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How Unusual is Tropical Storm Irene? A Case Study of Storm Deposition in Littleville Lake, Huntington, MA

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ABSTRACT

Tropical Storm Irene hit the northeastern United States in August 2011 with impressive rates of precipitation and river discharge. However, it was the combination of this heavy rain with high antecedent soil moisture that made Irene so unusual. The Connecticut River had a particularly high sediment yield after the storm, with a sediment concentration over 1,000 mg/L at the mouth of the river. Littleville Lake on the Westfield River was selected as a study site because of its flood control feature, which allows for the calculation of trapping efficiency in dammed rivers. Coring in the lake showed that there was not much sediment to be found, Irene or otherwise. Nevertheless, the Irene sediment that was successfully collected proved to be anomalously grey, fine grained, low in organics, high in potassium and low in zirconium, which is consistent with previous observations. The high potassium concentration is consistent with the unweathered glacial tills in the upstream reaches of the watershed. The unweathered nature of the sediment suggests that Tropical Storm Irene crossed a threshold that allowed for the eroding of material at deeper depths. Deep source material that was instantly mobilized resulted in deposited sediment with very little weathering. This previously unexposed material is now at the surface and depositing in the reservoir about four times faster than before Irene. Furthermore, comparing Irene to the Spring Flood of 1987, an equally large event on the Connecticut River, we are able to conclude that not everywhere in the Connecticut River Watershed is affected by storms and floods in the same way. Comparisons in peak discharge between the Westfield, Deerfield and Connecticut watersheds show that floods due to large meltwater events do not hit the smaller western tributaries, such as the Westfield, as hard as the main trunk of the Connecticut River.

INTRODUCTION

In the face of climate change, it is important to understand the nature of past weather events in order to quantitatively understand their effects on fluvial, sedimentological and geomorphic processes. The Connecticut River Valley is a good place to study the relative impacts of different kinds of storms as it crosses through five states (Fig. 1) and the influence of different kinds of storms will vary across its breadth. For example, the Spring Flood of 1987 delivered significant volumes of rain on top of melt-water from the north. The impacts of this event will vary from place to place across the watershed reflecting the total area of upstream areas, the relative contributions of rainfall and meltwater, and the path of the storm. In contrast, Tropical Storm Irene in 2011 was a very large system that delivered a more uniform volume of rainwater across the entire watershed.

The Connecticut River Valley is a good place to put the effects of Tropical Storm Irene into perspective because of the watershed's location relative to the storm, its geology, documented storm history, and the fundamentally different ways it was impacted by Irene and the Spring Flood of 1987. Irene hit the Connecticut River watershed especially hard, with five of its Massachusetts tributaries reaching 100-year flood stages or above and the watershed receiving an average of 15 to 20 cm of rain within 12 hours, with some places reaching up to 25 cm (Connecticut River Valley Flood Control Commission; Carlowicz, 2011). The flooding from Irene was even more severe due to approximately 18 cm of rain the month leading up to the storm, which was almost double the monthly average (Yellen et al., in review).

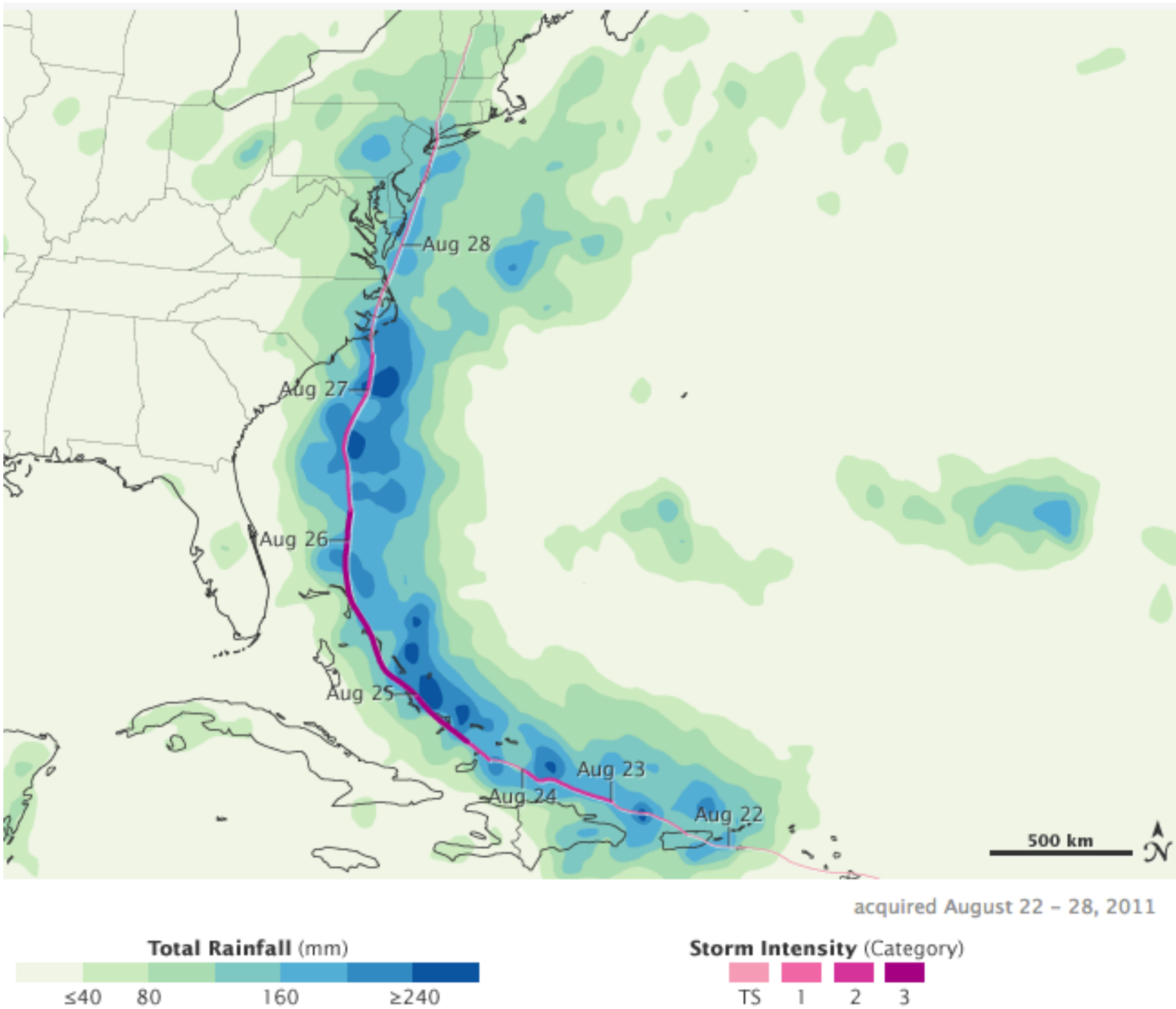

Figure 1 – The precipitation (in mm) and hurricane track for Tropical Storm Irene from August 22 -28, 2011, put together using data from the NASA Earth Observatory using TRMM satellite data. Because TRMM data notoriously underestimated rainfall, and since Irene touched down in New Jersey on August 28, this image most likely underrepresents New England's precipitation. Irene had yet to fully hit the Northeastern United States, so precipitation in this region is certain to be higher than is shown.

The increased precipitation led to increased river discharge, approximately 64 times higher than the average yearly flow in the Connecticut River, and increased erosion. The upland catchments were responsible for lasting landscape disturbances such as the removal of vegetation, gully formation, bank failure and increased channel scour (Yellen et al., in review). This lead to the erosion and mobilization of newly exposed deeper sourced sediment. High rates of erosion led to increased turbidity and suspended sediment concentrations (Carlowicz, M., 2011). Over the three days of peak flooding, sediment concentration at the mouth of the Connecticut reached a record high of over 1,000 mg/L (Kratz, 2012) (Fig. 2). The sediment load at the mouth of the Connecticut River was exceptionally high, however, its tributaries were relatively efficient at trapping some of this sediment because of the dammed nature of the river.

Figure 2 - Landsat 5 TM image acquired September 2, 2011 showing the sediment export at the mouth of the Connecticut River following Tropical Storm Irene. (Carlowicz, 2011).

The Connecticut River has 2,722 dams, 16 of which are for flood control (The Nature Conservancy). Flood control dams provide opportunities for studying sediment deposition because the reservoir impoundment provides a time stamp for initiation of sediment trapping. This time stamp is a sedimentary signature and can be used to identify past storms besides Irene in the sediment record. Furthermore, flood control dams allows us to see how these structures trap sediment, which may be different than hydroelectric dams due to the system's short residence time.

Recent Storm History of the Connecticut River Watershed

The Connecticut River Valley has been the site of many floods over the past century. The 1930s marked the first extreme floods in the Connecticut River's documented history. In March 1936, the flood was so great that the Connecticut River engulfed its 100 year terraces (Jahns, 1947). In September 1938, a hurricane hit the area and again flooded up to the terraces. The United States Department of the Interior published that the flood of 1936 was the worst that New England had seen since before it was settled, and that the chance of the same caliber flood hitting again was small (Jahns, 1947). However, large storms did occur 51 and 75 years later, but hit the tributaries harder than the main trunk.

