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In the path of the Hurricane: impact of Hurricane Irene and Tropical Storm Lee on watershed hydrology and biogeochemistry from North Carolina to Maine, USA

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Abstract Although many climate predictions suggest that the frequency and intensity of large storm events might increase in the coming decades, few studies document the full impact of such events along their path. Here, we synthesize information on the impact of Hurricane Irene (formed August 21 2011) and Tropical Storm Lee (formed August 30, 2011) on erosion and sediment transport, lake metabolism, riparian hydrology and biogeochemistry, and stream water quality, from North Carolina to Maine. In almost all cases, these storms generated unprecedented changes in water quality (concentrations, loads), from tenfold increases in DOC and 100-fold increases in POC in Maryland, to 100-fold increases in TSS concentrations in Pennsylvania. Overbank flooding and up to 200-year streamflow events were recorded in New York and Vermont. In many cases, particulate loads (e.g. POC, PP, TSS) occurring during Irene and Lee represented more than 30% of the annual load. The dominance of particulate exports over solutes during Irene and Lee is consistent with the mobilization of normally immobile sediment pools, and

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massive erosion as reported at many locations across the Northeastern US. Several studies reported long lasting (> 1 year) effects of Irene and Lee on cyanobacterial blooms, erosion, or stream suspended sediment concentrations. However, this review also highlighted the lack of a consistent strategy in terms of methods, and measured water quality parameters. This strongly hinders our ability to fully assess the large-scale impact of such events on our environment, and ultimately their impact on our economy and society.

Introduction

The US Northeast has been experiencing noticeable changes in its climate over the past few decades. Since 1970, the average annual temperature rose by 1 °C and the average winter temperature increased by over 2 °C (NECIA 2006). The region is also experiencing changes in precipitation patterns with heavy precipitation events increasing in magnitude and frequency, along with more winter precipitation falling as rain rather than snow (Karl and Thomas 2017; Higgins and Kousky 2012). Although climate predictions up to the year 2100 remain uncertain, research suggests that this trend will continue in the future and will bring more uncertainty in water supply, along with an increased number of extreme events to the region (Sarojini et al. 2012; Groisman et al. 2012; IPCC 2001, 2013). The specific impacts of a changing climate on flooding frequency in the US Northeast remain uncertain. On the one hand, it has been shown that increases in air temperature can decrease snowpack and flooding in the US Northeast, and that currently, there is no clear evidence of consistent changes in the number of floods over time in the US Northeast (Hodgkins and Dudley 2013). On the other hand, others suggest that with climate projections pointing to an overall increase in the amount of heavy precipitation throughout the Northeast and less wintery precipitation falling as snow, the region will most likely see an increased

number of floods, more droughts linked to decreased snowpack (albeit Hodgkins and Dudley 2013 have found no such link to date), increased erosion, and overall changes to existing ecosystems (Held and Soden 2006; Kunkel 2013; Peterson et al. 2013). However, regardless of the existing complexities of the climate—flood relationship, without adequate adaptation strategies to extreme events (e.g. hurricanes), water resources, human health, agricultural viability, forest health, and winter recreation are likely to be affected. Understanding how extreme precipitation events (e.g. hurricanes, tropical storms) impact this region of the country central to the US economy is therefore essential so that federal, state, and local government can develop strategies to adapt or mitigate the impact of such events on the environment, the economy, and society.

A recent example of how extreme weather events can impact many sectors of the economy may be found in the study of the impacts of events such as Hurricane Irene and Tropical Storm Lee (2011), which resulted in record-breaking rainfall totals and an estimated \$1 billion in damages. Within this broader context, one critical aspect of understanding how such events impact communities requires understanding how extreme events shift the hydrological and biogeochemical functioning of lakes, riparian zones, and streams, in order to design and implement strategies to improve system resiliency. Fortunately, as Hurricane Irene hit the coast of North Carolina before moving north along the Eastern shore of the US all the way up to Maine, many studies monitoring the hydrological and biogeochemical functioning of lakes, riparian zones, and streams were underway. Almost immediately after Irene hit North Carolina, Tropical Storm Lee hit the coast of Louisiana before moving in a northeast direction and generating heavy precipitation for days all the way up to central New York after the tropical storm itself subsided. After describing in detail the changing anatomy of Irene and Lee before and after landfall, we engage in a review of case studies reporting on the impact of Irene, and in some cases Tropical Storm Lee, on erosion and sediment transport, lake metabolism, riparian hydrology and biogeochemistry, and stream water quality from North Carolina to Maine. In all cases, we attempt to describe system responses in relation to baseline system conditions (when available) to more fully comprehend the exceptional nature of these events. We

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Fig. 1 Extreme event associated precipitation and study sites. ▶
The top panel shows our study sites. Middle panel shows total
rainfall over the northeastern USA for the dates NOAA
associates with Hurricane Irene and the remnants of Tropical
Storm Lee—August 27–September 10, 2011. Bottom panel
shows total rainfall from August 27 until September 29, which is
the date the remnants of Tropical Storm Lee reached upstate
New York. All rainfall data compiled from daily total archived
online by NOAA (https://water.weather.gov/precip/archive/
2011/). [Online version is a color figure]

subsequently offer a synthesis section where we
describe overall system response to extreme events
as a tool for adaptive management. It is our hope that
this work will be a catalyst for the development of
large scale studies of watershed and ecosystem
response to hurricanes and other large storms so
Federal, state, and local governments can more fully
comprehend the impact that such events have on our
environment and ultimately develop strategies to
assess the impact of such events at the continental
scale on our environment, the economy, and society.

