Connecting Flood-Related Fluvial Erosion and Deposition with Vulnerable Downstream Road-Stream Crossings

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Abstract

Fluvial erosion is increasingly responsible for infrastructure and building damages associated with floods as the intensity of extreme rainfalls hit rural and urban rivers in a variety of climate settings across the United States. Extreme floods in 2016 and 2018 caused widespread culvert blockages and road failures, including extensive damage along steep tributaries and ravines in the Marengo River, Wisconsin, watershed during 2016 and 2018. A study conducted by the U.S. Geological Survey (USGS), Wisconsin Wetlands Association (WWA), Ashland County, and the Northwest Wisconsin Regional Planning Commission (NWRPC) investigated the special concern of fluvial erosion hazards (FEHs) associated with gullying, streamside landslides, and the loss of wetland storage in headwaters. In 2019, a pilot study was begun to map and classify ephemeral and perennial streams and wetlands in terms of their sensitivity to FEHs. This study combined data from field-based rapid geomorphic assessments (RGAs) coupled with a stream network-wide geographic information system (GIS) approach for mapping stream segments, referred to as fluvial process zones (FPZ), sensitive to erosion, deposition, and channel change. The GIS approach used nationally available 10-meter (m) resolution topology and an extended stream network to map FPZs based on Strahler stream order, stream power, channel slope, presence of adjacent steep valley sides and headwater flats, and adjacent landform setting. Bankfull channel widths derived from RGA-based hydraulic geometry curves combined with drainage areas, an estimate of bankfull flow, and channel slope were used to calculate specific stream power for the FPZs. Lastly, the FPZs were characterized by their location within three major landform settings that affect erosion potential. The resulting vulnerability maps provided a screening framework to identify FPZs that are sensitive to incision, gullying and mass wasting along steep headwater ephemeral channels, as well as downstream perennial channels that have the potential for valley-side landslides, coarse sediment deposition, and channel change. Lastly,

each FPZ was characterized in terms of hydrologic alteration associated with ditching. The vulnerability mapping products and rankings of sensitivity of FPZs will ultimately be used by Ashland County and their collaborators to prioritize natural flood management projects that mitigate FEHs, restore hydrology, and reconnect channels with adjacent wetlands and floodplains.

Introduction

In recent years, flash floods across northern Wisconsin and other areas of the Upper Midwest have become increasingly problematic, with an extreme storm in 2016 causing regional damages of $35 million (WWA 2018) followed by another extreme flood in 2018 causing repeated damages to road-stream crossings including culverts and bridges (Figure 1). In the Marengo River watershed, a tributary to the larger Bad River and Lake Superior, infrastructure damages were concentrated in an area known locally as the transition area – a landform feature with steep terrain and intermixed sands, gravels, and clays associated with glacial and post glacial streams, paleo-shorelines, and glaciolacustrine deposits (Clayton 1984; Lenz et al. 2003; Leaf et al. 2015). This area generally lies between the bedrock-dominated Penokee Hills and Gogebic Iron Range to the south and a low-relief clay-dominated glaciolacustrine landform to the north (Clayton 1984). Post floods, there was an observable increase in erosion and landslides in ravines and confined valleys in headwaters. This caused erosion-induced wetland drainage and large backups of water and dam-breach-like failures of road embankments (WWA 2018). Similarly, steep valley side slopes near stream channels and the presence of glaciolacustrine clays were major factors in the location of landslides during extreme floods in tributaries to the St. Louis River in western Lake Superior (DeLong et al. 2022). In the Pacific Northwest and California, the majority of culvert failures during large floods were caused by excess sediment and woody debris, and hydraulic exceedances from overtopping at road-stream crossings (Furniss et al. 1998; Cafferata et al. 2017).

Geomorphic responses to floods, including channel and valley changes, are controlled by a balance of drivers of watershed hydrology, upstream sediment supply, and the resistance forces of the surrounding geology and landforms, which can vary greatly along stream networks and affect channel slopes, stream power, and channel and valley morphology (Church 1992; Lecce 1997; Brierley and Fryirs 2005; Bisson et al. 2006; and Montgomery and Buffington 1998). The surrounding landscape adds complexity to the expected zones of sediment supply, transport, and deposition that typically transition from headwaters with confined valleys to main stem streams with unconfined, alluvial valleys (Brierley and Fryirs 2005; Brierley and Fryirs 2009; and Schumm 1981). Characterization of valley setting from confined to partially confined to laterally unconfined is critical in understanding the interplay of potential channel adjustments from floods relative to sediment sources and sinks (Fryirs and Brierley 2010; 2018). Once this complexity is realized at a segment scale (100s of meters) along a stream network, usually in terms of variability in unit stream power, the immediate risk to infrastructure in the stream corridor can be better assessed (Sholtes et al. 2018). Headwater catchments with wetland storage also offer the first chance of slowing floodwaters and flood-related debris and potentially lowering the risks to downstream road-stream crossings (Fryirs and Brierley 2010; and Wheeler et al. 2022). The increase in availability of geospatial data, especially publicly available topographic data at a resolution of 10 m or less, and light detection and ranging (lidar)-derived digital elevation models (DEMs) at a resolution of 3 m or less, has allowed the development of mapping automation of FPZs along stream networks over large watersheds or geographic regions to assist in river management decisions (Fryirs et al. 2021).