The Spring Flood of 1987 hit the Connecticut River Valley especially hard because it combined rain associated with a storm from the Midwest (ca. 17 cm) with a warm spring inducing increased snowmelt (10 cm) in Maine. A few days later, another storm hit New England, bringing with it 10 to 18 cm of additional precipitation. The discharge from Maine was already making its way down the watershed, so the addition of fresh rainfall resulted in catastrophic flooding (Northeast River Forecast Center) that was so severe that a state of emergency was declared and included 34 Massachusetts towns with many towns experiencing washed out roads and flooded bridges (The Associated Press, 1987). This superlative discharge was also responsible for filling five United States Army Corps of Engineers flood control dams to full capacity (Connecticut River Joint Commission, 2009) and filling Littleville Lake to 90% of its capacity.

Figure 3 – Hurricane Irene hitting the Bahamas as a category 3 hurricane. Image from MODIS Terra on August 25, 2011. (NASA, 2011)

Tropical Storm Irene is a perfect example of how extreme precipitation events can drastically change the landscape through flooding, increased sediment transport and differing sediment depositional patterns. In late August 2011, Irene made its way through the Caribbean as a category 3 hurricane (Fig. 1), with peak intensity of 115 mph. Over the Bahamas, Irene had a high moisture content and a 1,000km wind field (Fig. 3). By the time the storm reached the northeastern United States it had been reduced to a tropical storm and had a storm field of only 750km. Nevertheless, it was still incredibly destructive (Coch, 2012) with rainfall totals from 10 to 25cm between New Jersey and Vermont in the six day period between August 26 and 30

(Fig. 1). These high levels of precipitation lead to record-breaking river discharges and mass flooding. This was responsible for widespread power outages, destroying 800km of roads, 300 bridges, entire towns, and for causing most of the 45 human deaths (National Weather Service, 2012). There is no doubt that Tropical Storm Irene was an extreme event in the northeastern United States, but it is important to determine how unusual of an event it was, historically and sedimentologically, so that communities can properly prepare for the future, especially since the magnitude of annual extreme event precipitation has increased over the past three decades (Douglas and Fairbank, 2010).

Fingerprinting

Yellen et al., (in review) identified the Irene sediment layer in their study on the Deerfield River using color, organics, grain size, and ^{7}Be dating. They found the layer to be anomalously grey and inorganic. The Irene layer had half the organic concentration of the underlying sediment, decreasing from 10% to 5%. The maximum size of the grains deposited in the Deerfield during Irene were around 35 μm, which is medium silt, compared to previously deposited sediment around 70 μm, fine sand. The thickness of this grey, inorganic clay and silt layer also matched the increase in the depth of measurable ^{7}Be between pre and post Irene sediment (Yellen et al., in review). This confirmed the anomalously grey layer was indeed sediment deposited by Tropical Storm Irene. Because of this confirmation, I am using this “fingerprint” to identify the Irene sediment in my own study.

Using sediment cores collected from Litteville Lake, a flood control reservoir that captured extreme flows during Irene flooding, this paper compares the meteorological and sedimentological patterns associated with Tropical Storm Irene and the Spring Flood of 1987. Yellen et al., (in review) found the effects of Tropical Storm Irene in the section of the Connecticut River near Deerfield, MA, but did not explore how this event fit into the past storm history of the area. However, they identified key parameters that are used here to understand the impacts of these two storms on a tributary near Littleville Lake and to compare them to what was found at the core of the watershed.

Geologic Setting

The creation of the Connecticut River Valley, and the rocks in the area, are mostly due to the formation of the Berkshire Mountains. The Berkshire Mountains, to the west of the Connecticut River, started forming in the Taconic Orogeny, approximately 470 million years ago, when island arcs were accreted to North America (Little, 2001). During the Acadian Orogeny, present day Europe slammed onto North America and as a result the Berkshires grew to roughly the size of the Himalayas (Little, 2001). The Berkshires were finally completed around 300 million years ago in the Allegheny Orogeny when Africa sutured onto Euramerica, forming the supercontinent Pangaea. Because of high levels of stress and deformation, many of the rocks in the area are metamorphic gneiss, schists and slates (Little, 2001). Eventually Pangaea began to rift and drift apart again, resulting in the formation of the Connecticut River Valley. Resulting cracks and faults were filled with igneous material (Little, 2001). This metamorphic and igneous material throughout the Connecticut River Valley has low permeability, and consequently may be a big factor in the high levels of runoff observed during Tropical Storm Irene (Coch, 2012).

Figure 4 – The extent of Glacial Lake Hitchcock in the Northeast (Rittenour, 1997).

Glaciation was another prevalent event in Massachusetts. Roughly 18,000 years ago, the Laurentide ice sheet retreated northward, forming a proglacial lake. The retreating ice sheet started to melt but was dammed by the large amount of previously dumped sediment, coarse sands, pebbles, and even boulders at the ice margin and this resulted in the formation of Glacial

Lake Hitchcock. This glacial lake was around 320 km, running from present day Connecticut to Vermont (Rittenour, 1997) (Fig. 4). Today the landscape is composed of glacial till and sediment from Glacial Lake Hitchcock's lakebed overlying the bedrock (Carlowicz, 2011). The glacial tills are what we find in the upland reaches, and glaciofluvial deposits and alluvium in the river valleys.

The upland region of the watershed is composed of glacial till dominated by illite clays and orthoclase (Quigley, 1980). Illite is defined as a fine grained muscovite and biotite structure held together by potassium (K) cations (Seidenstein, 2014). When biotite experiences weathering, the K is the first to weather out. Vermiculite is the breakdown product of this biotite weathering, and can easily be identified in the sediment record as high levels of zirconium (Zr). High levels of Zr are an indication of highly weathered material (Yellen et al., in review). Therefore, fairly weathered surface sediment will have a low K/Zr ratio, whereas deeper unexposed sediment will have higher K/Zr since they have yet to be broken down into vermiculite.

The Creation of Littleville Lake

Littleville Lake is a flood control reservoir on the middle branch of the Westfield River, a tributary to the Connecticut River. The lake lies to the east of the Berkshire Hills in Huntington, Massachusetts and also acts as a backup water reservoir to Springfield, Massachusetts. At Littleville Lake and along the Westfield, the bedrock is Lower Devonian Goshen Formation, which is composed of mostly fine to medium-grained quartz, micas, garnet, staurolite schist and fine-grained gray quartzite (Hatch, 1967; Zen et al., 1983). The flood control dam on Littleville Lake was built in 1962 and completed in 1965. It stands at 50 m tall with a storage capacity of

28 billion liters of water. The watershed is roughly 132 km^2 with a 27 m maximum depth supply pool. The Army Corps of Engineers stores an extra 1.5 to 2 m of water every spring so they can release this amount for the annual Westfield River canoe race in April. The dam is also drawn down by ca. 30 cm every few years when maintenance is needed on or around the dam (Tow Wisnauckas, personal communication, March 6, 2014). The dam cost $6.8 million to build but is estimated to have saved $148.5 million in flood damages as of September 2011 (U.S. Corps of Engineers).

METHODS

Field Methods

Over five days in July 2013, two other students and I took canoes out onto Littleville Lake to collect sediment cores that we hoped would show records of Tropical Storm Irene. We used gravity coring and push coring for the extractions. Gravity coring needed one canoe, while push coring required a motorized catamaran made from two canoes to create a stationary platform.

