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Historical Land-Use and Streambank Erosion

Developing a local, process-based streambank restoration strategy

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Abstract:

This capstone project explored the relationship between historic land use and current land management practices in rural upland watersheds. Specifically, the work analyzes how anthropogenic disturbances affect hydrogeomorphic change and determines how this might inform a process-based restoration plan for sites of local erosion within the watershed. The study area was a 31-acre agricultural property with a low-order stream flowing through it, where a section of the streambank was actively eroding. The goal was to provide the landowner with a restoration plan to stabilize and restore ecological functions of their stream-side area, while accomplishing multiple stakeholder goals. The methods included (1) a study of historical imagery of the property to map stream migration and identify possible anthropogenic disturbances, (2) a site survey to obtain cross-section, longitudinal profiles, and a reference-reach condition, and (3) an investigation of nearby land-use, local BMP guidance, and the regulatory framework for streamside work in Virginia. The results of this study showed historic mill-dam presence in the area, and upstream urban development over the last 30 years. The stream was found to be under active lateral migration at the erosion site, with several local, anthropogenically sourced factors identified during the site survey. Survey and historic imagery results informed the development of a process-based restoration strategy, which was then evaluated against stakeholder goals and potential BMP solutions to inform a practical streambank restoration plan to be delivered to the landowner.

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Chapter 1: Introduction

1.1 Introduction

The Shenandoah Valley, located in a unique geographic feature of the Appalachian Mountains, has a rich history of anthropogenic activity and development, and is an area long recognized for its fertile soils and agricultural potential (Emory, 1964). Since its early European settlement, this land – and particularly the waterways running through it – have continuously changed and adapted to anthropogenic influence. For the last 250 years, this valley has seen a rapid transformation into agricultural use (Lanier & Hofstra, 2005), and agriculture is highly dependent on a reliable water supply. To meet the needs of livestock and crops, headwaters to the Shenandoah River have been repeatedly re-routed, dammed, and altered in many ways (Walter & Merritts, 2008). Equally as important as the water itself, are the nutrient and sediment dynamics that have changed over this period. Records show evidence of heavy agricultural fertilization since 1850 and even prior (Schlebecker, 1971). These changes have adversely affected regional sediment loads, nutrient retention, and wetland quality; beyond the valley this development has had a far-reaching influence on water quality, soil integrity, and ecological health throughout the watershed (Chesapeake Bay Foundation, 2022).

Modern-day landowners are met with the challenge of managing land that has been shaped by generations of decisions over which they had no control, and about which they may hold little knowledge. A responsible landowner who wishes to steward their land to a fuller potential must carefully examine the land's history and understand its ecological context to inform a management strategy that will restore and nurture their land and water over time.

The goal of this research is to explore land-use change over time in a local watershed of the Shenandoah River, analyze how anthropogenic disturbances affect geomorphic change, and determine how this might inform a process-based restoration plan for sites of local erosion within the watershed. To do this, the research question addressed in this study is: "How do changes in upstream watershed land-use affect the long-term stability and management strategies of streambanks in low-order, rural streams?" This analysis should help inform landowner decisions in the management of their property, employing evidence-based mitigation and restoration strategies to their streambanks to counteract or redirect any historical degradation influenced by prior land-management decisions.

1.2 Problem Definition

The project site (*Figure 1*) is a privately-owned 31-acre property on Cub Run, a tributary to the South Fork Shenandoah River, where roughly 70 feet of the streambank have experienced heavy erosion. The property was purchased in 2021 by a local church, Church of the Lamb, at which time the management goals changed from strictly agriculture, to prioritizing ecosystem- and community-oriented management while maintaining some agricultural functions. Work has already been done to re-introduce riparian zones around the stream, fence off cattle from having access to the bank, and allocate areas for public use and enjoyment.

Although, anecdotally, some areas of the streambank are already showing indications of better health in the last three years, many sections retain mild to serious erosion throughout the property. This is typical of many streams throughout the Shenandoah Valley. Prior to the land-ownership change, this property had been used for intensive agricultural use for 40-plus years. Cattle were grazed along the bank, trampling and eating vegetation near the stream and changing the nutrient loads in the watershed. There is historic evidence of a mill-dam just above the project site – a ditch can still be seen where the water was diverted, and another mill-dam can be found washed-out downstream on the neighbor's property.

Other anthropogenic activity affecting the local stream can be found in a nearby urban development, Penn Laird, which grew substantially in the last 30 years and created a network of impermeable surfaces. A small tributary feeds into Cub Run just above the project site which collects water from Penn Laird and receives its stormwater runoff. Impermeable surfaces have the potential to flood downstream catchment systems, as they funnel stormwater into a single channel instead of allowing the ground to absorb the water, causing increased bank erosion, introduction of pollutants, and increased nutrient transfer (Hogan & Wallbridge, 2007).

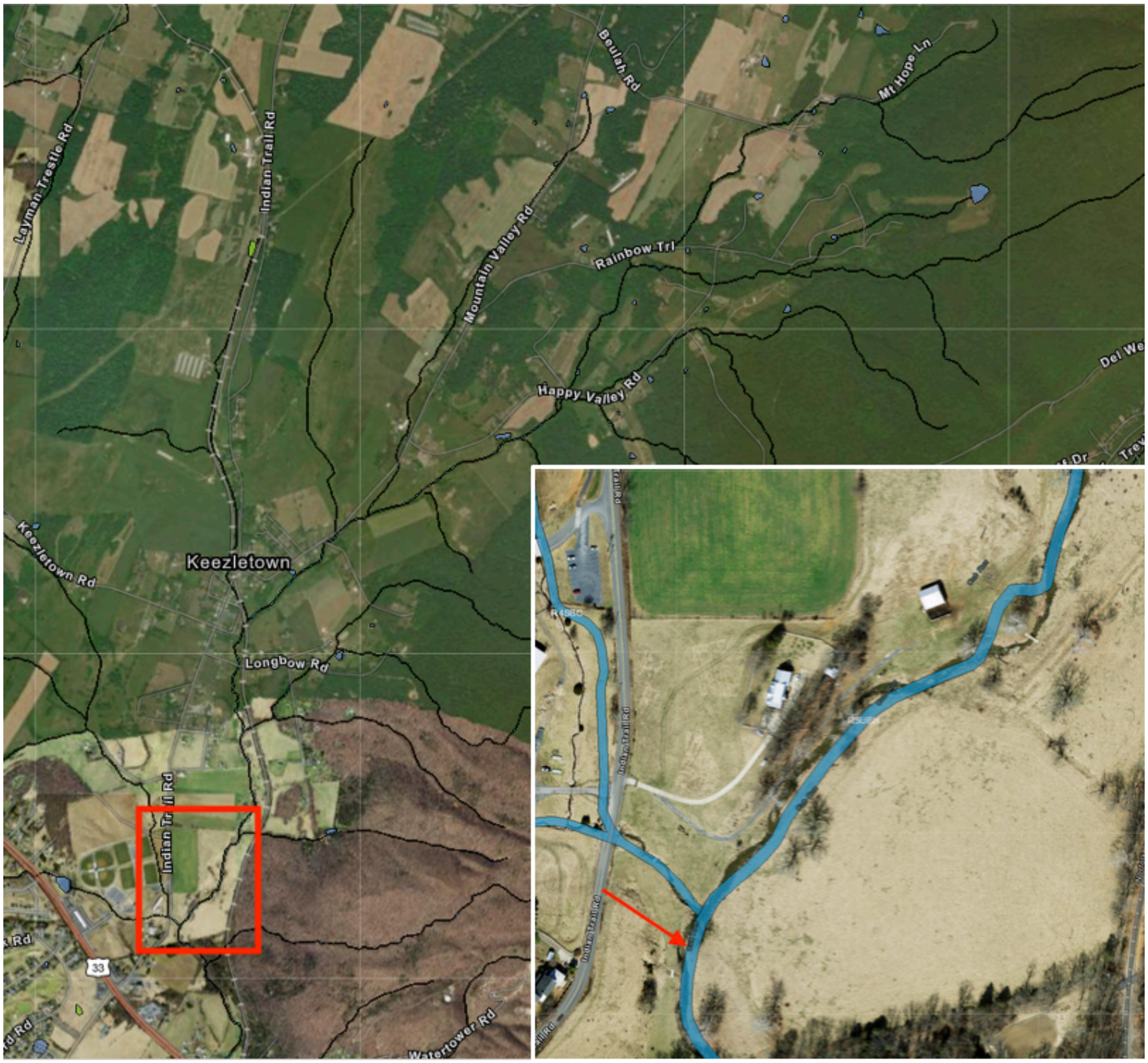

Figure 1: Location of project site, south of Keezletown, VA, in relation to its headwaters on the Western Slope of Massanutten. (basemap source: Fish and Wildlife Service, 2025.)

The location of heaviest erosion within the project site shows evidence of prior human intervention. The erosion occurs at a gradual bend in the stream, and there is a small rock island in the middle of this bend. The rocks located here are larger than what appear to be naturally dispersed throughout the streambed and appear to be placed in a manner where they might have lined the streambank at an earlier time in history. These boulders are significantly larger than what can be found throughout the rest of the property; a comparison of this difference is shown in *Figure 2*. The heaviest erosion is on the right bank (facing the direction of flow), indicating that these boulders might have prompted the stream to begin scouring the bank as the water sought the path of least resistance, eventually rerouting more of its flow behind the barrier.

