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Before the storm: antecedent conditions as regulators of hydrologic and biogeochemical response to extreme climate events

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Abstract While the influence of antecedent conditions on watershed function is widely recognized under typical hydrologic regimes, gaps remain in the context of extreme climate events (ECEs). ECEs are those events that far exceed seasonal norms of intensity, duration, or impact upon the physical environment or ecosystem. In this synthesis, we discuss the role of source availability and hydrologic connectivity on antecedent conditions and propose a conceptual framework to characterize system response to ECEs at the watershed scale. We present four case studies in detail that span a range of types of antecedent conditions and type of ECE to highlight important controls and feedbacks. Because ECEs have the potential to export large amounts of water and materials, their occurrence in sequence can disproportionately amplify the response. In fact, multiple events may not be considered extreme in isolation, but when they occur in close sequence they may lead to extreme responses in terms of both supply and transport capacity. Therefore, to advance our understanding of these complexities, we need continued

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development of a mechanistic understanding of how antecedent conditions set the stage for ECE response across multiple regions and climates, particularly since monitoring of these rare events is costly and difficult to obtain. Through focused monitoring of critical ecosystems during rare events we will also be able to extend and validate modeling studies. Cross-regional comparisons are also needed to define characteristics of resilient systems. These monitoring, modeling, and synthesis efforts are more critical than ever in light of changing climate regimes, intensification of human modifications of the landscape, and the disproportionate impact of ECEs in highly populated regions.

Keywords Extreme climate event · Hydrology · Sediment · Nutrients · Antecedent conditions

Introduction

Extreme climate events (ECEs) refer to the occurrence of weather or climate conditions that fall far outside of seasonal norms of intensity, duration, or impact upon the physical environment or ecosystem processes (Melillo et al. 2014; Smith 2011). Some of the most visible ECEs involve extremes in precipitation, such as hurricanes, large thunderstorms, and ice/snow storms (McDowell et al. 2013; Rustad and Campbell 2012; Vidon et al. 2018). However, extreme hydrologic and biogeochemical responses may also be generated by ECEs that do not involve significant precipitation, such as heat waves, droughts, unexpected frost/freeze events, and climate-related perturbations, such as wildfire. In some cases, the ECE may actually be an antecedent condition that strongly influences the later hydrological or biogeochemical response to routine storm events.

Antecedent conditions within a watershed prior to an ECE are determined by recent and historical human activities on the landscape, preceding weather conditions, and other ecosystem disturbances, which in turn influence the watershed's response. While the influence of antecedent conditions on hydrologic and materials export from watersheds under more common conditions have frequently been the focus of study (e.g., Biron et al. 1999; Turgeon and Courchesne 2008), gaps remain in the application of this knowledge base to ECEs, particularly in the context of multiple extreme events occurring in sequence. When a second ECE occurs before the landscape or ecosystem has recovered from a prior ECE, there may be serious implications for long-term ecosystem resilience (e.g. Havens et al. 2016). Ecological resilience was originally defined as the magnitude of disturbance that a system can experience before it shifts into an alternate state (Holling 1973) and modified to include the concept of reorganization such that the system returns to the same function, structure, identify, and feedbacks following disturbance (Folke et al. 2004). Here, we further focus our discussion of hydrologic and biogeochemical resilience on the size of water and material pools within the watershed and the subsequent input and output rates, which are strongly linked to vegetation and landscape structure (Turner et al. 1993; McLauchlan et al. 2014).

Because ECEs are disturbance events by definition, they regulate short-term responses, such as nutrient cycling and carbon storage, but also long-term productivity and soil development. While a single ECE can have a significant impact on human health and safety, landscape stability, and ecosystem function, responses can be altered or amplified when ECEs occur in succession and produce cascading effects (Kappes et al. 2012). For example, Hurricanes Irma and Maria occurred in sequence in 2017 and had devastating effects upon Puerto Rico, Turks and Caicos Islands and other Caribbean islands. Similarly, Vidon et al. 2018 show the impacts of Hurricane Irene and Tropical Storm Lee (which occurred within 2 weeks of each other in August/September 2011) on water quality along the eastern coast of the continental United States. The sequence of events yielded high rainfall totals, which mobilized typically stable sediment pools and triggered high particulate loads in many rivers that persisted for months to years (Yellen et al. 2016; Vidon et al. 2018).

Here we present a conceptual synthesis of the effects of antecedent conditions on hydrologic and biogeochemical response, including the effects of extreme precipitation events that follow long-term sediment deposition in river valleys (Inamdar et al. 2017), periods of drought (Loecke et al. 2017), wildfire (Murphy et al. 2015), and wet antecedent conditions (Rose et al. 2018). This framework is supported by case studies that illustrate the complexity in the type of conditions that precede the ECE and the temporal scales upon which they act. In this synthesis, we focus on the hydrological and biogeochemical response at the watershed scale, particularly related to water, solute and sediment export. We frame our discussion in the context of short- and long-term conditions that either amplify or dampen the response. We begin by providing a brief overview of the effects that antecedent conditions have on water and material export associated with storm events in general, and propose a unifying framework to apply these to ECEs. We follow with a synthesis of reported studies that specifically link the impact of ECEs with antecedent conditions and present four case studies that highlight scenarios where antecedent conditions are primary controls on ECE impacts. In the coming decades, ECEs are expected to occur at greater frequency and intensity, and in locations that may have not previously experienced them in the past (Melillo et al. 2014). Placing these ECEs in the context of antecedent conditions provides actionable knowledge as we seek to manage natural and human influenced landscapes for increased resilience.

