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The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding

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ABSTRACT

Geomorphologists have long studied the impacts of extreme floods, yet the association between the magnitude of flow parameters (discharge, velocity, shear stress, or stream power) and resulting geomorphic effectiveness remains vague and non-deterministic. Attempts have been made to include flow duration and total expenditure of stream power, in combination with peak unit stream power, as important variables, but there has been minimal exploration of this hydraulic combination. Taking advantage of Tropical Storm Irene's rapid track through eastern Vermont (USA) in late summer 2011, this paper presents the array of geomorphic responses to a short duration (time to peak of <8 h) but high magnitude flood that was the twentieth century flood of record for numerous watersheds. We present herein the geomorphic imprint of Tropical Storm Irene flooding within a larger context of fluvial theory concerning the role of, and trade-off between, the magnitude of energy expenditure during a flood and its duration. Focusing on a detailed field effort within the 187-km^2 Saxtons River basin in southeastern VT, augmented by select sites along the adjacent lower gradient Williams River (291-km^2), we elucidate (1) the geomorphic effects of a short duration flood in a humid, well-vegetated landscape; (2) the relationship between geomorphic response and (a) peak stream power, (b) total stream power, and (c) flow duration of stream power above a critical threshold; and (3) the spatial variation of geomorphic effects relative to reach-scale geologic and geomorphic controls. Flooding associated with Tropical Storm Irene ranged from the 1000 year recurrence interval (RI) flood (based on Weibull flood frequency analysis) to the 300 year RI flood (log Pearson Type III). Discharges spawned a peak unit stream power of 712 W/m^2 (Saxtons River) and 361 W/m^2 (Williams River), with total energy expenditure throughout the event of ~16,000 × 10^3 and 15,000 × 10^3 J, respectively. For the Saxtons River, channel widening was spatially infrequent and limited in magnitude; however, other geomorphic effects were profound (1) the entrainment, transport, and deposition of extremely coarse material; (2) stripping of floodplain surfaces; (3) channel avulsions and incision into Pleistocene-aged material; and (4) deposition of coarse material across floodplains. Based on our extensive field data and hydrologic/hydraulic analyses, we contend that short duration, high energy flows can have profound sedimentological effects but have limited erosive, channel widening impacts. Gravel entrainment and deposition of a catastrophic nature can certainly occur under these flow regimes, but the impacts of these extreme flows on channel geometry may have limited expression.

1. Introduction

The geomorphic signature of large floods depends on various intrinsic and extrinsic controls, often limiting a priori predictions. From a probabilistic perspective, extreme floods are rare occurrences but not all extreme floods generate unusual geomorphic impacts. In some instances, there is poor correspondence between a flood's recurrence interval and its immediate geomorphic effect(s) (Dury, 1973; Magilligan et al., 1998; Smith et al., 2010). This conundrum between an event's frequency and associated geomorphic response was partially resolved in the 1980s by shifting the focus away from flood discharge as the appropriate metric to that of flow energy, expressed as either shear stress, τ, or unit stream power, ω (Baker and Costa, 1987), yet flow dynamics do not singularly predict or explain the type and range of geomorphic responses to large floods. Realizing the limitations of flood power magnitude as the sole predictor of geomorphic response, Costa and O'Connor (1995) suggested that the flow duration of energy expenditure above a critical value needed to be incorporated, along with stream power, to better explain the driving forces of geomorphic change. They argue that, in some instances, a long duration event, even slightly above a critical threshold, may generate more pervasive effects than a short duration, but more peaked value for stream power (Fig. 1). Although they present several examples substantiating their

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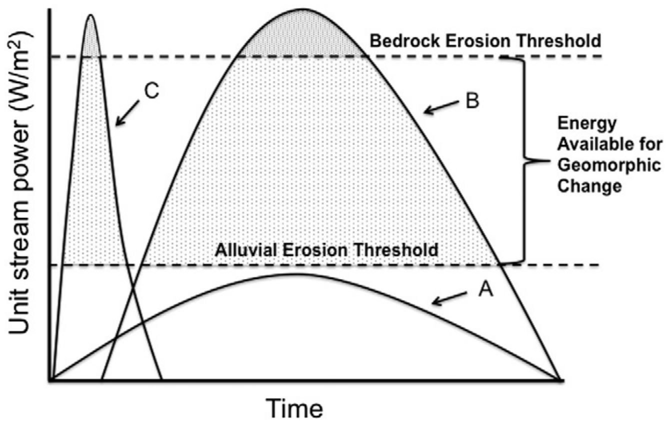

Fig. 1. Conceptual model of Costa and O'Connor (1995) describing the relative role of flow duration and unit stream power in generating a 'catastrophic flood'. Curve A represents a long duration flood but with limited peak unit stream power, perhaps typical of a snowmelt flood along a low gradient reach. Curve B corresponds to moderate to long duration floods with sufficiently high values for peak stream power, generating high mean unit stream power and also large total energy expenditure. Curve C represents floods that generate high peak values for instantaneous unit stream power but are of limited flow duration (modified from Costa and O'Connor (1995).

approach, their conceptual model incorporating the duration of energy expenditure lacks rigorous field-testing, especially at the watershed scale. Taking advantage of Tropical Storm Irene's rapid track through eastern Vermont (USA) in late summer 2011, this paper presents the array of geomorphic responses to a short duration (time to peak of ~8–10 h) but high magnitude flood that was the twentieth century flood of record for numerous watersheds in eastern Vermont.