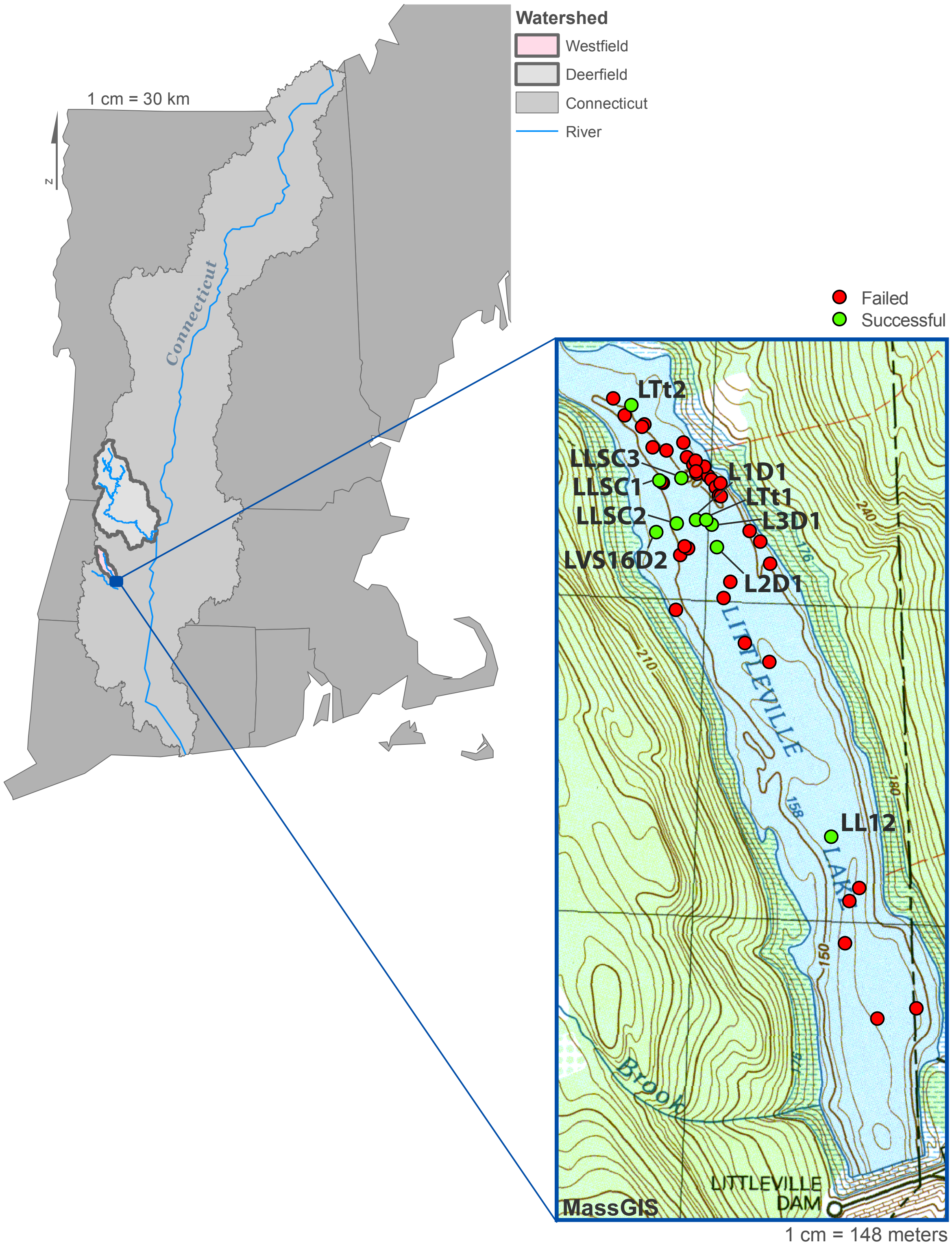

Figure 5 – A locations map showing the three watershed of importance to this study – Connecticut, Deerfield and Westfield. The coring locations on Littleville Lake show the sites where sediment was successfully captured as well as where we were unsuccessful.

Ten cores were successfully captured out of 56 attempts (Table 1; Fig. 5). Four long push cores were collected in a 2 meter long polycarbonate barrel with a 5 cm outside diameter. This barrel was attached onto a metal pull cap and had a piston threaded through and loosely secured at the bottom end on the barrel. Water depth at each core site was recorded using a Speedtech depth sounder. The starting depth of the corer was recorded and the metal piston wire was securely coiled onto the catamaran so that it could pull the piston up through the core barrel. Once in place, a large metal slide hammer was added onto the corer and used to drive the core barrel down into the lakebed, about a meter and a half on average. The driving depth was recorded, the piston wire uncoiled, and the core barrel pulled back to the surface, where the bottom of the barrel was quickly capped and taped. Once on the boat, the pull cap was detached from the core barrel and a hack saw or pipe cutters were used to saw down excess barrel so that floral foam could be inserted and pushed down to the sediment water interface, being careful not to disrupt the surface. Then the top of the barrel was capped, taped and stored upright until it was brought to the lab.

The remaining six cores were collected using a Uwitec Gravity Corer. The polycarbonate barrel used in the gravity corer was varied in length and had an 8.6 cm outside diameter. All cores were capped in the canoe and then brought back to shore. Cores LLSC1 and LLSC2 were then extruded in 0.5 cm depth increments and bagged for transport. Core LLSC3 was subsampled with a piece of 5 cm diameter polycarbonate barrel. Core LVS16D2 had to be capped and taped with the core catcher still inside the barrel.

Table 1 – Core attempts in Littleville Lake. The FAILED label indicates that the core captured no sediment. Latitude and longitude are accurate within +/- 3 meters.

Name	Date	Type	Lat/Long	Depth (m)	Sed Length (cm)
LTt1*	4/27/2013	Short Gravity	42.28411N, 72.88932W	14.1	29.0
LTt2*	4/27/2013	Short Gravity	42.28736N, 72.89228W	6.6	18
LLSC1	7/2/13	Short Gravity	42.28522N, 72.89116W	6.2	20.4
LLSC2	7/2/13	Short Gravity	42.28399N, 72. 89046W	12.0	35.7
LLSC3	7/2/13	Short Gravity	42.28529N, 72.89030W	11.5	24.9
Site 1	7/5/13	Short Gravity	42.26993N, 72.88242W	23.6	FAILED
Site 2	7/5/13	Short Gravity	42.27207N, 72.88371W	23.0	FAILED
Site 3	7/5/13	Short Gravity	42.27024N, 72.88092W	15.0	FAILED
Site 4	7/5/13	Short Gravity	42.27365N, 72.88320W	14.7	FAILED
Site 5	7/5/13	Short Gravity	42.27365N, 72.88357W	17.8	FAILED
Site 6	7/5/13	Short Gravity	42.28234N, 72.88835W	12.5	FAILED
Site 7	7/5/13	Short Gravity	42.28309N, 72.89029W	11.2	FAILED
Site 8	7/5/13	Short Gravity	42.28608N, 72.89089W	8.4	FAILED
Site 9	7/5/13	Short Gravity	42.28680N, 72.89177W	6.7	FAILED
Site 10	7/5/13	Short Gravity	42.28754N, 72.89299W	5.1	FAILED
L1D1	7/9/13	Long Push	42.17028N 72.53230W	9.2	97
L2D1	7/9/13	Long Push	42.17000N 72.53200W	11.7	133
L3D1	7/9/13	Long Push	42.17023N 72.53208W	12.3	93
LLC1	7/15/13	Long Grav	42.28706N, 72.89252W	6.0	FAILED
LLC2	7/15/13	Long Gravity	42.28615N, 72.89142W	9.1	FAILED
LLC3	7/15/13	Long Gravity	42.28631N, 72.89025W		FAILED
LVS1	7/17/13	Short Gravity	42.28008N, 72.88680W	15.5	FAILED
LVS2	7/17/13	Short Gravity	42.28061N, 72.88776W	14.1	FAILED
LVS3	7/17/13	Short Gravity	42.28188N, 72.88860W	12.1	FAILED
LVS4D1	7/17/13	Short Gravity	42.28329N, 72.89001W	11.4	FAILED
LVS4D2	7/17/13	Short Gravity	42.28335N, 72.89014W		FAILED
LVS5D1	7/17/13	Short Gravity	42.28515N, 72.89101W	9.7	FAILED
LVS5D2	7/17/13	Short Gravity	Same as LVS5D1+/- 4m	9.5	FAILED
LVS5D3	7/17/13	Short Gravity	Same as LVS5D1+/- 4m	8.8	FAILED
LVS5D4	7/17/13	Short Gravity	42.28517N, 72.89106W	8.2	FAILED
LVS6	7/17/13	Short Gravity	42.28542N, 72.88970W	7.4	FAILED
LVS7	7/17/13	Short Gravity	42.28589N, 72.89010W	6.7	FAILED
LVS8	7/17/13	Short Gravity	42.28674N, 72.89185W	8.3	FAILED
LVS9D1-4	7/17/13	Short Gravity	42,28536N, 72.88927W	8.4	FAILED
LVS9D5/6	7/17/13	Short Gravity	42.28526N, 72.88915W	8.6	FAILED
LVS10	7/17/13	Short Gravity	42.28505N, 72.88898W	8.4	FAILED
LVS11	7/17/13	Short Gravity	42.28563N, 72.88943W	5.8	FAILED
LVS12D1	7/17/13	Short Gravity	42.28568N, 72.88986W	7.3	FAILED
LVS12D2	7/17/13	Short Gravity	42.28580N, 72.88977W		FAILED
LVS13	7/17/13	Short Gravity	42.28549N, 72.88975W	7.4	FAILED
LVS16D2	7/17/13	Short Gravity	42.28374N, 72.89124W	4.5	26.3
LVS17D2	7/17/13	Short Gravity	42.28153N, 72.89043W	6.6	FAILED
LVS18	7/17/13	Short Gravity	42.28289N, 72.88684W		FAILED
LVS21	7/17/13	Short Gravity	42.28352N, 72.88722W		FAILED
LVS22	7/17/13	Short Gravity	42.28382N, 72.88765W	6.5	FAILED
LVS23D1	7/17/13	Short Gravity	42.28482N, 72.88885W	8.7	FAILED
LVS23D2	7/17/13	Short Gravity	42.28479N, 72.88877W	8.8	FAILED
LVS24	7/17/13	Short Gravity	42.28517N, 72.88880W	8.4	FAILED
LL12*	10/26/2013	Long Push	42.27511N, 72.88431W	17	60

* Collected by Brian Yellen

Many unsuccessful gravity core attempts were made (Table 1). However, these still provided useful information. In some areas of the reservoir the core barrels came back up cracked or with pieces completely broken off. These were interpreted as hitting hard bottom with little or no sediment accumulation. In other instances, the gravity core hit the sediment-water interface causing bubbles, retrieving only cloudy water and organics such as pieces of leaves and small sticks. This suggests that there could be a layer of leaves and organics coating the lakebed making it too thick for the gravity core to cut through. If this is the case then there could be sediment in these location, but we are unable to collect it from under the organic layer.

