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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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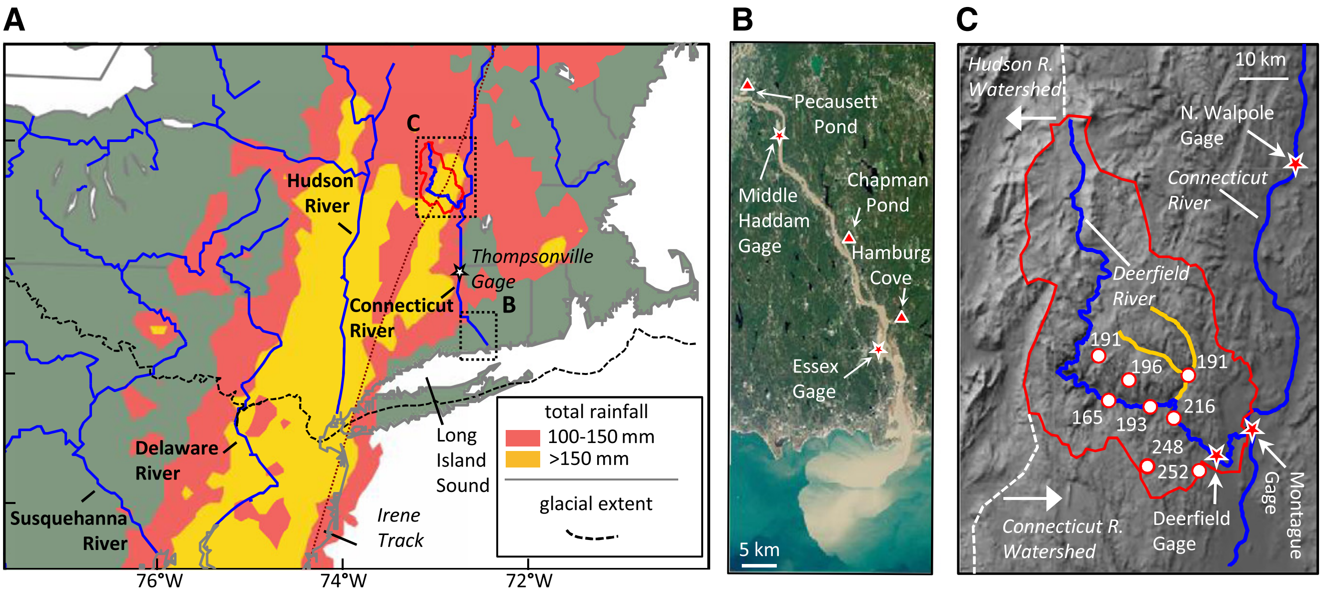

**Fig. 1.** (A) Major rivers in the glaciated northeast United States, and contoured rainfall totals for Hurricane/Tropical Storm Irene. Dashed boxes indicate areas shown in B and C. (B) Satellite image of the Connecticut River mouth during flooding from Irene. (C) Deerfield River watershed and North 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 surface erosion, slope failures, and landslides. Forest disturbance, destabilization of hillslopes, and oversteepening of channel banks as a result of tropical cyclone flooding act in concert to cause continued high sediment loads within river systems of the Western North Pacific for years following initial flooding (Milliman and Kao, 2005).

In contrast to the Western North Pacific, the passive margin of the Western North Atlantic is characterized by milder slopes and widespread glacial features still present on the modern landscape. Here in the Western North Atlantic, tropical cyclones are rare, but nevertheless provide the dominant mechanism for extreme precipitation (Barlow, 2011). With the exception of a few early studies (e.g., Jahns, 1947; Wolman and Eiler, 1958; Patton, 1988), observations for assessing the role of these extreme events in removing sediments from this post-glacial landscape are scarce. Furthermore, it has been unclear what information the imprint of extreme precipitation within depositional environments along these river systems provides regarding denudation mechanisms and primary sources of sediment mobilized by these events.

The following analysis of impacts of Hurricane Irene (2011) on the Connecticut River provides a unique evaluation of the geomorphic and sedimentological significance of extreme precipitation events on post-glacial watersheds and their floodplain lowlands. We make use of extensive water sampling and turbidity monitoring in the lower reach of the Connecticut River during flooding by Irene. We combine these event observations with subsequent retrieval of sediment cores from sediment sinks within the Connecticut River watershed following the event to evaluate the role that extreme precipitation plays in the erosion, transport and deposition of sediments within post-glacial landscapes of the western Atlantic Slope. This study is significant in that it: i) provides a new empirical assessment for the role of extreme precipitation in mobilization and transport of sediments, ii) evaluates transport and routing signatures within resultant floodplain sedimentation by these rare events, thus providing valuable information as a modern analogue of historic and prehistoric flood events, and iii) extends these evaluations to a new environment (i.e. glacially conditioned watersheds of the Atlantic Slope).

## 3. Methods

### 3.1. Hydrometric measurements

Real-time water-column observations of both sediment concentration and discharge during the Irene flood event were obtained from two USGS gages on the lower Connecticut River at Thompsonville, CT and Middle Haddam, CT. Just upstream of the beginning of the tidal section of the river at Thompsonville, CT (see Fig. 1A for location), a DH-95 depth integrated suspended sediment sampler collected daily samples during the flooding event. Data from this sampler are part of a longer term monitoring project relating discharge to suspended sediment concentration (SSC). The Thompsonville daily mean discharge is multiplied with depth integrated SSC to obtain an estimate of suspended sediment discharge during the three days of peak flooding by the Irene event.

Because these gages account for only material in suspension, they therefore implicitly underestimate total sediment discharge by ignoring bedload transport. Herein, all estimates of sediment load and yield account only for the suspended fraction, which is consistent with the broader literature on sediment discharge (e.g., Milliman and Meade, 1983). Suspended sediment accounts for most of the sediment transported in larger, meandering rivers like the lower Connecticut River (e.g., Milliman and Farnsworth, 2011). When quantifying sediment discharge, we use the term “sediment load” to refer to the mass of suspended sediment exported per unit time, and “sediment yield” to refer to sediment load estimates normalized for drainage basin area (also called “specific sediment yield”).