Anatomy of Hurricane Irene and Tropical Storm Lee

Hurricane Irene formed on August 21, 2011 over the
Atlantic Ocean. From August 24–26, Irene continued
its track across the Caribbean as a category 3
hurricane, weakening slightly and widening before
turning northward. Irene further weakened while
passing off shore of the Florida and Georgia coast
before making landfall over the continental United
States on August 27 as a category 1 hurricane near
Cape Lookout, North Carolina. From there, the storm
moved north back over the Atlantic Ocean before
making landfall again near Atlantic City, New Jersey
on August 28 and continuing northward over New
York City and the northeastern United States (Avila
and Cangialosi 2012). The storm track continued up
the Atlantic coast of the USA for several days,
dropping large amounts of rain and causing major
flooding as late as September 8 in upstate New York.
Rainfall totals reached as high as 560 mm in Gurabo
Abajo, Puerto Rico and 400 mm over Bayboro, NC.
Localized areas of heavy rain, greater than 250 mm in
total, were found to the western side of Irene's path
along the eastern United States (Fig. 1). Heavy rain
caused flooding, property damage, and casualties
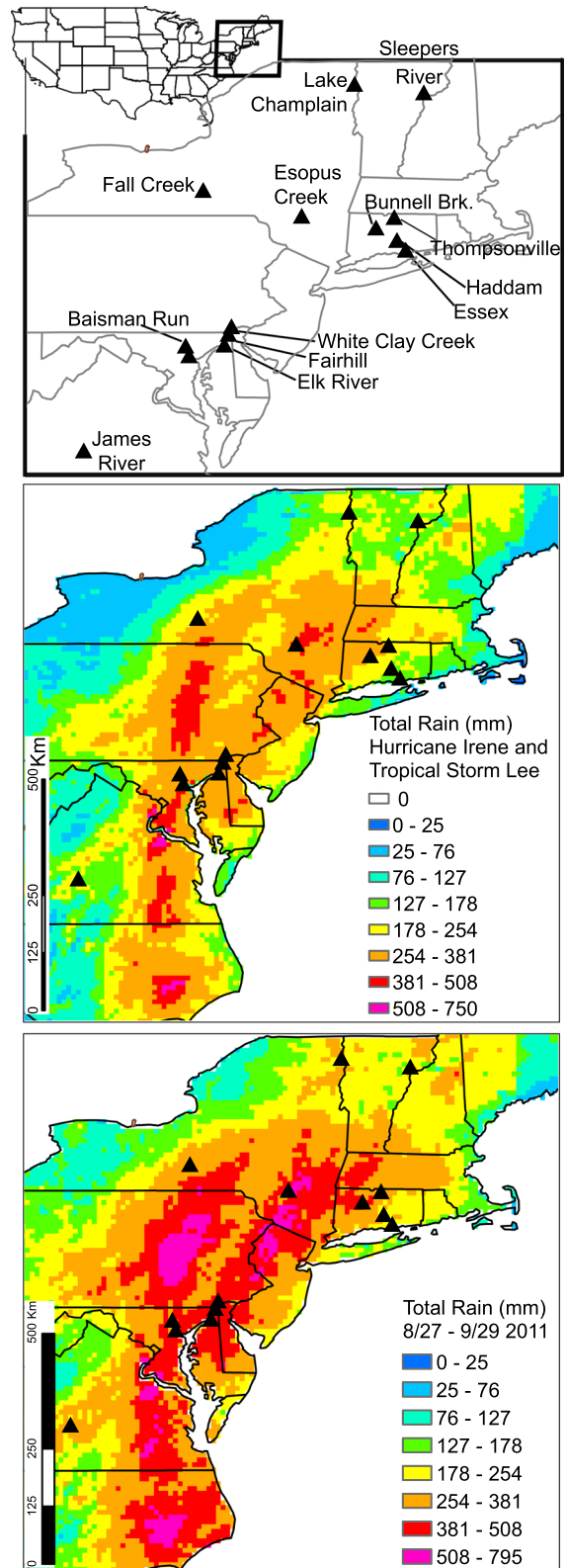
across the storm track, with estimated recurrence interval equal or greater than 100 years in New Jersey and other eastern states (Avila and Cangialosi 2012; Watson et al. 2014). In Vermont, some watersheds experienced 12-h rainfall amounts with return intervals greater than 500 years, and streamflows in the 300- to 1000-year return interval (Magilligan et al. 2015; Anderson et al. 2017).

Just 9 days after Irene formed over the Atlantic Ocean, Tropical Storm Lee organized over the Gulf of Mexico on August 30–31, 2011. Lee then strengthened into a tropical depression and then tropical storm on September 2, further transitioning to a subtropical cyclone on September 3 prior to making landfall on the Gulf coast of southern Louisiana on September 4. Lee produced rainfall of up to 380 mm along the Gulf coast with over 300 mm of rainfall in both New Orleans, LA and Mobile, AL (Brown 2011). Following landfall, Lee and its remnants traveled northeastward along a frontal boundary and caused heavy precipitation as late as September 29 in Freeville, NY, several days after NOAA stopped tracking this storm. Ultimately, Lee and its remnants produced large amounts of rainfall from the mid-Atlantic to New England regions of the USA within 2–3 weeks of Hurricane Irene depending on location (Brown 2011). Together, the combination of Hurricane Irene and the remnants of Tropical Storm Lee led to high rainfall totals (Fig. 1) and large and widespread flooding over many areas of the eastern United States. To put these storms in perspective, the National Centers for Environmental Information in the USA lists the 30-year average precipitation, computed from 1981 to 2010, for the month of September as 76.2–127 mm depending on location (data available online: https://www.ncdc.noaa.gov/climateatlas/). Together, Lee and Irene produced anywhere from 178 to 750 mm of rain and clearly exceeded these amounts at almost all locations on the US East Coast (Fig. 1). Specifically, the persistent rainfall for much of the northeast United States due to the remnants of Lee and Irene led the totals for September 2011 to be at least double the 30-year average precipitation over this region (Fig. 1). In turn, this time period was associated with extensive flooding, erosion, and sediment export (Fig. 2).

