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Sediment transport due to extreme events: The Hudson River estuary after tropical storms Irene and Lee

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[1] Tropical Storms Irene and Lee in 2011 produced intense precipitation and flooding in the U.S. Northeast, including the Hudson River watershed. Sediment input to the Hudson River was approximately 2.7 megaton, about 5 times the long-term annual average. Rather than the common assumption that sediment is predominantly trapped in the estuary, observations and model results indicate that approximately two thirds of the new sediment remained trapped in the tidal freshwater river more than 1 month after the storms and only about one fifth of the new sediment reached the saline estuary. High sediment concentrations were observed in the estuary, but the model results suggest that this was predominantly due to remobilization of bed sediment. Spatially localized deposits of new and remobilized sediment were consistent with longer term depositional records. The results indicate that tidal rivers can intercept (at least temporarily) delivery of terrigenous sediment to the marine environment during major flow events.

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1. Introduction

[2] Estuaries are efficient sediment traps, retaining much of the material input from the watershed [*Meade*, 1969; *Schubel and Hirschberg*, 1978]. Landward, near-bottom circulation due to the estuarine salinity gradient creates a sediment flux convergence at the transition from brackish to fresh water, leading to local maxima in suspended sediment concentration (SSC) and deposition rates [*Postma*, 1967; *Meade*, 1969]. Spatial gradients in stratification and tidal asymmetries in velocity shear provide additional mechanisms for sediment retention [*Geyer*, 1993; *Burchard and Baumert*, 1998]. These trapping processes depend on the salinity intrusion, yet many coastal rivers also have extensive tidally influenced regions landward of the limit of salt where other processes may be important. Far less is known about sediment transport processes in tidal rivers, including basic questions on transport efficiency from the watershed to the estuary by tidal and fluvial processes.

[3] Sediment discharge (Q_s) from rivers and streams is a nonlinear function of water discharge (Q_r), often written as a power law: $Q_s \sim aQ_r^b$, with an exponent between 1.5 and 3 [*Nash*, 1994]. Consequently, extreme events contribute disproportionately to the total sediment discharge. For example, Tropical Storm Agnes in 1972 introduced about 31 megaton (Mt) of sediment to Chesapeake Bay, about 30 times the long-term annual average [*Schubel and Hirschberg*, 1978], but an estimated 90% of this deposited in the estuary [*Nichols*, 1977]. Tropical Storm Lee in 2011 supplied about 6.7 Mt of new sediment to Chesapeake Bay, but model results suggest that most of it was deposited near the estuarine turbidity maximum (ETM) [*Cheng et al.*, 2013].

[4] In 2011, Tropical Storms Irene (28–29 August) and Lee (6–9 September) significantly increased discharge and suspended sediment in the Hudson River. The Hudson is tidal from the Battery at the southern end of Manhattan to Troy, New York, 240 km to the north, and the salinity intrusion typically varies from 30 km to 120 km with river discharge and the tides [*Abood*, 1974; *Ralston et al.*, 2008]. The largest tributaries are the Mohawk and Upper Hudson Rivers that converge above the head-of-tide and account for 70–80% of the flow and sediment supply, but lateral tributaries also discharge directly to the tidal river [*Wall et al.*, 2008]. ETMs have been identified in the lower (~15–20 km) [*Geyer et al.*, 1998] and upper (~60 km) estuary [*Ralston et al.*, 2012], but few observations have been made of sediment transport in the tidal freshwater [*Findlay et al.*, 1991; *Wall et al.*, 2008]. Monitoring stations provided some observations of the response to Tropical Storms Irene and Lee, but the data provided little information about the distribution of sediment trapping and remobilization. Here we use a calibrated hydrodynamic and sediment transport model supported by available observations to assess the fate of sediment that was delivered by these extreme events.

