Paunnacussing Creek Assessment and Conceptual Design Ideas for Solebury Township, PA

Prepared for

Wild and Scenic Rivers Program, National Park Service

and

Solebury Township, PA

Paunnacussing Creek in Solebury Township, PA

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November 2023

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1.0 INTRODUCTION

This report discusses an assessment of flooding, erosion, and deposition problems on Paunnacussing Creek in Solebury Township, PA and provides conceptual solutions for addressing the identified problems in a manner consistent with natural riverine processes. Paunnacussing Creek is federally designated as a National Wild and Scenic River (WSR) within Solebury Township, including the small villages of Carversville and Lumberville. Any actions taken to address flooding, erosion, and deposition must protect the free-flowing condition, water quality, and outstandingly remarkable values for which the creek was designated.

The assessment effort consisted of three primary work tasks: 1) research, 2) problem identification, and 3) the development of conceptual solutions to flooding, erosion, and deposition. The research consisted of: 1) a one-day geomorphic reconnaissance-level site survey (on November 21, 2022), 2) a data review of documents detailing the natural and human history of the creek, 3) an analysis of online historic maps of the area, and 4) follow-up discussions with landowners and town employees familiar with the creek and its history. These research sub-tasks were then used for problem identification by establishing: 1) how various problem sites may change through time, 2) the potential risk to infrastructure and river values, and 3) whether intervention is necessary (e.g., bank stabilization) and the possible effects of such actions. Conceptual design solutions are described to address at least some of the identified problems while being compatible with Wild and Scenic Rivers Act protections. The solutions are also considered feasible to implement with respect to cost, constructability, access, and other site constraints. Below, the results of the three work tasks described above are presented in a discussion of: 1) the distribution of flooding, erosion, and deposition on Paunnacussing Creek; 2) how the channel will change over time if no remedial restoration actions are taken; 3) potential solutions to the identified problems; and 4) the future studies needed to better document current conditions and to select the most appropriate conceptual solutions moving forward.

2.0 DISTRIBUTION OF FLOODING, EROSION, AND DEPOSITION

Flooding, erosion, and deposition are essential riverine processes that enable streams to adjust to natural conditions and human activities both in the channel and the surrounding watershed. Natural topographic relief generated by long ago climatic and tectonic events is the major driver of flooding, erosion, and deposition on Paunnacussing Creek. This is most evident in the lower section of the creek between Carversville and the Delaware River where the creek falls over 140 feet in approximately two miles through a deep and narrow valley carved through the escarpment between the Delaware River valley and surrounding highlands (a gradient of 1.33%). Upstream, the creek falls approximately 80 ft over 1.2 mi (a gradient of 1.26%) between the Buckingham town line and Carversville along the north branch of Paunnacussing Creek, the steepest of the three branches. Streams typically decrease in gradient in a downstream direction, so the five percent increase in slope in a downstream direction on Paunnacussing Creek is considered significant and reflects the natural topographic constraints in the watershed. Combined with both the greater valley confinement downstream of Carversville that increases erosive forces during floods and steeper tributaries that increase sediment transport to the creek, the increasing slope downstream of Carversville at least partially explains why most of the problem areas highlighted by Solebury Township officials and residents during the site visit occur in this area.

European settlement in Solebury Township began in the late 17th century (Web citation 1). In the following centuries, human activity in the creek and surrounding watershed altered the location and scale of flooding, erosion, and deposition on Paunnacussing Creek. A few examples are highlighted below.

2.1 Artificial channel straightening

Paunnacussing Creek was rerouted in the early 1840's from behind the houses at the northwest corner of Carversville and Wismer Roads to the front of the houses where the creek remains today (Granzow, no date). Field and map evidence downstream of the Paunnacussing Creek Road bridge suggest the channel was also realigned and straightened, perhaps in association with the homes and yards along the right bank. Verifying that straightening occurred in areas of greater confinement where the floodplain is narrow is difficult, so past straightening downstream of Carversville cannot be established with certainty, but cannot be definitively ruled out either.

Channel straightening was a widespread practice throughout the northeastern United States in the 19th and 20th centuries with meanders commonly reforming over time (Field, 2007). Straightened channels are steeper than the original meandering configuration given the shortening in their length. With greater erosive force, straightened channels go through a phase of downcutting below the floodplain level before a period of bank erosion widens the channel (Brookes, 1985; Simon, 1989). Downstream, beyond the straightened section, excessive deposition and increased flooding can occur as the channel returns to an unaltered meandering condition. Consequently, a risk may still exist for sudden and significant bank erosion near homes and roads on those portions of Paunnacussing Creek that remain in an artificially straightened configuration, even decades or centuries after the initial straightening.

2.2 Mill dams

Five mill dams and associated ponds were present between Carversville and Lumberville in the 18th and 19th centuries (Figure 1; Granzow, no date). At least one of these dams, at Michener's Mill, was quite high, likely more than 15 feet high based on historical photographs (Figure 2). Flooding from a hurricane in 1885 is believed by some people to have filled the mill ponds with sediment, after which most of the mills did not recover (Graznow, no date). However, others have voiced skepticism as to the flood's impact on the mill dams (Bill Tinsman, email communication, 2023). Regardless of the timing, the mills and associated dams are no longer present. When dams are removed or degrade over time, the sediment accumulated in the impoundment erodes and increases sediment loading downstream. Deep gullies have formed by erosion of accumulated sediment behind dozens of former mill dams in Pennsylvania (Walter and Merritts, 2008).