Role of antecedent conditions

Antecedent conditions strongly influence the size and location of the mobile pool of water, the concentration/speciation of constituents in the water, the timing and magnitude of downstream transport, and the potential for transformation during or prior to transport (e.g., Lintern et al. 2017). Antecedent conditions can drive watershed export of water and constituents for two main reasons: (1) they influence availability of water and constituents (nutrients, pollutants, sediment, and dissolved organic carbon (DOC)), or "source availability" and (2) they strongly impact which hydrologic flowpaths are activated, or "hydrologic connectivity" (Fig. 1). Antecedent conditions can play a role at multiple time scales. Both source availability and hydrologic connectivity can be modified over short time scales, such as during a series of precipitation events or seasonal shifts in the release or uptake of water and constituents (e.g., Macrae et al. 2010). Underlying this are long-term drivers, such as disturbance regimes, changes in climate, successional stage of vegetation, and level of human alteration to the landscape, such as land use history, drainage infrastructure, levees that change river network connectivity (e.g., Carpenter et al. 2018). Long-term drivers can alter not only source availability and connectivity, but also the hydrologic architecture that determines how flowpaths change with wetness conditions and water inputs.

The infrequency and intensity of ECEs present great challenges toward documenting and understanding the effects of antecedent conditions on hydrological and biogeochemical responses. Extrapolating the effects of antecedent conditions during typical hydrologic events to ECEs has large uncertainty but fundamentally depends upon source availability and hydrologic connectivity. While we base our hypotheses on responses to more common or typical events, responses to ECEs may differ substantially. For example, under typical storm conditions it is well known that runoff and flooding are highly sensitive to initial soil moisture (e.g. Dingman 2015; Brocca et al. 2015). However, the sensitivity of flooding to antecedent soil moisture tends to be lower for larger storms (e.g. Zehe and Blöschl 2004; Grillakis et al. 2016), so extrapolation to ECEs is not straightforward. Very high precipitation during an ECE could lead to soils becoming fully saturated in the early stages of the ECE, and therefore hydrologic response may be less sensitive to soil moisture later in the ECE. As discussed in Sects. "Source availability" and "Hydrologic connectivity", entirely new sources of transportable material and new pathways of hydrologic connectivity, not activated during typical storm events, may be established during ECEs. The potential nonlinear responses in terms of both source availability and hydrologic processes suggest that linear extrapolation from typical storm responses are likely not accurate for ECEs.

Source availability

The scale of ECE impact on hydrology and biogeochemical fluxes is driven by the amount of transportable constituents within the terrestrial landscape at the time of the event, which is largely driven by the legacy of inputs. For example, the agricultural application of fertilizer at levels that exceed the ability of crops to remove added nutrients can result in accumulation of nitrogen and phosphorus in the soil (Sharpley et al. 2013). Such an accumulation may