2. Methods

2.1. Observations

[5] Tributary discharge measurements were obtained from U.S. Geological Survey (USGS) gaging stations on the Mohawk River (Cohoes), Upper Hudson River (Waterford and Fort Edward), Esopus Creek, Rondout Creek, Wappinger Creek, and Croton River (Figure 1). Additionally, monitoring stations for discharge and suspended sediment were installed a few months prior to Irene on Normans Kill, Kinderhook Creek, Catskill Creek, and Roeliff Jansen Kill. Tributary sediment discharges were calculated from calibrated turbidity measurements or directly from samples [*U.S. Geological Survey*, 2012, 2013] (Figure 1). Tidal volume and sediment

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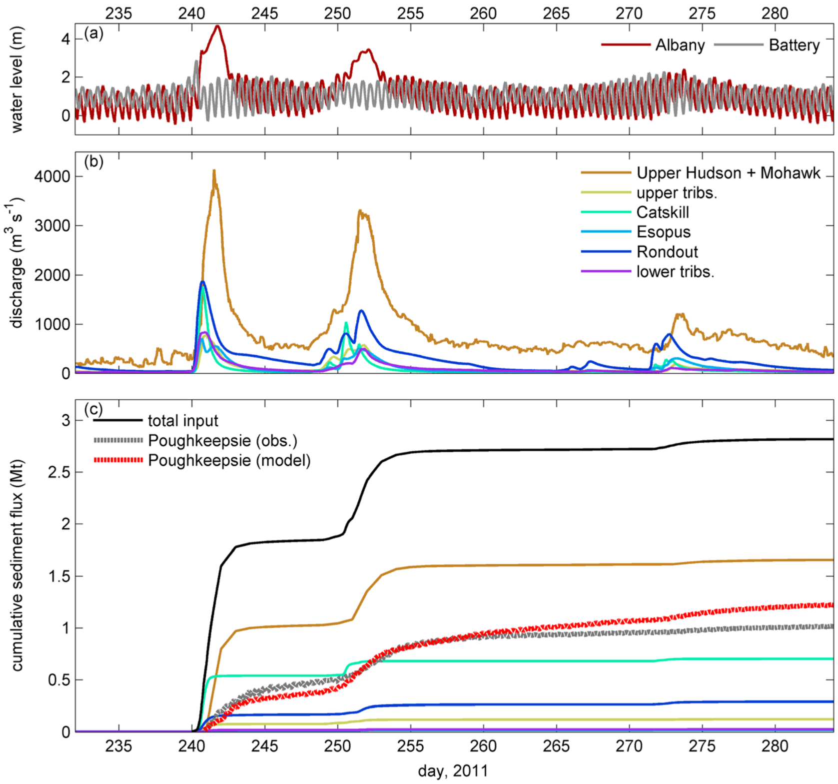

Figure 1. Water level, river discharge, and sediment input from Tropical Storms Irene and Lee. (a) Water surface elevation at the Battery and Albany. (b) Discharge in tributaries of the Hudson, including the Upper Hudson and Mohawk Rivers, Catskill Creek, Esopus Creek, Rondout Creek, and smaller tributaries in the upper (Normans Kill, Kinderhook Creek, and Roeliff Jansen Kill) and lower estuary (Wappinger Creek and Croton River). (c) Cumulative sediment fluxes (millions of metric tons) measured or calculated for the tributaries and the total sediment input, with net seaward fluxes at Poughkeepsie from observations (dashed black) and the model (dashed red).

fluxes were monitored at Poughkeepsie (120 km). The calibration for the acoustic backscatter at that station failed due to the substantially finer particles after the storms. Instead, sediment concentrations from an optical turbidity sensor at Norrie Point (134 km) were used to calculate fluxes (Hudson River Environmental Conditions Observing System, HRECOS). The turbidity sensor was calibrated with a regression to bottle samples of suspended sediment ($n = 10$) taken before, during, and after the discharge events. Turbidity measurements at the Poughkeepsie Water Treatment Plant were consistent with the Norrie Point sensor, albeit at lower temporal resolution. Water level and salinity data from NOAA, USGS, and HRECOS stations were also used for model evaluation.