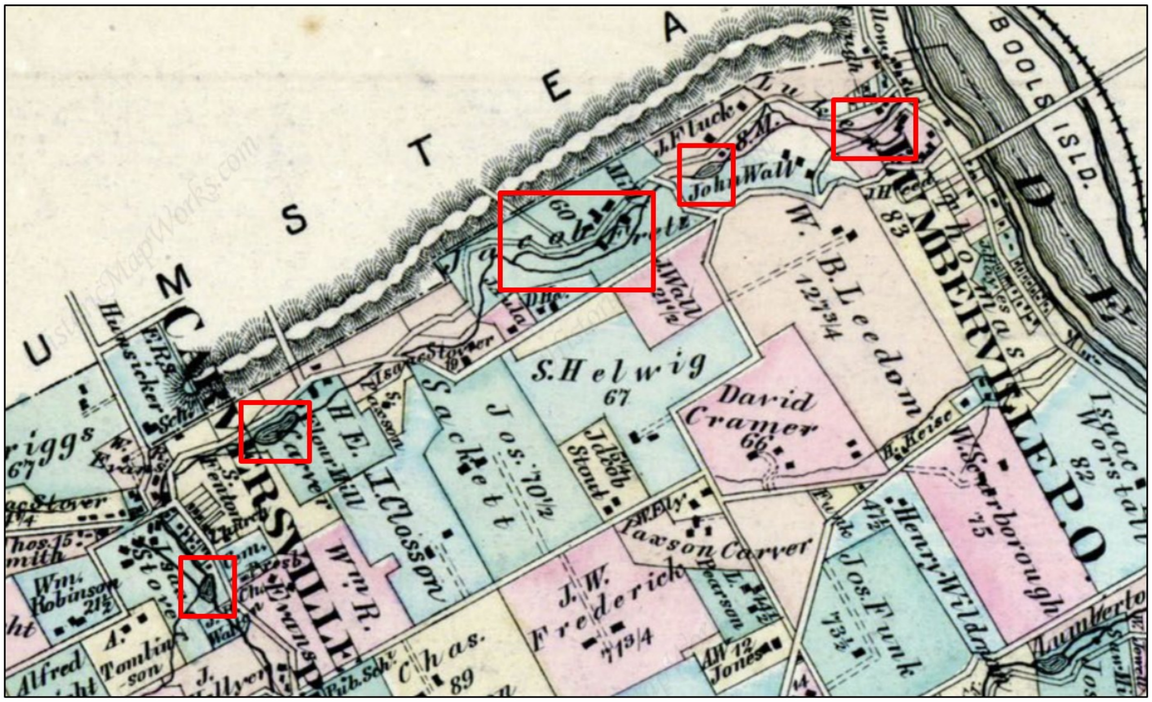


Figure 1. A portion of the 1876 Bucks County Atlas (Web citation 3) showing the five mill ponds that were present from Carversville to Lumberville (highlighted with the red boxes). Note also the absence of a large delta at the mouth of Paunnacussing Creek in the Delaware River.

Some continuing erosion on Paunnacussing Creek may be linked to the demise of the former mill dams. While bedrock was observed on the bed of Paunnacussing Creek during the site visit, no waterfalls were observed, so sediment behind the dams could have accumulated to the full height of even the tallest dam (Figure 2). The stream banks viewed near the intersection of Fretz Mill and Fleecydale Roads expose sediment that may have been deposited behind a mill dam, perhaps during the 1885 flood (Figure 3). The ongoing erosion of the banks may reflect the downcutting and widening of the channel through the old mill pond sediments. A natural gas pipeline crosses the creek (Figure 4a) immediately upstream of a former dam (Figure 4b) near the end of Short Road. The pipeline is protected by articulated concrete matting that has become partially undermined (Figure 4a). The damage to the matting could be due to downcutting and widening of the sediments deposited behind the former dam.

Figure 2. Double cascading dam at Wall Mill on Paunnacussing Creek in a photograph believed to have been taken around 1880 (about 1,500 ft upstream of River Road- see also Figure 1). From Graznow (no date).

Figure 3. Near vertical eroding bank exposing possible mill pond sediments, including 1885 flood deposits.

Figure 4. a) Erosion protection matting undermined at natural gas pipeline crossing immediately upstream of b) the remnants of a former mill dam.

Sediment from the 1885 and other floods, coupled with erosion from behind the former mill dams, has resulted in excessive deposition further downstream. The delta present in the Delaware River at the mouth of Paunnacussing Creek is not shown on the 1876 Bucks County Atlas when the mills were still active (Figure 1) but does appear on the 1891 historical topographic map (Web citation 2) surveyed shortly after the 1885 flood. If accurate, these maps are consistent with the 1885 flood and demise of the dams resulting in the delta's formation – a feature not seen at the mouth of other nearby tributaries. Excess deposition continues today near Lumberville where backwatering of the Delaware River during flood stage reduces flow velocities enough on Paunnacussing Creek to cause the formation of large gravel bars (Figure 5). This deposition in turn concentrates flow against the banks, causing further erosion and flooding as the channel infills with sediment.