Impact of Hurricane Irene and Tropical Storm Lee on lake and riparian zone hydrobiogeochemistry in Northeastern USA

Few studies document how hurricanes typically affect lake dynamics or riparian zone hydrology and biogeochemistry. Klug et al. (2012) nevertheless report on the effect of the remnants of Hurricane Irene on the thermal structure and metabolism response of a series of nine lakes and reservoirs in the Northeastern US. The heavy precipitation associated with Irene decreased the thermal stability of the lakes, and changes in lake/reservoir temperature directly affected lake primary production. The addition of terrestrial organic carbon contributed to higher respiration, which in turn became the primary driver of ecosystem metabolism. Over time, the thermal disturbance associated with Irene was shorter lived than the disturbance of lake metabolism associated with input of terrestrial carbon. Furthermore, the impact of Irene on lake physics and biology was more severe and persistent in systems with higher watershed area to lake volume ratio, suggesting an important baseline physical control on the response of these events on lakes. Although more studies need to be conducted to validate these observations, this study clearly highlights how heavy precipitation, high wind, and organic carbon input from streams draining into lakes affect not only the thermal profile of the lakes, but also in-lake heterotrophic processes.

Elsewhere in the US Northeast, Vidon et al. (2017) reported on the impact of the remnants of Hurricane Irene and Tropical Storm Lee on riparian zone hydrology and biogeochemistry on Fall Creek, NY. At the site, precipitation associated with the remnants of Hurricane Irene generated 172 mm of rain between September 4–8, 2011, while the remnants of Tropical Storm Lee dropped 47 mm of rain between September 26–29, 2011. In Fall Creek, stream specific discharge rose from 0.2 mm d^{-1} on September 4, 2011, to a daily average of 26.2 mm d^{-1} on September 8. Before storm Lee hit this site, specific discharge had receded to 0.6 mm d^{-1} on September 18, but peaked at 9.2 mm d^{-1} on September 29. From a hydrological standpoint, these storms were able to reset the water table in the riparian zone to spring-like levels for weeks to months. Although precipitation has often led to the development of anaerobic conditions in the subsurface in many riparian zones (Groffman et al. 2009), the
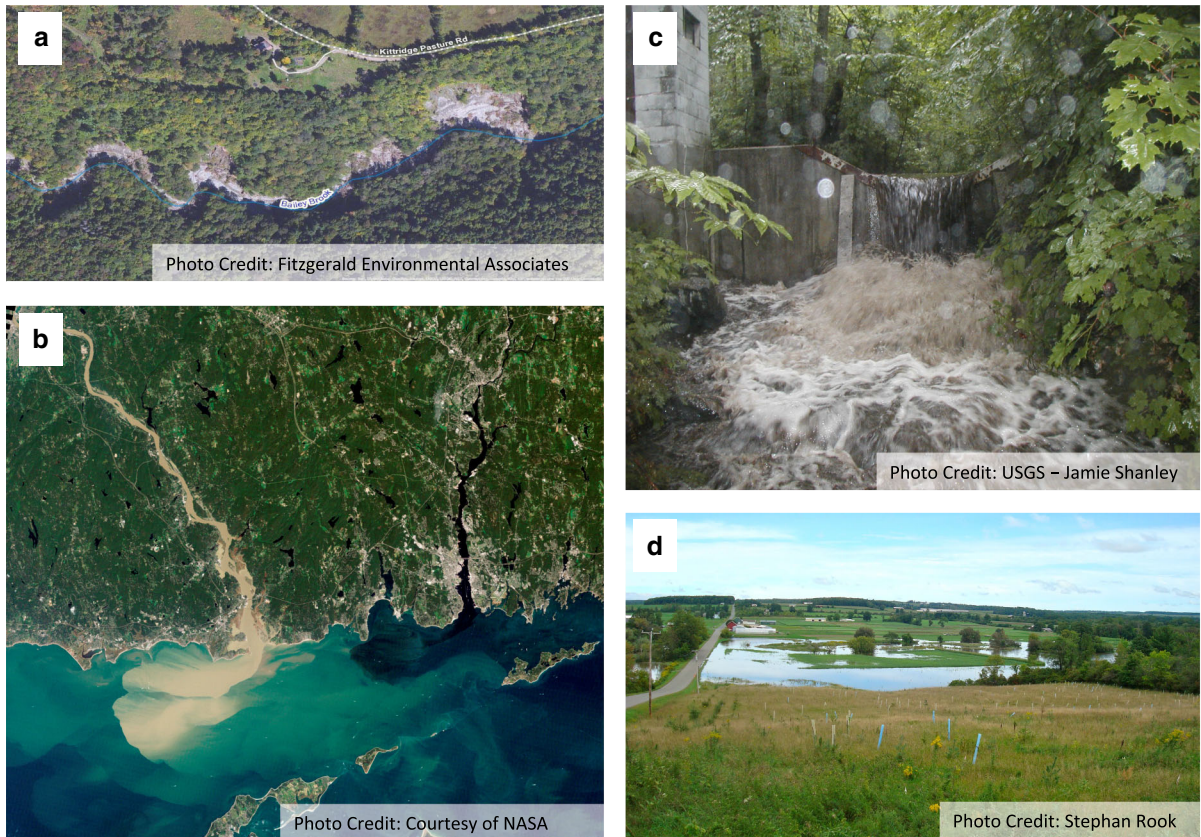
Fig. 2 Examples of impacts of Hurricane Irene and Tropical Storm Lee on a few of the sites discussed in this study: **a** example of mass wasting caused by Irene along the Mill Brook in Windsor, Vermont (110 km SSW of Sleepers River, Vermont; Fig. 1), **b** sediment plume at the mouth of the Connecticut River following Irene, c) high flow conditions at Sleepers River W-9, Vermont during Irene, d) Flood at the Freeville riparian site, New York (near Fall Creek; Fig. 1)

overbank flooding that occurred at this site led to the infiltration of well-oxygenated stream water into the riparian zone, which in turn led to the development of aerobic conditions at depth in the saturated portion of the soil profile (higher dissolved oxygen, higher oxidation–reduction potential). Near the soil surface, anoxic conditions nevertheless developed within soil aggregates and led to increased N_2O and CH_4 fluxes at the soil-atmosphere interface. However, although groundwater NO_3^- increased from less than 0.1 mg N L^{-1} before Irene to more than 1 mg N L^{-1} post Lee, neither Irene nor Lee led to any significant increase in PO_4^{3-} concentration in the riparian groundwater. Although different riparian hydrological and biogeochemical responses may be observed in other settings, this study highlights the direct impact that heavy precipitation and flooding can have on riparian water table dynamics, and the more

complex interactions that such storms can have on biogeochemistry, and ultimately groundwater quality and greenhouse gas emissions at the soil-atmosphere interface.