The efficacy of large floods on landscape formation has long fascinated geomorphologists, generating some of the more impassioned debates in the discipline's history. Having to overcome more than a century's dismissal of catastrophism, J. Harlan Bretz, for example, found minimal acceptance of his extreme flood hypothesis for the formation of the Channeled Scablands (Bretz, 1925; Baker, 2008, 2009) in part because of his questioning of uniformitarianism — a backbone of geologic reasoning. Similarly, even within the realm of meteorologically generated floods, debates still linger about the role of large floods in accomplishing significant geomorphic work (Wolman and Miller, 1960); in generating significant geomorphic change (Baker, 1977; Wolman and Gerson, 1978; Smith et al., 2010); or in spawning lasting effects on landscape form (Wolman and Gerson, 1978). At its most fundamental level, the discussion within fluvial geomorphology centers on the driving forces generating change (e.g., stream power, flood magnitude), intrinsic resistance thresholds (Schumm, 1973), and the timeframe and dominant processes associated with watershed recovery (Costa, 1974a; Wolman and Gerson, 1978; Harvey, 2002).

Although geomorphologists frequently evoke 'catastrophic' or 'extreme' to characterize a given flood's effect on the landscape, no singular definition exists. Broadly speaking, past research has shown that geomorphic impacts from floods may be pronounced where resistance thresholds are low (Baker and Costa, 1987), energy expenditure is enhanced by local and regional controls (Nanson, 1986; Miller, 1990a), and where the timing of coarse and fine sediment inputs coincides with the peak discharge (Cenderelli and Kite, 1998; Magilligan et al., 1998). In some instances, responses may relate to significant erosion, including channel widening (Krapesch et al., 2011), floodplain stripping (Nanson, 1986) or intensified mass wasting (Miller, 1990b; Newson, 2006). In other instances, the catastrophic effects include massive overbank deposition (Knox, 1987, 2006), the transport of channel bed gravels onto floodplains (Ritter, 1975), or the entrainment and transport of coarse bedload material (Eaton and Lapointe, 2001). Broadly speaking, the formative effects of a flood may be considered catastrophic if they exceed the normative range of existing conditions (e.g., largest flood in a long discharge record), if they significantly disrupt 'normal' geomorphic sequences (e.g., overbank flood gravels interrupting the general fining-upwards sequence of floodplain formation); or if the type and magnitude of the event's geomorphic effects correspond more closely with Holocene-aged impacts.

In this paper we examine the geomorphic effects of a rare and catastrophic flood in eastern Vermont associated with the intense rainfall of Tropical Storm Irene. Extreme precipitation events, and their associated large floods, provide a rare opportunity to observe the broader connectivity between hillslopes, floodplains, and stream channels. For many parts of the mid-latitudes, hurricanes and typhoons are major drivers of extreme flooding and subsequent geomorphic change (cf. Mallin and Corbett, 2006; Kao and Milliman, 2008), including landslide genesis, channel widening, accelerated floodplain sedimentation (or stripping), and mobilization of coarse material. Generating some of the largest discharges on record for a region that has the longest record of USGS gages in the U.S., Tropical Storm Irene spawned the full palette of geomorphic responses having significant effects on hillslopes and river channels. Coupling detailed field analyses with pre- and post-flood aerial imagery in several basins in eastern Vermont (VT), our goal in this paper is to present the geomorphic imprint of Tropical Storm Irene flooding within a larger context of fluvial theory concerning the role of, and trade-off between, the magnitude of energy expenditure during a flood and its duration. This study considered three major research questions: (i) what are the geomorphic effects of a short duration flood in a humid, well-vegetated landscape, (ii) what is the relationship between geomorphic response and (a) peak stream power, (b) total stream power, and (c) flow duration of stream power above a critical threshold, and (iii) how does the spatial variation of geomorphic effects relate to reach-scale geologic and geomorphic controls?

2. Background

After a relatively quiescent period of several decades lacking significant hurricane landfalls, Tropical Storm Irene ravaged New England, especially in eastern Vermont where upwards of 280 mm of precipitation fell on 28 August 2011 (Fig. 2). The intense precipitation led to the flood of record for many gages and generated significant damage to homes, roads, and other infrastructure with estimated regional damages approximating US $1 billion, making it the 10th costliest disaster in U.S. history. Besides the impacts on infrastructure, Irene-induced flooding spawned record-setting stages and discharges contributing to major geomorphic adjustments documented herein. For eastern North America, and especially for coastal and inland New England, hurricane-induced floods represent some of the most extreme floods in many long-standing stream gage records and are fundamentally important geomorphic agents (Jahns, 1947; Patton, 1988; Magilligan and Graber, 1996). New England has been battered by hurricane-induced floods with notable floods occurring in 1927, 1938, 1947, 1954 and 1955 with the latter being the inspiration for the classic paper by Wolman and Eiler (1958) on the lithologic and reach-scale controls on floodplain deposition and erosion.

The specific meteorological and hydrological details of Tropical Storm Irene indicate that for broad regions of east-central VT, the storm equaled or exceeded the 100-year, 24-hour precipitation event generating unprecedented recurrence interval floods, especially in central & southeastern VT (Fig. 2). Moreover, the nature of the storm, where the highest intensities occurred well after the ground was saturated, in combination with the orographic uplift along the eastern flanks of the Green Mountains, led to record intense floods of relatively short duration. For example, Saxtons River (187 km^2) in southeastern VT went from 10 m^3/s to >611 m^3/s in ~10 h (Table 1). These rapid rise rates and regional topography meet the general conditions posited by O'Connor et al. (2002) favoring significant erosion and deposition. O'Connor et al. (2002) indicated that flood conditions are enhanced regionally where storm tracks are intercepted by local topographic relief