Figure 5. Large gravel bars infilling the channel upstream of River Road near the Delaware River confluence.

2.3 Roadways and stream crossings

The road network along Paunnacussing Creek and throughout the watershed artificially constrains the channel in multiple ways that may be exacerbating flooding, erosion, and deposition. Undersized stream crossings (i.e., bridges or culverts narrower than the channel's width) behave like temporary dams during floods with backwatering upstream. This causes excess deposition upstream of the crossing and increases the likelihood of bank erosion as flow is diverted around the emerging sand/gravel bars. The resulting sediment deficit downstream of the structure can sometimes lead to severe localized scour of the bed and banks. Similar channel responses can also occur during large floods even at crossings equal in width to the channel if the floodplain flow is blocked by the road approaches to the stream crossing or where one or more mid-channel piers is present. This may be the case at the Fleecydale Road bridge in Carversville where the triple-arch structure largely spans the channel (Figure 6a) but still significant deposition has occurred upstream along the right bank (looking downstream) with continuing erosion of the left bank (Figure 6b). The road approaches to the bridge impede floodplain flow (Figure 6a) and large wood could temporarily block one or more of the bridge's barrels during a flood, thus enhancing sediment deposition upstream.

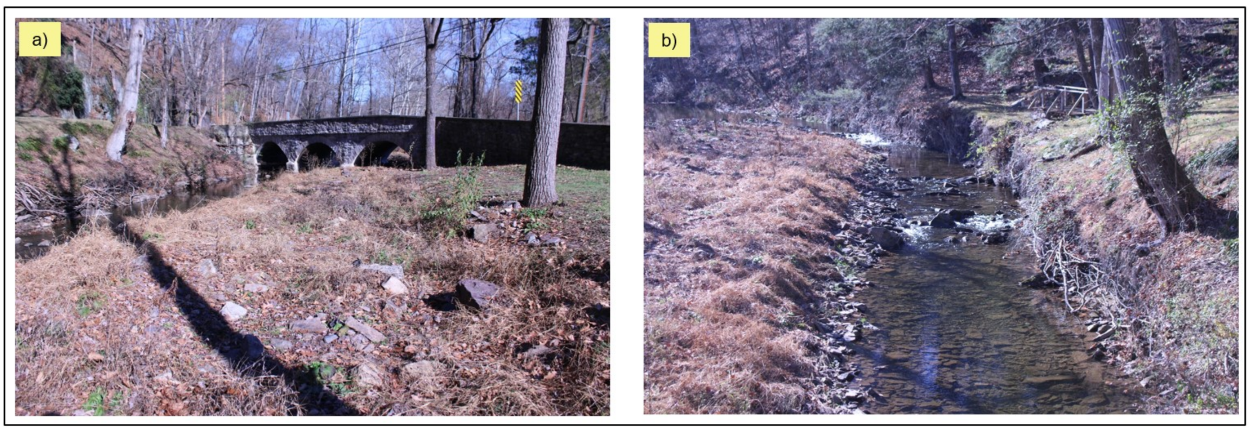


Figure 6. a) Triple-arch Fleecydale Road bridge with elevated road approaches blocking a portion of the floodplain may be responsible for b) deposition on the right bank (left side of photo) and erosion of the opposite bank.

Severe scour at an undersized culvert damaged a portion of Short Road on a small steep tributary (undergoing repair at the time of the site visit) (Figure 7). This site highlights the potential for the tributaries and the dozens of small culverts on them to impact Paunnacussing Creek itself. Scour at the outlet of a culvert is only one potential source of excess sediment that can be transported downstream to Paunnacussing Creek. In addition, the initial scour at a culvert outlet has the potential to initiate much larger mass failures by undermining the steep high banks common to many of the watershed's tributaries, particularly those between Carversville and Lumberville. Finally, years of sediment stored upstream can be released suddenly if a culvert is swept away during a large flood. These sources of excess sediment (i.e., above what might occur naturally) can increase the sediment load to the less steep and unconfined Paunnacussing Creek where deposition becomes more likely. Rapidly growing sand/gravel bars, in turn, increase the risk for flooding and bank erosion on Paunnacussing Creek. While these issues would arise only during a large storm event, the presence of numerous undersized culverts on tributaries throughout the watershed increase the risk of large sudden sediment pulses entering Paunnacussing Creek.

Figure 7. Short Road under repair from scour damage at undersized culvert.

Not only do road crossings potentially exacerbate flooding, erosion, and deposition on Paunnacussing Creek but roads built along the banks of the creek can as well. Fleecydale Road runs right along the edge of Paunnacussing Creek for much its length between Carversville and Lumberville. This creates a need to protect the road from bank erosion and the edge of the road is indeed armored in many places with large rock (i.e., riprap) and/or a wall (Figure 8). The road occupies a portion of the former channel and floodplain and has likely initiated the erosion and subsequent armoring of the opposite bank (Figure 8). By constraining the channel, flow velocity and erosive force increase, which can potentially undermine the road itself or cause erosion and deposition elsewhere.