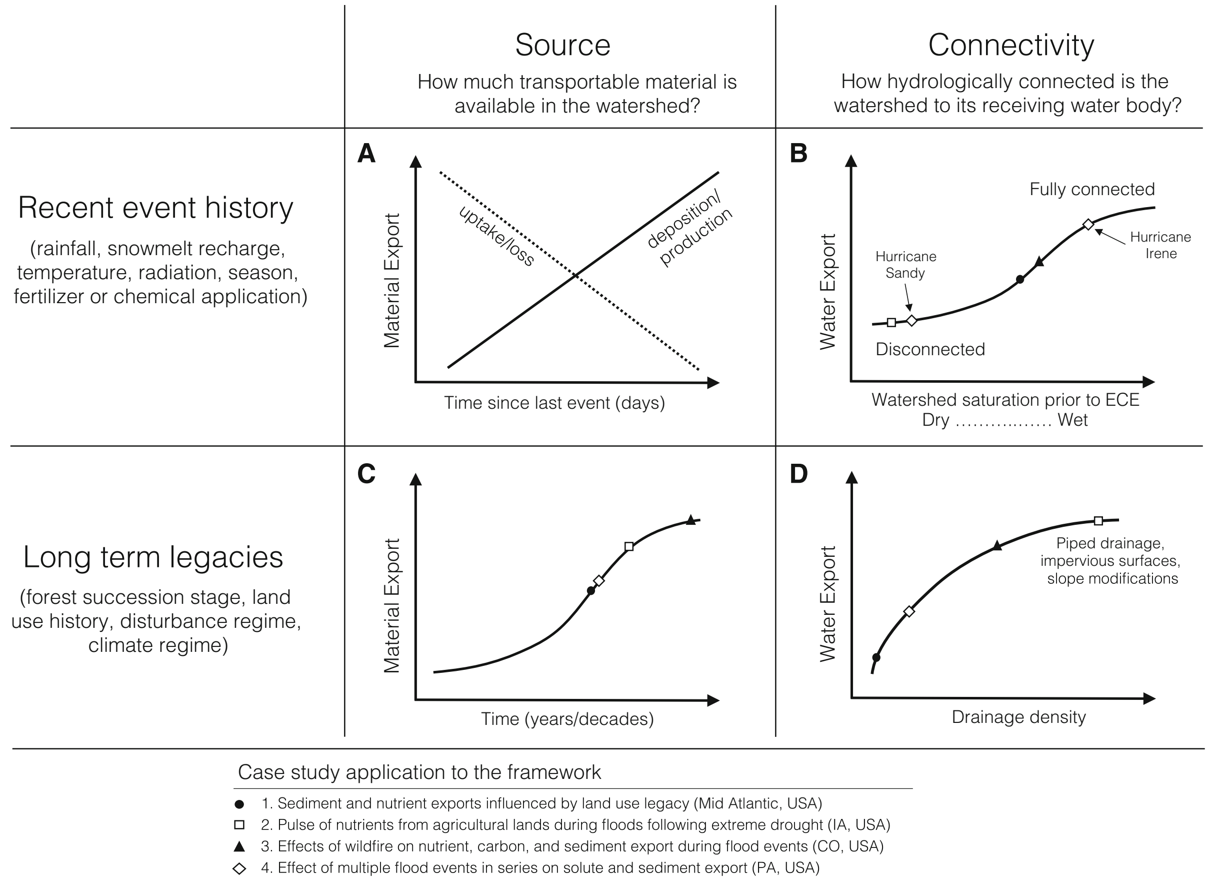

Fig. 1 Conceptual framework for the effects of short- and long-term antecedent conditions on source availability and hydrologic connectivity. Case studies are plotted with additional details presented in Table 1. **A** Common trajectories occur in all systems that result in increased production and decreased loss as the time since the last event increases. **B** As the watershed wets up prior to onset of the ECE, connectivity is expected to follow a threshold pattern as it transitions from a disconnected to fully connected state when the watershed storage is maximized. **C** Accumulation of materials (e.g., nutrients, carbon, sediment) within the system likely reaches a plateau as maximum storage capacity is reached. **D** Water export will quickly increase as engineered drainage density increases (e.g., urban stormwater, agriculture drainage/channelization). Note that the shape of each relationship is not well quantified yet and could vary based on biogeochemistry of the pollutant and intensity of management of land use and drainage network

occur over a short-term period following unexpectedly low crop yield caused by drought or flooding (Randall and Mulla 2001) or after multiple years of inputs of a particular element in excess of demand. Such an example has been observed in locations where manure has been applied as the primary nitrogen source to field crops. Long-term accumulations of phosphorus commonly results, given the low N:P ratio of manure in relation to demand of most plants (Eghball and Power 1999; Sharpley et al. 2013). Accumulation over time, when export is limited, can theoretically lead to an infinite supply. Such accumulation may take decades or longer to be depleted, so short-term antecedent conditions and average-sized export events may have little effect on the size of this pool (Basu et al. 2010). High inputs of water during extreme-precipitation ECEs can connect multiple and distant source areas within the catchment and may amplify export. Conversely, large storms in series may deplete mobile pools of reactive solutes, thereby changing a predominantly transport-limited system (increased concentration and yield with increased flow) to a source-limited system (dilution of instream concentrations and reduced yield with similar increase in flow; e.g., Dhillon and Inamdar 2013).

Table 1 Characterization of each case study based on the conceptual framework presented in this synthesis (Fig. 1)

Case study	Recent event history		Long term legacies	
	Source	Connectivity	Source	Connectivity
1. Sediment and nutrientexports influenced byland use legacy (MidAtlantic, USA) Inamdar et al. (2017)	*Deposition/production*: freeze–thaw events cause sediments to lose cohesion and slump/collapse at the base of the streambank	Varies by event	Large amounts of legacy sediments were deposited behind mill dams following erosion with land clearing. Many dams have been removed or lost exposing legacy sediment	Primarily forested watersheds with little artificial drainage so potential for watershed storage is high
2. Pulse of nutrients from agricultural lands during floods following extreme drought (IA, USA); Loecke et al. (2017)	*Deposition/production*: N fertilization in year prior to flooding; drought conditions enhanced nitrification to create mobile pool of NO_3^- *Uptake/loss*: Low soil moisture during drought resulted in little potential for denitrification or leaching	Low connectivity of upland to streams following drought conditions	Centuries of agricultural production and fertilizer application created a large pool of nutrients	Tile and surface drainage of agricultural land has substantially increased drainage density and reduced surface water storage in the region resulting in a rapid flow increase with extreme spring precipitation despite dry soils prior to the event
3. Effects of wildfire on nutrient, carbon, and sediment export during flood events (CO, USA); Murphy et al. (2015)	*Deposition/production*: Wildfire altered soil properties causing reduced soil infiltration and overland flow during thunderstorms; burned vegetation and combusted surface organic matter left as ash on the surface, soil and mining waste exposed *Uptake/loss:* burned vegetation unable to assimilate nutrients	High surface connectivity, low subsurface connectivity during thunderstorms	Second-growth forest following forestry and mining operations (1860s–1940s); large pool of transportable material	Moderate connectivity, subsurface flow paths (minimal overland flow)
4. Effect of multiple flood events in series on solute and sediment export (PA, USA); Rose et al. (2018)	*Deposition/ production*:Summer storms mobilize sediments stored within the channel and cause bank erosion; freeze-thaw cycles can dislodge banks similar to case study (1); upland landscape erosion associated with agricultural activity	*Irene*: prior events created wet antecedent conditions prior to the hurricane *Sandy:* summer drought created dry antecedent conditions	Legacy sediment in valleys from former mill dam deposits and colluvial toe-slope deposits	Agricultural lands have low level of engineered channels; expansive riparian forest replanted since 1970s buffers channel from uphill agriculture