2.2. Model

[6] The hydrodynamic and sediment transport model is the Regional Ocean Modeling System with the Community Sediment Transport Modeling System [*Shchepetkin and McWilliams*, 2005; *Haidvogel et al.*, 2008; *Warner et al.*, 2008]. The application built on a previous Hudson model [*Ralston et al.*, 2012], with the domain extended north to the tidal limit at Troy and expanded seaward to Upper New York Harbor and the East River [*Warner et al.*, 2010]. Freshwater and sediment were input at the upstream boundary and from tributaries along the tidal Hudson. Typically, the lateral tributary discharges are small (~30%) compared to the Upper Hudson and Mohawk [*Wall et al.*, 2008]. However, intense, localized precipitation from the tropical storms dramatically increased flow and sediment discharge in a few of the smaller tributaries, requiring explicit representation in the model. Water levels at the open boundaries were forced with observations at Sandy Hook and Kings Point.

[7] Sediment in the model had bed sediment size classes representative of medium sand, fine sand, and silt [*Ralston et al.*, 2012]. The settling velocities (w_s) were 40, 5, and 0.6 mm s^{-1} respectively, and all had erodibility (E_0) of 1×10^{-4} kg m^{-2} s^{-1}. River sediment was divided into two classes: a fine fraction with slow settling and high erodibility ($w_s = 0.01$ mm s^{-1}, $E_0 = 30 \times 10^{-4}$ kg m^{-2} s^{-1}), and a silt class with $w_s = 0.2$ mm s^{-1} and $E_0 = 3.0$ kg m^{-2} s^{-1}. To represent flocculation and aggregation that increase settling velocity at the transition from fresh to brackish water, river sediment properties were made equivalent to the silt bed sediment class at grid cells where salinity was > 0.5 practical salinity unit (psu) [*Ralston et al.*, 2012].

[8] The model results were evaluated against water level, discharge, salinity, and suspended sediment observations (Figure S1 in the supporting information). The model matched the timing and magnitude of the flow past Poughkeepsie and reproduced the combined influences of river discharge and coastal storm surge on water levels in the tidal river [*Orton et al.*, 2012]. Suspended sediment in the model was largely consistent with the increased concentrations recorded by turbidity sensors, but the model skill was lower than for the tides and mean flow. While the cumulative flux past Poughkeepsie was similar to the observed, the rate at which the sediment

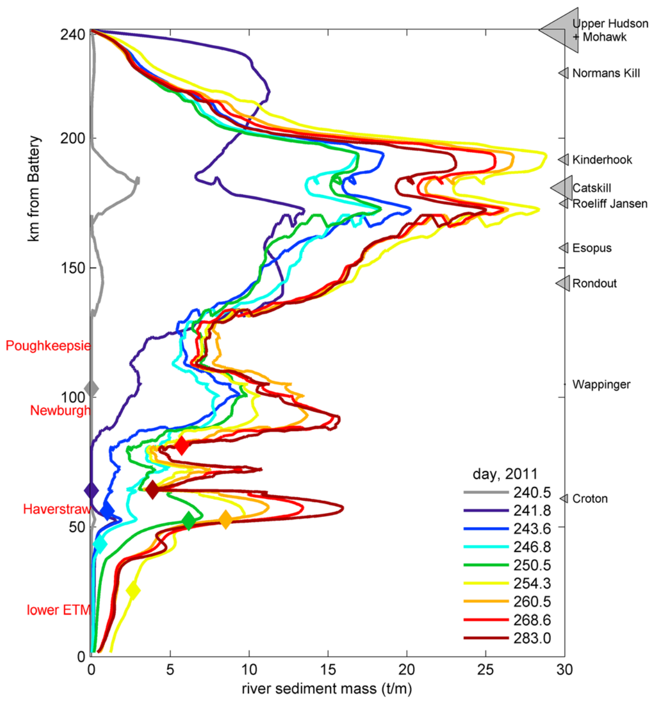

Figure 2. Distributions of new, watershed sediment through time, with colored lines representing successive snapshots of the mass distribution from the model; discharge from Irene began around day 241 and from Lee around day 250. Diamond markers indicated the position of the 1 psu isohaline at each time. On the right axis, the locations of the tributary inputs are shown, with the size of the marker scaled to the total sediment input from each source.