A higher-resolution (15 min) time-series of turbidity is also available further downriver at Middle Haddam, CT (Fig. 1B). During flooding by Irene an ISCO 6600 EDS pumping sampler collected near hourly discrete water column samples adjacent to this turbidity sensor, thus providing the data necessary to convert the high-resolution turbidity time-series to SSC in accordance with standard USGS methods (Guy, 1969; Rasmussen et al., 2009). This continuous Middle Haddam record is used to assess higher-resolution temporal trends in transport beyond that recorded by daily SSC measurements at Thompsonville. We time shift the continuous surface SSC record back 17 h (corresponding to the travel time between the two gages) and compare the SSC value at sampling time to the average SSC for that day. Thereby, we can evaluate whether the timing of the three discrete upstream depth-integrated samples at Thompsonville likely over- or under-estimated total sediment discharge calculations.

To understand sediment mobilization and transport in mountainous watersheds during the flooding event, we focus our analysis on the 1770 $km^2$ Deerfield River basin (see Fig. 1C for location). This tributary to the Connecticut River is well gaged for both discharge and precipitation, lacks significant flood control and was subject to some of the most extreme precipitation (Fig. 1A) and flooding within the entire Connecticut River catchment during Irene. Annual peak discharge values from the North River, the Deerfield's largest gaged and undammed tributary, were used to perform a log-Pearson type III approximation of flow return period in order to put Irene flooding into a longer-term context (US Water Resources Council, 1981).

We utilize discharge time-series available from the Deerfield River and the much larger upper Connecticut River at North Walpole, NH (see Fig. 1C for location) during the Irene event to evaluate contributions from these two sub-basins to the hydrograph observed just below their confluence at Montague, MA (Fig. 1C). We also estimate fractional contributions from each sub-basin to the total sediment discharge fluxed past the Thompsonville and Middle Haddam gages.

### 3.2. Sedimentary analyses

To further evaluate the source of sediments delivered to the mouth of the Connecticut River during the Irene event, several ~30 cm gravity cores were collected from cutoff meanders and an off-channel cove that are connected to the lower Connecticut River by permanent narrow (<10 m) tie channels. Cesium-137 chronologies of prior sediment records in these cored off-channel waterbodies indicate high deposition rates (2–4 cm/year) due to tidal pumping (Woodruff et al., 2013), a mechanism by which tides regularly introduce sediment from the river channel that settles out of suspension during each tidal cycle. Irene's sedimentation was compared to sediments sampled previously following more routine seasonal discharge events of the preceding 2011 spring floods in order to assess differences in depositional characteristics. To aid in this comparison, the time-series of discharge and SSC for the Irene event relative to the preceding 2011 spring freshet is provided (Fig. 3C). Core locations visited following both the 2011 spring freshet and the late-August/early-September 2011 Irene flood event include PCT1 at Pecausett Pond (41°34′08″ N, 72°37′02″ W), CMP2 at Chapman Pond (41°26′21″ N, 72°26′45″ W) and HMB1 at Hamburg Cove (41°22′30″ N, 72°21′43″ W) (see Fig. 1B for locations).

Gravity cores were collected using a Uwitec Gravity Corer. Sediments were immediately extruded in the field and subsampled at 0.5 cm depth intervals. In the laboratory, organic content was estimated based on loss on ignition (LOI) measurements following methods described in Dean (1974). Grain size depth profiles for select cores were obtained using a Coulter LS 200 laser particle analyzer. Organics were removed with a 6% hydrogen peroxide ~60 °C bath prior to grain size analysis. The near maximum grain sizes within deposits were assessed using $D_{90}$, the particle size of which 90% of the sample is finer than.

Elemental abundances for each sub-sample were obtained using an ITRAX X-ray fluorescence (XRF) core scanner (Croudace et al., 2006) following methods similar to Woodruff (2009). For XRF analyses, samples initially extruded in the field were dried, powdered and placed in

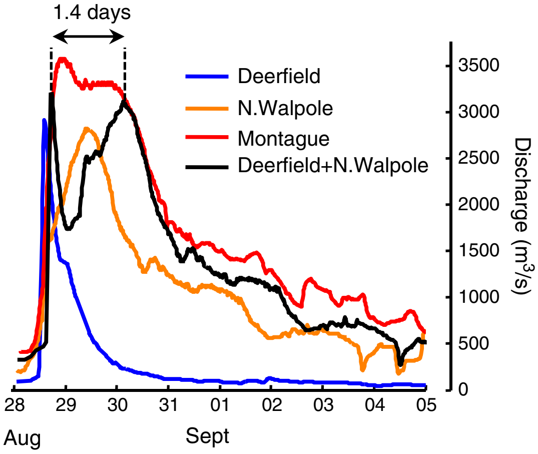

**Fig. 2.** Discharge for the Deerfield River (blue), the upper Connecticut River at N. Walpole, NH (orange) and for the Connecticut River directly below the Deerfield confluence at Montague, MA (red). See Fig. 1B for gage locations. The combined contribution from the Deerfield and upper Connecticut Rivers at N. Walpole to the hydrograph at Montague, MA is shown in black. The 1.4 day separation between the Deerfield and upper Connecticut peaks at Montague is noted. Time lags of 3.2 h and 17.6 h are applied to the Deerfield and N. Walpole time-series to obtain combined contributions at Montague. These time lags correspond to similar respective stream velocities of 4.4 and 4.6 km/h for flows in the main river during the event, but were obtained independently based on assumptions that: i) the onset of high discharge at Montague is initiated by contributions from the Deerfield, and ii) falling discharge from the upper Connecticut River at N. Walpole marks the tail end of the hydrograph at Montague.

individual ~1 cm-long sampling trays. Samples were counted with a Molybdenum tube operating at 30 Kv and 55 mA for 10 s per measurement. Scans were performed at a 200 μm resolution, resulting in ~20 individual measurements per sample with mean elemental abundances presented. Sedimentation from Irene was in part identified through the increase in depth of detectable $^7$Be activity ($t_{1/2} = 53$ days) between cores collected just prior to and just following the Irene event. Because atmospheric $^7$Be adsorbed to particles decays quickly, it can be used to identify sediments deposited roughly over the previous few months. For these radioisotope analyses powdered sediment was counted on a Canberra GL2020R Low Energy Germanium Detector for 48 h following methods similar to Woodruff et al. (2013) and Woodruff et al. (2001).