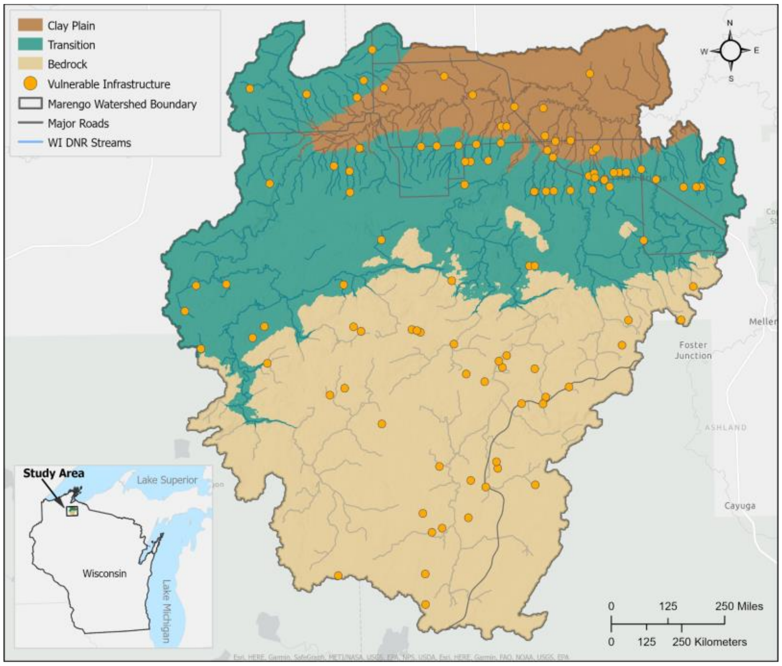

Figure 1. Location of the Marengo River watershed, major landform settings (from Clayton et al. 1984; and U.S. Department of Agriculture, 2022), and vulnerable infrastructure (State of Michigan, 2023)

The extreme floods in 2016 and 2018 in northern Wisconsin and the upper Midwest are evidence of what can be expected from increases in precipitation and frequent extreme events into the mid and late 21st century (Xue et al. 2022; Wisconsin Initiative on Climate Change Impacts 2021; Angel et al. 2015). Northern Wisconsin, like other areas of the Upper Midwest, is mostly forested, yet historical alterations, including ditching and draining of wetlands, has likely exacerbated runoff-related erosion (WWA 2018; Association of State Floodplain Managers, Inc. [ASFPM] Riverine Erosion Hazards Working Group 2016). Headward extension of ravines and gullying during floods can lead to the repeated and irreversible loss of flood storage provided by headwater wetlands. Consequently, tributaries become more efficient at transporting floodwater and sediment to downstream reaches (Faulkner 1998; Wheeler et al. 2022). Depending on the interaction of surrounding landforms and valley characteristics, excess sedimentation in downstream reaches is spatially heterogeneous (Lecce 1997; Faulkner 1998; and James 2013).

Mapping river corridor geomorphic zones prone to fluvial erosion, excess deposition, and channel change hazards are becoming increasingly popular at the state and national levels (Technical Mapping Advisory Council 2015; LeRoy et al. 2020). Examples include the Indiana FEH Mitigation Manual (Burke Engineering LLC 2018), Vermont's river corridor protection approach (Kline and Cahoon 2010), Massachusetts's flood damages from geomorphic processes (Warner et al. 2017; Gartner et al. 2019) and Colorado's fluvial hazard zones (Blazewicz et al. 2020). At the heart of each of these approaches is identifying the potential corridor along the river prone to erosion and (or) imbalances in sediment transport and delivery. The river corridor mapping approaches are linked to hydrology and flow characteristics, field-based geomorphic assessments, and historical aerial photography assessments (for example, Robinson 2013). This corridor, also called the active river area by The Nature Conservancy (Smith et al. 2008) and the active stream corridor in Colorado's Fluvial Hazard Zones (Blazewicz et al. 2020), is similar but not necessarily the same as the floodplain, valley bottom, or the stream's active meander belt (Gartner et al. 2019).

