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Source, conveyance and fate of suspended sediments following Hurricane Irene. New England, USA

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ABSTRACT

Hurricane Irene passed directly over the Connecticut River valley in late August, 2011. Intense precipitation and high antecedent soil moisture resulted in record flooding, mass wasting and fluvial erosion, allowing for observations of how these rare but significant extreme events affect a landscape still responding to Pleistocene glaciation and associated sediment emplacement. Clays and silts from upland glacial deposits, once suspended in the stream network, were routed directly to the mouth of the Connecticut River, resulting in record-breaking sediment loads fifteen-times greater than predicted from the pre-existing rating curve. Denudation was particularly extensive in mountainous areas. We calculate that sediment yield during the event from the Deerfield River, a steep tributary comprising 5% of the entire Connecticut River watershed, exceeded at minimum 10–40 years of routine sediment discharge and accounted for approximately 40% of the total event sediment discharge from the Connecticut River. A series of surface sediment cores taken in floodplain ponds adjacent to the tidal section of the Connecticut River before and after the event provides insight into differences in sediment sourcing and routing for the Irene event compared to periods of more routine flooding. Relative to routine conditions, sedimentation from Irene was anomalously inorganic, fine grained, and enriched in elements commonly found in chemically immature glacial tills and glaciolacustrine material. These unique sedimentary characteristics document the crucial role played by extreme precipitation from tropical disturbances in denuding this landscape.

1. Introduction

In late August of 2011, the remnants of Hurricane Irene passed directly over the Connecticut River watershed in the northeastern United States (Fig. 1A), causing particularly severe flooding and fluvial erosion in narrow river valleys. Peak discharges in many lower-order upland and mountainous catchments were unprecedented in the historical record, including eight stream gages in the Connecticut River watershed that registered flows in excess of 500 year return periods (Olson and Bent, 2013). The remarkable resultant sediment plume could clearly be seen in satellite images (Fig. 1B) even though discharge on the lower Connecticut River registered only a relatively modest one-in-seven year event.

High flows in the mountainous terrains of the Connecticut River watershed during Irene provided a unique opportunity to generalize about geomorphic effects and legacies resulting from large floods. Here we present detailed hydrologic and sedimentologic observations from the lower Connecticut River and relate these observations to causal processes within mountainous catchments of this largest watershed in New England. Most of the land surface in the uplands and mountains of the Connecticut River watershed is mantled in till, resulting from multiple continental-scale glaciations. We pay special attention to the role of high rainfall-induced flooding in denuding a landscape shaped by Pleistocene glaciations, the legacy of which results in excess sediment storage and landscape disequilibrium (Church and Ryder, 1972).

Although disasters relating to flooding and inundation have generally received more attention in steep terrains of northeastern North America (Gares et al., 1994), fluvial erosion during large discharge events presents perhaps the greatest natural hazard. Specific causes and effects of fluvial erosion differ depending on geomorphic and climatologic context. Here, we show that the combination of extreme rainfall from tropical disturbances and excess glacially-derived sediments from upland and mountainous catchments produced anomalously high specific sediment yields that approach those associated with floods in more recently uplifted terrains. Record peak flows in the northeastern United States associated with the passage of Hurricane Irene in late August 2011 allowed for unprecedented observation of

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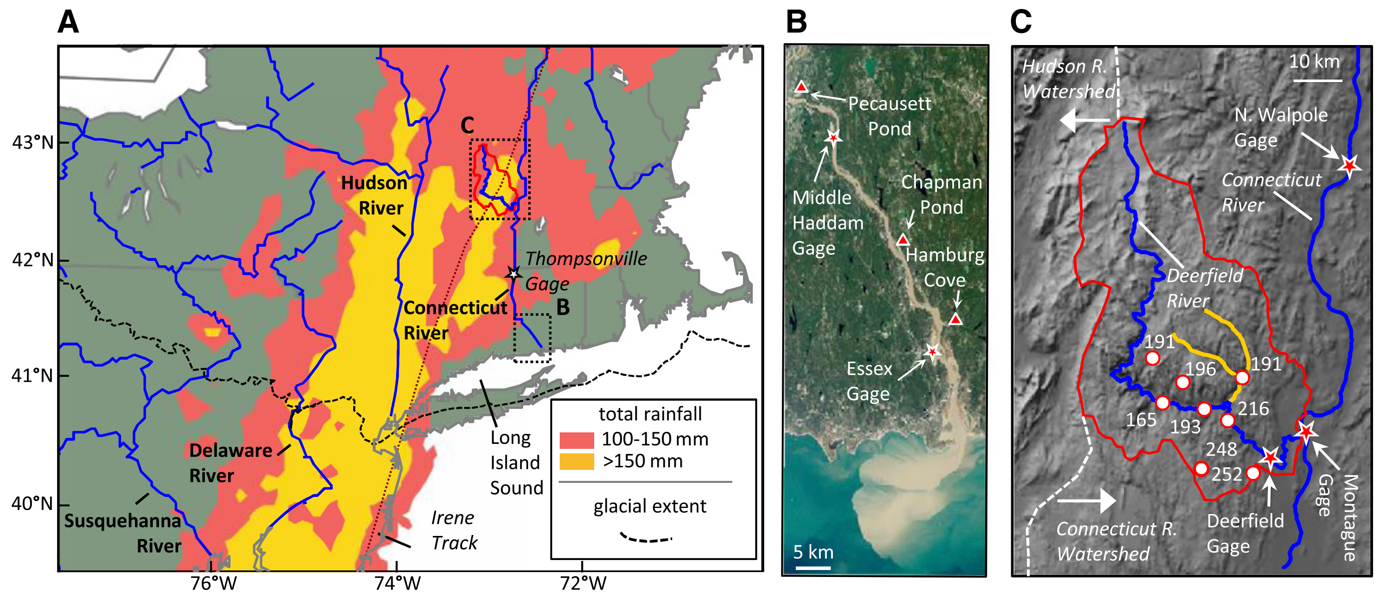

