Key Principles to Consider When Discussing Flood Mitigation and Management Alternatives For Streams in North-Central Pennsylvania

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Introduction

When discussing flood mitigation, two facts must be considered:

(1) the **magnitude** and **type of flooding** (e.g., snowmelt, rain-on-snow, convective thunderstorms and micro-bursts, tropical storms, and atmospheric rivers), **varies considerably** across Pennsylvania and therefore our flood management scenarios should be tailored to the specific region under consideration; and

(2) **gravel bed streams in the northern tier of Pennsylvania readily self-adjust to floods, and often experience more erosion and channel instability than streams in other regions across the Commonwealth.** Understanding how these streams self-adjust is important for watershed managers, emergency responders, stream restoration practitioners, planners, and civil engineers when considering flood mitigation and post-flood restoration alternatives.

Figure 1. Lycoming Creek, an example of watershed in the Deeply-incised Valley Section of =the Appalachian Plateau Province in north-central Pennsylvania. The high relief, steep hill slopes, and complex alluvial architecture in the valley bottom makes streams in this region especially vulnerable to catastrophic flooding, stream instability, and channel change during intense and prolonged storms.

Detailed scientific assessments and engineering perspectives of flooding and stream response in the northern tier of Pennsylvania can be found in the published literature (e.g., Kochel and Hayes, 2017; Hayes and others, 2013; Figure 2). However, since "a picture is worth a thousand words," this document is a selection of slides from presentations given at professional conferences, stream restoration workshops, and other public events sponsored by watershed groups, conservation districts, consulting engineers, and professionals at the PA Fish and Boat Commission, PA Department of Environmental Protection, Pennsylvania Emergency Management Authority (PEMA), Pennsylvania Department of Conservation and Natural Resources, the U.S. Geological Survey, National Weather Service, and the U.S. Fish and Wildlife Service. The principles presented herein have been tested and verified by extensive field studies, laboratory analyses, and hydrologic models conducted by the author in watersheds across the Commonwealth beginning in 1972, when Hurricane Agnes devastated watersheds across the state.

Figure 2. Detailed studies of the impact of floods on streams in northern tier watersheds have been published and are available to the public. Copies will be available for today's Senate hearing.

Rivers in the north-central Pennsylvania remain in a state of disequilibrium and a protracted phase of adjustment to events that took place over a 150 years ago, when the forested hillslopes were clear cut and the streams straightened, dredged, and bermed to promote the rafting of logs during the timber era. Sediments eroded from the barren hill slopes during several large floods in the 1880s and 1890s, were delivered to the valley bottoms, burying the channel and floodplain by several feet. The gradient of tributaries were greatly steepened, further stressing the fluvila system, which was able to accommodate these changes until the watersheds were hit by large floods in the 1950s and 1960s, which began to destabilize the tributary streams. Massive, widespread rains and flooding by Hurricane Agnes in August 1972 cause widespread destabilization across the region and many streams crossed a threshold, where they began seeking a new state of equilibrium, new channel gradient, and eroding high spots and depositing in low spots throughout the fluvial networks. Channel change peaked in 2011, when Tropical Storms Irene and Lee caused catastrophic flooding and damage. More recently, intense rainfall from Tropical Storm Debbie tore apart the glaciated highland regions in Bradford and Tioga counties. The streams are breaching relic berms, filling the channels and reoccupying old, isolated channels across the valley floor.

The combination of geology, geography, valley architecture, land cover, and infrastructure makes **streams in the Deep Valley and Glaciated Plateau provinces of north-central Pennsylvania some of the the most vulnerable to catastrophic flooding, stream instability, and damage to properties and infrastructure** (Figure 3).   These watersheds include Pine Creek, Lycoming Creek, Loyalsock Creek, Muncy Creek, White Deer Hole Creek, White Deer Creek and Fishing Creek. Hurricanes that impact the entire state such as Irene, Lee, Debbie cause flooding, but not as severe and damaging as what residents in north-central Pennsylvania experience.

Geography. These watersheds lie in the pathways of major storms coming northward up the Chesapeake Bay and Atlantic Coast, as well as fronts coming from the Great Lakes region to the west. A combination of higher elevations and their proximity to the lake-effect snows, these high-relief watersheds experience greater snow and ice accumulations during the winter and spring months than southern provinces. Its location in the tracks of tropical storms during the late summer and early fall, which combined with orographic effects as the northward-trending fronts ramp up onto to the higher elevations of the Appalachian Plateau, causing especially intense rainfalls and downdrafts.

Geology. The drainage networks have evolved over geologic time by cutting down through relatively flat layers of sandstone, shale, and siltstone to form deep valleys with steep hillslopes. The morphology and patterns of these gravel bed tributaries and main stem rivers are complex, with multiple channels and marginal wetlands flowing across broad valleys underlain by unconsolidated glacio-fluvial outwash sediments. The sides of the valleys and tributaries are characterized by very steep forested hillslopes that are mantled in unconsolidated boulder colluvium and glacial till. During intense rainfall, water travels quickly downslope through the colluvium and onto to the valley bottoms, causing intense flood peaks tend to arrive more quickly and are more severe. Residents living in the valley bottoms don't have time to evacuate and damage to bridges, roads, and homes is very severe. Also, emergency responders have a difficult time navigating the roads and highways that traverse through the flooded valley bottoms.

This concludes the written summary. The following pages contain illustrations and captions that explain the key concepts and other important information to consider in discussions of flood mitigation, post-flood cleanup alternatives, new approaches to restoring fluvial processes, increasing stream stability and resiliency, and improving habitat and stream health.

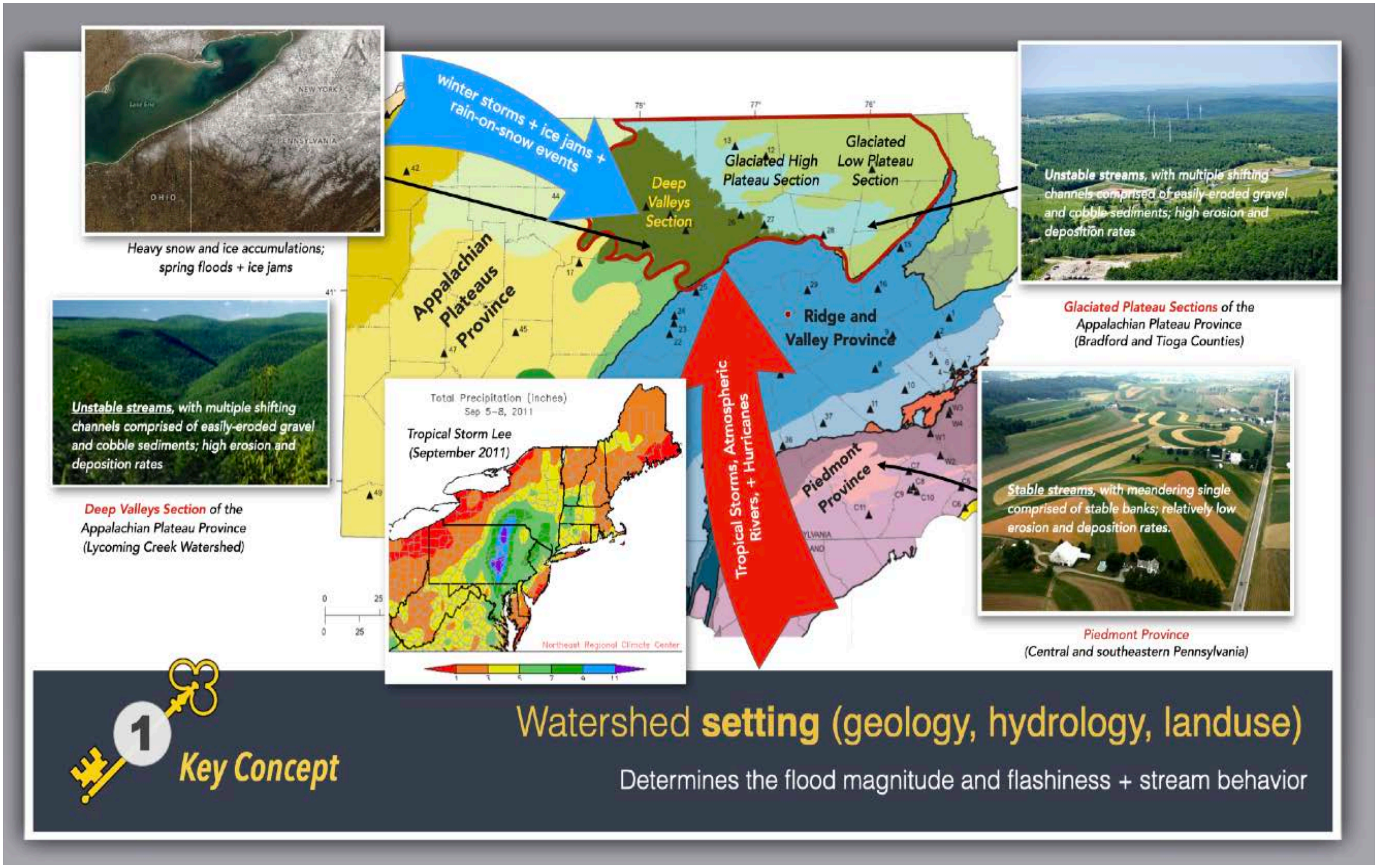


Figure 3. Physiographic provinces of Pennsylvania. North-central region highlighted on the map in red. The watershed geology and topography and stream pattern and stability vary considerably between different provinces. As a result the magnitude and type of floods as well as the channel response is distinctly different, even for a given storm event. As an example a picture of Lancaster County in the Piedmont Province is inset to the lower right, and watershed setting in the Deep Valley Section and Glaciated Highland Sections are inset in the left and upper right, respectively. The path of topical storms, atmospheric rivers, and hurricanes depicted with red arrow, and winter snowpack and ice floods shown with blue arrow.

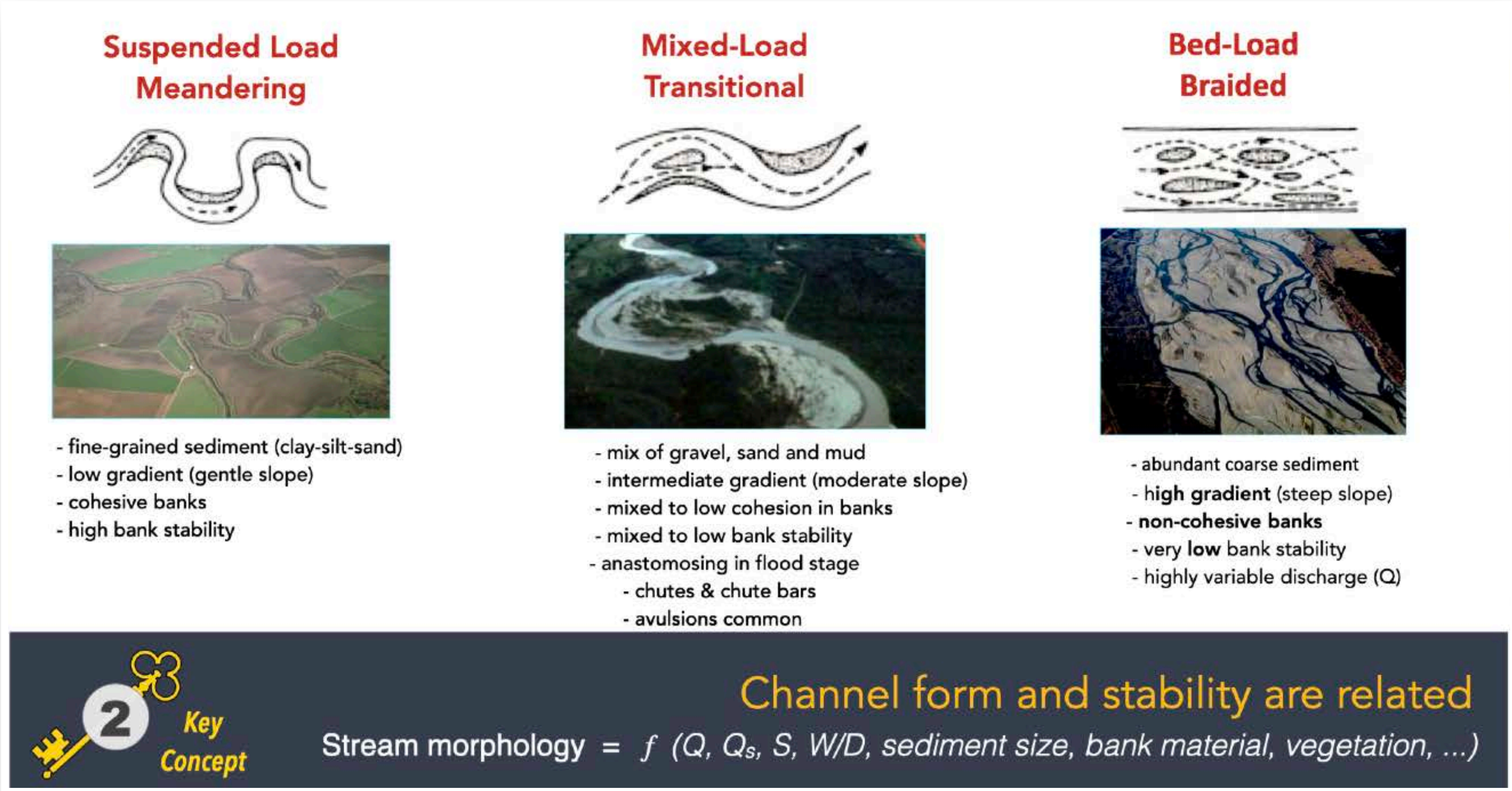


Figure 4. The form (e.g., single-thread meandering channel vs. multiple threaded braided channel) and stability are a function of the water discharge (Q), sediment load (Qs), slope of the channel (S), the width/depth ratio (W/D), sediment size (e.g., silty and sandy vs. gravel and cobble), bank material (cohesive silt and clay banks vs easily erode sand and gravel banks) and amount and type vegetation growing on bars and along the banks of the channel (grass and shrubs vs riparian forests). Suspended load meandering streams (left) are typical of the valley and ridge and piedmont provinces in south-central and south-eastern Pennsylvania. Mixed-load transitional and bed-load braided streams are typical of watersheds in the northern tier of Pennsylvania.

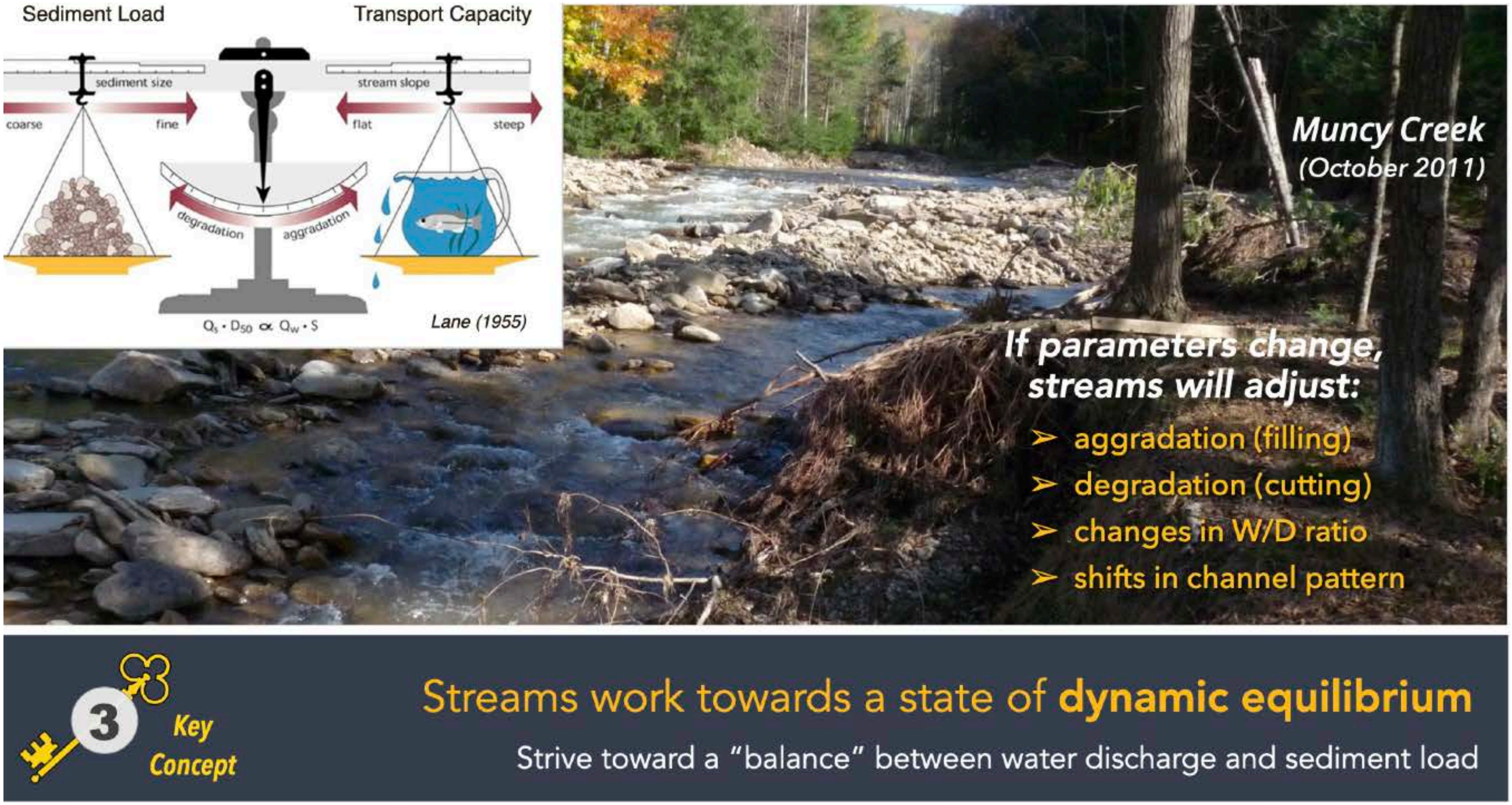


Figure 5. Streams naturally work to establishing a state of equilibrium, a balance between the amount of sediment delivered to the channel and its transport capacity. A change in the size and/or amount of sediment (e.g., a pulse of coarse logging legacy gravel delivered to the stream from a tributary during a major event, such as shown in Muncy Creek during Tropical Storm Lee in Sept. 2011), will result in rapid increase in the stream's sediment load. In the illustration of the scales of balance in the upper left, the the left side of the balance will go down, swinging the needle to the right which predicts "aggradation," which refers to a stream filling its channel with sediment it deposits at the waning stages of the flood. The photo in the background shows exactly that, where coarse cobbles and boulders were deposited in the Muncy Creek, filling it completely, which forces flow laterally, causing massive bank scour and undercutting (visible in foreground).

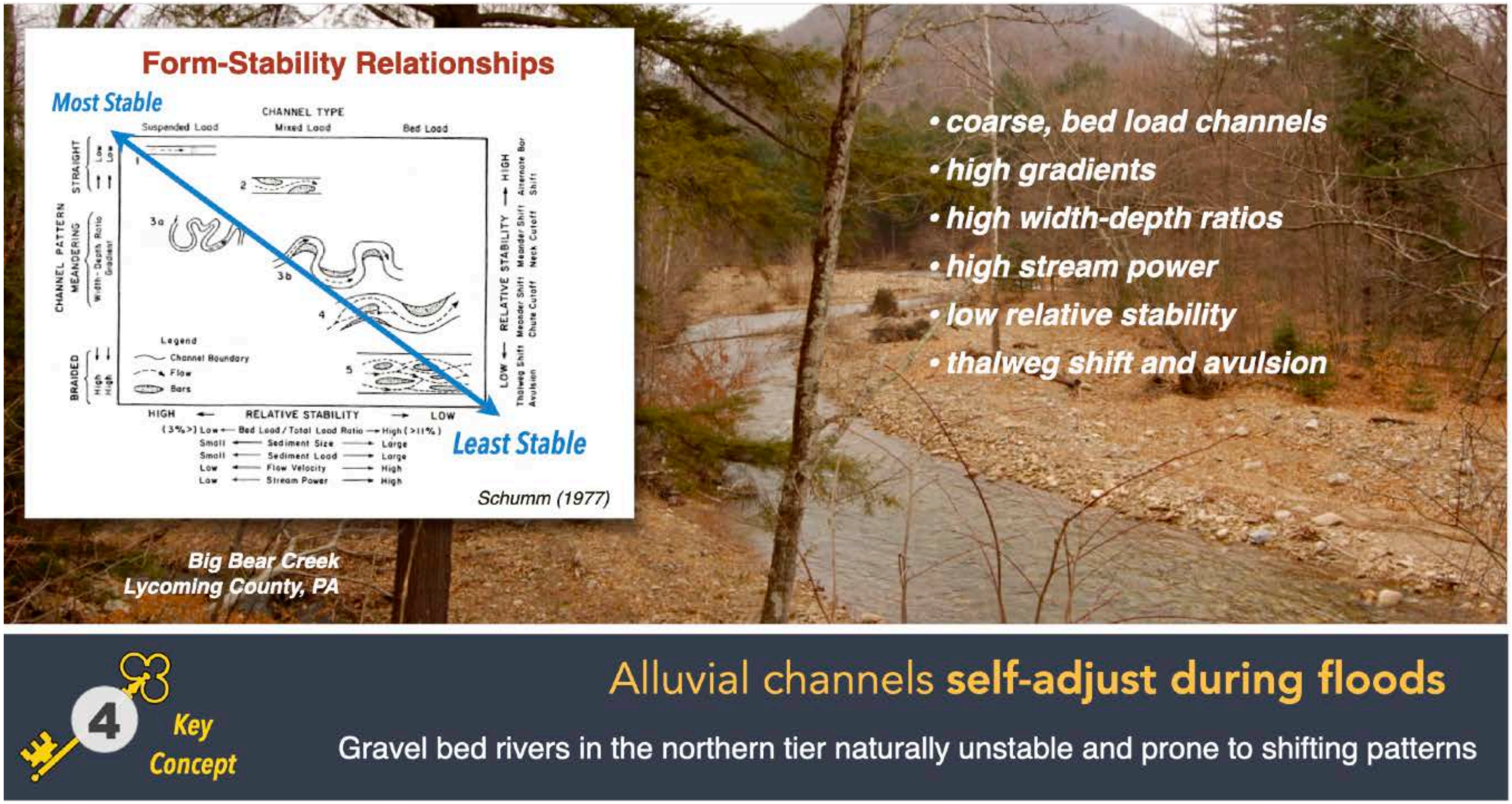


Figure 6. Alluvial channels self-adjust during floods to balance the amount of water and sediment delivered to the channel. Coarse bedload streams in high gradient watersheds in the northern tier of Pennsylvania naturally wide and shallow (high width-depth ratios), very powerful, and a thalweg (center part of the stream where the water is deepest and fastest) that is constantly shifting as sediment is eroded and deposited to form gravel bars and chutes. In the continuum of channel patterns and relative stability (graphic in upper left), the gravelly braided streams in the northern tier of Pennsylvania are much less stable than the suspended load meandering streams found in central and southeastern Pennsylvania.