In 2019, the USGS partnered with WWA, NWRPC, the National Oceanic and Atmospheric Administration (NOAA), and U.S. Environmental Protection Agency (EPA) to assist Ashland

County and the Federal Emergency Management Agency in identifying FEH features and related loss of headwater wetland storage that has potentially contributed to past and future road-stream crossing failures. FEHs are areas such as eroding ravines, gullies, and incised channels where flood flows are concentrated and energized. The study included field-based rapid geomorphic assessments (RGAs), hydrologic monitoring, and development of new geospatial data layers, including extending the stream network into headwater ephemeral channels to map ravines, and to better understand the connection between future incision and flood storage loss in headwater wetlands. This paper describes the development of a geomorphic, GIS-based screening tool to map and characterize stream corridors that are vulnerable to excess erosion and deposition, especially ravines and confined valleys prone to extension into headwater wetlands. We expanded the traditional definition of FEH to include headwater ephemeral channels in steep landforms prone to incision, gullying and landslides that can cause downstream erosion, deposition, and debris related failures in road-stream crossings. This mapping exercise is the first step in connecting upstream geomorphic processes to downstream flood risks and mechanisms that induce road-stream crossing failures.

Study Area

The Marengo watershed (Figure 1) has a drainage area of 560 square kilometers (km^2) and is largely rural with a mix of forest (67%), agricultural land (13%), wetland (17%), and developed land (2%) (NOAA 2016). The Marengo River feeds into the Bad River and eventually to Lake Superior. The watershed has a mean annual precipitation of 84 centimeters (cm), mean annual snowfall of 218 cm, and a maximum 24-hour precipitation with a 1% exceedance probability of 15.2 cm (Huff and Angel 1992). The saturated hydraulic conductivity of the soils is 49.3 micrometers per second (U.S. Department of Agriculture, 2022). The study area has a relatively steep transition area characterized by tributaries cutting through paleo-shorelines and old lake plains (Clayton 1984) (Figure 1). The mix of sand and clay layers in this area make the area particularly vulnerable to fluvial erosion. The transition area is bounded by bedrock at the surface to the south and more gentle sloped clay glaciolacustrine deposits to the north.

Methods

Field-Based Rapid Geomorphic Assessments

Reaches were mainly selected for RGAs based on their potential for excess erosion and deposition and proximity to severe infrastructure damages from the 2016 and 2018 floods. Some reaches were nested in sub-watersheds to document the longitudinal progression of geomorphic characteristics from the surficial bedrock into the transition area and clay plain. We were looking for worst-case examples from the 2016 and 2018 floods relative to known problems with culverts and bridges downstream. The reaches included perennial and ephemeral channels and were assessed in September of 2020. Assessment techniques followed methods used in other Great Lakes tributaries to Lakes Superior and Michigan (Fitzpatrick et al. 2016, Fitzpatrick et al. 2019; Blount et al. 2022). Quantitative measurements of eroding banks and valley sides, coarse sediment bar deposition, and hydraulic geometry were made along generally 150-m reaches. The length and height of eroding banks and valley sides were multiplied by observation-based lateral retreat rates (Wisconsin Natural Resources Conservation Service 2015) to estimate annual volumes of eroded sediment. The aerial extent of bars were measured based on length and average width above water levels during base-flow conditions. Bankfull width and depths were measured at five equidistantly spaced transects. Qualitative indicators of dominant geomorphic processes and mode of sediment transport were also noted, following reconnaissance methods in Thorne (1998). Dominant geomorphic processes that were noted included headcutting, incision, valley bluff and terrace erosion, bank erosion, widening, lateral migration, overbank sedimentation, levee formation, bar formation, and bed aggradation. From these measurements, estimates of bank and valley side erosion, bar area, and bankfull widths were generated. Data from the RGAs are available at Fitzpatrick et al. (2022).

Generating Stream Network and Fluvial Process Zones

From the nationally available 10-m digital elevation dataset (NED) (USGS 1999, Archuleta et al. 2017) a more detailed flow network was generated in ArcMap using ArcHydro tools with a starting drainage area of 0.1 km^2 in order to include headwater ephemeral channels in ravine settings. These channels may be ephemeral and geomorphically active, which can affect headwater wetland storage and be a source of sediment and woody debris to downstream areas. There were a small number of visually noticeable errors in the more detailed flow paths in the vicinity of road-stream crossings, especially if two road crossings were close to each other. Correcting the entire flow network was outside the scope and scale of a screening-level mapping effort for a watershed of this size.