Figure 2: Comparison of upstream streambed rock (left) to in-stream boulders at erosion site (right).

1.3 Spatial and Temporal Context

The project site is located within the township of Keezletown, a rural and historic community on the western slope of Massanutten Mountain. Much of the land has been farmed for generations, and its citizens value the natural beauty of the land and the stream which runs through it. Recent years have seen increased community efforts to capture a sense of identity within Keezletown, closely tied to their land use, in which they have set goals to preserve the small-town feel and natural beauty through conservation efforts and collaboration with state programs to enhance water quality in streams and rivers (Alliance for the Shenandoah Valley, 2023).

Similar initiatives throughout the Commonwealth of Virginia have been going on for decades, largely driven by interests related to the Chesapeake Bay Watershed, a protected estuary whose watershed stretches across six Mid-Atlantic states. As more research begins to show the effects of agricultural practice on stream health, more legislative attention is being paid to water quality and streambank integrity throughout the state.

Farmland, such as is found at the project site, epitomizes average land use and historical land use throughout the Valley. As new goals for land management emerge at the federal, state, and local levels, it becomes increasingly important to develop scientific and informed, adaptive management practices for landowners to utilize. This specific research will be an important resource to help Church of the Lamb manage their property but will also contribute to other stakeholder goals for restoring stream health in the community and the broader watershed. Beyond these specific stakeholders, it is also a relevant study that will add to the body of knowledge needed to develop land management practices throughout the Shenandoah Valley and the Commonwealth of Virginia.

1.4 Scope of Work Summary

The broader goal of this research is to tie anthropogenic disturbance to hydro-geomorphic change and let that inform process-based streambank management and restoration. The specific goal of this research is to develop a concise, actionable plan that will help the landowner restore their streambank. The key components of this project are:

1) A temporal and spatial analysis of the property, tracking streambank migrations and land-use changes over the last 100 years.
2) A site survey to assess streambank erosion, riparian potential, and stream characteristics.
3) A detailed stakeholder discussion. This work is important to many stakeholders beyond Church of the Lamb, and developing a plan of action that remains aligned with all interests will make its chances of long-term success much stronger.
4) A streambank restoration plan for the landowner. This will take information gleaned from the historic analysis, survey, and stakeholder analysis to inform a restoration and adaptive management plan that is specific to the project site.

This final deliverable, a restoration plan, will be developed by evaluating common restoration options, like planting a riparian buffer or bank regrading, in terms of the broader watershed dynamic and its historic geomorphology, thus informing a process-based restoration that will continue to allow the streambank to self-heal and become more resilient.

Chapter 2: Background

This chapter describes the significance of anthropogenic influence on hydrogeomorphic change and provides a comparison of traditional restoration practices to process-based methodologies. A detailed review of regional stakeholders is presented to guide the development and interests of this project.

2.1 Hydrogeomorphology and Anthropogenic Influence

River ecosystems are highly variable and full of natural system complexity (Arlington et al., 2006); they move, erode, and evolve naturally, as external controls such as climate or geology prompt fluvial systems to move from one state of equilibrium to another. In recent history, anthropogenic controls have also emerged as another dominant driver of geomorphic change in streams and rivers (Beechie et al., 2010). In the event of an anthropogenic disturbance, a river will react as it does to any other outside force: it will dynamically adjust elsewhere within its system to find a new state of equilibrium. For example, an increase in impervious surfaces within a watershed will increase downstream channel flows. Streams will adjust to these new flows by widening and deepening; lateral and vertical adjustments often manifest as bank erosion and channel incision. In general, when a stream channel is altered, an immediate rebalancing of the stream's dynamic equilibrium will initiate, with these adjustments balancing and fading out over time. However, impacts of anthropogenic influence can be difficult to predict, as a river's response is "often nonlinear, with thresholds and feedbacks making it difficult to predict consequences of channel alterations" (Bouska & Stroebner, 2015).

Anthropogenic influences on streams may also be indirect. Changes in land-use may be accompanied by changes in vegetation cover, which have a trickle-down effect the land's hydrologic and geomorphic state. Researchers have argued that there is a strong correlation between vegetation cover and hillslope erosion (Liebault et al., 2005). Agriculture and urbanization are increasingly becoming areas of concern for freshwater stream health, as drivers that have aggravated the transport of sediment and pollutants downstream (Walter & Merritts, 2008). Agricultural land-use decisions have the potential to strip vegetated buffer zones around streams by allowing livestock access or clearing the land for crops. Urbanization introduces buffer zone challenges due to increased volume and flow rates throughout a stream's channel; impermeable surfaces funnel larger amounts of stormwater through waterways which would otherwise have entered the groundwater reservoir or nourished vegetation. Overall, loss of riparian vegetation leads to channel-narrowing and incisions, which reduces the stream's ability to process pollutants and weakens ecosystem health. Areas with lower buffers tend to have increased water velocity, lower benthic habitats, and lower bed roughness (Sweeney et al., 2004).

Buffer zones provide many important ecosystem services. They prevent nonpoint pollutants from entering the water stream and increase the stream's ability to process pollutants once they enter the stream. They increase bed roughness, trap sediment, and aid in floodplain connectivity. This increased channel width is particularly important in low-order streams for nutrient dynamics such as their integration into bed sediments, and uptake by microbial communities (Sweeney et al., 2004). Shrubs and trees are often promoted as primary buffer vegetation (Virginia Department of Forestry, 2025), but native grasses have also been known to be incredibly beneficial for carbon sequestration, habitat protection, and erosion control (Sweeney et al., 2004). Whether grasses, shrubs or trees, re-integrating a buffer that is suited to its ecological context (utilizing native species) is critical to restoring long-term health in a stream.

Another key area of anthropogenic disturbance, specific to the Mid-Atlantic region, is the historic presence of mill dams. Between the 17th and 19th centuries, tens of thousands of mill dams were constructed in this region, systematically restructuring stream features from small, anabranching channels and extensive wetlands into meandering, gravel-bedded channels (Walter & Merritts, 2008). Historically, these streams accumulated little sediment and stored a substantial amount of organic carbon, but their modern-day equivalents have deeply-incised channels, eroded banks, and carry incredible amounts of suspended sediment. These problems are often attributed solely to agriculture and urbanization, which have certainly aggravated sediment transport. However, there is significant evidence that ties such stream characteristics to the rapid transformation of river valleys through damming in the early days of European settlement (Walter & Merritts, 2008). In terms of fluvial equilibrium this is a more complex example of anthropogenic disturbance leading to channel adjustments as streams seek a new steady state; a combination of deforestation, damming, and agricultural use severely altered a landscape – both in terms of what was removed, and the deposition of new sediment from the dams. In the wake of these disturbances, rural streams throughout the Mid-Atlantic are still adjusting and recovering, a process which includes carving new paths through legacy sediments and creating new areas of erosion.

2.2 Traditional Restoration

Stream restoration is a unique and challenging process, as it seeks to bring a complex ecosystem from a state of simplicity and degradation, into a more complex – and ideally more "natural" – alternative way of being (Jansson & Malquvist, 2007).

Traditional restoration practices have been a mix of engineered interventions within a neatly defined "reach" of the project, where information about the watershed is inferred by a sampling location (Beechie et al., 2010). Much valuable watershed information can be gained by establishing a reference reach, but building a restoration framework which only looks at the reference reach can be risky; assumptions often ignore the river's broader geomorphological context, and tend to "fossilize" rivers, limiting floodplain connectivity and channel migration (Biron et al., 2014).

Even the definition of a reference condition has many interpretations and introduces levels of uncertainty. It is difficult for scientists or engineers to identify a moment in history that is completely without human interference, and therefore it is hard to identify what is a natural condition of the stream. “Reference reach” is a relative metric, since there are varying degrees of disturbance in every location, and it is difficult to distinguish between what might be a pristine condition, or simply the best available option (Stoddard et al., 2006). However, critical stream information can still be gained from a reference survey, including flow characteristics, channel profile, bankfull depth and width, and habitat data. It helps paint a scenario within the same ecosystem of what the river’s post restoration status could be like. The Process Domain Concept describes the correlation between terrain (space) and river function: that “spatial variability in geomorphology governs geomorphic processes and disturbance regimes, which in turn influence ecosystem structure and function” (Bellmore & Baxter, 2014). Much can be learned about important stream processes and functions – impaired or not – by studying the watershed and the land around it. Therefore, immense value can be obtained for restoration work through field survey studies and reference conditions.

Reference-reach restoration should be utilized responsibly, understanding its benefits and limitations; this will ensure that critical assumptions do not turn out to be harmful to the larger watershed dynamics. River ecosystems are highly variable and full of natural system complexity. There is a tendency in restoration efforts to abide by environmental management rules, but such approaches may contribute to further degradation of the river. Rather, solutions should aim to incorporate natural flow variability, in ways that can be empirically validated (Arthlington et al., 2006). While it is convenient to ignore complexity in natural fluvial systems, this complexity must be honored to achieve long-term viability in restoring and sustaining river ecosystems.

Finally, an important component of traditional restoration practice is that stream restoration has historically been initiated in response to anthropogenic activities that impaired or damaged the stream (Bennett et al., 2011). This motive is both reactionary and rooted in a desire to make rivers more convenient to further anthropogenic utility; two things which drive an approach heavily focused on immediate intervention rather than long-term stability.