A few times the gravity core was sent to the bottom of the reservoir and brought back up without an attempt to cap the sediment. This was to test the sediment availability and observe the bubbles possibly due to organics. The bubbles tell us that the core barrel is hitting organics, but that the barrel is not sharp enough to cut through. For the analytic purposes of this study, these uncapped attempts are not included in the analysis due to their inconclusive nature.

Lab/Analytic Methods

All samples were taken to the Quaternary Lab at the University of Massachusetts, Amherst for analysis. The long push cores and LVS16D2 were run through the Geotek-MSCL-S for bulk density, before being sliced open on a Geotek Core Splitter. After slicing, one half of the core was wrapped in plastic and archived in a cold room. Samples were collected every centimeter from the other half and placed in ceramic crucibles or open-faced aluminum tins.

All samples were weighed and dried in a 105° C oven overnight. The samples were then reweighed to determine the amount of water removed as a proxy for porosity. Then, they were placed in a 550° C oven for at least three hours to combust the organics and determine the loss on ignition (LOI). Reservoirs in forested landscapes are usually high in organic material, so a low organic layer of sediment would suggest a change between the sediment deposited regularly and the sediment deposited during Irene. Yellen et al. (in review) found that sediment deposited by Tropical Storm Irene near Deerfield, MA had relatively low organics, about 5% compared to the background values of 10%.

Table 2 – Lab methods run at the University of Massachusetts, Amherst on the ten successful cores

Name	Porosity	LOI	Density	Grainsize	Mercury	XRF
LLSC1	X	X			X^	
LLSC2	X	X				
LLSC3	X	X		X		
L1D1	X	X	X		X^	X
L2D1	X	X	X	X+	X^	
L3D1	X	X	X			
LVS16D2	X	X	X	X+		
LTt1*	X	X	X			X
LTt2*	X	X	X			X
LL12*	X	X	X			X

* Collected by Brian Yellen
^ Run at Amherst College
+ Run at Mercyhurst University

Grain-size analyses were run on the cores (Table 2) but on two different Coulter LS laser particle analyzers, one at the University of Massachusetts, Amherst and one at Mercyhurst University. The difference between the two models was that one required the sediment to be sonicated before analysis, while the other sonicated during analysis. At the University of Massachusetts, the Coulter LS 200 required a beaker of post-LOI sediment and distilled water to be sonicated for around five minutes and then placed on a Fisher Vortex mixer before being poured into the Coulter LS 200. The Mercyhurst Coulter LS 13 320 did not require sonicating before running, so the post-LOI sediment was placed in a test tube with distilled water and mixed on a Fisher Vortex Genie 2 and poured into the machine. The machine sonicated the sediment for five seconds prior to the run, and then continued sonicating during the full 60 second run time.

Controls were run at Mercyhurst, as well as three reruns from the core LLSC3 to test for consistency between the two machines. The controls yielded similar outcomes and the reruns showed almost identical mode values between the two cores. In both labs the grain-size data were computed using the Faunhofer 780d algorithm and reported as D_{90} in microns, where 90% of the grains in the sample are smaller than the cited value. Yellen et al., (2014) argue that D_{90} represents the maximum grain size a river is capable of transporting under the conditions in which it was deposited.

At the University of Massachusetts, X-ray fluorescence (XRF) was run on the archived half of four cores (Table 2) to detect elemental abundances in potassium and zircon. The XRF produces an X-ray image of the core, which gives good representation of density. Superimposed on the X-ray image are elemental signatures for potassium (K) and zirconium (Zr). K is a strong indicator of unweathered clays usually found in tills. Conversely, Zr is an indicator of weathered material. Yellen et al. (in review) used this to identify sediment deposited by Tropical Storm Irene near the Deerfield River, arguing that K is a main component in the un-weathered glacial that is found in the upland region and is dominated by illite (Quigley, 1980). Sediment deposited during Irene is Zr deficient because high concentrations of Zr are only found in highly weathered sediment and the upstream tills are highly resistant to weathering (Yellen et al., in review). This suggests that high Zr concentrations are a result of surface weathering and shallow erosion.

Mercury (Hg) analysis was run on organic-rich subsamples every centimeter from three cores (Table 2). Scott Kugel and Anna Martini ran the samples on Amherst College's Teledyne Leeman Labs HYDRA IIc mercury analyzer following procedures summarized in Woodruff et al. (2013). Because Hg is adsorbed to organics, the Hg values were normalized by dividing the Hg concentration by the LOI and are reported as ng of Hg per gram of organics.

A large spike in Hg concentration in cores L1D1 and L2D1 was interpreted as the closure of the dam in 1965. Using this spike in Hg and the base of the Irene layer as time markers, an average sediment deposition rate was calculated. This was used to constrain the approximate position of the 1987 storm in both of the cores.

In an attempt to create an accurate age model in the cores, fallout short-lived radioisotope analysis (^{137}Cs and ^{210}Pb) was run on dried organic rich sediment from the L1D1 core following methods similar to Woodruff et al. (2013). The samples were packed in one-centimeter increments and sealed for three weeks before being run on a Canberra BeGE Germanium Detector for 72 hours. The samples were analyzed for ^{137}Cs to determine the 1954 onset and the 1963 peak, and unsupported ^{210}Pb for dating using its 22.3 year half-life. No unsupported ^{210}Pb was detected in the initial sample from the top of L1D1. Levels of ^{137}Cs were so low and had such high errors that an accurate reading would require a 13-day run per sample. Thus, this method was not used for analysis.

River discharge data from the Connecticut River, the Deerfield River and the West Branch of the Westfield River was downloaded from the United States Geological Society. The West Branch was used because it does not have a dam, therefore giving a more accurate volume of water going through the area. The West Branch discharge does not give the exact volume of water moving through Littleville Lake, but the patterns should be consistent with what enters the lake. These values were also converted from m^3/second into mm/day for further analysis.

X-Ray Diffraction (XRD) was run on the clay portion of the sediment from pre-Irene, Irene and post-Irene sediment from core L1D1. XRD was also run on exposed glacial till in the upstream areas. Julia Seidenstein ran all XRD methods following Seidenstein (2014).

ArcGIS Methods

I downloaded the average monthly precipitation data for the Eastern United States at a 4 km resolution from the PRISM Climate Group. Using ArcGIS I delineated the watershed and created visual representations of the amount of monthly precipitation in the Westfield and Deerfield watersheds when the two storms hit.

Using the Irene thickness found in my successful cores, I interpolated the data over the entire reservoir and calculated sediment yield. I did this using the thickness of the Irene sediment and the location in which it was cored. Because I do not have cores from across the entire reservoir, I created 100 m buffers zones around each location to try to give an estimation of Irene sediment cover. I then calculated the volume of each pixel in the reservoir, and added them together to find the volume of all the pixels. Then I calculated the total thickness of Irene-related sediment in each of the cores, which allowed for the total mass of sediment to be found. By dividing the total mass by the area of the watershed, I found the sediment yield.

RESULTS

Precipitation

Using PRISM data, the monthly precipitation for the Westfield and Deerfield watersheds was calculated for April 1987 and August 2011 (Fig 6). Comparing the mean rainfall between the Westfield and the Deerfield within a single year shows little to no difference. In April 1987, the mean precipitation in both watersheds was 24 cm. However, if we take a look at the minimum and maximum values within these regions we can see the differences. The April 1987 rainfall ranges in the Westfield with a 23 cm minimum and a 25 cm maximum, compared to a 20 cm minimum and 31 cm minimum in the Deerfield. In August 2011, mean precipitation was 30 cm in the Westfield and 29 cm in the Deerfield. The Westfield had a range of 29 to 30 cm, while the Deerfield had a range of 21 to 40 cm.

In both 1987 and 2011 the area with the highest amount of monthly precipitation was the northern region of the Deerfield watershed that lies in Vermont.

