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Geomorphic response to catastrophic flooding in north-central Pennsylvania from Tropical Storm Lee (September 2011): Intersection of fluvial disequilibrium and the legacy of logging

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ABSTRACT

More than 25 cm of rainfall from Tropical Storm Lee (TS Lee) over 2 days in September 2011 resulted in catastrophic flooding (U.S. Geological Survey estimated recurrence interval >100 yr) on several Susquehanna River tributaries emanating from the Appalachian Plateau in north-central Pennsylvania (USA). Helicopter photography and field work were used to prepare a detailed geographic information system database of geomorphic response to the flood along ~250 km of Loyalsock, Muncy, Lycoming, and Fishing Creeks. Unlike the response of many streams to previously described Appalachian floods, fluvial response to the TS Lee flood was extensive in these gravel bed streams, characterized by (1) large-scale avulsions and chute development on the insides of meanders, (2) erosion of gravel from channel margins and transport downstream in large pulses, (3) headwater landslides and alluvial fan activation, (4) major floodplain erosion and deposition, and (5) breaching of anthropogenic berms and reconnection of the main channel to prehistoric floodplain anabranches. Geomorphic work, expressed both as bedload sediment transport and landform change (geomorphic effectiveness) was significant: as much as 55,000 m^3/km of gravel was transported within a single watershed. Landform changes included erosion of chutes (to 500 m long), gravel bars (point bars and mid-channel bars), channel widening (in places >100%), and reoccupation of former multithread channels previously cut off from the mainstem by historic channel straightening, berming, and dredging.

Streams in this region appear to be in a phase of disequilibrium largely in response to major shifts in sediment delivery from their watersheds caused by historic logging and a series of floods ~100 yr ago. Widespread clearcutting (A.D. 1850–1920) contributed large volumes of sediment to these streams. Dendrogeomorphic data bracket a period of aggradation of these logging legacy sediments between the 1870s and 1930s, creating a significant low terrace inset into Pleistocene outwash and glacial sediments. Recent floods in 1972, 1996, 2004, and especially TS Lee in 2011 initiated an enhanced phase of disequilibrium as a geomorphic threshold was crossed, resulting in widespread erosion of logging legacy sediments deposited nearly 100 yr ago. The change in sediment load (increased coarse bedload) as a result of widespread bed and bank erosion caused a change in channel pattern from single thread to multithread. Pattern change was facilitated by aggradation of gravel bars above floodplain elevations which promoted avulsion and chute formation. Based on preflood and postflood geomorphic mapping, >6,700,000 m^3 of gravel were mobilized during the flood across 4 watersheds. Mobilization of logging legacy sediment is occurring as pulses of gravel move downstream episodically.

This paper demonstrates the important influences of drainage basin morphometry (e.g., ruggedness number) and fluvial history (land use and geomorphic) in understanding current channel dynamics and basin response to heavy precipitation and flooding. The findings presented herein have significant implications for watershed management and planning. Streams in this region are likely to remain in a protracted phase of readjustment for many decades as complex response to historical land-use change continues. In this disequilibrium phase most significant rainfall events will likely trigger additional readjustment and channel change.

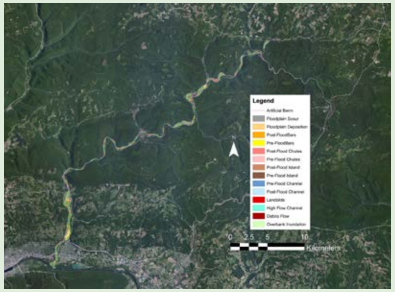
INTRODUCTION

Catastrophic flooding from Tropical Storm Lee (TS Lee) rainfall, 7–8 September 2011, caused large-scale geomorphic adjustments in gravel-bed streams emanating from the Appalachian Plateau in north-central Pennsylvania (USA), including widespread channel erosion and deposition, channel pattern changes, and floodplain disruption (Fig. 1). These streams are characterized by narrow valleys with steep slopes. The relative role of infrequent, large-magnitude floods such as this versus the cumulative effect of frequent, small-magnitude floods on stream channels and floodplains has been the focus of considerable debate for many years (i.e., Wolman and Miller, 1960; Baker et al., 1988; Kochel, 1988). Other than floods characterized by widespread debris flows (i.e., Hack and Goodlett, 1960; Williams and Guy, 1973; Kochel, 1987; Wieczorek et al., 2000; Eaton et al., 2003), most large-magnitude floods in the Appalachians have resulted in only minor erosion and deposition along channels and floodplains (i.e., Wolman and Eiler, 1958; Wolman and Miller, 1960; Costa, 1974; Gupta and Fox, 1974; Moss and Kochel, 1978; Kochel, 1988). A notable exception was the 1985 flood in the Cheat and South Branch Potomac Rivers, which underwent major geomorphic response (Jacobson et al., 1989; Miller, 1990). Miller (1990, 1995) demonstrated that exceedance of threshold values for unit stream power was associated with erosion and deposition along channels and floodplains in streams with narrow, steep-sloped valleys.

Figure 1. Examples of erosion and deposition in north-central Pennsylvania from Tropical Storm Lee. (A) Extensive gravel bars formed in a disequilibrium zone on lower Fishing Creek. (B) Washed out bridge in upper Muncy Creek. (C) Eroded road along Big Bear Creek, upper Loyalsock Creek watershed. (D) House eroded on a Pleistocene terrace, Loyalsock Creek.

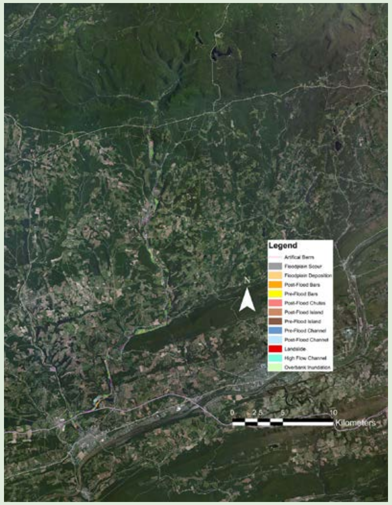
Detailed ground and geographic information system (GIS) based mapping using preflood air photos taken in June 2011 and postflood low-altitude photography from a helicopter survey (3 November 2011) were used to map geomorphic changes along ~250 km of 4 major tributaries to the West and North Branches of the Susquehanna River, Lycoming Creek, Loyalsock Creek, Muncy Creek, and Fishing Creek (Fig. 2A). Chutes were scoured across floodplains and terraces along the insides of many meander bends, bed and bank erosion was widespread, and many stream reaches underwent adjustments in channel pattern from single to multithread channel systems. Perhaps most remarkable was the volume of coarse gravel transported by the flood (Fig. 1A).

A significant geomorphic threshold appears to have been crossed by the TS Lee flood; large quantities of coarse sediment were remobilized and transported and deposited downstream, resulting in avulsion and a change in channel pattern from single to multithread. As a result, small and moderate flood flows now occupy multiple channels across the valley floor. Gravel bars are moving episodically downstream through the affected watersheds as large pulses. Streams in this region are likely to remain in a protracted phase of readjustment for many decades as complex response to historical land-use change continues. The TS Lee flood caused erosion of highways, damage to bridges, damage to 1000 homes and businesses, and destruction of hundreds of acres of farmland on floodplains and terraces (Figs. 1B–1D). Damage to highways in Pennsylvania was estimated to exceed $400 million, including the loss of 9 bridges (T.J. Cunningham, Pennsylvania Department of Transportation, 2012, personal commun.). Sediment delivery to the Chesapeake Bay was among the highest on record (Hirsch, 2012).

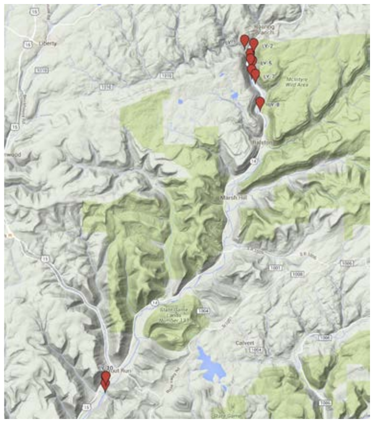


[1]Supplemental File 1. Detailed geographic information system–based geomorphic map of Loyalsock Creek, one of the three watersheds most affected by the Tropical Storm Lee flood. Please visit http://dx.doi.org.10.1130/GES01180.S1 or the full-text article on www.gsapubs.org to view Supplemental File 1.

[2]Supplemental File 2. Detailed geographic information system–based geomorphic map of Muncy Creek, one of the three watersheds most affected by the Tropical Storm Lee flood. Please visit http://dx.doi.org.10.1130/GES01180.S2 or the full-text article on www.gsapubs.org to view Supplemental File 2.

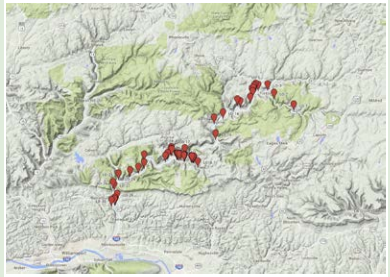


[3]Supplemental File 3. Detailed geographic information system–based geomorphic map of Fishing Creek, one of the three watersheds most affected by the Tropical Storm Lee flood. Please visit http://dx.doi.org.10.1130/GES01180.S3 or the full-text article on www.gsapubs.org to view Supplemental File 3.



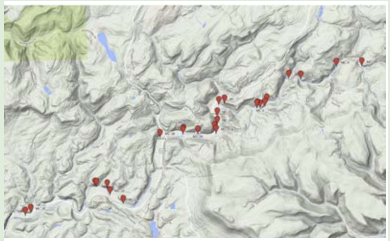
Map LY-1. Map of Lycoming Creek showing locations of Slides LY-1 through LY-11.

[4]Supplemental File 4. Lycoming Creek virtual tour. Please visit http://dx.doi.org.10.1130/GES01180.S4 or the full-text article on www.gsapubs.org to view Supplemental File 4.



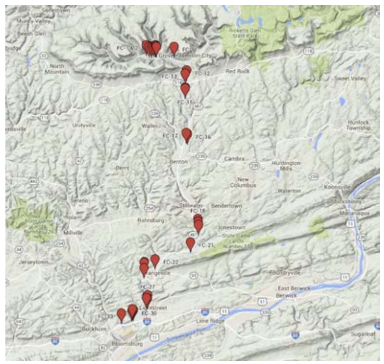
Map LO-1. Map of Loyalsock Creek, showing locations of slides LO-1 through LO-30.

[5]Supplemental File 5. Loyalsock Creek virtual tour. Please visit http://dx.doi.org/10.1130/GES01180.S5 or the full-text article of www.gsapubs.org to view Supplemental File 5.



Slide MC-1. Map of Muncy Creek, showing locations of slides MC-1 through MC-36.

[6]Supplemental File 6. Muncy Creek virtual tour. Please visit http://dx.doi.org/10.1130/GES01180.S6 or the full-text article of www.gsapubs.org to view Supplemental File 6.



Map FC-1. Map of Fishing Creek, showing location of all slides, numbers FC-1 through FC-33.

[7]Supplemental File 7. Fishing Creek virtual tour. Please visit http://dx.doi.org/10.1130/GES01180.S7 or the full-text article of www.gsapubs.org to view Supplemental File 7.

Basinwide deforestation and channel modification associated with logging during the nineteenth and early twentieth centuries destabilized these fluvial systems; shifting channel patterns in these gravel-bed streams from a natural multithread system into a single channel system by the construction of berms that disconnected the main channel from its floodplain. Berms, used mainly for log drives, are composed of gravel dredged from the channel and piled along the banks to heights ranging from 1 to 4 m. Subsequent farms, highways, and towns continued the practice of berming and dredging to encourage development and minimize flooding. Historical aerial photos and interviews with residents indicate that the previous flood of record (TS Agnes; June 1972) initiated the breaching of berms and erosion of logging legacy sediments. Subsequent floods (e.g., January 1996 snowmelt flood and TS Ivan in September 2004) furthered the trajectory of channels returning to a multithread system. The TS Lee flood (September 2011) appears to have been a geomorphic threshold-crossing event with respect to channel morphology (channel pattern). This study characterizes the geomorphic response and spatial patterns of gravel erosion and deposition to the TS Lee flood.

Geomorphic response to the TS Lee flood was dramatically larger in the rugged Appalachian Plateau streams (Loyalsock, Lycoming, Muncy, and Fishing Creeks) compared to several Valley and Ridge streams (Chillisquaque and Swatara Creeks) that also underwent record flooding during TS Lee. The contrast in channel response can be attributed to differences in geomorphic history, drainage basin morphometry, and land-use history.

Understanding the trajectory of geomorphic adjustment of the streams in this region will be critical in making wise management and land-use policy decisions. It is easy for these complex channel dynamics to be overlooked when designing roads, bridges, and homes. Our goal is to share these data and observations with a broad community of geoscientists interested in flood geomorphology and fluvial response by using a format that permits the inclusion of a significant number of photos, maps, and figures as well as a link to the entire high-resolution GIS-based map of geomorphic response to the flood over 250 km in several watersheds (Supplemental Files 1[1], 2[2], and 3[3]). Readers are invited to view Supplemental Files 4–7 to see virtual tours of the four streams studied. The virtual tours provide a number of aerial and ground images moving in the downstream direction along Lycoming Creek (Supplemental File 4[4]), Loyalsock Creek (Supplemental File 5[5]), Muncy Creek (Supplemental File 6[6]), and Fishing Creek (Supplemental File 7[7]).

TS LEE AND REGIONAL GEOLOGY IN NORTH-CENTRAL PENNSYLVANIA

Rainfall from TS Lee ranged from 150 to 330 mm over the 4 watersheds (Fig. 2A) between 7 and 8 September; most of the area received ~26 cm (Fig. 2B). The storm moved as a narrow band of moisture training from south to north, resulting in significant orographic effects as the moisture-laden air was affected by the Ridge and Valley region near Harrisburg and again along the boundary of the Appalachian Plateau, where the four watersheds have their

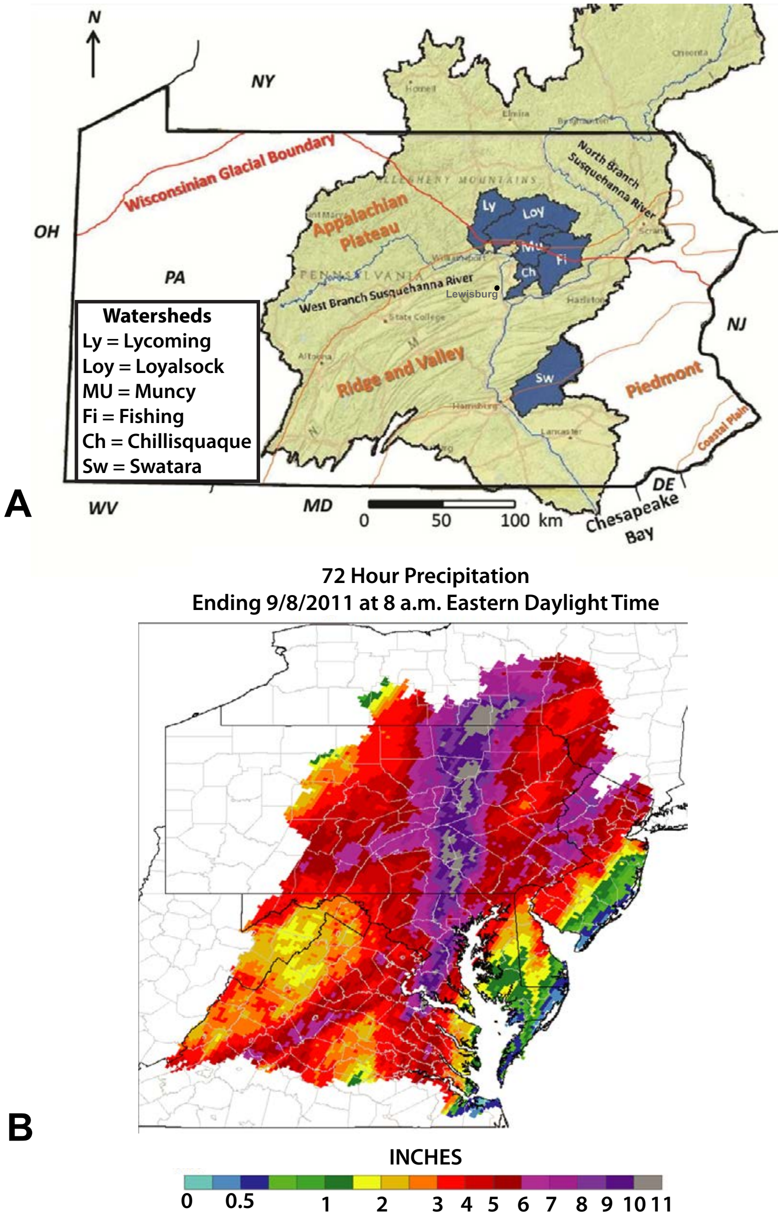


Figure 2. Study location and rainfall map of north-central watersheds affected by Tropical Storm (TS) Lee. (A) The study watersheds are in blue, as well as the physiographic provinces and late Pleistocene glacial boundary. (B) Rainfall distribution map for TS Lee (map provided by William Marosi, National Oceanic and Atmospheric Administration National Weather Service, State College, Pennsylvania, 2012).

headwaters. The duration of heavy rainfall was increased by Hurricane Katia, situated 500 km east of the mid-Atlantic coast, which served to slow the eastward progression of TS Lee (William Marosi, National Oceanic and Atmospheric Administration, 2012, personal commun.). In addition, some amplification to the moisture flow appeared to stream from the Chesapeake Bay as steady winds blew from the south along the bay axis.

The headwaters of all four streams (Lycoming, Loyalsock, Muncy, and Fishing Creeks) are within a topographically high section of the Appalachian Plateau northeast of Williamsport, underlain predominantly by sandstone with steep slopes and narrow valleys (Fig. 3). Gravel bedload in these streams is sourced both from the sandstones and late Pleistocene glacial deposits. In contrast, Chillisquaque and Swatara Creeks watersheds are in the Ridge and Valley to the south, and are dominated by shale and limestone with minor ridge-forming sandstones along their basin margins; they were not glaciated during the late Pleistocene. Postflood field visits and comparisons of preflood and postflood aerial photos show that channel response was minimal in the Ridge and Valley and Piedmont watersheds even though rainfall was similar. Flooding in Swatara Creek reached its record, exceeding Hurricane Agnes in 1972, yet there were no significant gravel bars, chutes, or instances of bank erosion. Similar lack of geomorphic response to flooding was noted during the TS Agnes flood in nearby piedmont channels (Moss and Kochel, 1978).

Table 1 shows the recurrence intervals for the TS Lee flood at U.S. Geological Survey gaging stations in the study area. The flood exceeded the 100 yr event for Loyalsock, Muncy, and Fishing Creeks, and ranks as the largest flood of record. Lycoming Creek had a lesser flow because its watershed was on the western edge of the precipitation.

The geomorphic effectiveness (Wolman and Gerson, 1978) of the TS Lee flood was so great that erosion of prehistoric landforms can be used to provide long-term geomorphic information on the recurrence interval of the flood. Costa (1978) used this method to estimate the recurrence of the 1976 Big Thomson Canyon flood in Colorado to be ~10,000 yr based on the age of sediments exposed in eroded tributary alluvial fans. Figure 4 shows examples of terraces and alluvial fans eroded by the TS Lee flood. Figure 4A is a cut into a Pleistocene terrace on lower Loyalsock Creek caused by chute erosion (also seen in Figs. 5, 6, 7, and 8). Radiocarbon dating of a buried organic horizon showed an age of 2490 ± 30 ^{14}C yr B.P. Since that time, only two flood sedimentation events were recorded in the floodplain stratigraphy, the surface layer from TS Lee and one older Holocene event. The entire depositional package overlies late Pleistocene outwash. Figure 4B shows a small tributary fan in upper Muncy Creek that was truncated during the emplacement of the large gravel bar during the TS Lee flood. A radiocarbon date near the center of the exposed fan stratigraphy yielded an age of 500 ± 30 ^{14}C yr B.P. Older (probably early Holocene) fan sediments were exposed below the dated horizon. These dates suggest that the true geomorphic recurrence interval of the TS Lee flood may be significantly >100 yr. Further support for this interpretation was observed at numerous sites where Pleistocene outwash terraces were eroded by the TS Lee flood (Fig. 4C).