The more detailed flow network was divided into 60-m segments in order to capture the heterogeneity in slope and valley confinement resulting from intersecting and adjacent glacial landforms and bedrock outcrops. There are multiple approaches for defining segment lengths and smoothing techniques to determine channel slope (Garter 2016); however, the smaller than usual lengths used in this analysis are fitting for representing the abrupt changes in channel slope and not over-representing lengths where the channel is near a steep valley side. Channel slopes were generated using average values for each 60-m segment from the NED slope grid. Slopes were grouped into six categories: less than 0.3%, 0.3% to less than 1%, 1% to less than 2%, 2% to less than 4%, 4% to less than 8%, and 8% or greater. The slope groupings are similar to what was used for the Duluth-area streams geomorphic assessment (Fitzpatrick et al. 2016) and stream corridor sediment budgets (Fitzpatrick et al. 2017; Blount et al. 2022). This methodology was adapted from process-based channel classifications developed by Montgomery and Buffington (1993; 1997; and 1998). Drainage area for each 60-m segment was calculated from the NED flow accumulation grid.

Several techniques were explored to characterize valleys and quantify valley types and included the V-BET tool (Gilbert et al. 2016) and geomorphon classification (Jasiewicz and Stepinski 2013). Because of the complex heterogeneity and discontinuous nature of valleys in Lake Superior watersheds, the project team decided to utilize a simpler approach. A buffer of 8 times the estimated bankfull width was generated for each 60-m segment to characterize the proximity of steep valley sides, with a minimum buffer width of 30 m for small channels (15 m each side). Bankfull widths were estimated for each 60-m segment by applying the bankfull width (in m, W_{bf}) and drainage area (km^2, A) based regression equation estimated from the field-based RGAs (Equation 1):

$$W_{bf} = 2.42A^{0.44}\ (R^2 = 0.94) \tag{1}$$

A buffer width of 8 times the bankfull width was chosen as an estimate of potentially active zones of channel lateral migration (Burke Engineering, LLC 2018). Buffers that had an average of 15% side slopes or greater based on the NED were considered steep valley sides adjacent to the channel. A cutoff of 15% was used to be similar to the soil mapping units and 15% or greater slope classes in the area with landform settings of steep shoulders, backslopes, ravines, and escarpments (U.S. Department of Agriculture 2022).

Many of the headwater channels intersect large flats with current or potential wetland storage. To characterize this feature, a hydrologic-related terrain raster was computed, using the Height Above Nearest Drainage (HAND) tool (Lamont et al. 2019, Lui et al. 2020) applied to the 10-m DEM data. The tool approximates the relative elevation difference between a 10-m DEM cell and the nearest streamline and can also help to identify natural floodplains or areas prone to overbank deposition. A cell was considered hydrologically connected to the 60-m segment if its relative difference was 1 m or less. For the screening tool for headwater incision, the FPZs were considered connected to a headwater flat if 20% of the cells in a 200-m buffer around the segment were 1 m or less. For FPZs prone to coarse sediment deposition, a 50% cutoff for cells 1 m or less on at least one side of the segment was used as a surrogate for the segment having an adjacent flat. This technique was also used to identify current or potential floodplains adjacent to channels in downstream segments with expansions and constrictions in valley bottoms.

Specific stream power (SSP) was estimated for characterizing segments prone to erosion and deposition as well as changes in channel dimensions and lateral migration during floods (Gartner 2016). Stream power is a product of channel slope, streamflow and the weight of water. For this study, SSP was calculated by dividing the stream power estimated for an annual flood by the channel bankfull width. For this characterization we used channel slopes and drainage areas generated from the 10-m DEM and bankfull widths estimated from the field-based RGA data (Equation 1). Estimates of annual floods for the segments were based on annual peak flood magnitudes for surface-runoff dominated streams of 0.034 cubic meters per second (cms)/km^2 (3.2 cubic feet per second/square mile) for streams in the nearby Chequamegon-Nicolet National Forest (Higgins 2007; Savery et al. 2007). The relative range of SSPs using these approximations for a frequent flood size served as a surrogate for similarly expected spatial variability for out-of-bank, less frequent floods. Resulting SSPs were grouped based on categories in the Massachusetts coarse screening tool (Task Force on Stream Power circa 2020) and floodplain characteristics classified in Nanson and Croke (1992). The five groupings (in units of Watts[W]/m^2) included: >1000, >300-1000, >60-300, 10-60, and <10. Risk of erosion was considered high for segments with SSP > 300, moderate for 60-300, and low for 0-60 Watts/m^2). Nanson and Croke (1992) characterized SSPs of less than 10 W/m^2 as low energy, gentle sloped anastomosing channels with fine-grained organic or cohesive floodplain deposits.