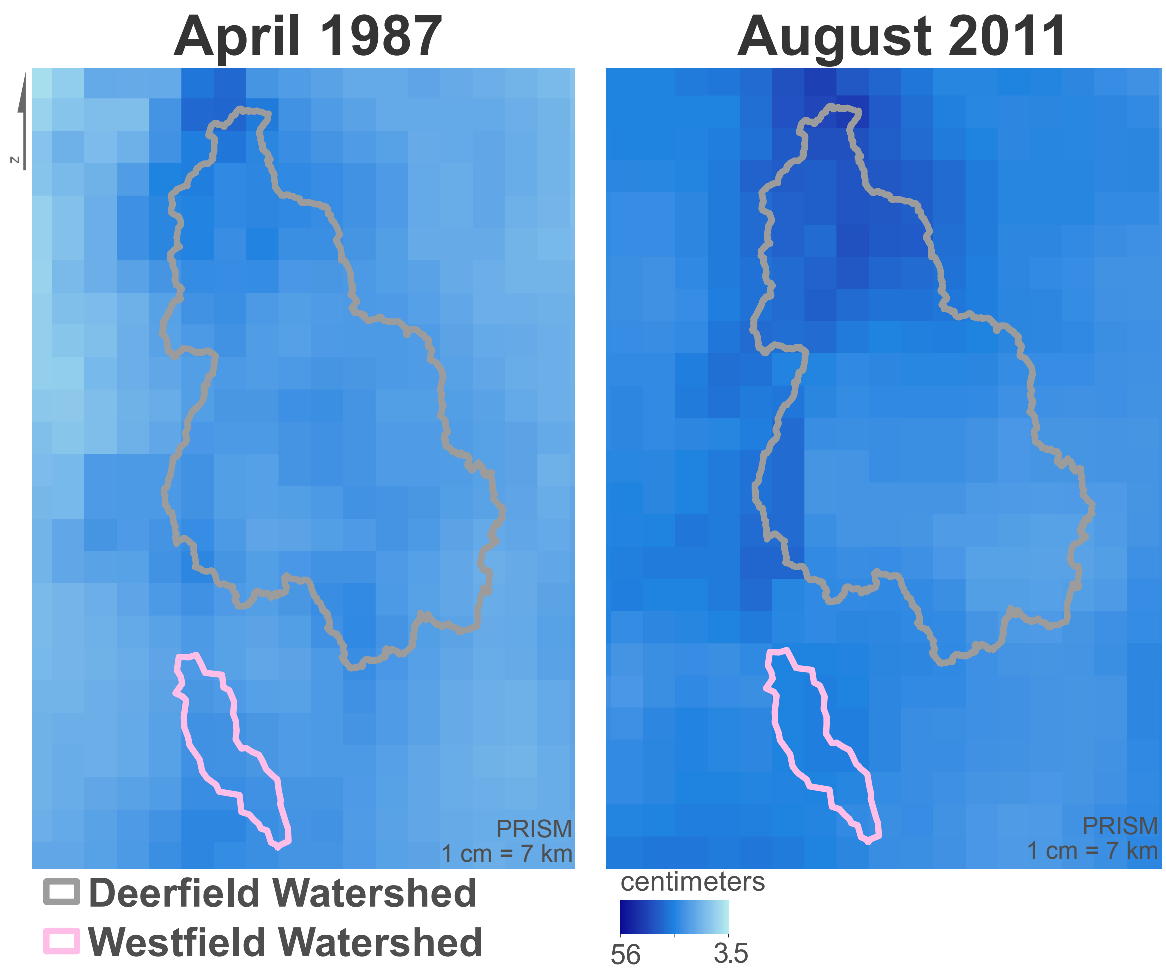

Figure 6 – Monthly precipitation in the Westfield and Deerfield watersheds during April 1987 and August 2011. Calculated using PRISM data. The Deerfield Watershed has noticeably more precipitation in August 2011 than April 1987.

Hydrographs

Discharge data from the Westfield River (Fig. 7a) shows that 2011 had a peak in the spring for annual snowmelt and an incredibly high peak in late August and early September representing Irene. This high peak corresponds to a 425 m^3/second peak discharge on the Westfield River during Irene. The data also show that the highest peak in 1987 was in late March and early April during the Spring Flood, but there are no peaks in late August. The peak discharge on the Westfield during the Spring Flood of 1987 was 138 m^3/second, which is significantly smaller than that of Irene.

Discharge data from the Deerfield River (Fig. 7b) show exactly the same shape as the Westfield River, but with discharge values roughly twice as high. The only place on the hydrograph where this is not the case is early April 1987. The peak discharge for the Spring Flood of 1987 in the Deerfield is more than three times that in the Westfield. This peak discharge from the Spring Flood was 478 m^3/second. The Irene peak discharge was 634 m^3/second.

The discharge from the Connecticut River (Fig. 7c) shows that much larger volumes of water travel down the main trunk of the river than in the other two locations. The shape of the hydrograph in 2011 shows the same general shape as the Westfield and Deerfield, but much more exaggerated, especially in the spring. The peak Irene discharge was around 3,341 m^3/second. The discharge in 1987 for the Spring Flood was much larger than in the other two locations, and actually slightly larger than Irene with a peak of 3,454 m^3/second.

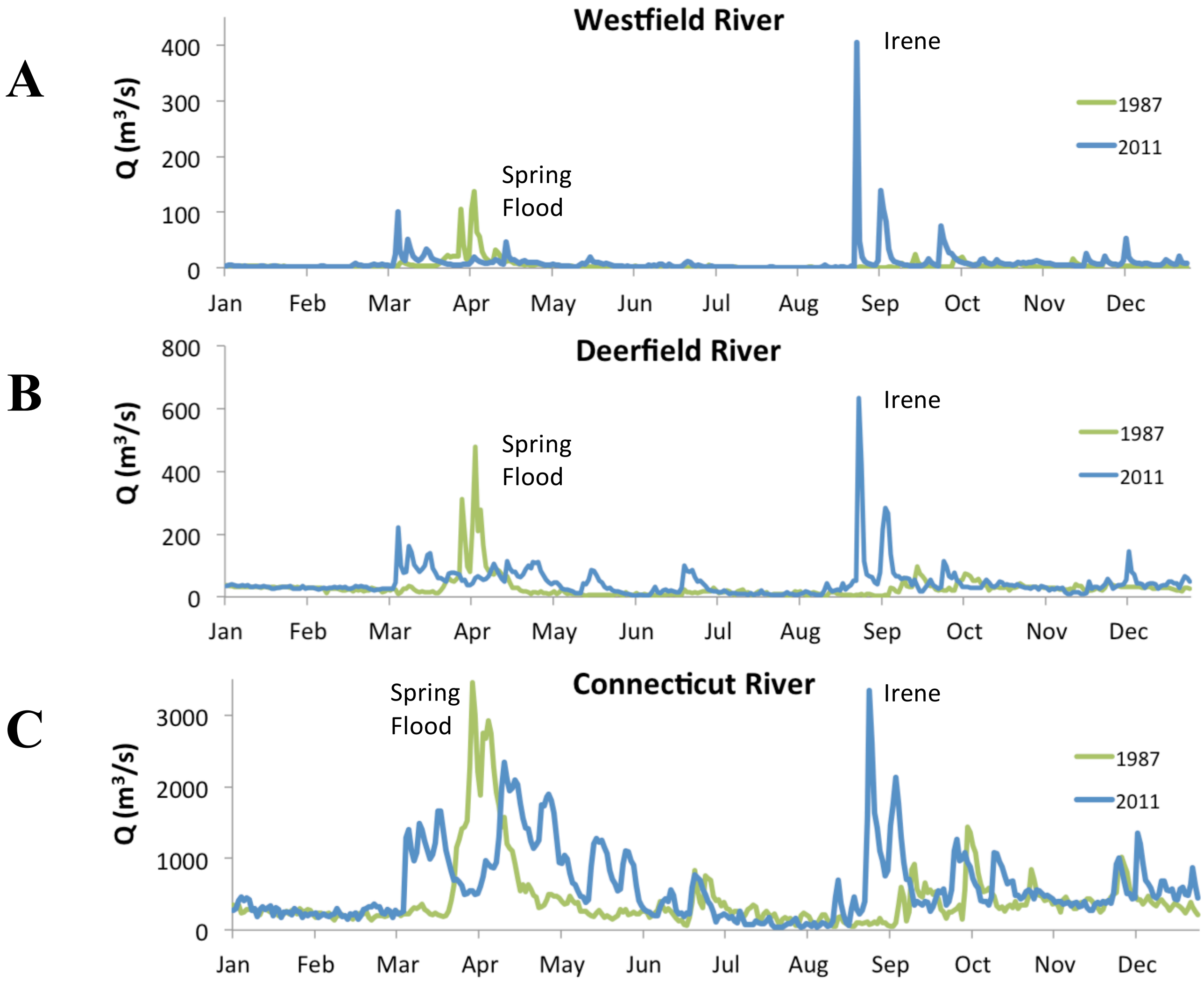

Figure 7 – USGS daily river discharge data from the West Branch of the Westfield River, the Deerfield River and the Connecticut River for 1987 and 2011. A) shows that the April 1987 discharge was roughly three times smaller than discharge during Irene in 2011. However, in B) and C) the volume of water in April 1987 is much closer to that of Irene.

Irene

The sediment cores show a few general trends. Both L1D1 and L2D1 show dramatic increases in Hg concentration about halfway up the core (Fig. 8 and Fig. 9), which I interpret as the dam closure in 1965. A thin layer of grey sediment was seen towards the top of four of the sediment cores. LOI results show these thin grey layers to have a slightly lower organic percentage in cores L1D1, L3D1 and LTt1. Grain-size data in core L2D1 also shows that this grey layer had finer grains than the sediment surrounding it (Fig. 9a). The Hg concentration in L1D1 and L2D1 also strongly dips at this grey layer (Fig. 9c). Following Yellen et al. (in review) I interpret this as the anomalous Irene layer.