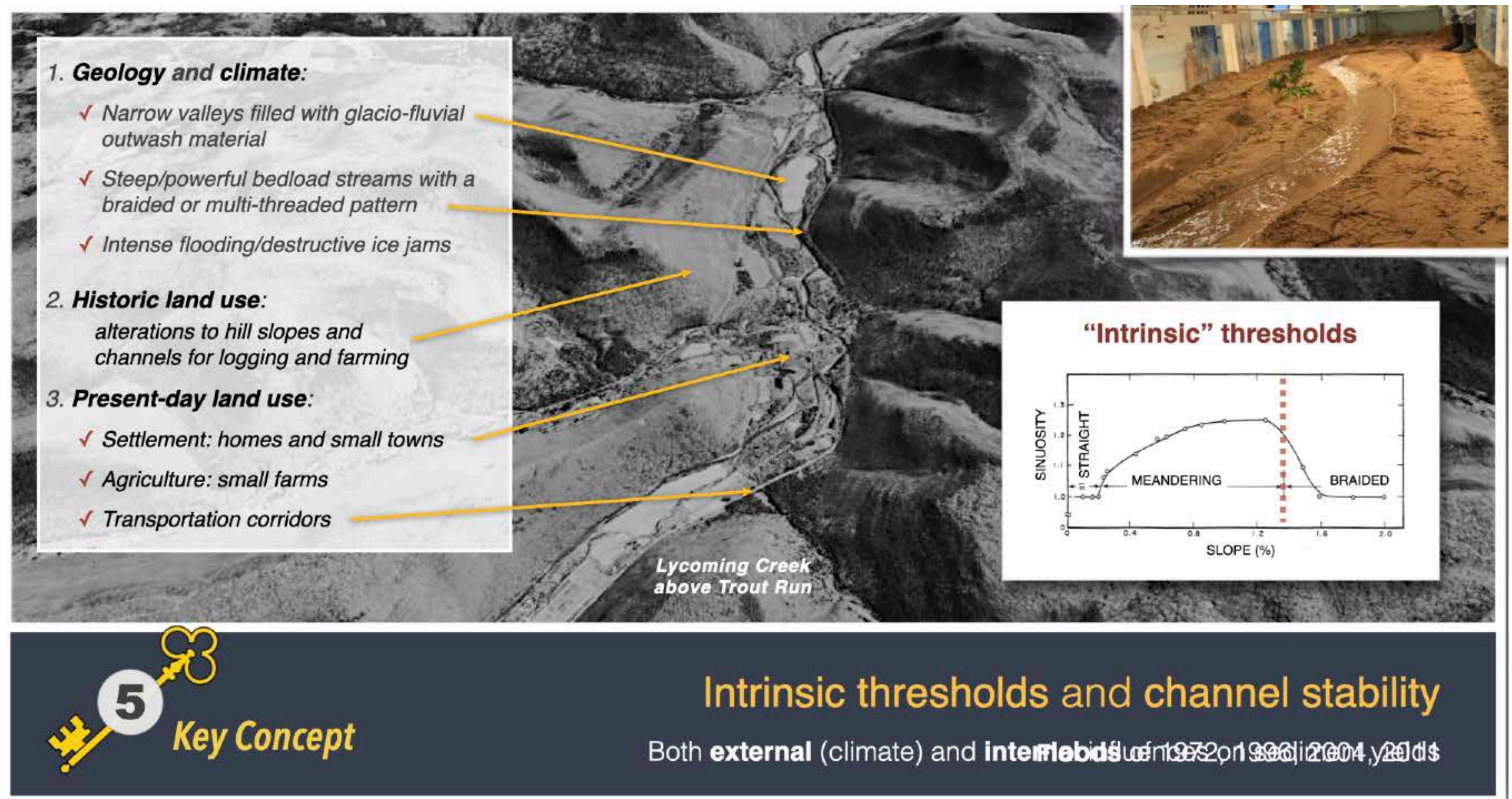


Figure 7. View of the braided, complex channel network of Lycoming Creek above Trout Run, PA, as viewed obliquely from Google Earth. Multiple factors that must be considered in regional planning, river corridor management, and protection of infrastructure are identified in the inset box on the left. The graph and photos inset on the right show laboratory flume experiments which explain what we observe in reality during major foods - that streams have "thresholds" or limits to their ability to retain legacy sediments and channel form. During large flood events, massive quantities of water and sediment stress these fluvial systems beyond these thresholds, causing them to rapidly change form and pattern. For example, during Tropical Storm Lee, streams changed overnight from single-thread channels they were forced into during the logging era back to multiple-channel braided streams afterwards.

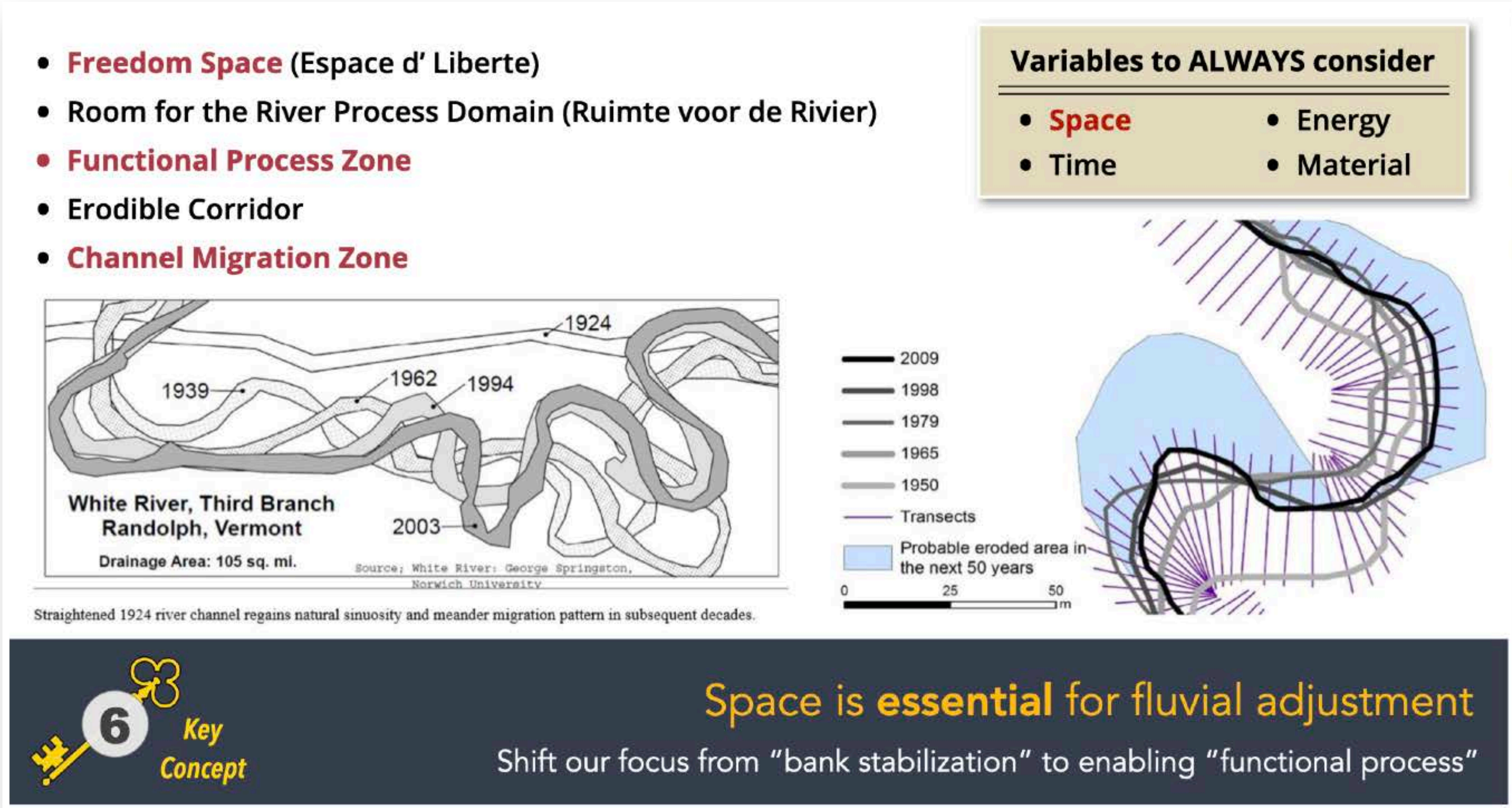


Figure 8. Adopting a river corridor approach to planning and maintaining roads, bridges, and other infrastructure is based upon the understanding that rivers must have space. They naturally erode their banks and deposit sediment, often skating back and forth across the valley bottom. This behavior reflects the streams striving to achieve equilibrium between the energy provided it by water discharge and how steep it is and the amount and type of material delivered to the channel throughout the year. The images illustrate just how much gravel bed rivers in Vermont and Pennsylvania change from decade to decade.

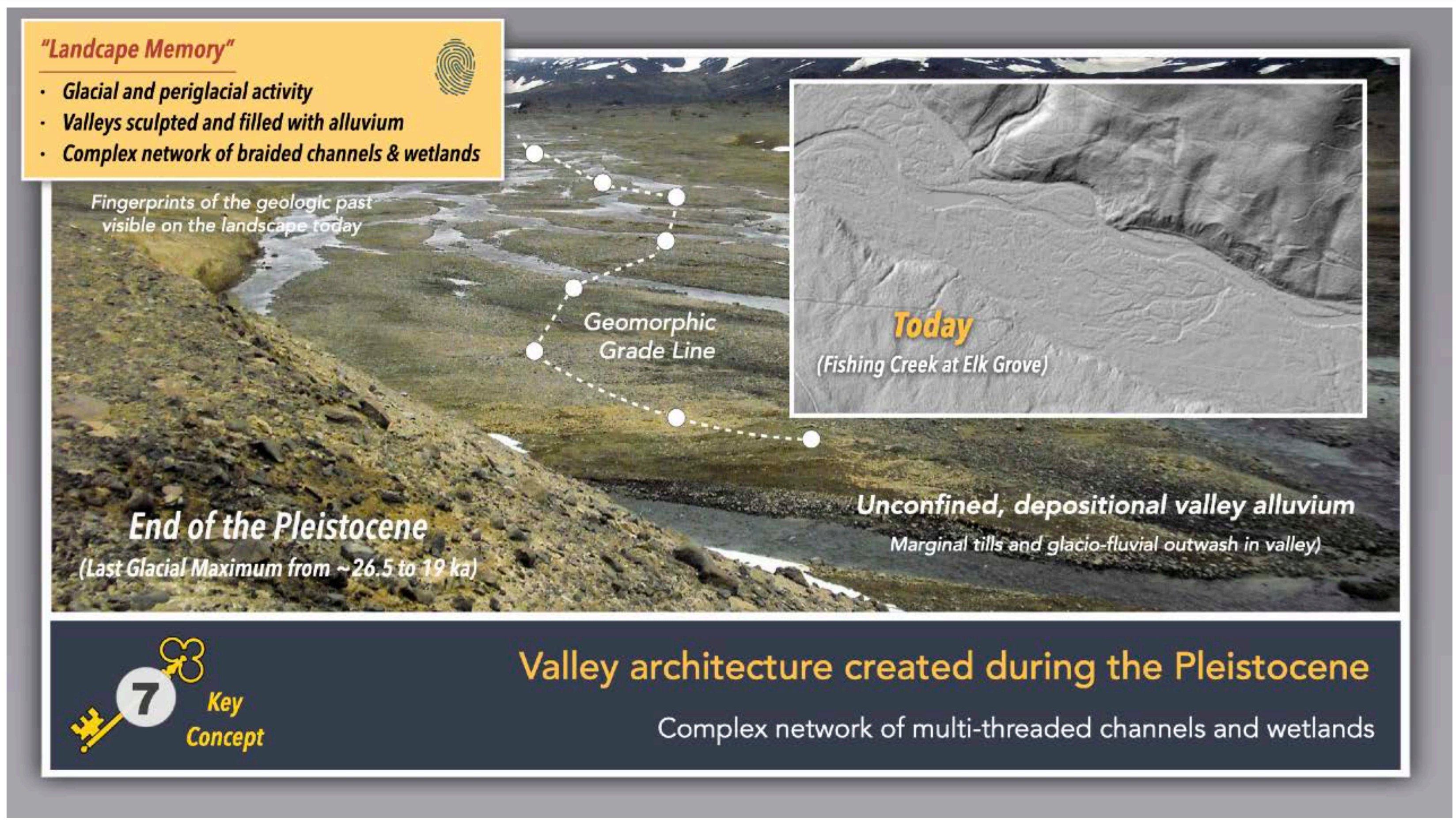
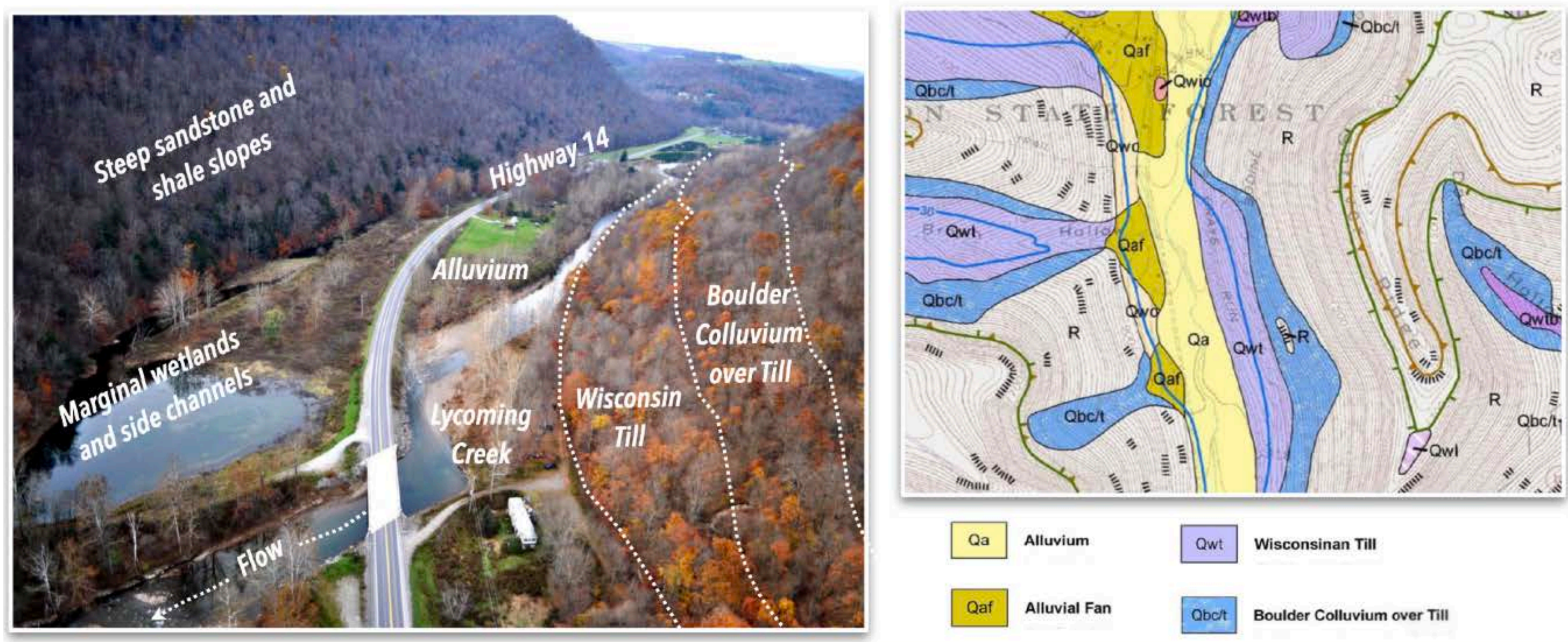


Figure 9. The valley architecture - the width, gradient (slope), channel pattern, and groundwater-table configuration for streams in northern Pennsylvania was largely determined by the end of the Pleistocene period, when the massive ice sheets retreated northward. Massive quantities of water and sediment in the meltwater fill the valley floors with as much as 150 ft of coarse sand, gravel, and boulder "alluvium." A complex network of multiple stream channels and wetlands remained on the floodplain surfaces, which often have distinct levels or "terraces," reflecting multiple glacial epochs over the past million years. These events are "remembered" by the landscape as evident in the Lidar images shown for Fishing Creek in the upper right. The fingerprint of these glacial processes remains evident on the landscape today.



7 Key Concept

Broad alluvial valleys with glacial tills manteling steep hillslopes

Sediment source areas not only in the channel but in valley margins, alluvial fans, and colluvium

Figure 10. Lycoming Creek and Highway 14, the only access route to homes in this valley for over 40 miles (left). Superimposed on the photo are labels pointing out the complex multi-threaded channel-wetland complexes that cover the valley floor. During floods, waters jump across the valley (avulsion) occupying areas near homes and bridges The geologic map (right) shows the valley fill deposits in yellow, the hillslope colluvium in gold, and pockets of loose glacial till mantling the bottom of the hillslopes. During prolonged rains, such as the Tropical Storm Irene and Lee (August-Sept 11, 2011), waterlogged sections of this till slumped into the valley bottom as landslides, where the river undercut the slope during the flood.