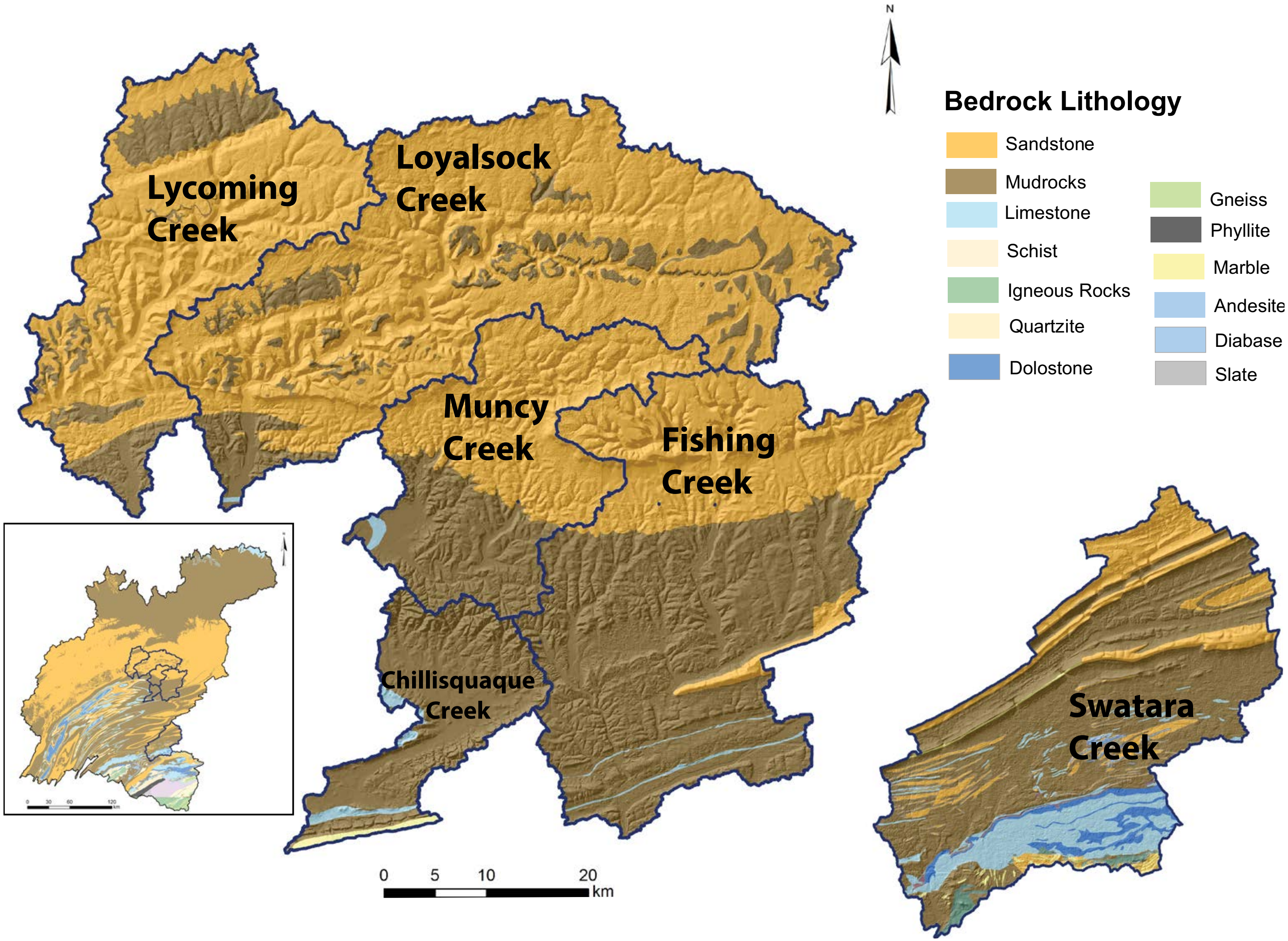


Figure 3. Generalized bedrock geology of the study area. The position of Swatara Creek has been shifted north to save space (true location can be seen in the inset map of the Susquehanna watershed).

FLOOD GEOMORPHIC MAPPING

Detailed geomorphic maps were created using GIS along >250 km of the channels of Lycoming, Loyalsock, Muncy, and Fishing Creeks using 2 sets of aerial imagery. Figures 5 and 6 show examples of the flood geomorphic mapping. High-resolution preflood aerial photos (2011 Microsoft Corporation Bing Maps) were used to map channel morphology at 1:5000 scale and were compared to aerial images taken from a postflood helicopter survey on 3 November 2011. More than 4000 oblique images taken during the helicopter flight were stitched to create continuous coverage of the same reaches mapped

TABLE 1. U.S. GEOLOGICAL SURVEY GAGE RECURRENCE INTERVALS

Drainage area (mi²; *km²*)	Stream gage name	2011 peak (ft³ s⁻¹; *m³ s⁻¹*)	Rank of 2011 peak	Number of years used in analysis	Updated annual exceedance probabilities (ft³ s⁻¹; *m³ s⁻¹*) 0.02 (50 yr)	0.01 (100 yr)	0.002 (500 yr)
274 *~709.6*	Fishing Creek near Bloomsburg, Pennsylvania	56,000 *~1585.7*	1	76	36,500 *~1033.6*	45,200 *~1279.9*	71,000 *~2010.5*
173 *~448.1*	Lycoming Creek near Trout Run, Pennsylvania	26,200 *~741.9*	2	98	23,300 *~659.8*	28,000 *~792.8*	41,100 *~1163.8*
435 *~1126.6*	Loyalsock Creek at Loyalsockville, Pennsylvania	69,100 *~1956.7*	1	85	49,900 *~1413*	60,100 *~1701.8*	89,600 *~2537.2*
24 *~62.1*	Muncy Creek near Sonestown, Pennsylvania	6970 *~197.4*	1	71	5060 *~143.2*	5990 *~169.6*	8560 *~242.4*
196 *~507.6*	Muncy Creek near Muncy, Pennsylvania	46,600 *~1319.6*	1	23	36,100 *~1022.2*	45,500 *~1288.4*	74,600 *~2112.4*

Note: Data source is U.S. Geological Survey, LeMoyne Water Science Center.

in preflood imagery. Images were georeferenced using 4–6 points (bridges, houses, trees, outcrops, boulders) shared by adjacent images, but they were not orthorectified. Flood geomorphic features (bars, chutes, areas of bank erosion) visible in the stitched oblique images were then digitized onto the orthorectified preflood Microsoft Corporation Bing Maps images. Care was taken to ensure that the horizontal accuracy of the lines delineating geomorphic features mapped was within 1–2 m. Field visits to dozens of bars, chutes, and erosion sites were used to ground truth flood features delineated from the oblique aerial images. High-definition video footage taken from the helicopter was also used to verify mapping interpretations.

Complete geomorphic maps of the four streams can be found in Supplemental Files 1, 2, and 3. Preflood and postflood geomorphic features mapped using GIS included (1) low-flow channels; (2) gravel bars; (3) vegetated islands; (4) chutes; (5) landslides; (6) areas inundated during the flood; and (7) artificial berms constructed along channels for logging and agricultural purposes. The quality of the Microsoft Corporation Bing Maps images and the helicopter images was excellent. Geomorphic features <50 cm could be resolved in these aerial photographs.

The flood geomorphic maps were used to quantitatively assess the impacts of the TS Lee flood. Geomorphic changes measured included (1) changes in active channel width, (2) spatial and volumetric changes in gravel bars, and (3) adjustments in channel pattern. Field surveys were made at representative locations along all four streams to better understand geomorphic impacts and to estimate hydraulic parameters during peak flood conditions over the large gravel bars. The focus of our field surveys included (1) impacts in headwater regions; (2) sedimentological investigation of in-channel gravel bars and chute bars; (3) estimating hydraulic parameters associated with gravel transport on the bars; and (4) estimates of the recurrence interval of the flood using a geomorphic approach focusing on landforms eroded by the flood.

GEOMORPHIC RESPONSE

Most floods in the mid-Atlantic region are characterized by significant floodplain-terrace inundation but have relatively minor landform modification by erosion and deposition (i.e., Costa, 1974; Moss and Kochel, 1978; Kochel, 1988). In contrast, the geomorphic impact of the TS Lee flood along Lycoming, Loyalsock, Muncy, and Fishing Creeks was catastrophic. Observations of geomorphic maps in Figures 5 and 6 and especially Supplemental Files 1, 2, and 3 (maps of entire reaches) show episodic variation in channel stability, with distinctive zones of disequilibrium along channels alternating with reaches where relatively minor change occurred. A similar pattern of large-scale channel instability was noted along the Current River in Missouri by Jacobson and Gran (1999).

Significant geomorphic impacts of the flood included (1) chute erosion and chute-bar formation along the inside of meander bends; (2) floodplain disruption by excessive sedimentation and erosion; (3) large-scale gravel transport and deposition of gravel bars; (4) bank erosion and increase of active channel width; (5) reconnection of channels to floodplain anabranches cut off by artificial berm construction; and (6) shallow mass wasting, channel avulsion, and alluvial fan activation in headwater regions. Overbank flooding inundated most of the valley floors (pale green areas in Figs. 5 and 6; Supplemental Files 1, 2, and 3), including Pleistocene terrace surfaces. Former high-flow channels (shown in pale blue) that had been disconnected by historical activity such as berm construction (red), were reoccupied during the flood. Preflood lidar (light detection and ranging) and aerial photos clearly show that these streams were formerly multithread systems. In some cases, berms were breached, resulting in large chute channels (salmon) scoured across floodplains and terraces. Large volumes of sand and gravel were deposited within channels as bars (orange) and on floodplain surfaces (tan). Floodplain scour (gray) occurred where chutes formed as well in other floodplain areas.

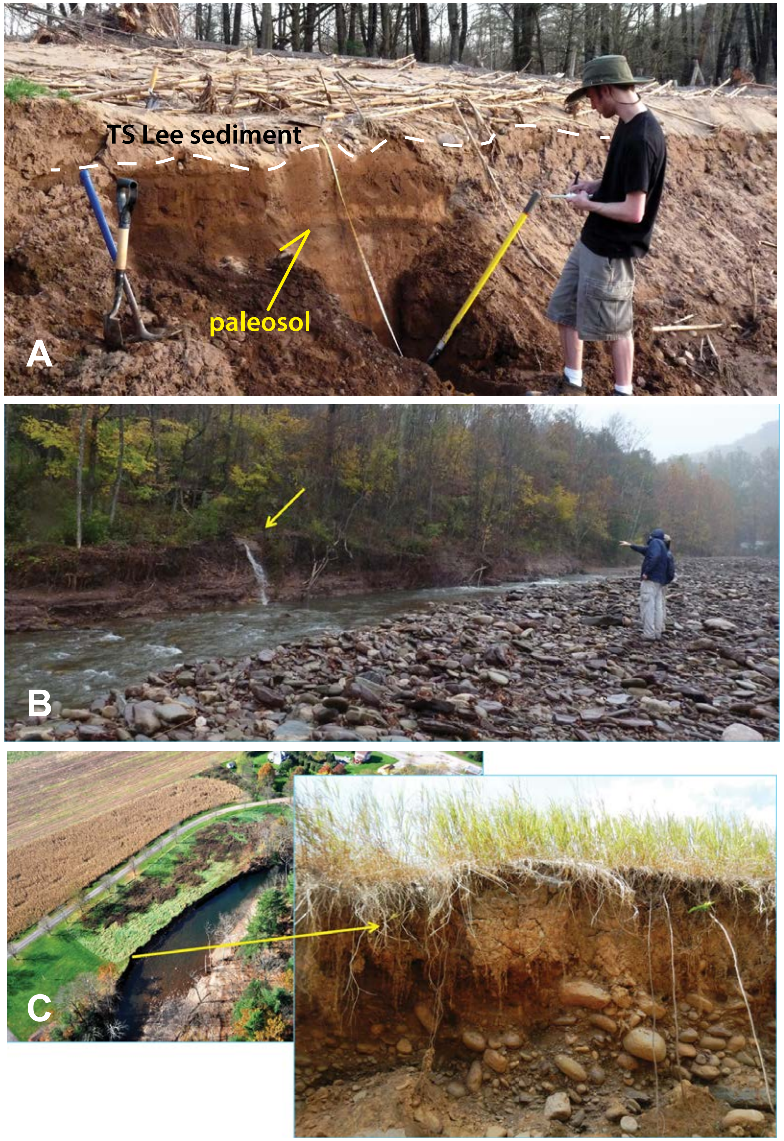


Figure 4. Geomorphic evidence of the recurrence interval for the Tropical Storm (TS) Lee flood. (A) Paleosol (arrow) dated as 2490 ± 30 ^{14}C yr B.P. in Holocene flood sediments buried by TS Lee sediments. (B) Tributary alluvial fan (see arrow) in upper Muncy Creek, truncated by the TS Lee flood with sediments near its center dated as 500 ± 30 ^{14}C yr B.P. (C) Pleistocene terrace along middle Fishing Creek eroded by TS Lee flood. Note the well-developed blocky ped structure and orange color in the B-horizon. Height of the exposure shown here is ~2 m.

Chute and Chute-Bar Formation

Incision of channels across the insides of meander bends to form chutes and chute-bar complexes was one of the most common and dramatic geomorphic changes in these gravel-bed streams in north-central Pennsylvania during the TS Lee flood (Figs. 6–9). Chutes were cut into Holocene floodplains and Pleistocene terraces as the fluvial systems adopted a multithread pattern during high flow with a much-reduced sinuosity within their valleys. Figure 6 (inset) illustrates valley straightening where the upstream portion of the constructed berm was breached. A large chute (600 m long × 30 m wide) was eroded across the floodplain to the right of the farm buildings (standing water occupies part of the chute in the photo). A broad chute bar deposited sand and gravel across the entirety of the farm fields downstream of the chute before the flood channel reconnected with Muncy Creek at the downstream part of this bend. Some chutes were reactivated from preexisting chutes cut off from the main channel for decades by artificial berms (Figs. 6 and 9) and others cut new channels into previously undisturbed terraces (Fig. 7–9). Chute incision averaged 2 m while deposits downstream and lateral to the incised reach commonly exceeded 1 m (Figs. 7 and 8). Most chutes were partially backfilled with imbricated gravel during waning stages of the flood (Figs. 8A, 8C). Deposition on floodplains and terraces was mostly gravel; however, there were significant deposits of sand at some locations (Figs. 7 and 8). Sand thickness along the right flank of the lower Loyalsock Creek chute complex shown in Figure 7 averaged >1 m thick. Gravels vary in size between sites, but they are typically in the cobble to boulder size range. Chute gravels displayed well-developed imbrication and clast support at their surfaces. Grain size typically decreased in the downstream direction along the axes of chutes. In some cases, the decrease in gravel size was dramatic where chutes formed after catastrophic failure of artificial berms constructed along the main channels, resembling a pattern commonly seen in breakout floods from ice dams or jokulhlaups (i.e., Maizels, 1997) (Figs. 9D, 9E). Figure 9E illustrates this dramatic reduction in grain size along a chute formed on Loyalsock Creek near Hillsgrove. Grain size did not appear to vary across chute bars transverse to the channel axis; however, grain size decreased downstream along the chute axes (Muhlbauer, 2013).

Chute and chute-bar complexes are characteristic geomorphic features of gravel-bed streams (Church, 1983; Miall, 1996; Nanson and Knighton, 1996). Interpretations of preflood lidar and aerial photography suggest that chutes were common along these streams prior to the construction of artificial berms that were designed to confine channels to single-thread systems (Fig. 9C).

Floodplain Sedimentation and Erosion

In sharp contrast to geomorphic response to other historical large-magnitude floods in Pennsylvania (i.e., Moss and Kochel, 1978), modification of floodplains by erosion and deposition was significant during the TS Lee flood. Sand and gravel deposits ranging from a few centimeters to >1 m were common along large reaches of the streams studied. In some locations, gravel ramps facilitated tractive movement of coarse gravel onto floodplain surfaces.

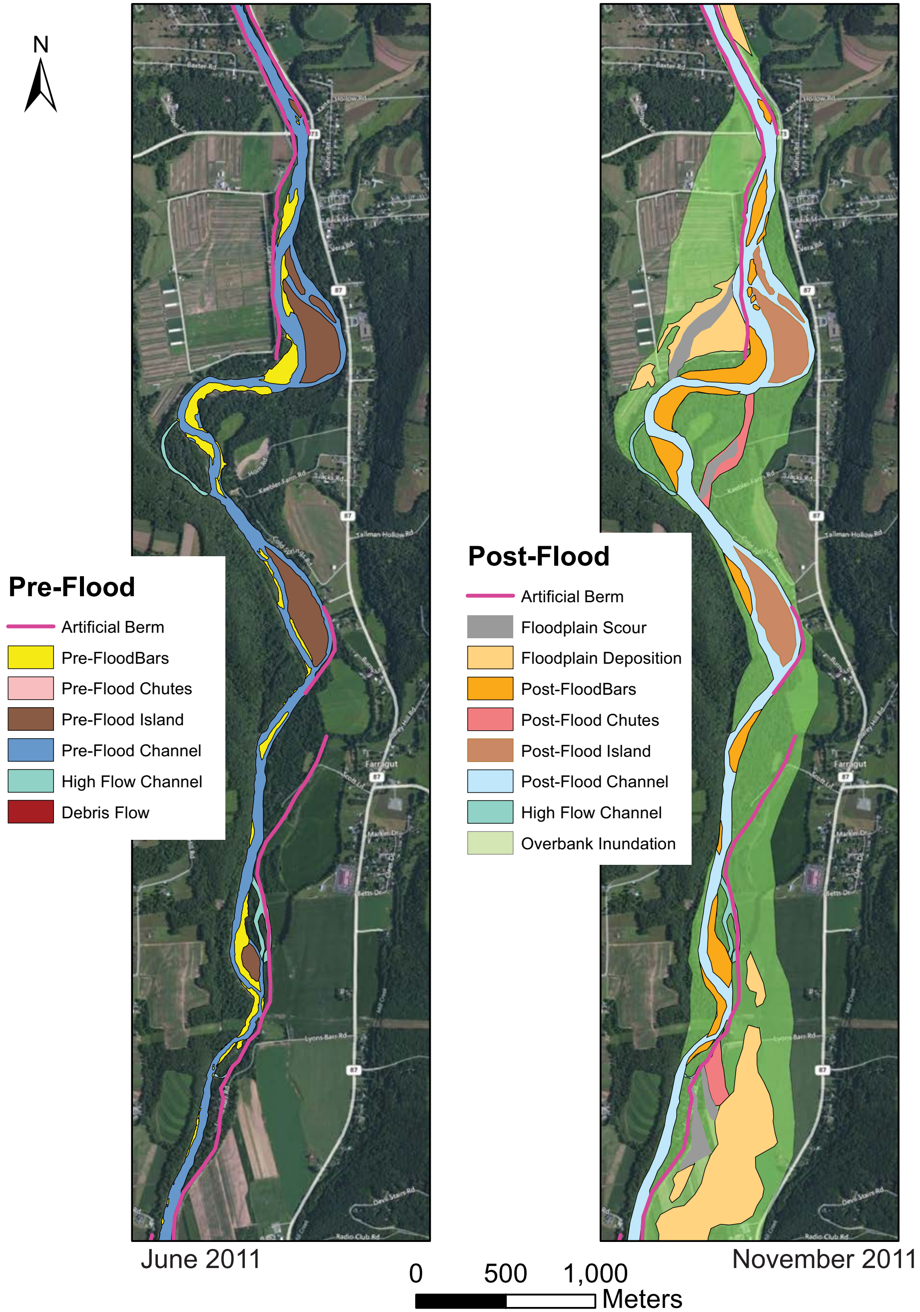


Figure 5. Example of geographic information system (GIS) based flood geomorphic mapping along lower Loyalsock Creek. Note the alternation between stable and disequilibrium reaches as well as the large-scale disruption of floodplain-terrace systems by chute scour and floodplain deposition. GIS-based flood geomorphic mapping for the 3 watersheds most affected by the flood (~250 km of stream channel) can be found in Supplemental Files 1, 2, and 3.

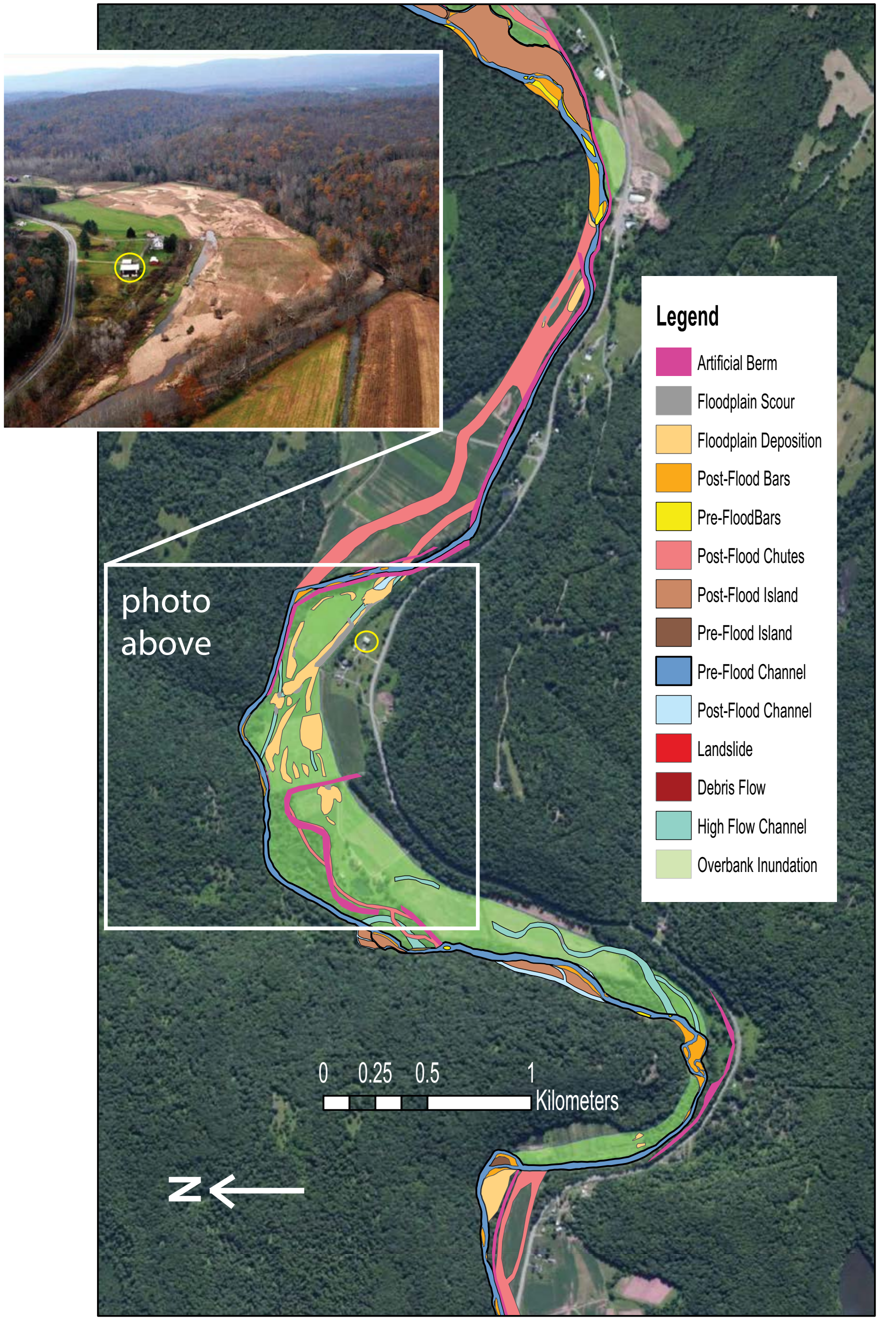


Figure 6. Example of flood geomorphic mapping along central Muncy Creek. Downstream is toward the bottom (west). Note the chute scour and destruction of farms where valley-wide inundation occurred. The inset photo shows a view downstream of the reach boxed in white on the map. The yellow circle shows the same barn on the map and inset photo.