2.3 Process-Based Restoration

Contemporary river management is transitioning from hard-engineered solutions to an ecological restoration approach, and while there is broad agreement that this is an important shift, there are still conflicting opinions about what constitutes successful river management (Palmer et al., 2005). Reach scale may be more widely acknowledged as a quick-fix approach, but there is still room for generous interpretation of what may constitute an “improved” or “natural” system (Wohl et al., 2005).

Recent restoration and conservation efforts have sought to capture the natural connectivity across a single fluvial system by developing management strategies which focus on process-based restoration. Process-based restoration addresses hydrologic and geomorphic processes, ecological integrity, and dynamic variability across a river, prioritizing restoration efforts that help a river ecosystem self-heal (Biron et al., 2014). Holistically, this approach seeks to identify and restore psychical, chemical, and biological processes throughout the river and its floodplain, to correct historic disruption, but correct it in a way that empowers the river to recover with the absolute minimum amount of human intervention (Beechie et al., 2010). With this approach, much uncertainty remains – yet restoration efforts aimed at the process have a higher chance of addressing the root cause of degradation, compared to traditional efforts that have focused on fixing the symptom of degradation (Wohl et al., 2005).

Two important concepts for capturing the dynamic variability of rivers are freedom-space, and connectivity. Freedom space refers to the integration of the river's natural mobility with its flood zones and wetlands to create a single common space wherein the river is expected to move and exercise domain (Biron et al., 2014). It emphasizes that mobility is key to allowing a river to change over time in ways that maintain its health and core processes. This is especially important in relation to traditional bank stabilization efforts, where restoration planning must not be solely focused on preventing channel migration, thereby isolating the river's connection to its floodplain. Such efforts could fossilize the river and fight against the forces of existing processes over the course of time (Biron et al., 2014).

Freedom space is closely related to hydrological connectivity throughout the stream. Connectivity may be defined as: the flow of energy, matter and organisms between landscape components via water (Ward et al., 2002). A useful reference for this connectivity is the 4-dimensional model for stream ecology: flow along the stream (longitudinal), between the stream and the riparian and upland areas (lateral), and between the channel and the hyporheic zone (vertical) varying over time (Ward, 1989). Lateral connectivity is particularly relevant to restoration efforts on streambanks dealing with erosion. Eroded banks prevent a stream from utilizing its floodplain; an important function for any stream. Floodplains are ecologically critical, acting as filters for organic matter (Bellmore & Baxter, 2014), but they also dissipate flow laterally, increasing retentive capacity of the stream and the water table below ground, and providing lower velocity storage zones critical to many tiers of living organisms (Bellmore & Baxter, 2014). Stream restoration usually implies that some level of connectivity within the stream has been improved; better lateral, longitudinal or vertical connectivity should be attained through whatever activities are undertaken, and projects should always be monitored over time to support adaptive management and continuous learning (Jansson & Malmqvist, 2007).

Foundational to process-based restoration, is the understanding that it must utilize a systems-thinking perspective. This approach should focus on capturing system complexity through multi-disciplinary efforts, comprehensive stakeholder analysis, understanding dynamic behaviors of natural systems, being able to objectively measure, explain and implement a management strategy, and developing a plan for adaptive management over time (Slocombe, 1998). Complexity and dynamism must be integrated in any successful ecosystem-based management, meaning that any analysis of change should also capture feedbacks; analysis cannot stop at identifying the first change, it must continue to track the evolution over time and the unexpected correlations of an event. Such a strategy requires increased spatial and temporal scales, as is deemed appropriate for the ecological context. This means that goals should ride the balance of being practical and driving action yet remain broad enough to be widely and consistently applied (Slocombe, 1998). Uncertainty must be addressed by planning for adaptability.

2.4 Process Methodology

To meet this holistic-management challenge, there are some guiding process-based principles that have been developed: (1) restoration actions should address the root cause of degradation. (2) actions must be consistent with the physical and biological potential of the site. (3) Actions should be at a scale commensurate with environmental problems. (4) Actions should have clearly articulated expected outcomes for ecosystem dynamics (Beechie et al, 2010). Other complementary perspectives on these principles suggest a more ecologically focused approach; one which ensures the river system is improved, becomes self-sustaining and resilient, and requires minimal impact through the restoration process (Palmer et al., 2005).

To synthesize literature and industry practice for process-based restoration within the state, the Vermont Agency of Natural Resources developed a practical restoration framework to protect river corridors, wetlands and floodplains. Their strategy specifically aims to establish dynamic fluvial equilibrium and restore habitat features by assessing stream data under 3 focuses: 1) Current condition – understand the stream condition compared to a reference condition. 2) Sensitivity – what is the likelihood and to what degree will the stream respond to a disturbance, whether natural or anthropogenic. 3) Adjustment process – understand what current lateral or vertical migrations are already underway due to a disturbance (Kline & Cahoon, 2010). Good management strategies must look at temporal and systemic qualities of the stream's natural flow, such as the magnitude, frequency, duration, and predictability of its change (Arlington et al., 2006).

These steps are beneficial to guide quantitative research that can unfold the layers of interacting temporal and spatial scales at work within a river; however process methodology is equally reliant on qualitative measures. Restoration efforts are ecological, but also social (Wohl et al., 2005). Their success is often measured socially and economically, as well as ecologically. Various stakeholders have different opinions about what to prioritize, whether the restoration is viable or even beneficial based on their individual interests.

Finally, long-term adaptive management practices are critical to the process of capturing remaining uncertainties and complexities. Good management takes time, and this can often conflict with external interests and stakeholders, driving a temptation to revert to old "rule of thumb" practices (Arlington et al., 2006). Adaptive management seeks to fulfill the ultimate requirement of process-based restoration: that the river become self-sustaining and resilient, requiring the minimum amount of maintenance (Palmer et al., 2005). Assurance that this target is being met comes only from post-assessment and continued monitoring.

Methods for monitoring and evaluating the river after restoration should consider that even stable systems have variability (Wohl et al., 2005); they continue to be dynamic and complex.

2.4 Stakeholder Interests

When developing a site-specific restoration strategy, there also exist various scales of stakeholder interests and agendas. Often, projects may have the added benefit of being able to achieve complimentary objectives or multiple stakeholder goals. However, a good restoration plan must recognize where there are social, economic, and land-use objectives that may constrain the restoration work (Beechie et al., 2008). Watershed assessments should provide most of the information used to identify prioritized actions, but assessments should also identify local land and water uses that may limit the restoration.

2.4.1 Stakeholder: Landowner

The property is owned by Church of the Lamb, a parish of the Anglican Church of North America. The church's vision for the property is to use it as an abbey modeled after the old Anglican Way, as a place that can support members of the community in all areas of life; in both the spiritual and the practical. To this end, the church uses their property to teach craftsmanship and stewardship and seeks to steward its own property in a way that would maximize the flourishing of all things that use the space – be that person, animal, or plant.

Many native trees have already been planted throughout the property, and cattle have been fenced out of the creek. Ongoing efforts are underway to plant wildflowers for the bees, keep small crops, plant a nursery, and promote biodiversity throughout the area.

Through their management practice, the church seeks to draw out the land's potential as a place for continued agriculture, for forestry, ecology, native plant pollination, and a healthier river system. They wish to see the land recover from decades of agricultural activities that have stressed the health of the stream and trampled vegetation and seek to protect the stream from further erosion.

2.4.2 Stakeholder: Keezletown Community

For the project location on Cub Run, there are stakeholders at the community, state, and watershed (Chesapeake Bay) scales. Keezletown, the community around Cub Run, has an initiative for sustainable community development including a priority to protect soil and water (Alliance for the Shenandoah Valley, 2023). Led by a local nonprofit, with funding from the National Parks Service, this community project aims to maintain open landscapes, promote agriculture, and protect Keezletown's natural and scenic assets. Their action plan includes 2 relevant priorities, out of the 6 identified.

Priority 1, to "Protect Farmland and Rural Character" (Alliance for the Shenandoah Valley, 2023), the community seeks to increase landowner participation to keep land in continued farming or forestry. This expresses a desire to invest in natural spaces and to preserve the scenic and natural integrity of the landscape. A notable implementation measure indicated for this plan is to encourage landowner participation in conservation funding programs from the state-level.

Priority 2 is to “Protect Natural Environment and Views” (Alliance for the Shenandoah Valley, 2023). Through this priority, the community aims to place protections over valued natural resources. It includes initiatives to seek conservation opportunities and engagement with farm operations by providing technical education and financial incentives to help property owners understand Best Management Practices (BMPs) and restore riparian buffers along Cub Run.

Also worth a mention is Priority 6, which is focused on “strengthening community connections” (Alliance for the Shenandoah Valley, 2023) and seeks to build engagement and work together with all members of the community to achieve its collective vision.

2.4.3 Stakeholder: Commonwealth of Virginia

Virginia has many guidelines around rural stream management, as well as programs available to incentivize landowners to fence off cattle and establish riparian zones. Much of this information is provided by the Virginia Department of Forestry (VDOF). For Streamside Management Zones (SMZs), VDOF recommends maintaining 50 feet of protected riparian width from the stream. Within this zone, landowners should minimize ground disturbances within this area (Virginia Department of Forestry, 2019). Virginia DOF has published many BMP fliers meant to help landowners reduce soil erosion and protect against nonpoint source pollution resulting from anthropogenic disturbances, namely agriculture and urban development. Their goal is to prevent soil from entering water systems and causing further damage in the wake of any disturbance.

