numerical modeling efforts include both the development of models specific to dam removal (Cui et al., 2006; Cantelli et al., 2004) and the application of general hydraulic-sediment transport models, including one-dimensional (1D) (Chang, 2008; Rathburn & Wohl, 2003; Wells et al., 2007; Tullos et al., 2010) and quasi-2D and 2D models (Rathburn & Wohl, 2003; SPNP, 2011) to analyze sediment dynamics of dam removal.

However, as many of these efforts have shown, numerical modeling of sediment pulses is a particularly difficult problem (Wu, 2004), in part because channel response depends on a number of spatially and temporally variable site characteristics (Tullos & Wang, 2014) that can be difficult to estimate with certainty and to represent accurately in numerical models. For example, the volume and caliber of sediment stored behind a dam and contributed from upstream of the site can strongly influence channel response to sediment pulses (Pizutto, 2002; Lisle, Cui et al., 2001). However, measurements of sediment characteristics and transport rates, which are needed as input or boundary conditions for sediment models, can be logistically challenging and expensive to collect (Emmett, 1980; Hubbell, 1987), highly variable in space and time (Wilcock et al., 1996; Hubbell, 1964; Gomez, 1991), and generally prone to error (McLean, 1985; Hubbell, 1987). These uncertainties are compounded when applied in the estimation of sediment transport capacity from the various functions available (Gomez & Church, 1989; Barry et al., 2004). Furthermore, the temporal and spatial variability of some site characteristics can also be difficult to represent in hydraulic models. For example, the

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depth and erodibility of the underlying geologic material can be highly variable in space and time and have been shown to influence channel gradient and transport capacity (Goode & Wohl, 2010). Yet, direct measurements of bedrock exposure and incision are uncommon in field surveys (Stock et al., 2005) and bedrock depths are commonly represented as uniform in hydraulic models. In addition, lateral variability in velocities and shear stresses produce local patterns in erosion and deposition (Wilcock et al., 1996). While some authors (Downs et al., 2009) have reasonably argued that 1D numerical simulation of reach-level channel changes is the most appropriate scale for modeling channel responses to sediment pulses, others (Ferguson & Church, 2009) are critical of the ability of 1D models to represent the spatial and temporal variability of sediment dynamics across and down rivers. However, for all of these ways in which modeling may poorly represent reality, it is unclear how important any of omitted details are on predictions of erosion and deposition.

Thus, the broader goal of this effort is to investigate how different representations of channel variability influence fit of post-hoc modeling to field observations of the Dahan River, Taiwan following the failure of Barlin Dam. More specifically, the objectives of this analysis were to a) estimate fit ofa 1D model and of increasing discretization of quasi-2D simulations, based on the hypothesis that quasi-2D simulations better represent lateral variability in erosion and deposition, and b) evaluate sensitivity of the 1D and quasi-2D models to the selection of sediment transport functions and to the treatment of temporal variability in the depth of the active layer thickness. The results contribute to ongoing discussion regarding strategies for modeling dam removal sediment dynamics, based on a case study with an exceptionally large (8.3 million m^3over15 months) pulse of sediment released during a large typhoon in 2007.

In this paper, we briefly review the Barlin Dam failure, report fit of simulated and observed longitudinal profiles, investigate differences in patterns and magnitudes of erosion and deposition between the simulated and observed profiles and cross sections, present results of a sensitivity analysis, and discuss implications for modeling sediment dynamics of dam removal.

1.1. Context and Study Area

We report results of sediment modeling associated with the pulse release of sediment associated with the failure of the Barlin Dam on the Dahan River, Taiwan. Barlin Dam, constructed in 1977, was a 38-m-high concrete gravity dam with rotary-arm gates. It was among the largest of over 100 sediment retention structures built in the catchment to reduce erosion and sediment delivery to Shihmen Reservoir, which is located approximately 40 km downstream and generates municipal, industrial, and irrigation water, hydropower, and flood protection benefits. Barlin's initial storage capacity of 10.5 million $m^3$was filled with sediment by 2003 and bedload material was passed over the dam. In 2004, a 'defense dam' constructed for energy dissipation immediately downstream of Barlin Dam was damaged due to undercutting, which allowed incision to propagate upstream to the base of Barlin Dam. Barlin Dam then failed during Typhoon WeiPa in September 2007, a roughly 5-year return event with an estimated peak discharge of 225 cms (Tullos & Wang, 2014).