## 4. Results

### 4.1. Sediment routing and yields

Sediment load observations during Irene were exceptional in light of the historic sediment load–discharge rating curve (Fig. 4A). Although Irene discharge only amounted to a ~7 year discharge event at Thompsonville, CT, SSC exceeded all prior observations from the 40-year record by roughly an order of magnitude (Fig. 4B). Unprecedented resultant sediment loads for the event of 500,000 t/day exceeded previous measurements for the same discharge by more than 15 times (Fig. 4A). In total, approximately 1.2 Mt of suspended sediment passed the Thompsonville gage during the three days of peak flooding from Irene, roughly twice the annual average load for the river (Patton and Horne, 1992). In considering bias introduced by the timing of the three depth-integrated SSC samples (i.e. how SSC at sampling time compared with average SSC for that day), we find that this value of 1.2 Mt could be adjusted ~2–3% higher. This minor adjustment is smaller than the error associated with our rough estimates and therefore not applied.

The SSC time series towards the mouth of the Connecticut River reconstructed from discrete samples and more frequent turbidity readings at Middle Haddam, CT reveals an unusual double peak, with two separate SSC maxima separated by roughly 1.4 days (Fig. 3B). This time separation between SSC peaks matches the lag in arrival of the

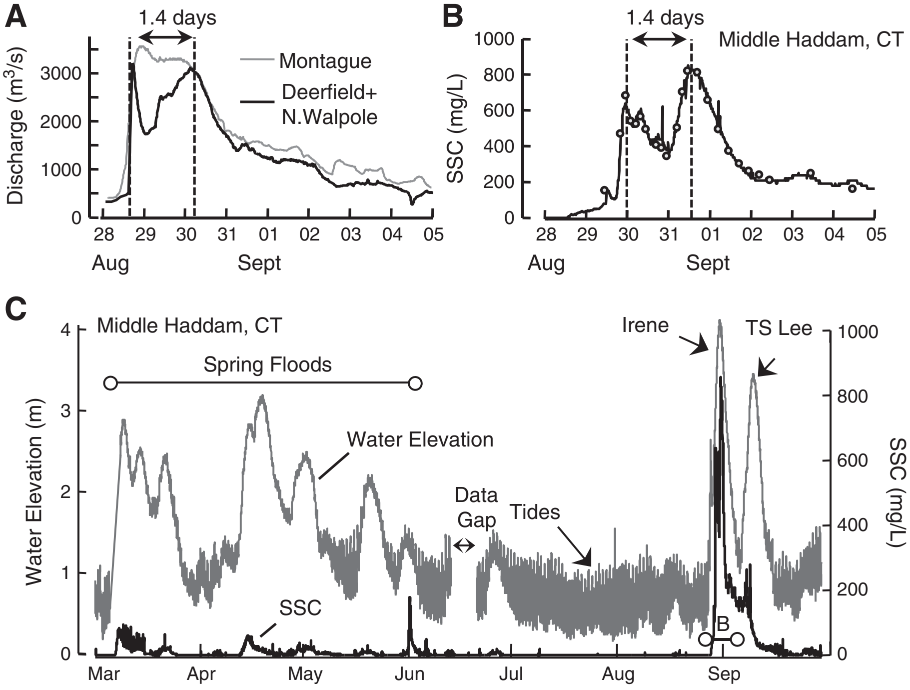

**Fig. 3.** (A) Connecticut River discharge during Irene flooding at Montague, MA, along with combined contributions from the Deerfield River and upper Connecticut River at N. Walpole, NH (see Fig. 2 for individual hydrographs). (B) Surface SSC near the mouth of the Lower Connecticut River at Middle Haddam over the same time interval as A. (C) Long-term time-series from Middle Haddam, CT of water-level (gray) and surface SSC (black) beginning at the onset for the 2011 spring freshet and ending after floods from Irene and Tropical Storm Lee. Line B in C indicates the SSC interval shown in B.

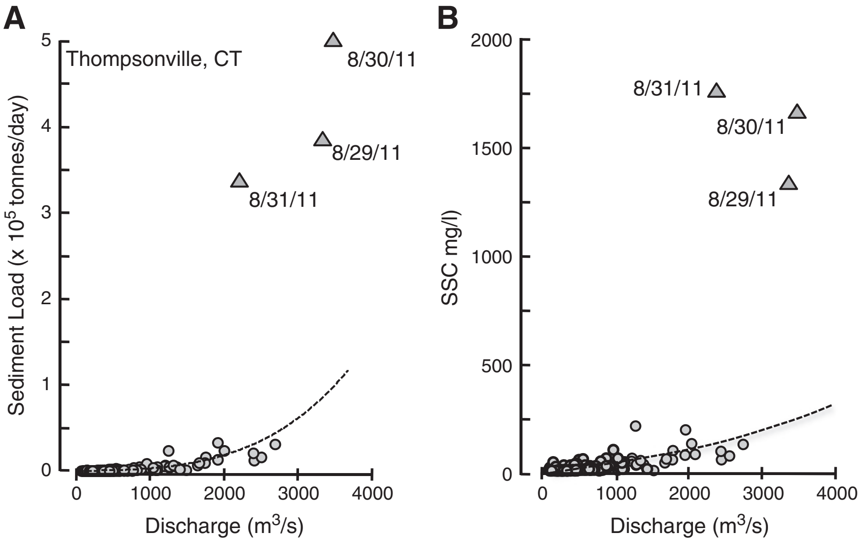

**Fig. 4.** (A) Mean daily suspended sediment loads at Thompsonville, CT measured before the Irene event (circles) compared to the three days of peak Irene flooding (triangles). The dashed line presents the discharge vs. sediment load rating curve derived previously by Patton and Horne (1992). (B) Pre-Irene SSC data (circles) corresponding to sediment load data in (A) with Irene SSC (triangles) measured from three depth-integrated samples at Thompsonville, CT. Dashed line depicts the SSC vs discharge rating curve for Q > 500 $m^3/s$ from Woodruff et al. (2013).