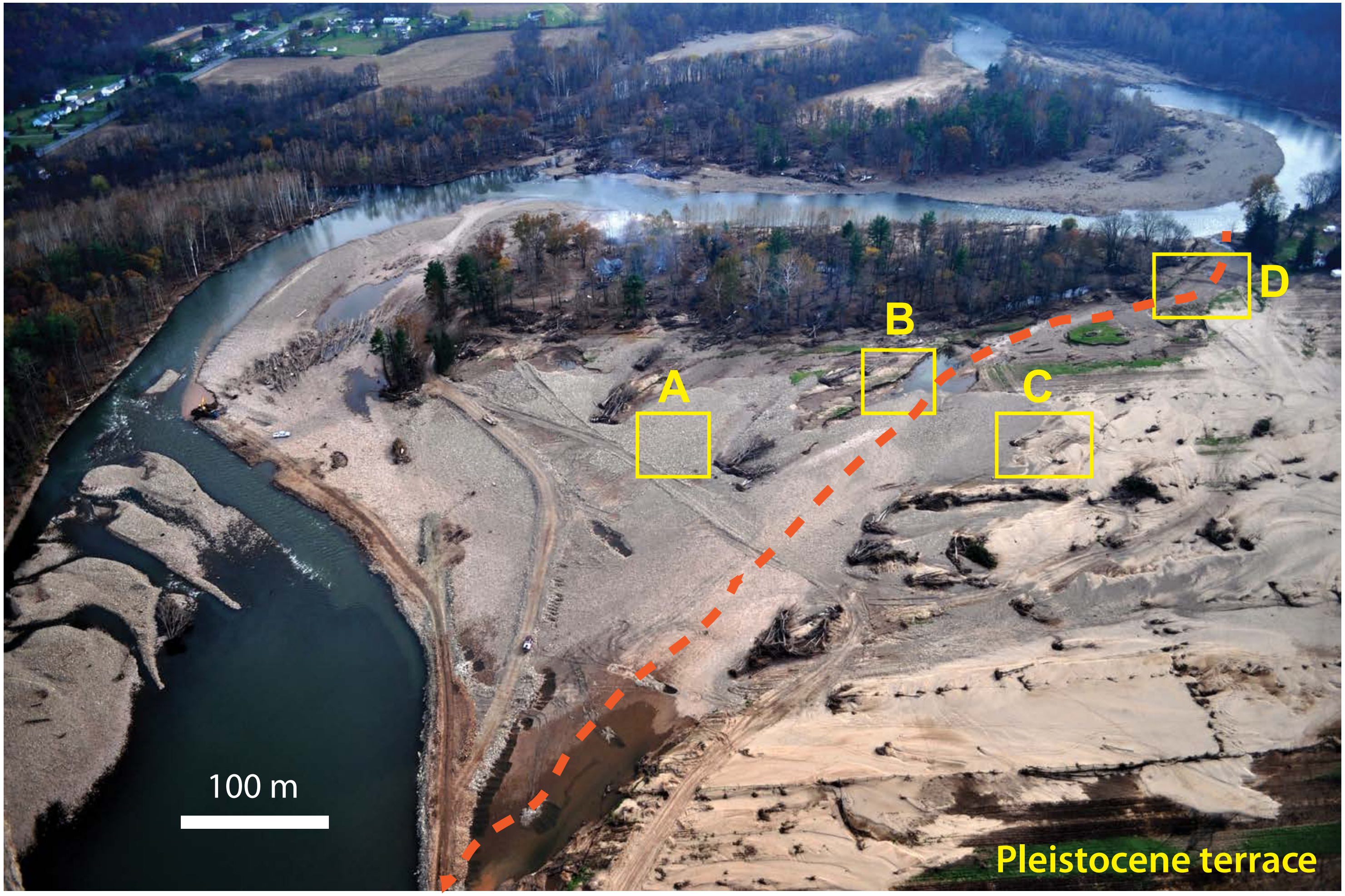


Figure 7. Oblique aerial photo of chute complex along lower Loyalsock Creek near Loyalsockville. Yellow boxes are ground views shown in Figure 8. Red dashed line is the axis of the new chute eroded by the flood. Note white trucks and backhoe along right bank in the left portion of image where mining of flood gravel is occurring along that section after the flood.

In many locations, however, gravel to small cobbles were observed scattered on floodplains, apparently deposited from suspension. No evidence of erosion from tractive transport processes was observed at these locations. Sand waves were common on floodplains, particularly in areas where flow was slowed by trees, artificial structures, or tree jams. In these areas, it was not uncommon to see >1 m of sand and gravel deposited on floodplains (Fig. 10A). Sand and gravel appeared to have been transported downstream except where flow velocity was somewhat reduced. Downstream transport of sand was measured on the West Branch Susquehanna River at Lewisburg (~50 km downstream from Williamsport), where a peak suspended sediment concentration of 941 mg/L was measured using a P-48 depth-integrated sampler with a 15 kg Columbus weight suspended from the bridge. Flow velocities averaged 4 m/s were measured using a SonTek RiverSurveyor and compared with discharge measurements collected by the U.S. Geological Survey at the same location. From these data we estimate 427,000 T of suspended sediment were transported by Lewisburg in 24 h. Notable was an unusually high concentration

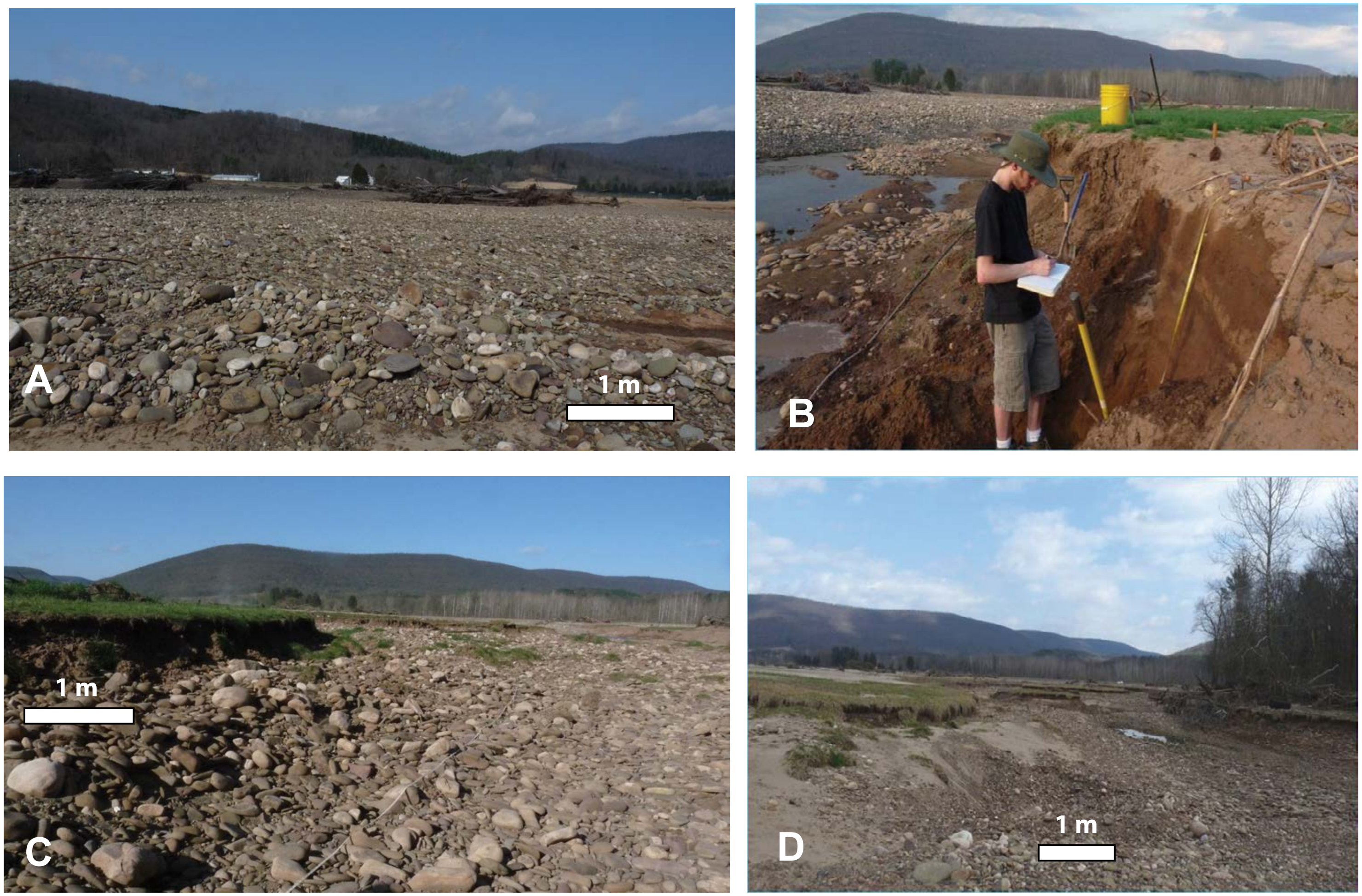


Figure 8. Ground views of the Loyalsock Creek chute complex from Figure 7. (A) View along axis of chute channel filled with ~2 m of imbricated flood gravel. (B) Upstream portion of chute, showing Holocene flood stratigraphy (Tropical Storm Lee sediment is the light colored sand at the top, burying the corn stalks). (C) View upstream within the chute of steep, unstable margins of the chute edge eroded into the Pleistocene terrace. (D) View upstream showing deep scour within lower reach of the chute near where it rejoins Loyalsock Creek.

of sand in suspension, visible in surface eddies and sand boils on the West Branch Susquehanna River. The sand volume during the TS Lee flood was dramatically higher than that of floods sampled during recent floods of similar or higher discharge at Lewisburg. We interpret this unusual sand load in the river as having been sourced by extensive erosion of the channel bed, banks, and floodplain in upstream tributaries flowing out of the Appalachian Plateau.

In addition to the large chutes, other channels were eroded into early Holocene and late Pleistocene outwash terrace surfaces, exposing well-developed soils. Soils on these eroded terraces are characterized by well-developed blocky and prismatic structure, significant clay, and reddish-brown colors (7.5 YR 4/3). These smaller channels, averaging >1 m deep and 10–25 m wide, were eroded into floodplains (Fig. 10B), resulting in the development of a multithread pattern during flood flow that often spread across the entire expanse of valley bottoms. These channels were also eroded into unconsolidated late Holocene sediments that had insignificant soil development.

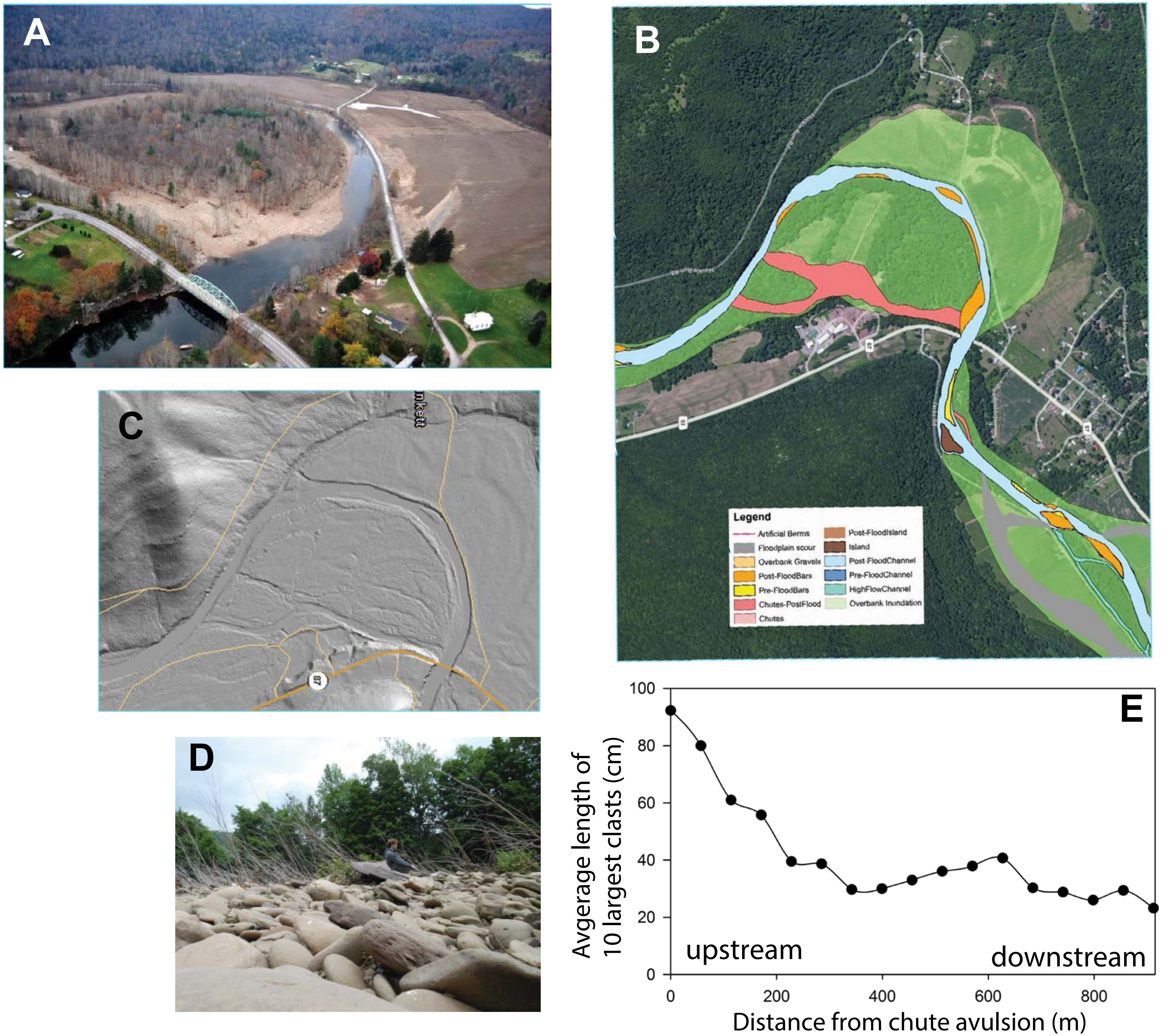


Figure 9. Hillsgrove chute complex on central Loyalsock Creek. (A) Oblique aerial view of the chute. (B) Geomorphic map. (C) Preflood lidar (light detection and ranging) image showing berm and paleochute. (D) Ground view of imbricated gravel in the upstream portion of the chute (flow from right to left). (E) Surface grain-size variation along chute axis.

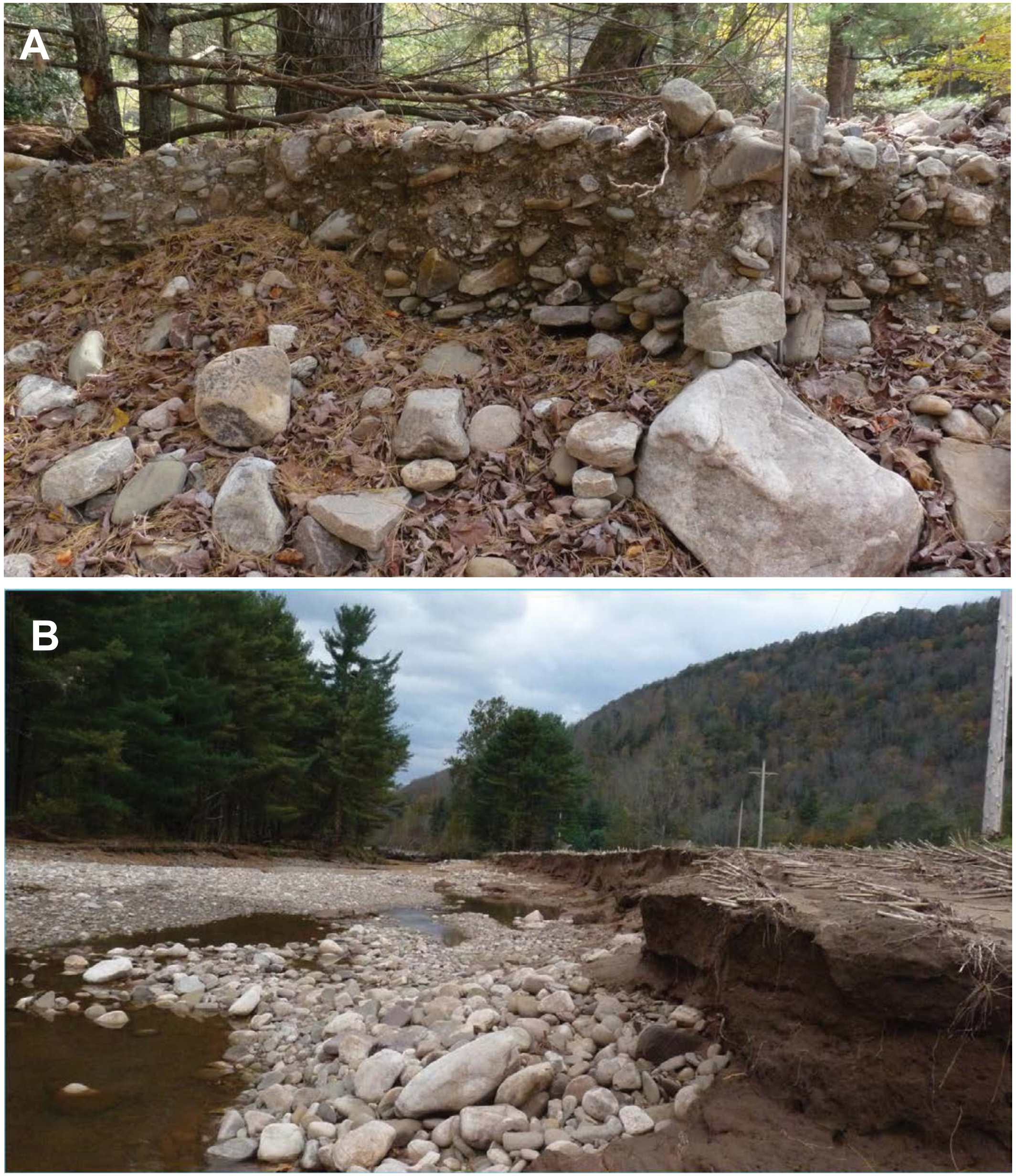


Figure 10. Floodplain deposition and erosion. (A) Floodplain sedimentation upstream of tree jam at avulsion site along lower Big Bear Creek, tributary to Loyalsock Creek. Note the abundance of matrix in the sediment. Bar is 1.5 m high. (B) 30-m-wide chute channel eroded into farm field in Loyalsock Creek floodplain south of Forksville (view upstream).

Gravel Bars and Gravel Transport

Enormous volumes of gravel (mostly cobble to boulder size) were deposited as large gravel bars. Detailed GIS mapping from preflood and postflood aerial photos (see Supplemental Files 1, 2, and 3) showed that preexisting point bars grew significantly, new point bars formed in some locations, mid-channel bars formed in disequilibrium zones along the channels, and massive chute-bar complexes were formed along numerous bends. Gravel bars formed in all tributaries, with lengths to 200 m, widths to 30 m, and average thickness of 2 m (Fig. 11). Bars are composed of well-imbricated coarse-grained cobbles and boulders with intermediate diameters to 1.7 m (see Table 2). Gravel bar surfaces typically accreted to the elevation of adjacent floodplains, and in some cases above the floodplain, thereby accelerating the erosion of channel banks and promoting avulsion onto floodplains (Fig. 12). In many cases, straightening of channel reaches associated with bank erosion and avulsion resulted in postflood bar morphology that would be more appropriately referred to as alternate bars instead of point bars (Fig. 11A). Local knickpoints, with headcuts to 2 m, formed at riffles between the alternate bars where the coarsest boulders were deposited (Fig. 11D). These knickpoints have armored the channels from further adjustment until a discharge of similar magnitude occurs, thereby making it unlikely that adjustments in channel configuration will recover to preflood patterns anytime soon. A significant geomorphic threshold (Schumm, 1973) appears to have been crossed during the flood, best described as a shift from a single-channel meandering pattern to a multithread pattern with significantly higher width/depth ratio and lower sinuosity.

Surface gravels on the bars are generally well imbricated and are clast supported. Excavations along the edges of gravel bars revealed a distinctly different sedimentology with depth. Gravels typically coarsened upward with the surface containing the coarsest fraction (Fig. 13). Gravels below the surface were finer, typically matrix supported, and generally did not show fabric or imbrication. Typical fining-upward sequences common to point bars (Bernard et al., 1970; Miall, 1996) were not observed at any of the gravel bars visited in our field surveys. Overall, there exists a distinctive bimodality in grain size in gravel bar sediments.

Postflood field surveys show that peak flow depths were <2 m above the bar surface when the coarsest surface gravels were deposited. Reconstructed peak flow velocities ranged from 2.2 to 6.7 m/s (Table 2). Flow depths directly observed by residents and others estimated from high-water marks measured in the field after the flood were consistently much lower than would have been predicated for transporting clasts on the bar surfaces by tractive forces using paleoflood techniques described in Costa (1983) (Table 2). In most cases, peak flows were between 0.5 m and 1.6 m deep over the bar surfaces. These observations are consistent with sediments deposited by hyperconcentrated flow processes, particularly in a model similar to that described by Pierson (2005), where a lower layer of hyperconcentrated flow could exist below the more turbulent tractive flow higher in the water column. Field settings where hyperconcentrated flows were particularly common occurred below tree-jam dams and small landslide dams where floodwater was temporarily impounded, followed by catastrophic breakout as these dams failed (see Fig. 10A). Hyperconcentrated flows are not common in watersheds this large, particularly in the eastern USA; the interpretations here emphasize the magnitude of the sediment transported by the TS Lee flood.