In order to characterize the surrounding effects from geology and landforms relative to the stream network, two main digital thematic maps were used. The combination of SSURGO soils (U.S. Department of Agriculture 2022) and Pleistocene geology (Clayton 1984) provided a summary of the three landform zones – surficial bedrock, transition area of interstratified coarse- and fine-grained glacial deposits in paleo-shorelines and glacial stream valleys, and the clay plain.

Hydrologic alteration associated with the 60-m segments was generated from 200-m buffers overlaid with ditches previously digitized (Benck et al. 2017). A relative ditch density raster (km/km^2) was created using the digitized ditch network. Circular buffers (200 m) generated from the segment centroids were used to derive summary statistics from the ditch density raster.

Higher resolution lidar-based DEMs were available for the two counties encompassed by the Marengo River watershed, but there were data and computational hurdles in extracting stream network characteristics in a watershed of this size. Generating streamlines with the 10-m data resulted in some errors in the new 1st and 2nd order stream delineations especially near road- and railroad-stream crossings. Hydro-enforced 10-m DEMs became available as the study neared completion.

Results and Discussion

After generating the more detailed stream network and 60-m segments, a team made up of local and regional experts met virtually numerous times over a period of about a year to compile the FPZ mapping characteristics that helped to describe segments prone to excess erosion, deposition, and hydrologic alteration. The more detailed stream network added two additional Strahler stream orders and almost 1,000 km of headwater channels (1st and 2nd order) to the nearly 370 km of 3rd to 7th order channels represented by the National Hydrography Dataset Plus Version 2 (McKay et al. 2012). The team used aerial photography, 2015 and 2019 county lidar-based hillshade maps, preliminary 2015-19 volumetric change analysis maps, the Great Lakes Road Stream Crossing Inventory, RGA data, drone imagery, and other field reconnaissance after the 2016 and 2018 floods to verify the resulting FPZ characteristics, sensitivity factors, and scores (Table 1). Each FPZ could be scored as "1-low", "2-moderate", "4-high", or "5-very high". A score of "3" was not used.

Table 1. Sensitivity factors, proposed vulnerability scores, and fluvial process zone (FPZ, 60-m segment) characteristics used in the fluvial erosion hazard (FEH) vulnerability screening framework
[SSP, specific stream power, in Watts/square meter (W/m²); >, greater than; <, less than; %, percent]

Factor	Score	General 60-m segment FPZ characteristics
Landslide potential (all stream orders) [LP]	5 (very high)	SSP > 300 with steep valley sides in transition area.
	4 (high)	SSP > 60 with or without steep valley sides in transition area and clay plain.
	2 (moderate)	SSP > 10 with or without steep valley sides in transition area and clay plain, steep valley sides in bedrock.
	1 (low)	SSP < 10 with steep or no steep valley sides in transition and clay; no steep valley sides in bedrock.
Headwater incision potential (1st and 2nd order) [HIP]	5 (very high)	Steep headwater channel slope > 2%; channel connected to flat in transition area.
	4 (high)	Steep headwater channel slope > 1%, channel connected to flat in transition area and clay plain.
	2 (moderate)	Steep headwater channel slope > 1%; flat absent in transition area or clay plain.
	1 (low)	Any bedrock channels or channel slope < 1% connected or not connected to flat in transition area or clay plain.
Coarse sediment deposition & channel change (3rd order and higher) [CSDCC]	5 (very high)	SSP < 1,000 connected to flat in transition area.
	4 (high)	SSP <1,000 connected to flat in clay plain.
	2 (moderate)	SSP variable but flats absent in transition area and clay plain; SSP <60 and connected flats in bedrock.
	1 (low)	SSP >300 and no connected flats in transition area and clay plain; Any bedrock channels with flats absent.
Hydrologic alteration (all stream orders) [HA]	5 (very high)	Ditch density exceeds 3-km per sq. km density within 200-m buffer of headwater channels.
	4 (high)	Any ditches present near headwater channels (within 200-m buffer).
	2 (moderate)	Ditch presence or high density near non-headwaters channels.
	1 (low)	No known ditches present.

Multiple vulnerability screens were compiled to determine the sensitivity of FPZs to: 1) landslides along ravines and confined and partially confined valleys for all stream orders, 2) headwater incision into flats for stream orders 1 and 2, 3) coarse sediment deposition and channel change for stream orders 3 and higher, and 4) hydrologic alteration due to ditching in all stream orders (Table 2). FPZs with sensitivity scores of "very high" and "high" likely experienced geomorphic changes of incision, landslides, and (or) coarse sediment deposition during the 2016 and 2018 floods. A score of “moderate” was given for FPZs that might have experienced geomorphic changes based on their characteristics but also might be in the geospatial resolution error of a 10-m topological representation of the streamlines. A score of “low” indicated a low chance of geomorphic change for FPZs that were mainly in the bedrock landform setting. A headwater FPZ (1st and 2nd order channels) might have a high sensitivity to incision and landslides. Third order and higher FPZs might also have a high landslide and high coarse sediment deposition sensitivities in the form of bars and overbank sedimentation. Ditches hydrologically connected to the FPZs increased the potential for geomorphic change. Example maps for each vulnerability screen are shown in figures 3-5 using areas where natural flood management techniques are being discussed with county and regional planners, engineers, and natural resources, road, and emergency managers.