upper Connecticut River hydrograph behind that of the Deerfield River at Montague, MA (Fig. 2). Thus, observations are consistent with the first peak in SSC comprising the arrival of Deerfield River waters at the turbidity sensor at the mouth of the river, followed 1.4 days later by the arrival of a slightly larger peak in SSC from the upper Connecticut River. Record-setting peak flows on the Deerfield River and all of its gaged tributaries provide further support for the interpretation that Deerfield River discharge was responsible for the first of the two primary turbidity peaks observed downstream at Middle Haddam. By separating the sediment discharge series according to corresponding contributing areas, we obtain a rough estimate for total sediment yield of a lower-order mountainous basin for an extreme flood event. This is especially useful because SSC in lower-order rivers is rarely systematically measured. Furthermore, we know of no previous estimates of sediment yields during extreme events from post-glaciated watersheds draining the western Atlantic Slope.

Assuming that the first peak in SSC observed at Middle Haddam, CT is due primarily to the arrival of Deerfield River water, measurements indicate a fine-grained specific sediment yield of ~350 $t/km^2$ ($t/km^2$) from this mountainous basin during the Irene flooding event. Implicit in this calculation, we assume minimal SSC contributions aside from Deerfield River waters in the first turbidity spike. We feel that this is a reasonable assumption given the timing between the two turbidity peaks as well as the lack of any large non flood-controlled tributary entering the Connecticut in the intervening reach between the Deerfield and Thompsonville gages. Furthermore, a yield of ~350 $t/km^2$ is almost certainly a minimum estimate of sediment export since it represents only suspended sediment, and does not account for considerable observed deposition between the mouth of the Deerfield and the observation gage for depth-integrated SSC located 94 km downstream at Thompsonville, CT. Nonetheless, this estimate of specific sediment yield for this brief event exceeds those published from nearby basins for an entire year by more than ten times, thus highlighting the importance of the event in removing sediments from upland and mountainous terrain in the region.

To further place sediment yield estimates during Irene in a longer-term context, a compilation of available mean annual yields from small post-glaciated watersheds in the region is provided in Table 1. Annual sediment yields for nearby watersheds to the Deerfield range between 8 and 30 $t/km^2$. On the basis of this new compilation, the minimum estimate of fine grained sediment yield from the Deerfield catchment of 350 $t/km^2$ during the Irene event represents a rough equivalence to the total sediment discharge for the watershed during 10-to-40 years of more routine discharge conditions. Furthermore, this yield was roughly five times that of the larger Connecticut River watershed at Thompsonville, where the three-day event yield was only 48 $t/km^2$.

### 4.2. Deposition from Irene versus the 2011 spring freshet

To evaluate the defining characteristics and potential source imprinting of sediments routed through the mouth of the Connecticut River during the Irene event, we examined resulting deposition within a series of cut-off meanders and an off-channel cove that serve as natural traps for sediments routed through the lower river. Following the Irene event, a new layer of anomalously gray clayey-silt could be clearly delineated in cores collected from the study's three off-river waterbodies (Fig. 5). Increases in the depth of measurable short-lived Be-7 activity

**Table 1**
Published sediment yield estimates for small streams and rivers near the Connecticut River.

| Location | Watershed ($km^2$) | Period of record | Mean annual load (t/year) | Mean annual yield ($t/km^2$/year) | Source |
|---|---|---|---|---|---|
| Housatonic River at Great Barrington, MA | 730 | 1994–1996 | 5986 | 8.2 | Bent (2000) |
| Coginchaug River near Middlefield, CT | 78 | 1982–1986 | 897 | 11.5 | Morrison (1998) |
| Muddy Brook near Woodstock, CT | 47 | 1981–1983 | 573 | 12.2 | Kulp (1991) |
| Yantic River at Yantic, CT | 231 | 1976–1980 | 3950 | 17.1 | Kulp (1983) |
| Green River near Great Barrington, MA | 256 | 1994–1996 | 7834 | 30.6 | Bent (2000) |

