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Morphological evolution of the North Fork Toutle River following the eruption of Mount St. Helens, Washington

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ABSTRACT

The North Fork Toutle River (NFTR) has undergone extensive morphological changes following the catastrophic eruption of Mount St. Helens, Washington, in 1980, especially the upper reaches affected by a 2.5-km^3 debris-avalanche deposit caused by the eruption. This paper reports analysis and interpretation of vertical adjustments to the thalweg long-profile at some 33 km river reaches redeveloped on the debris-avalanche deposit during the 30-year period since the eruption. The results confirm that adjustments in the upper part of the study reaches have generally been led by degradation, while that in the lower reaches have been led by aggradation, with the middle reaches acting as a hinge zone. Trends of change in the thalweg long profile and bedslope reveal that channel gradients have decreased nonlinearly through time and with distance downstream from the volcano. Values of stream power have decreased with time commensurately owing to reductions in slope and channel widening (while the bed has coarsened) so that rates of erosion of the debris-avalanche deposit in the upper NFTR have slowed to the point that the long profile, now perched and slightly steeper, is relaxing toward a new equilibrium or graded condition. Thirty-year relaxation paths for thalweg elevation were simulated at seven key cross sections using newly developed, comprehensive rate law models based on nonlinear decay in rates of morphological response to perturbation. The results indicate that both single- and multistep rate law models can simulate the observed records. Consequently, the rate law approach provides an effective method for studying and simulating morphological response of the fluvial system to a major, instantaneous disturbance, such as a volcanic eruption.

1. Introduction

An alluvial river can be represented as an open system, in which mass and energy transfer takes place across the boundaries (Leopold and Langbein, 1962). An important characteristic of the river system is its capacity for self-regulation through the operation of negative feedback mechanisms that moderate the effects of external perturbation and promote recovery (Knighton, 1998). A relaxation time is needed for it to respond to disturbance through a series of damped, oscillatory changes that tend to achieve a balanced state between flow, sediment conveyance, and channel form (Graf, 1977; Brunsden and Thornes, 1979; Knighton, 1998). Therefore, morphological adjustments of rivers generally lag behind changes in process intensity indicating the important characteristic of delayed response of the fluvial system (Knighton, 1998; Wu et al., 2012). As a result of delayed response, river adjustments are most intense immediately following perturbation, with rates of change slowing and becoming asymptotic as a relaxed condition or equilibrium state is approached (Graf, 1977; Williams and Wolman, 1984; Qian et al., 1987; Simon, 1992; Church, 1995; Surian and Rinaldi, 2003; Nanson and Huang, 2008). Overall, the response of the fluvial system to disturbance generally lags behind external changes and is characterized by a nonlinear, asymptotic adjustment rate so that the system tends to achieve a steady or equilibrium state.

On the basis of the characteristics of channel adjustment mentioned above, many studies have attempted to develop quantitative methods for simulating the relaxation processes of disturbed fluvial systems. For example, in light of the well-recognized nonlinear decreasing rate of channel adjustment, nonlinear decay functions have been used to describe relaxation paths and recovery times of multiple morphologic parameters in disturbed fluvial systems. Of all the nonlinear decay functions, the rate law (an exponential decay function) has been most widely used since the pioneering work of Graf (1977), which introduced the rate law into fluvial geomorphology (Simon, 1992; Hooke, 1995; Madej and Ozaki, 1996; Simon and Thorne, 1996; Richard, 2001; Soufi, 2002; Surian and Rinaldi, 2003; Kasai, 2006; Wu et al., 2008a,b; Leon et al., 2009). Although not as delicate and theoretically robust as numerical models, the rate law approach has been applied as a relatively simple and efficient way to describe

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the relaxation paths of river channel changes during decades or longer time periods. For instance, Simon and Robbins (1987) used exponential equations to calculate decadal gradient adjustments triggered by channel modification in the South Fork of the Forked Deer River, west Tennessee, and obtained satisfactory results. Adopting an exponential model for transient slope adjustment, Leon et al. (2009) estimated that the Rio Grande River, New Mexico, needed about 20–25 years to finish 90% of slope adjustment to obtain equilibrium. Similarly, Richard (2001) applied negative exponential equations to predict some 80 years of changes in channel width downstream of a dam at Rio Grande. Surian and Rinaldi (2003) argued that bed-level adjustments of two disturbed, Italian rivers during the last century could also be described by exponential decay functions.

Despite the wide application, the rate laws employed by most researchers are relatively simple functions of time as disturbance and the essential physical mechanisms have generally not been fully considered. Moreover, most of the simple mathematical equations developed based on the rate law can only describe the decreasing or increasing process of parameters of fluvial systems and are incapable of predicting the forms or sequences of transitional geometries displayed by frequently disturbed channels (Wu et al., 2012). Recognizing the limitations inherent to existing rate law methods and applications, Wu et al. (2012), also based on the basic rate law, presented a general framework including three morphological response models for the prediction of morphological adjustment in disturbed fluvial systems. These models in the framework are generally more complex in forms and applications than those exponential decay functions used earlier, but they consider the delayed response of channel adjustment, making them capable of representing variable relaxation paths and times for a range of characteristic morphological parameters in the fluvial system (Wu et al., 2012). These models in the framework, referred to as rate-law models or the delayed-response models, were successfully applied to simulate the sequence of morphological responses of river reaches downstream of Hoover and Davis dams in the Colorado River, the Yellow River and its tributaries (Wu and Li, 2011; Wu et al., 2012).