pulse moved down the tidal river during the events was somewhat slower in the model than was inferred from observations. Note that model simulations with different parameters can give solutions that compare similarly to the observations, as the settling velocity, erodibility, and bottom stress were not well constrained by observations. The primary results on cumulative sediment fluxes in the tidal river are supported by the observations, and the model is used to evaluate processes associated with the storm events in greater detail.

3. Results

[9] Tropical Storm Irene produced rainfall totals of 10 to 25 cm over eastern New York and western New England, but parts of the eastern Catskill Mountains in the Hudson watershed received up to 45 cm. About 2 weeks later, the remnants of Tropical Storm Lee dropped heavy precipitation over northeastern Pennsylvania and central New York. Rainfall in the Hudson watershed was less than from Irene, but 8 to 20 cm fell on saturated soils and led to substantial runoff. The consecutive events produced flooding in the Hudson watershed and in the Catskills in particular, most notably Schoharie Creek that discharges into the Mohawk River and Catskill Creek that discharges into the tidal Hudson [*U.S. Geological Survey*, 2012, 2013]. In the tidal river at Poughkeepsie, maximum cross-sectionally averaged velocities are typically 0.4 to 0.6 $\mathrm{m\,s^{-1}}$, but the combined river discharge and storm surge after Irene produced velocities of 0.9 $\mathrm{m\,s^{-1}}$, with seaward flow over a full tidal cycle. The subtidal velocity at Poughkeepsie before the storms was about 0.05 $\mathrm{m\,s^{-1}}$, but it increased to 0.6 $\mathrm{m\,s^{-1}}$ during Irene and 0.4 $\mathrm{m\,s^{-1}}$ during Lee.

[10] Collectively, Tropical Storms Irene and Lee introduced about 2.7 Mt of new sediment to the tidal Hudson (Figure 1). Previous estimates of sediment input range from 0.2 to 1.0 Mt annually [*Panuzio*, 1965; *Olsen*, 1979; *Wall et al.*, 2008], with lateral tributaries accounting for 20–40% the sediment discharge under normal flow conditions [*Wall et al.*, 2008]. The long-term average sediment input is about 0.5 Mt per year based on sediment rating curves [*Ralston and Geyer*, 2009], so Irene and Lee combined to deliver about 5 times the annual average sediment supply in less than 1 month.

[11] An important finding from both the observations and model is that much of the sediment input by Irene and Lee was retained in the tidal river. Measurements at Norrie Point and Poughkeepsie found only about 1 Mt of seaward sediment flux during the month after Lee, or roughly one third of the total, and model results were consistent with the observations (Figure 1). Despite the high flows, sediment fluxes in the tidal river were limited because the high sediment concentrations moved seaward more slowly than the pulse of elevated velocities. Peak concentrations at Poughkeepsie lagged the maximum seaward velocities by about 2.5 days after Irene and 1.5 days after Lee. High concentrations were observed in the lower estuary immediately after Irene, but the model results suggest that this was not primarily new sediment from the watershed. Instead, the new sediment was largely retained in the tidal river hundreds of km to the north. This apparent trapping in the fresh tidal river is distinct from the sediment trapping at the limit of the salinity intrusion and presents a significant impediment to delivery of terrigenous sediment to the coastal zone.