They place a heavy emphasis on riparian buffers as a means of slowing sediment, both by retaining soil in root systems and by slowing the velocity of runoff to allow sediment to settle before entering the main waterway. Riparian buffers also help reduce the volume of water entering streams, so downstream systems are not overwhelmed and have the added benefit of providing food, shelter and cooler water for local biota (Virginia Department of Forestry, 2025). Tax credits are available to approved Virginia landowners for improving their riparian buffer zones.

This focus on buffer zones is not unique to Virginia, and many states, such as Washington, New Hampshire and Ohio, have similar initiatives to promote an increase in tree and vegetation planting along streambanks. These are good improvements but are still subject to criticisms that these measures are not enough to counteract generations of anthropogenic disturbances resulting in widespread channel incisions; a deeper analysis of fluvial geomorphic processes may be necessary (Kline & Cahoon, 2010).

2.4.4 Stakeholder: The Chesapeake Bay

Goals for the reduction of agricultural pollution in Virginia were imposed largely thanks to tireless work by the Chesapeake Bay Foundation. Established in 1966, this organization has transformed conservation efforts in the mid-Atlantic in support of protecting critical populations and habitats in the Chesapeake Bay. Since the 90s, the organization has been tracking measurable indicators of ecological health throughout the watershed, educating landowners about best management practices, and lobbying for states to do their part to reduce sources of pollution flowing into the Bay. Their primary tool for monitoring and enforcement (although indirect) of pollutant-reduction goals is through Total Maximum Daily Load (TMDL) goals.

The Chesapeake Bay TMDL is the largest and most complex TMDL in the United States, covering a 166,000 km^2 area across six states in the Mid-Atlantic region, including Virginia. A complex watershed model was developed in 2010 to track land use and simulate water flows and the transport and fate of nutrients and sediment. This model can help isolate individual state contributions and identify management plans for each basin under the different jurisdictions (Shenk & Linker, 2013). At the time, the study estimated that up to a 33% reduction in sediment by 2025 could be achieved by following their watershed implementation plan. To keep an eye on TMDL progress, facilitate public education, and provide visibility on ecological health throughout the Bay, CBF has been publishing a "State of the Bay" report annually, since 1998. This report contains detailed year-to-year comparisons on nutrient levels, water clarity, dissolved oxygen, toxins, vegetation, and all kinds of biological indicators (Chesapeake Bay Foundation, 2022).

In 2000 the Chesapeake Bay watershed was listed as an "impaired water body" due to excess fine-grained sediment, which has negative impacts on aquatic life due to the lowered water clarity (Gellis & Walling, 2011). In the Chesapeake Bay, sediment loads in rivers are a leading cause of ecological and water quality impairment (Cashman et al., 2018). Much of this fine sediment can be traced back to cropland development and management. Upland area and stream corridor erosion is a natural process of hydrogeomorphology and can manifest itself in many ways depending on the soil, geology, or climate. However, across the Chesapeake Bay watershed, sediment yields are found to be significantly and routinely higher coming from agricultural land use than forested areas (Langland & Cronin, 2003). Similar observations have been made about areas undergoing urban development, where urbanization more than doubled the amount of natural sediment production in a stream (Langland & Cronin, 2003).

Many resources have been expended studying sediment dynamics throughout the watershed to understand behaviors and factors in order to develop BMPs at the local level. There are three main geographic principles that guide management: scale, time, and land use (Noe et al., 2020). Scale has an impact, as sediment processes are different for headwater streams and larger rivers; headwater streams have higher erosion and less storage, larger rivers tend to have less erosion and higher storage potential. Across all orders of streams, there are lag-times in response to management actions, which will vary in how sediment moves and is stored over time based on the specific geomorphology of the stream and other stream-specific dynamics. This can make effects of BMPs difficult to measure. Time is an important factor regarding legacy soils and the spatial-time lag mentioned in regard to scale. Land use varies significantly over time and space, and discussions around agriculture, developed land, and stream banks are especially important for sediment transfer.

These three factors – scale, time and land-use – make a complex recipe for determining BMPs, yet there is some specific guidance provided by a few government entities such as USGS, VDOF and Virginia Department of Environmental Quality (VDEQ). This guidance is generally provided according to land-use categories; in this case the Cub Run site can be classified as a combination of “headwater streams” and “agricultural areas” landscapes. For a headwater stream, BMPs are to focus on preventing erosion through runoff control and stream restoration. For agricultural areas, the advice is similar: implement measures to restrict soil erosion, plant stream buffers, and remove legacy sediment if possible (Noe et al., 2020).

Chapter 3: Methodology

The key research objectives of this project are to gather historical and survey data of this property and apply them to a process-based framework that will accomplish stakeholder goals within the local regulatory framework.

The first two sections focus on data collection and analysis of:

- Historic aerial imagery (Section 3.1)
- Surveyed conditions of the stream and surrounding landscape (Section 3.2)

The last section (Section 3.3) aims to research land-use in the Keezletown region, which will inform a discussion of BMPs and legal guidance in Chapter 4. The combination of these parts will build a holistic understanding of the problem and provide the tools necessary to develop a restoration recommendation for the landowner.

3.1 Historic Imagery

3.1.1 Data Collection

Imagery was collected from historic satellite records in Google Earth Pro, and from physical prints of aerial images (taken by the USFS) which are stored in James Madison University (JMU) archives. *Table 1* shows a summary of all imagery collected for analysis.

Year	Month	Image Source
2024	March	Google Earth Pro
2021	March	Google Earth Pro
2012	October	Google Earth Pro
2011	May	Google Earth Pro
2007	April	Google Earth Pro
2002	December	Google Earth Pro
1994	April	Google Earth Pro
1989	March	Google Earth Pro
1966	November	JMU Archives
1951	July	JMU Archives
1937	September	JMU Archives

Table 1: Historic imagery sources.

Google Earth Pro Satellite Imagery

Using the timeline feature in Google Earth Pro to obtain historic imagery of the property, each image was evaluated by two criteria: resolution and seasonality. Only samples with sufficient resolution (clear enough to locate the stream's perimeter), and samples that showed adequate flow (enough water present to clearly outline the stream's perimeter) were retained; a total of eight images were identified for further analysis, between the years of 1989 and 2024. Most imagery taken between the months of May to October did not display a clear stream path since the water level was too low. Many of the older images between 1987 and 2010 were too low-resolution, but a few quality images were able to be extracted.

Historic Aerial Photographs

Historic aerial photographs were obtained from JMU archives in the Integrated Science & Technology (ISAT) laboratory. Flight path maps were available from September 20, 1937, July 21, 1951, and November 24, 1966. Each path had crossed Cub Run just south of Keezletown, and the associated printed photo was able to be identified and scanned using a high-resolution scanner at the University library. As was discovered when filtering Google Earth imagery, the photos taken in September (1937) and July (1951) did not display an adequate water level for analysis; however, the photo from 1966 showed a clear stream path. This difference is evident in the comparison of scans shown in *Figure 3*; the stream is only visible in the 1966 image.

Figure 3: Hi-resolution scans of the historic aerial photographs.

3.2.1 Imagery Analysis in GIS

Georeferencing

Using the selected imagery from 1966-2024, each PNG was imported to ArcGIS Pro by adding a dataset file. Georeferencing was selected and three control points identified before auto-apply was enabled. Once auto-apply was enabled, an additional five-to-six control points were added, primarily using the county road, railroad track, and property outbuildings as references – however the oldest images utilized fewer structures as control points, making their referencing less reliable. All samples share at least four common references, with a few samples having slightly more or less depending on the year and resolution.

Each georeferenced image was exported to a KML file, so that it would be compatible with ArcGIS Online to conduct analysis.

Boundary Definitions and Comparisons

The georeferenced imagery was imported to ArcGIS Online to a single project map, and for every individual image, a new sketch layer was created. This sketch outlined the boundary of the stream as a polygon, corresponding to a specific image/year. These stream boundaries were then colored and adjusted for transparency so that the layers could be overlaid for comparison.

To compare stream boundaries year-to-year, the most current polygon (2024) was made visible and set to semi-transparent blue. Each other polygon was set to non-transparent and red and then made visible/invisible to take snapshots of every year, comparing that current year to the 2024 reference year. These snapshots were compiled into a table using Python and an AI resource to generate and edit code.

3.1.3 Limitations

The most significant limitations with the historical data analysis were 1) seasonality, and 2) georeferencing precision.

Cub Run is a low-order stream, in this case meaning that it undergoes significant seasonal fluctuations: after a spring storm event it may surge and use much of its floodplain, whereas during summer drought and into the fall it may run at a mere trickle. The oldest historic aerial photographs, 1937 and 1951, were excluded from the study for this reason. In general, imagery taken between the months of June and October was largely unusable, since the stream depth was not adequate to identify water boundaries from above. Most of the selected imagery was taken between the months of November and April to maintain bankfull consistency. Even with the selected imagery, establishing mean stream thalweg was still uncertain, considering seasonality, since bank width adjustments for fluctuations in flow cannot be assumed symmetric.

Additionally, seasonality and diurnal change posed some challenges of identifying the stream below riparian obstructions in the imagery. Specifically at the project site there is a large tree present, where either too much foliage or a low-angle shadow could obscure the stream's profile at critical points, rendering several images useless for analysis.