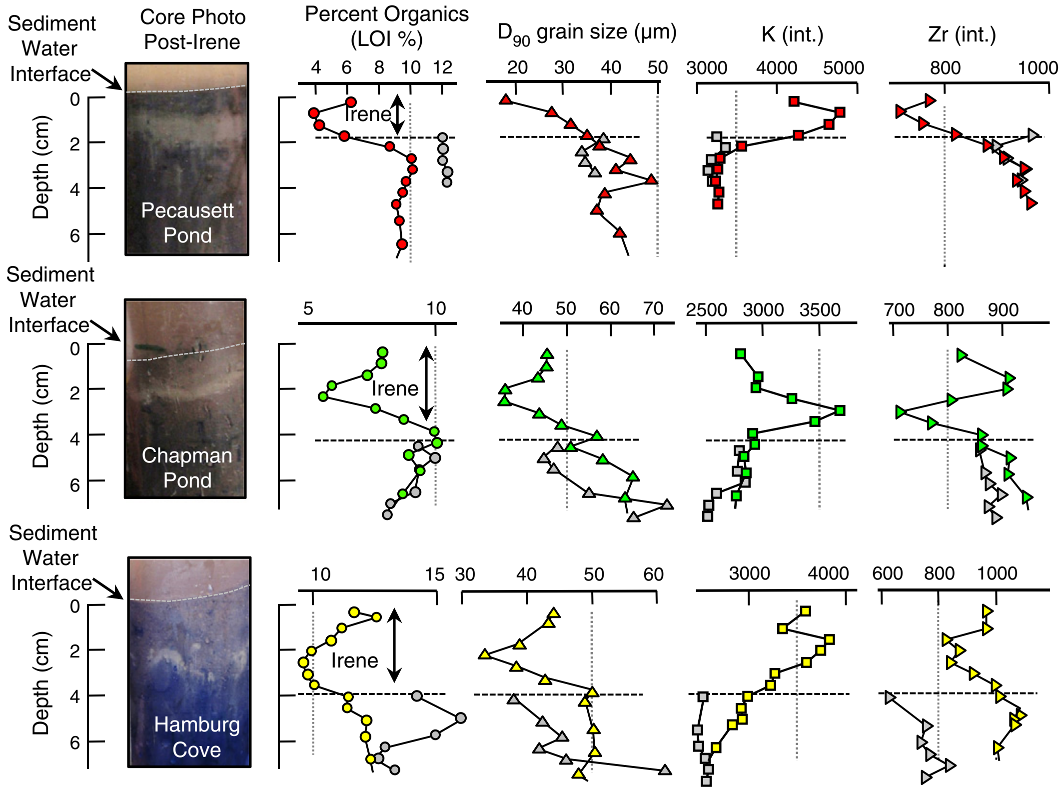

**Fig. 5.** Post-Irene sediment core photos and depth profiles of organic content (in LOI%), grain size, and the relative abundances of K and Zr. Note the distinct gray layer associated with Irene just below the sediment–water interface in each photograph. Irene sediments (colored markers in depth profiles) are compared to sediment collected after the 2011 spring freshet (gray markers). Profiles from the spring freshet are aligned below the Irene deposit with the surface of pre-Irene sediments denoted with dashed black line.

between pre- and post-Irene cores matched the thickness of this distinctive event deposit (horizontal dashed lines in Fig. 5), and thus confirmed that the distinctive gray color represents sedimentation by Irene.

Irene's sediments exhibited clear compositional differences from those collected just after the 2011 spring freshet (gray marked depth profiles in Fig. 5), as well as material immediately below the Irene deposit. For example, at Chapman Pond, organic content in the Irene deposit decreased to approximately half the percentages observed in underlying sediments — from 10% loss on ignition (LOI) in pre-Irene sediments to 5% in the Irene layer (Fig. 5, middle row). Maximum grain sizes for resulting deposition from Irene were also notably finer grained in Chapman Pond when compared to material deposited during the more moderate 2011 spring flood events, with inorganic $D_{90}$ grain size not exceeding 25–35 μm (medium silt) in the Irene layer, compared to 60–70 μm (very fine sand) for material underlying the deposit. Similar scale decreases in organic content and grain size were observed in all of the backwater sites sampled following the Irene event (e.g., top and bottom panels in Fig. 5). At each site along a 60 km transect of the Connecticut River's low discharge tidal reach, we observed very little variability in Irene's unique sedimentary signature. Sedimentological observations therefore consistently indicate the blanketing of 2011 freshet sediments with an anomalously inorganic layer of finer clays and silts.

### 4.3. Glacial imprinting in the Irene deposit

Elemental abundances within the Irene layer provide an additional diagnostic tool for the source of sediment deposited during flooding from the Irene event. A consistent signature for the Irene layer was enrichment in potassium (K), and deficiency in zirconium (Zr) (Fig. 5, 6). K is a major constituent in illite and muscovite clays and orthoclase silt grains commonly found in the fines of glacial drift that still mantles much of the region's upland and mountainous landscapes (e.g., Quigley, 1980). In contrast, Zr is associated primarily with the erosion-resistant mineral zircon, which tends to become concentrated in highly weathered sediments (e.g., Koinig et al., 2003). Glaciolacustrine sediments were collected from newly incised hill-slope gullies in the Deerfield River watershed to compare to the downstream event layer's elemental abundances. These samples serve as spatially averaged accumulations of fine grained sediments originally derived from upslope tills immediately following deglaciation. High K/Zr ratios within the Irene deposit confirm K enrichment relative to Zr, reaching levels equaling those measured in upland

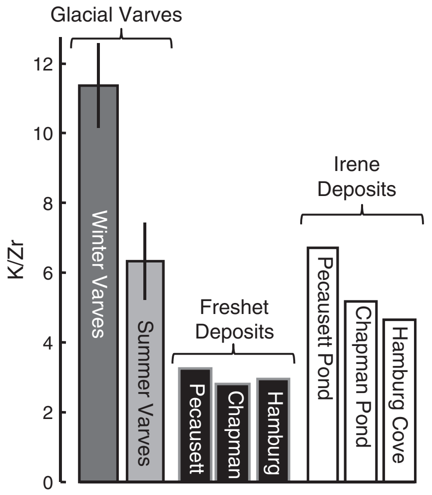

**Fig. 6.** Relative K/Zr XRF abundances of upland glaciolacustrine sediments compared to backwater sediments deposited during the 2011 spring freshet and flooding from Irene.

varves (Fig. 6). In contrast, K/Zr ratios in sediments collected from Connecticut River meander cut-offs following the 2011 spring freshet are on average 50% lower than Irene sediments (black bars in Fig. 6). Irene sediments therefore appear to contain a distinct elemental fingerprint marking the rapid introduction of glacial fines from upland and mountainous sources during the event. The abundance of these fines in the event layer suggests the direct routing of chemically-immature glacial material from upstream sources transported directly to the tidal reach of the river.

### 4.4. Flooding and upland erosion

Hydrologic observations from the Deerfield River support our findings that a disproportionate quantity of the Connecticut River's sediment originated from hillslope and streambank tills within this mountainous watershed. Five rain gages situated at lower elevations within the watershed recorded 180–250 mm of rain in less than 12 h, with likely higher rates at higher elevations where there are no weather observation stations. Prior to Irene, nearly double the monthly average precipitation fell, resulting in soil moisture values across the watershed in the 90th percentile (NOAA, 2012). The combination of intense rainfall and high antecedent soil moisture resulted in a record (since gaging began in 1940) peak discharge for the Deerfield River (USGS site 01170000) of 3100 $m^3/s$. This value exceeded that of the ten times larger contributing area of the upper Connecticut River at North Walpole, NH, highlighting the severity of flooding in mountainous catchments like the Deerfield. On the Deerfield's largest tributary, the North River (watershed = 230 $km^2$, record = 73 years), a peak discharge of

**Fig. 7.** Examples of common erosional impacts to the Deerfield River watershed from Hurricane Irene.

1585 $m^3$/s corresponded to a roughly 400-year return period when performing log-Pearson type III analysis and including the Irene event itself (return period increases to 2200 years if the Irene event is excluded from the analysis record).