Detailed geomorphic mapping of gravel bars can be used to provide a semiquantitative estimate of gravel volume transported by the flood and to look for spatial patterns in the deposition (see Supplemental Files 1, 2, and 3). Areal dimensions of the new gravel deposits were estimated from low-altitude aerial photos using GIS. Field surveys of dozens of bars suggest that a reasonable average thickness is ~2 m. We applied this estimate of average thickness to obtain an approximation of gravel volume deposited by the flood (Table 3). Approximately 6,700,000 m^3 of gravel were transported along over 200 km of channel, yielding an average rate of 33,500 m^3/km. This sediment does not imply denudation, but represents the remobilization of stored sediment. However, to put this into perspective, if the volume was integrated over the basin area, it would be equivalent to a basin-averaged denudation of 3 mm. If all of this sediment was exported from the 4 watersheds, it would represent ~18,000 yr of average annual denudation for the Mid-Atlantic watersheds based on a composite average of regional denudation studies (Judson and Ritter, 1964; Sevon, 1989; Portenga and Bierman, 2011). Obviously, most of the gravel remains in bars within the watershed, thus there is not a direct correlation between gravel transported during the flood and regional denudation; however, it shows that the magnitude of sediment moved during TS Lee was significant.

Spatial patterns in the distribution of volume of gravel deposited by the TS Lee flood are shown in Figure 14 for Loyalsock, Muncy, and Fishing Creeks. Significant increases occurred in the volume of gravel bars along the entire length of the study reaches. Preflood moving averages show peak zones of bar gravel. Gravel appears to be moving through these watersheds in distinctive pulses. Postflood moving averages of gravel volume show that these pulses migrated downstream during the flood. The spatial pattern of these gravel pulses varies between watersheds. The largest gravel pulse in Fishing Creek occurs in the upstream reach, while the largest pulse in Loyalsock Creeks is in the downstream reach. Gravel pulses along Muncy Creek are distributed more uniformly along its channel. Although not shown here, gravel distribution in Lycoming Creek watershed also occurs in pulses concentrated in the upper reaches of the watershed, similar to that shown for Fishing Creek. The spatial variations in gravel distribution between watersheds reflect a complex response phenomenon (Schumm, 1973, 1981). These streams may be undergoing nonsynchronous multiple phases of gravel mobilization related to differences in recent flood history and geomorphic response between watersheds.

Cumulative gravel bar area was plotted along the mainstream channels in an effort to determine whether flood gravels were sourced from channel and bank erosion or from headwater sources through tributaries (Fig. 15). In several locations there are distinctive increases in cumulative gravel (Fig. 15; steps in the red line) that coincide with tributary junctions (green arrows in Fig. 15).

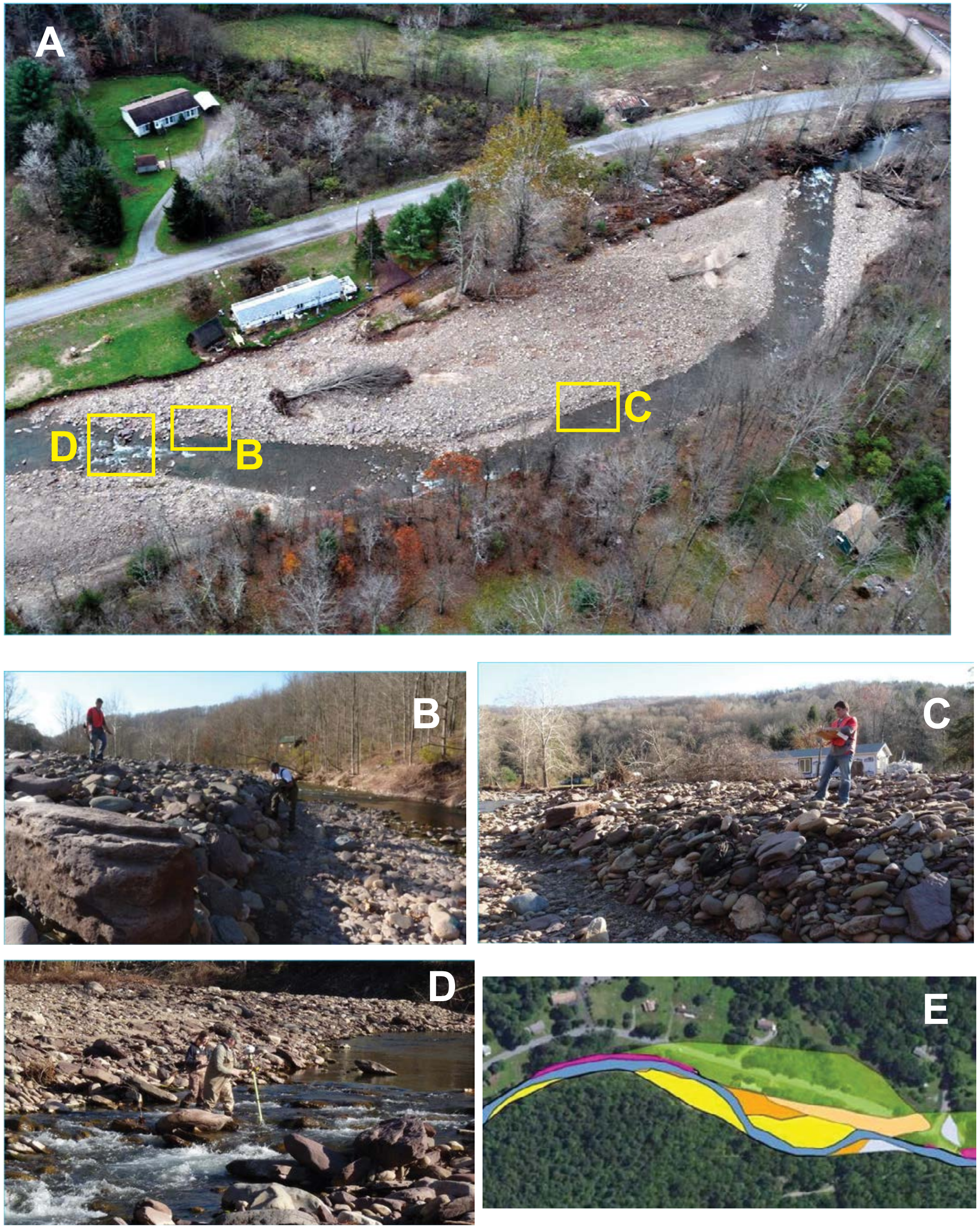


Figure 11. Flood gravel bar in upper Muncy Creek near Sonestown. Yellow boxes inset into A show locations for B–D. (A) Aerial view. (B) Ground view of gravel bar showing coarse grain size. (C) Gravel bar showing imbrication. (D) New knickpoint at upstream end of bar. (E) Geomorphic map (see Fig. 5 for legend).

TABLE 2. HYDRAULIC ESTIMATES AT PEAK FLOW FROM FIELD BAR SURVEYS

Bar Location	Average. 10 largest intermediate clasts (cm)	Approximate bar thickness (m)	Water depth above bar (m)	Channel gradient	Estimated peak velocity* (m s^{-1})	Estimated depth* (m)	Estimated unit stream power (W m^{-2})
Muncy Creek. upstream	84	2.0	0.78	0.0221	4.8	3.2	576
Muncy Creek above Lund 1	74	2.0	1.67	0.0159	4.5	2.2	514
Muncy Creek Lund Bar	82	2.0	1.57	0.0136	4.7	2.6	560
Muncy Creek Covered Br.	74	2.2	1.49	0.0137	4.5	2.3	956
Muncy Creek Ski Lodge	67	2.0	0.89	0.0115	4.3	2.2	831
Muncy Creek Gavitt Site	51	2.2	1.44	0.0010	3.7	1.5	777
Fishing Creek Popp Bar	77	2.0	1.30	0.0140	4.6	2.4	442
Fishing Creek Elk Grove Br.	88	2.0	0.56	0.0209	4.9	2.0	915
Fishing Creek Elk Grove Store	47	2.0	0.55	0.0085	3.6	2.0	833
Fishing Creek Zac Bar	17	1.5	1.7	0.0065	2.2	1.0	554
Loyalsock Creek Worlds End	167	1.8	0.55	0.0125	6.7	7.0	638
Loyalsock Creek Forksville	58	2.3	0.83	0.0075	4.0	2.2	778
Loyalsock Creek Rinker Farm	28	2.2	1.95	0.0105	2.8	1.3	997

*Velocity and depth using average of techniques in Costa (1983).

However, other gravel increases appear to be unrelated to tributary inputs (see especially the large steps on the cumulative plot in lower Loyalsock Creek; Fig. 15B). For example, there are significant steps at the entry of Elk Creek and Big Bear Creek to Loyalsock Creek, but other significant steps appear at locations unrelated to tributary entry positions. The absence of an abrupt increase in gravel volume where many tributaries enter mainstems could be interpreted as evidence for limited gravel sourcing from the tributaries. In contrast, however, field observations in the tributaries (especially headwaters regions) show significant bank erosion, channel widening, and gravel transport (Fig. 16A). In several places on both the tributaries and mainstems, we observed vertical instability by bed scour down to bedrock. The lack of sharp increases of gravel at the mouths of tributaries may simply indicate that much of the gravel emanating from tributaries was transported farther downstream in the mainstem. Bed and bank sources along the mainstems were also important contributors to the supply of gravel to downstream reaches of the main channels. Mainstem bank erosion was common at many locations, sometimes to an extraordinary degree (see Figs. 16B and 17). Low terraces and floodplains composed of gravel were heavily eroded at many locations along the affected stream channels. It appears that gravel was sourced from bed and bank erosion of the mainstem as well as tributary channels.

Bank Erosion and Increases in Active Channel Width

Bank erosion and channel widening were common throughout the study region, but were especially extensive in the tributaries and headwater regions. Bank materials throughout the headwater region are predominantly gravel derived from sandstone and shale or Pleistocene glacial sediments, both having relatively low cohesion. Figure 16A shows an example where >100% widening occurred. Areas where extensive widening occurred typically resulted in the destruction of a recently formed low terrace-floodplain lacking soil development. Increases in active channel width, defined as the entire extent of channels inundated during flood flow, were substantial along these streams, as shown in the example from Loyalsock Creek (Fig. 17). Reaches with exceptionally large increases occurred in locations where artificial berms and a variety of grade control structures had been constructed.

Reconnection of Low-flow Channels to High-flow Floodplain System

One of the most dramatic geomorphic adjustments resulting from the TS Lee flood was breaching of historic artificial berms and reconnection of low-flow active channels to abandoned high-flow floodplain channel systems. Prior to historic berm construction (before 1850) these gravel-bed rivers exhibited a multithread channel pattern, particularly during flood flows. This channel pattern is readily evident in the field and from inspection of preflood lidar images (Figs. 18 and 19) and historic photos archived in the Thomas T. Taber Museum of the Lycoming County Historical Society in Williamsport, Pennsylvania. For example, one historical berm along Muncy Creek (Fig. 18C) shows prominently as a reflective line in along the left bank of the channel in the lidar image (Fig. 18B). Figure 19 illustrates a similar pattern along a reach of Loyalsock Creek just south of Forksville. The artificial berm, shown in the geomorphic map (Fig. 19B, red line) and appearing as a bright reflective line in the preflood lidar image (Fig. 19C), was breached at two locations. Once the berm was breached it resulted in the reconnection of the main channel with the high-flow multithread system on the floodplain–valley floor.

Figure 12. Examples of bar aggradation filling channels above floodplain surface. (A) Bar in upper Fishing Creek near Elk Grove. (B) Fill and channel avulsion onto floodplain in Little Bear Creek, tributary to Loyalsock Creek, near Barbours.

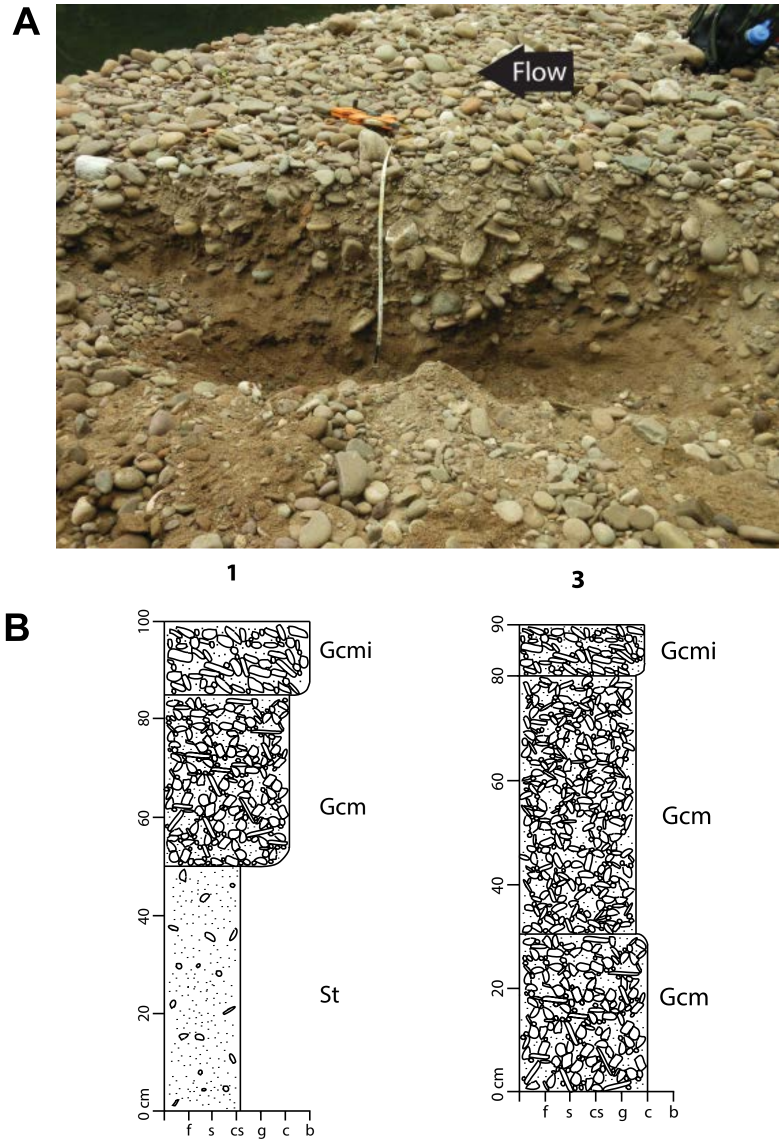


Figure 13. Coarsening-upward gravel facies on chute bar on Loyalsock Creek near Hillsgrove. (A) 1-m-deep pit showing upper imbricated gravel with finer, matrix-rich sediment below. (B) Generalized facies diagram showing inverse grading common on bars deposited by the Tropical Storm Lee flood (Muhlbauer, 2013). Lithofacies: Gcmi—massive, clast-supported, and imbricated gravel; Gcm—massic, clast-supported gravel; St—medium to coarse sand with pebbles.

TABLE 3. ESTIMATED GRAVEL TRANSPORT VOLUME, TROPICAL STORM LEE FLOOD

Stream	Gravel volume transported (m^3)	Gravel transport (m^3 km^{-1})
Lycoming Creek	400,600	14,837
Loyalsock Creek	3,975,200	54,830
Muncy Creek	975,200	19,740
Fishing Creek	1,349,500	25,224

Enhanced incision of floodplain channels occurred during the flood in part because of the break-out nature of the flows when the artificial berm was breached. Eyewitness accounts at this site noted that standing waves on the water surface over the floodplain exceeded 2 m during the flood peak, resulting in substantial shear stress on the floodplain surface. Figure 10B shows a ground view of the channel eroded at site F in Figure 19A. Reactivation of multithread floodplain channel systems that were historically disconnected from mainstream channels was repeated at many locations along the study streams. In all cases, the pre-berm channels were readily visible on lidar imagery. In essence, the TS Lee flood removed the berm barrier and now the channels will likely remain in a protracted phase of adjustment as they return to a multithread pattern. As a result of this threshold-crossing event, gravels will probably be mobile for many decades.

Headwater Regions

Headwater regions of the affected watersheds underwent significant geomorphic changes characterized by shallow landslides, extensive channel widening and bank erosion, channel avulsion, and activation of alluvial fans. Although the headwater regions have steep slopes, debris flows were not common. A few small debris flows were observed in upstream reaches of Fishing Creek and Muncy Creek, but were not important to the supply of gravel to the main channels. In contrast, shallow landslides were common in headwater tributaries of most watersheds, particularly within the limits of late Pleistocene glaciation. Bank erosion and channel widening was extreme along many headwaters reaches in tributaries. Noncohesive bank sediments were readily peeled back by high-velocity gravel-laden flood flows, leaving drapes of the root-matted former forest floor (Fig. 20A). In many locations, channels were excavated to bedrock during the flood (Fig. 20B).

Glacial sediments, including till, kames, and outwash, are especially unstable in these areas, resulting in several shallow planar and rotational landslides into these tributary channels (Fig. 20C). Because these regions are heavily forested, the landslides contributed large numbers of trees and sediment to the channels, often resulting in temporary damming of the stream by logs. Upstream of these temporary tree jams, as much as 2 m of accretion of coarse sediments occurred rapidly (see Fig. 10A), followed by modest breakout floods.

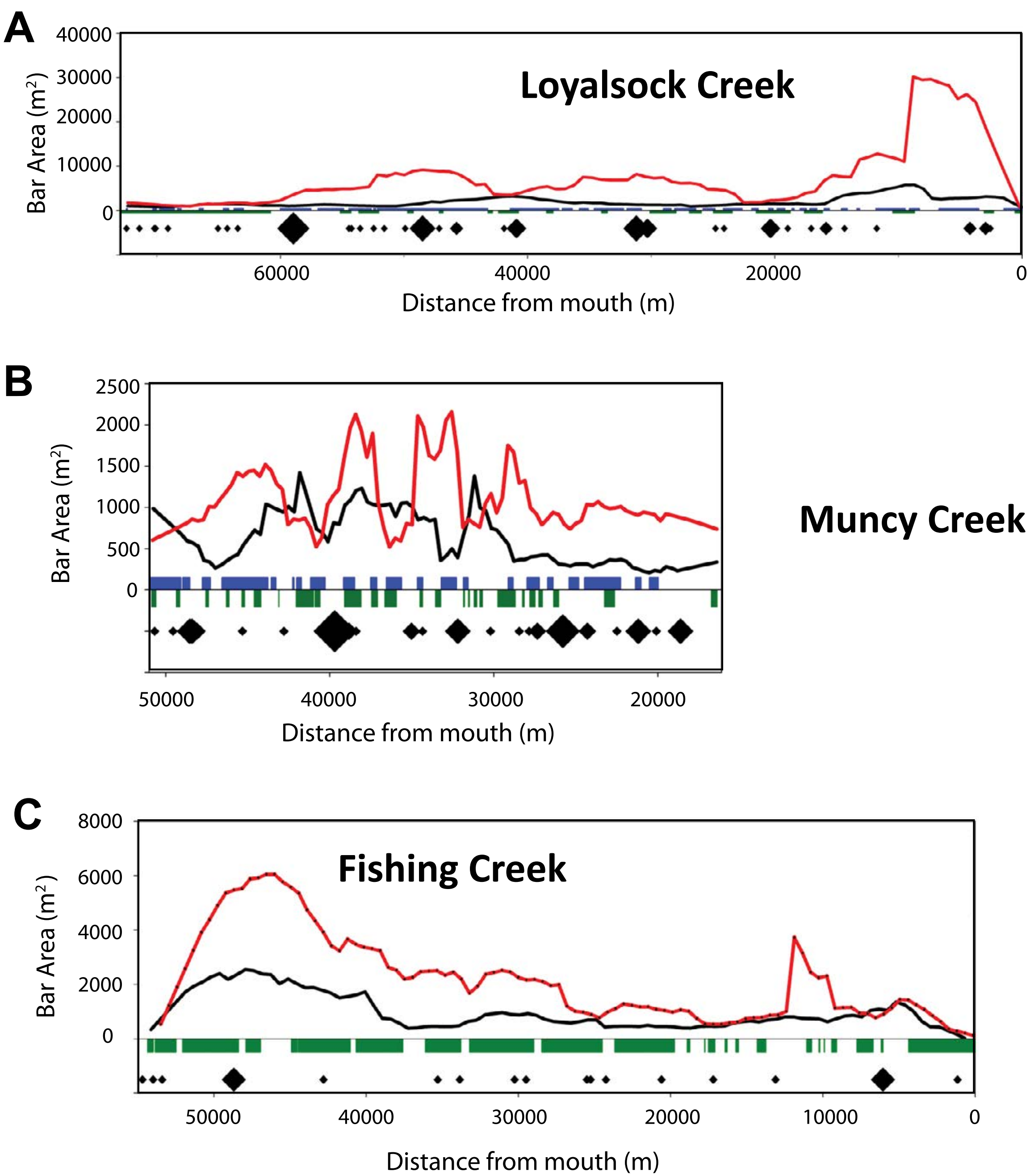


Figure 14. Spatial patterns of gravel deposition from the Tropical Storm (TS) Lee flood measured using geographic information system–based geomorphic maps made before and after the flood. Basal scale reflects distance along the channel upstream from the mouth in meters. (A) Loyalsock Creek. (B) Muncy Creek. (C) Fishing Creek. Key to graphs: black lines—preflood moving average; red lines—postflood moving average; black diamonds—locations of tributaries and their relative basin areas. Blue segments above the baseline are disequilibrium reaches; green segments below baseline are unbermed reaches. Humps in the red lines that show distinct gravel pulses and significant increases in flood bar area measured along these streams. Comparison of preflood and postflood areas shows the gravel pulses were amplified and translated downstream (to the right) by the TS Lee flood.