Figure 8. Fleecydale Road and its protection along the edge of Paunnacussing Creek occupy a portion of the channel and may be the cause of erosion and subsequent armoring of the opposite bank.

2.4 Bank armoring and blockage of side channels

Additional channel encroachments are present along Paunnacussing Creek besides channel straightening, (former) dams, and roads. Bank stabilization done with hard armoring (i.e., large rocks, concrete wall) constrains the channel's natural migration and, thus, could destabilize nearby areas. Often the misguided tendency is to try to stop all erosion even where no infrastructure is threatened (Figure 9a). Similarly, when the creek spills over its banks and carves a side channel, efforts are undertaken to keep the channel to a single flow path by blocking the upstream end of the secondary channel (Figure 9b). While bank stabilization and blockage of side channels may be necessary to protect infrastructure in some instances, the use of these practices where no infrastructure is imminently threatened may, in fact, divert erosive forces and inadvertently add stress on infrastructure elsewhere.

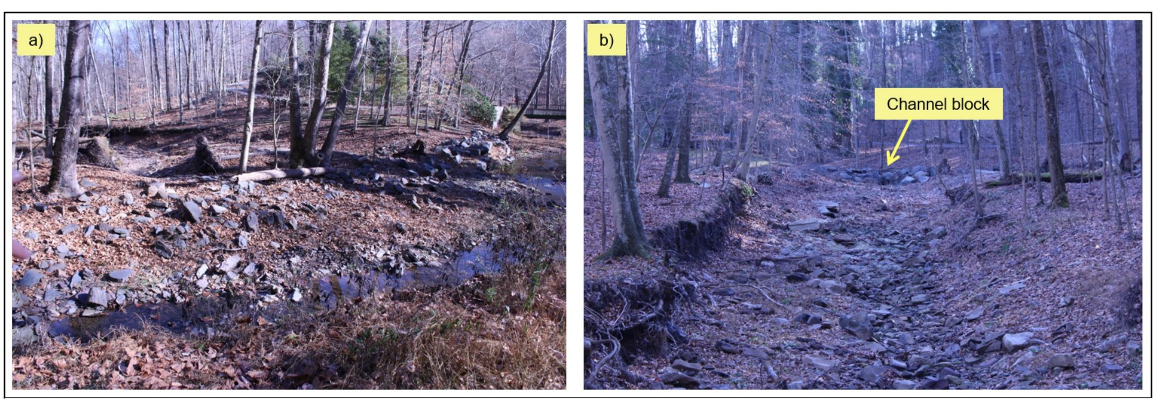


Figure 9. Constraints such as a) rock armor and b) channel blocks where no infrastructure is present divert erosive forces and may inadvertently add stress on infrastructure elsewhere.

3.0 FUTURE CHANNEL EVOLUTION IF NO ACTION IS TAKEN

Flowing water carries sediment. Streams adjust their dimensions (e.g., width, depth, meander pattern) in such a way that the amount of sediment carried by the flowing water remains relatively constant along the length of the river. Changes along a stream, either natural or human caused, trigger a channel response that ultimately reestablishes this continuity of sediment transport. These channel responses and adjustments take the form of erosion or deposition. Erosion widens a channel and/or decreases its slope (by lowering the channel bottom elevation) both of which reduce the stream's sediment carrying capacity. In contrast, deposition narrows a channel or increases its slope and, thus, increases a stream's capacity to carry sediment. Severe erosion, deposition, and flooding often reflect an ongoing response to past disturbances. The severity and location of erosion, deposition, and flooding can often be anticipated by understanding how the disturbance has impacted the sediment carrying capacity of the streamflow. A couple of examples related to Paunnacussing Creek are highlighted below and are useful for understanding the current conditions along the creek and how those conditions may evolve over time.

3.1 Artificially straightened channels

Artificially straightened channels, present upstream of Carversville on Paunnacussing Creek, locally increase the sediment carrying capacity of the stream since the shortened channel has a steeper slope. As described above, this increased capacity leads to erosion with the excess sediment conveyed downstream. When the transported sediment reaches an undisturbed meandering section of channel further downstream, rapid deposition and increased flooding may result. The erosion in the straightened reach reduces the sediment carrying capacity back towards the initial undisturbed condition. The reformation of meanders along the straightened channel can put infrastructure at risk. The extent of straightening and the degree to which the process of meander reformation has progressed along Paunnacussing Creek could not be determined during this reconnaissance-level assessment. Further study is warranted to identify if and where further erosion and downstream deposition could threaten infrastructure as the channel continues to adjust to past channel straightening.

3.2 Mill dams

Flowing water carries sediment but slack water does not, so sediment typically accumulates in areas of hydraulic constrictions such as the impoundment upstream of dams. When a dam is removed or falls into disrepair, the stream will undergo a series of adjustments through the former impoundment, referred to as a channel evolutionary process, that will return the channel to a more natural pre-dam condition (Figure 10). First, a deep narrow gully erodes through the former impoundment as the flow initially passes over the steep exposed face of accumulated sediment where the hardened (e.g., rock, concrete) face of the dam once existed (Figure 10a). This gully formation begins at the dam site and migrates upstream through the impounded sediments over time until the original pre-dam channel bed level is reestablished. Eventually, the steep banks of the deepening gully become unstable, initiating a widening process (Figure 10b). The widening will continue until even large floods can pass through the channel without further widening. At this point, smaller more frequent floods are less able to transport sediment through the widened channel, so sediment deposition ensues and ultimately creates a new floodplain inset below the former impoundment sediments (Figure 10c).