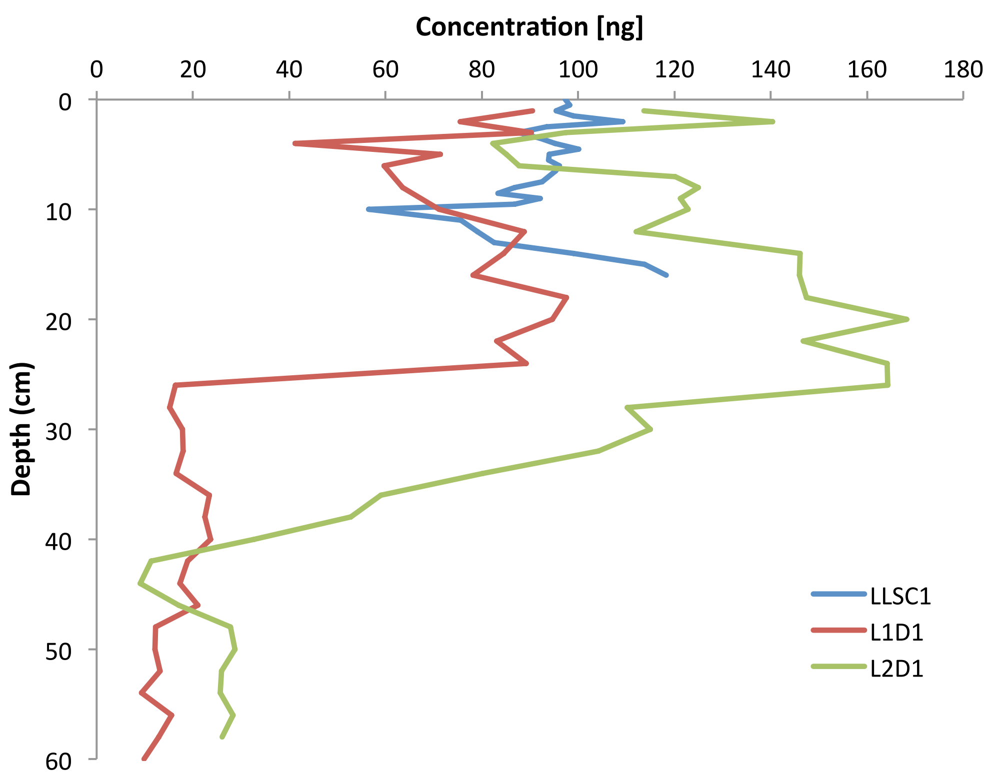

Figure 8 – Mercury (Hg) concentrations in three different cores show the same general patterns. Reading the cores from bottom to top, a large rise in Hg is seen at 25 cm in L1D1 and 41 cm in L2D1. These large peaks represent the closure of the dam in 1965.

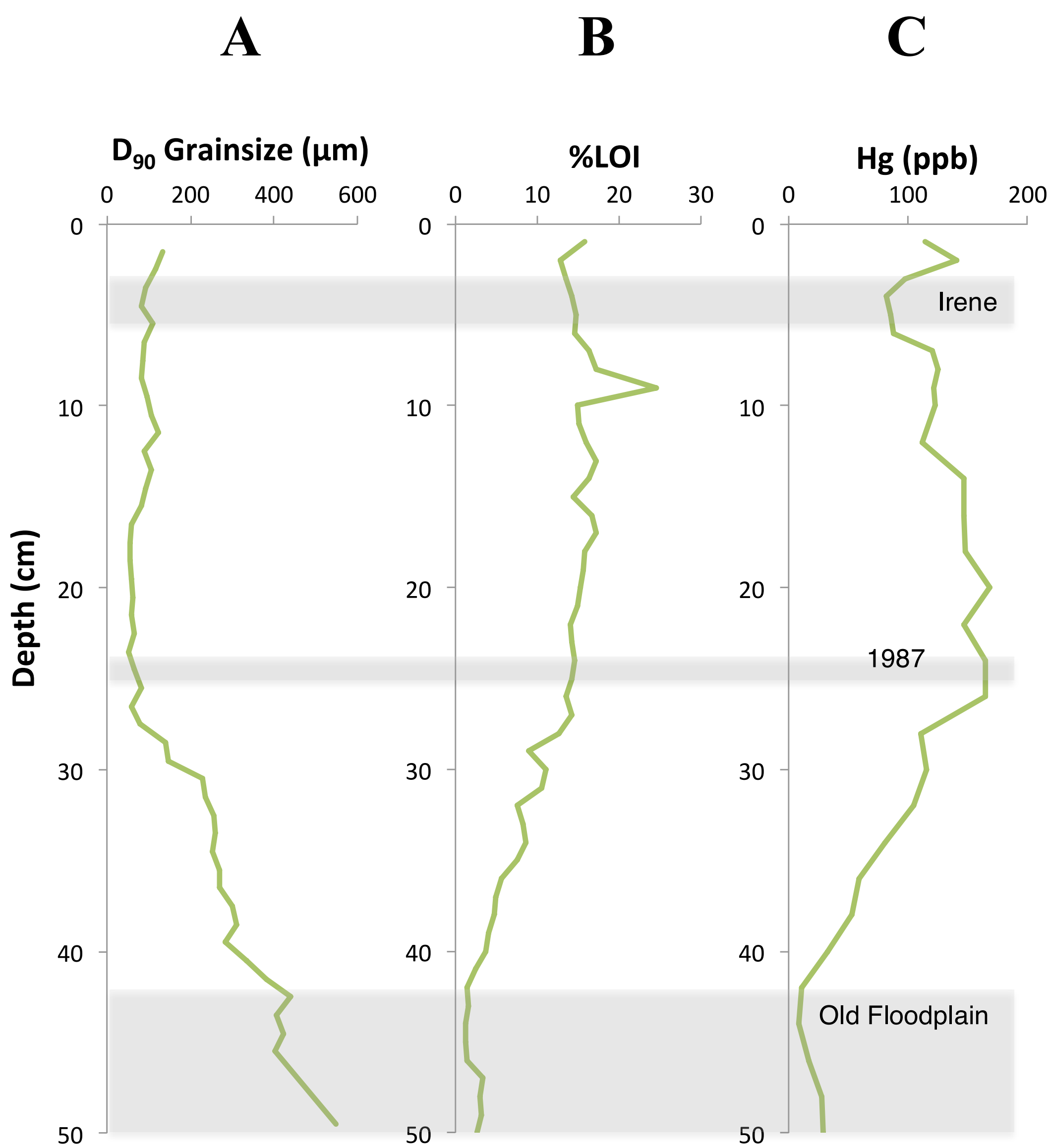

Figure 9 – The grainsize (A), organic (B) and mercury (C) analyses run on L2D1 with the event layers identified. Smaller grain size and lower organics and Hg concentrations can easily be observed in the Irene layer.

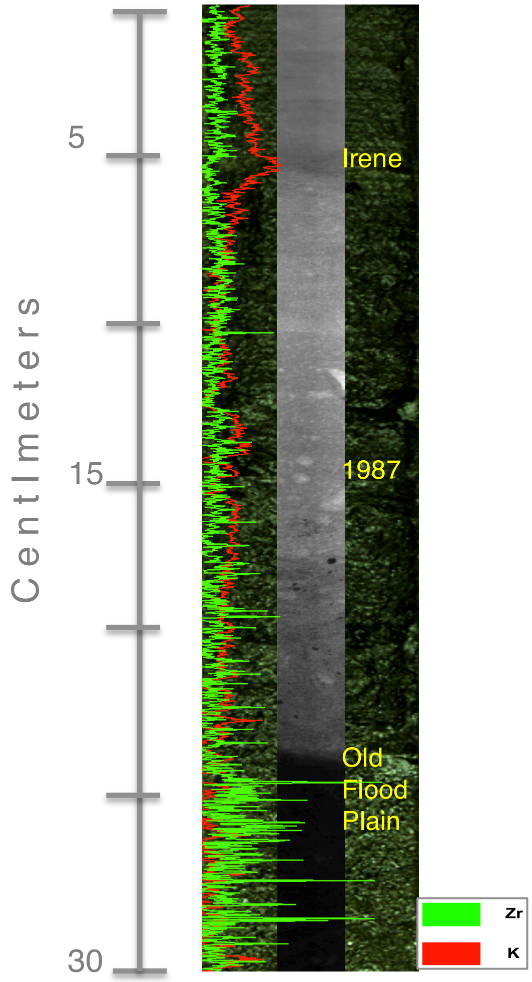

Figure 10 – Potassium (K) and zirconium (Zr) signatures in L1D1 superimposed on a radiograph showing density. A clear increase in K can be seen in Irene but nowhere else in the core. A slight dip in Zr is seen in Irene as well, but is held more or less constant throughout the dammed portion of the core.

Trends in potassium and zirconium signatures in the sediment cores not only help identify the Irene layer, but also shed light on the depth of upland erosion. The XRF radiograph shows two darker regions in the image (Fig. 10). The darkest portion, about 6 cm from the bottom of the core, most likely represents the denser material now making up the old flood plain. The other dark region occurs at around 5 cm from the top of the core and represents the pulse of Irene sediment. The 5 cm deposited since Irene are darker than the sediment deposited before Irene.