Although SSC is not monitored on the Deerfield, observations from Middle Haddam, CT indicated that the Deerfield exported a massive amount of sediment relative to routine annual yields. Following the storm, observational accounts throughout the Deerfield watershed as well as neighboring catchments provide evidence of severe erosion. Several mechanisms combined to provide fine-grained material for transport downstream. In areas of particularly high rainfall accumulation with steep north- and eastward-facing slopes, till slopes gave way to mass wasting, often directly into surface drainages (Fig. 7A, B). On many slopes, headward gully erosion and new gully formation directly suspended fine-grained till particles within the stream network (Fig. 7C). Along the margins of larger streams, high stream power eroded valley alluvium (Fig. 7D), as well as banks comprised of hillslope tills (Fig. 7E). Once sediments were introduced to the stream network, high bottom shear stresses due to flooding rapidly scoured fine grains from these glacial sediments. The coherent peak in SSC from the Deerfield River, 144 km downstream within the main stem of the Connecticut River at Middle Haddam, CT (Fig. 3B), as well as the enrichment of resultant deposition from Irene with chemically-immature clays and sites (Fig. 5 and 6), all support efficient channel conveyance once glacial fines were initially mobilized from steeper, low-order tributaries during the event.

## 5. Discussion

### 5.1. Comparisons to post-glacial landscapes of the Pacific Northwest

Observations of Irene flooding and resultant deposition illustrate the importance that extreme rainfall from tropical disturbances plays in exporting sediment from the relatively understudied glacially conditioned uplands and mountains of the western Atlantic slope. This mechanistic understanding is consistent with high magnitude, low frequency events playing a leading role in sediment delivery from lower-order tributaries. It also indicates that post-glacial landscapes of the Atlantic slope behave differently from those of the Pacific Northwest. Whereas in the Pacific Northwest, erosion of glacially-derived sediments is significantly greater in lowland reaches relative to upland and mountainous catchments (Church and Slaymaker, 1989), specific sediment yields in the post-glacial eastern United States increase dramatically in upland and mountainous reaches.

Two main factors explain differences between findings presented herein and previous insights of post-glacial landscape denudation from the Pacific Northwest. First, rather than inter-annual to decadal scale monitoring of routine sediment yield (Church et al., 1989), here we evaluate very short-term sediment contributions of a single extreme event. Thus, it is unsurprising that scaling relationships between catchment size and yield differ given that we present data from a very different erosional mechanism. However, when reporting on sediment transport in watersheds with high-relief, it is of upmost importance to consider extreme events, since single floods have been shown to remove as much as 100 times the mean annual yield in upland temperate environments (Wolman and Gerson, 1978). Furthermore, Ralston et al. (2013) show that Irene flooding provided about five times the long-term annual average load to the Lower Hudson River (neighboring our study site), but roughly two thirds of this material remained trapped within that river's long freshwater tidal section. Therefore, erosion events due to extreme precipitation in upland and mountainous reaches likely play a key role in the delivery and storage of sediments in lower trunk valleys for later and more gradual export.

Second, significant landscape differences result from continental-scale versus Cordilleran deglaciation. Whereas the Laurentide Ice Sheet retreat, as well as previous deglaciations in the northeastern United States, progressed more or less northward due to regional climactic forcing, steep elevation and associated temperature gradients mediated the Cordilleran deglaciation of the Pacific Northwest. Additionally, unlike the intrusive volcanic lithology that comprises much of the Cascades and Coastal Ranges, the underlying pelitic schistic bedrock in our study region tends to readily form clay and silt sized particles due to mechanical weathering by glaciation. In our study region, northward retreat of the ice front from multiple glaciations has left a thick (average 5–15 m) blanket of indurated till across the entire landscape, including areas at high elevation (Koteff and Pessl, 1981). Conversely, immediately following the Cordilleran ice sheet collapse, alpine glaciation continued in disconnected mountainous areas, thus largely removing till from higher elevation areas and reworking it into moraines (Clague and James, 2002), whose loose material may be much more easily removed than the resistant lodgement till of eastern North America. Church and Ryder (1972) noted that bases of alluvial fans in trunk valleys in British Columbia tended to be composed of much finer grained sediments than those in upper portions, thus providing evidence of this rapid removal of fine grained till material from mountainous terrains. In New England landscapes, this difference in continental-scale deglaciation allowed for the retention of fines in till that mantles the region's higher elevations. The area's glaciolacustrine sediments and Pre-Wisconsin lower till are particularly cohesive, with a high threshold for mobilization likely exceeded primarily by only the most extreme events and associated shear stresses.

In addition to differences in surficial geology, climate controls on extreme high flows in Eastern North America are dramatically different from those of British Columbia. Eastern North America's hydrology differs from that in British Columbia in that it receives rare but extreme precipitation from tropical disturbances, which play a dominant role in generating record precipitation events in the region (Barlow, 2011). Record peak stream flow magnitudes in the northeast are controlled in large part by these rare, but large autumn events (Magilligan and Graber, 1996). For instance, an analysis of high flows of 17 long-term (>70 years) stream gages in tributaries of the Connecticut River watershed shows that 77% of floods of record have occurred during the August to November peak hurricane season in New England (Fig. 8). Even on the larger Connecticut River at Hartford, CT, the longest operating gage in the watershed ($t > 180$ years), two out of three of the largest flows are August hurricanes, despite nearly 50% of the annual peak discharges occurring during April. Hurricane-induced flooding in this region is therefore infrequent, but extreme when it occurs. Furthermore, gross under-prediction of SSC by the historical rating curve (Fig. 4) illustrates that hurricanes play an even greater role in mobilizing sediment from regions of higher-relief than lowland peak flow data along the main stem would indicate.