The dramatic and fast adjustment of the North Fork Toutle River (NFTR) following the catastrophic eruption of Mount St. Helens, Washington, on 18 May 1980, provides an exceptional opportunity to study the relaxation paths and times of the fluvial system in response to transient and violent disturbances. The morphological adjustment of the NFTR have drawn wide interest from geologists, geomorphologists, and engineers; and many studies have been carried out to investigate the characteristics of the morphological changes and recovery processes of the river (Meyer and Dodge, 1988; Meyer and Martinson, 1989; Pitlick, 1992; Seal and Paola, 1995; Simon and Thorne, 1996; Dinehart, 1998; Simon, 1999; Major and Mark, 2006; Mueller et al., 2007; Pitlick et al., 2007; Major et al., 2009; Simon and Klimetz, 2012). For example, Meyer and Martinson (1989) analyzed the relaxation paths of the channels of the NFTR following the 1980 eruption and developed a four-stage conceptual model for the channel's adjustment with time. The four stages are consisted of (i) channel initiation, (ii) channel incision with relatively constant width-to-depth ratio, (iii) channel widening and aggradation, and (iv) channel widening accompanied by scour-and-fill with little change in average channel elevation. Moreover, for the adjustment of the NFTR in space, it has been reported that the upper part of the NFTR generally responded by degradation while the lower reaches aggraded, widened, and braided as a result of the excessive input of sediment from upstream in the initial period following the eruption (Simon, 1999). A more specific generalized conceptual model with five stages was proposed to illustrate both vertical and lateral changes at the upstream and downstream channel reaches of the Toutle River system (Simon, 1999).

The spatial adjustment pattern of 'degradation upstream and aggradation downstream' recognized in the NFTR was also observed in fluvial systems affected by eruptions at Mount Pinatubo, Philippines, and Taupo, New Zealand (Hayes et al., 2002; Gran and Montgomery, 2005; Manville et al., 2005); and it is typical behavior of other fluvial systems disturbed by large influxes of sediment in nature (Madej et al., 2009) and in flume experiments (Germanoski and Schumm, 1993; Madej et al., 2009). For instance, long-term cycles of aggradation and degradation with time in response to volcanic activity were also recorded in the western Grand Canyon, Arizona, where it was found that fluctuations in bed elevation were directly related to changes in the water and sediment regimes (Lucchitta et al., 2000). By studying adjustments of channel beds affected by an eruption of Mount Hood, Oregon, Pierson et al. (2011) found that large sediment caused by volcanisms accumulated in channels producing sediment waves, which evolve and propagate downstream by interactions between flow and sediment transport and channel morphology. They argued that cycles of aggradation and degradation observed at fixed points along the channel resulted from the passage of one or more sediment waves through which excess sediment, including not only sediment input caused by volcanism but also that mobilized from ambient channel boundaries, was transported downstream.

Regardless of the many studies on the adjustment of the NFTR following the eruption, a quantitative method for simulating the whole 30+ years' relaxation path of the channel bed aggradation and degradation processes of the NFTR remains rare. As one example for quantitative simulation of the channel bed adjustment of the NFTR, a dimensionless, nonlinear decay function based on the rate law or exponential decay function was used to describe temporal variations in bed elevations and to assess the vertical adjustments at cross sections subjected to different magnitudes of disturbance during about the first 10 years after the eruption (Simon and Thorne, 1996; Simon, 1999). This exponential decay function can be expressed as follows:

$$z/z_0 = a + be^{-kt} \tag{1}$$

where z and z_0 = channel bed elevations at time t (m) and at the initial time $t = 0$, respectively, and a, b, and k = dimensionless coefficients determined by regression. Note that a = the dimensionless elevation (z/z_0) at which Eq. (1) becomes asymptotic, with $a > 1$ for aggradation and $a < 1$ for degradation; b = total change in dimensionless elevation (z/z_0) at which Eq. (1) becomes asymptotic, with $b < 0$ for aggradation and $b > 0$ for degradation; and k indicates the nonlinear rate of change of bed elevation per unit time, the negative sign signifying that this decreases, or decays, as a function of time. Site-specific values of a, b, and k in Eq. (1) were obtained by regression based on observed data in the study time period.

Satisfactory results were obtained by Eq. (1) for cross sections generally underwent aggradation or degradation during the simulated time period. Nevertheless, for cross sections where the channel bed underwent transitional changes between aggradation and degradation, two separate equations with the form of Eq. (1) were fitted to simulate the aggradational and degradational phases, respectively (Simon, 1999). Fig. 1A shows the measured channel bed elevation and the noncontinued calculations at TL1100, a cross section at Toutle River main stem (the location can be found in Fig. 2). Recently, Simon and Klimetz (2012) used a power function relating channel bed elevation with time since the eruption to simulate the 30-year adjustment of channel bed at NFTR. For cross sections characterized by transitional changes of channel bed aggradation and degradation, such as NF345 at NFTR (see Fig. 2 for its location), the aggradational and degradational phases of the channel bed had to be simulated separately (Fig. 1B).

Clearly, a more comprehensive rate law model is needed to simulate the entire fluctuated relaxation path of the channel bed elevation of the NFTR while taking into account the driving forces, such as water and sediment conditions. In this paper, we analyze the 30-year record of adjustments to channel bed elevations in the NFTR, using the latest data available. We then apply the new rate-law models or delayed-