Table 2. Sensitivity screens for landslide potential, headwater incision potential, and coarse sediment deposition and channel change associated with FPZs in the Marengo River watershed

[SSP, specific stream power, in W/m^2 (Watts/square meter); >, greater than; <, less than; %, percent; VH, very high, score of 5, red; H, high, score of 4, pink; M, moderate, score of 2, orange; L, low, score of 1, yellow; HAND, Height above nearest drainage]

Landform Setting	**Landslide Potential (LP)**						**Headwater Incision Potential (HIP)**				**Coarse Sediment Deposition and Channel Change (CSDCC)**					
	Steep Valley or Ravine	Specific Stream Power (W/m^2)					Headwater Flats (20%+ HAND)	Channel Slope (Stream Gradient)			Floodplain Flats (50+% HAND)	Specific Stream Power (W/m^2)				
		>1000	300 - 1000	61 - 300	10 - 60	<10		>2%	1-2%	<1%		<10	10 - 60	61 - 300	300 - 1000	>1000
Transition Area	Present	VH	VH	H	M	L	Present	VH	H	L	Present	VH	VH	VH	VH	H
	Absent	H	H	M	M	L	Absent	H	M	L	Absent	H	H	M	M	L
Clay Plain	Present	H	H	H	M	L	Present	H	H	L	Present	H	H	H	H	M
	Absent	H	H	M	L	L	Absent	M	L	L	Absent	H	M	M	L	L
Bedrock Surface	Present	M	M	M	M	L	Present	L	L	L	Present	M	M	L	L	L
	Absent	L	L	L	L	L	Absent	L	L	L	Absent	L	L	L	L	L

Of the 1,365 km of channels in the Marengo River watershed, only 106 km (8%) of FPZs were scored as high or very high for landslide potential (Figure 2). The combination of stream power greater than 60 W/m^2 and presence of steep valley sides or ravines were generally along the mainstem of the Marengo River and some of the larger tributaries (Figure 2). Scores of moderate were located in some smaller tributaries and headwaters. The more detailed map of the Brunsweiler River FPZs showed a range from moderate to very high in the transition area of Brunsweiler River depending on changes in channel slope and proximity to steep valley sides (Figure 2). Upstream, where bedrock is close to the surface, the deep valley was not present along the main channel of Brunsweiler Creek or its tributaries. Flood-related consequences of landslide potential were mainly large episodic contributions of both coarse and fine-grained sediment and woody debris to downstream FPZs. Some of the valley side failures were large enough to cause temporary sediment dams in nearby rivers, which caused meander cutoffs and pulses of sediment and debris to downstream areas when the sediment dams are breached.

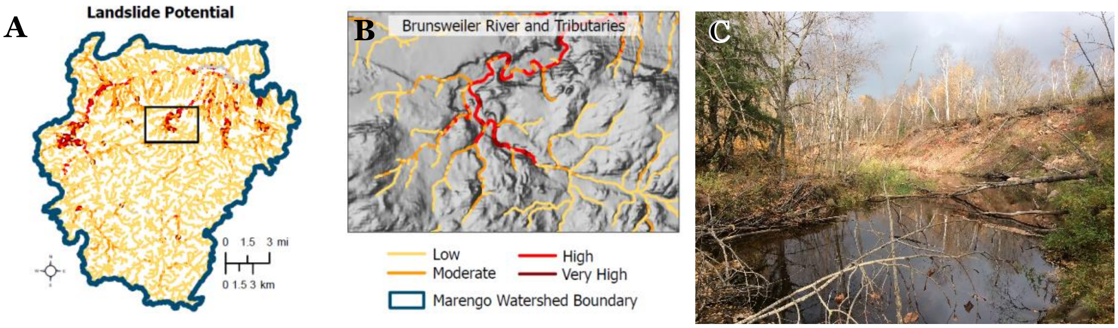

Figure 2. Example of landslide potential vulnerability for A) fluvial process zones (FPZs) in all stream orders in the Marengo River watershed, B) example of Brunsweiler River relative to 2015 lidar-based hillshade map (NOAA 2015), and C) photo of an eroding valley side of Trout Creek at the upstream end of the transition area (Photo Kyle Magyera)