Impact of Hurricane Irene and Tropical Storm Lee on sediment and suspended solid dynamics, streambank erosion, and mass wasting

Extreme amounts of sediments were exported by coastal rivers from Virginia to Maine as a result of Irene and Lee (Cheng et al. 2013; Horowitz et al. 2014; Ralston et al. 2013; Yellen et al. 2014). Antecedent precipitation was low in the affected southern areas, e.g. Virginia (Caverly et al. 2013) but unusually high in New England (Yellen et al. 2016). As a result of relatively dry antecedent conditions and the storm

tracks, Irene resulted in much less sediment export to the Chesapeake Bay through the Susquehanna River than did Lee (Cheng et al. 2013). Further north, three days of peak flow from Irene produced twice the normal annual load of sediment loss from the Connecticut River, while Lee had a much dampened effect (Yellen et al. 2014). For the Hudson River, the combined sediment inputs from Irene and Lee were about five times the annual average (Ralston et al. 2013).

The source of this increased sediment load has been investigated in a number of watersheds (Caverly et al. 2013; Dethier et al. 2016; Dhillon and Inamdar 2014; Gellis et al. 2017; Yellen et al. 2016; Rose et al. in review). In Virginia, the combination of Irene and Lee produced unprecedented high erosion in an incised ephemeral channel draining a coastal plain agricultural field (Caverly et al. 2013), and Lee induced erosion on 82% of the streambank segments monitored in an urban-suburban stream, Difficult Run (Gellis et al. 2017). Working in a small watershed in Maryland (Fairhill Watershed, Fig. 1), Dhillon and Inamdar (2014) found that sediment from Irene and Lee had a variety of sources, some unidentified but assumed to be from erosion of upland sediments, while under non-extreme conditions, most sediments could be traced to streambed or streambank sources. In Pennsylvania, streamflow associated with Hurricane Irene exported 64,379 kg of suspended material (88.9 kg ha^{-1}) in White Clay Creek (7.24 km^2), with maximum total suspended solid concentration (TSS) of 856 mg L^{-1} or 100 times those observed at baseflow. However, because of wet antecedent moisture conditions when Tropical Storm Lee hit the area 8–10 days after Irene, maximum streamflow was much higher during Lee (6.81 mm h^{-1}) than Irene (3.72 mm h^{-1}), even though precipitation amounts were similar for Irene (168 mm) and Lee (175 mm). Together, these two events exported over 126,000 kg of suspended material (171.7 kg ha^{-1}), equal to approximately 35% of the average annual suspended load of White Clay Creek (361 kg $\pm$ 77 kg; Williamson 2013).

Further north, the major source of sediment from Irene has been linked to a high occurrence of mass wasting in steep upland headwater areas (Dethier et al. 2016; Yellen et al. 2016). Analyzing aerial photography from 14 000 km^2 of Vermont and Massachusetts, Dethier et al. (2016) found that Irene initiated 534 and

reactivated 460 landslides, increasing the regional erosion rate more than threefold. Landslides were more numerous along the spine of the Green Mountains where slopes were steepest and rainfall amounts the highest. In particular, Yellen et al. (2016) were able to identify a distinct and unique layer from Irene in sediments of the upper Connecticut watershed, enriched in unweathered fine particles from legacy glacial sediments uncovered due to scour during these storms. These previously inaccessible glacial deposits may have been significantly eroded for the first time since stabilization after glacial retreat (Yellen et al. 2014). In a separate study in the Connecticut River, turbidity exhibited a double peak that straddled the hydrograph peak, with the higher second peak near 600 FNU both at Middle Haddam (Fig. 3) and at Essex, at the mouth of the Connecticut. This translated to 800 mg L^{-1} suspended sediment concentration, similar to that reported in the Pennsylvania study. At a third location upstream of the two others (Thompsonville, Fig. 1), suspended sediment concentration reached two times higher than the downstream site (1760 mg L^{-1}). The double-peaked chemographs superposed on a single-peak storm hydrograph at Middle Haddam reveal shifting sources from differential travel times and precipitation amounts in this larger basin, while the site contrast reveals the potential for downstream attenuation of sediment concentrations.