[12] The temporal evolution of the new sediment distribution in the model highlights the retention in the tidal river (Figure 2). Shortly after Irene, new sediment was concentrated near the major fluvial sources: the Mohawk River (240 km) and Catskill Creek (180 km). After the storm, the new sediment moved seaward and accumulated in several depositional regions, particularly near the source tributaries. The mass of new sediment in the upper river was greatest shortly after Lee (~day 155) and then decreased as it was remobilized and moved seaward. Sediment continued to accumulate in the lower tidal river (Newburgh Bay, 85–110 km), which remained fresh throughout. In the month after the storms, new sediment began to deposit in the estuary, particularly in upper Haverstraw Bay (~60 km), consistent with observations of trapping near the limit of the salinity intrusion [*Nitsche et al.*, 2010; *Ralston et al.*, 2012].

[13] Theory predicts that the salinity intrusion limit should be a locus of sediment trapping and accumulation, but most of the new sediment was retained landward of salt after Irene (Figure 3). Pulses of new sediment moved 50–70 km seaward during the few days of elevated discharge, but after that, transport decreased substantially. Secondary concentration maxima originated from lateral tributaries and advected seaward of the sediment pulse from upstream (Figure 3b). The discharge due to Tropical Storm Lee carried some sediment from Irene to the estuary, but again, transport in the tidal river was limited.

[14] Rather than new sediment from the watershed, the increased concentrations in the lower estuary after Irene were due mostly to remobilization of bed sediment (Figure 3c).

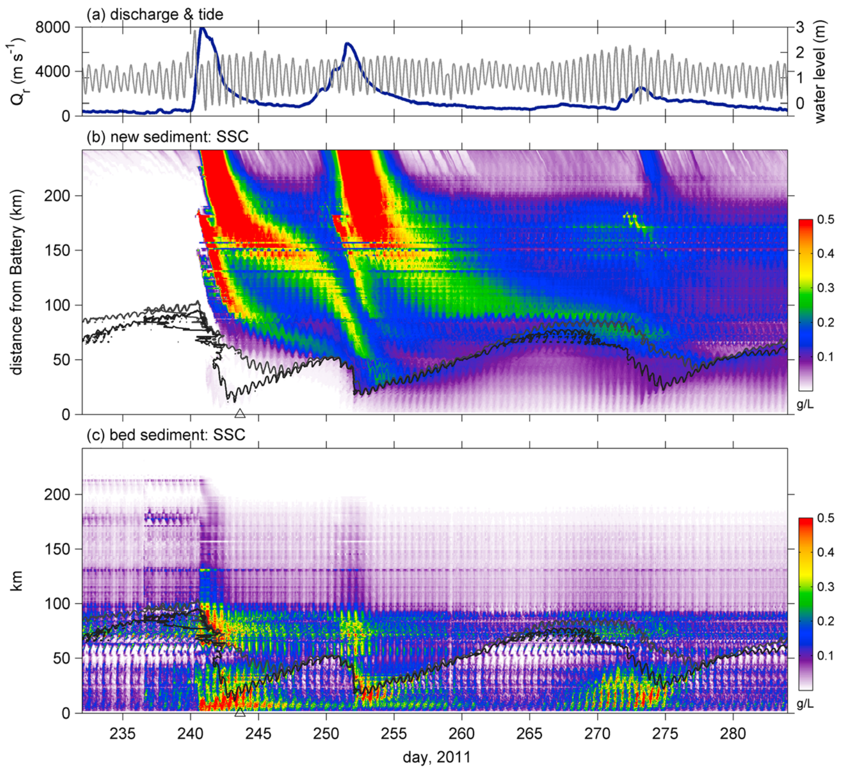

Figure 3. Along-estuary distributions of salinity, new sediment, and resuspended bed sediment through time. (a) Observed total river discharge and tides at the Battery (mean lower low water), (b) modeled near-bottom concentration of new sediment, with salinity contours at 1 psu and 5 psu, and (c) modeled near-bottom concentration of remobilized bed sediment. The marker on day 243 notes the time of the satellite photo in Figure S2.

Storm surge and river discharge significantly enhanced bottom stresses and resuspension where the salinity intrusion had been prior to the storms. Prior to Irene, the salt front was at ~100 km; less than 24 h later, it had been pushed nearly to the Battery. Bed sediment was resuspended due to the increased stresses and decreased stratification, creating high concentrations in regions that do not normally have turbidity maxima.