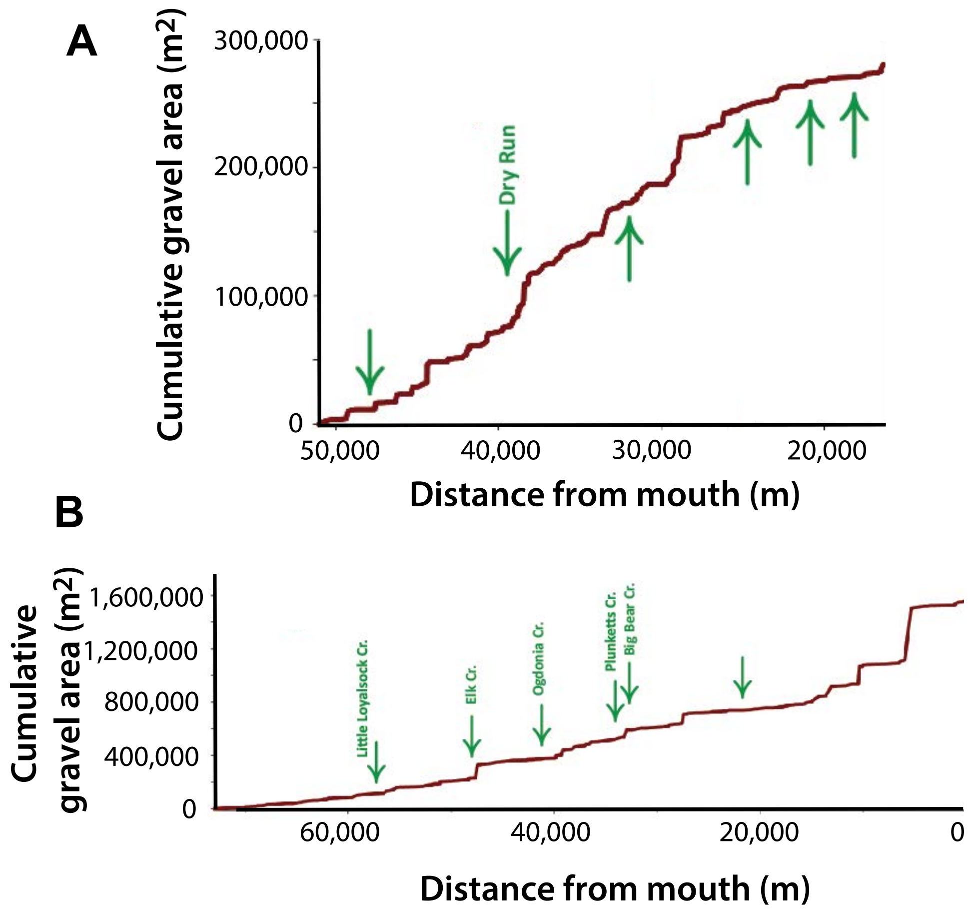


Figure 15. Gravel sources and tributary junctions. (A) Cumulative gravel area versus distance from the mouth of Muncy Creek. Green arrows show junctions of major tributaries, most of which are unnamed. (B) Cumulative gravel area versus distance from the mouth of Loyalsock Creek.

These sites typically have complex gravel terraces emanating downstream from these temporary dams. In some cases, landslide and tree-jam dams resulted in complete aggradation of stream channels above the floodplain and avulsion of the stream channel into a new location (Fig. 21). Concurrent with these avulsions there was significant floodplain erosion associated with formation of the channel in a new location.

Alluvial fans in some headwater regions received flows and activation during the TS Lee flood. Most of the active fans in the region are incised into larger Pleistocene fans and represent minor reworking of the older sediments during floods. Hyperconcentrated sediment flows were especially common on these fans. Figure 22 shows an example of the Bloody Run alluvial fan (upper Fishing Creek) activated by the TS Lee flood. Bank and bed erosion in the proximal fan and upstream contributed a large volume of cobble and boulder gravel to the Bloody Run fan. The gravel filled the active channel to ~1 m above the fan surface along a tree jam (Figs. 22C, 22D), resulting in avulsion and formation of a new channel flowing through the forest to the south of the former channel (Fig. 22E). Post-avulsion flood gravel buried trees with as much as 0.75 m of gravel and forced the new channel to flow across the forest floor and onto the primary road through the valley. Several floods since September 2011 have resulted in further extension of gravel into the forested area created by the avulsion (Fig. 22F). Similar aggradation above floodplain levels and related floodplain avulsion at tree jams on Little River, Virginia, during a 1985 flood were described in Kochel et al. (1987); the complexity of terrace surfaces and ages resulting from these kinds of avulsions were noted.

Figure 16. Examples of bank erosion and channel widening. (A) More than 100% widening along Big Bear Creek, tributary to Loyalsock Creek. Note the lack of soil on the eroded channel bank and the abundant newly exposed tree roots. (B) Collapsed guardrail and eroded highway along lower Loyalsock Creek. Note the extensive reddish soil on the eroded bank of this Pleistocene terrace.

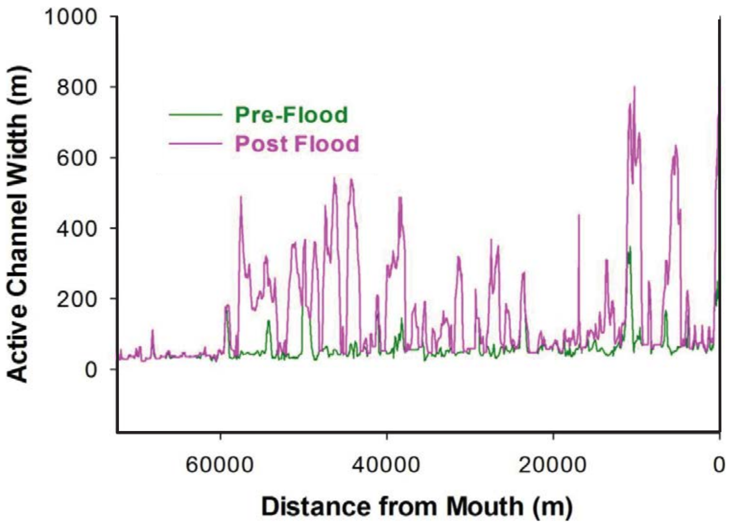


Figure 17. Example of large increases in active channel width along Loyalsock Creek. Changes were measured from comparing preflood and postflood aerial photography using geographic information system.

VARIATION IN GEOMORPHIC IMPACTS BETWEEN WATERSHEDS IN THE SUSQUEHANNA BASIN

Depending upon the physiographic setting, geomorphic response to TS Lee flooding varied considerably. In the four watersheds within the Appalachian Plateau province (Lycoming, Loyalsock, Muncy, and Fishing Creeks), geomorphic response was catastrophic, including hillslope, floodplain, and channel change. In the two Ridge and Valley–Piedmont Province watersheds (Chillisquaque Creek and Swatara Creek), geomorphic response was relatively minor with little bank erosion, lack of sedimentation, and negligible channel change. Comparison of preflood and postflood aerial photos showed no instances of measurable bank erosion or floodplain deposition. Small changes were observed in a few gravel bars along the entire length of Swatara Creek, none of which were >5% in aerial extent. U.S. Geological Survey gaging stations showed that runoff rates in the Ridge and Valley and Piedmont watersheds, where little geomorphic change occurred, equaled or exceeded those in Appalachian Plateau where catastrophic changes occurred (Table 4). Swatara Creek underwent record flooding with floodplain inundation >6 m, with negligible changes occurring to stream banks, floodplains, and hillslopes. A similar to the lack of geomorphic changes were observed during TS Agnes (June 1972), the previous flood of record for the entire Susquehanna River region (Moss and Kochel, 1978).

To help explain differences in flood geomorphic response between Plateau and Valley and Ridge-Piedmont watersheds, 1 m resolution digital elevation models were used to quantify differences in basin morphometry parameters such as area, stream order, drainage density, ruggedness number, channel gradient, and basin slope (Fig. 23). Table 5A shows the results of basin morphometric analyses. The four Appalachian Plateau watersheds have significantly higher basin slope, steeper channel gradient, and higher drainage density compared to Ridge and Valley watersheds. Ruggedness numbers (the product of basin relief and drainage density) are substantially higher for the Appalachian Plateau watersheds. In a large-scale regional study of basin morphometry and flood discharge maxima, Patton and Baker (1976) suggested that ruggedness number correlated strongly with peak flood runoff. The combination of high runoff rates with steep channel gradients likely resulted in higher flow velocity and thus higher stream power in the Appalachian Plateau streams compared to Ridge and Valley streams, similar to the observations of Miller (1990, 1995) in West Virginia and Virginia. It is interesting to note that the runoff rates predicted for Q_{max} (maximum flood flow) using equations derived from basin morphometry of gaged streams in the Appalachian Plateau of western Pennsylvania by Patton and Baker (1976) were very close to runoff rates in the four Appalachian Plateau streams during the TS Lee flood (Table 5B).

In addition, the abundance of coarse gravel in Appalachian Plateau streams resulting from the dominance of sandstone bedrock and unstable glacial sediments (leading to frequent small landslides) provided a supply of abrasive tools to the streams that enhanced erosion of less cohesive banks and bed. A large percentage of the coarse sediment that was in suspension during this flood, possibly as hyperconcentrated flow (Costa, 1988), likely increased the geomorphic effectiveness of the flood. In contrast, Ridge and Valley watersheds were not glaciated and contain much less exposed sandstone. Bedload tends to be significantly finer and banks appear to be much more cohesive in Ridge and Valley and Piedmont streams. Geomorphic change was dramatically less in Ridge and Valley watersheds with lower channel gradient, lower stream power, lack of bedload, and more cohesive banks. Moss and Kochel (1978) noted similar distinct differences in the response of channels and banks in steeper headwater tributaries underlain by sandstone compared to downstream reaches of the Conestoga River, where gradient was lower and bank materials more cohesive in areas underlain by shale and carbonate rocks.

FLOOD GEOMORPHIC CHANGES AND LINKS TO LAND-USE HISTORY

These dramatic differences in geomorphic response to flooding from TS Lee between Plateau watersheds in north-central Pennsylvania compared to the Valley and Ridge basins cannot be explained entirely by differences in bedrock geology, Pleistocene history, and basin morphometry. Consideration must also be given to the extensive impact of basinwide clearcutting in the four Appalachian Plateau watersheds (Lycoming, Loyalsock, Muncy, and Fishing Creeks) between 1850 and 1920.

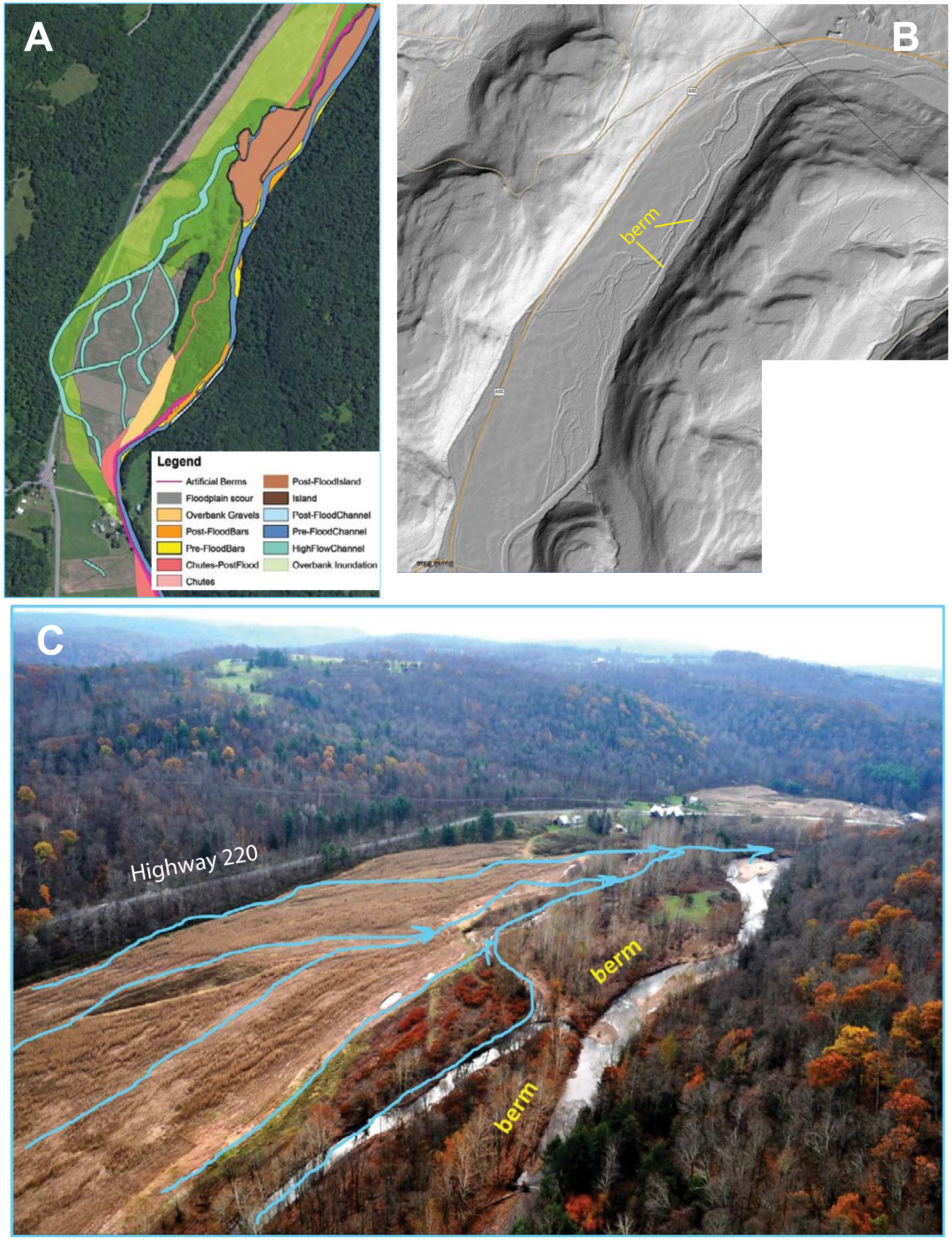


Figure 18. A reach along Muncy Creek with multithread channels. (A) Geomorphic map. (B) Preflood lidar (light detection and ranging) hillshade showing multithread channels on the floodplain disconnected from the low-flow channel by the artificial berm (bright white along the channel–yellow arrows). (C) Postflood view showing the multithread channel system activated during the Tropical Storm Lee flood when the berm was breached.

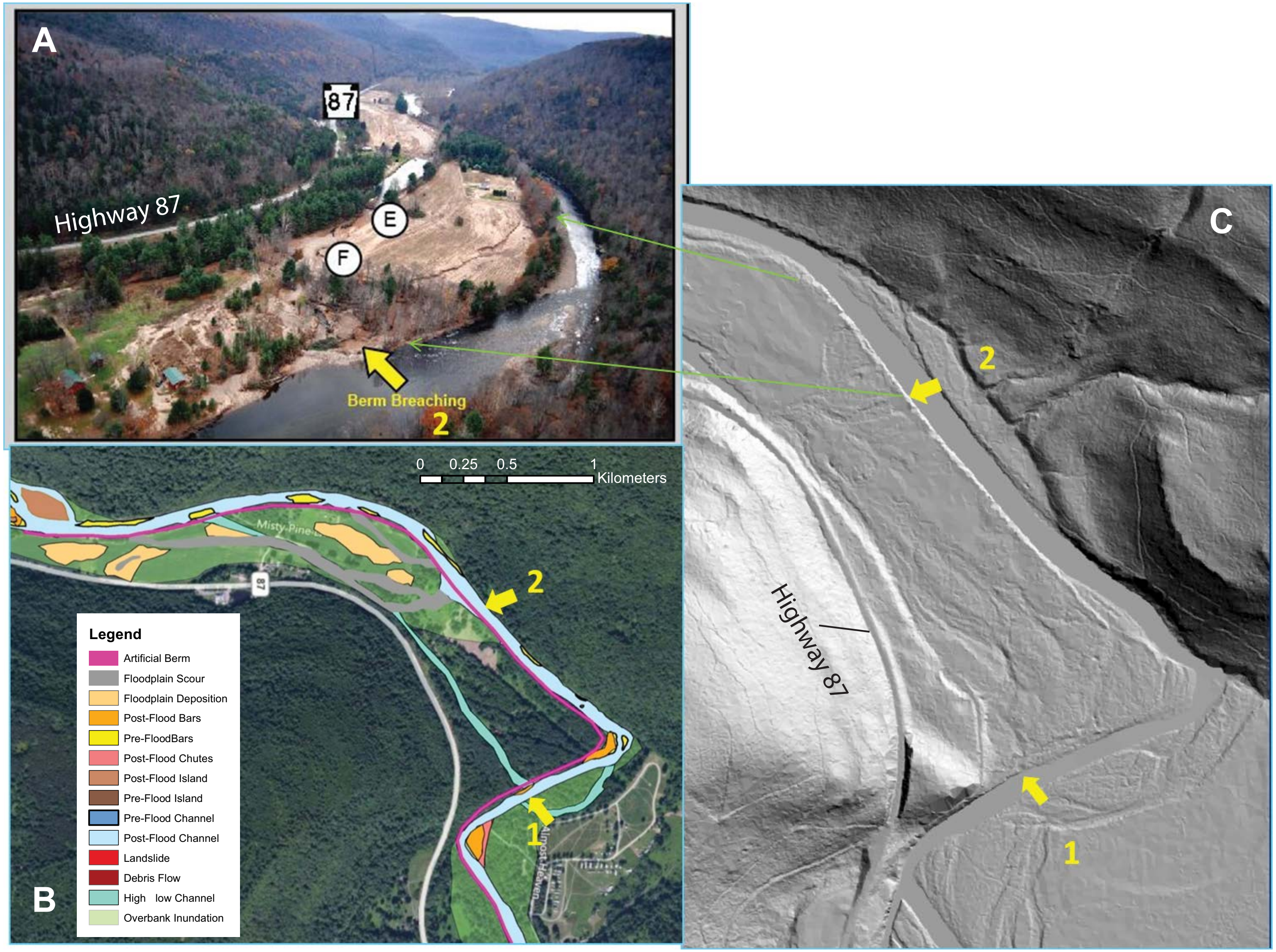


Figure 19. South Forksville bend of Loyalsock Creek with berm breaches (sites 1 and 2) and floodplain reconnection. (A) Postflood aerial view looking downstream. The lower breach in the berm is shown by the arrow at site 2. Note the extensive floodplain sedimentation and erosion that occurred here. The channel eroded into the floodplain at site F is shown in Figure 10B, while gravel was deposited on the floodplain downstream at site E. (B) Geomorphic map showing the two major breaches in the berm and floodplain impacts. (C) Preflood lidar (light detection and ranging) hillshade showing multithread channels on the floodplain that were disconnected by the berm (berm shows as bright line). Locations of the two berm breaches are shown by the yellow arrows.

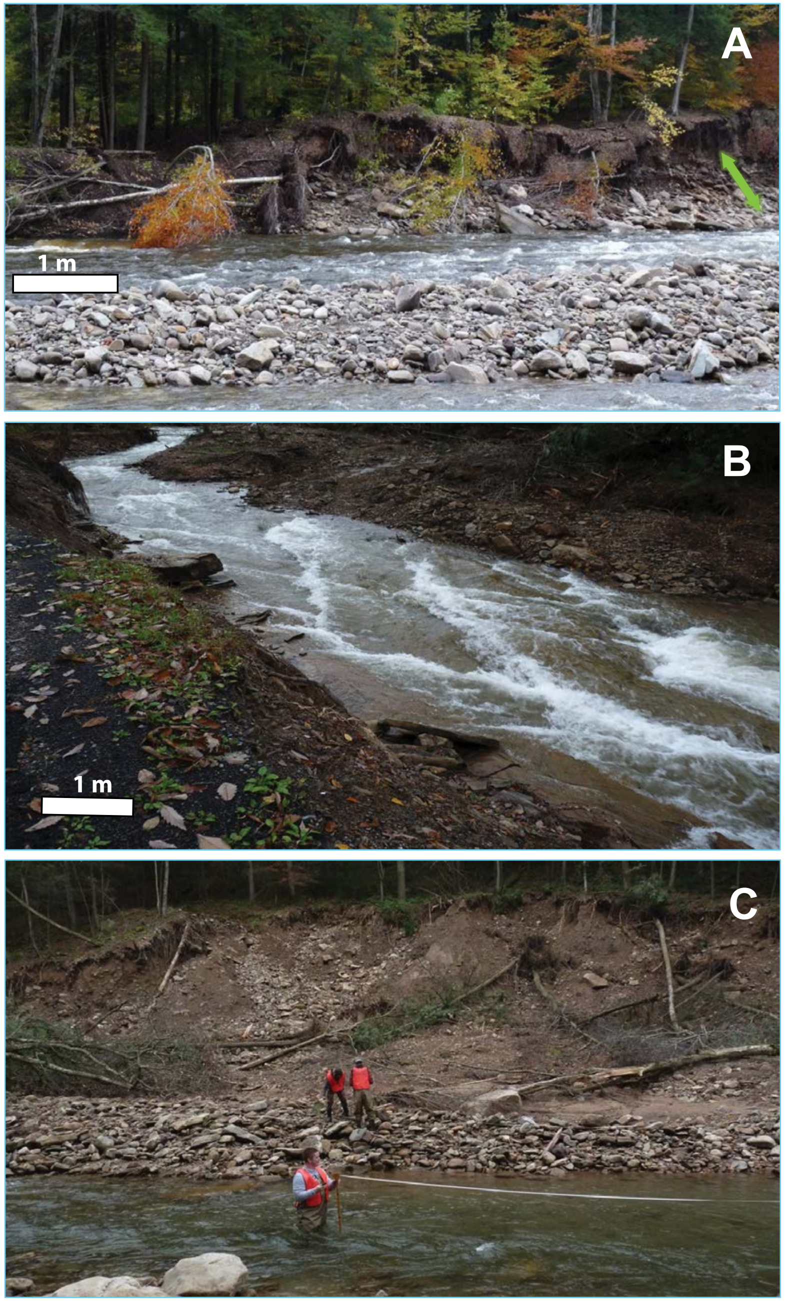


Figure 20. Examples of bank erosion in headwater regions (Big Bear Creek). (A) Root mat drape from the former forest floor was exposed as banks were cut back. (B) Incision down to bedrock. Foam lines occur along bedrock joint trends. (C) One of many shallow landslides and tree jams.