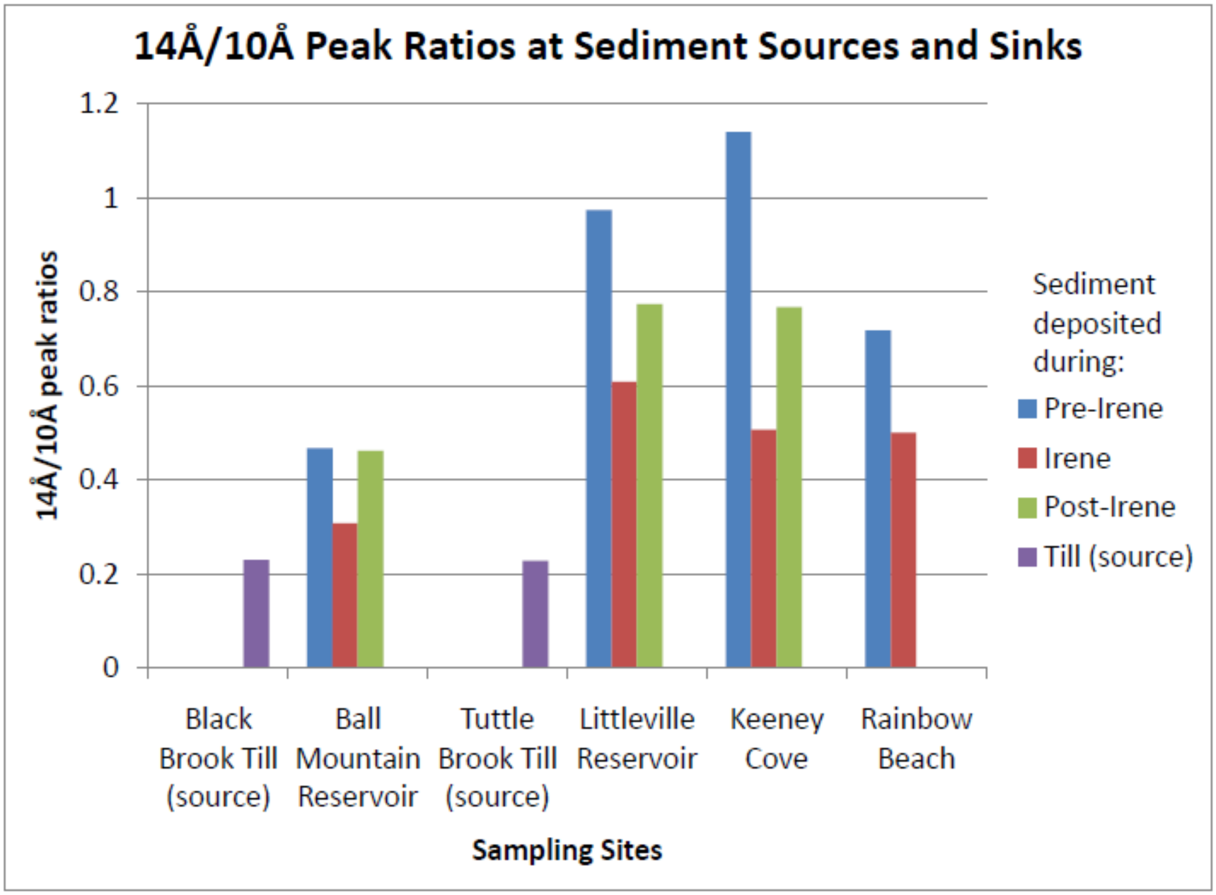

Figure 11 – XRD data from the clay fraction of Pre, Post and Irene sediment. It shows that the sediment1deposited during Irene was the least weathered and most similar to the till. The post-Irene sediment is different from the pre-Irene sediment, which suggests that the landscape is still responding to the effects of Irene (figure from Seidenstein, 2014).

The K and Zr signatures superimposed on the radiograph (Fig. 10) show that K had a large spike at the dense Irene layer, and has continued to deposit sediment with higher K concentrations since Irene. This agrees with the observation that the sediment deposited since Irene appears denser in the radiograph. A high concentration of K means that the deposited sediment is sourced from extremely unweathered material. Unweathered material includes the sediment eroded from newly formed gullies and bank collapses. Zr signatures show a slight dip at the proposed Irene layer. This dip represents a decrease in weathered sediment, which is most commonly sourced from surface material.

XRD data run on the clay fraction of the exposed glacial tills and the lake cores was helpful in classifying which material is weathered and which is unweathered. The exposed glacial till was classified as a source material and found to have an incredibly low vermiculite to illite ratio (Fig. 11), identifying it as extremely unweathered. The sediment deposited before Irene hit was found to have high vermiculite to illite ratios, classifying it as highly weathered. The Irene sediment was found to have a low vermiculite to illite ratio (Fig. 11), but higher than the source ratio. This suggests that the material is eroded from the unweathered source material and becomes slightly weathered on its way into the reservoir. The post-Irene sediment has vermiculite/illite ratios in between those of the Irene and pre-Irene sediment (Fig. 11).

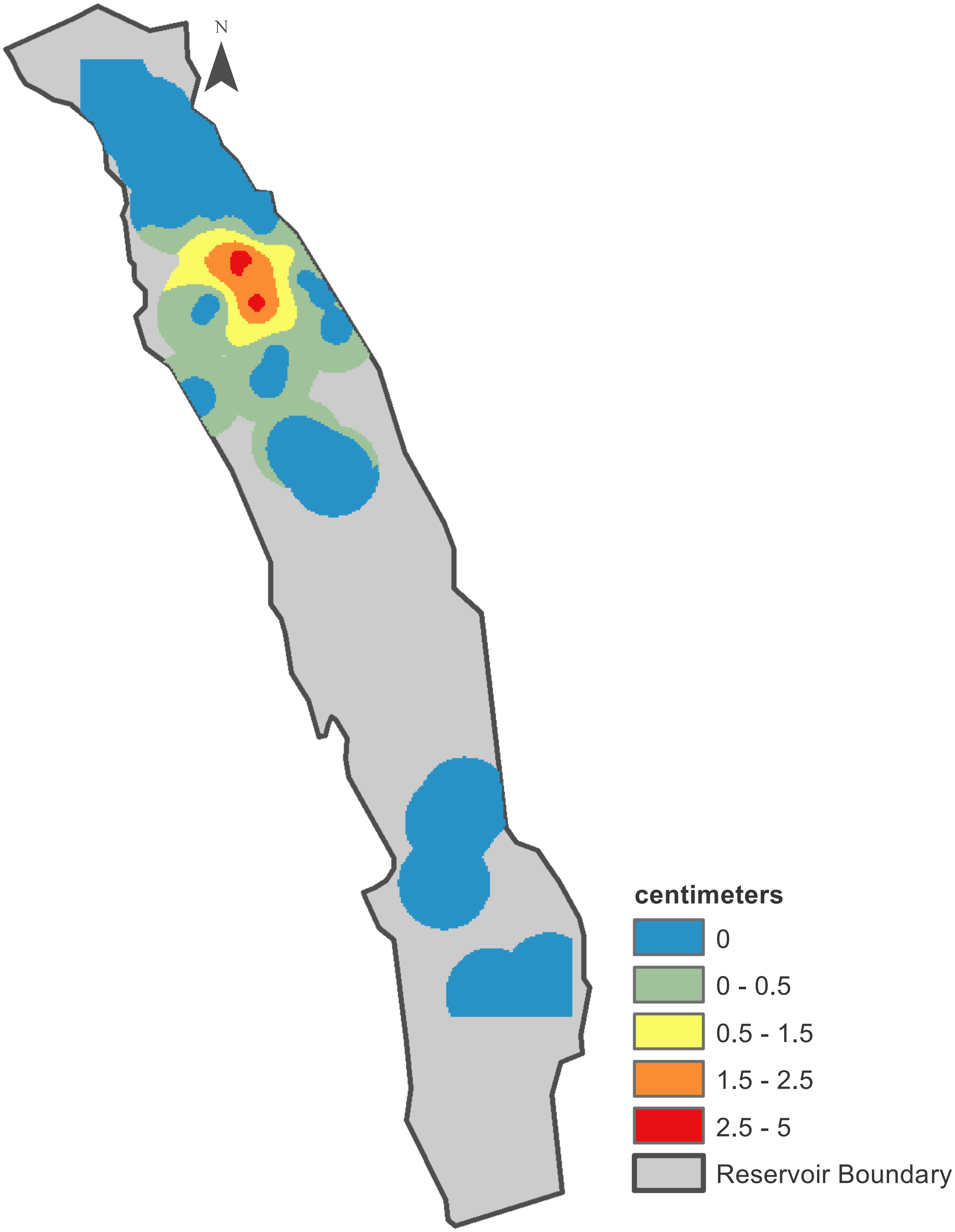

Figure 12 – The interpolated Irene sediment deposition was calculated using 100 m buffer zones around each core location. The sediment deposition patterns show that Irene sediment was only deposited on the northern delta side of the reservoir. The grey represents areas of no data.

Using the interpolated sediment thickness of the Irene layer (Fig. 12) and the calculated porosity from my samples, I was able to calculate an estimated sediment yield for Tropical Storm Irene. Using the average thickness of the Irene layer, around 3 cm in the northern end of Littleville Lake, and the watershed area of 132 km^2, I came up with a sediment yield of 282 kg/km^2. This sediment yield is relatively low for the amount of sediment eventually deposited at the mouth of the Connecticut River.

Spring Flood of 1987

Unlike Irene, the Spring Flood of 1987 was not visually identifiable in the cores. The identified Irene Layer and the old floodplain were used to calculate a 0.43 cm/year sediment deposition rate in L1D1 and 0.80 cm/year rate in L2D1 and to approximate 1987 in the other cores. At this point, there appeared to be a dip in the 1987 Hg concentration, as was seen in the Irene layer. However, there is no increase in K concentration or decrease in grainsize. This suggests that the Spring Flood of 1987 was not a distinct sedimentary event in the Westfield River watershed. Identifying the Irene layer as August 2011 and the top of the core as July 2013, I was able to calculate a roughly 2.5 cm/year sediment deposition post-Irene. This rate is a significant increase over the previous rate.