Georeferencing precision also presented levels of uncertainty for this analysis. The major challenge was image resolution, where many images were so low-quality that they could have facilitated 4-6 foot precision at best. Most images that were selected for analysis could likely achieve a 2-3 foot precision. Imagery after 1989 maintained constant structural reference points, so common georeferencing elements could be used across these images.

The lack of common structures is a major limitation for the oldest imagery analyzed (the scanned aerial from 1966). Only two buildings were available for reference in this image and, to triangulate the image, terrain features had to be referenced. This makes the georeferencing far less reliable, as is evident in the property-scale comparison of the stream's boundaries between 1966 and 2024; there are some obvious offsets that can only be explained by poor referencing. As such, it did not seem advisable to base bank migration measurements off 1966 as the earliest reference; rather 1989 was used as the baseline.

3.2 Site Survey

3.2.1 Data collection

A site survey was conducted in mid-April, 2025, over the course of two days and followed no significant storm events within the preceding month. Basic survey equipment was used: a laser level, receiver and stadia rod, 100' tape, and GPS. The survey objectives were to:

1. Obtain a longitudinal slope of the stream over a distance of roughly 500 feet upstream of the site.
2. Obtain a channel cross-section of both the eroded site, and a reference site, within the site's reach.
3. Map the terrain, identifying riparian buffers, terrain features and pinch-points, man-made structures, and any other observations.
4. Measure the full-bank width within the reference reach to establish baseline hydrologic requirements of the stream.

Procedures for the longitudinal, cross-section, and bankfull width surveys were developed as outlined in Appendix II, utilizing guidance published by Penn State (Penn State Center for Dirt and Gravel Studies, 2022a, and 2022b).

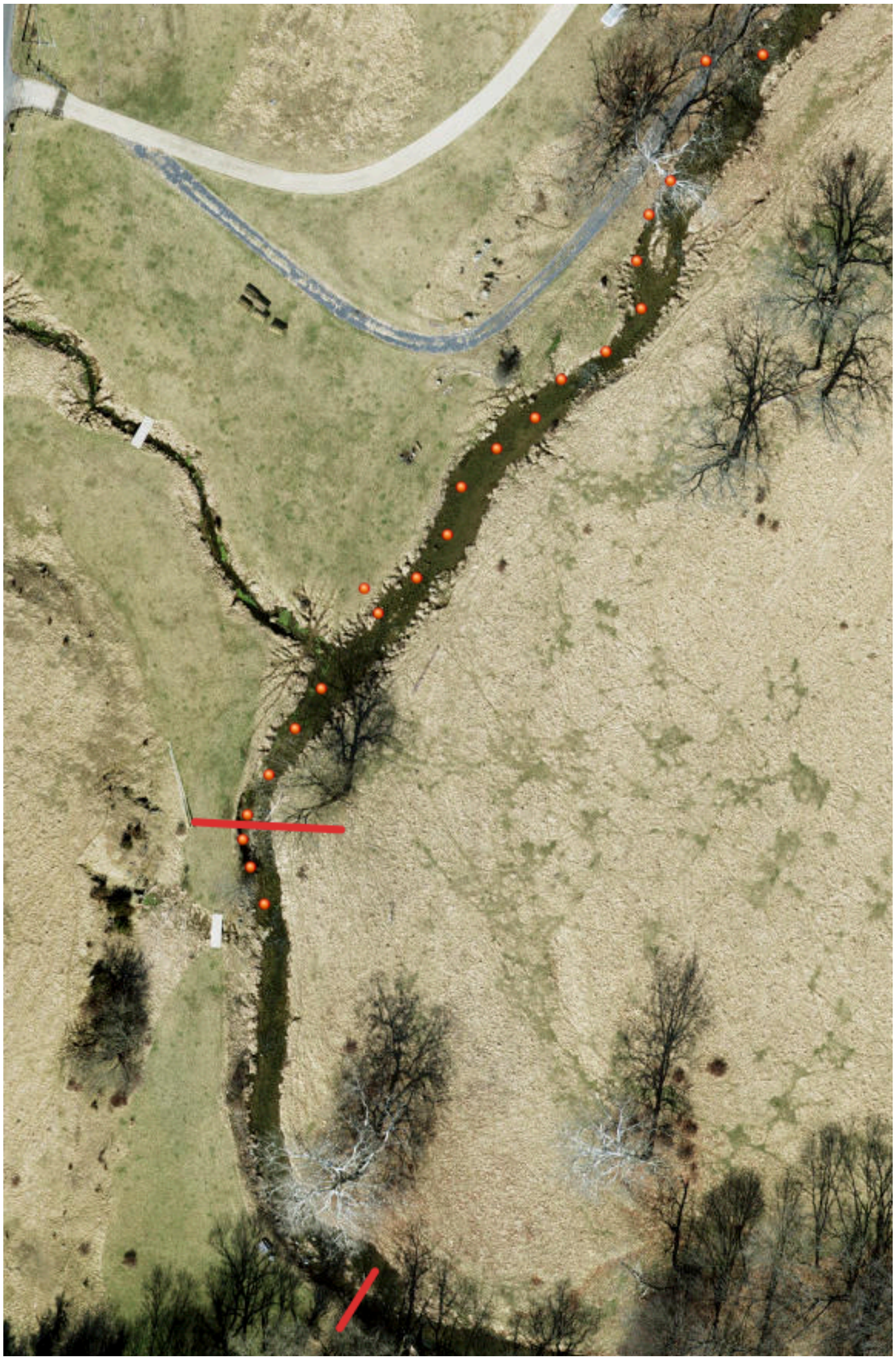

Figure 4: Survey locations.

Survey locations are shown in *Figure 4*. Longitudinal GPS locations are shown as points along 500 feet of the stream, upstream of the erosion site. Not all GPS readings for the longitudinal survey were accurate; some outliers may be noticed. The cross-section location of the eroded bank is shown here as a line in the center of the figure, and the reference cross section is shown at the bottom.

Longitudinal Survey

Starting roughly 500 feet upstream of the cross-section coordinates, samples were taken every 25 feet along stream thalweg (deepest centerline) until roughly 25 feet downstream of the cross-section coordinates. Where the longitudinal survey intersected the cross-section line, a few additional measurements were taken for resolution. For every data entry, the following was recorded: (1) GPS coordinates, (2) elevation at the bottom of the stream thalweg, (3) stream depth, and (4) the linear distance along thalweg from the last sample. The same laser level station was used for all samples.

Cross-Section & Reference Reach

For the cross-section survey at the restoration site, the laser level was anchored near the cross-section (at the same station as the longitudinal survey) and a tape was anchored perpendicularly across the stream and its floodplain, at the point of deepest erosion in the channel. Readings were taken across the extent of the tape: while in the floodplain a reading was taken every 1-foot, and within the stream channel a reading was taken every six inches. For each data entry, the following was recorded: (1) station number (STA), and (2) foresight (FS). When applicable, the waterline was recorded and any other terrain features intercepted at the cross-section.

For the reference reach, the procedure was the same as the restoration site, but the laser level station was relocated. No backsight reading was taken, but coordinates were recorded for each.

Bankfull Width

Bankfull width helps to establish flow seasonality within a stream by determining the max volume of flow it receives at a given time within the 1.5-2 year interval. While the measurement is straightforward, the determination of its extents is flexible and subjective to the judgement of the examiner. Using Penn State's Bankfull-Guidance document (Penn State Center for Dirt and Gravel Road Studies, 2022), the following indicators were assessed for the bankfull measurement: (1) change in bank slope, (2) depositional features, (3) changes in particle size, (4) vegetation cover, (5) scour features.

Fourteen measurements were taken upstream of the site, specifically in areas without significant bedrock, stream braiding, logjams, or hard bends forcing the stream to move laterally. The average of these measurements was taken to determine bankfull width.

Site Mapping

On standard engineering paper (to capture scale), two site drawings were developed – one for the erosion cross-section, and one for the reference cross-section. Each of these drawings depicted an aerial view of the survey site, notating the following: (1) terrain and fluvial features surrounding the cross-section, (2) relative position to other sites, (3) direction of flow, (4) information pertaining to trees, grass, and man-made structures. These site sketches can be found in Appendix III: Survey Data.

3.2.2 Analysis

Once all survey data was recorded into tables, the data was visualized in python, with the help of AI to generate and edit useful code. Plots were generated to visualize the site cross-section, the reference condition and the longitudinal survey.

3.2.3 Limitations

A watershed or local review of hydrology, hydraulics and soils is the baseline material for any bank stabilization effort; however when considering a holistic management strategy (as process-based implies), there are significant ecological limitations to this method. Biogeochemical and biologic studies would help inform additional management around water quality – such as nutrient transfer, buffer filtration – and habitat conservation.

From a hydrology and hydraulics perspective, there are additional limitations given the spatial and temporal scope of the study. The most useful piece of missing data in this report is seasonal flow data and bankfull depths for the one-year, two-year, and ten-year peak storm events. Seasonal flow data would help ensure that the selected BMP would not be in conflict with recurring velocities above the BMP design threshold. For example, VA DEQ BMP guidance for Vegetative Streambank Stabilization recommends that bankfull velocity not exceed 5 ft/s, since at this rate the bank stresses are too high for average soils to withstand (Virginia Department of Environmental Quality, 2024). Annual flow and mean water data also informs the height of streambank vegetation strata, and where to transition from aquatic, bank, shrub and forested zones up the bank slope. These benches can be easily estimated, but the lack of supporting flow data will mean that more careful monitoring and management will be needed throughout the period where new riparian plantings are establishing their root structures.