Coarse sediment deposition and channel change was sometimes collocated or immediately downstream of segments with landslide potential, and valleys were partially confined with discontinuous connected flats, similar to findings of Sholtes et al. (2018). Flood-related consequences of streamside landslides along valley sides and ravines include:

- Contributions of sediment and woody debris that can plug downstream culverts
- Downstream sedimentation and loss of floodplain storage for future floods
- Burial of wetlands and spawning habitat and filling of overwintering pools
- Loss of forest health and agricultural field washouts

Of the 996 km of 1st and 2nd order channels, 25% had high and very high scores for potential headwater incision (Figure 3). Similar to the landslide potential, more FPZs were located in southern tributaries of the Marengo River, especially eastward where there is more relief in the transition area.

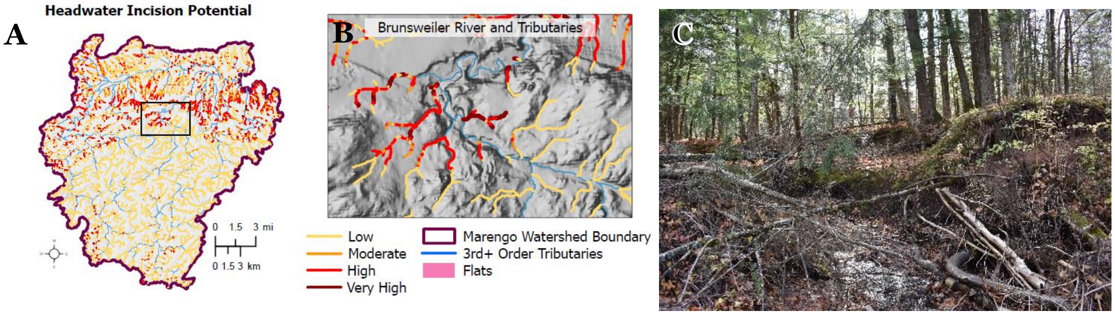

Figure 3. Example of headwater incision potential for A) 1st and 2nd order fluvial process zones (FPZs) in the Marengo River watershed, B) example of Brunsweiler River and tributaries relative to the 2015 lidar-based hillshade map (NOAA 2015), and C) photo of an eroding ravine tributary to Silver Creek (Photo Kyle Magyera)

Sensitive FPZs were those with relatively steep channel slopes downstream of headwater flats where headcutting, gullying and drainage network extension can cause large losses in wetland storage. Flood-related consequences of headwater incision include:

- Loss of headwater and upland wetland storage
- Decrease in water table and dried wetlands
- Contributions of sediment and woody debris that plug downstream culverts
- Additional runoff volumes and magnitude of downstream flood sizes
- Decrease in the length of overland flow
- Potential for more landslides downstream

- Downstream sedimentation and loss of floodplain storage for future floods
- Large release of carbon and possible contaminants
- Loss and change of wetland, riparian, and aquatic habitat
- Loss of soil and forest health and agricultural field washouts

Excessive coarse sediment deposition and channel change potential was high or very high for 55% of the 3rd order and higher FPZs (Figure 4). The FPZs span segments that may or may not have steep valley sides. Of the 13 RGA reaches with streamside valley side or terrace failures, 9 had excess bar formation, levee formation, overbank sedimentation, and or recent lateral migration. Two of the 13 reaches had bed aggradation upstream of sediment and debris dams from landslides. The observations from the RGA's are important because they document the coincidence of streamside landslides and high SSP with coarse sediment deposition and channel change in partially confined valley settings with flats adjacent to the channel. The coarse sediment deposited in the overbank areas during floods will likely not be eroded until the channel laterally migrates through the floodplain. This could take millennia. Flood-related consequences of excess coarse sediment deposition and include:

- Excess sediment and woody debris that contributes to blockages and overtopping of culverts downstream
- Additional runoff volumes and shorter amount of time to reach flood peaks
- Loss of floodplain wetlands and floodplain storage
- Increase in entrenched channels increasing the size of floods needed to overtop the banks and spill out onto a floodplain
- Increase in magnitude of downstream flood sizes
- Increased potential for valley side failures as channel migrates around bars during smaller floods
- Downstream sedimentation and loss of floodplain storage for future floods
- Burial and change of wetland, riparian, and aquatic habitats
- Loss of riparian forest and wetland health