[15] Qualitatively, the model was consistent with satellite images of the Hudson just after Irene (Figure S2). In Upper Haverstraw Bay, there was a sharp discontinuity between high concentrations of reddish sediment to the north, likely due to input from the Catskills, and apparently lower concentrations of grayer sediment to the south that was likely remobilized bed material. North of Haverstraw, apparent concentrations in the satellite image also were lower, consistent with the model results showing a local minimum in SSC between the Catskill Creek and Mohawk River sources.

[16] After the storms, suspended sediment in the model was dominated by trapping at the salinity intrusion and bottom salinity fronts, including the lower ETM (15–20 km) and upper Haverstraw Bay (60 km) [*Ralston et al*., 2012] (Figure 3). The fraction of sediment in suspension decreased as the discharge decreased and sediment mobilized by the events deposited in lower energy areas. Concentrations in the tidal river dropped to near background levels by a month after Lee, as tidal currents did not significantly remobilize the excess new sediment. In the lower estuary, concentrations returned to normal after several weeks, with intensification at frontal zones and enhanced resuspension during spring tides. By a month after Lee, the erosion and deposition patterns from the storms were quasi-stationary. Only about 0.5 Mt of the new sediment (or 20% of the total) reached the saline estuary over this period, and export to the harbor was less than 0.1 Mt. In the estuary, bed sediment was redistributed, including ~0.4 Mt of bed sediment that was eroded from north of the Battery and moved into the harbor. In Haverstraw Bay, deposition patterns in the model were consistent with long-term observations [*Nitsche et al*., 2010].

4. Discussion

[17] Back-to-back tropical storms introduced a massive amount of new sediment to the Hudson River, but a surprising conclusion from this study is that much of that new material was retained in the tidal, freshwater river for an extended period after the storms. The estuarine salinity gradient has long been known to promote sediment retention, but the tidal river might be expected to convey sediment more efficiently seaward. However, the flushing associated with the discharge events was insufficient to carry the sediment the length of the tidal river, and resuspension by tidal processes did not maintain significant seaward transport after discharge decreased. One consequence is that residence time of sediment and particle-associate material in the tidal river may be relatively long [*Woodruff et al*., 2001; *Wall et al*., 2008]. While high rates of watershed export of particle-associated carbon and nutrients might be expected to yield high rates of delivery to the ocean, transport may instead be arrested in the tidal river, providing time for biogeochemical transformation.

[18] Another key result was the significant bed resuspension in the estuary due to the retreat of the salinity intrusion and increased bed stresses. In urban estuaries such as the Hudson,

this has consequences for contaminated sediment transport. Many contaminant inputs have diminished in recent decades due to environmental regulations, so higher levels of contamination are typically buried subsurface [*Bopp et al.*, 1982; *Valette-Silver*, 1993]. Bed erosion at certain locations in the model exceeded several centimeters, suggesting that extreme events could reintroduce contaminants that had been sequestered. Poststorm deposits were a mixture of new and remobilized bed sediment. This mixing of new and old material is consistent with a study that found no distinct changes in the geochemical composition of bed sediments as a result of Irene and Lee, in the Hudson as well as in other rivers along the U.S. Atlantic Coast [*Horowitz et al.*, 2013].

[19] Sediment transport in tidal rivers remains poorly understood. Tidal currents provide the dominant source of energy in the Hudson, and while the enhanced velocities due to the storms were significant, they lasted only a few days and the net transport was modest relative to the exponential increase in sediment supply. Transport in the model depended on the sediment properties, particularly settling velocity and erodibility, and those may change significantly during events or between the tidal freshwater and the estuary. Unfortunately, this variability in sediment properties is not well characterized by observations or well constrained in the model. Observations are needed to characterize sediment retention and particle dynamics in tidal rivers to help quantify time scales for transport of terrigenous material to the ocean.

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