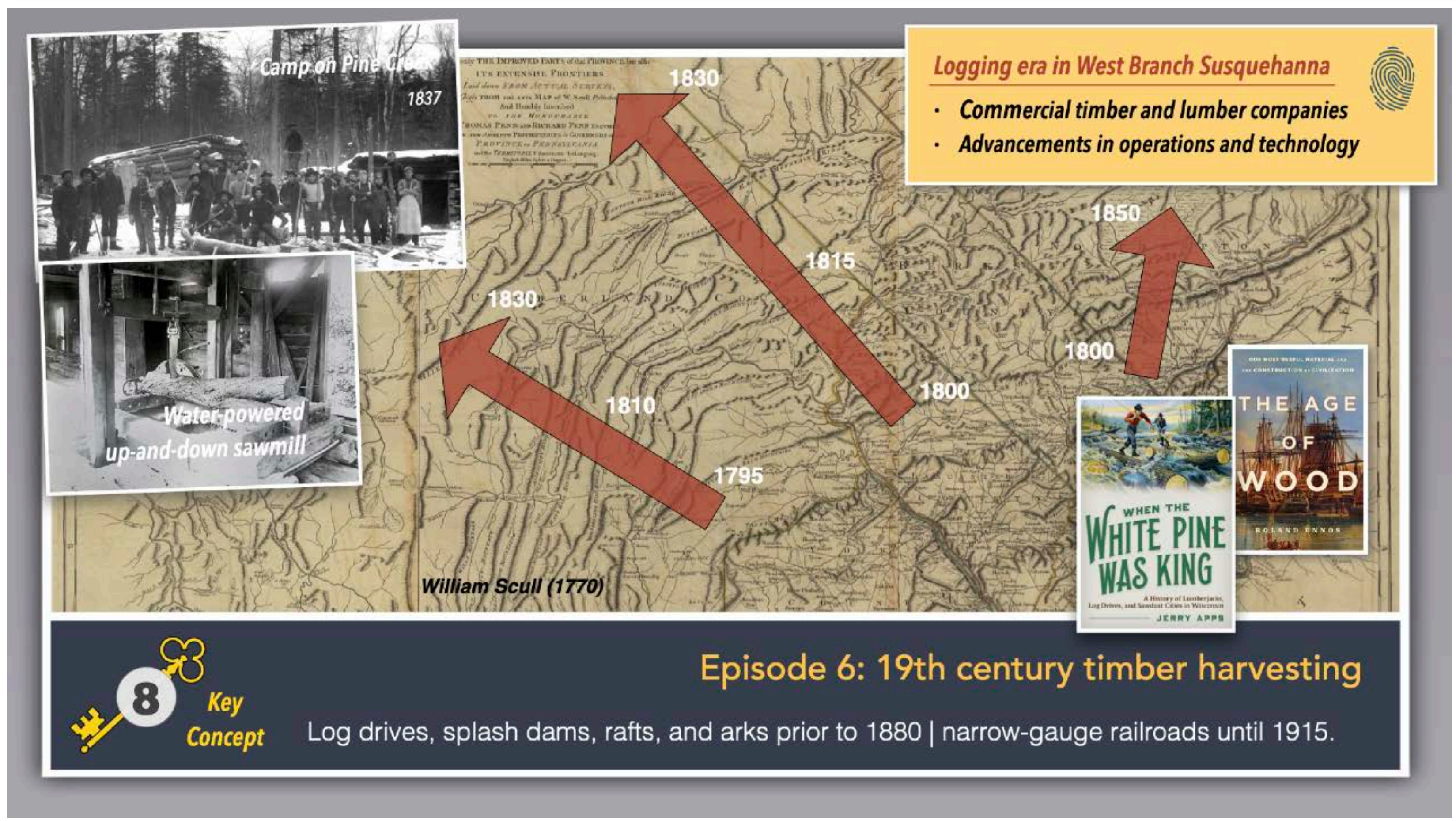


Figure 11. Beginning in the early 1800s, timbering companies had developed the technology of how to cut and transport large amounts of wood from the forested watersheds in northern Pennsylvania down to lumber mills along the Susquehanna and all the way down to the Chesapeake Bay. Records from the Tabor Museum and Williamsport document that the largest log drives in the United States took place on the West Branch of the Susquehanna River, making Williamsport the "lumber capital of the world." In 1860s, the state legislature declared all streams in Pennsylvania a commercial transportation routes, which ushered in the greatest period of log drives, arks and rafts, and stream modification in the history of the United States.

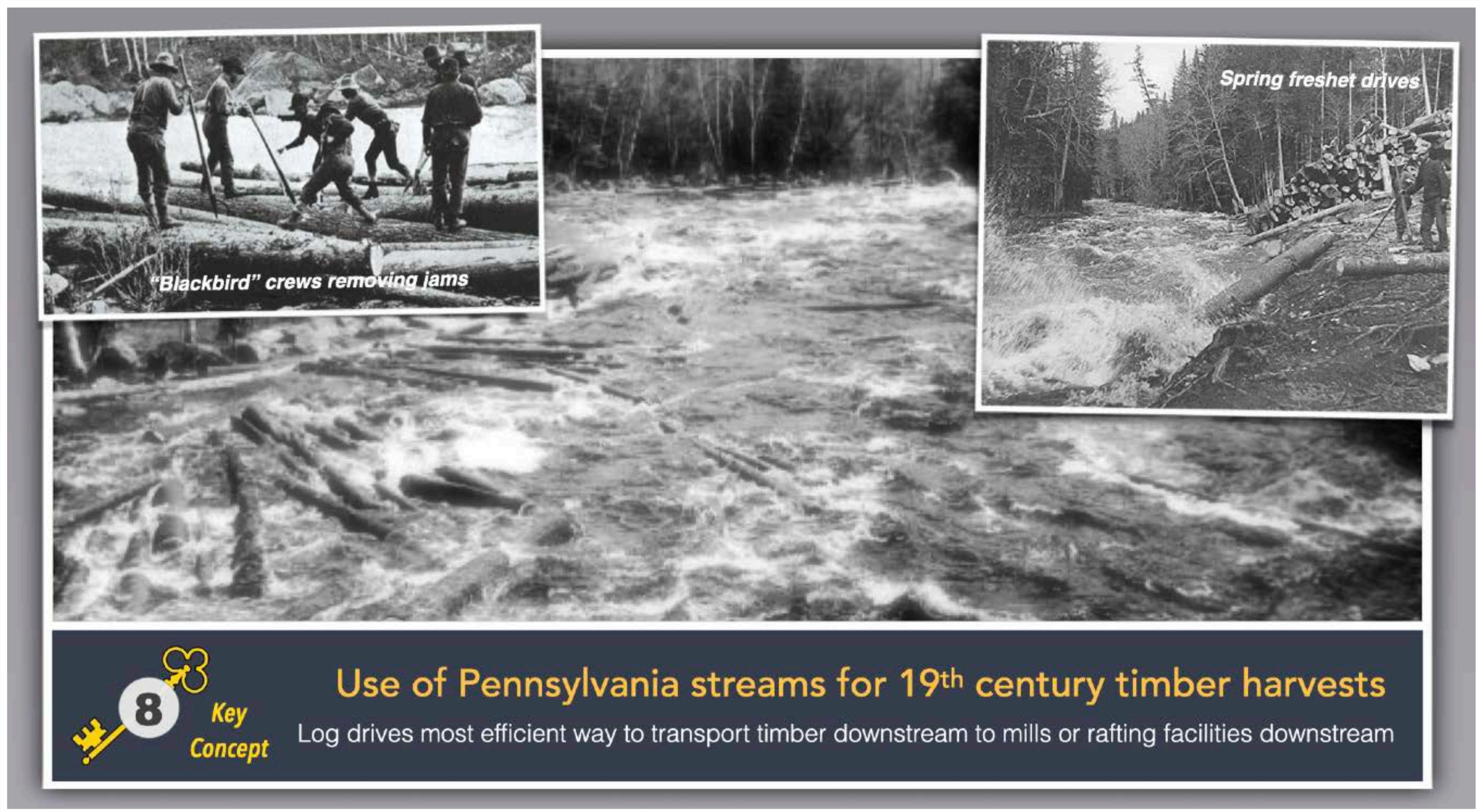


Figure 12. Log drives took place in the spring, following snowmelt and freshets, where logs that had been cut during the previous winter months were stacked in sidings along the stream bank at the foot of the hillslope. Logs would snag on rock outcrops, boulders, and other obstructions, and the elite "blackbird" crews would break up the jams using their spikes and pevees. Eliminating these obstructions became top priority for the timber companies, so that during the dry fall months, crews will walk the stream and mark where it should be dredged of boulders, logs, and other natural features.

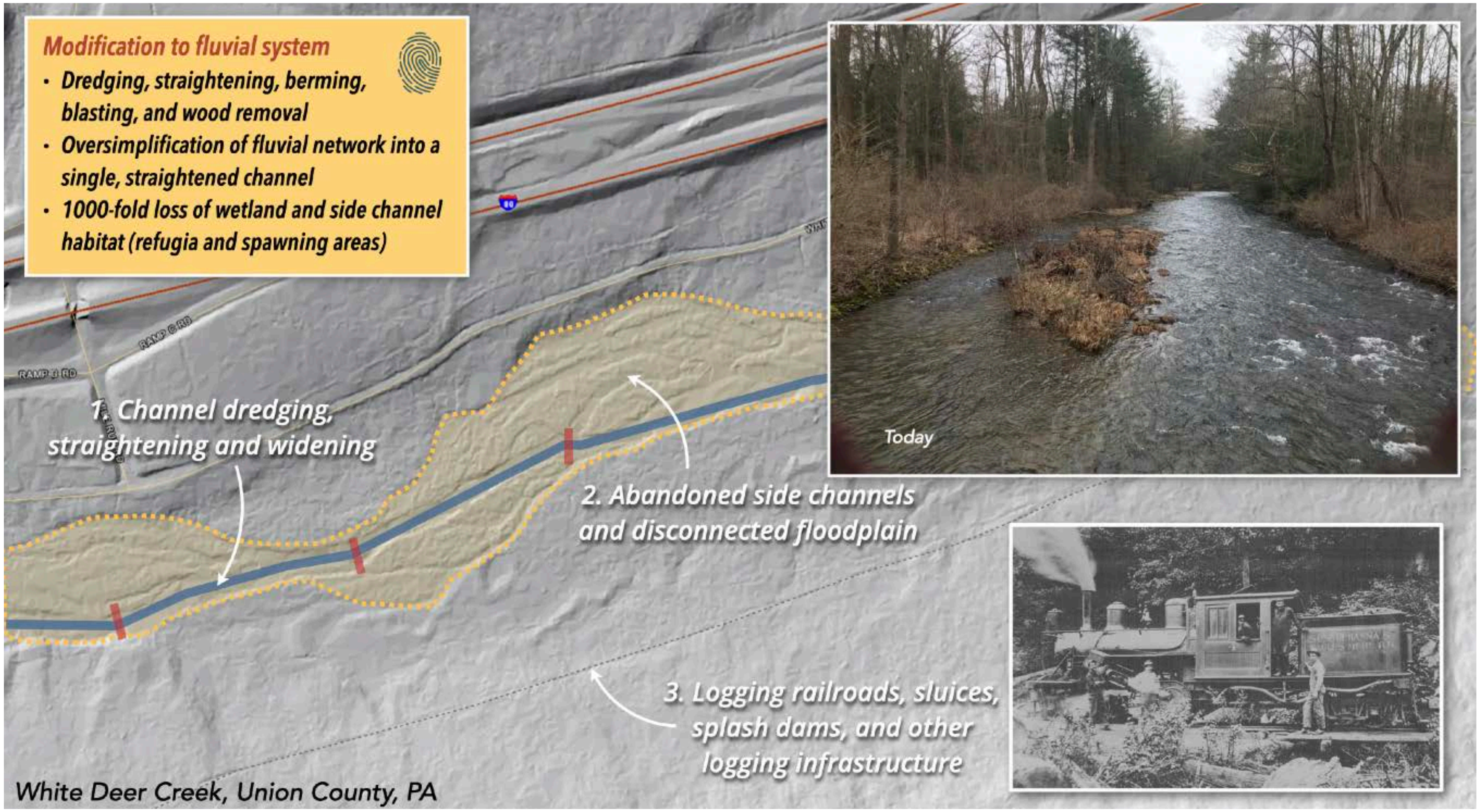


Figure 13. By the mid-1800s, wholesale modification of the streams was underway to facilitate log drives: (1) channels were dredge and straightened, (2) converted from braided, multi-threaded pattern to an oversimplified single channel, thereby disconnecting the stream from its floodplain, (3) by the late 1800s, after the invention of the steam engine, narrow gage railroads were built up the valley sides to transport logs from the headwaters down to mills and sorting facilities near the Susquehanna River, where they would be assembled into rafts and arks that were floated down to the Chesapeake Bay.

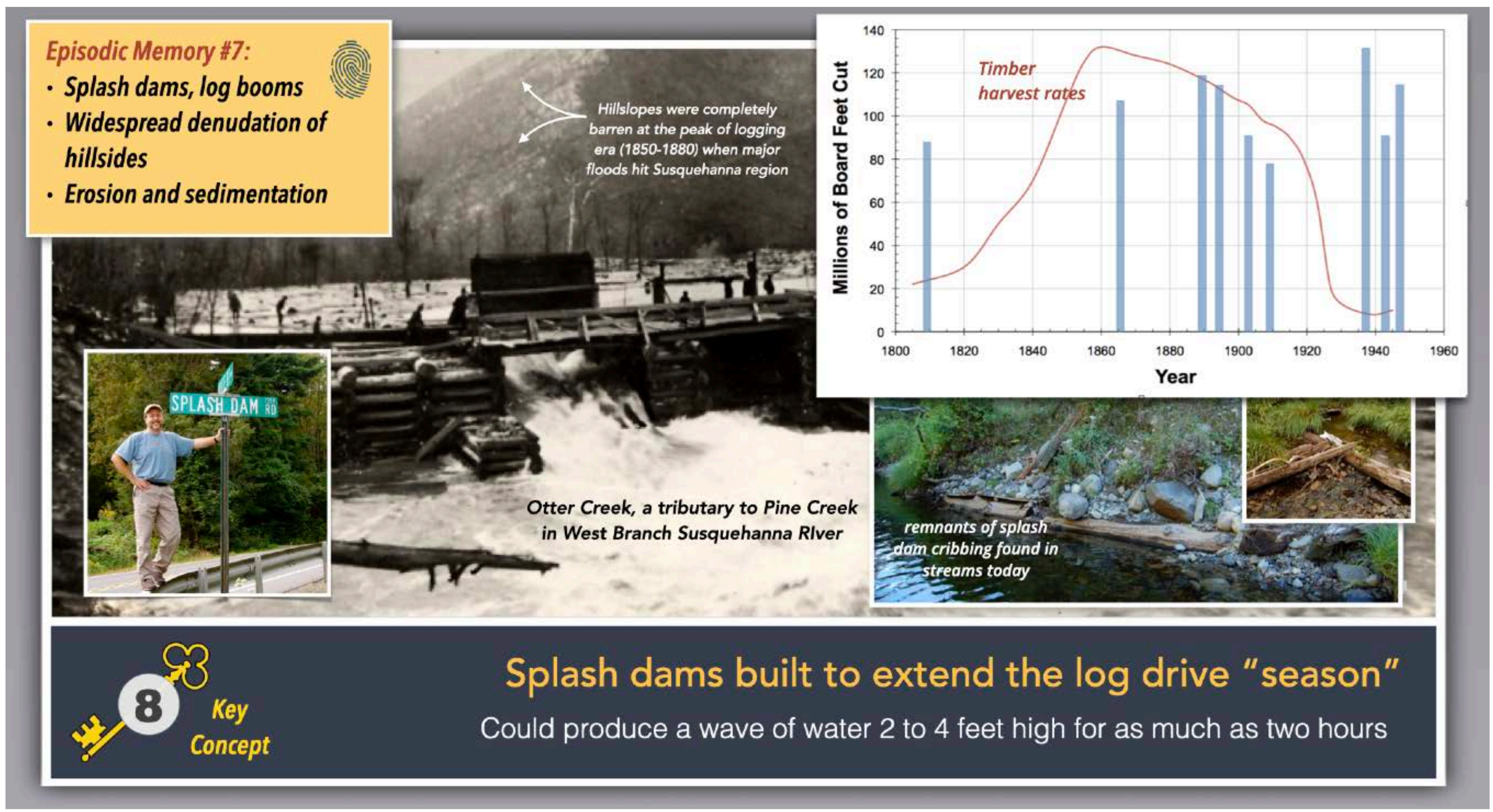


Figure 14. To extend the log driving season into summer months, temporary "squirt" and more-permanent "splash" dams were built on remote tributaries. The splash dams would hold water behind a wall of logs, some equipped with sluice gates, that could be lifted to create waves of water as deep as 2 to 4 ft that lasted several hours. The picture in the background shows a splash dam built on Otter Creek, a tributary to Pine Creek on the West Branch Susquehanna River. Note the barren hillslopes in the background; eventually the region was completely denudated and referred to as the "Pennsylvania Desert." . The graph in upper right shows timber harvest rates (red line) and major floods in the Susquehanna watershed. Just as the hillslopes were bare, major floods washed millions of tons of sediment down the hillslopes and delivered it to the tributary streams and valley floor.

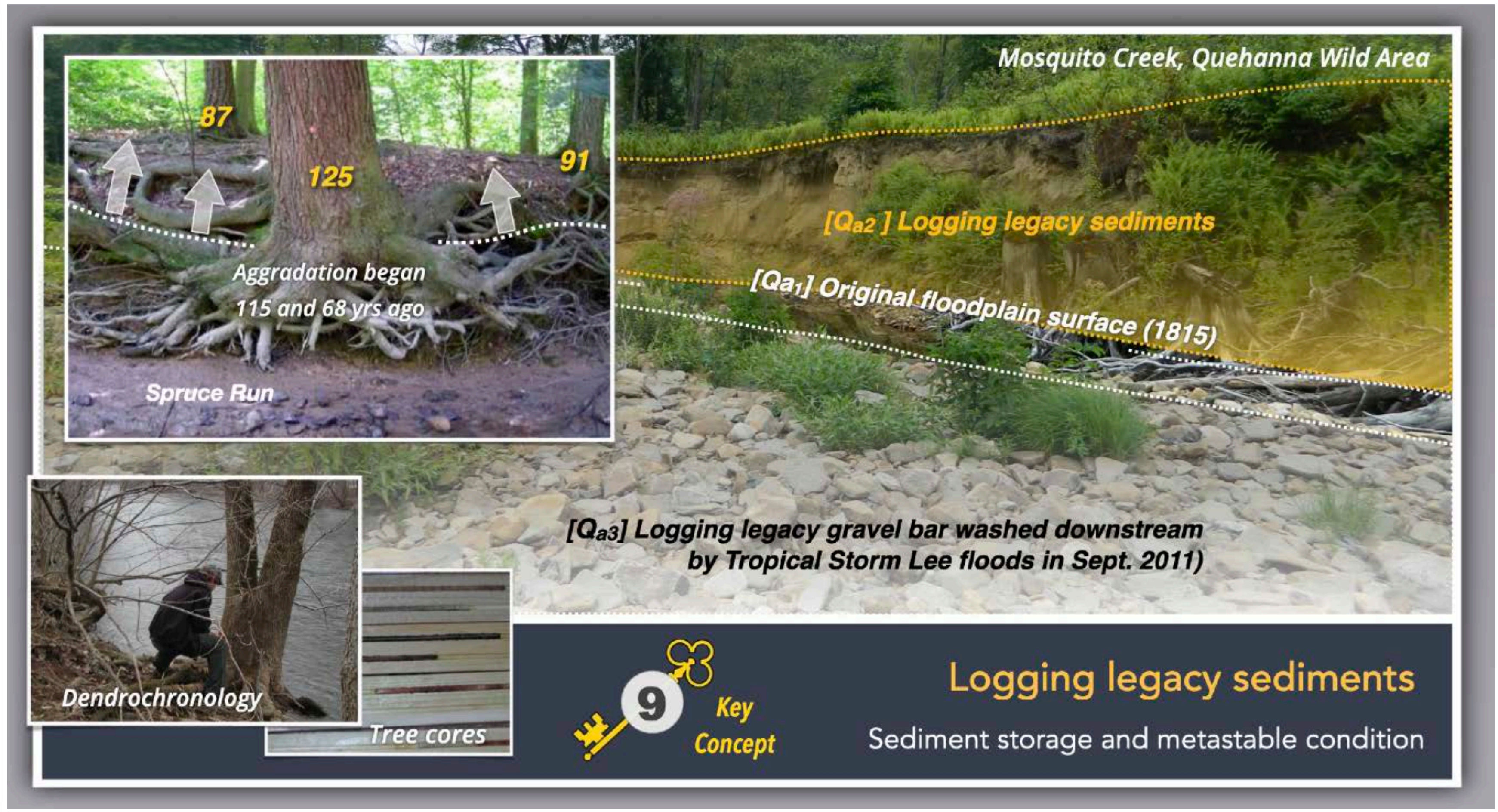


Figure 15. These logging "legacy" sediments are visible in the valley bottoms today. The background photo shows a thick accumulation of sediments behind a splash dam built on Mosquito Creek in the Quehanna Wilderness Area. The legacy sediments buried the original pre-logging era floodplain. Tree rings (dendrochronology) is used to date the timing of this sedimentation (lower right). In the upper left shows a cut bank of one stream showing how trees buried by the logging legacy sediments developed advantageous roots. Numbers are the ages of the trees. The streams had the capacity to "hold" the stress of these logging era sediments for decades, however after Hurricane Agnes, many of them cross a stability threshold and massive quantities of coarse legacy gravels began to flushed from the headwaters and began working their way downstream as pulses of sediment. A gravel bar deposited during Tropical Storm Lee is visible in the foreground of the photo.