3.3 Land-Use Data

3.3.1 Resource Discussion

An initial database search was conducted in the USGS archives for usable LandSat imagery to use in a land-cover time series analysis of the property. LandSat data was available as far back as the 1960s, however, upon further investigation, this imagery proved to be so low quality that it could only provide macroscopic trends and would not reveal the level of detail needed to assess land cover changes at the scale of the project site, or even the headwaters of the Cub Run watershed.

During this process, a few other resources were uncovered that were useful for understanding land use within the area. The Chesapeake Conservancy published a LandSat / Land Cover Data Project with available GIS files ("CBP Land Use/Land Cover Data Project," 2024), which proved to be a useful visualization of land use between 2013 and 2022 but did not provide historic land-use information. Further visualizations of this data were found in a DEQ report for Rockingham County, shown in *Figure 5* (Virginia Department of Environmental Quality, 2004).

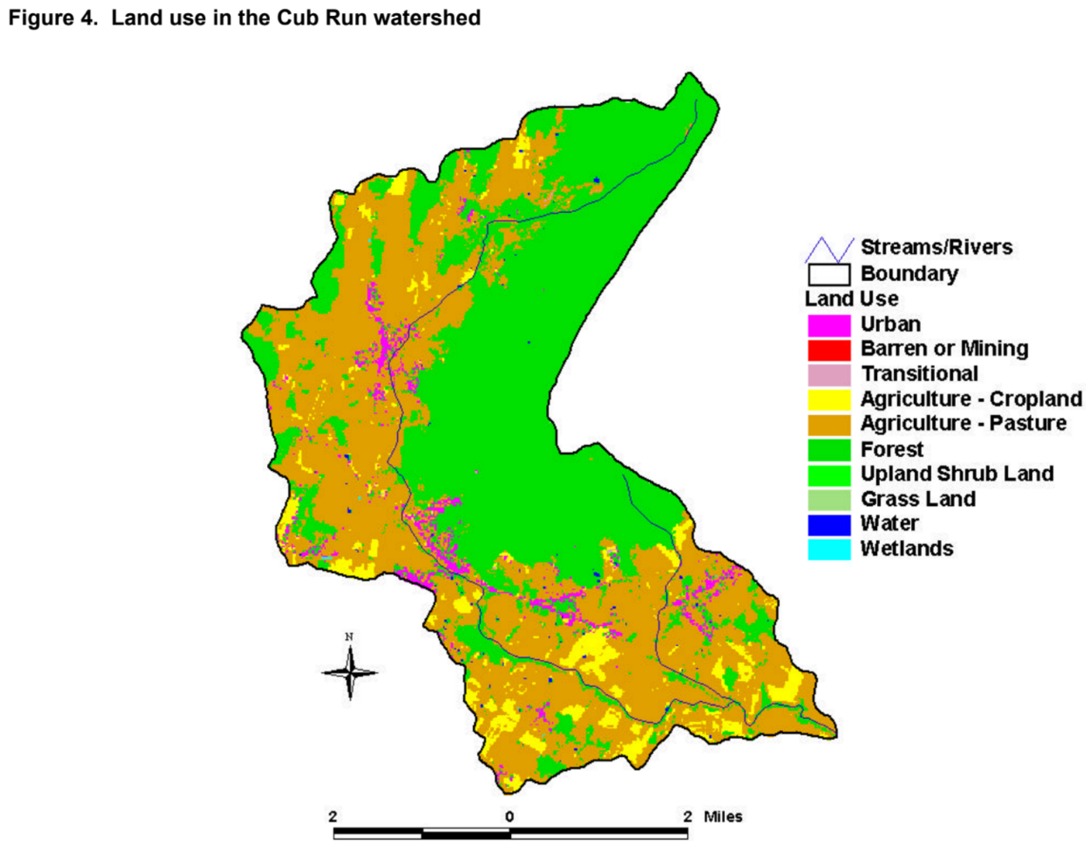

Figure 5: Cub Run Land Use Data (Virginia Department of Environmental Quality, 2004).

Additional information was available through public record: the Rockingham County GIS database designated useful zoning and land-use categories, discussed in Chapter 4.

3.3.2 Limitations

As discussed in the literature review, the complex nature of streams often causes its hydrodynamic changes to persist across decades or even centuries in the wake of a disturbance. Therefore, such a short period of land-use or land-cover change provides a mere snapshot of what forces may be at play within the watershed. Further information around historic mill-dam use in the area would be highly beneficial for determining changes in bank profile and legacy sediment accumulation. Additionally, land cover change during early development of Keezletown (likely mid-late 1800s) would provide valuable insight for the stream's pre-development condition, to have a natural reference for its meander.

Chapter 4: Findings and Discussion

Results for the three research components – historic imagery, site survey, and regional land-use – are presented and discussed in this chapter. These results are evaluated in terms of the process-based framework presented in Chapter 2 and then followed by a discussion of applicable BMPs that could be utilized to restore current site conditions by addressing the root cause(s) of degradation and acknowledging any long-term processes at play.

4.1 Historic Imagery

4.1.1 Results

Figure 6 shows a stream profile at the survey site at intervals between 1966 and 2021, each individual year (red) is compared to the stream profile in 2024 (blue) as a reference condition.

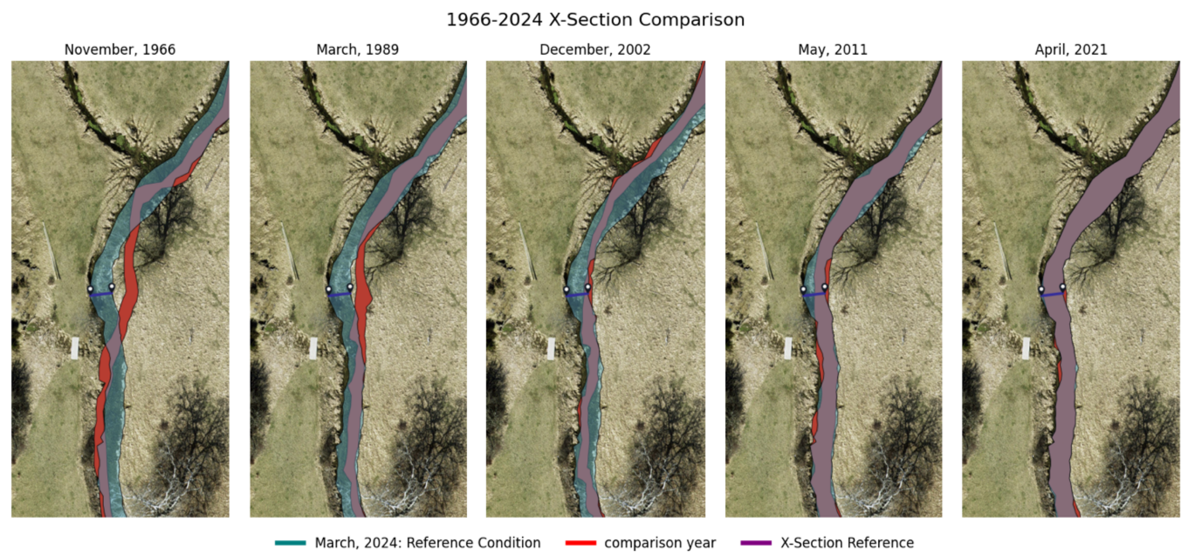

Figure 6: Comparison of stream migration between 1966 and 2024 (2024 shown in blue).

Comparing 1989 to 2024, the bank migration distance at the erosion site is slightly over 21 feet. When compared to 1966, this difference is even more substantial; however, the precision of georeferencing was less reliable in this year, as was discussed in the limitations of the methodology.

Upstream of the site, historic imagery shows the presence of a mill-race. This difference is highlighted in the comparison of 1989 and 2024 stream profiles, shown in *Figure 7*. Based on available imagery, this race was diverted to a new (and possibly its original) path sometime between the years of 1994 and 2002. Upstream and downstream adjustments in the stream's meander are apparent after this event.

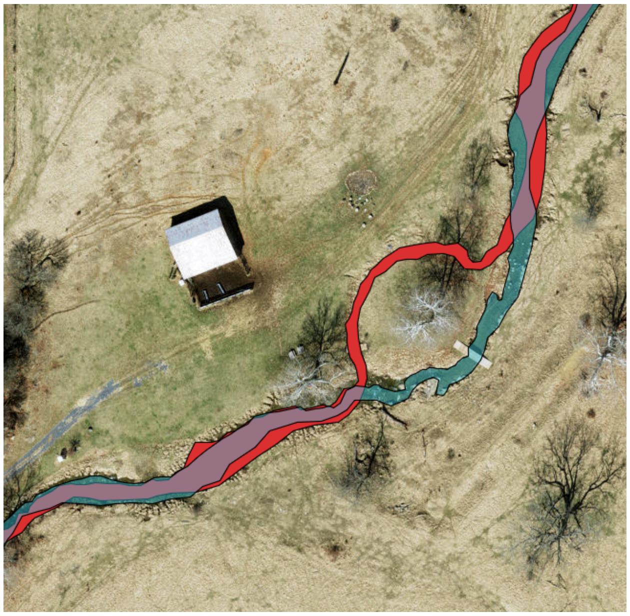

Figure 7: Comparison of stream profiles at mill race diversion, 1989 (red) and 2024 (blue).