Different areas along the stream may be in different stages of channel evolution at the same time, especially when multiple dams fall into disrepair at different times, such as on Paunnacussing Creek. Although speculative, the initial incision on Paunnacussing Creek may be ongoing in some areas (Figure 4a), widening in others where the channel has downcut to bedrock (Figure 3), and elsewhere floodplains are present that have been reestablished within the former impoundments or perhaps were never disturbed by the dams. Anticipating where and how severe erosion may be in the future will require: 1) confirming the presence of impoundment sediments in the stream banks; 2) identifying areas of continuing channel incision by analyzing a longitudinal profile of the channel; and 3) better understanding where erosion is currently occurring relative to the former dam locations. At a minimum, bank erosion and widening of the channel will likely persist in places as the channel's response to the absence of the dams continues.

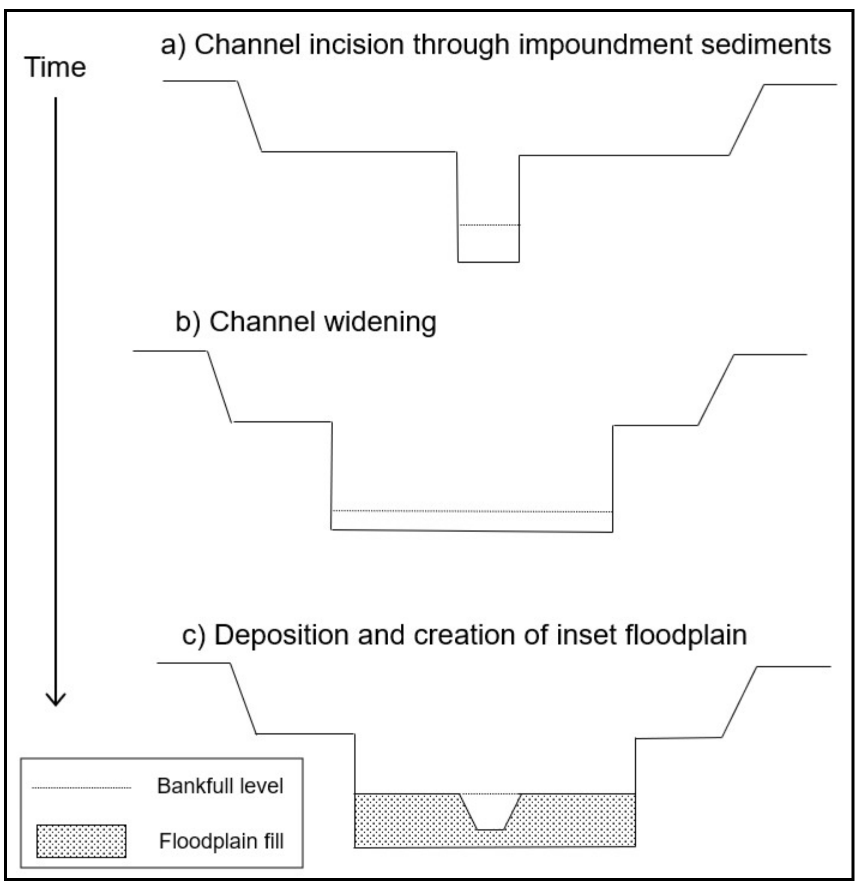


Figure 10. Channel evolutionary steps as a channel forms through a former impoundment.

4.0 POTENTIAL SOLUTIONS TO THE IDENTIFIED PROBLEMS

Flooding, erosion, and deposition problems are unlikely to be ever fully resolved on Paunnacussing Creek given that the natural physiography of the watershed concentrates runoff into a narrow valley downstream of Carversville where small steep tributary streams can rapidly input large volumes of sediment. These problems have been exacerbated by centuries of human land use along Paunnacussing Creek that continue to focus erosion and deposition where the capacity to transport sediment rapidly changes (e.g., at undersized stream crossings). Sustainably reducing the severity of flooding, erosion, and deposition depends on removing human constraints that alter sediment transport capacity and otherwise prevent Paunnacussing Creek from achieving sediment transport continuity.

Past activities along Paunnacussing Creek, even efforts intended to address flooding, erosion and deposition, have largely been undertaken in isolation without fully appreciating how one project can negatively impact others elsewhere on the creek. Effective solutions will depend on a holistic watershed-scale vision that promotes sediment transport continuity and natural channel processes. The first three approaches discussed below, over a long period of time, could lead to measurable reductions in flooding, deposition, and erosion. No single silver-bullet solution exists to quickly resolve the riverine problems on Paunnacussing Creek that are the consequence of centuries of human activities. Table 1 (appended to the end of this report) prioritizes and summarizes the potential solutions to these problems described below and provides, in most cases, specific examples of where these techniques might be applied along the creek or surrounding watershed.