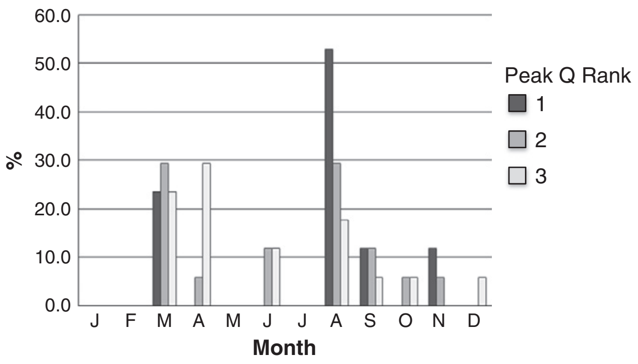

**Fig. 8.** Timing of the top three recorded peak flows from 17 upland stream gages ($n = 51$) within the Connecticut River watershed. Note that over 50% of number 1 ranked peak recorded flows have occurred during August.

### 5.2. Limitations of lowland rating curves

Observations from Irene highlight the importance of estimating sediment discharge from a lower-order tributary with higher relief (e.g., from the Deerfield River) during a historic peak flow event if we are to understand the fundamental mechanisms by which non-uplifting, post-glacial terrains denude. Sediment load versus discharge rating curves are generally applied to the downstream sections of major rivers. However, we show that during an extreme precipitation event like Irene, most sediment is entrained in lower-order, streams with high relief watersheds. Therefore, the Connecticut River's main stem rating curve, for which measurements are made near the head of tides, greatly under-predicts sediment loads. An accurate prediction of sediment loads for extreme precipitation events like Irene would be better obtained by adding the cumulative of multiple upland/mountainous tributary rating curves to capture how sediment is delivered to the lower reaches of the river. In order to predict decadal to century-scale sediment yields in landscapes with excess glacially-derived sediment stored in low-order catchments, observations from Irene show that models must incorporate the ability of extreme precipitation events to mobilize these legacy sediments from mountainous areas.

### 5.3. Event-driven hysteresis

Water column measurements from Middle Haddam, Connecticut indicate an additional but smaller peak in SSC of ~300 mg/L associated with the passage of Tropical Storm Lee a little less than two weeks after the larger initial spike in SSC associated with flooding from Hurricane Irene (Fig. 3C). The relatively smaller peak in SSC during Lee compared to that during Irene could be interpreted as evidence for negative hysteresis, where sediments were cleared out of the system by Irene resulting in less available material for mobilization by the subsequent Lee event. However, maximum river discharge during Tropical Storm Lee was only 11% higher than that observed during the 2011 spring freshet, yet SSC at Middle Haddam during Lee was as much as 3 times higher than peak levels observed during the preceding freshet (Fig. 3C). Sediment yields during Lee thus appear to be elevated when compared to periods of flooding prior to the Irene event and therefore provide an example of positive hysteresis.

Anomalously high turbidity persists in the years following the Irene event. Average daily turbidity measurements at Middle Haddam in the two water years following Irene were 72% and 69% higher than pre-Irene turbidity for a given discharge value (Fig. 9). Fig. 9 also likely indicates proportional increases in SSC of similar magnitude given that SSC most often scales linearly with turbidity (for example SSC in mg/L equals 1.44 times NTU turbidity using Middle Haddam measurements collected during Irene flooding, $R^2 = 0.97$, $n = 26$). Elevated SSC in the years following Irene provides a clear example of lasting positive hysteresis in the system and highlights the need for both i) recalibration of sediment discharge rating curves following extreme events, as well as ii) prolonged monitoring to assess the time-scale for relaxation back to pre-event conditions.

Two likely mechanisms may explain why turbidity (and SSC) has remained high in the Connecticut River in the years following Irene. First, sediment discharge from larger, low-lying rivers often represent recycled sediments initially exported from upland/mountainous tributary watersheds by more extreme events, and later remobilized from ephemeral depocenters downstream (e.g., Meade, 1982; Woodruff et al., 2001). These temporary traps for sediment in turn provide an important source of sediments transported by more moderate seasonal floods, with extreme events serving as a key mechanism for supplying new sediments to the river. Second, enhanced sediment removal from mountainous catchments likely persists due to lasting landscape disturbances including now unvegetated hill-slopes, over-steepened channel banks, continued growth of gullies formed by the event, and amplified channel scour due to flow confinement by gravel fans and deltas now built out into these tributaries. It is unclear how long the impacts of Irene will persist with respect to elevated sediment loads within the lower Connecticut River. However, elevated turbidity does not appear to decrease between year 1 and year 2 following the event.

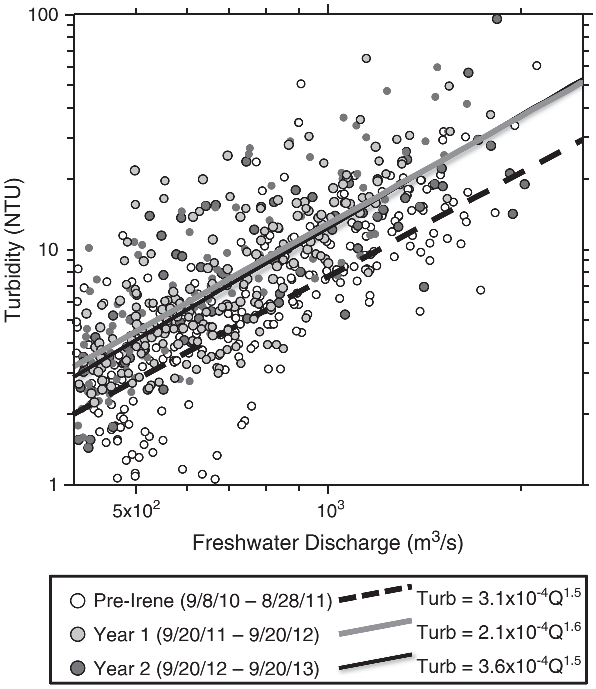

**Fig. 9.** Available daily averaged turbidity data at Middle Haddam, CT prior to Irene (open circles) compared to observations from the following two water years (gray and black circles respectively). Irene turbidity values have been omitted above to eliminate outlier effects; values during flooding ranged as high as 600 NTU. Lines represent best-fit for log–log data. Although water samples are limited for this period, measurements during Irene suggest a linear relationship between turbidity and SSC.