These watersheds were completely clearcut (most within a few decades), resulting in significant erosion of steep, unstable hillslopes delivering sediment to downstream channels (Taber, 1972, 1995); by the 1920s this region became known as the Pennsylvania desert (Ostman and Littell, 2006). Corroboration of this widespread clearcutting and erosion was documented using historical photos and sawmill records in the archives of the Thomas T. Taber Museum of the Lycoming County Historical Society in Williamsport, Pennsylvania (Fig. 24A). Logging in the Ridge and Valley and Piedmont watersheds was less aerially extensive and more gradual, beginning in the 1600s and progressing until the lumber demand peaked in the 1800s (Defebaugh, 1907; Cox, 1984; Williams, 1992). Large floods during the latter half of the logging period (Fig. 24B; 1880–1915) undoubtedly contributed to extensive denudation of deforested hillslopes during this interval.

Our field research over the past few years documented a significant and widespread low terrace along many reaches of Pennsylvania Appalachian Plateau streams (Delaney et al., 2006; Tully and Kochel, 2006; Forsburg and Kochel, 2007). This low terrace is composed largely of clast-supported gravel and sand with negligible soil development, except for a modest A-horizon in most locations (Fig. 25A). The absence of a B-horizon indicates that the sediments in this low terrace are recent. The presence of this low terrace, combined with our knowledge of recent clearcutting of these watersheds, led us to hypothesize that these represent logging legacy sediments (Hayes and Kochel, 2010; Kochel and Hayes, 2012). Fine-grained sediments have likely been transported downstream in the Susquehanna River (perhaps to the Chesapeake Bay) during floods. These logging legacy sediments are coarse grained and have relatively low cohesion, in distinct contrast to millpond legacy sediments (Walter and Merritts, 2008; R. Walter and D. Merritts, 2009, personal commun.).

Sediments average 1–2 m thick in this surface and typically bury older trees dating to the late 1800s that have younger adventitious roots near the terrace surface (Fig. 25B). Table 6 shows a summary of ages bracketed by dendrogeomorphic surveys of the logging legacy sediments in three north-central Pennsylvania streams derived using dendrogeomorphic techniques like those described by Hupp (1988). Dendrogeomorphic dates show a distinct cohort of trees that established on two distinct surfaces. The oldest set (95–130 yr old) of trees was not harvested during the logging. The logging legacy terrace surface is typically colonized by trees dating from the 1930s to the 1950s, interpreted as a cohort established when logging legacy aggradation ceased (probably 1920–1930). Recent decades have been marked by erosion of the logging legacy sediments as streams have been adjusting to sediment-free water emanating from reforested hillslopes in these watersheds since they were acquired by the Pennsylvania Department of Conservation and Natural Resources as part of reestablishing an extensive state forest system (Defebaugh, 1907; Williams, 1992).

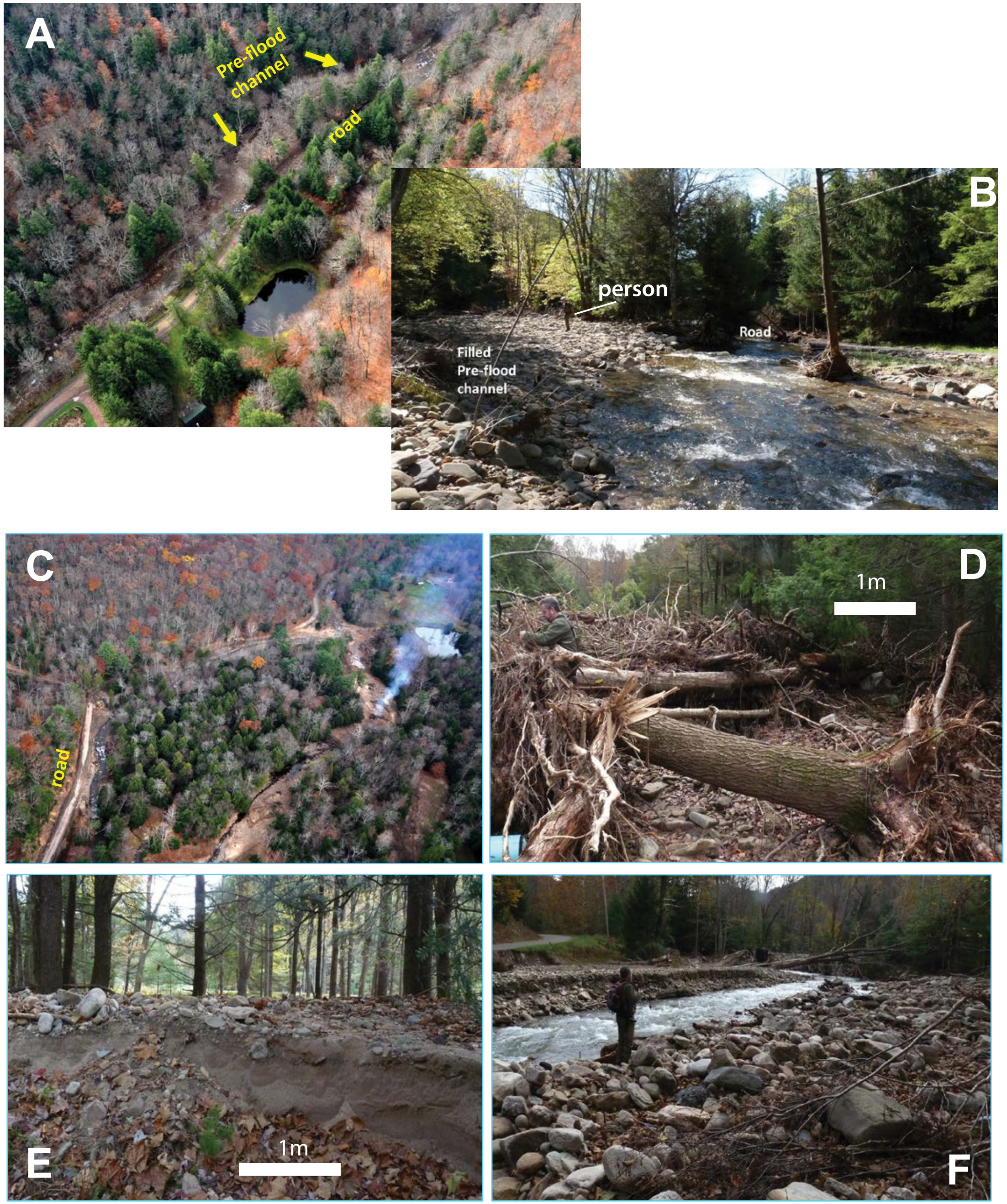


Figure 21. Landslide, tree-jam dams, and channel avulsion in headwater regions. (A) Upper Muncy road avulsion site from the air. Landslide and tree jam occurred at right arrow. (B) Ground view of upper Muncy road avulsion site showing the filled preflood channel (left) and new route of the channel on the former road bed. C–F show upper Loyalsock–Big Bear Creek avulsion complex. (C) Aerial view looking upstream. Smoke billows from the area of the tree jam as downed trees are being cleared. (D) Ground view of part of the tree jam in the filled preflood channel. (E) Aggradation and damming above floodplain level at upstream end of the tree jam. (F) Complex terraces formed during dam failure and breakout flood downstream.

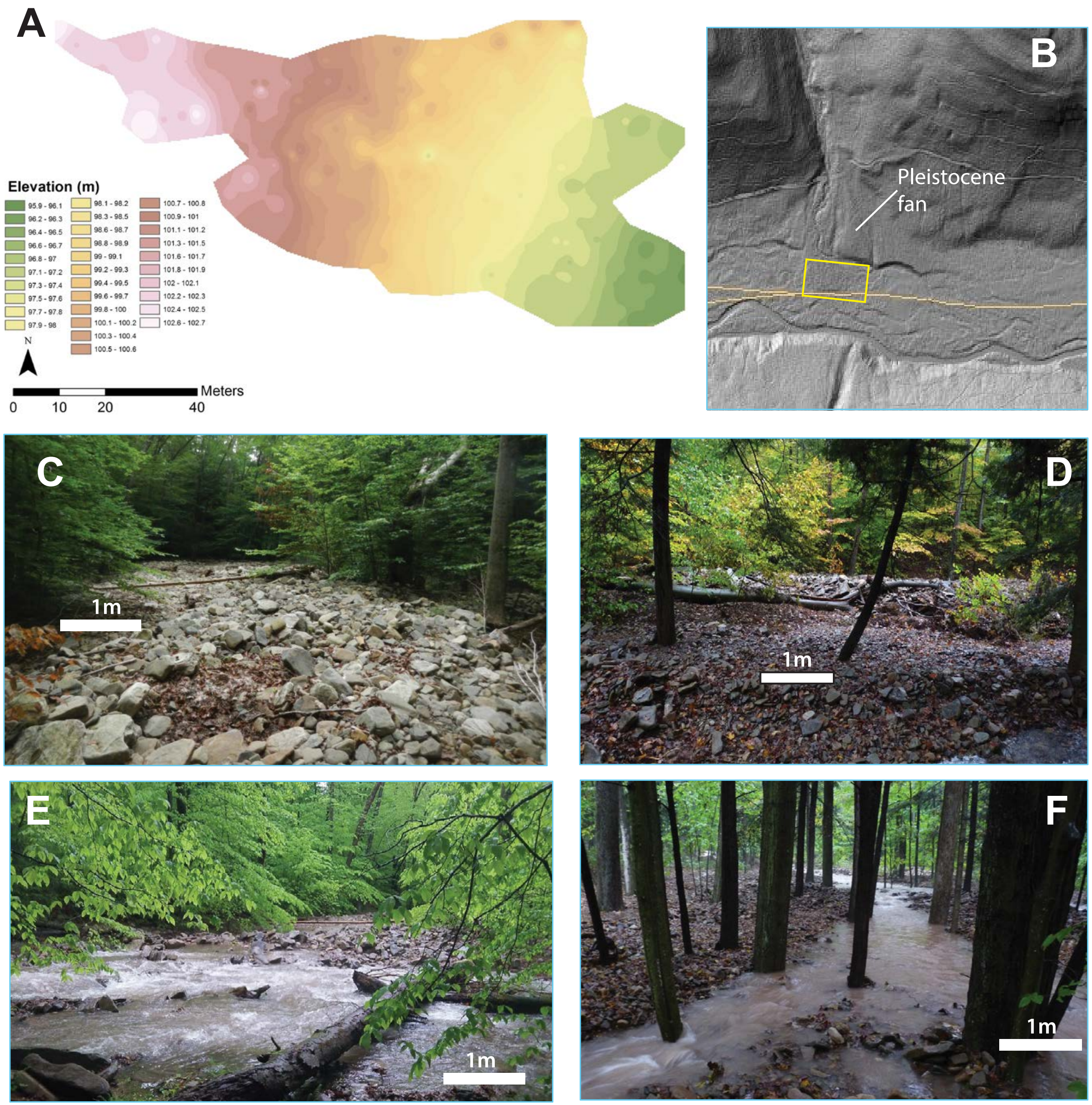


Figure 22. Bloody Run alluvial fan and avulsion site in upper Fishing Creek. (A) Topographic map surveyed in the field after the flood (colors show relative elevations in meters). (B) Preflood lidar (light detection and ranging) hillshade showing Bloody Run fan (within yellow box) incised into a much larger Pleistocene fan. (C) Former channel filled above the floodplain behind a tree jam during the Tropical Storm Lee flood. (D) Side view of the fill in the former channel aggraded >1 m above the floodplain. (E, F) Active flows down the newly avulsed channel across the forest and onto the highway during floods after the 2011 event.

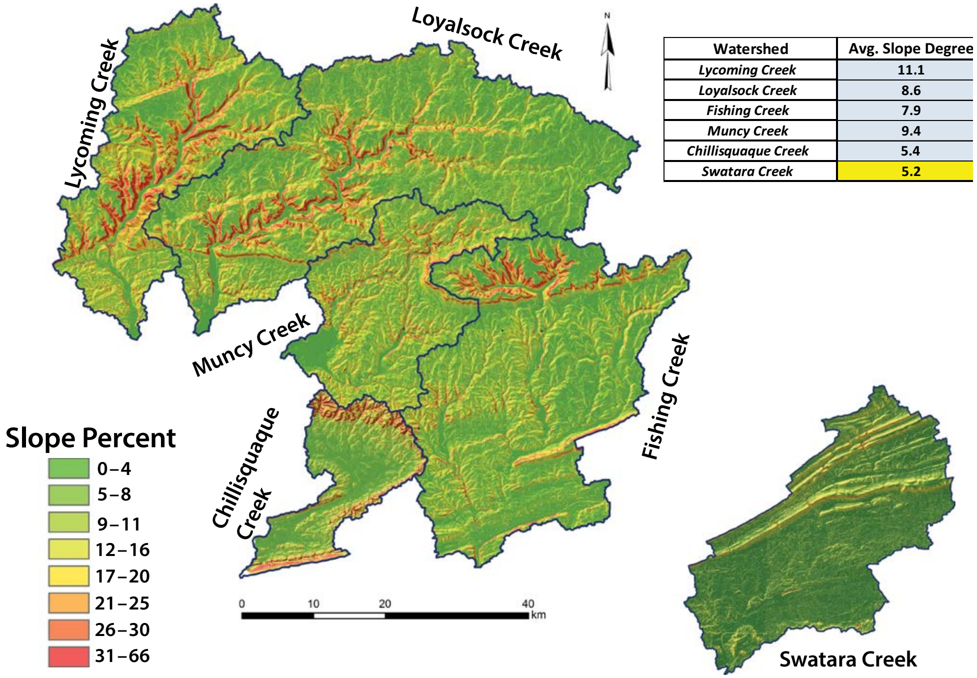
TABLE 4. FLOOD RUNOFF RATES FROM 6 U.S. GEOLOGICAL SURVEY GAGED WATERSHEDS (TROPICAL STORM LEE)

Watershed	Peak discharge* ($m^3 s^{-1}$)	Area (km^2)	Peak discharge per unit area ($m^3 s^{-1} km^{-2}$)
Lycoming Creek	983	694	1.42
Loyalsock Creek	1957	1126	1.73
Fishing Creek	1586	710	2.24
Muncy Creek	1320	541	2.44
Chillisquaque Creek	183	133	1.40
Swatara Creek	2743	1251	2.20

*U.S. Geological Survey, LeMoyne Water Science Center.

Figure 26 is an example of suspended sediment loads from a typical 1–5 yr recurrence interval flood in a local watershed (Buffalo Creek) that we have been monitoring for the past 11 yr. The values shown for the April 2004 event are typical of 12 floods studied since 2003. The map shows a distinctive lack of sediment emanating from the forest and a rapid increase in sediment load with distance downstream in agricultural areas. This pattern is representative of reforested watersheds throughout the study region.

Sediment-free floodwater has been aggressively eroding logging legacy sediments in north-central Pennsylvania since the 1970s. Episodic large-magnitude floods in recent decades (1972, 1996, 2004, 2011) have been eroding logging legacy sediments composing this low terrace (Figs. 27A, 27B), and moving them downstream as pulses (Fig. 27C). In some reaches gravel bars have aggraded above floodplain elevations, promoting local disequilibrium and avulsion across forested valley floors during large floods (Fig. 28). A detailed field survey (Figs. 29A, 29B) along the length of Grays Run, a tributary to Lycoming Creek (Delaney et al., 2006), shows at least two major disequilibrium zones where gravel pulses are moving downstream (Fig. 29C). Upstream reaches where logging legacy sediments have been eroded show incised channel cross sections. Gravel from this reach has filled channels in the disequilibrium reach, causing extensive avulsion (Fig. 29, reaches 5 and 6). Even small floods (<2 yr recurrence interval) result in widespread inundation of the valley floor (Fig. 29, reach 6). Instability characterizes these disequilibrium reaches as former channels are filled with gravel and avulsions redirect streams across forested valley bottom floors, creating new knickpoints and incising new channels (Figs. 28 and 29B). Downstream from the disequilibrium reach, incised channels reappear (Fig. 29, reach 7). A second pulse of gravel appears farther downstream (Fig. 29, reach 8), resulting in another zone of disequilibrium. Aggradation of gravel in these disequilibrium zones promotes



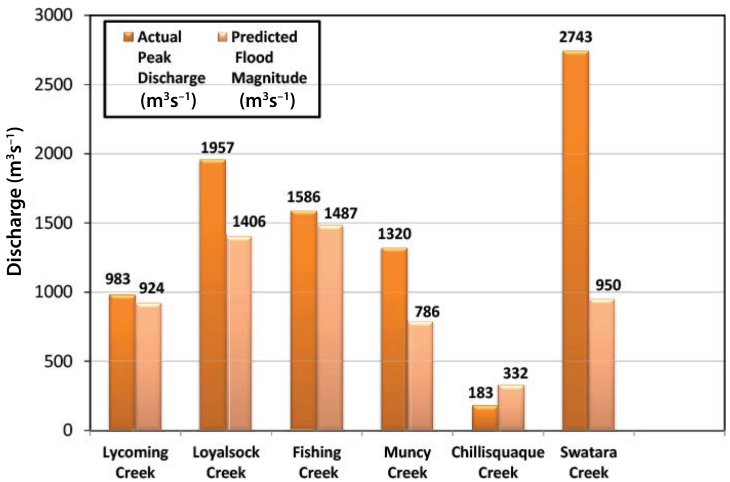
Watershed	Avg. Slope Degree
Lycoming Creek	11.1
Loyalsock Creek	8.6
Fishing Creek	7.9
Muncy Creek	9.4
Chillisquaque Creek	5.4
Swatara Creek	5.2

Figure 23. Slope percent map of the six study watersheds. Note the greater abundance of steep slopes in the Appalachian Plateau watersheds. Inset table shows the average basin slopes.

TABLE 5A. SUMMARY OF NORTH-CENTRAL PENNSYLVANIA BASIN MORPHOMETRIC PARAMETERS FROM GEOGRAPHIC INFORMATION SYSTEM DIGITAL ELEVATION MODELS

Watershed	Basin area (km^2)	Basin length (km)	Basin width (km)	Basin shape (k)	Divide averaged relief (m)	Bifurcation ratio	First-order stream frequency (km^{-2})	Drainage density (km km^{-2})	Ruggedness number	Total number of streams	Total stream lengths (km)	Number of first-order streams	Forested area (%)
Lycoming Creek	702	46	28	2.39	530	5.7	4.6	3.2	1.7	4,191	2238	3250	82
Loyalsock Creek	1277	71	22	3.12	490	4.5	5.4	2	0.98	8,886	2613	6952	85
Fishing Creek	1125	55	40	2.13	546	3.6	5.1	3.3	1.8	7,263	3762	5732	66
Muncy Creek	532	37	24	2.04	460	3.7	5.5	3.5	1.6	3,680	1842	2928	80
Chillisquaque Creek	290	32	17	2.7	271	4.01	3.4	2.8	0.76	1,269	815	994	75
Swatara Creek	1479	65	37	2.20	301	4.02	2.2	2.3	0.69	4,272	3389	3292	72

TABLE 5B. COMPARISON OF PREDICTED RUNOFF VALUES*



*Equations for Q_{max} (maximum flood flow) are from Patton and Baker (1976), derived from plateau watersheds in western Pennsylvania.

the disruption of these reaches that are characterized by simultaneous channel aggradation and erosion and/or mobilization of logging legacy sediments. These new channels have eroded roads and other infrastructure.

The mainstream channel of Lycoming Creek, upstream from the junction with Grays Run, displays a 5 km disequilibrium reach resulting from pulses of logging legacy sediment emanating from Roaring Branch tributary (Fig. 30). Several houses that were located on the valley floor were destroyed by floods in the past 40 yr as the logging legacy surface has been reworked in this reach between Roaring Branch and Ralston. Highway 14 was installed along the axis of the valley in what was not recognized as a multithread system. The highway was placed on a fill while the low-flow channel was restricted by constructing 2–4-m-high berms to protect the highway and other infrastructure from flooding. A new bridge constructed in 2010, visible in Figure 30B, is already undergoing erosion. Repeated pulses of remobilized logging legacy sediments originating from Roaring Branch have moved down Lycoming Creek and are triggering destruction of the floodplain-terrace system where roads, farms, and homes have been developed since the 1930s. Figure 31 shows an example of the problems maintaining passage for streams transporting sediment under bridges along disequilibrium reaches in this region. When constructed in the 1970s there was ~4 m of clearance between the bridge deck and the creek. Before the highway department cleared the gravel in 2010, clearance had been reduced to ~1 m. The larger gravel pulses are probably related to large floods, as in the mapping of gravel pulses from the TS Lee flood in Figure 14. These flood-related gravel pulses appear as distinctive aggradational bar surfaces within the disequilibrium section of the Lycoming Creek channel; each surface has distinctive cohorts of similar aged trees dating to major recent floods in 1972, 1996, and 2004 (see Fig. 27C). Observations by local residents along Lycoming Creek support this interpretation; they first noticed gravel aggradation following the TS Agnes flood in 1972. Three subsequent large floods, the January 1996 snowmelt (Leathers et al., 1998), the TS Ivan (September 2004), and the TS Lee flood (2011), resulted in renewed pulses of gravel and aggradation of local channels above the floodplain along this reach.

Our conceptual model for the channel response and episodic movement of logging legacy gravel in north-central Pennsylvania is based upon a similar model of fluvial response to land-use change from logging, documented in southern Illinois by Miller et al. (1993); their findings (Fig. 32A), applicable to several streams across southern Illinois, show a recent episode of catastrophic floodplain erosion concurrent with transport of a large pulse of gravel moving downstream. This followed several decades of valley-floor aggradation from the 1880s to 1930s during a period when extensive clearcutting took place in the uplands. Kochel and Ritter (1990) discussed similar disequilibrium as the channel of Sexton Creek in southern Illinois transformed from a sinuous meandering channel with mud-rich sediments and low width/depth ratio to a relatively straight pattern dominated by large gravel bars and a high width/depth ratio. Eaton (1991) described a similar geomorphic evolution for Wolf Creek in southern Illinois where remobilized logging legacy gravel filled its channel, causing large-scale avulsion. Figure 32B shows a similar model of channel response related to land-use change adapted for north-central Pennsylvania.