Lateral migrations in the stream are seen throughout the property between 1966 and 2024. *Table 2* shows the comparison of seven different stream migration points throughout the property, where location #7 is the erosion site. The 2024 stream profile was used as a constant for comparison, and measurements were taken from the right bank (measured as the difference in feet between 2024 water's edge and reference year water's edge). *Figure 8* shows the locations of these points within the property; location #1 is displayed at the top right, and numbers follow in descending order down the direction of flow.

Location	**1966**	**1989**	**1994**	**2002**	**2007**	**2011**	**2021**
1	6.3	9.5	10.3	9.8	4.7	4.1	0
2	15.3	9.6	9.2	4.2	2.5	0	0
3	18.5	0	0	0	1	0	0
4	12.3	4.3	3.7	3	3	1	0
5	14.2	10.2	10.2	6.6	3.9	0	3.8
6	6.5	10	10.2	4.6	2.5	2.4	0
7	26.7	21	9.6	13.3	7.1	8.5	5.9

Table 2: Stream migration distance (in feet) as compared to 2024.

First, this table highlights how unreliable the 1966 georeferencing might have been; most values in this column are significantly higher than any other year recorded, even in the case of the location #3, where no migrations were seen in any other year beyond what could be explained by seasonality.

Second, in most of these locations there appears to be an adjustment period between 2002 and 2007, with the stream showing signs of stabilization around 2011. This is an expected reaction to the removal of the mill-race sometime between 1994 and 2002, as the stream sought to reach a new state of equilibrium.

Third, the one location which does not stabilize at the same rate is the erosion site at location #7. There is a jump in bank migration between 1989 and 1994, which may explain the impetus for placing boulders along the toe of the shore – an effort to mitigate erosion. The stream makes additional adjustments between 1994 and 2021, with a mean migration pattern that continues to erode into the right bank. The footbridge was installed sometime around 2021, and this is when another spike in lateral movement is observed, with the bank shifting nearly 6 feet between 2021 and 2024. Site visits between late 2024 and early 2025 also confirm a visible bank migration of between 1-2 feet in just six months.

Figure 8: Location of reference points for lateral migration measurements.

4.1.2 Discussion

Cub Run is experiencing an active migration into the right (facing direction of flow) bank at the project site. The historic aerial imagery study shows clear dynamic adjustments throughout the property, specifically in the aftermath of the mill-run disturbance between 2002 and 2007. Shifts in stream meander are apparent directly around the mill area, but also occur throughout the property, indicating a larger connectivity of the waterbody. The stream as a whole appears to equalize after about a 10-year period, apart from the erosion site at the south side of the property. This area continues to make a slow and steady migration into the bank, which appears to accelerate after 2021 when the footbridge was installed.

4.2 Site Survey

4.2.1 Results

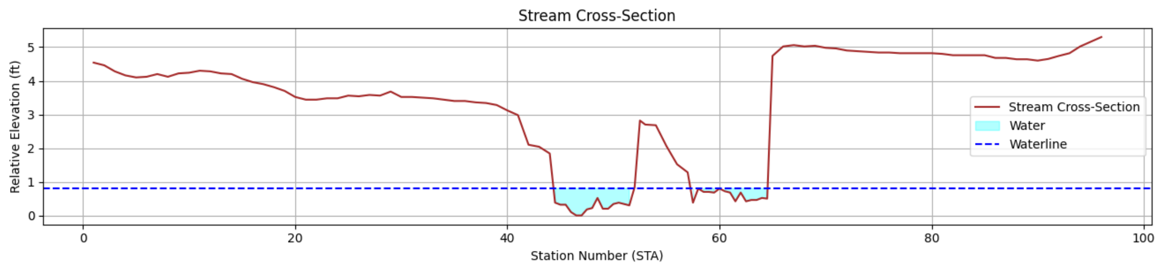

Figure 9: Cross-section of eroded bank. On-the-ground conditions of the vertical bank edge shown has a 1-2 foot undercut.

The cross-section profile of the project site (*Figure 9*) shows an incised channel, with differences on the right and left banks. The left bank is slightly graded but climbs abruptly to its floodplain elevation. The right bank has no grading and immediately jumps from streambed elevation to the floodplain. Bank heights are 4.5 and 5 feet at the top of the measured floodplains, and on the right bank the floodplain slopes away from the stream, dropping from 5 feet to 4.5 feet. The wetted width is 14.5 feet.

Between the banks, the channel is narrow and is divided in the middle by an island; the left channel shows a deeper water profile, indicating slower velocities on the inside of the bend. It shows an unconnected floodplain on the right with streambed conditions that facilitate higher velocities along the right bank, which will continue to exacerbate the existing erosion.

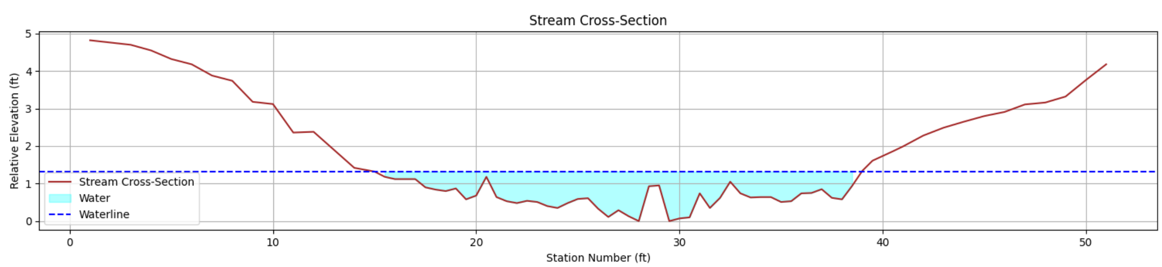

Figure 10: Cross-section of reference condition.

In contrast, the cross-section of the reference condition (*Figure 10*) shows stable, graded streambanks, with water distributed across the streambed. The left bank shows a 25% grade, and the right bank shows a 33% grade. The wetted width at this site is 23 feet, and highest velocities were observed near stream thalweg at the 30-foot mark on the graph. This reference profile is also situated at a bend in the stream (outside edge on the right), so it's unsurprising that the right bank forms a slightly steeper profile, as the topography is driving a redirection in the stream here. Despite the asymmetry, it can demonstrate stable bank slopes for this stream.

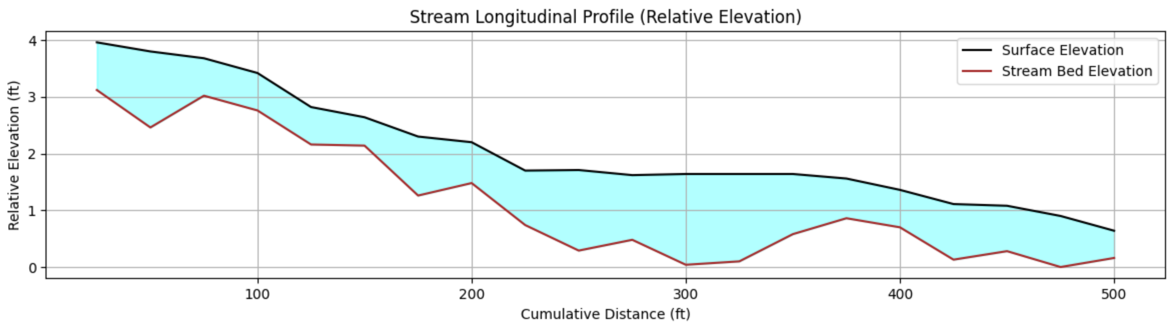

Figure 11: Longitudinal profile 500 feet upstream of erosion site.

The longitudinal profile (*Figure 11*) returned an average streambed slope of 1.7% in the 500 feet upstream of the erosion site (site is located at the 500-ft mark of the graph). Along this distance, significant drops in elevation are evident in the first 250 feet, with the slope leveling as it approaches the project site. Between 300-400 feet the stream deepens and levels, indicating pooling. Downstream, the average leveling of the slope could mean lower velocities and better energy dispersion; however, at the 500 mark the stream becomes shallow again which could mean higher velocities if the stream does not widen horizontally in this area.

The mean bankfull width was also measured at 14 sample locations within the longitudinal survey area, measurements are shown in *Table 3*.

Sample Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	**AVG**
Bankfull Width (ft)	22	24.6	31	18	20	26	24	22.5	25.7	32	22	17	21	21	**23.3**

Table 3: Bankfull width field measurements.

These measurements returned an average bankfull width of 23.3 feet throughout the survey length, which also closely matched the wetted width of the reference reach cross-section. This width provided an indication of routine flow expansion within the stream, and can be used as a guide to design the optimal wetted width for a re-graded channel.

4.2.2 Discussion

There were two hydraulic constraints readily apparent for the stream: the first was the rock island in the center, and the second was the footbridge situated immediately downstream. The rocky island appears to be a viable explanation for the stream's initial deviation into the bank. If the boulders were not naturally posited (a reasonable assumption, given their size compared to the surrounding streambed rock), they were likely placed along edge of the bank as a stabilization and erosion mitigation practice. The historical study provided evidence that this migration into the right bank has been underway for many years but has had two periods of accelerated erosion: 1989-1994, and 2021-2024. The first period of acceleration could have prompted the placement of these boulders and furthermore could have been a factor in preventing this section from stabilizing in the aftermath of the mill-race removal, where the rest of the stream was able to stabilize over the next decade. Over time, water has scoured behind the boulders as the stream sought the path of least resistance. Velocities are naturally faster along the outside corner of a bend, and as of 2025 the island blocked part of the channel, funneling additional water into the bank (see *Figure 12*).