4.1 Removing channel constraints

Removing channel constraints along Paunnacussing Creek imposed by past human activities (e.g., road construction, bank armoring) is key to achieving sustainable reductions in flooding, erosion, and deposition. Conserving land along the river is often key to implementing projects focused on removing one or more channel constraints. Some landowners may be open to removing constraints on their properties; others may be steadfast against the idea. Since some current landowners may be reluctant to agree to removing channel constraints that are perceived to be protecting their properties, one strategy might be a long-term effort to acquire (or place into conservation easement) river front lands when opportunities arise. Once easements are established, a variety of channel constraints could be removed (listed in priority order based on their potential to reduce flooding, erosion, and deposition on Paunnacussing Creek): 1) undersized crossings (see further discussion below); 2) all or parts of roadways that have been damaged by erosion and are unlikely to be repaired (e.g., Fleecydale Road, see Figure 8); 3) rock armor that is not protecting infrastructure (e.g., Figure 9a); 4) artificial blockages of side channels (e.g., Figure 9b); and 5) impervious cover to reduce stormwater runoff to the stream. Removing small areas of impervious cover will have limited effect in a large watershed like Paunnacussing Creek, but could have benefits on the smallest tributaries.

Removing channel constraints, regardless of the type, would help to slow the flow of sediment and water downstream, thus protecting other areas where infrastructure remains threatened by flooding, erosion, and deposition. Encouraging reforestation of upland and riparian areas could have a similar impact. Also, to prevent future constraints from being built along the river, land use tools such as zoning ordinances can be employed to direct or limit development of the valley bottom.

Removal of a single constraint on a small land parcel is unlikely to have a noticeable effect on flooding, erosion, and deposition problems elsewhere on the creek. But the cumulative impacts of a concerted and enduring effort to remove constraints, supported by valley-bottom land conservation, will be recognizable. If efforts do not start soon, however, the current problems will persist for decades as no quick-fix solution exists to resolve issues centuries in the making. Not all constraints can be easily removed from along the creek such as the gas pipeline crossing (Figure 4a) but options do exist (see further discussion below). As channel constraints are steadily removed, protecting key infrastructure will become less difficult as the creek will have more opportunities to adjust over long continuous sections of the channel, thus putting less stress on those areas in greatest need of protection.

The removal of constraints along the creek could be prioritized to address the most significant issues sooner, but the whole process will be predicated on landowner willingness to establish easements or otherwise allow such work to proceed. Financial assistance that partly or wholly covers implementation costs can incentivize landowners to remove constraints that may in fact be responsible for flooding and erosion on their land or adjacent parcels. Financial and tax incentives are sometimes used by lands trusts and other entities to support land acquisition or to establish easements on privately held lands (e.g., pay landowners for lost production/value of land). Solebury Township should consider engaging with local land trusts to emphasize the benefits of prioritizing valley-bottom lands for conservation and also consider zoning ordinances to prevent future developments that further constrain the channel. In addition to long-term reductions in flooding, erosion, and deposition, conservation of valley-bottom lands would also lead to improved aquatic and riparian habitat and greater public access to the creek that has played such an instrumental role in the township's history.

4.2 Resizing stream crossings

Numerous roads cross Paunnacussing Creek and its tributaries throughout the watershed. Many of these crossings are undersized (i.e., narrower than the channel width), resulting in backwatering and deposition upstream (Figure 6a) during storm events and scour downstream (Figure 7). By resizing the crossings to at least match the width of the channel and also providing for supplementary relief culverts where floodplains are present, the deposition and erosion around the structures can be minimized as the continuity of sediment transport is restored. Appropriately sized crossings also enable more efficient transport of woody material and aquatic organism passage, so resizing the structures would have an environmental benefit as well. Resizing numerous crossings throughout the watershed will take considerable time and money to complete, so basin-wide benefits from these actions will likely take decades to emerge. However, immediate benefits will accrue in the vicinity of each structure replaced. A comprehensive crossing assessment should be completed throughout the watershed to identify the highest priority crossings to replace based on: 1) the relative size of the structure compared to the channel and anticipated effects of climate change; 2) whether the road approaches block the floodplain; 3) the severity of deposition and erosion at the crossing; and 4) the remaining life expectancy of the structure. Hydraulic modeling should be completed with the crossing assessment to ensure that the replacement of one crossing will not lead to more severe problems at a remaining undersized crossing downstream.