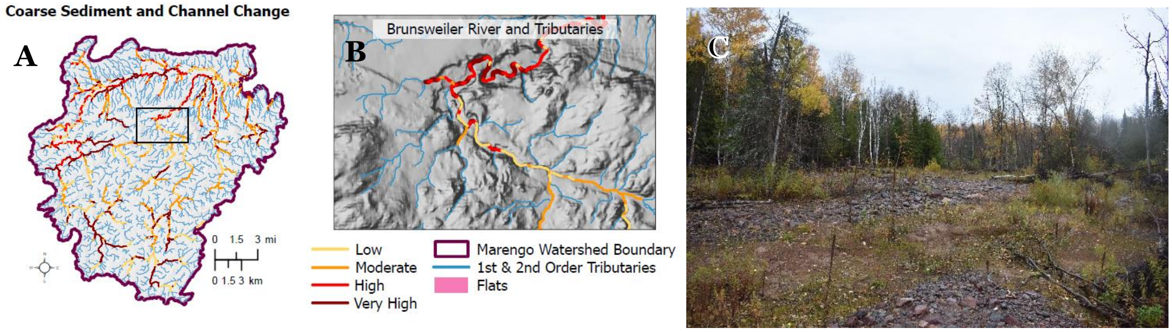

Figure 4. Example of coarse sediment deposition and channel change potential for A) 3rd order and higher fluvial process zones (FPZs) in the Marengo watershed, B) example of Brunsweiler relative to the 2015 lidar-based hillshade map (NOAA 2015), and C) photo of cobble deposition on the Brunsweiler River floodplain (Photo Kyle Magyera)

An example of overall vulnerability to FEHs is shown in Figure 5. This map contains the summed scores for headwater incision potential, landslide potential, coarse sediment deposition and channel change, and hydrologic alteration with a possible minimum score of 4 and maximum score of 20. Scores of 6 or less represent FPZs with minimal potential for geomorphic change. These segments are mostly located in the bedrock surface landform setting. FPZs with scores of 7-9 have the possibility of geomorphic change and may have one sensitivity ranking in the high or very high category. Scores of 10-14 or higher are expected to have geomorphic change and likely have at least two sensitivities in the high or very high categories and are mainly clustered in the transition area. Some short sections of scores of 10 or greater are located in the northern section of the clay plain.

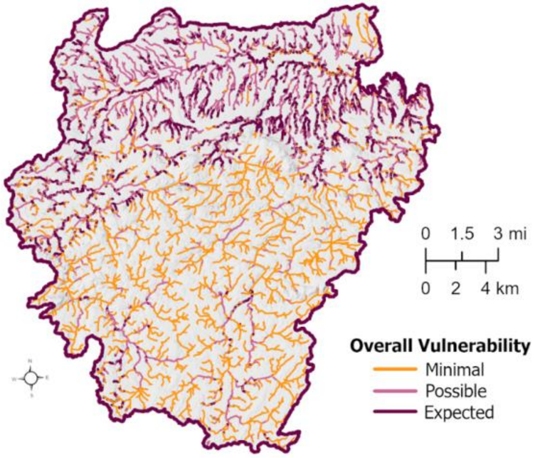

Figure 5. Example of summed scores representing overall vulnerability for geomorphic change for fluvial process zones (FPZs) in the Marengo watershed.

Benefits, Limitations, and Additional Applications

The screening tools are a relatively quick and easy method to identify geographic areas of concern that are prone to flood-caused erosion and deposition and are upstream of vulnerable infrastructure. The screening framework is not suitable for site-specific mitigation activities without additional field data collection and assessment of restoration opportunities. Of note was that the hydro-enforced version of the 10-m DEM was not available at the time of analyses. However the 60-m segment slopes and identification of steep valley sides was confirmed in the lidar and field data. Concerning the landform setting, it was difficult to describe the surrounding landform and geology relative to the stream network especially where a partially confined valley setting was present. We were aware that groundwater sapping and flood-related saturation of steep slopes adjacent to the channels from shallow subsurface flow is an important process that adds to slope failures, especially in the transition area where sand units are interlayered with silt and clay units. The FPZ sensitivity screens are intended to link cumulative risks and downstream stream road-crossings and other infrastructure, but further validation is needed.

In conclusion, the Marengo study helped to validate the locations of FPZs that contributed debris and sediment and have the potential to increase flood-related failures of downstream road-stream crossings. Our FEH vulnerability screening framework semi-automates this type of analysis and could be transferred into an interactive, web-based decision support tool to enable desktop review of hazards, vulnerabilities, and stream and wetland restoration opportunities in the future. Expanding the FEH methodology to include headwater ephemeral channels provided extensive information about erosion related to incision and streamside landslides in ravines and confined valleys and helped to explain where flood flows are potentially being energized with continued wetland storage loss. The FPZ sensitivity mapping data can be used to prioritize where natural flood management can mitigate FEHs, restore hydrology, and slow the flow of water, helping watersheds to better cope with and adapt to the impacts of extreme weather and flooding.

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