Antecedent conditions also influence the relative amounts, bioavailability, and export potential of different forms of reactive solutes (e.g., dissolved versus particulate, organic and inorganic). Extreme droughts can enhance this effect, as demonstrated by the buildup of nitrate via nitrification in dry surface soils in the agricultural Midwest (Sect. "Pulse of nutrients from agricultural lands during floods following extreme drought"; Loecke et al. 2017). Dry antecedent conditions lead to mineralization of organic carbon and nitrification of ammonium, creating a pool of DOC and NO_3^- that can be more readily flushed from near surface soils during a storm event (this is discussed in detail in the case studies presented in Sect. "Case studies"). Phosphorus pools can also be greatly affected by short-term antecedent conditions. Phosphorus can be loosely sorbed to soil particles and released during short periods of flushing when soils become temporarily anoxic, thereby depleting the pool of transportable P. However, more tightly bound P associated with iron and aluminum oxides is only released during prolonged periods of flooding, which can persist following ECEs (Young and Ross 2001; Amarawansha et al. 2015).

Antecedent conditions can also influence the potential for transformation of reactive solutes. During high-flow events, within-storm retention and transformation occurs as constituents are deposited or transformed along hydrologic flow paths. It is well established that terrestrial and riverine locations that slow the movement of water and allow time for transformation may reduce export (e.g., McClain et al. 2003). These may be natural or constructed depressions in the landscape (e.g., wetlands) or complexities within the channel (e.g., hyporheic flow through bioreactive streambed sediments). The effectiveness of constituent reduction in these locations will vary as a function of residence time and the fraction of stormflow moving through them. Some transformation may even occur during storms, when natural and human structures such as dams, riparian areas, and floodplains store material and reduce export (Noe and Hupp 2005; Wohl et al. 2017; McMillan and Noe 2017).

Hydrologic connectivity

The importance of antecedent precipitation in determining hydrologic connectivity is well established and presented in most hydrology textbooks (e.g. Dingman 2015), although the precise formulation of the relationship between surface connectivity (through surface runoff), subsurface connectivity (through shallow lateral or groundwater flow), and antecedent precipitation varies widely with location and meteorologic forcing conditions (Heggen 2001). In general, hydrologic connectivity of a watershed increases with the magnitude and intensity of precipitation inputs (Bracken et al. 2013). Analysis of hillslope-scale connectivity argues for "fill and spill" mechanisms that suggest highly non-linear threshold type relationships between wetness and spatial connectivity (Tromp-van Meerveld and McDonnell 2006; Lehmann et al. 2007). In cases where this mechanism applies, antecedent wetness conditions will determine the amount of water needed during a storm to reach the "spill" threshold.

Wet antecedent conditions generally increase the extent to which storm water inputs expand flowpath connectivity independent of storm size (Bracken et al. 2013). However, hydrologic control on the export of dissolved and suspended constituents is closely tied to source availability (e.g. Godsey et al. 2009; Maher 2011) and this relationship is complex, highly variable across landscape types, and often difficult to quantify. In watersheds with relatively large pools of exportable constituents (e.g., nutrients, sediment) and homogenous spatial distributions, predictable and often linear relationships exist between flow and export (Basu et al. 2010). However, when the source pool of that material is unevenly distributed throughout the watershed, spatial hydrologic connectivity will vary as a function of antecedent conditions, resulting in non-proportional and non-linear relationships between discharge, concentration, and export (Ali et al. 2017). If multiple precipitation events occur in close succession, storage areas in the subsurface and in surface waters can be filled, resulting in larger volumetric export. If such "fill and spill" water storage areas coincide with areas in watersheds where constituents of interest accumulate (e.g., nutrients in spatially isolated wetlands), then large increases in both concentration and yield can be anticipated when hydrologic connection occurs. Conversely, if a pool of constituents is small in areas with high hydrologic storage, then during times of hydrologic connection (e.g. melting of a large snowpack or ice), dilution is likely, and multiple precipitation events may act to deplete pools of materials so constituent yield decreases.

The classic "flushing" hypothesis (Hornberger et al. 1994) suggests that high constituent concentrations at the watershed outlet during storm events reflect a shift in hydrologic flowpaths to "new" sources that have not been recently "flushed" or depleted. In other words, as a hillslope or watershed "wets up," new areas become hydrologically connected to streamflow and these areas are more likely, all else being equal, to have high source availability. Repeated storm events, or even later periods in a given storm event, will ultimately show dilution in export concentrations as these "new" sources become depleted. The rate at which this depletion occurs depends on a variety of watershed hydro-geologic and biological properties and the background amount and distribution of sources (Weiler and McDonnell 2006). For example, alternating between dry and wet states may ultimately increase N-export during an event if a preceding dry period allows for buildup of reactive solutes due to reduced uptake or biogeochemical transformation (Greaver et al. 2016). Source depletion combined with intensive overland flow caused similar patterns in DOC concentrations from tropical wet forests following multiple hurricanes in Puerto Rico (Hugo in 1989, Hortense in 1996, Georges in 1998) with concentrations initially increasing with flow but then decreasing at the highest flows (Shanley et al. 2011).