Beyond specific empirical studies, estimates of TSS exports based on applications of the WRTDS (Weighted Regressions on Time, Discharge and Season) models (Hirsch et al. 2010) for a variety of locales along the path of Irene and Lee showed that depending on local relief and antecedent moisture conditions, TSS exports likely varied widely from one location to the next (Fig. 4; Medalie 2016). For instance, in the steep mountainous sections of the Mettawee River basin in Vermont, sediment loads were estimated to exceed annual averages by 580%. Conversely, in Lewis Creel in Central Vermont (flatter topography), modeled TSS exports during Irene only represented 9% of the typical annual load. Overall, lower relief watersheds of the Champlain Valley proportionally exported much less sediment (< 20% of their annual load) than central Adirondack, Green and northern Taconic Mountain watersheds where precipitation associated with Irene was more severe and persistent. In these more montane catchments,
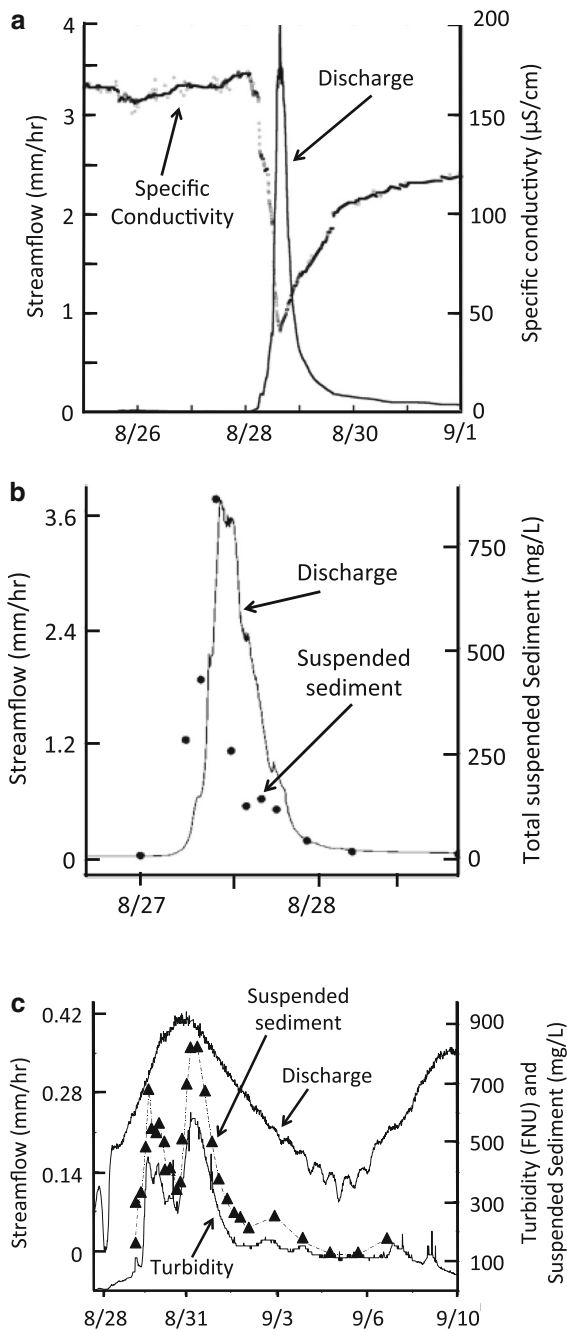
Fig. 3 a Drop in specific conductance at Sleepers River, Vermont during Irene; b Total suspended sediment concentration and streamflow in White Clay Creek, Pennsylvania, during Irene; c Streamflow, turbidity, and total suspended sediment concentration in the Connecticut River at Middle Haddam, Connecticut, during Irene

large scale slope failure and erosion also occurred, presumably enhancing TSS cumulative export during
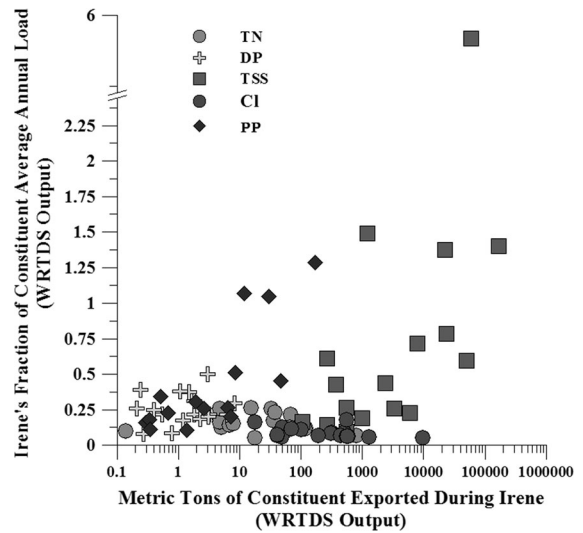

Fig. 4 Fractional export of sediment and geochemical solutes during Irene (flows from 8/27-9/3/11) relative to cumulative 9-month mean export for each solute (or sediment) (Y axis) plotted against cumulative export values for the Irene hydrologic event for each solute (or sediment) (X axis) for Lake Champlain tributaries (Medalie 2016) and the Connecticut River basin (TN and Cl only) (Mullaney 2016). Only TP (not DP) was measured in the Connecticut River basin, but results indicated similar Irene event-based P loading impacts as in the Lake Champlain Basin; 0.61 fraction of annual loading in the Connecticut River, and 1.18 in Bunnell Brook. (*TN* total nitrogen, *TP* total phosphorus, *DP* dissolved phosphorus, *TSS* total suspended sediment, *Cl* chloride, *PP* particulate phosphorus)

this event. Precipitation amounts and duration, watershed slope, and hillslope-stream connectivity all likely played essential roles in regulating stream responses to Irene based on load distributions across the Lake Champlain and Connecticut River basin.

In addition, the TSS and erosion studies presented above also indicated that Irene and Lee had long lasting impacts on many watersheds. For instance, these storms seem to have moved many streams in New England to a new state with respect to sediment loading. Since Irene occurred in 2011, suspended sediment concentrations at many USGS-monitored sites as of 2016 have remained one order of magnitude higher, relative to streamflow (Dethier et al. 2016). Unusually high deposition of coarse materials onto floodplains and channel avulsions into previously unaccessed glacial deposits were also observed following Irene (Magilligan et al. 2015), again contributing unweathered sediment to the streams similar to mass wasting.

Impact of Irene and Lee on dissolved and particulate organic carbon

From Maryland to New York and Vermont, several studies captured changes in dissolved organic carbon (DOC) and particulate organic carbon (POC) in streams during Irene and Lee. For instance, in a forested watershed in New York (Esopus Creek, 165 km^2), the maximum streamflow recorded during Irene was equivalent to a 200-yr event, and Irene and Lee resulted in 330-fold and 20-fold increase in streamflow (Yoon and Raymond 2012). This rapidly rising streamflow during Irene resulted in a fourfold increase in DOC concentration without showing any dilution effect, and yielded a 5-day DOC load of 102.5 t C or 1.24 kg C ha^{-1} d^{-1}. Lee, on the other hand, generated a DOC export of 46.2 t C or 0.56 kg C ha^{-1} d^{-1}. Combined, the two storms respectively exported 43 and 21% of the mean annual DOC load of the watershed. The quality of DOM exported during Irene also showed a drastic change commensurate with its unprecedented load. As the water level rose, the quality of DOM shifted toward more humic and aromatic DOM with less protein-like components indicating more export of degraded soil organic matter. A direct measurement of biological lability also revealed a similar pattern where the lability was inversely correlated with the rising DOC concentration. In a forested watershed in Vermont (Sleepers River), DOC reached 13.7 mg L^{-1}, which was one of the highest concentrations ever recorded in this watershed and compares to typical baseflow DOC concentrations near 1 mg L^{-1} (Sebestyen et al. 2008). In that same watershed, Fluorescent Dissolved Organic Matter (FDOM) increased by a factor of about 4.5, consistent with the DOC increase, and its peak was approximately synchronous with the streamflow peak, in contrast to its usual lag (Pellerin et al. 2012).