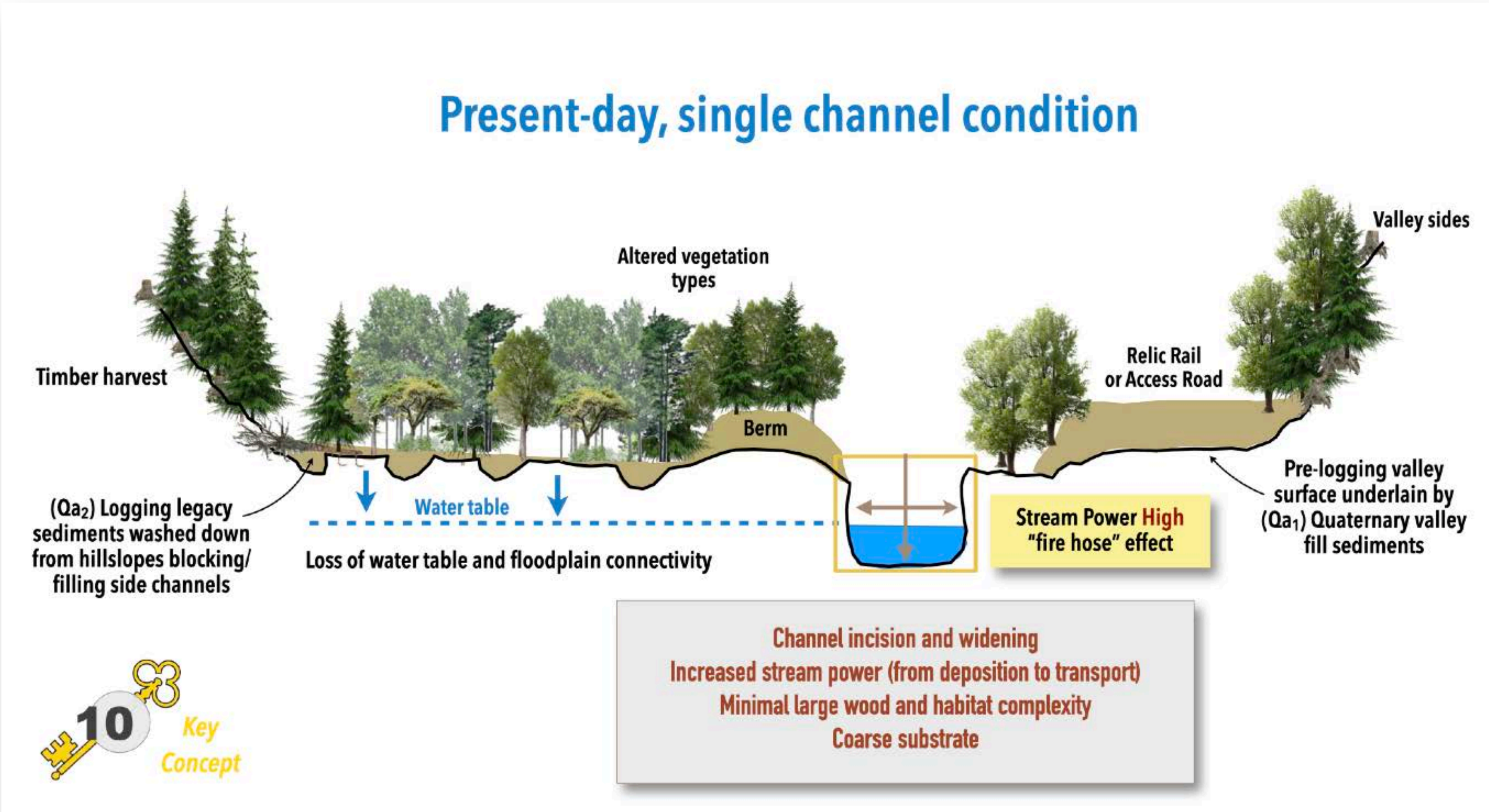


Figure 16. A schematic cross-sectional diagram of how these streams remain in a degraded condition today, out of balance and equilibrium, and prone to rapid channel adjustment during floods. It mainly is due to the fact that dredging, deepening, and berming of the streams to facilitate log drives keeps the channel disconnected from its floodplain. Floods cannot spread out onto the floodplain and be distributed to side channels, that remain perched above the present-day channel. Marginal wetlands and valley bottom habitats remain a fraction of what they used to be and many are filled with legacy sediments. The oversimplied, single-channel system continues to deepen and widen as flood waters act like a "fire hose" during peak discharges. Also, because the bed of the channel is lowered, the groundwater table remains depressed, reducing baseflow to the stream during the drier summer and fall months.

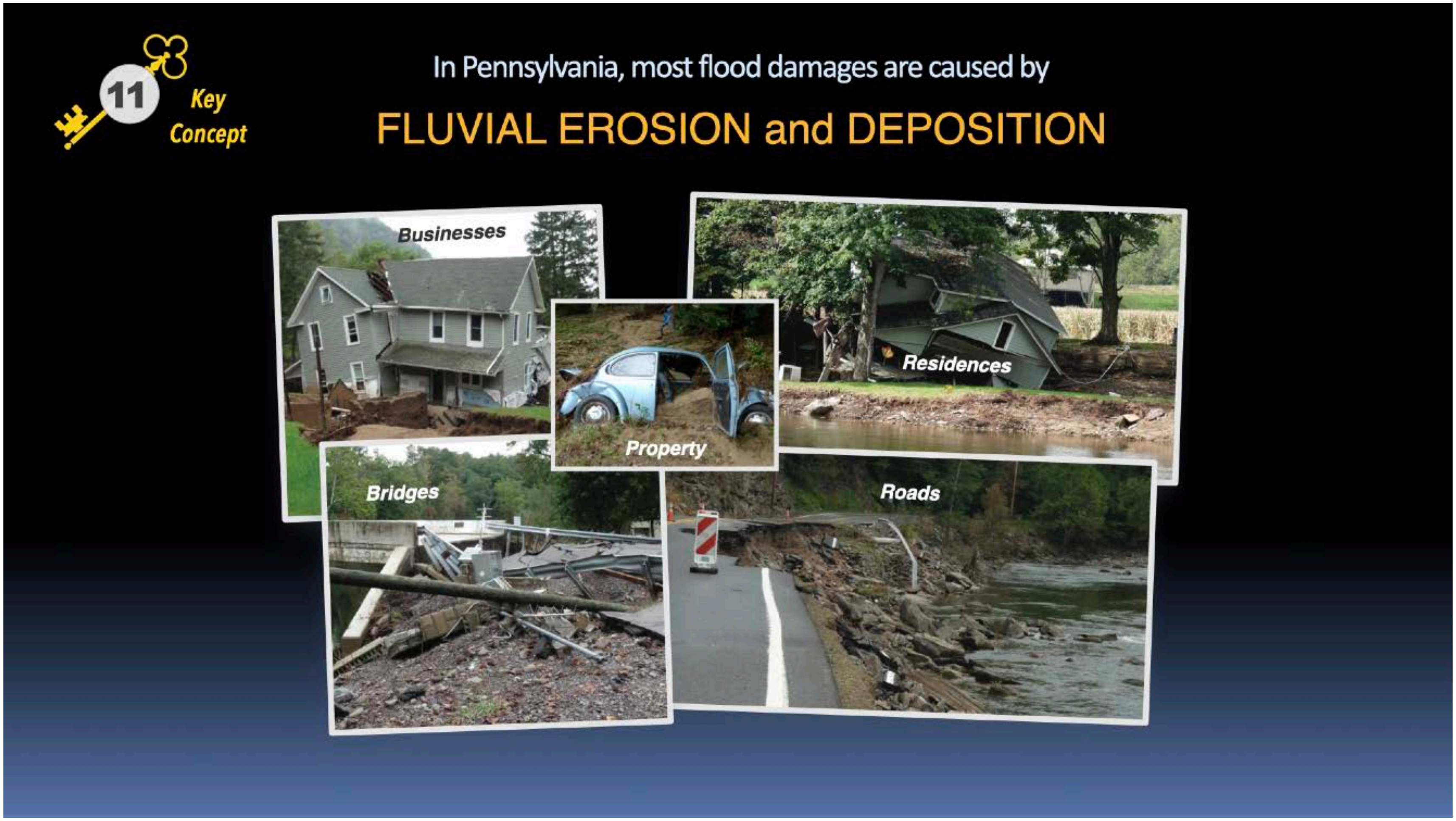


Figure 17. Developing flood mitigation and stream maintenance programs that incorporate these understandings is critical to reducing the costs of floods in Pennsylvania. PennDOT and insurance companies report that fluvial erosion and deposition are the number one cause of property damage. A more nuanced understanding of how gravel bed streams in the northern tier behave during floods can help planners, engineers, and first responders anticipate sections of the streams that need protection and other sections of the stream that need space to adjust during floods.

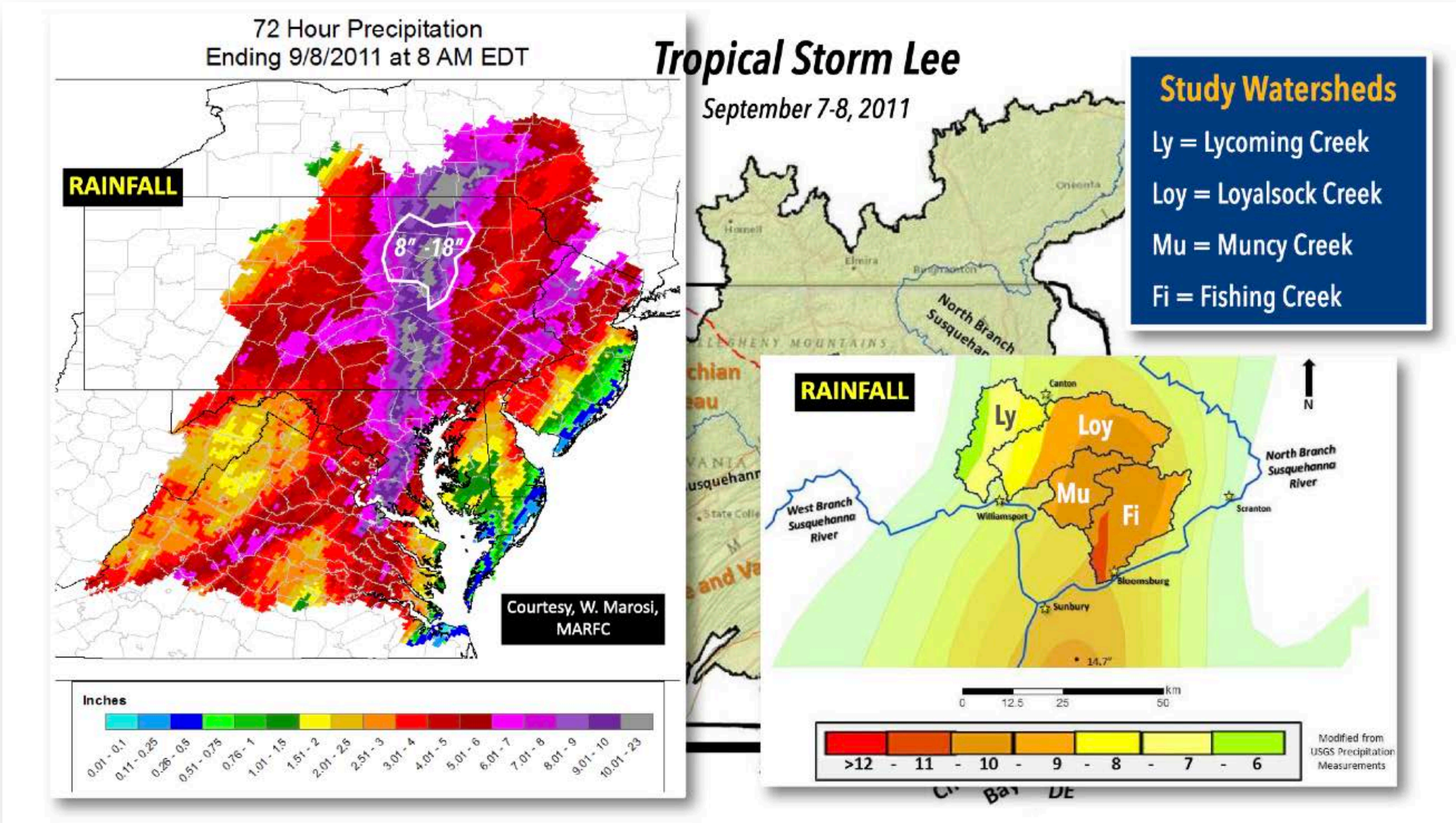


Figure 18. Map of central Pennsylvania showing the distribution of Tropical Storm Lee, an "atmospheric river"that swept up the Chesapeake and Susquehanna River just a week after Tropical Storm Irene had soaked the region. Hillslopes were already saturated, streams flowing above normal discharge and high water tables, meant that antecedent conditions were such that the steep, narrow watersheds in north-central Pennsylvania were vulnerable to catastrophic flooding and channel change.

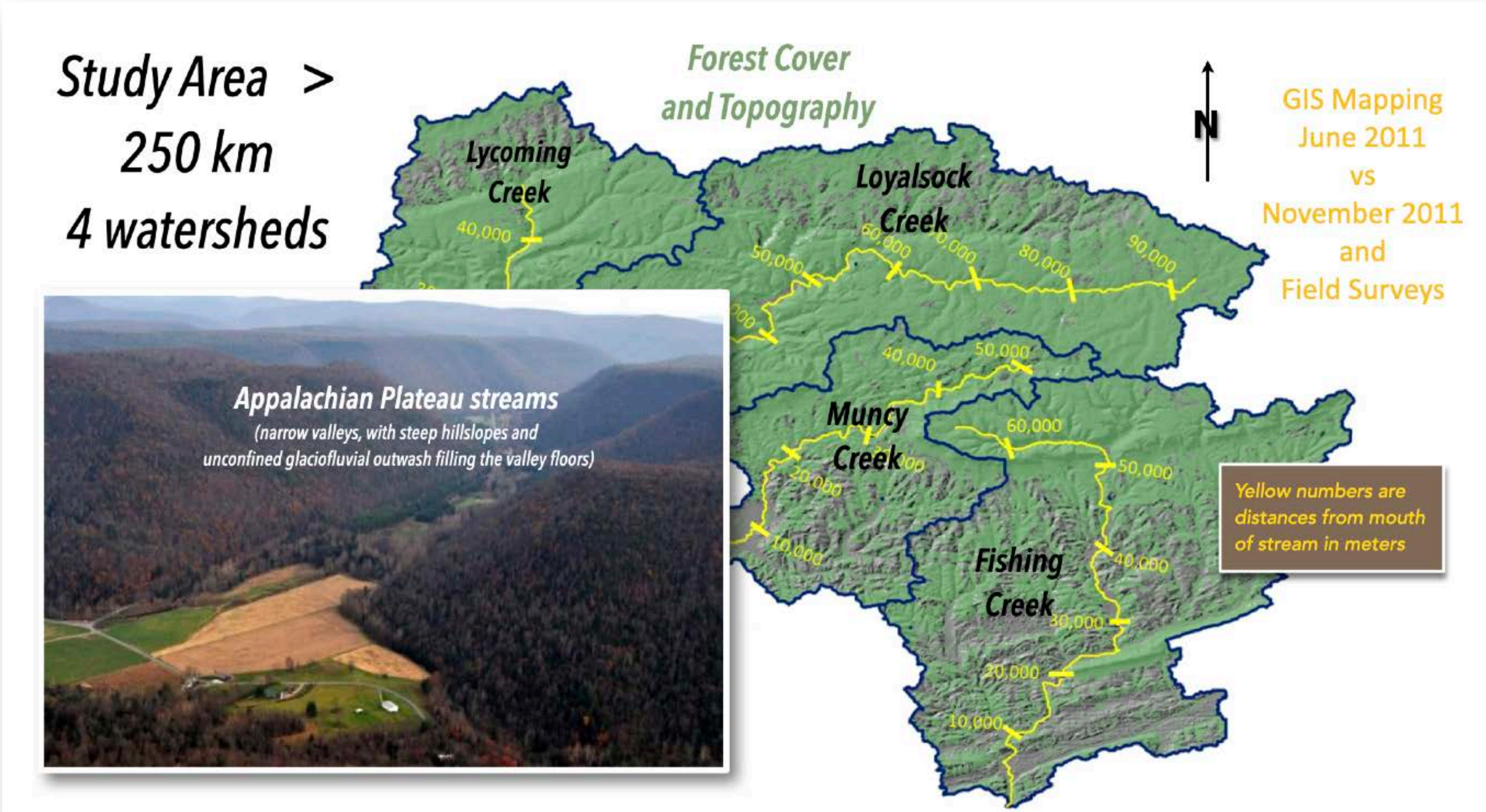


Figure 19. Following Tropical Storm Lee, geomorphology professors from Bucknell University (R. Craig Kochel and Benjamin Hayes) and their students conducted a detailed study of four watersheds impacted by flooding - Lycoming Creek, Loyalsock Creek, Muncy Creek, and Fishing Creek. Their study involved aerial flyovers by helicopter, ground surveys, and detailed mapping using geographic information systems (GIS) software. The data and findings were published in the journal Geosphere under open-access privileges, meaning it available for free to the public.

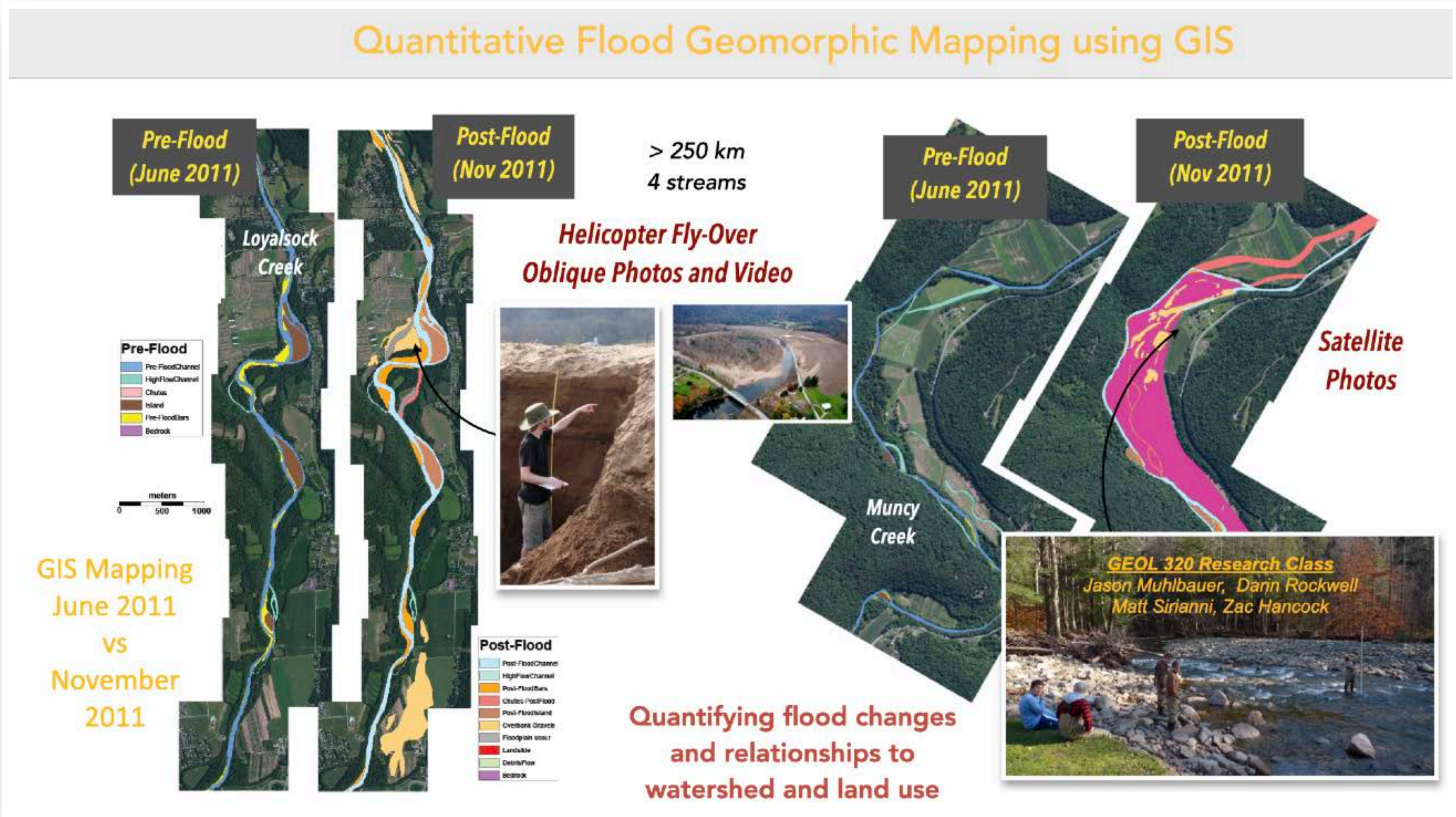


Figure 20. This slide provides an example of the data and maps produced in the study. The digital maps in the GIS software were combined with notes from the field surveys to quantitatively assess the amount of erosion and deposition that took place during and after the flood, as well as document how the network looked before and afterwards. Oblique photos and videos taken during the low-altitude helicopter floods were combined with aerial photographs (Google and Bing satellite images) as well as Lidar digital terrain data to determine change in three dimensions.