Antecedent conditions can also affect more nuanced aspects of transport through watersheds by influencing the dominant biogeochemical and physical processes. Drying of fine textured soils can lead to shrinking and cracking, creating pathways for more rapid preferential flow from the surface and movement of dissolved solutes, such as DOC, NO_3^-, and soluble reactive phosphorus, to deeper soils or to receiving streams (Simard et al. 2000). In human-modified landscapes, modified drainage (e.g., tile drains in agriculture and stormwater collection systems in urban land uses) exacerbates these preferential flows resulting in rapid delivery to receiving waters (Randall et al. 1997). In vegetated natural landscapes, ECEs such as wildfires remove vegetation and can lead to hyper-dry soil conditions, thereby reducing infiltration and increasing overland flow (Ebel et al. 2012; Moody and Ebel 2012). A similar reduction in subsurface flow occurs annually in northern climates, linked to soil temperature and the significant reduction in infiltration rate observed with freezing (Zhao et al. 1997). Freezing of soil may reduce potential for upland erosion and transport of particulate material (Hansen et al. 2002), but high transport rates of dissolved materials present at the soil surface are likely to be observed when ECEs occur in watersheds with frozen soil conditions (e.g. phosphorus; Liu et al. 2013).

In summary, antecedent conditions can alter source availability and hydrologic connection in ways that influence the responses to ECEs. This of course is true for all events, but ECEs are by definition less frequent and more intense than typical conditions (Smith 2011), and thus the importance of antecedent conditions may be magnified. Because extreme-precipitation ECEs have the potential to export large amounts of water and materials, spatial patterns of source availability and the longer-term antecedent conditions that influence source magnitudes may be more critical. ECEs also have greater potential to connect locations within the watershed that are less frequently connected. The strong non-linearity may mean that ECEs are either less or more sensitive to antecedent wetness. If storage zones within watersheds are well connected because of recent events and wet antecedent conditions, then only moderate amounts of additional precipitation may be needed to reach critical thresholds and can result in a disproportionately large response to rainfall. The relative higher water input intensity associated with ECEs will likely lead to high connectivity regardless of antecedent conditions. However, in less connected or arid environments, antecedent conditions are more likely to determine the extent of connectivity even in the case of large amounts of water inputs during ECEs.

Recovery and return to pre-disturbance condition

Recovery of hydrologic and biogeochemical function following an ECE will vary depending on human (e.g., current and prior land use) and natural (e.g., geology, vegetation, climate) factors, and also on recent and historical occurrence of ECEs and other disturbance events (Ebel and Mirus 2014; McDowell et al. 2013; McDowell and Liptzin 2014). In some cases, ECEs reset the physical structure of the ecosystem and irreversible thresholds are crossed leading to a new system state (Bahn et al. 2014). Thus ECEs themselves create antecedent conditions for subsequent ECEs. Our understanding of these thresholds is hindered by ongoing chronic changes in climate, availability of monitoring data before/after ECEs and tendency for experimental work to explore likely climate scenarios (e.g., 3 °C warming) rather than functional response to extreme events. Even when recovery trajectories tend towards pre-ECE states, the time scales of recovery may be long enough to influence subsequent ECE responses. A recent meta-analysis of post disturbance recovery of carbon processes in forests found that leaf area index (LAI) and other carbon variables typically require multiple decades to recover to pre-disturbance values (Fu et al. 2017). Recovery times were different based on severity and type of the disturbance. Drought recovery, for example, typically occurred within several years while fire recovery required multiple decades (Fu et al. 2017). While the link between hydrologic, biogeochemical cycling recovery and vegetation recovery can be complex, these examples highlight the multi-year time scale of vegetation recovery and suggest a long window during which the impacts of subsequent ECEs can be influenced by impacts of a prior disturbance. Repeated ECEs of similar types, such as two tropical storms, can compound hydrologically driven export of materials (Vidon et al. 2018). High hydrologic connectivity and source depletion from the first ECE can delay and alter the rate of recovery to pre-disturbance conditions following the second sequential ECE. A series of ECEs creates conditions whereby the first ECE increases system vulnerability and/or decreases resilience to the second ECE if the system is still highly wetted and connected from the first.

Climate fluctuations are predicted to increase in frequency, intensity, and duration in the next century (IPCC 2014), and thus the contributions to more extreme events to antecedent conditions must be examined more closely. Many terrestrial or ecological systems have response times that are decadal or longer, in which case the potential for the system to recover to its baseline condition before being affected by another ECE may be compromised. This can set up a legacy effect or "memory" in the system from the initial ECE, prior to the next ECE, and could set up the potential for a system to never fully recover and push it toward a threshold change or new ecological state (e.g. Havens et al. 2016; Scheffer et al. 2001; Sadro and Melack 2012). More data is critically needed to determine ecosystem-specific recovery mechanisms and identify thresholds for ecosystem functions across regions, particularly as we seek to model these responses over larger spatial and temporal scales (Bahn et al. 2014).

Case studies

The following sections illustrate the effects of antecedent conditions on hydrologic and biogeochemical response to ECEs by describing four specific case studies on sediment, nutrient and carbon export during high flow events that follow either periods of wet antecedent conditions (sequence of multiple storms), periods of drought, or wildfire.