Further south in a small forested watershed (0.12 km^2, 61% forest) in Maryland (Fairhill watershed), strong increases in organic carbon (OC) were also observed, with saturation excess overland flow and near surface flow paths being the primary hydrological pathways that mobilized both particulate and soluble C during these storms (Dhillon and Inamdar 2013, 2014; Inamdar et al. 2015). More specifically, Irene exported a total of 24.5 kg C ha^{-1} (soluble + particulate organic C), which is equivalent to 44% of the annual OC export for 2011 or approximately 6 times the annual baseflow OC export (4.2 kg C ha^{-1}). Most of the OC export occurred in particulate form. In terms of concentration only, peak POC concentrations were nearly 100 times higher than baseflow values, while DOC peaked at 11 mg L^{-1} compared to concentrations around 1 mg L^{-1} during baseflow. Interestingly, while concentrations of POC continued to increase through the storm events, DOC showed a slight dilution at peak flow, indicating supply limitation. In a broader context, it is likely that the elevated export of sediment and particulate nutrient forms from this and other mid-Atlantic Piedmont watersheds during large storms are linked to the large stores of valley-bottom legacy sediments that have accumulated in these watersheds due to colonial-era agricultural erosion and milldam activities (Walter and Merritts 2008).

Impact of Irene and Lee on nitrogen and phosphorus species

Also in Maryland, we compared the impact of Irene and Lee on nitrogen (N) and phosphorus (P) in two watersheds draining into the Chesapeake Bay. One of these watersheds is completely forested (Big Elk Watershed, Fig. 1), while the other is a low-density residential watershed (1% impervious surface cover) with mostly forest land cover (Baisman Run Watershed, Fig. 1). During Irene and Lee, there was a rapid increase in total N and P on the ascending limb of the hydrograph in Baisman Run. Total nitrogen (TN) increased from 1.45 mg N L^{-1} during baseflow to a peak of 2.27 mg N L^{-1} on the rising limb of the storm. Similarly, total phosphorus (TP) increased from a low of 0.007 to 0.133 mg L^{-1} on the rising limb of the storm. At peak TN and TP concentrations, nitrate (NO_3^-) represented 67% of TN and soluble reactive phosphorus (SRP) represented 2% of TP. Both TN and NO_3^- showed dilution patterns during peak streamflow, with highest NO_3^- concentrations (1.93 mg N L^{-1}) occurring weeks after the storm ended. This may have been due to flushing of groundwater enriched with nitrate from septic systems in the watershed (Kaushal et al. 2011). Another possibility is that there could have been rapid mineralization of N and P in organic matter deposited on floodplains and streambeds following the storms (Kaushal et al. 2008, 2014).

A comparison of Big Elk and Baisman Run watersheds demonstrates that particulate N and P can be an important mode of transport during storms. However, nitrate was still the dominant form of N in Baismans Run, a modestly developed watershed containing septic systems, which suggests that even a small number of septic systems or modest changes in land use/land cover (i.e. 1% impervious surface cover) can alter the mode of downstream nutrient transport during large storm events like Irene and Lee (Kaushal et al. 2011, 2014).

In another study, USGS tracked TN and TP along the Connecticut River during Irene and Lee. At Essex at the mouth of the Connecticut River (Fig. 1), TN (maximum concentration 1.6 mg L^{-1}) and TP (0.83 mg L^{-1}) were all highest on the first peak of the Irene/Lee hydrograph. More upstream at Thompsonville, sampling was limited but captured TP concentrations as high as 1.07 mg L^{-1}. Although these are not technically N or P species, it is also important to note that in the headwaters of the Connecticut River (i.e. Sleepers River, Fig. 1), weathering and atmospheric solutes and Acid Neutralization Capacity (ANC) experienced a marked dilution, as indicated by a specific conductance drop from 172 to 41 μS cm^{-1} (equivalent to 45% to 71% dilution depending on solute; Shanley et al. 2015). In turn, streamwater concentrations of the diluted solutes (K^+, Si, Mg^{2+}, Ca^{2+}, ANC, Na^+, Cl^-, SO_4^{2-}) approximately matched their lowest levels in the 20 years of record to that point (Shanley et al. 2015). This is in contrast to DOC and NO_3^- that both increased by approximately sixfold during Irene at Sleepers River.