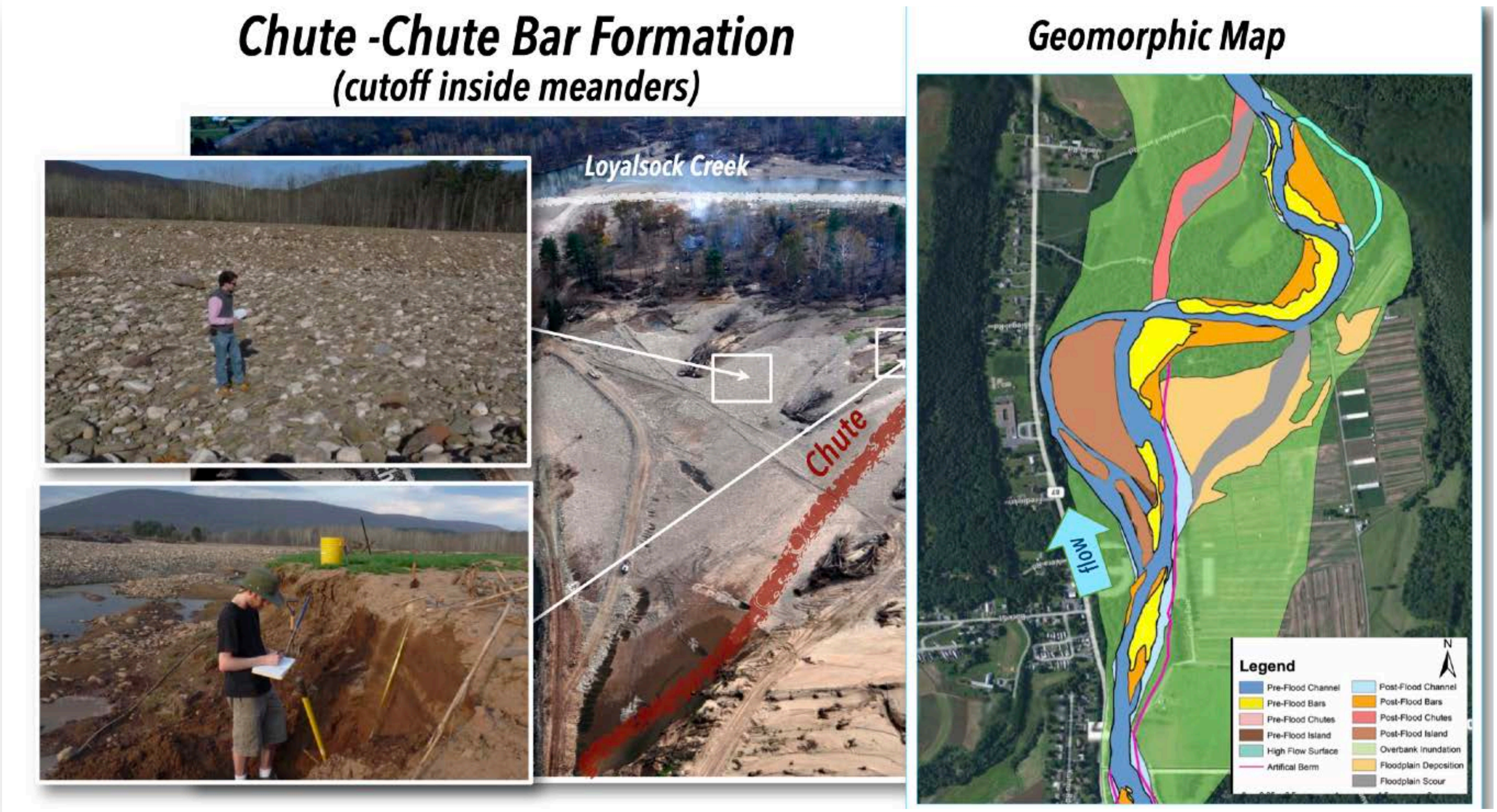


Figure 21. Photos and maps showing catastrophic change as massive amounts of sediment and water in Lycoming Creek worked its way past the area near the Game Commission Farm. As much as 4 feet of sand and gravel were deposited over tens of acres of cropland and the stream eroded "chutes" or side channels on the inside of meanders, cutting off the river and in other places fill the former channel and newly-carved chutes with bars and lag sediments deposited during the waning stages of the food. The geomorphic map on the right shows the degree to which the channel reoccupied old side channels that it used to accommodate flood flows in the historic past, before the channel was straightened and bermed in the 1800s.

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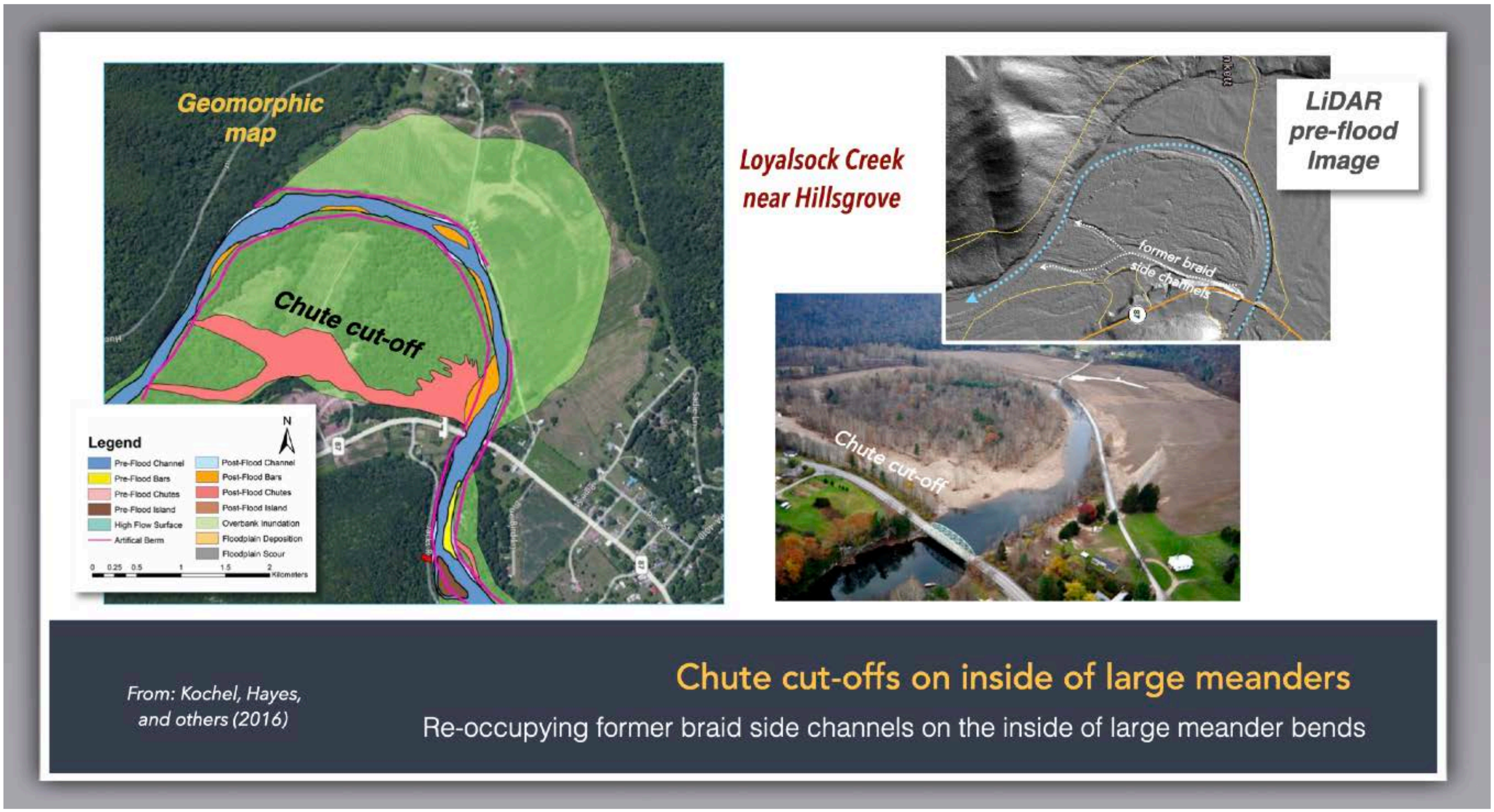

Figure 22. Another example of "chute cut-offs," which was the dominant way flood waters in the main stem rivers (Loyalsock Creek near Hillsgrove in this example) caused property damage. With so much energy, the stream erodes a "chute" or channel in a former side channel on the inside of the meander (visible in the Lidar image in the upper right). This newer "chute" channel essentially cuts-off flow in the outside of the meander of the main channel, hence the term "chute cut-off."

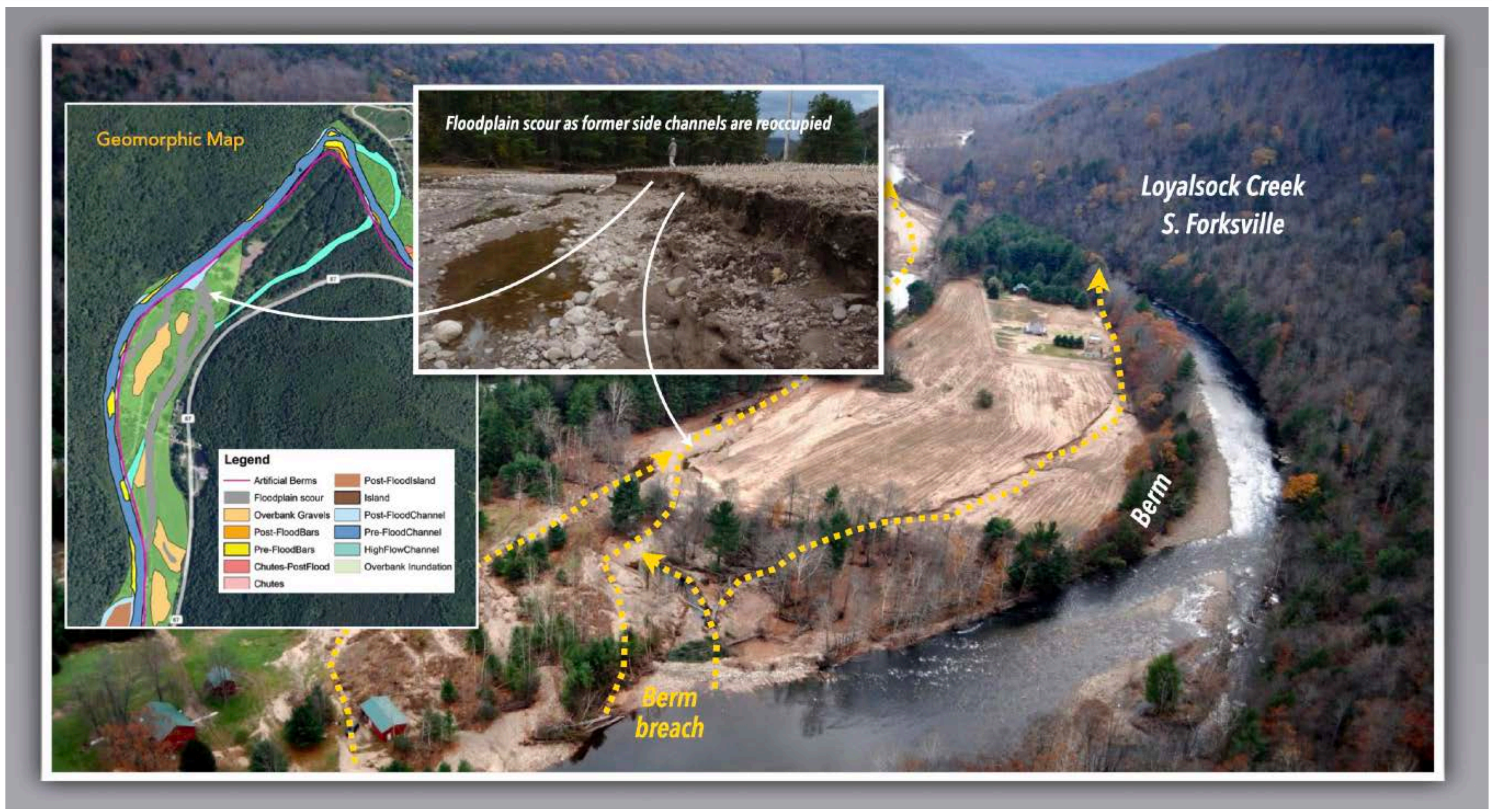

Figure 23. Another mode of failure during major floods is the breaching of relic logging berms, which allows flood waters to carve new channels across properties on the insides of the meanders, threatening homes and destroying farm fields in these locations. The Lidar images (lower left) reveal that prior to the construction of these berms, the river used to flow there.

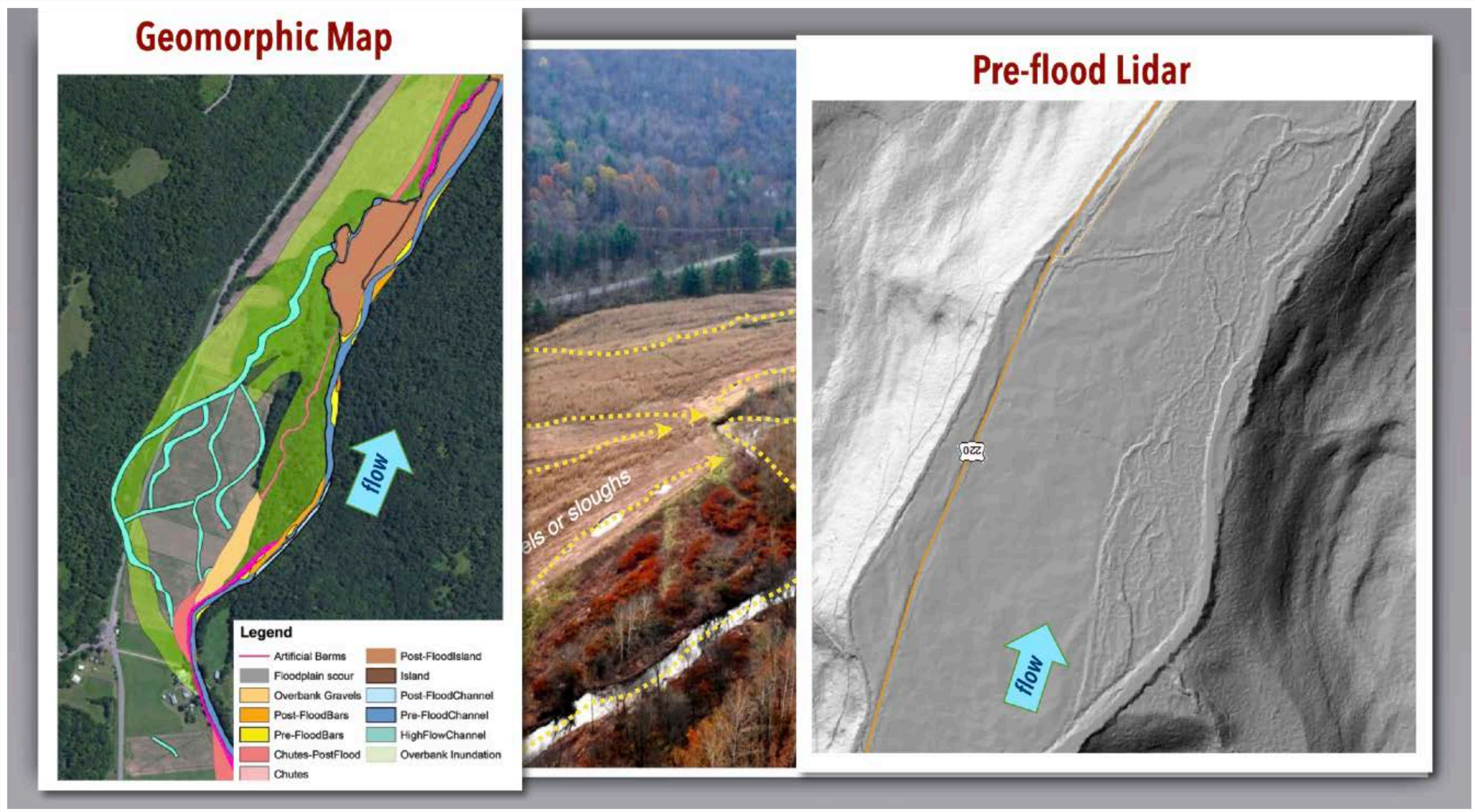

Figure 24. A view of Muncy Creek, showing the naturally multi-threaded braided channel pattern that existed for thousands of years prior to European settlement and the conversion of the valley bottoms to farmland and transportation routes. During major floods, the streams in the northern tier are in a state of disequilibrium as they adjust to the logging legacy sediments making their way down the system, both changing the gradient of the stream (steeping it) and pattern of the channel. Streams are reoccupying their former side channels to adopt a braided pattern, reducing flood peaks downstream, creating new aquatic habitat across the valley bottom, and sequestering orders of magnitude of carbon and food for aquatic life and health of the river.

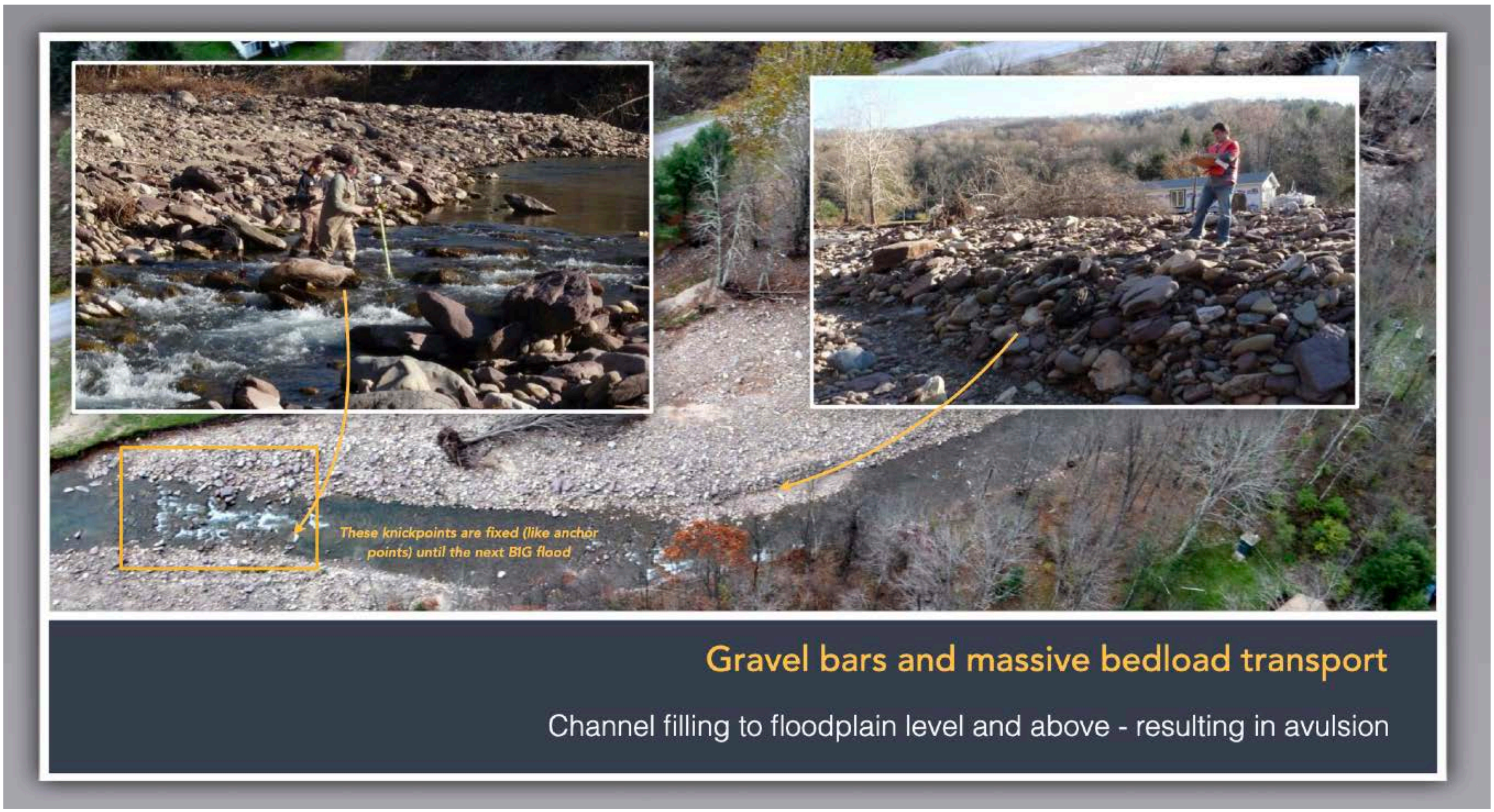

Figure 25. The steeper headwater tributaries are especially prone to sediment erosion and transport during major floods. his image shows the degree of floodplain stripping and subsequent new gravel bar deposition that can take place within one flood event. The size and amount of boulders moved during these floods is staggering. Many of the boulder clusters will remain in the channel to act as grade control structures until the next major flood. Adjustments in the gradient (slope) of the channel is one way braided gravel bed rivers rapidly respond to floods. The streams appear to be establishing a new equilibrium channel gradient, blasting away relic logging dams and structures that impeded this adjustment and seeking a new channel gradient and pattern that can accommodate modern flood magnitudes..