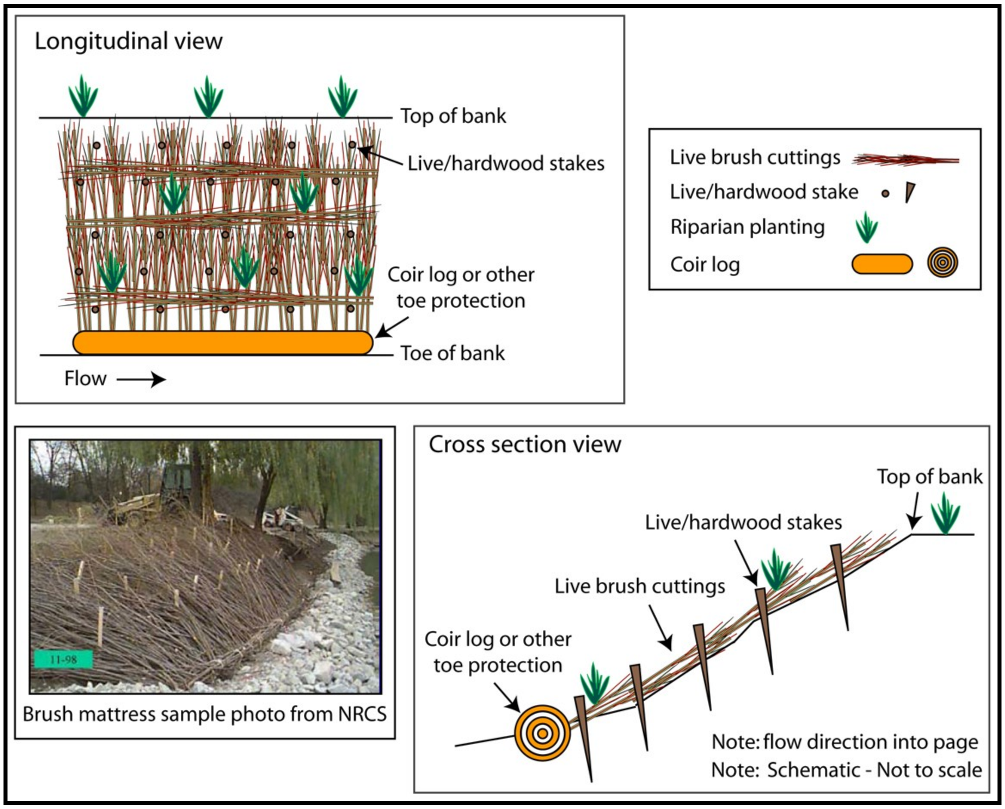
4.3 Relocating critical infrastructure

Infrastructure constraining a stream can sometimes be relocated to restore natural channel processes. The gas pipeline is perhaps the most threatened critical infrastructure crossing Paunnacussing Creek as the current scour protection has been damaged by undermining (Figure 4a). The hardening of the bed and banks of the channel through the use of articulated concrete matting is inconsistent with Paunnacussing Creek's WSR status, so an alternative approach to protecting both the pipeline and the creek's outstandingly remarkable values is needed. Directional horizontal drilling offers a method for relocating the pipeline at a greater depth safely below the maximum expected scour depth of the creek bed (Web citation 4 – see pages 3-20 to 3-21). Geotechnical studies will need to be completed to determine if the soils and rock underneath the stream bed are suitable for this type of drilling. If horizontal drilling is deemed possible, the current concrete matting on the bed and banks could be removed and natural channel adjustments allowed to proceed without threatening the pipeline.

4.4 Nature-based bank stabilization

Pursuing the potential solutions outlined above are unlikely to result in noticeable reductions in flooding, erosion, and deposition for many decades. In the interim, local bank stabilization projects may be required to protect infrastructure that cannot be readily relocated or retired. Nature-based bank stabilization techniques (also referred to as bioengineering) rather than hard armoring approaches should be used in these instances as they enhance aquatic habitat, minimize impacts to adjacent reaches, and are more consistent with Paunnacussing Creek's Wild and Scenic River designation. Numerous nature-based bank stabilization techniques are available for use (Web citation 5 – see p. 113-180). Where erosive forces are low, native riparian planting or the use of native live stakes of quick rooting species (e.g., willows) may be sufficient to stabilize the banks. A brush mattress (Figure 11a) or fascine bundles can be used to provide initial surface protection until the plantings and live stakes take root. In higher energy environments, such as between Carverville and Lumberville, the use of root wad revetments, log crib walls (Figure 11b), or soil lifts may be required at least at the base of the bank to withstand the stronger erosive forces. The use of plants and wood in bank stabilization creates roughness on the bank surface to baffle the flow and reduce erosive forces rather than transferring that energy downstream as is more typical of hard armoring techniques (e.g., riprap). The use of rock or concrete walls to line the banks should be avoided altogether and nature-based techniques only used where infrastructure is imminently threatened by erosion.

a)



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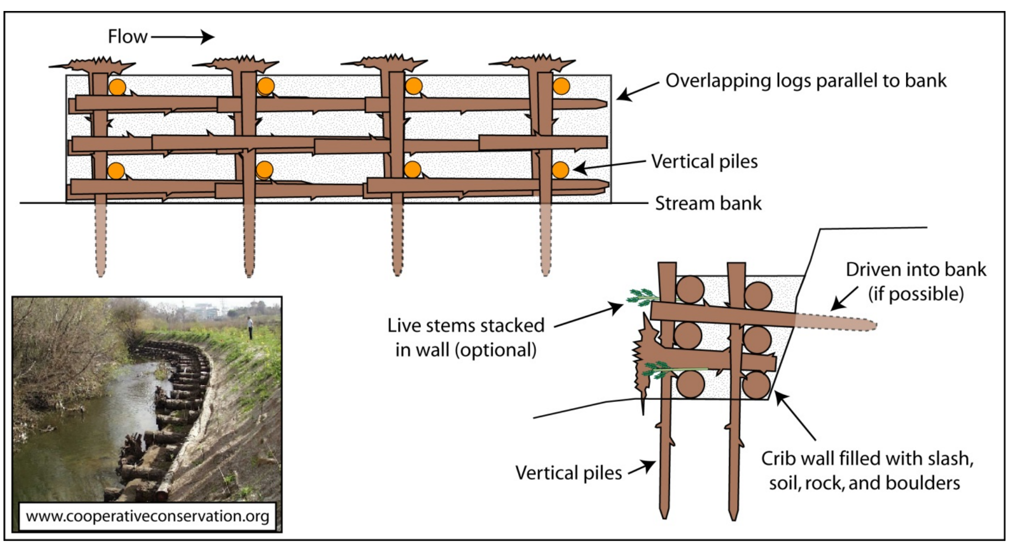