Similar to TSS (see above), Medalie (2016) also used the WRTDS model described in Hirsch et al. (2010) to estimate N and P exports during Irene and Lee for a series of tributaries to Lake Champlain, Vermont (Fig. 4). Specifically, modeled solute loads during Irene (August 27, 2011 to September 3, 2011) were compared to cumulative 9-month average (March to November) export values calculated for each year in the 1990–2014 time series (Medalie 2016). In the adjacent Connecticut River Basin, output loads for TP, Cl^-, and NO_3^- were also computed by WRTDS for the main stem of the Connecticut River at Thompsonville and Bunnell Brook (Fig. 1; Mullaney 2016). For this modeling exercise, it is important to note that WRTDS export projections rely on historical concentration-discharge (C-Q) dynamics in each

watershed for a range of streamflows, all likely smaller than Irene (and Lee). Thus, much uncertainty exists in the modeled concentrations and loads as flow conditions during Irene exceeded the range for which the models were developed. However, we believe that although WRTDS findings should be taken with caution, they provide a solid basis for the purpose of contextual discussion. Specifically, WRTDS estimates indicate that dissolved phosphorus (DP) loads proportionally increased more than TN loads during Irene and represented up to 50% of annual DP loads. Although not mechanistically represented in the statistical WRTDS model, we would suggest that the relatively high proportional DP export could be due to P desorption and dissolution from P bound to suspended sediments, or to the flushing of distal terrestrial DP stores during Irene. Relative to DP, TN loads were proportionally lower and represented no more than 20% of annual TN loads for any catchment. This is consistent with highest N loads being typically observed at snowmelt in these catchments as opposed to late summer storms (Mitchell et al. 1996; Pellerin et al. 2012). Beyond DP and TN, Irene was also extreme in terms of particulate phosphorus (PP) export. Those watersheds that exported a particularly high fraction of their annual load of sediments during Irene (e.g. Mettawee River, Ausable River) were also associated with some of the highest PP exports, sometimes representing 100% or more of the annual average PP load. These high PP loads likely contributed to cyanobacterial blooms in shallow bays of Lake Champlain in the years following Irene (Isles et al. 2015).

Synthesis and implications for management

Our review of studies documenting the impact of Hurricane Irene and Tropical Storm Lee on various aspects of watershed biogeochemistry highlights multiple points. First, multiple individual studies have been published based on individual or pairs of watersheds within the path of these storms. Even with the numerous studies, there remains a critical lack of information on some systems like riparian zones (only one study). However, these studies all stress the exceptional nature of these storms with respect to particulate and solute exports to streams, erosion, and mass wasting (Table 1). These studies also highlight

Table 1 Summary of the impact of the remnants of Hurricane Irene and Tropical Storm Lee on the hydrobiogeochemistry of watersheds on the east coast of the United States from North Carolina to Maine

Impacts on lakes	Impact on lake thermal stability: Impacted primary productivity
	Water quality impacts: Terrestrial organic inputs impacted respiration and in turn ecosystem metabolism
Impacts on Riparian zones	Water quantity impact: Overbank flooding reset the water table to spring-like levels for weeks to months
	Water and air quality impacts: Increases in NO_3^- concentration in groundwater, and strong pulses of N_2O and CH_4 gases at the soil-atmosphere interface were observed
Impact on stream flow	Water quantity impacts: In Sleepers River, Vermont, Irene led to one of the highest flows ever recorded at Sleepers River (4 mm hr^{-1} vs. 0.044 mm hr^{-1} for baseflow). A 45% to 71% stream water dilution was recorded at Sleepers River (lowest level in 20 years of record). In the lower Connecticut River, flow peaked at 0.42 mm.hr^{-1} vs. 0.06 mm.hr^{-1} at baseflow. In Esopus Creek, New York, streamflow increased by a factor 330 for Irene and 20 for Lee. Return intervals for peak flows ranged from 200 to 1000 years
Impacts on sediment and suspended solid dynamics, streambank erosion, and mass wasting	Short-term impacts: Sediment loads during Lee and Irene were 2 to 5 times the annual sediment loads depending on antecedent moisture conditions + many landslides were tied to Irene and Lee in New England
	Long-term impacts: Baseline sediment loads in many New England streams are 10 times higher than before Irene and Lee
	Impact on TSS: In Pennsylvania, highest TSS concentrations were 856 mg/L (Irene) and 622 mg L^{-1} (Lee). TSS exports were 88.9 kg ha^{-1} (Irene) and 85.2 kg ha^{-1} (Lee). Irene and Lee combined exported 35% of the average annual TSS load for White Clay Creek, PA. In the lower Connecticut River, turbidity reached 600 FNU, peak TSS reached 1760 mg L^{-1}
Impact on DOC and POC	Impact on organic carbon (OC): In Maryland, 24.5 kg C mg ha^{-1} or 44% of the 2011 annual total OC load was exported during Irene and Lee. DOC increased tenfold relative to baseflow, POC increased 100-fold. In Vermont, DOC (13.7 mg L^{-1}) increased sixfold. In Esopus Creek, NY, DOC concentration increased fourfold. Irene and Lee exported 43 and 21% of the mean annual DOC flux for the watershed, respectively. Most of the DOC exported was from deep soil layers with limited potential for biological utilization
Impact on nitrogen and phosphorus species	Impact on nitrogen: In Maryland, 2.04 kg ha^{-1} of TN or 32% of the 2011 annual TN load was exported during Irene and Lee. In a watershed with 1% impervious surface, NO_3^- represented 67% of TN. In forested watersheds, particulate N dominated TN transport. In Vermont NO_3^- concentration increased sixfold
	Impact on phosphorus: In Maryland, TP increased from 0.007 mg L^{-1} to 0.133 mg L^{-1} on the rising limb of the storm. Soluble reactive P only represented 2% of TP. In the lower Connecticut River, TP reached 0.83-1.07 mg L^{-1} depending on locations

NO_3^- nitrate, N_2O nitrous oxide, CH_4 methane, *TSS* total suspended solids, *FNU* Formazin nephelometric units, *DOC* dissolved organic carbon, *POC* particulate organic carbon, *TN* total nitrogen, *TP* total phosphorus

the legacy effect of intense storm events where the impact on local hydrology and water quality can persist for months or years.