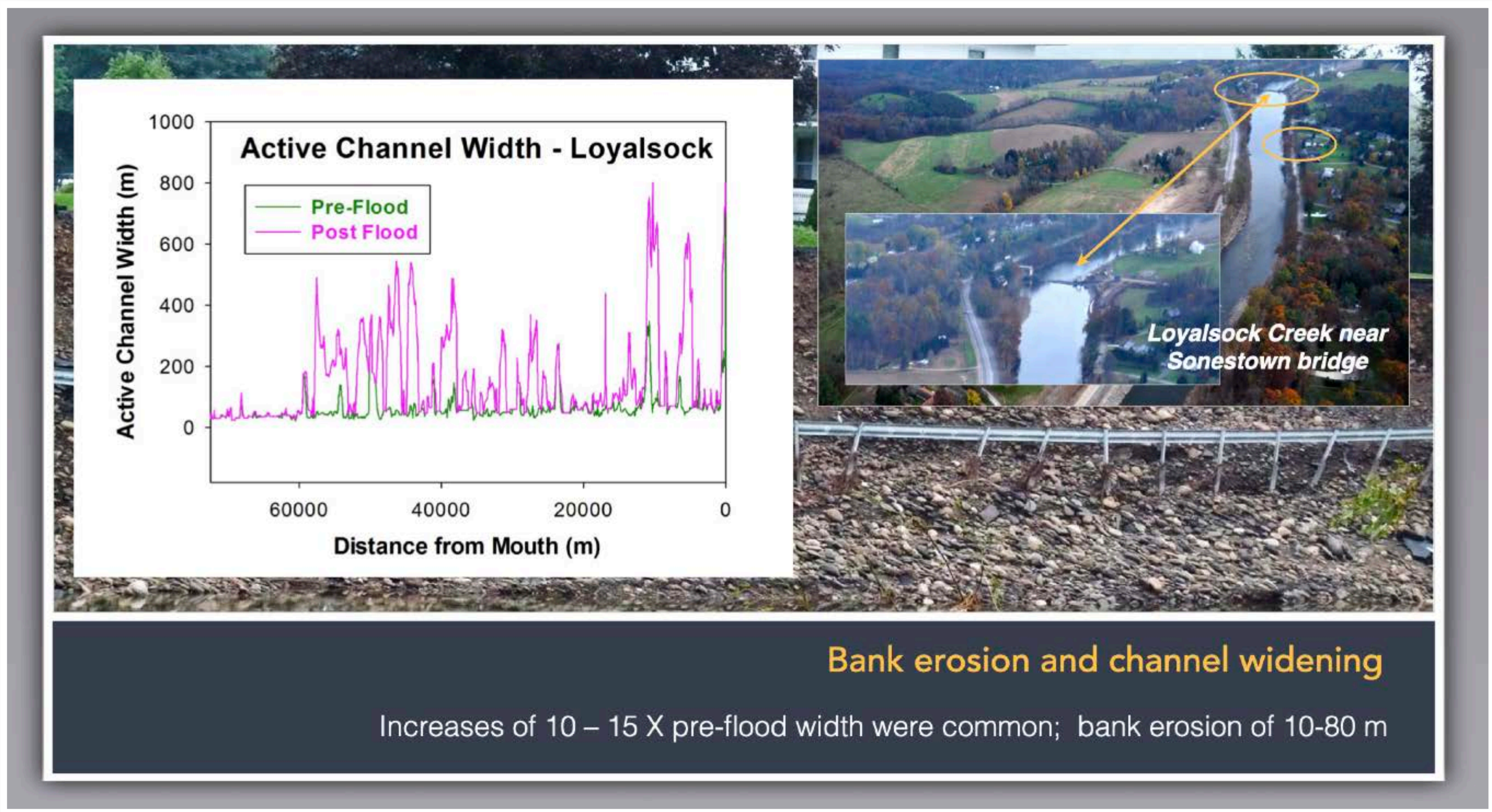

Figure 26. In addition to eroding its bed to establish a new channel gradient or slope, in sections of the streams that have been straightened and aligned to protect infrastructure (roads and bridges), the streams tended to accommodate the flood energy by eroding their banks, widening their cross sections and causing bridge failure, undercutting of banks and destruction of roads.

Figure 27. Glacial tills and unconsolidated colluvium cover the base of the hill slopes in many watersheds. These loose materials were weakened by heavy rains during Tropical Storm Irene and Lee and became unstable, slumping into streams that flowed closed to the toe of the slope. The landslides caused temporary dams of the tributaries and when these dams burst, a wall of water went rushing down stream with orders of magnitude more erosive and transport capacity of even the flood floes. In this example of Big Bear Creek, boulders the size of cars were transported over a half mile and deposited in imbricated fashion, like a stack of fallen dominoes.

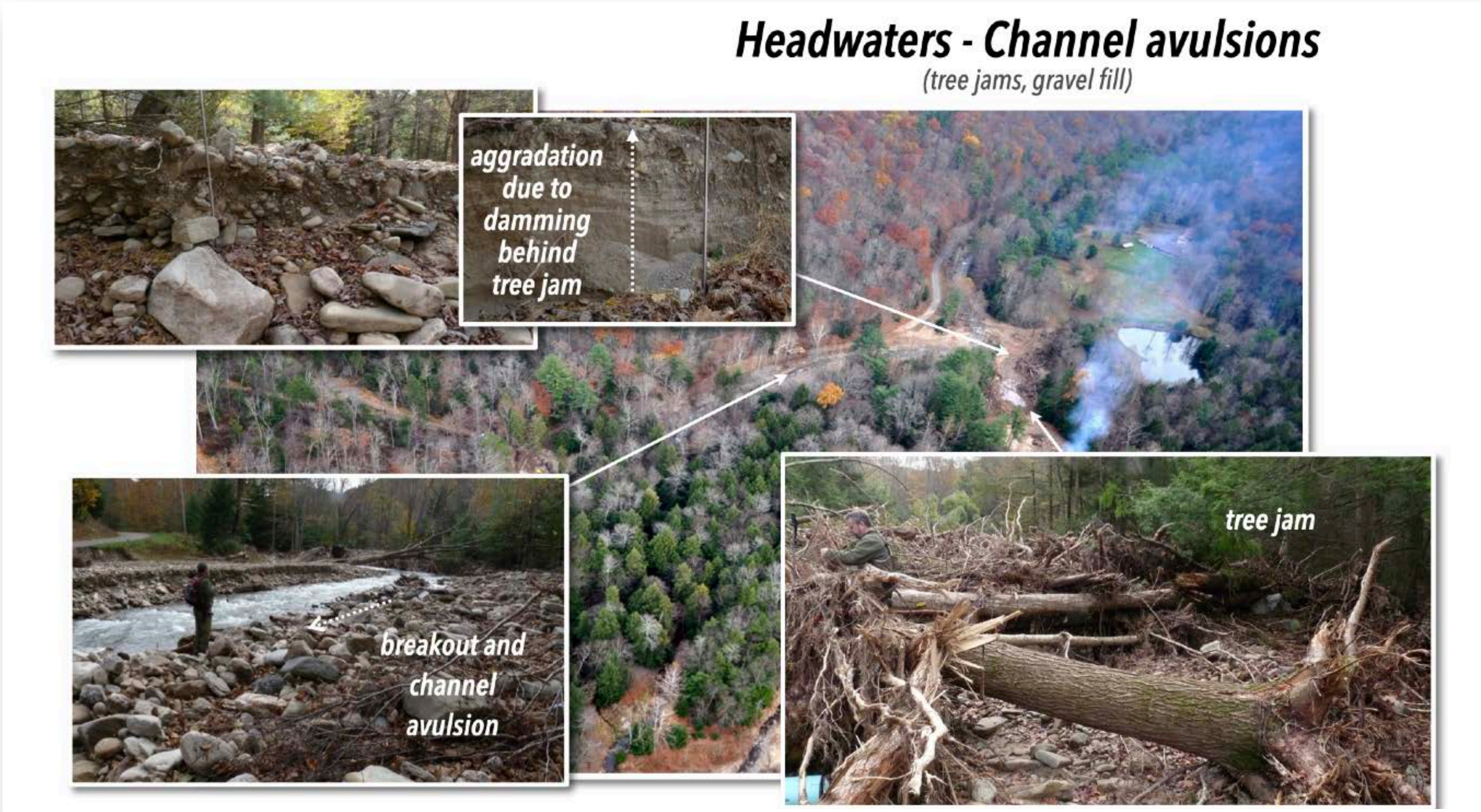

Figure 28. Headwater streams experienced "avulsion" where the stream channel becomes completely filled with tree jams and sediment, causing the stream jump out of its channel and reoccupy another area of the valley bottom. These breakout events initiate a complex sequence of jams, temporary damming of the stream, catastrophic breaching of the dam, massive erosion and deposition as the flood wave shifts to another part of the valley and makes it way downstream.

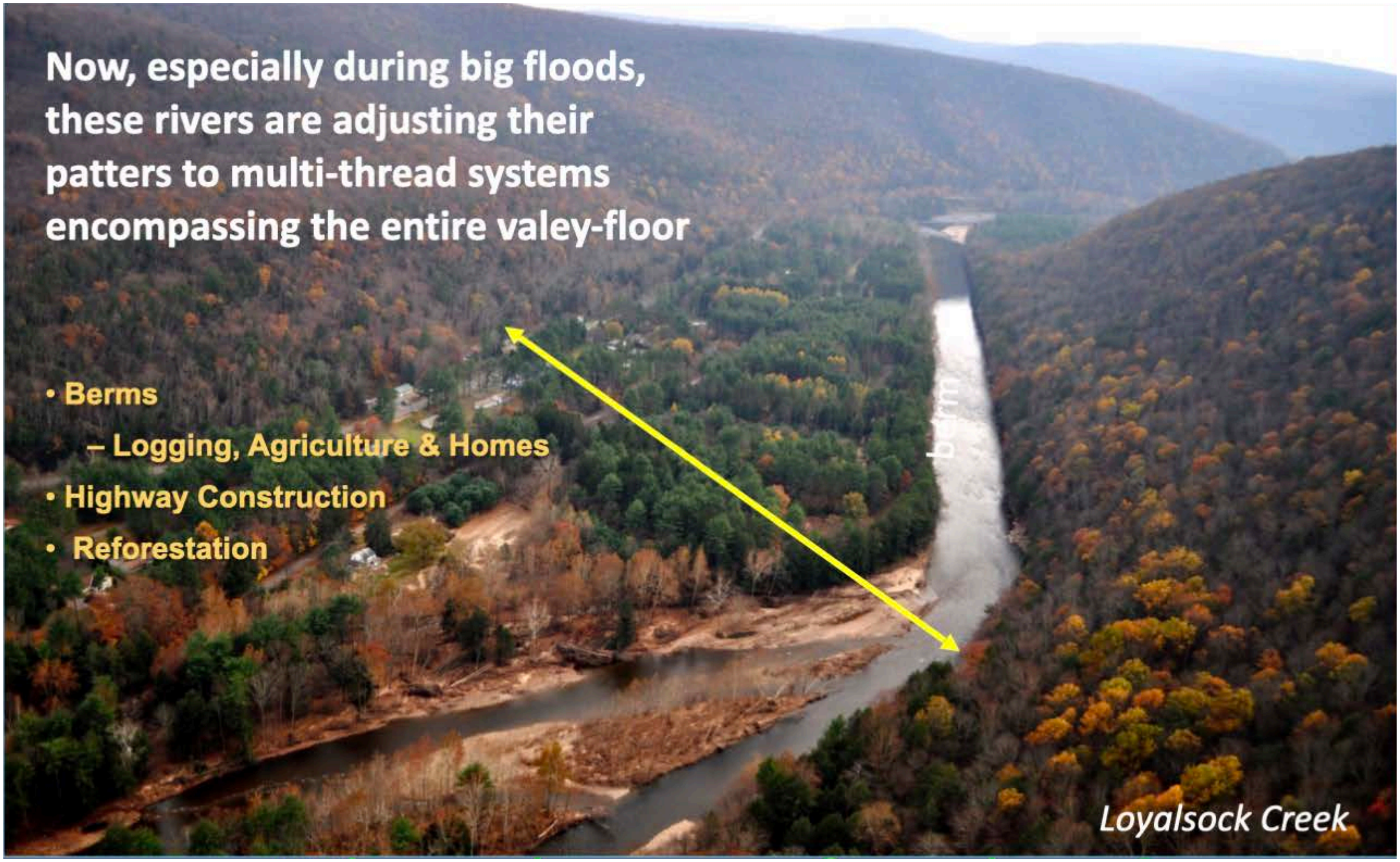

Figure 29. In the past we have altered the pattern of these streams, converting them from a naturally occurring multi-threaded state to an oversimplified single channel condition, primarily by dredging, straightening and berming them. Following threshold-crossing floods since Hurricane Agnes fluvial the fluvial system is out of equilibrium and can be expected to remain in an unstable, constantly shifting condition for decades to come.

Figure 30. Considering these changes as the fluvial networks seeks a new state of equilibrium provide the stream space for it to dissipate energy and store materials (wood and sediment) is critical. The need for the creation and/or expansion of riparian corridors is needed more than ever.

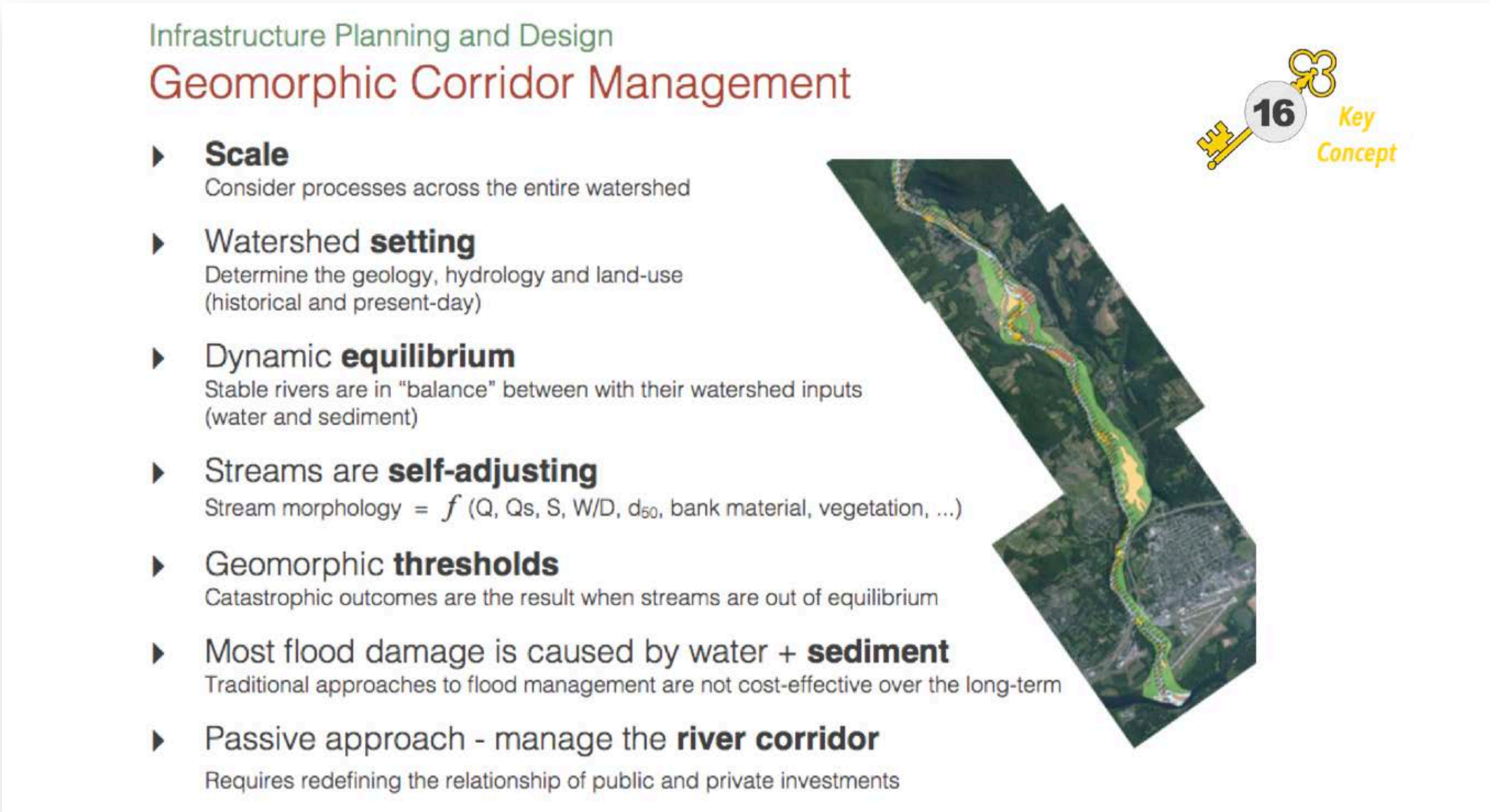

Figure 31. This slide summarizes several of the key concepts and findings presented earlier in the context of "river corridor" approaches to managing streams and rivers in the northern tier of Pennsylvania. This type of approach is adaptive and proving cost-effective, but not easy. It will require stakeholders and management agencies to create opportunities for knowledge transfer, the building of trust and understanding, recognition of property values and communities living within flood0prone areas, and funding mechanisms to set aside unstable sections of the river.

Figure 32. The practice of "stream cleaning" following major flood events can be traced back to the logging era when similar practices were done to get the logs and the flood pulses downstream and "out of the way" quickly. Channelization and dredging remained valid engineering practices taught at universities until the 1980s and are still practiced in some areas of the Commonwealth today. However, a long body of evidence and experience by civil engineers and stream restoration practitioners has demonstrated that in fact, stream cleaning makes things worse. Flooding and erosion are increased because the floodwaters are forced back into a single channel and not allowed to spread out into side channels and adjacent properties, allow the energy to dissipate and sediment to be deposited and stored. Moreover, aquatic habitat is completely destroyed, often for a decade or permanently. Healthy gravel bed streams that are native to north-central PA have multiple side channels that provide refuge for aquatic life during storms, spawning habitat for fish and amphibians, and much more surface area for biofilms and wood material to promote "nutrient spiraling," which helps reduce nutrient pollution to areas lakes and rivers downstream.

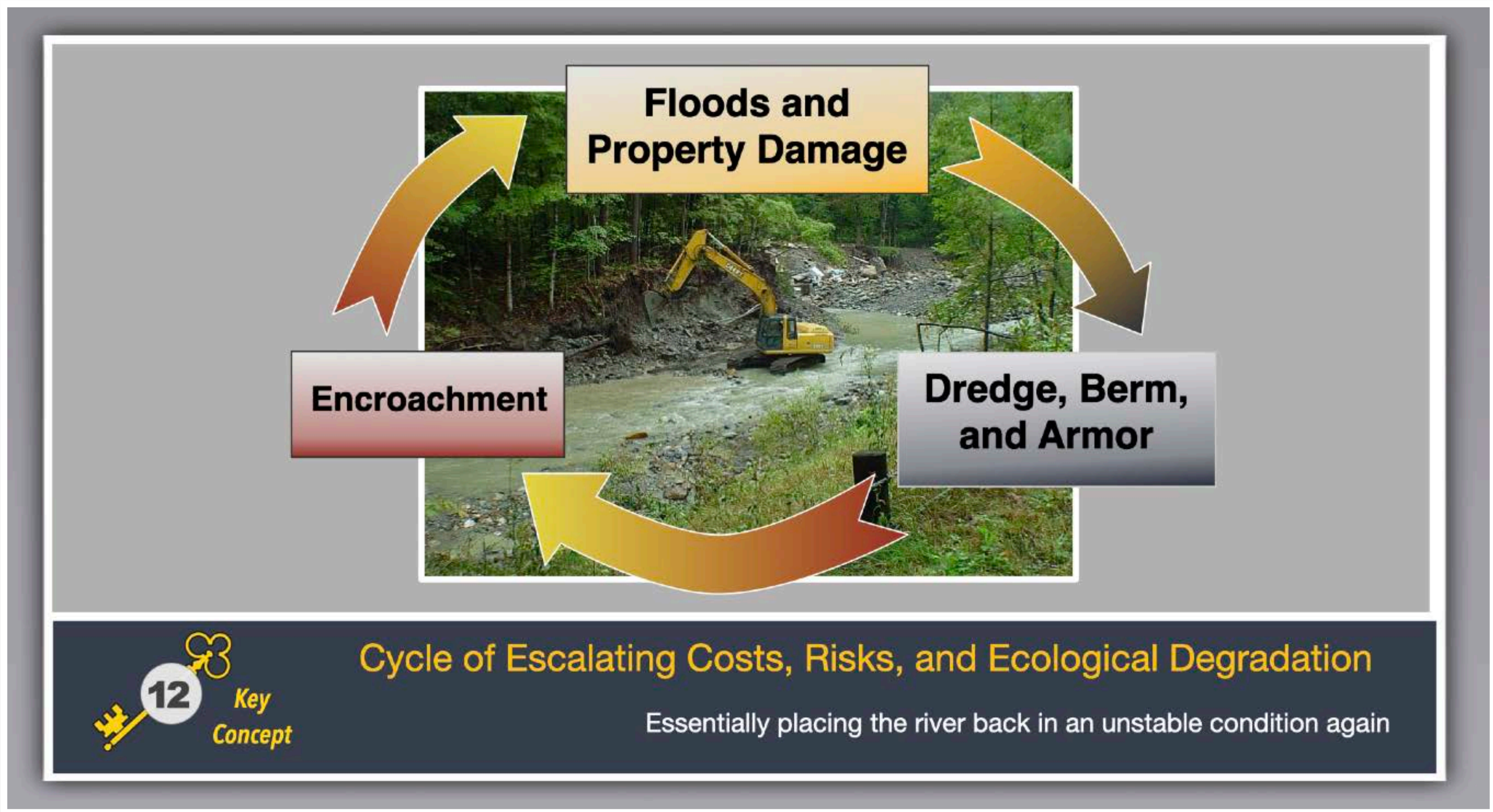

Figure 33. There will always be tension or conflict between (1) the need for highly dynamic streams such as those in the northern tier of Pennsylvania to have space to erode and deposit sediment and (2) the need to protect property and infrastructure. However, planners and watershed managers can incorporate much of the recent findings about how to focus attention on maintaining property and infrastructure (bridges and roads) in towns and communities along the rivers, but to stop (1) further encroachment of the river, (2) eliminate stream cleaning by individual residents or fishing clubs in remote tributaries, and (3) incorporate adaptive stream management, conservation, and restoration practices into their work.