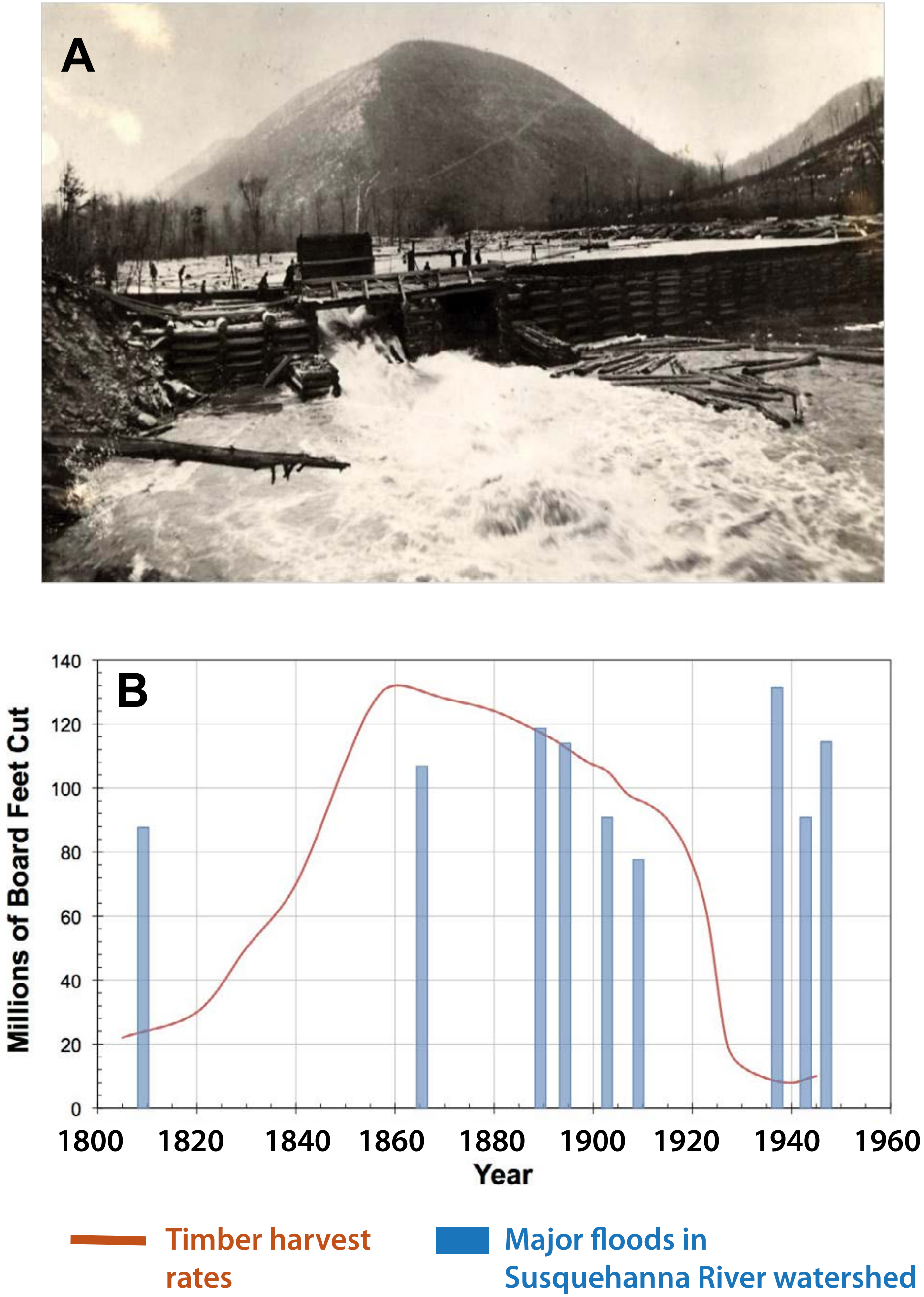


Figure 24. Impact of widespread clearcutting on north-central Pennsylvania watersheds. (A) Photo in Pine Creek watershed in 1908. Note the bare hillslopes and logs moving through the splashdam in the foreground. (B) History of timber harvest on the West Branch Susquehanna River (red line). Blue bars show large floods on the river.

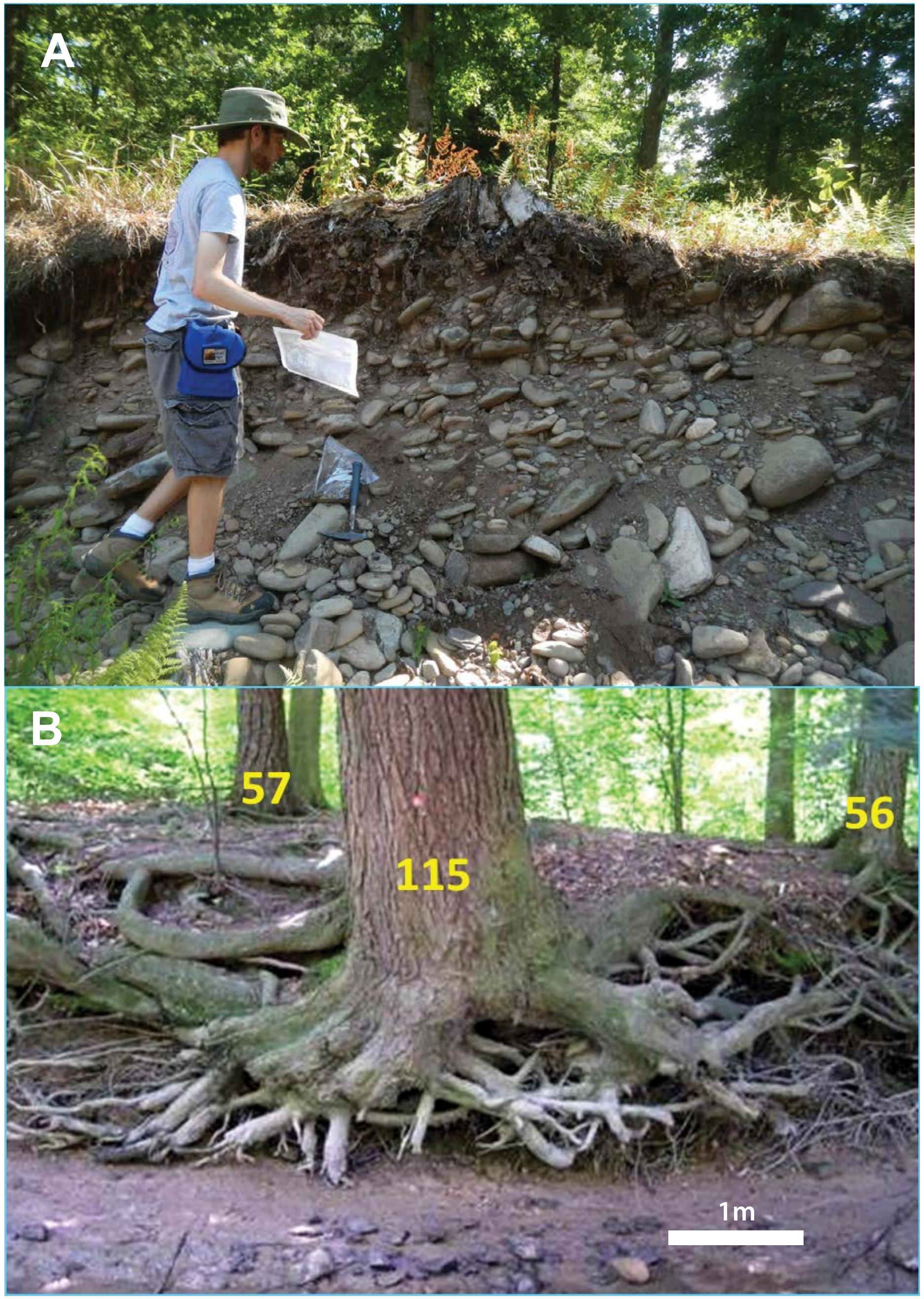


Figure 25. Examples of logging legacy surface and sediments. (A) Logging legacy sediments with extremely weak soil development (A-horizon only) along upper Fishing Creek. (B) Older trees buried by logging legacy sediments and cohorts of younger trees established on the surface of logging legacy sediments. Ages of the trees (before 2010) are shown in yellow. Timing of the aggradation of logging legacy sediments was bracketed using dendrogeomorphology (Table 6).

TABLE 6. DENDROGEOMORPHIC BRACKETING OF TREES ON LOGGING SEDIMENTS IN NORTH-CENTRAL PENNSYLVANIA

Stream	Site	Age of trees whose bases are buried by logging legacy sediment (yr before sample date)	Age of trees growing on surface of logging legacy sediment (yr before sample date)
Grays Run (sampled in 2007)	XS 1		87
	XS 3	118	68
	XS 5	125	78
	XS 8	114	57
	XS 17	106	69
	XS 23	109	64
	XS 24	136	90
	XS 27	–	82
	XS 39	111	90
	XS 39	101	76
	XS 40	165	76
Spruce Run (sampled in 2009)	XS 4	106	68
	XS 5	112	81
	XS 7	102	75
	XS 11	115	62
	XS 13	130	64
	XS 14	98	82
	XS 15	134	–
	XS 20	128	62
	XS 29	115	64
Rapid Run (sampled in 2010)	XS 5	105	67
	XS 8	130	85
	XS 11	95	70
	XS 12	107	70

Note: Dash indicates that no data was obtained.

The bracketing of the stages of geomorphic evolution in Figure 32B is based on dendrogeomorphic data in Table 6. This geomorphic model illustrates that channels are currently in a protracted phase of adjustment involving simultaneous downcutting, widening, and extensive mobilization of gravel as they adjust to watershed-scale changes in sediment supply due to historic logging more than 100 yr ago.

SUMMARY AND IMPLICATIONS FOR MANAGEMENT

TS Lee flooding had a catastrophic geomorphic effect over broad areas of north-central Pennsylvania, similar to the extreme response described for floods in semiarid regions (i.e., Baker, 1977; Wolman and Gerson, 1978). Detailed geomorphic mapping of four watersheds showed that the flood caused extensive channel changes, including formation of chutes, breaching of artificial berms, and reactivation of abandoned floodplain anabranches, channel scour and bank erosion, and floodplain deposition. Matrix-rich gravel exposed in field excavations suggests that floodwaters may have achieved hyperconcentrated flow in places. Breakout flows, resulting from berm breaching, accelerated erosion and damage to floodplains and destroyed farmland. Approximately 6,700,00 m^3 of coarse gravel was mobilized along ~250 km of channels in 4 watersheds. The spatial distribution of gravel shows episodic movement along the channels as distinct pulses that are mobilized by large floods. The apparent source of the gravel is a combination of bed-bank erosion as well as contributions from tributaries.

Erosion of Holocene and Pleistocene fans and terraces indicate that the recurrence interval of the flood may exceed 100 yr. These observations enrich the long-standing discussions of flood frequency and magnitude related to both landscape modification and bedload transport and geomorphic work (see the seminal paper by Wolman and Miller, 1960). In contrast to the impact of Agnes in 1972 (Moss and Kochel, 1978), the geomorphic impacts of this flood were catastrophic. However, we notice distinct differences in geomorphic response to flooding between watersheds in the Appalachian Plateau versus those in the Valley and Ridge and Piedmont. In combination with the availability of

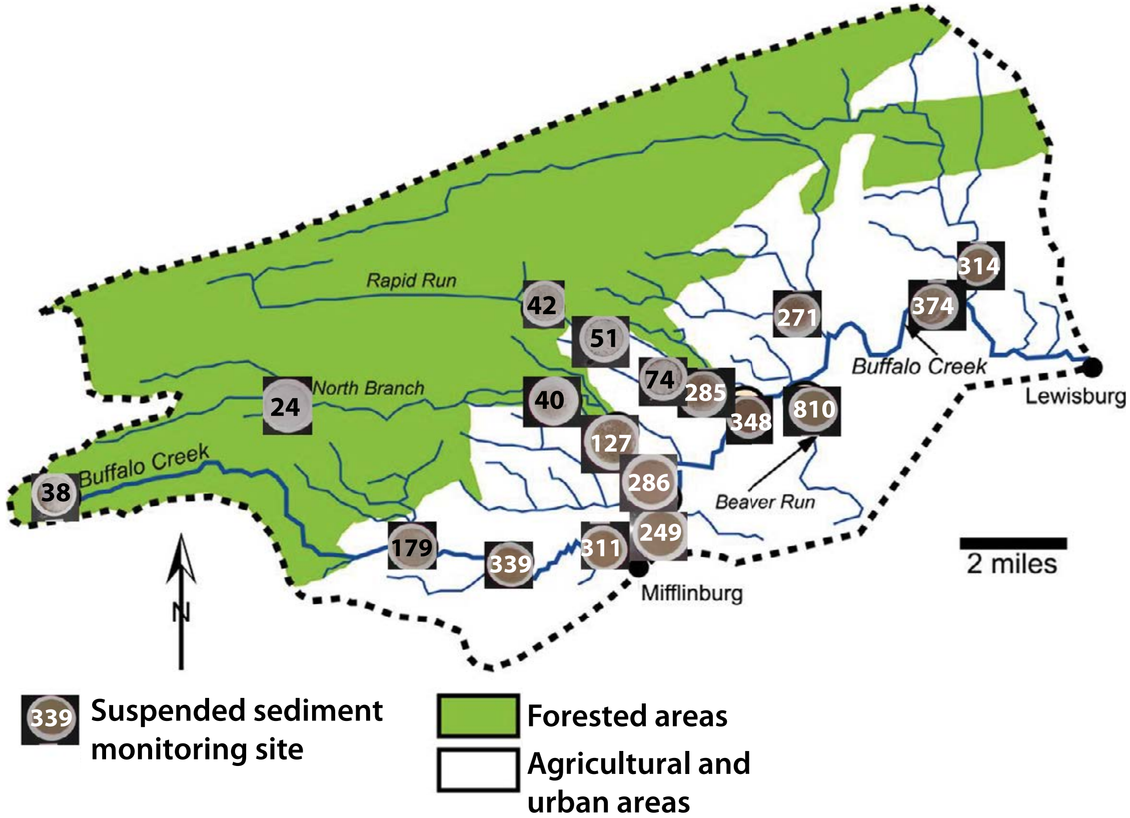


Figure 26. Suspended sediment yield (ppm) at 17 monitoring stations sampled during a flood in April 2004 (illustrated by photographs of sediment collected on filters) in Buffalo Creek. The data shown here are typical of >12 floods sampled since 2003. Buffalo Creek enters the West Branch Susquehanna River at Lewisburg (see Fig. 1). The upper half of the watershed was logged between 1850 and 1920 and is responding in fashion similar to that of the watersheds in the Appalachian Plateau.

abundant coarse bedload, morphometric parameters such as ruggedness number appear to have strongly influenced basin response to flooding.

A significant hypothesis evaluated here is that the geomorphic response to flooding has been dramatically enhanced by the pattern and history of land use and infrastructure development in the region during the past 150 yr. Foremost in this scenario has been the fluvial adjustment to basinwide clearcut logging between 1850 and 1920. Enhanced erosion of steep hillslopes resulted in the formation of a valley-filling low terrace composed of noncohesive sand and gravel. Although the timing of this aggradation varies slightly between watersheds, dendrogeomorphic bracketing indicates that the deposition of these logging legacy sediments was between 1880 and 1930. Concurrent with and subsequent to the logging era, berms were constructed along mainstems and many large tributaries to facilitate floating of logs. These berms disconnected low-flow channels from valley-wide multithread channels activated frequently during most floods. Reduction of frequent valley-floor flooding by the berms promoted the establishment of farms across the bottomlands, a network of highways, and development of homes. Once reforestation was established by the middle 1900s, clear and aggressive water emanating from headwater tributaries began to erode the logging legacy sediments. Erosion of the logging fill was greatly accelerated during large floods such as those in 1972, 1996, 2004, and most recently and catastrophically in 2011, sending major pulses of gravel downstream into the berm-narrowed single-channel system. Increased gravel loading resulted in formation of large gravel bars within the channels to elevations of the floodplain level or higher at many locations, resulting in extensive bank erosion, channel widening, and avulsion. A process-based geomorphic model was developed to explain the evolution of these channels in response to sedimentation from nineteenth century logging.

This paper connects geomorphic changes observed during a flood to the legacy of historic land-use changes and highlights a threshold-crossing event and resulting complex response between and within watersheds as they adjust to the impacts of historic logging and flooding. Prior to 2011, channels and floodplain of these streams were already unstable, and streams responded

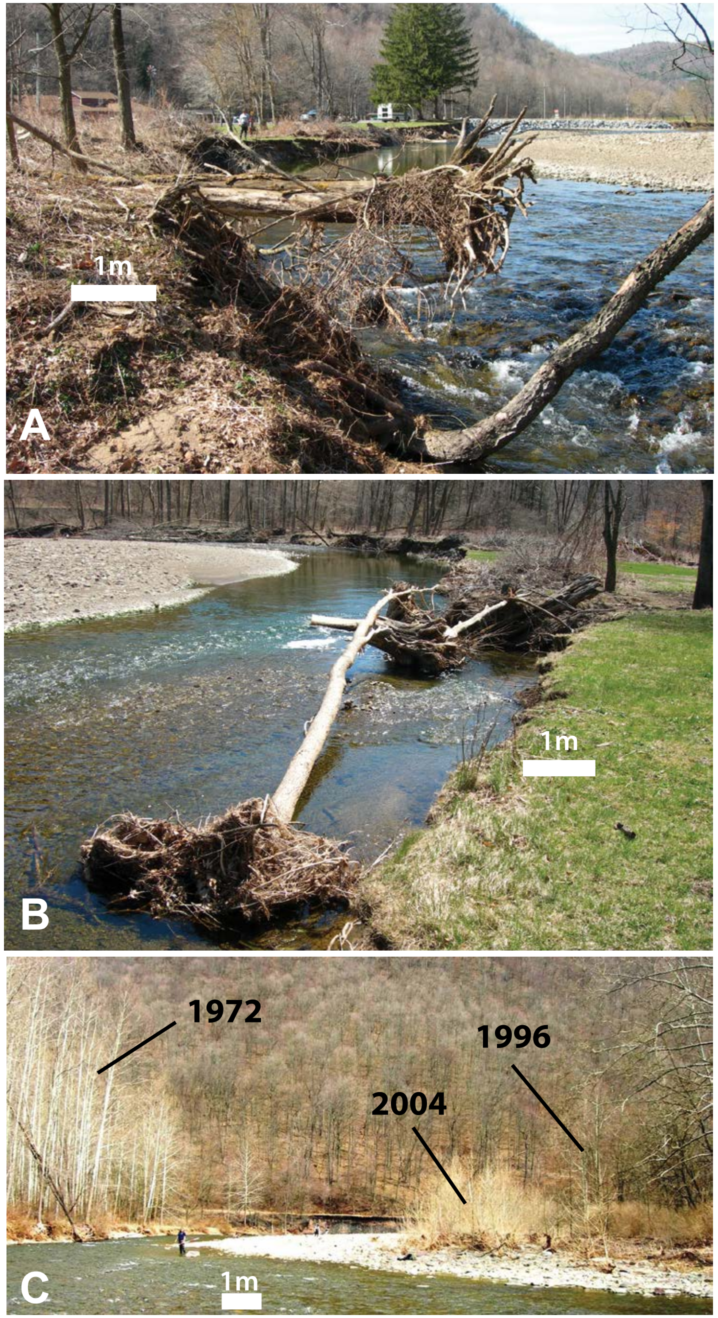


Figure 27. Floodplain and terrace destruction during Tropical Storm (TS) Lee along upper Lycoming Creek near the junction with Roaring Branch. Two houses have already been eroded along a reach between here and Ralston, 3 km downstream. (A) Rapidly eroding logging legacy floodplain surface. Floodplain trees show ages dating to 1930–1940 when aggradation from the logging era was completed. (B) Eroding logging legacy surface with trees contributed from eroding floodplains upstream. Note new gravel bar aggrading in channel. (C) Gravel pulses, deposited as progressive surfaces along Lycoming Creek during major recent floods. Cohorts of trees established on the bars correlate to floods in 1972, 1996, and 2004. The photo was taken in 2009, before the TS Lee flood.

catastrophically with avulsions, erosion and deposition, and changes in channel patterns. Geomorphic adjustments began in response to large floods in 1972, 1996, and 2004 in Lycoming Creek and other area streams (Delaney et al., 2006; Tully and Kochel, 2006; Forsburg and Kochel, 2007).

The TS Lee flood represents a geomorphic threshold-crossing event that dramatically accelerated adjustment of these fluvial systems, primarily manifested as an adjustment of channel morphology from a single-thread channel to a multithread channel pattern. Prior to the TS Lee flood, floods were largely contained within the artificially bermed main channels. The enormous volume of gravel mobilized in the channels during the TS Lee flood resulted in widespread avulsions and berm breaching, enabling the mainstem channels to reconnect with the multithread floodplain channels that had been abandoned since channel alterations during the logging era ~100 yr ago.