Figure 11. Examples of nature-based solutions for bank stabilization include a) brush mattresses for low energy environments and b) log crib walls for higher energy settings.

5.0 FUTURE STUDIES

Based on the reconnaissance-level nature of the geomorphic assessment, the findings and conceptual solutions provided here must be considered preliminary. Further studies should be completed on Paunnacussing Creek to confirm whether: 1) any bank sediments exposed along the creek were deposited in impoundments upstream of the former mill dams (through stratigraphic and sedimentological analyses), 2) the channel is continuing to deepen upstream of the former dams (i.e., migrating headcuts), potentially undermining infrastructure such as the gas pipeline (through topographic surveys to complete longitudinal profiles); and 3) the stage of channel evolution (Figure 10) varies relative to the former locations of the dams (through detailed geomorphic mapping). In addition, as mentioned above, a comprehensive bridge/culvert assessment should be completed in conjunction with hydraulic modeling to prioritize the replacement of undersized crossing structures to maximize reductions in flooding, erosion, and deposition near critical infrastructure.

6.0 CONCLUSIONS

The reconnaissance-level geomorphic assessment has identified numerous potential causes for the flooding, erosion, and deposition that remain problematic along portions of Paunnacussing Creek. Long-term relief of these problems will require the removal of channel and floodplain constraints that are preventing the creek from achieving a continuity of sediment transport that would reduce the severity of flooding, erosion, and deposition along the length of the creek while simultaneously improving environmental conditions. Given the natural setting of Paunnacussing Creek, some problems will persist and protecting critical infrastructure when needed should be done with nature-based solutions to minimize the transfer of erosive forces or excess sediment downstream while improving aquatic and riparian habitat.

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Table 1. Prioritized list summarizing potential techniques useful for addressing flooding, erosion, and deposition problems on Paunnacussing Creek.

Technique	Priority*	Description	Benefit	Example location†	Notes
Changes to infrastructure					
- Resizing crossings	2	Ensure single-span crossing matches width of channel; include also floodplain relief	Prevent deposition upstream and erosion downstream of structure	Carversville bridge (40.38762, -75.06135)	This site would benefit from floodplain relief culverts
- Removing unused roads	3	Removal of damaged roads unlikely to be rebuilt due to high costs or other reasons	Provide additional space for flood flows and channel adjustments	Fleecydale Rd	Closed portion from Old Carversville Rd to Fretz Mill Rd
- Relocating infrastructure	4	Relocate infrastructure so no longer in conflict with natural river processes	Provide additional space for flood flows and channel adjustments	Gas pipeline crossing (40.38967, -75.05995)	Relocate pipeline vertically so below expected scour depth
Watershed management					
- Land conservation	1	Conserve riverside land through purchase or easements by working with land trusts, etc.	Provide control of lands to allow for removal of constraints	No specific location identified	Likely required to enable other actions (e.g., reforestation)
- Reforestation	6	Encourage growth of forests in currently open upland and riparian areas	Reduce flood peaks and sediment entering the river	Along creek (40.39158, -75.05900)	With landowner permission only
- Remove impervious cover	8	Remove pavement and other impervious surfaces no longer in use	Reduce runoff to creek and provide space for vegetation	No specific location identified	Applicable wherever home, barn, road, etc. no longer in use
In-stream actions					
- Remove hard armor	5	Removal of rock, concrete, or steel used on banks but not protecting infrastructure	Allow for natural processes and reduce erosive forces elsewhere	Gas pipeline crossing (40.38967, -75.05995)	Assumes pipeline relocated below scour depth
- Remove channel blocks	7	Remove berms blocking side channels if no infratructure will be threatened	Allow for natural processes and reduce erosive forces elsewhere	Along creek (40.39676, -75.05593)	With landowner permission only
- Bioengineering	9	Nature-based bank stabilization solutions to protect critical infrastrcture	Stabilize banks while improving habitat and minimizing impacts	No specific location identified	Use only to stabilize banks near critical infrastructure

*Lower number indicates a higher priority and is based on not only value of technique in reducing flooding, erosion, and deposition problems between Carversville and Lumberville but also how widely it can be applied (e.g., channel blocks given a low priority primarily because only one observed during assessment). Cost not considered.

† Numbers are latitude and longitude of site in decimal degrees