### 5.4. Irene's sedimentary imprint

In the wake of severe flooding, poor correlation has been observed between the level of flooding and resultant overbank sedimentation along lowland floodplains (Costa, 1974; Gomez et al., 1995; Magilligan et al., 1998; Sambrook Smith et al., 2010), in part because the magnitude of floodplain deposition often relates less to the overall size of the flood and more to the rate at which water rises during the event (Aalto et al., 2003). Although smaller and more frequent flood events are largely considered to carry a majority of the total sediment through larger low-lying river systems (Wolman and Miller, 1960), it is shown here that extreme flooding within smaller and steeper reaches in northeastern North America can contribute a different type of sediment to these rivers — specifically, previously inaccessible immature glacial fines.

The level of flooding during Irene was relatively moderate within the Lower Connecticut River, while record breaking discharges in steep tributaries like the Deerfield mobilized indurated glacial deposits normally inaccessible for transport. Once deposited downstream along the low-lying floodplain, these glacial fines provide a distinct geochemical signature that may serve to mark flooding events in the region's high relief catchments. The Irene event therefore provides an important modern analogue for improved interpretations of floodplain sediments for rivers draining post-glacial landscapes. The counter-intuitive observed decrease in grain size in Irene's downstream depositional event layer is likely explained in part by the extensive fine grained material entrained from eroded till and glaciolacustrine deposits in the steeper reaches of the watershed. Therefore, floodplain event deposit characteristics in this case are more symptomatic of headwater erosion within a post-glacial landscape than of local flooding conditions. Recent studies of floodplain deposition in low relief landscapes following flooding have reported a complete lack of discernable sedimentary evidence of the event (Gomez et al., 1995; Sambrook Smith et al., 2010). This absence may be due to homogeneity of sediment sources within the watershed, which makes event sediment difficult to distinguish from more routine sedimentation.

### *5.5. Anthropogenic impacts*

Several questions remain about how to interpret the distinctive sedimentary signature of this type of flooding event. In addition to removing glacial sediments from stream banks and hill-slopes, mill pond legacy sediments to which Walter and Merritts (2008) drew considerable attention, also likely comprised some of the sediment transported during Irene. Their findings indicate that artificially aggraded landscapes behind now breached 19th century mill dams may provide excess sediment in low relief areas, providing an additional mechanism to glaciation to cause sediment yield disequilibrium within a watershed. However, we believe that this effect was likely minor during Irene given the chemical immaturity of the floodplain event layer. In addition to anthropogenic changes resulting from mill dams, near complete deforestation of the region during the 19th century caused increased rates of downslope sediment transport in Vermont (Bierman et al., 1997). The current reforested landscape may still be responding to this century old disturbance. However, given the current predominance of forest-cover in both the Deerfield River watershed (>90% forested; Yellen, 2012) and the broader Connecticut River watershed (>85% forested; Marshall and Randhir, 2008), we conclude that deforestation was not the reason for the remarkably high fine grained sediment yields during the 2011 Irene event.

Perhaps the largest anthropogenic change to northeastern denudation patterns has been the widespread construction of large dams, especially those intended for flood control, which undoubtedly diminish peak flows in the Connecticut River as well as stream power in mountainous tributaries that no longer reach extreme discharge levels (Magilligan et al., 2008). How these human-made modifications influenced the landscape's response to periods of extreme precipitation remains unclear. Regardless, Irene's impact on the Connecticut River serves to highlight how the legacy of glaciation remains a dominant driver in governing denudation processes, fine-grained sediment yields and sedimentological responses of watersheds of the western Atlantic Slope to periods of extreme precipitation.

## 6. Conclusions

Hurricane Irene's impacts on the Connecticut River watershed provide new insights into the effects of extreme precipitation on the erosion, transport, and deposition of fine grained sediments within post-glacial landscapes of the western North Atlantic slope. Upland and mountainous catchments in this region are driven to instability by intense rainfall. Landslides, gully erosion and channel bank failure all serve to transfer fine-grained glacial legacy deposits into low-order tributaries during these events. Once transferred to the open channel, torrential flows quickly winnowed and suspended chemically immature clays and silts from these glacial legacy sediments. Mobilized fines were then transferred directly to the river's main stem mouth as washload. Resultant floodplain deposition exhibits a unique sedimentary imprint consistent with the transfer of glacial fines directly from steeper lower-order reaches to the river's tidal reach. A summary of key findings includes:

1. Rainfall from tropical disturbances serves as the primary means of exporting sediment from steep post-glacial tributaries of the western Atlantic slope. This observation is consistent with high magnitude, low frequency events playing a leading role in sediment delivery from lower-order tributaries.

2. Rating curves for post-glacial rivers greatly under-predict sediment loads during extreme precipitation because they fail to describe the capacity of these events to mobilize glacial fines still stored in upland catchments. Specific sediment yields during intense rainfall events increase with decreasing drainage area, a behavior opposite to that observed for post-glacial landscapes of the Pacific Northwest.

3. During extreme precipitation, winnowed clays and silts from upland sources are efficiently delivered directly to the lower river. Resultant floodplain deposits are anomalously fine grained and inorganic when compared to coarser deposits associated with seasonal spring floods. Elemental abundances within this Irene layer exhibit a preserved sedimentary imprint consistent with the enrichment of glacial fines mobilized from mountainous catchments during the event.

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