This resulting shift in channel pattern is particularly notable in the behavior of these streams now during even minor floods. The trajectory of these changes are such that the streams do not appear to be returning to their preflood single-channel meandering systems, but instead are adopting a permanent multithread pattern, similar to that prior to logging. Much of the discussion and interpretation of the threshold concept results from a failure to emphasize the importance of time in the analysis of threshold crossings. Schumm (1973, 1977) emphasized that true threshold crossings occur only when changes happen over a graded time interval (decades to millennia). Thresholds are exceeded when changes in process and/or form occur that are irreversible over graded time and adjusted to altered controlling parameters. Ritter et al. (1999) argued that a threshold is only crossed if a system does not quickly return to its pre-event condition. Because both equilibrium and recovery (e.g., Wolman and Gerson, 1978) are time-dependent phenomena, it follows that threshold crossings must be dependent on time. Ritter et al. (1999) also argued that threshold crossings of true geomorphic significance exhibit the following characteristics: (1) they are characterized by nonreversible changes in process or form where the system cannot return to its original condition before the advent of another disruptive event; (2) they require that the system develops a new equilibrium condition adjusted to the characteristics of the altered controlling factors; (3) they are time-dependent phenomena; and (4) they can be identified by parameters that characterize landforms and/or processes. In the case of the four streams studied here, sediment load was the primary change in the controlling parameters. Increased supply of bedload

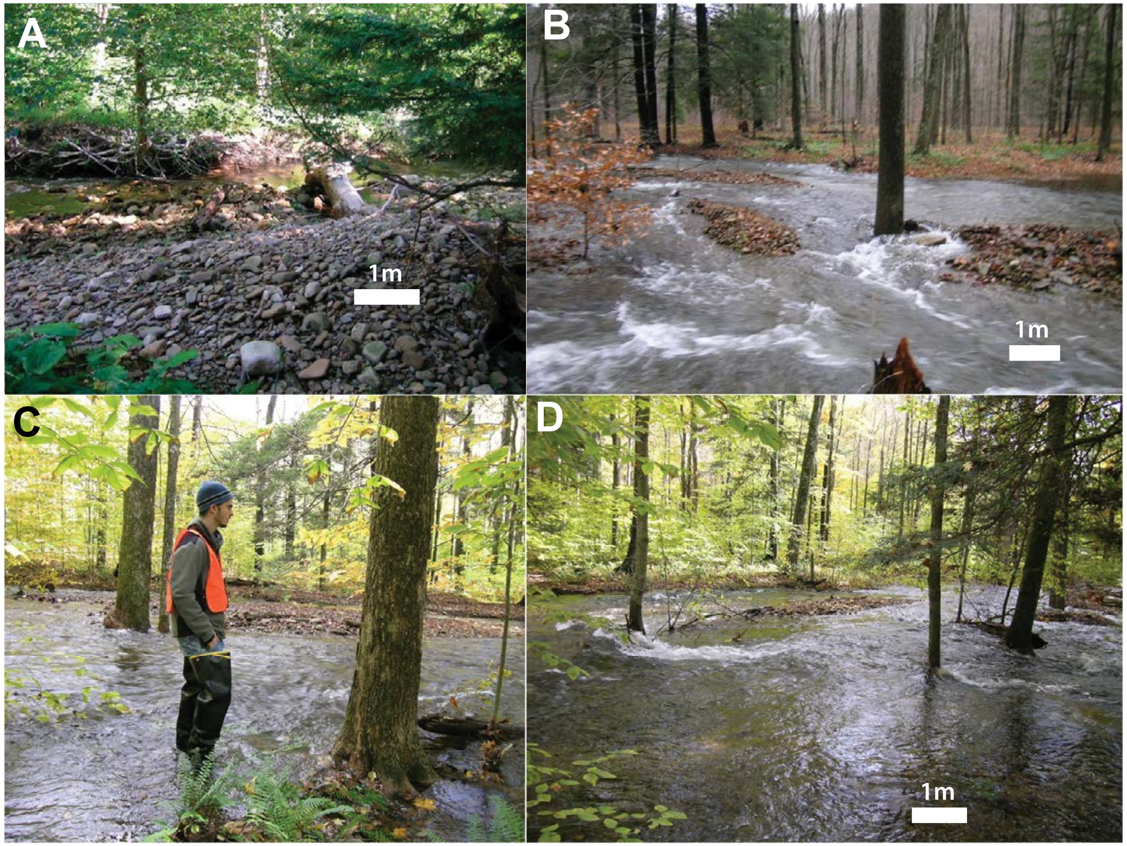


Figure 28. Disequilibrium zones in Grays Run (upper Lycoming Creek tributary) showing an example of avulsion and disruption of the logging legacy surface prior to Tropical Storm Lee. (A) Simultaneous bank erosion of the logging legacy sediment and bar aggradation (bar sediments sourced from erosion of logging legacy sediment upstream of the site). (B–D) Examples of unchanneled flow across the valley floor during a small flood in 2007 because the former channel had been filled with remobilized logging legacy sediment, resulting in avulsion. Note the clarity of the sediment-free water during this flood.

gravel from tributaries and mainstem bank and bed erosion during flooding resulted in massive gravel transport and deposition of mid-channel gravel bars that accreted to or above floodplain elevations, which caused extensive avulsion, breaching of historic berms, and activation of chutes and multithread floodplain channels that had been abandoned for >100 yr since channel modifications associated with logging. Since the TS Lee flood, the increased availability of gravel in the channels continues to promote further development of chutes and mid-channel bars, resulting in a shift in channel pattern from single thread to a valley-floor–wide multithread pattern during high flows. Postflood channels typically have shallowed and widened significantly (higher width/depth ratios) compared to their pre–TS Lee flood counterparts.

Wolman and Gerson (1978) noted that threshold-crossing events are typically characterized by the inability of a fluvial system to return to its pre-event morphology because flood events capable of altering morphology are so frequent that they can't return. Then, a true threshold has been crossed and a new system has been established. This is the case for the four streams studied here. Minor floods since 2011 have been capable of moving gravel and furthering the adjustment to the multithread channel pattern that was abruptly created by the TS Lee flood.

We mapped discrete areas of disequilibrium along many of the streams. Although these streams have undergone a significant change in sediment delivery from the days of clearcutting to the current era of hillslope stability attendant to reforestation, the response and adjustment to the new prevailing conditions are ongoing and have yet to be completed. The hillslopes are reasonably stable, but the channels are inherently unstable and are particularly sensitive to disturbance during extreme hydrologic events. Readjustment occurs when threshold discharges needed to entrain gravel are exceeded. Postflood surveys of gravel bars deposited by TS Lee show that much of the gravel can be entrained with flow depths <1 m above the gravel. This corresponds to flows just slightly over bankfull stage.

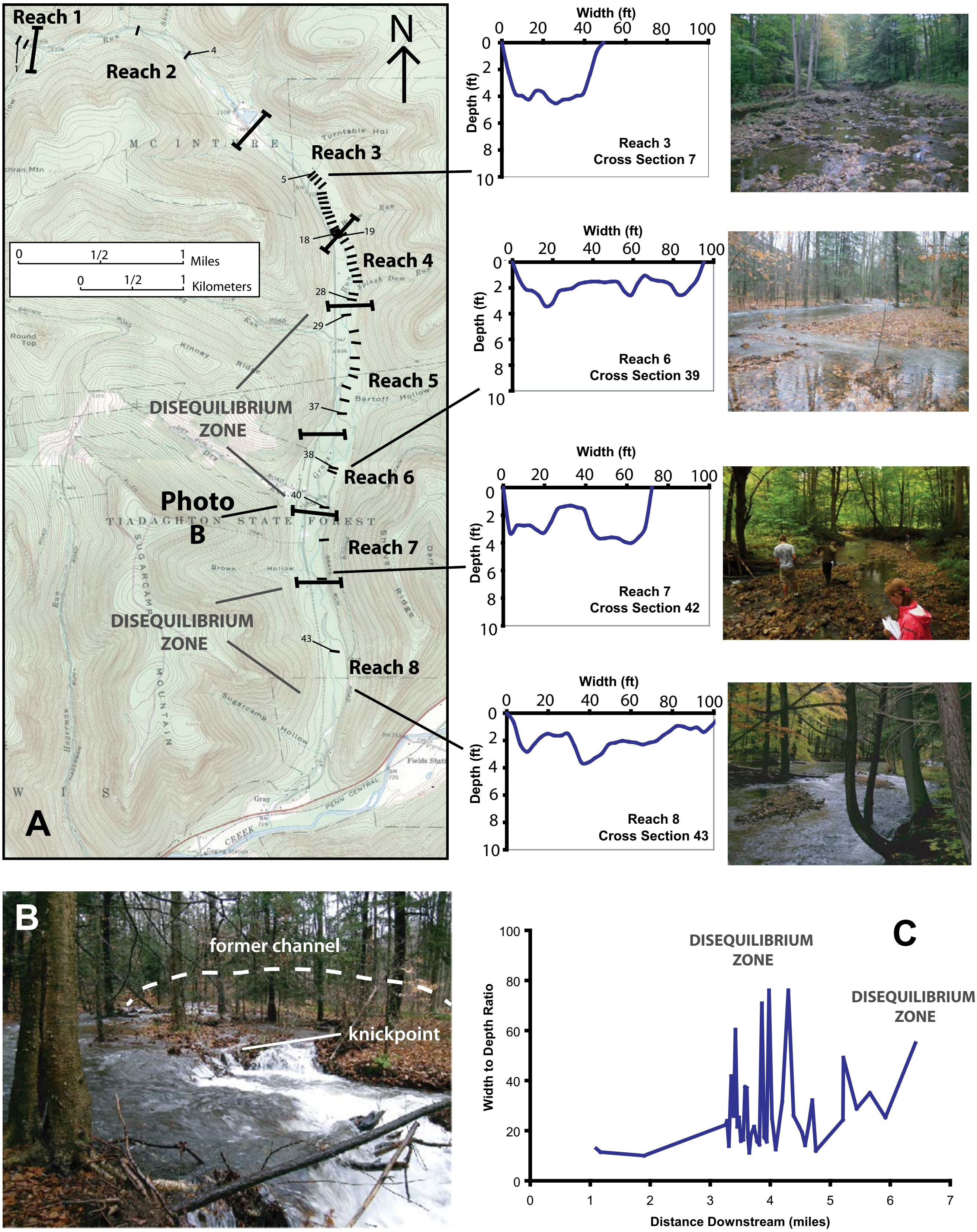


Figure 29. Complex response and disequilibrium zones along Grays Run, tributary to Lycoming Creek, established prior to Tropical Storm Lee (Delaney et al., 2006). (A) Detailed geomorphic mapping, including 43 cross sections, continuous longitudinal profile, pebble counts, and dendrogeomorphic sampling along Grays Run. Selected cross sections show the nature of downstream changes in channel morphology. Reach 3 (cross-section 7) shows an incised channel in the headwaters. Downstream cross sections in reaches 5 and 6 show progressive downstream aggradation of mobile logging legacy sediments, culminating in a disequilibrium zone with widespread avulsion (cross-section 39). Further downstream (reach 7) channels are again incised (cross-section 42). A second pulse of gravel occurs downstream in reach 8 (cross-section 43), representing another disequilibrium zone. (B) A dramatic example of avulsion in the disequilibrium zone (reach 6) where a new channel is forming by upstream migration of a knickpoint across the forest floor. The location of the former channel (now filled with gravel) is in the background ~100 m shown by the dashed line. (C) Changes in width/depth ratio of the Grays Run channel over a 7 km survey distance. Note the abrupt channel widening in the two disequilibrium zones identified.

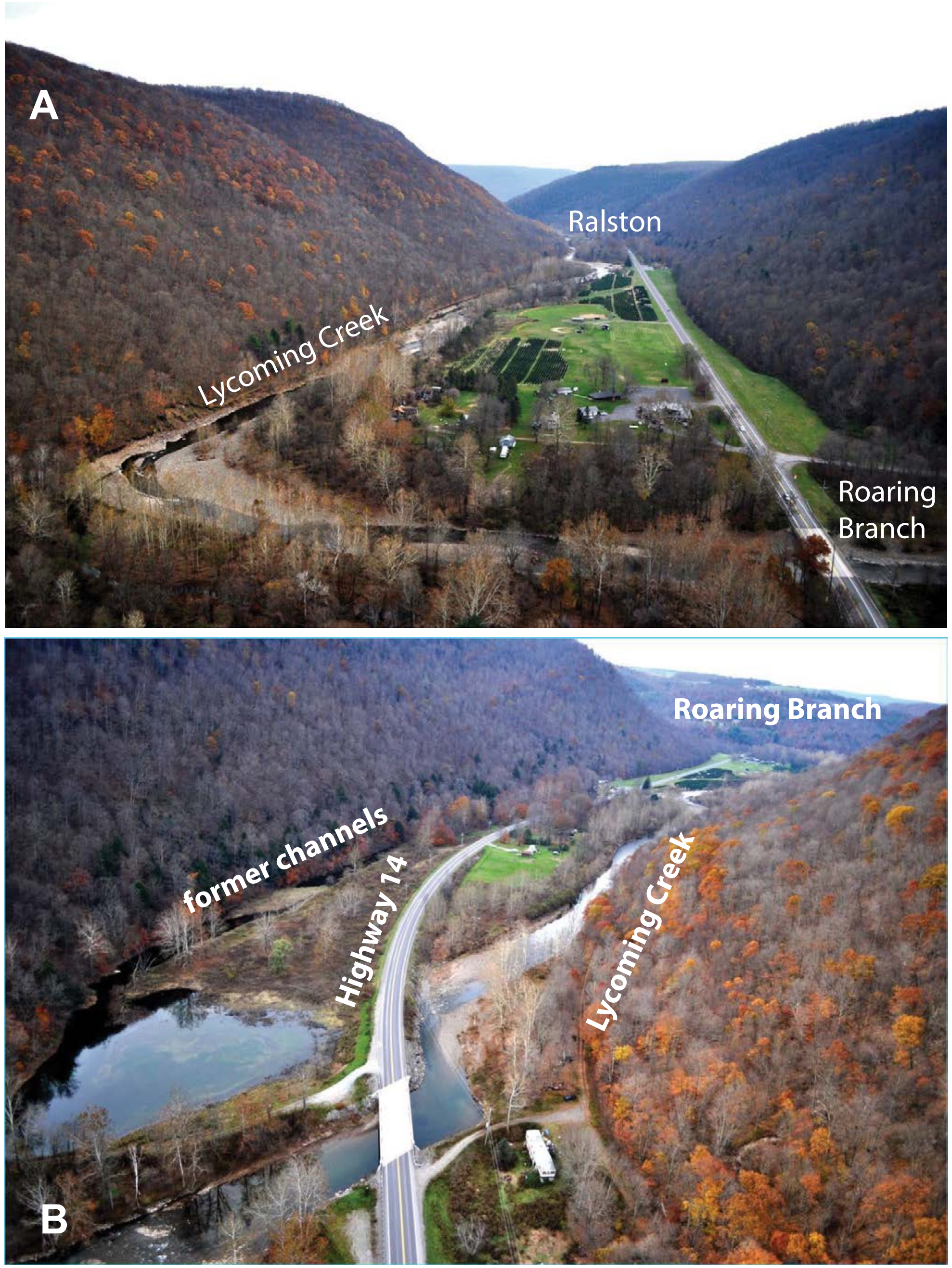


Figure 30. View of Lycoming Creek from Roaring Branch to ~1 km upstream of Ralston. Highway 14 has been constructed on an artificial fill placed in the center of the former multithread channel system, cutting former side channels from the mainstem. (A) View looking downstream from Roaring Branch bridge (at far right and shown in Fig. 31). (B) View upstream of the same reach from a new bridge (built in 2010) already in jeopardy at the sharp bend as the channel is rapidly shifting. Note the abandoned channel on the left now isolated from the mainstem and ponded by the berm leading to the new bridge.

Figure 31. Ground view of aggradation at Highway 14 bridge at Roaring Branch. Several meters of remobilized logging legacy gravel had to be removed from under the bridge several times in the past 20 yr. (A) View in July 2007. (B) View in October 2010, showing ~1 m of aggradation in 4 yr.

The observations highlighted in this paper, especially the detailed maps in Supplemental Files 1, 2, and 3, will be valuable not only to geomorphologists interested in floods, but also to engineers, planners, aquatic ecologists, restoration scientists, and students. Concepts such as geomorphic thresholds, complex response, and channel-pattern change are often poorly understood and not considered during the design of roads, bridges, and other hydraulic structures. The issues with Highway 14 in Figures 30 and 31 illustrate the increased maintenance and short lifespan of infrastructure in these unstable settings. The propensity for continued geomorphic adjustment in the Appalachian Plateau streams of north-central Pennsylvania is high. Even though it may have appeared that these fluvial systems had adjusted to the impacts of logging and appeared to be stable, this study clearly shows that they had not fully recovered. Extensive disruption occurred during a flood of sufficient magnitude (here the TS Lee Flood in 2011) and revealed the inherent state of metastability in these fluvial systems. Now that the threshold has been crossed, these streams exist in a state of disequilibrium where moderate floods result in widespread gravel movements and large changes in spatial patterns of channels. Pulses of coarse-grained sediment continue to move with major hydrologic events in what appears to be the beginning of a protracted period of adjustment that will likely last many decades, exceeding the period of land-use change that initially triggered the instability.

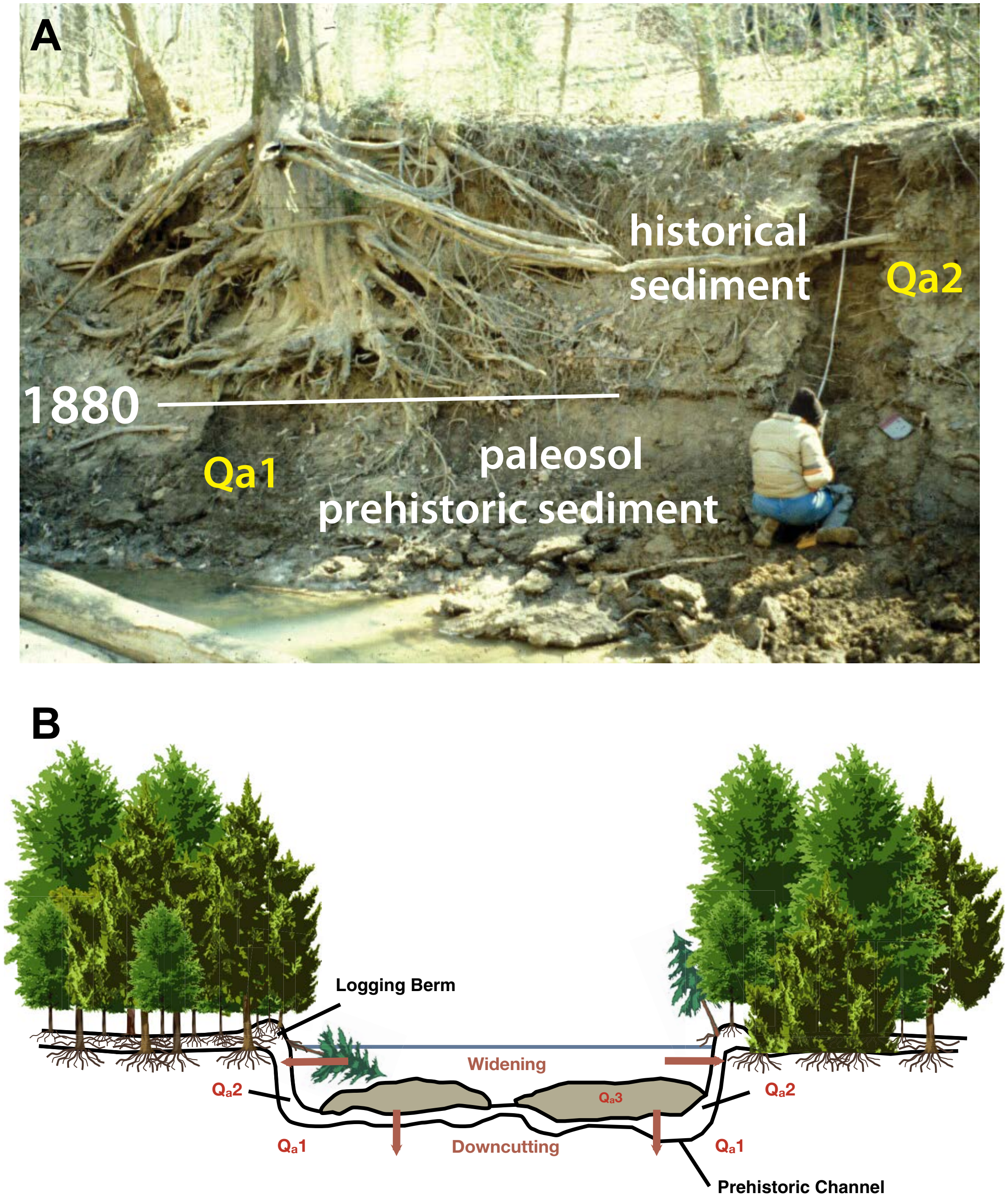


Figure 32. Channel evolution model resulting from disequilibrium associated with widespread historic logging in Illinois and Pennsylvania. (A) Southern Illinois model (from Miller et al., 1993). Qa1 is the pre-logging sediment with well-established paleosol on its surface. Qa2 represents rapidly accreted sediment resulting from logging of upland areas. Note the large tree with buried adventitious roots. Qa3 (not visible here) is composed of active gravel bars formed concurrent with the rapid erosion of Qa2 by clear floodwater emanating from reforested uplands of the Shawnee National Forest. (B) North-central Pennsylvania model showing a similar geomorphic evolution. Qa1 represents Holocene alluvium formed by a multi-thread channel that existed prior to logging. Qa2 is the logging legacy sediment that accumulated between 1850 and 1930. Since about the 1970s these channels have been widening as Qa2 sediment is remobilized and moved downstream during floods as Qa3 (shaded inset gravel bars) following reforestation of the upland.

Logging legacy sediment is moving downstream through the system episodically during floods. As these gravel pulses aggrade in reaches they cause avulsion and instability that damages property and infrastructure developed in the post-logging era. Because of these complexities, it has been difficult for watershed planners and highway engineers to understand how streams could be simultaneously eroding their banks while undergoing significant aggradation of gravel during floods. Fluvial systems should be evaluated on a watershed scale to address adjustments in sediment load and channel pattern produced by natural changes as well as historical land-use practices. This paper provides a geomorphic explanation for the widespread adjustment and evolution of fluvial systems in this area, and highlights the important influence and complex interaction of drainage basin morphometry, geology, fluvial dynamics, and land-use history on channel response.

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