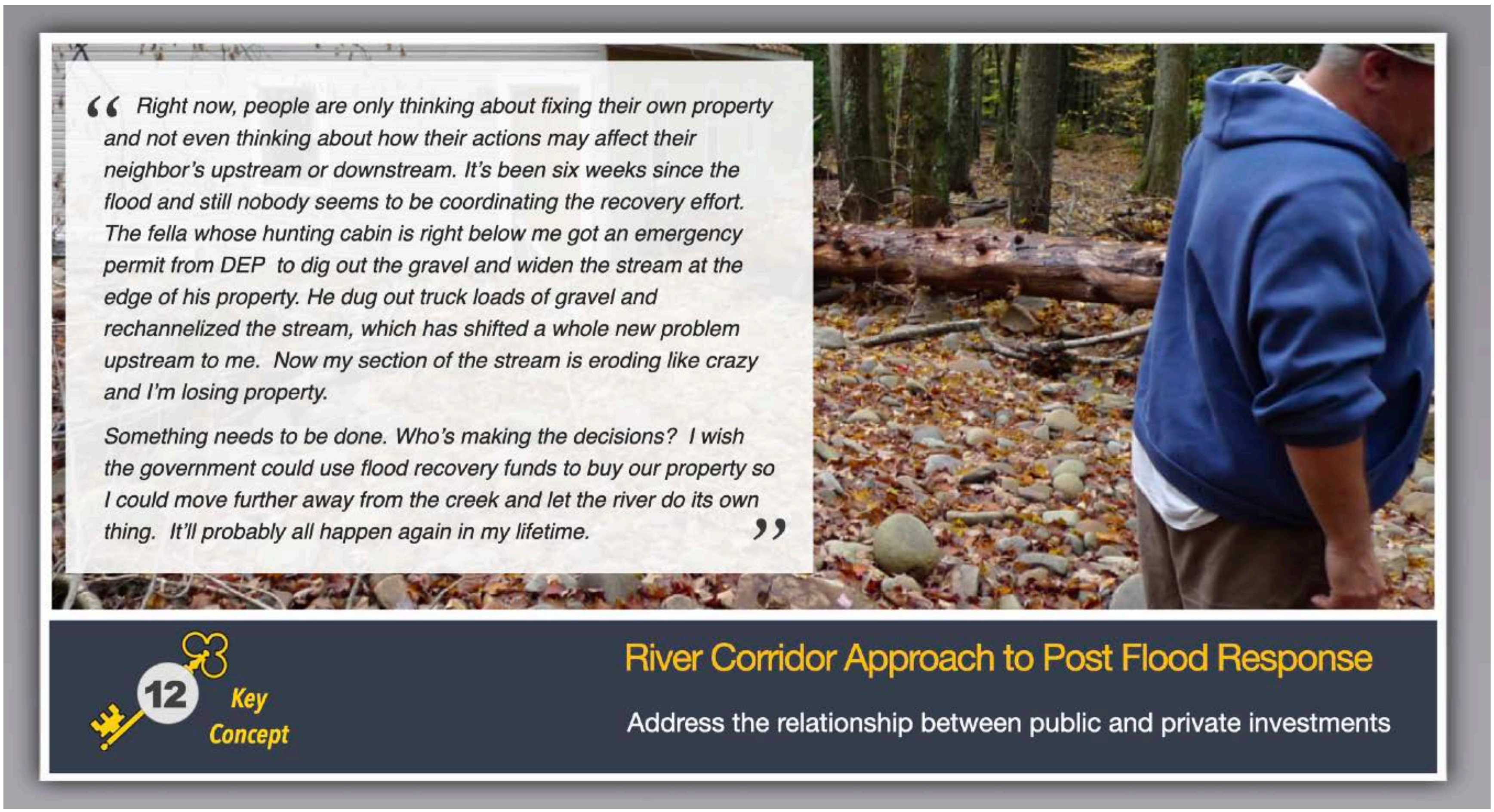

Figure 34. Adopting a river corridor approach described earlier ensures more organized and effective post-flood cleanup efforts.

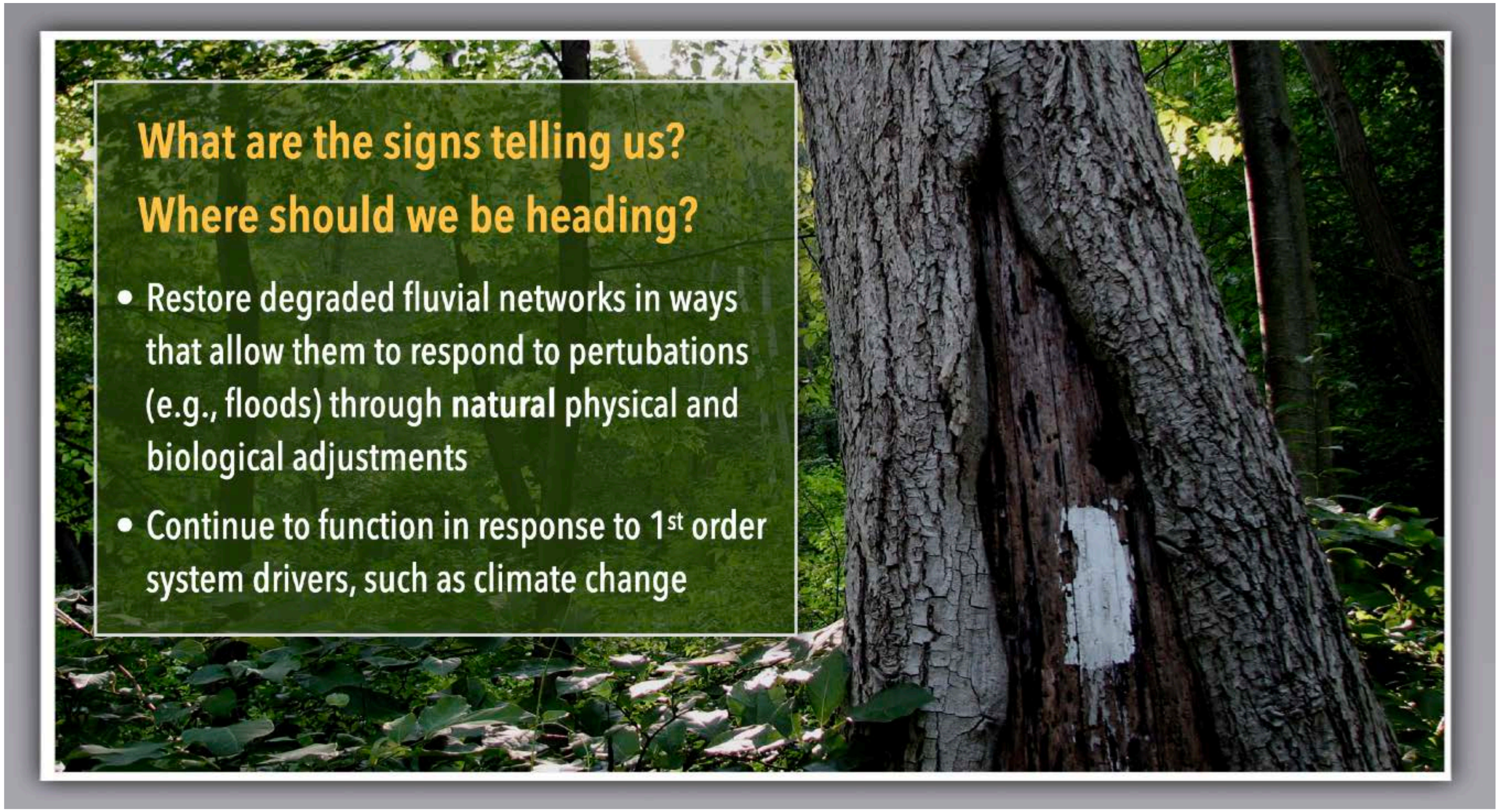

Figure 35. Two factors to incorporate into river corridor management plans for the near future.

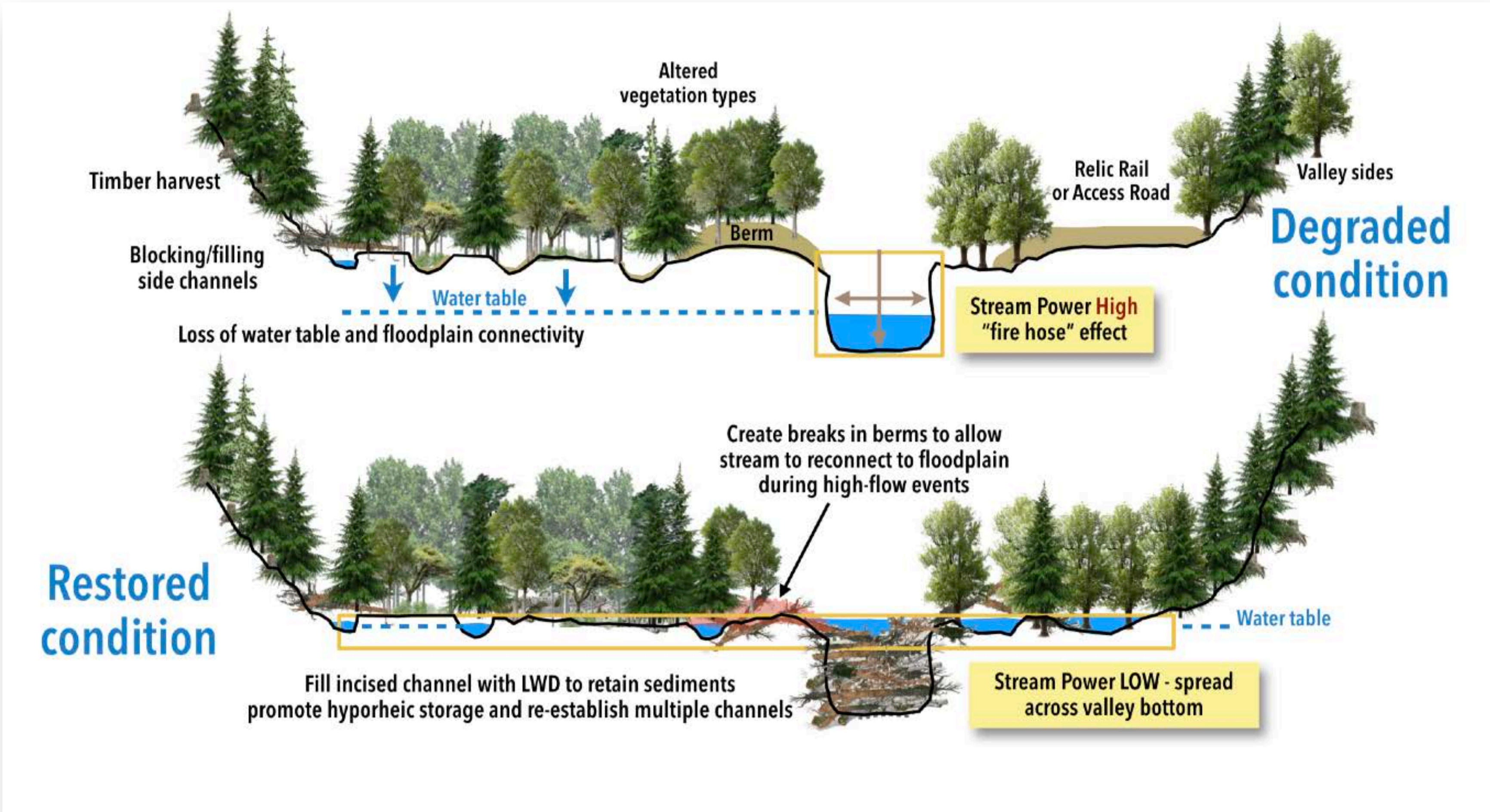

Figure 36. Stream restoration practices in northern-tier streams no longer focus on channel form, such as the building bank hardening structures (mud sills, j-hooks, weirs) or grade control structures (cross-vanes, W-weirs). New approaches focus on restoring fluvial processes, namely (1) removal of legacy barriers (berms, splash dams) and use of logs and sediment to reconnect the single channel to its abandoned floodplain. (2) raising the water table and improving hyporheic exchange (the flow of groundwater into the stream and back again). This method requires more space and time, but is much cheaper and effective and restoring channel and marginal habitat conditions and improving water quality and temperatures.

Figure 37. An example of removing berms and splash dams that prevent lateral and longitudinal connectivity of the stream to its floodplain and downstream-upstream reaches that are essential for restoring ecosystems, both aquatic and terrestrial.

Figure 38. An example of "chop and drop" method of adding large woody debris (LWD) to tributary channels, which slows and dissipates flood flows, sequesters carbon and sediment in the system, adds food for aquatic life, and creates new, complex habitat types.

Figure 39. An Large woody debris (LWD) additions are naturally sorted during annual flood flows, greatly improving channel complexity and micro-habitat.

Figure 40. An example of naturally sorted LWD additions tend to create natural step-pool sequences in headwater streams for native brook trout. Notice the cut log in the foreground where the sawyer dropped the tree into the channel. Also note the retention of spawning gravels behind the log jams.

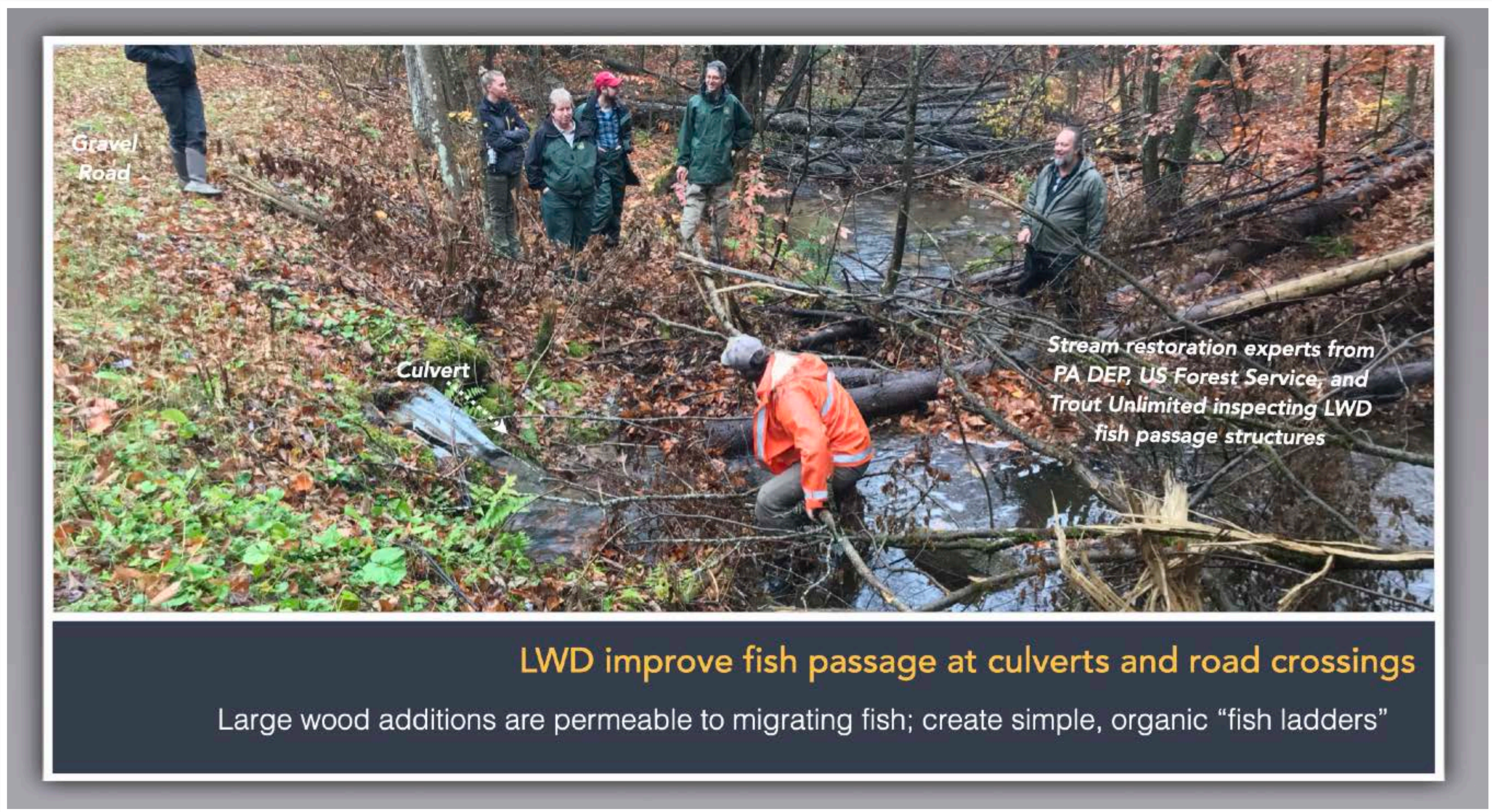

Figure 41. Smaller, carefully placed and tiered large woody debris additions to the channel at culvert and bridge crossings are proving very effective to promoting fish passage and reducing scour in the channel, as the wood debris dissipates energy from the culvert.

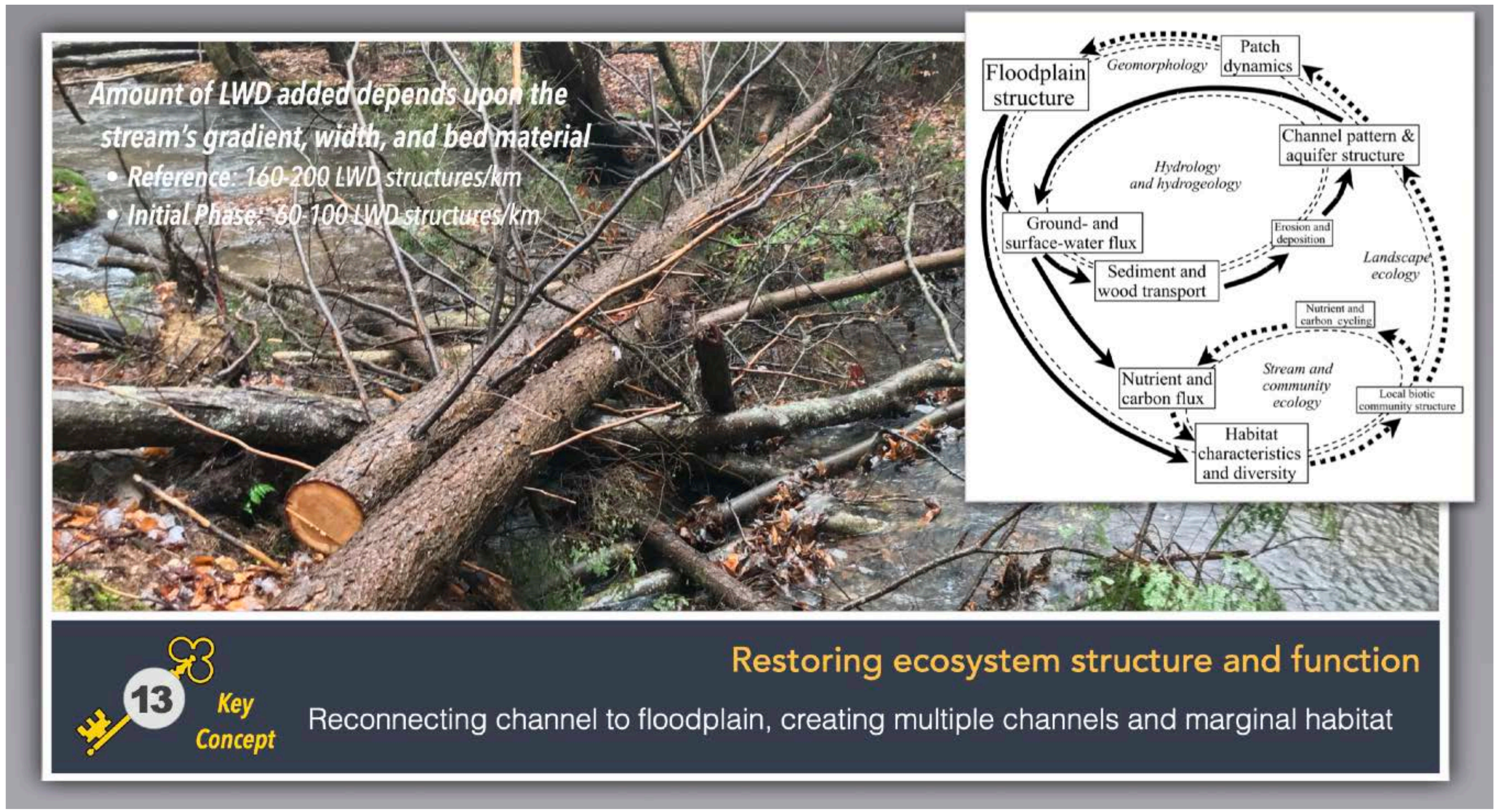

Figure 42. The amount and placement of LWD to streams depends upon its width, gradient, and bed material. Often they are placed at the confluence of two small channels as shown in the photo in the background. The goal of this type of stream restoration is shown in the figure in the upper right.