Sediment and nutrient exports influenced by land use legacy

Long-term antecedent conditions or land use legacy can have a significant influence on how landscapes respond to ECEs with regard to nutrient and contaminant exports by altering the supplies, pools, or stores of sediments, nutrients, or contaminants in watersheds. This case study describes how large and widespread deposits of legacy sediments in the valley bottoms of the Piedmont in the eastern US, particularly the Mid-Atlantic region (Pennsylvania, Delaware, Maryland and Virginia) created the antecedent conditions and led to an extreme response in sediment export following tropical storms (Fig. 1, Table 1; James 2013; Walter and Merritts 2008). Walter and Merritts (2008) attributed some of these legacy sediments to deposition associated with numerous mill dams that were built along streams and rivers in the region for several centuries after Colonial settlement (late 17th to early 20th century). Low head mill dams raised base water levels (typically 1–3 m), reduced flow velocities, and resulted in substantial sediment accumulation behind and upstream of the dams (Walter and Merritts 2008). Widespread erosion associated with land clearing and agriculture added to the delivery and deposition of sediments in valley bottoms (James 2013). Many of the mill dams have now been removed or lost their structural integrity over time, resulting in highly incised contemporary streams with exposed vertical streambanks that are vulnerable to erosion (Merritts et al. 2011, 2013; Pizzuto and O'Neal 2009; Wegmann et al. 2012).

Not surprisingly, studies have reported anomalously elevated rates of streambank erosion and sediment exports from these watersheds (Merritts et al. 2011; Donovan et al. 2015; Gellis et al. 2009; Voli et al. 2013). Streambank sediments have been found to contribute as much as 50–100% of the suspended sediment loads in Piedmont watersheds (Gellis and Noe 2013; Voli et al. 2013). Bank erosion and sediment yields have been attributed to mechanisms such as fluvial erosion with large storm flows (e.g., Gellis et al. 2009); freeze–thaw activity during winter (e.g., Couper 2003); desiccation and cracking in summer (Lyons et al. 2015); and mass wasting of the stream banks (Fox et al. 2016). In particular, freeze–thaw cycles and desiccation cause bank sediments to lose their cohesive strength with subsequent detachment and slumping/collapse at the base of the streambank (Wolman 1959). The loose, fine, detached sediment (largely silts and clays) is then flushed out by streamflow and transported downstream (Merritts et al. 2011, 2013). These provide ideal sorptive surfaces for nutrients and contaminants resulting in elevated concentrations of nitrogen and phosphorus (Merritts et al. 2011; Weitzmann et al. 2014).

Studies by Dhillon and Inamdar (2013, 2014) and Inamdar et al. (2015) in a forested watershed in this region with legacy sediment deposits have revealed substantial sediment and particulate nutrient exports following ECEs (tropical storms). Stream runoff from a 12-ha forested watershed following Tropical Storm Irene in 2011 (precipitation, 155 mm) exported more than half the annual suspended sediment and organic carbon load in just 59 h (Dhillon and Inamdar 2013, 2014). A majority (87%) of the total runoff organic carbon load was in particulate form (Dhillon and Inamdar 2013). The same storm exported one-third of the annual nitrogen export, primarily as particulate nitrogen (Inamdar et al. 2015).

Elevated sediment and nutrient exports have also been observed for large winter and spring storms that have followed freeze–thaw episodes (Inamdar et al. 2017). Recently, an intense February 2016 rainfall event (54 mm total and 21 mm in one hour on February 24, which was the most intense February rainfall event in 10 years of record) followed a sharp freeze–thaw episode and yielded the highest measured suspended sediment concentrations in streamflow (~ 5000 mg/l) over the past 10 years (Inamdar et al. 2017). Sediment and particulate nutrient mass exports for this storm from the 12-ha watershed, while less than that recorded for tropical storm Irene, were comparable to those measured for other tropical storm events. Suspended sediment and particulate nutrient response for this event demonstrated how freeze–thaw episodes (recent event history—Fig. 1) amplified sediment and nutrient exports from watersheds with large reservoirs of stream-bank legacy sediment (long term legacies—Fig. 1).

Pulse of nutrients from agricultural lands during floods following extreme drought

The widespread 2012 drought in the U.S. was one of the most severe, extensive, and costly in the history of the contiguous US (Peterson et al. 2013). In this case study, the extreme drought was in itself an ECE but also created the antecedent conditions that led to disproportionate increases in N export in the agricultural Midwest, USA (Fig. 1, Table 1). Corn is a dominant commodity crop in the region and heavily fertilization dominates N cycling. The drought reduced the corn harvest by 22% and set up conditions that contributed to decreased N export as harvested grain via a proportional reduction in corn yield (Al-Kaisi et al. 2013). The low soil moisture content also contributed to reductions in other soil N removal pathways, such as denitrification and NO_3^- leaching (Balkcom et al. 2003). Because N fertilizer application in the region was completed in the fall (2011) and spring (2012) before the full effects of the drought, the soils received a typical N fertilizer load (Al-Kaisi et al. 2013). As the drought progressed through following fall and winter (2012–2013), the cumulative effect was a landscape enriched in NO_3^- relative to non-drought years.