The Dahan River drains a geologically-active 1,163 km^2 basin in the northern Central Range of Taiwan (Fig. 1). Steep hillslopes (exceeding 55% in over two-thirds of the drainage basin), fractured bedrock, and intense monsoonal precipitation (over 2000 mm annually), result in frequent landsliding and sediment yields that are among the highest in the world (Milliman & Syvitski, 1992; Huang, 1994; Dadson et al., 2003). At the Yufeng gauging station, located approximately 22 km upstream of the former Barlin Dam site (Fig. 1), the long-term (1957–2002) suspended sediment yieldis 0.583 million tons per year, based on rating curves

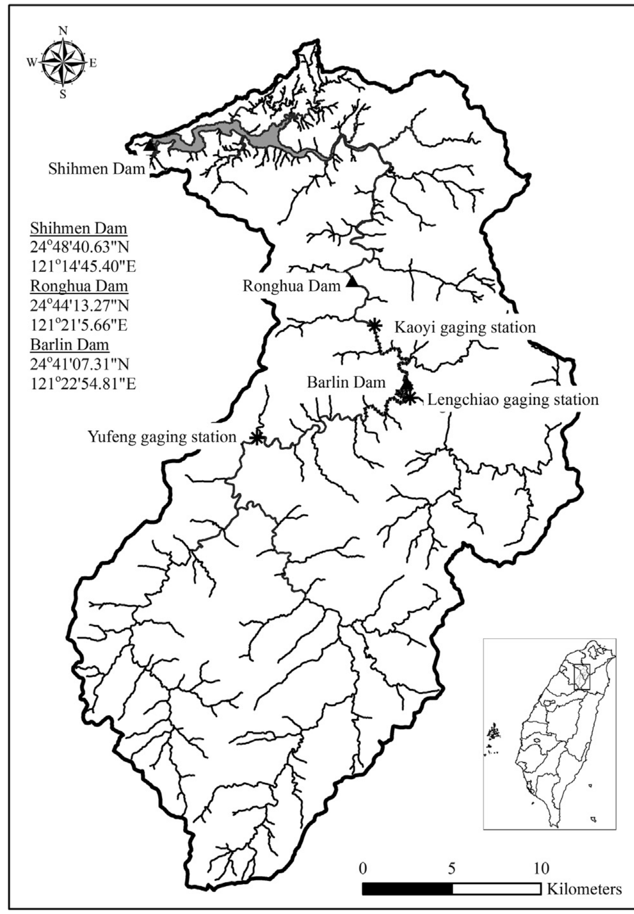

Fig. 1. Map of the Dahan River catchment in Taiwan. The frame indicates the simulation reach. Inset: location map of Dahan River basin.

developed by Shihmen Reservoir Administration (2006). With suspended load comprising approximately 70% of the total load (Dadson et al., 2003), the average annual bedload at the Yufeng station is estimated to be 0.251 million metric tons.

Within the study reach, defined by the former reservoir extending 4.8 km upstream and 5.2 km downstream of the former dam site, the Dahan River is a forced-meander river with bedrock locally exposed along the margins of the river. The valley gradient is 0.01 and sinuosity is approximately 1.6. Prior to dam failure in 2006, the mean reservoir width was 116 m while the mean width of the downstream channel was 155 m, owing to differences in valley configurations of the two reaches. Substrate varied between years as a function of landslide inputs and the frequency and magnitude of high flows. In 2007, prior to dam failure, both the reservoir and downstream substrates were dominated by very fine gravel, with mean D_{50} of 3.9 mm and 2.1 mm, respectively. A major tributary (Sankuan Creek, catchment area = 392 km^2) enters the Barlin impoundmentapproximately 1500 m upstream of the dam (Fig. 1). While we have no quantitative information about the depth of bedrock in our study reach, the authors observed bedrock exposure along the margins and lining the valley walls near the dam, and that the exposure varied in space.

2. Methods

2.1. Observed erosion and deposition

We analyzed fifty cross-sections from bathymetric field surveys conducted by the Taiwan Water Resources Agency (WRA) on