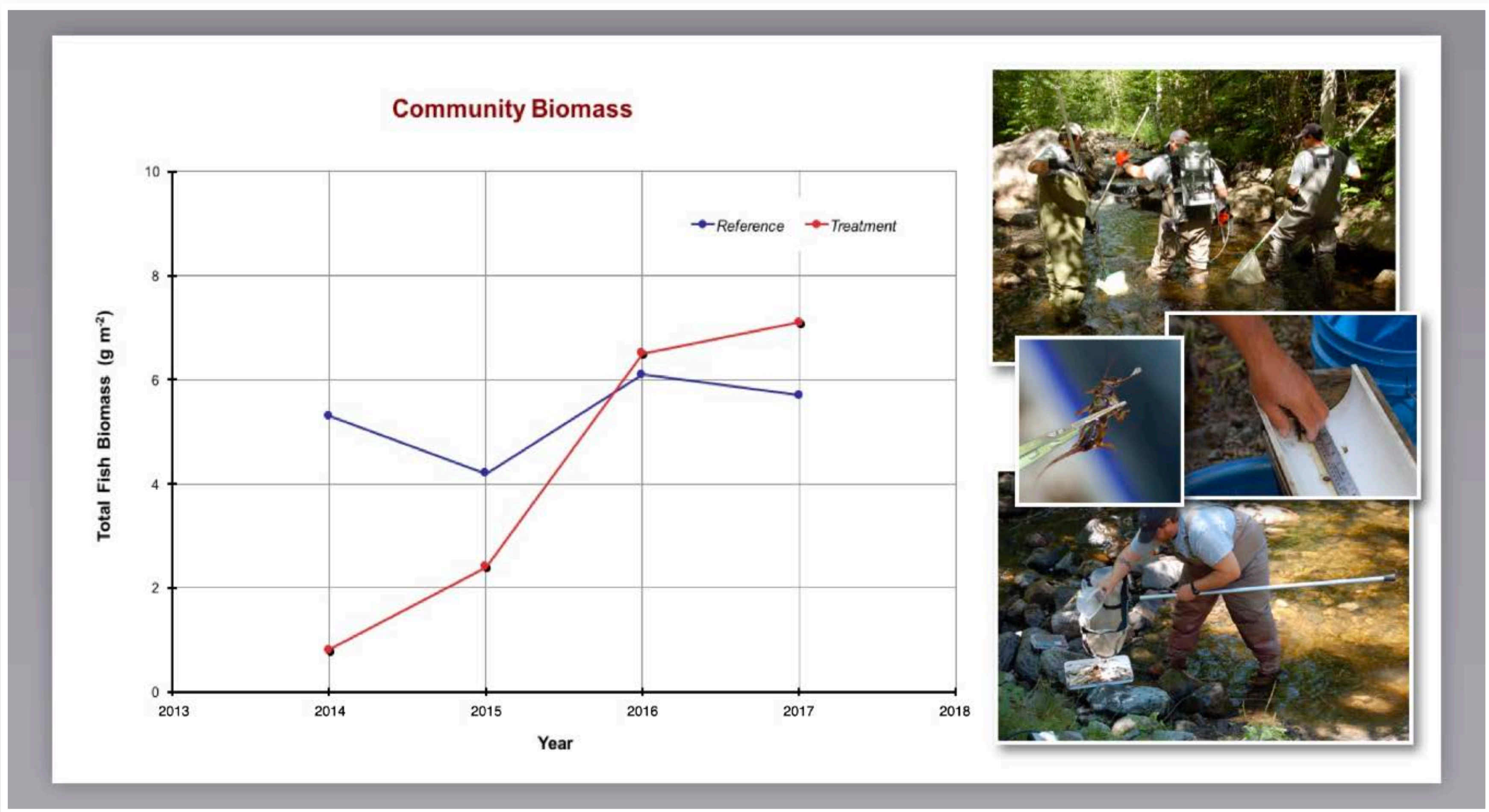

Figure 43. Because this stream restoration approach focuses on restoring lateral flows and improving water chemistry, the response of the ecosystems is near instantaneous and sustained for decades. This graph shows 400% improvement in biomass (aquatic insects and fish) in a stream (red line) after only three years.

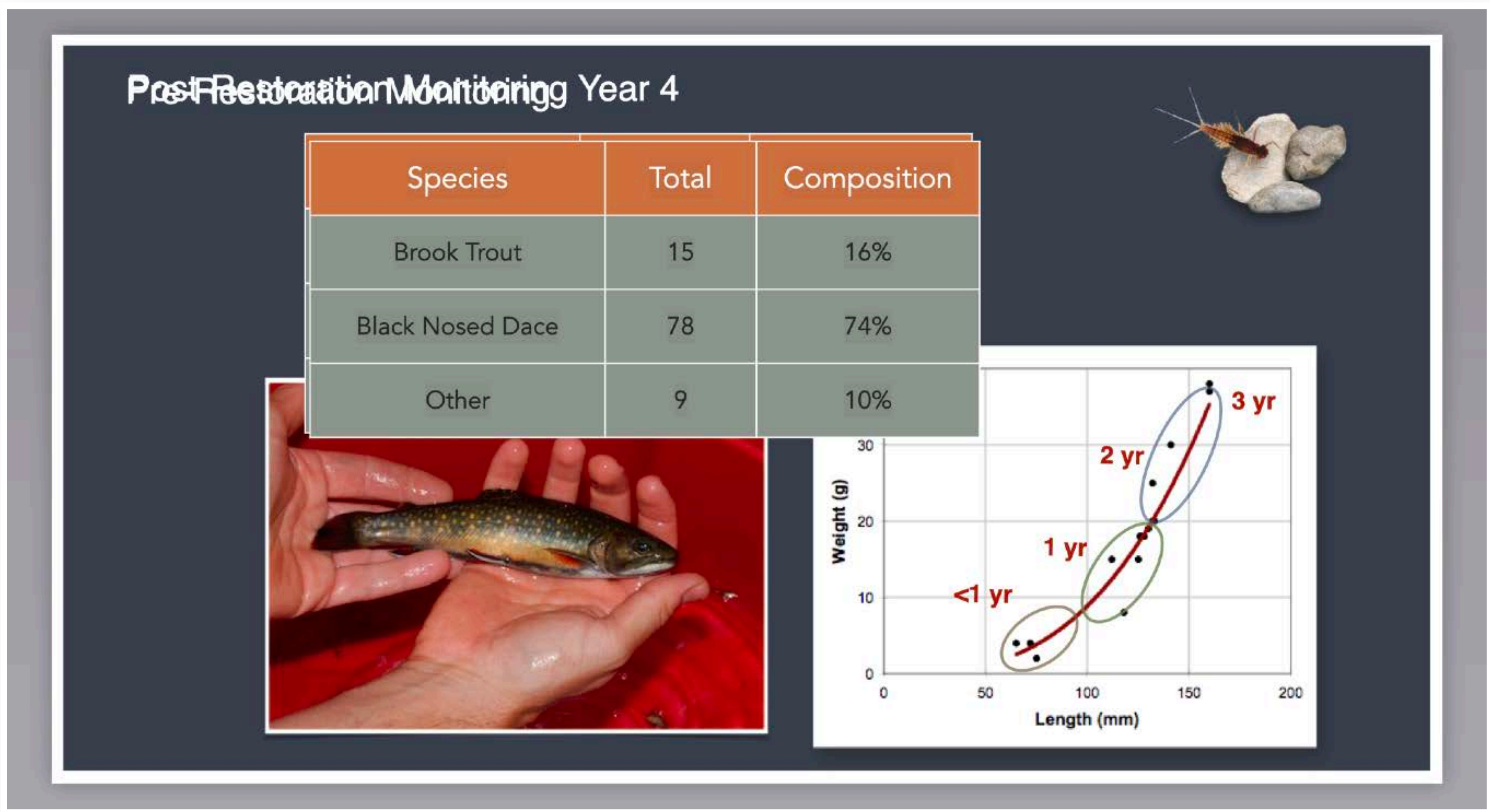

Figure 44. Another important aspect of this type of stream restoration is the retention of sediment, especially spawning gravels for fish so that populations of native species such as brook trout (shown in photo) can be self-sustaining over the long term and not require stocking.

Change in Brook Trout population

Age	Before	After
YOY	7	19
1 yr	12	27
2 yr	5	12
> 3 yr	0	4
Total	**24**	**78**

8-inch brook in redd

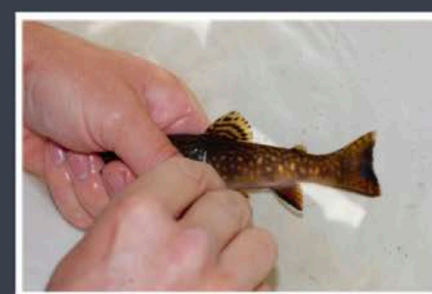

Figure 45. Within a short period of time the fish communities went from mostly dace to brook trout and age determinations show that their ages are self-sustaining.

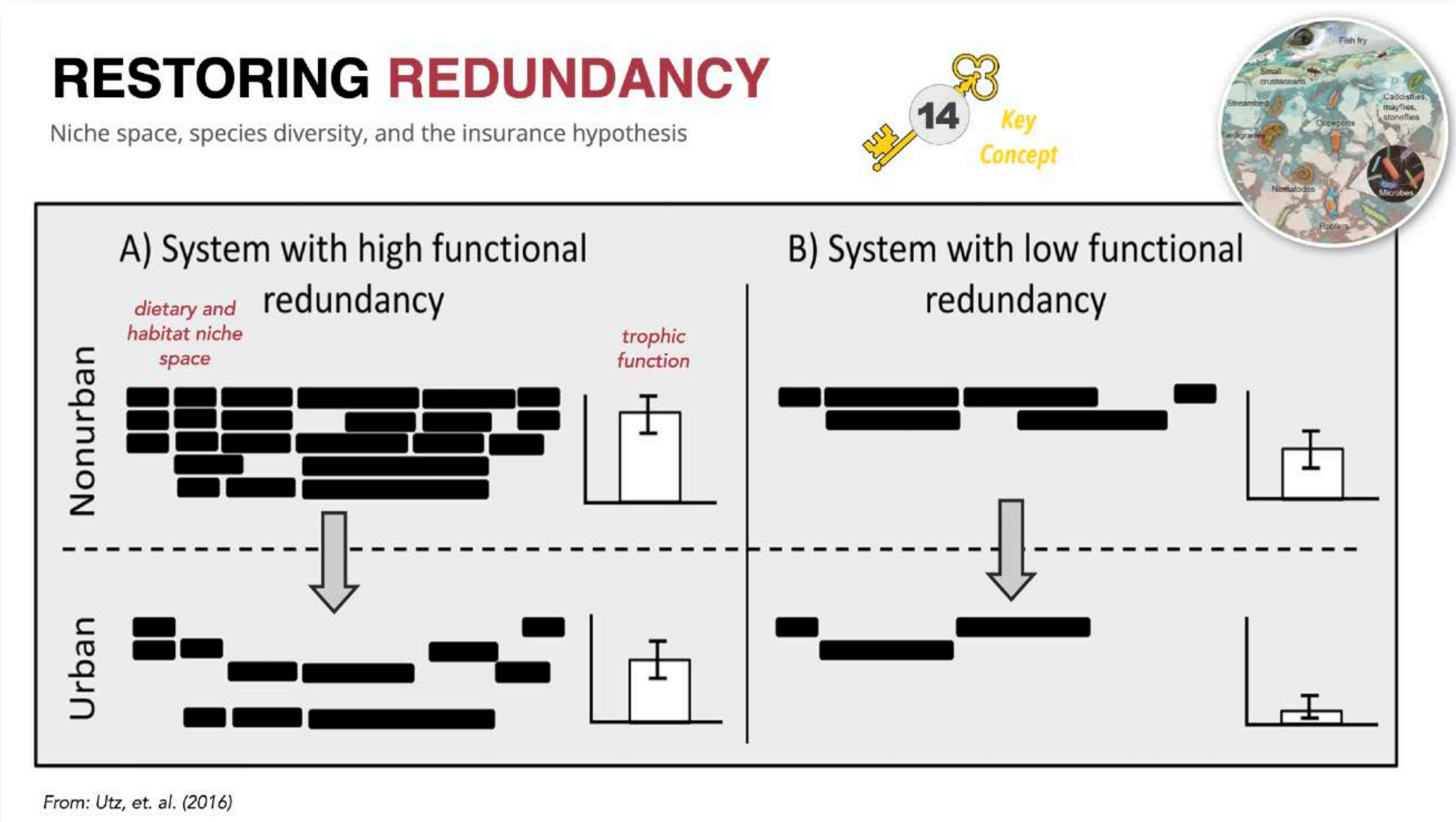

Figure 46. With their complex network of side channels and wetlands, braided streams provide much more redundancy to aquatic and ecosystems. This means that if the event of a natural (e.g. flood) or man-made disaster (e.g, spill), if one portion of the habitat is lost, there are many other similar (e.g., "redundant") habitats in the stream corridor that could accommodate those plants and animals.

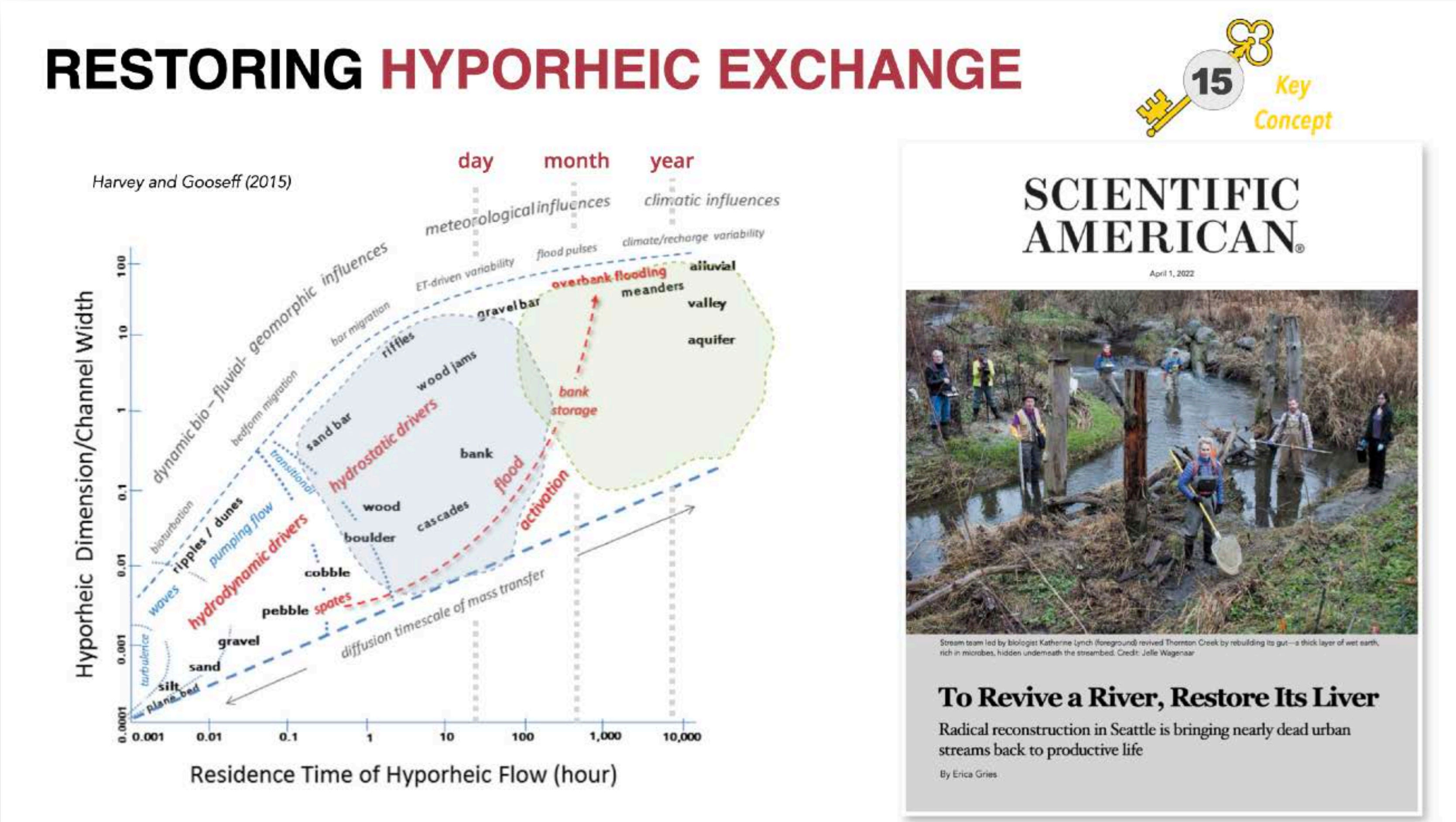

Figure 47. With rising temperatures threatening cold-water fish species like brook trout, increasing attention is being give to improving the hyporheic zone - the area beneath and aside of the stream channel where water in the stream mixes with the water in the shallow unconfined aquifer in the valley alluvium. Groundwater temperatures remain cool (58°F) year round, and increasing the dimensions and degree of connection between the stream and its adjacent aquifer may be the single most effective way to offsetting the predicted warming of headwater streams as canopy cover decreases due to forest loss by invasive species.

Figure 48. Several reasons to consider reducing floodplain encroachment.

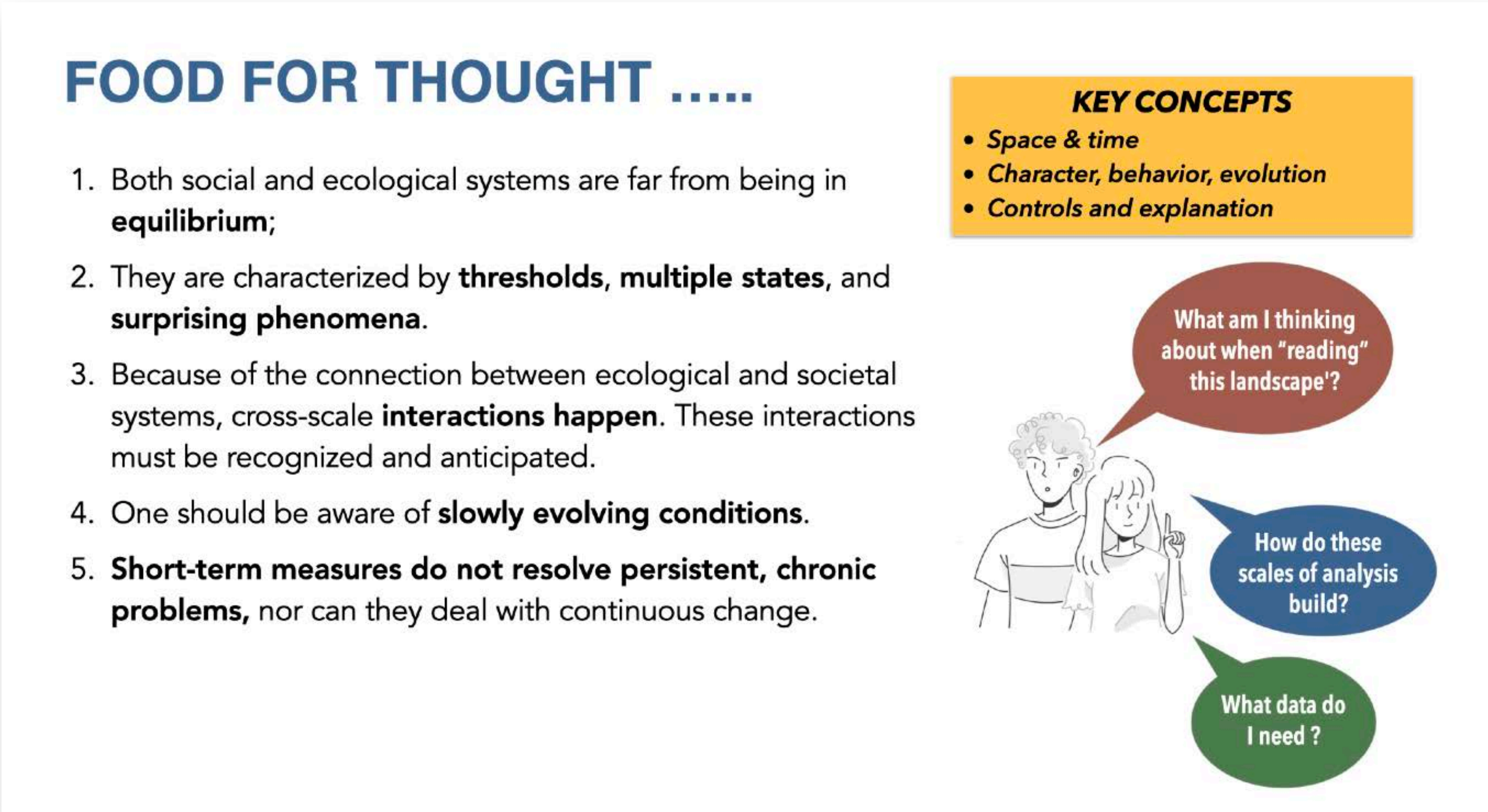

Figure 48. Thoughts to promote discussion.