This extreme drought ended in the spring of 2013 with extreme flooding events that in some basins exceeded the 99th percentile of historic (1971–2010) discharge, thus rapidly restoring hydrologic connectivity (Loecke et al. 2017). The popular media referred to this rapid transition from drought to flood as "weather whiplash." Loecke et al. (2017) parameterized the seasonal transition in precipitation (i.e., antecedent conditions) as a contrast between summer and fall precipitation versus spring precipitation as the Weather Whiplash Index (WWI). Applying this approach to 65 years of continuous precipitation data, the 2012–2013 drought to flood transition was the most extreme (Loecke et al. 2017). A drought of similar magnitude in 1989 ended with a gradual return to normal hydrologic conditions and in contrast, the WWI in 1989–90 was only the sixth most extreme.

Nitrogen cycling and in particular NO_3^- loading into streams following the 1989 and 2012 droughts clearly demonstrate the importance of antecedent conditions in driving biogeochemical response. In the spring of 1990, the Iowa River near the confluence of the Mississippi River averaged 8.8 mg NO_3^- L^{-1}. At the same location in the spring of 2013, the NO_3^- concentration was 23% greater (10.8 mg NO_3^- L^{-1}) and the flow-weighted concentration was 34% higher than the average of surrounding years (2010–2016). It is well established that droughts set up conditions for higher riverine NO_3^- concentrations (Davis et al. 2014), however the influence of the subsequent flow regime is complex. Loecke et al. (2017) tested the effects of extreme transitions in hydrologic conditions on N loading by comparing the WWI and late spring NO_3^- concentrations (mean of May and June) at approximately 160 USGS monitoring sites across the Upper Mississippi River Basin for all available years of data. The results were consistent with the 1989–2012 drought comparison, as years of the highest NO_3^- concentrations were observed when the watersheds experienced dry periods (particularly in the summer/fall) followed by extraordinarily wet periods in the spring. In fact, the most extreme transitions (e.g., from dry to wet conditions) lead to the most extreme NO_3^- concentrations.

Effects of wildfire on nutrient and carbon export during flood events

Here we present a case study in which the ECE, an extreme wildfire, resulted in highly modified antecedent conditions that led to disproportionately high sediment, carbon, and nitrate export during subsequent large storms (Fig. 1, Table 1). Wildfires kill vegetation, combust surface organic matter, and alter soil hydraulic properties, which can reduce infiltration to soil and groundwater (Dahm et al. 2015; Larsen et al. 2009; Moody et al. 2013). Reduced infiltration leads to increased overland or near-surface flow, often resulting in peak stream discharge that is orders of magnitude greater than under the pre-burned condition (Neary et al. 2005). Thus after wildfire, a common climatic event can cause a watershed to respond as if the event were an extreme-precipitation ECE. In addition, wildfire can alter source availability by leaving ash on the surface (Table 1).

The Fourmile Canyon Fire burned 23% of the 6330-ha Fourmile Creek watershed near Boulder, Colorado in September 2010, destroying 160 homes and leaving the area at risk of substantial erosion and potential degradation of drinking-water supplies (Writer and Murphy 2012). Although pre-fire water-quality data were limited, similar geology, pre-fire land cover, land-use history, mean basin slope, and precipitation regimes upstream and downstream of the burned region, allowed the use of upstream water-quality sampling sites to serve as reference sites (i.e., no fire-induced antecedent conditions) (Murphy et al. 2015). The wildfire occurred near the end of thunderstorm season (July-mid September), and only low-intensity rain or snow fell in the burned area for nine months after the wildfire; therefore, the hydrological and water-quality response was minimal through the following spring runoff period (Murphy et al. 2012; Writer and Murphy 2012; Writer et al. 2012). However, during the summer thunderstorm period, relatively common, moderate-intensity (annual exceedance probabilities between 20 and 50%) convective thunderstorms resulted in stream discharge and concentrations of total suspended solids (TSS), DOC, and NO_3^- that were significantly higher downstream of the burned area compared to upstream (Murphy et al. 2015). Maximum concentrations of these constituents reached 120,000 mg TSS L^{-1}, 12 mg NO_3^- L^{-1}, and 71 mg DOC L^{-1}, and were 10–31 times greater downstream of the burned area than maximum upstream concentrations.

Water-quality impacts were caused by alteration of both source availability and hydrologic flow path connectivity (Fig. 1). Reduced infiltration after the wildfire led to overland flow during thunderstorms, which conveyed constituents elevated in wildfire ash and/or exposed soil (e.g., sediment, DOC, NO_3^-) to streams (Murphy et al. 2015). The wildfire lowered the threshold of rainfall intensity required to induce a hydrological and biogeochemical response: snow or low-intensity rain storms falling on the burned area resulted in downstream TSS and DOC concentrations that were statistically similar to concentrations measured upstream in response to higher intensity rainfall events (Murphy et al. 2015). Peak discharge downstream of the burned area was three times greater than prior to the wildfire in response to rain storms of similar intensity. Lastly, similar to case study 1, the Fourmile Creek watershed is subject to another antecedent condition: legacy sediment from historical land use. In this case study, the watershed was subjected to hard-rock mining and forestry from the

1860s to 1940s (Murphy 2006; Dethier et al. 2018). Floods after wildfire, including another ECE in September 2013 (when about half of average annual precipitation fell in 7 days, an AEP of 0.1%), remobilized this mining waste (Dethier et al. 2018).