Indeed, in almost all cases, Irene and Lee generated unprecedented changes in water quality (concentrations, loads), from tenfold increases in DOC or 100-fold increase in POC in Maryland, to TSS concentration as high as 1760 mg L^{-1} in Connecticut. Overbank flooding and up to 200-year streamflow events were recorded in New York. In many cases, particulate loads (e.g. POC, PP, TSS) occurring during Irene and Lee represented more than 30% of the

annual load. Lower magnitude responses were however often observed for solutes (e.g. DOC, NO_3^-, SRP), which in some cases showed slight dilution patterns during peak flow. The dominance of particulate exports over solutes during Irene and Lee is consistent with the mobilization of normally immobile and/or disconnected sediment pools, and massive erosion and mass wasting in many locations across the northeastern US. Particulate material sourcing in White Clay Creek and a small forested watershed in Maryland indicates different sources of particulate material in this sequence of events when compared to baseflow and/or more frequent events (Karwan et al. in review; Dhillon and Inamdar 2014). In Connecticut, Yellen et al. (2016) also indicate a change in the provenance of sediments concurrent with the massive suspended sediment loads of Irene in the Connecticut River watershed. In general, this review demonstrates that to examine regional impacts of extreme hydrometeorological events such as Irene on water quality, researchers should place priority on developing consistent monitoring protocols to identify and quantify both the provenance and chemical composition of suspended sediment loads, which is rarely coordinated across monitoring sites.

Antecedent moisture conditions and large rainfall totals have been established as the main drivers of the dramatic results related to sediments from the mid-Atlantic northward in the United States. In White Clay Creek, PA, the timing of Tropical Storm Lee approximately 1-week after Hurricane Irene hit the site further highlights the importance of antecedent moisture conditions (1–2 punch) in impacting watershed response to large storm events. Although Irene and Lee produced almost the same rainfall amount in that watershed (168 mm vs. 175 mm), peak flow was nearly double for Lee (13.7 m^3 s^{-1} or 6.81 mm h^{-1}) than Irene (7.5 m^3 s^{-1} or 3.73 mm h^{-1}). Consistent with this finding, the unprecedented incidences of landslides and mass wasting events in the upper Connecticut River watersheds, which have left a legacy of increased TSS loads, have been attributed to high precipitation amounts during this sequence of events.

Some of the studies reported here also highlight how large storms like Irene and Lee can have long lasting effects. For instance, in a riparian zone in New York, flooding associated with Irene and Lee reset the water table to spring-like levels for weeks to months.

In the Lake Champlain Basin (VT and NY), strong cyanobacterial blooms in the summer of 2012 in shallow bays of Lake Champlain likely utilized some of the P derived from the high PP loads of Irene. Similarly, regional erosion rate increased more than threefold in Vermont and Massachusetts. In turn, recent USGS data show that following Irene and Lee, suspended sediment concentrations in many New England streams have remained one order of magnitude higher than before Irene and Lee. This suggests that for some watersheds, Irene and Lee have moved the system to a new state. The studies reporting persistent effects on biogeochemical processes and exports were in the northern area of the region of our synthesis (VT and NY) (Fig. 1). Such persistent effects were not noticed, for example, in the suspended solid and other biogeochemical outputs in the mid-Atlantic region. In particular, the persistent increased sediment concentrations observed in New England were not noticed in the mid-Atlantic. Here, studies in both Fairhill and White Clay Creek (Fig. 1) reported increases in suspended solids and particulate biogeochemical loads during extreme events as well as a shift in the watershed sources of this material (Dhillon and Inamdar 2014; Karwan et al. in review). However, these effects did not persist in time to the extent seen in New England. Only time will tell if the persistent increased loads in New England are permanent or whether the watersheds will eventually prove resilient and return to pre-storm conditions like their mid-Atlantic counterparts.

Finally, this review of existing studies on the impact of Irene and Lee on watersheds also stressed how these events can generate large amounts of precipitation for days or weeks after the National Weather Service stopped tracking them as named storms. For instance, the remnants of Lee generated 47 mm of rain between September 26–29 in Freeville, NY, almost 3 weeks after the storm officially dissipated according to the National Weather Service. Although this lag was due to the remnant of Tropical Storm Lee slowly moving in a northeast direction along a seasonal frontal boundary for weeks, this highlights not only the long-lasting effects that these storms can have at the continental scale, but also how monitoring watersheds in the weeks and months following storms can lead to a better understanding of their impacts on watersheds at the continental scale.

From a management standpoint, this review of case studies highlights the importance of extreme precipitation events in terms of both particulate and solute exports at the watershed scale during and immediately after such events, and how these events can impact water quality for years following their occurrence. However, this review also highlights the lack of a consistent strategy to measure the impact of such events on watersheds. For example, many studies evaluate only one or a few aspects of watershed exports and biogeochemistry. Because the case studies presented here were culled from diverse projects set up by diverse institutions for diverse purposes, sampling strategies, protocols, and intervals differ. Not surprisingly, among the many studies summarized in this paper, there were no consistent approaches of methods and measured water quality parameters. This strongly limits our ability to develop a complete picture, with consistent measured variables (e.g. SRP vs. DP, PP, TP) across watersheds, so one can really understand what causes the variability in the responses observed from one watershed to the next over the entirety of the storm-effected area.

Considering the importance of such events, we therefore argue that there is a need to develop standard approaches for extreme event monitoring. One way to achieve this would be to develop novel funding strategies whereby rapid assessment teams (e.g. teams of scientists) received baseline funding to be able to go out in the field on short notice at key locations to measure a predetermined set of streamflow and water quality parameters when storms are forecasted. Also, this collection of case studies highlights the high value of long-term site-based repeated measurements that provide context for assessing the magnitude of extreme events and their impacts, and the imperative to preserve these sites despite threats to their funding (e.g. Tetzlaff et al. 2017; Laudon et al. 2017). Note that we saw locally extreme responses to Irene and Lee with respect to a range of water quality indicators (e.g. NO_3^-, TSS, TP), but that the lack of systematic measurements across a broad range of locations along the path of the storms prevented us from fully establishing how relevant these measurements were in a broader context. We argue that such a "rapid-response" protocol of uniform measurements at a network of established sites is the best path toward a thorough assessment of the potential water quality impacts (both short-term and long-term) of such

events on our environment, and ultimately their impact of our economy and society. Indeed, until the impacts of such events are consistently quantified, it will remain challenging for federal, state, and local agencies to estimate the real need for adaptation and mitigation strategies, and develop a plan to allocate resources toward these goals.

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