Fig. 1. (A) Major rivers in the glaciated northeast United States, and contoured rainfall totals for Hurricane/Tropical Storm Irene. Dashed boxes indicate areas shown in B and C. (B) Satellite image of the Connecticut River mouth during flooding from Irene. (C) Deerfield River watershed and North River tributary (in gold) with discrete rain-gage totals for Irene in mm. Stars in A–C identify USGS gaging stations referenced in text; triangles are off-river waterbodies sampled during the study. Precipitation data presented in Fig. 1A are obtained from the National Weather Service-Hydrologic Rainfall Analysis Project. Image in Fig. 1B was acquired using a U.S. Geological Survey (USGS) Landsat 5 Thematic Mapper on 09/02/11.
Rain gage data shown in Fig. 1C are obtained from the Community Collaborative Rain, Hail & Snow Network.

downstream transport and sedimentation following severe upstream erosion.

2. Background

A comprehensive understanding of river systems requires evaluating the geomorphic and sedimentological importance of extreme events. Wolman and Miller (1960) suggested that river systems transport the majority of their sediment during less extreme, seasonal flood events because they provide the optimal combination of relatively frequent occurrence and sufficient magnitude to exceed threshold conditions for sediment transport. However, seasonal events have later been recognized to have less of an impact on upstream, low-order tributaries, where flow variability increases and seasonal events are less likely to exceed transport competence (Church, 2002). Within these steeper catchments, extreme floods and resultant landscape disturbances (e.g., landslides, gully erosion, channel incision, and scour) play a major role in making sediment available for transport (Hack and Goodlett, 1960; Wolman and Gerson, 1978; Jacobson et al., 1989). Yet, due to their infrequence, few quantitative observations of the real-time transport and subsequent sedimentological characteristics of extreme floods exist, especially in post-glacial environments along major rivers draining to the western North Atlantic, as described herein.

In addition to questions about the relative roles of seasonal versus extreme discharge events, several studies have attempted to identify predictive landscape factors for sediment yield, or the mass of sediment transported per unit catchment area (Meade, 1969; Ahnert, 1970; Milliman and Meade, 1983; Milliman and Syvitski, 1992). Many early studies proposed a simple power inverse relationship between basin area and suspended sediment yield (Brune, 1948; Dendy and Bolton, 1976; Milliman and Syvitski, 1992). They found that low-order streams tended to be in upland and mountainous areas where stream gradients were higher and thus produced more sediment. As one measured progressively downstream, the addition of low gradient, less sediment productive areas with more accommodation space for sediment storage reduced the specific sediment yield of the whole basin. However, Church and Slaymaker (1989) noted that a simple inverse relationship between watershed area and sediment yield was not sufficient to describe post-glacial landscapes in British Columbia. For these watersheds of the Pacific Northwest, vast stores of glacially-derived sediment within low-gradient trunk valleys actually caused sediment yield to increase in the downstream direction due to disproportionately large volumes of sediment introduced during routine bank collapse.

While the results of Church and Slaymaker (1989) appropriately characterize sediment yield trends in the Pacific Northwest, it remains unclear whether they reveal robust relationships that can be extended to other post-glacial landscapes. Compared to British Columbia, the terrain along the passive margin of eastern North America is generally less steep and contains significant stores of erosion-resistant lodgement till and glaciolacustrine sediments in upland and mountainous areas (Melvin et al., 1992). Tills within the study area are generally rich in silt and clay-sized material, ranging 34–46% depending on the underlying parent material and method of emplacement (Newton, 1978). Rivers of note that drain glacially conditioned landscapes of the western Atlantic Slope include the Susquehanna, Delaware, Hudson and Connecticut Rivers (Fig. 1A). These systems contribute sediment, organic material, and contaminants to some of the most productive estuaries and active ports and harbors in North America, including Chesapeake Bay, Delaware Bay, New York Harbor, and Long Island Sound. Understanding how the major rivers of the western North Atlantic continue to actively respond to the area's glacial history is critical for their effective management (e.g., Snyder et al., 2009).

Sediment yields from post-glacial landscapes are generally greatest immediately following glacial retreat, with relatively short relaxation times for steep sediment-mantled hillslopes (Ballantyne, 2002). However, mountainous landscapes can experience later rejuvenations of glacial drift mobility by external perturbations (Church and Ryder, 1972; Church and Slaymaker, 1989), such as exceptional rainfall events (Ballantyne, 2002). Direct observations of the upland geomorphic effects of extreme precipitation events are rare though due to their infrequency. In the more mountainous coastal regions of the Western North Pacific Ocean (e.g., Taiwan), tropical cyclones are more common and resultant impacts have been studied in greater detail. There, torrential rains associated with tropical cyclones are one of the main triggers for