DISCUSSION

Irene

It is hard to determine sediment yield from Littleville Lake from Tropical Storm Irene because there is no suspended load data from United States Geological Survey or United States Corps of Engineers stream gauges. Interpolating Irene sediment deposition in the reservoir is not accurate because the data are coming from four cores that are close to one another. I attempted coring at many locations around the reservoir, but numerous core barrels came back empty or shattered from hitting bedrock or former lakebed cobbles – indicating areas of non-deposition in the lake. Some of the coring attempts were successful in capturing sediment, but not in capturing Irene. ArcGIS took this cluster of successful Irene cores to mean that there is only one small pocket of Irene sediment in the reservoir and that everything else is bedrock or sediment that does not contain Irene. This could very well be the case, but it resulted in the low sediment yield of 282 kg/km^2. More core data containing an Irene layer would likely result in a more complete sediment distribution in the reservoir and a more accurate sediment yield. On the other hand, Littleville Lake may simply not be the best place to determine sediment yield because of the underrepresented sediment yield during Irene that was already calculated. The Irene layer was thin and scarce in Littleville Lake and it is difficult to determine why.

A possible explanation for the missing sediment in the reservoir is drawdown. Drawdown would explain why many of the cores did not contain the recent Irene sediment, or any sediment at all. However, if drawdown was forcing the sediment to erode and be carried through the dam, then the most erosion would be seen on the delta side of the lake. Yet, we see that the only pocket of sediment in the entire lake is on the delta side. And according to the data provided by the Army Corps of Engineers, the amount of drawdown occurring at Littleville Lake is almost negligible. This disproves the drawdown theory.

A more likely scenario is that Irene sediment deposition only occurred on the delta side of the lake. This is likely due to the discharge dynamic and sediment carried by the storm. When Irene hit the Westfield watershed, roughly 50% of its precipitation instantly became runoff (Yellen et al., in review). This resulted in large volumes of water flowing down the Westfield River. By the time this water reached Littleville Lake it was probably moving at a relatively high velocity. Once the heavy flows hit the reservoir their velocity would have significantly decreased. This allows for finer grains to fall out of suspension. This also explains why we only see the Irene sediment on the northern delta side of the dam. But it does not explain why the Irene sediment layer is so thin. Since the reservoir is not significantly drawn down there is no evidence pointing to the eroding of Irene sediment. This then implies that there was not a lot of sediment in suspension when the Westfield reached Littleville Lake. However, without suspended load data it is impossible to know with complete certainty.

The Irene layer was successfully identified in the colors using the sediment fingerprint from Yellen et al. (2014). This grey, fine grained, K rich, organic and mercury poor sediment from Irene suggests unweathered glacial tills to be the source material of the Irene sediment, and still being eroded and deposited in the present. As seen in the successful cores, the amount of deposited Irene sediment was small, but not insignificant. Considering that the time scale I determined shows the rate of sediment deposition in Littleville to only be between 0.4 and 0.8cm/year, a 2 cm Irene layer is therefore substantial relative to background rates of sedimentation. This means that Irene deposited more sediment in a few days then is usually deposited all year. The much higher present day sediment deposition rate of 2.5 cm/year suggests that the upstream landscape is still responding to the effects of Irene. This increased sediment deposition rate confirms that during the landscape is still responding to Tropical Storm Irene.

The Seidenstein (2014) 14Å/10Å ratios from L1D1 indicate the amount of weathering in the clay portion of the sediment (Fig. 11). A low ratio represents lower concentration of vermiculite, and therefore less weathered sediment, while a high ratio represents more weathered. Low 14Å/10Å ratios are seen in the potentially sourced illite rich Irene material, and then slightly higher 14Å/10Å ratios in the actual Irene layer. This suggests that as Tropical Storm Irene made its way through the northeastern United States it ripped up vegetation, formed new gullies, and caused bank failures and channel scour. These processes all involve exposing previously unexposed and buried upstream glacial tills and quickly eroding them. After the storm passes, these newly exposed materials are now at the surface and subjected to weathering. Since these grains are loosely packed because of the storm, they are easily picked up and transported in the reservoir. This post-Irene sediment is more weathered than the source material or the Irene layer because of the time it has spent at the surface being weathered. However, it is not mature enough to have weathered out the K in the illite as was seen pre-Irene.

The existing literature on sediment transport in post-glacial landscapes mostly focuses its research in western Canada. Church and Slaymaker (1989) explored sediment yields and drainage areas in post-glaciated landscapes in the British Columbian Cascades and found that in undisturbed landscapes, sediment yield increases with drainage basins up to 3×10^4 km^2. Church and Slaymaker (1989) attribute their observed downstream increase in sediment yield to processes such as bank collapses rather than hillslope erosion or gullying in low order streams. In extreme events such as Irene, bank collapses and other deeper sourced erosion would be a more likely source of sediment since there is no time to heavily weather the material during the storm's short duration. Yellen et al. (in review) challenge the validity of applying Church and

Slaymaker (1989) to other post-glaciated areas, such as the Connecticut River Valley, because of topographic and sediment composition differences. The unweathered nature of Irene sediment also suggests a deep hillslope origin rather than weathered bank alluvium.

Church and Slaymaker (1989) results are from land undisturbed by humans and show that the rivers are still working with and distributing glacial sediment. Unlike the study sites in the Pacific Northwest, humans have disturbed the Connecticut River Valley through agricultural and industrial land use changes. Yellen et al. (in review) note that the reforested landscape of the Connecticut River Valley is no longer responding to land use changes. Regardless, post-glaciated Atlantic watersheds do not show a direct relationship between land clearance and an increase in sediment yield (Meade, 1982). This is attributed to the erosion resistant nature of glacial tills.

Spring Flood of 1987

The mean amount of precipitation entering the Westfield and Deerfield watersheds in April 1987 and August 2011 are almost identical. However, when we look at the minimum and maximum values in each watershed we start to notice some interesting trends. In the Westfield, the range in precipitation values only changes by 2 cm in both time periods, while in the Deerfield the precipitation ranges by 12 to 19 cm. The homogeneous rainfall seen throughout a watershed only occurs in the Westfield, and can be explained by the watershed size. The Deerfield watershed is roughly six orders of magnitude larger than the Middle Branch of Westfield. That leaves much more room for variability in rain cover throughout the watershed. In a small watershed it is likely for a storm to go by and for rainfall to equally cover the entire area. In a larger watershed the storm path may only cover the northern half of the region and precipitation will not even reach the other parts.

In April 1987, the maximum value of monthly precipitation in the Deerfield was 6 cm higher than the maximum in the Westfield. Six cm of rain in one month is not a large amount, so this suggests that the rainfall from the Midwest associated with the Spring Flood of 1987 hit both watersheds more or less equally. In August 2011, the Deerfield watershed received 10 cm more rainfall than the Westfield. Ten cm is still not an unusually large amount, so we can assume that the rainfall from Tropical Storm Irene hit both watershed around equally.

The precipitation information would be more useful if we had access to daily precipitation data. Daily data would allow us to isolate the storms, calculate how long it took for the water to end up in the river, and possibly calculate a rainfall rate during the storm.

Leading up to Irene, the northeast was rainy and wet, resulting in high soil saturation and therefore runoff. The high soil saturation previous to Irene combined with high rainfall rates was the reason why Irene was such a large event. The quickly falling rain was not able to infiltrate the wet soil so it did not take much time for the water to reach the rivers. This resulted in high river discharge during and after Irene. In the Westfield and Deerfield Rivers, the peak discharge from Irene was the largest in the river's monitored history.

As seen in the hydrographs (Fig. 7), the Spring Flood hit the three watersheds differently. In the Westfield the Spring Flood's peak discharge is about one third of the peak discharge from Irene, and does not look much differently than the small peak in 2011 for seasonal snowmelt. Looking at the Deerfield Watershed, we see that the Spring Flood peak discharge is comparably larger than in the Westfield. This means that there is more water entering the river than in the Westfield. However, comparing the precipitation data shows that roughly equal amounts of rainfall hit the two watersheds. This then implies that the storm coming in from the Midwest is hitting both watersheds, but that the snowmelt from the north is not. The Westfield is a small tributary in the southwest region of the Connecticut Watershed, so it is possible that none of the snowmelt from the north is entering the watershed. Because the Deerfield is a larger watershed with its uplands in Vermont, is most likely experiencing the surge of snowmelt meeting up with the storm precipitation. Comparing the Spring Flood of 1987 in these two areas proves that floods and storms can affect regions within the same watershed differently, which can result in different erosional patterns.

CONCLUSIONS

Topical Storm Irene signifies a threshold crossing where the sediment mobilized and deposited during the storm was sourced from deep, unexposed glacial illite that had been disturbed and brought to the surface. The fine grained, low organic, low mercury and high K signature left by this unweathered Irene sediment is different than anything else seen in the sediment record, which contains mostly highly weathered, surface sediment eroded and deposited pre-Irene. The sedimentary record also suggests that the landscape is continuing to respond years after the storm. The Spring Flood of 1987 had similar amounts of precipitation as Tropical Storm Irene, but left no signature in the sediment record. The Spring Flood of 1987 shows how smaller tributaries within the watershed do not react to large storms and floods in the same way as larger tributaries or the main truck of the river.

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