Other studies similarly demonstrate that wildfires generate antecedent conditions that can have substantial impacts on subsequent responses to ECEs, including elevated peak flows (Coombs and Melack 2013), debris flows (Cannon and DeGraff 2009) and nutrient, sediment and contaminant fluxes (Burke et al. 2010), although the magnitude of these effects vary markedly with climate, fire characteristics and other landscape properties (Saxe et al. 2018) A recent salient example is the Montecito debris flows that followed the Thomas Fire in Southern California in 2017 that resulted in 20 deaths and millions of dollars in damages (State of California 2018). The debris flow was initiated in the area above Montecito where the high severity fire denuded slopes of vegetation the preceding December. An extreme rainfall event the following January triggered the debris flow and had 15-min rainfall intensities with annual exceedance probability $< 1\%$.

Effect of multiple flood events in series on suspended sediment export

Antecedent conditions can have a large impact on both the magnitude and type of material transported. White Clay Creek, a small watershed in southeastern Pennsylvania, USA, experienced increasing export and shifts in material source with increasing antecedent moisture from two extreme storms, Hurricane Irene and Hurricane Sandy (Fig. 1, Table 1). The 7.25 km^2 third-order White Clay Creek watershed lies within the Piedmont physiographic region, specifically the Mid-Atlantic. Land cover is dominated by cropland (28%) and pasture (34%) in the uplands and deciduous forest (27%) in much of the riparian corridor. Forested areas also exist in the uplands, particularly within one of the sub-watersheds. Shrubland and low-density housing comprised the balance of the area and are distributed throughout the uplands. The role of antecedent conditions in watershed response was well illustrated by a series of convective thunderstorms storms leading up to Hurricane Irene (August 28, 2011) that increased soil moisture throughout the watershed. Rose et al. (2018) used short-term fallout radionuclides (^{7}Be and excess ^{210}Pb) to show that the source of exported suspended sediment shifted throughout the sequence of events. During the thunderstorms, suspended sediment originated within and immediately connected to the channel, while during Hurricane Irene the sources included eroded landscape surface material. In fact, particulate organic material (POM) on the falling limb of the hydrograph of Hurricane Irene consisted of 100% landscape surface material. Isotope hydrograph separations showed that overland flow dominated both water discharge over the entire storm. These results are contrasted during Hurricane Sandy (October 29, 2012), which followed a relatively dry month and season in White Clay Creek. Despite the occurrence of another hurricane, soil water, rather than overland flow, strongly dominated the discharge, while surface sources comprised less (maximum of 88%) of the POM. In addition, a lower proportion of the suspended solid export, based on fallout radionuclide activity, was comprised of surface erosion. Taken together, these data indicate a hydrologic connection via overland flow and gully expansion and connection in events with relatively high antecedent moisture. This increased hydrologic connection facilitates the movement of eroded soils and sediments to the stream channel.

Implications for management and direction for future research

The defining role of antecedent conditions in shaping hydrologic and biogeochemical response at the watershed scale is well studied under typical hydrological conditions. The extension of this body of work to ECEs, presented in this synthesis, reveals that similar drivers related to source availability and hydrologic connectivity are key to regulating watershed response to such events. However, the integration of these drivers over short (days to months) and long time scales (years to decades) and interaction of multiple types of ECEs creates challenges in establishing a unifying theory about response and recovery. ECEs can have different outcomes for watershed behavior based on each watershed's condition at the time of each ECE. Multiple examples of “1–2 punches” in recent history (Irene—Lee in 2011, Irma—Maria in 2017) show increased system vulnerability and/or decreased resilience to the second sequential ECE while the system is still highly wetted and connected based on the first. In addition, this synthesis shows that in isolation, an event may not be considered “extreme” but when multiple events occur in sequence, they amplify water, sediment, and nutrient exports by increasing both the supply and transport capacity in the system under consideration (e.g., large wildfires increase organic carbon supply that is transported during later storms).

While data opportunistically collected before and/or after ECEs are clearly important to understand impacts, by definition these events rarely occur, so sufficient monitoring to identify non-linear responses to ECEs would be expensive. However, long-term monitoring programs are critically needed to identify trends, provide pre-event context, characterize ecosystem-specific recovery mechanisms, and identify thresholds for ecosystem functions across regions. We have shown through multiple case studies that similar ECEs with different antecedent conditions can lead to very different impacts on hydrologic and biogeochemical responses. To capture this variability, we need continued development of a mechanistic understanding of how antecedent conditions set the stage for watershed ECE response across multiple regions and climates. Cross-regional comparisons and synthesis will help define characteristics of resilient systems and identify potential irreversible thresholds. In this context, monitoring is required during rare events to model these responses over larger spatial and temporal scales. This is more critical than ever in light of changing climate, intensification of human modifications of the landscape, and the disproportionate impact of ECEs in highly populated regions.

Through a management lens, multiple opportunities exist to affect antecedent conditions of the landscape. For example, reduction of source availability (e.g., nutrient accumulation in agricultural landscapes) and hydrologic connectivity (e.g., drainage connectivity in urban areas) is possible through regulatory and policy mechanisms. Addressing sources and connectivity will not only reduce impacts of ECEs on ecosystems, but during more typical hydrologic conditions as well.

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