The second period of acceleration is recent, and the timeline aligns with the placement of new footbridge below the project site. The footbridge is creating a hydraulic restriction, both as a lateral pinch-point, and vertically has been observed to act as a dam in storm events. It restricts the stream's floodplain access and impedes its flow, even at the frequency of an average spring storm event. In the discussion of *Figure 8*, it was noted that the right bank sits at a higher elevation than the left, and backslopes to a more natural floodplain elevation. This is also evident when considering the flooded condition shown in *Figure 13*: the footbridge sits at an angle, lower on the left bank and slowing flow, but higher on the right bank which funnels high velocities against the bank to pass under the bridge.

Figure 12: Rocky island in stream, October 2024.

Figure 13: Downstream footbridge during a spring storm event, May 2025.

Figure 14: View from upstream of the project site during a spring storm event, May 2025.

Another key finding of the survey is that the eroded bank has isolated the stream from the floodplain. Active erosion is ongoing in this area; over the course of this project, between November 2024 to April 2025, the bank was observed to have eroded as much as a foot further within that period. *Figure 14* shows the difference in floodplain access between the two sides. Where the stream can access its floodplain, velocities are slower, and energy is dispersing across the floodplain. On the right where the channel is incised and the stream is isolated from its floodplain, water is moving quickly and forcibly against the bank, turning up soil.

When comparing cross-sections of the eroded bank and its reference reach (*Figure 15*), there are obvious differences. The reference reach shows gentle grading on either side of the stream, whereas the eroded bank is starkly incised on one side, and moderately on the other. The left side shows a concave-down profile, yet it's not so incised that it has lost floodplain access. At the erosion site, the right side of the bank is deeply incised. An incised stream is defined having a bank height ratio greater than 1.0 ft/ft, at which point the bankfull height is below the bank height and is considered unstable (Department of Conservation and Recreation, 2004). Compared to the reference condition, the eroded bank could be graded to a similar slope utilizing roughly 12.5-13 feet of the bank width. Over a vertical rise of 4.5 feet, this would result in an approximate 1:3 rise-over-run slope grading.

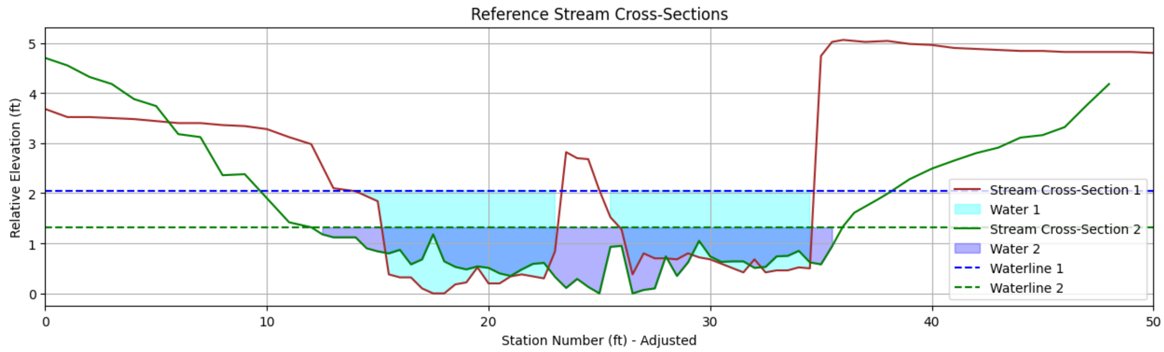

Figure 15: Comparison of cross-section profiles. The reference profile (in green) shows an alternative profile to mimic by regrading the incised channel (in red).

Current bank grades above and below the site allow for adequate floodplain access, with a 70-linear-foot eroded section in the middle. Such a short section with achievable connecting slopes on either end could lend itself well to a simple regrading effort to facilitate adequate bankfull width and floodplain access. The longitudinal survey indicates a favorable trend for this approach as well; vertical drop is more pronounced 300-500 feet upstream, with the profile flattening out as it reaches the project site (see *Figure 11*).

It's possible that, given time, the existing bank profile could become so scoured that the rooted topsoil eventually collapses, and naturally creates a new slope in this area. However, there is a risk of the cycle repeating without adequate bank stabilization, and there is risk of losing valued trail access to the southwest corner of the property.

The surveyed length of 70 linear feet of erosion along the streambank indicates that stabilization work could qualify for an exemption under the Army Corps Nationwide Permit 13, as described in Section 4.5.

4.3 Land Use

4.3.1 Results

Nearly all the upstream lots adjacent to Cub Run are zoned as agricultural land. *Figure 16* shows public land data for the Keezletown area, where A-1 is for protected and promoting agricultural activities, A-2 zoning allows mixed agricultural and residential development. RR1 is for low-density residential and recreation, B1 is general business, and R-4 allows for medium-density residential development. Specifically at the headwaters of Cub Run, the adjoining parcels are documented as being forested land > 100 acres. These parcels are owned by Great Eastern Belleview LLC (Massanutten Resort); while its primary use is currently for recreation, the resort could choose to develop this area for profit in the future.

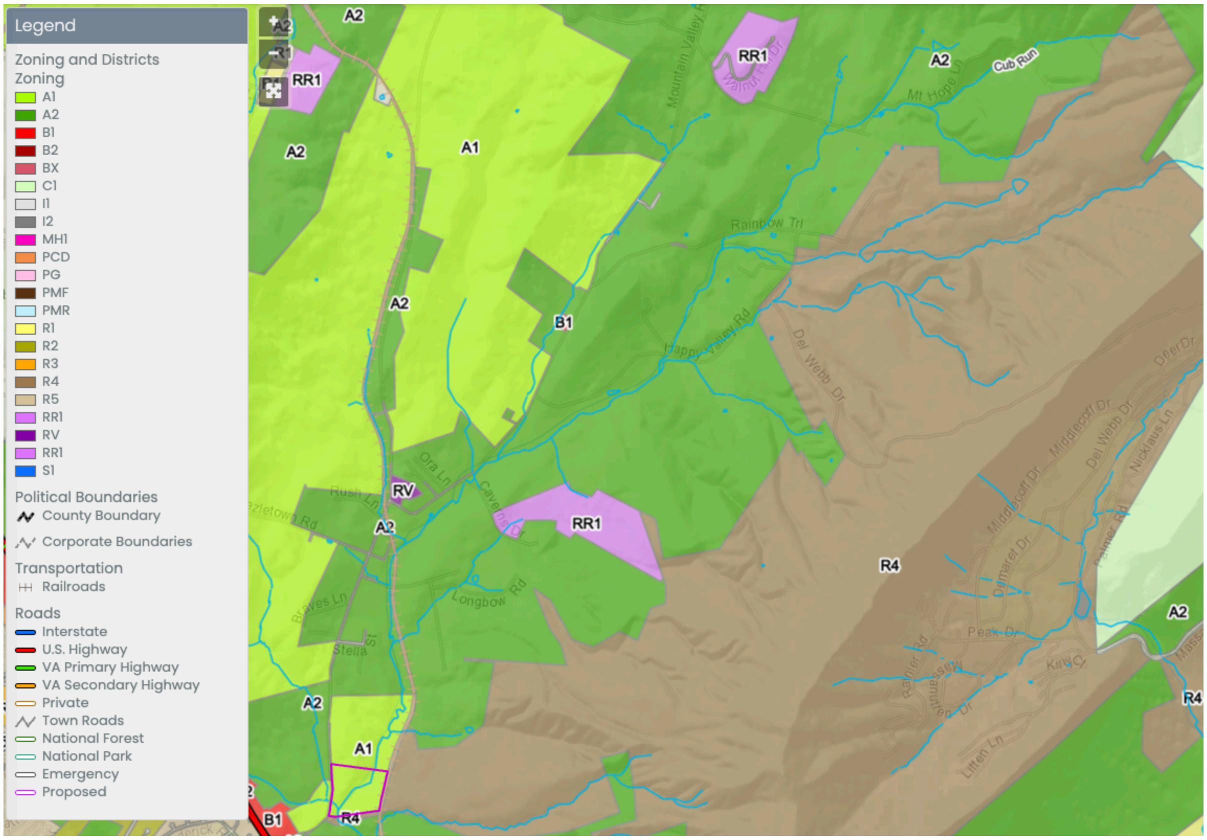

Figure 16: Rockingham County GIS - Zoning along upper Cub Run. Church of the Lamb property boundary shown in bottom left polygon. (Rockingham County Virginia, 2025).

No land-use change data was available earlier than 2013, but the Land Use/Land Cover Data Project from the Chesapeake Bay Program produced a high-resolution dataset comparing data from 2013/2014 and 2021/2022 ("CBP Land Use/Land Cover Data Project," 2024). This data is accurate up to one meter of land cover, identifies areas of change, and classifies the change into a landcover category. Upon close inspection of Cub Run, the spatial resolution and classification both appear to be quite accurate. However, many areas where changes were identified show the "change" (e.g. a small building) condition as present in both satellite images from 2013/2014 and 2021/2022. As a result, the total land use change may be an overestimation. *Figure 17* shows an estimation of this land change in the Keezletown area, color coded by land type. Pervious surfaces are marked in green (natural succession) and yellow (pervious developed), and impervious structures are in red.

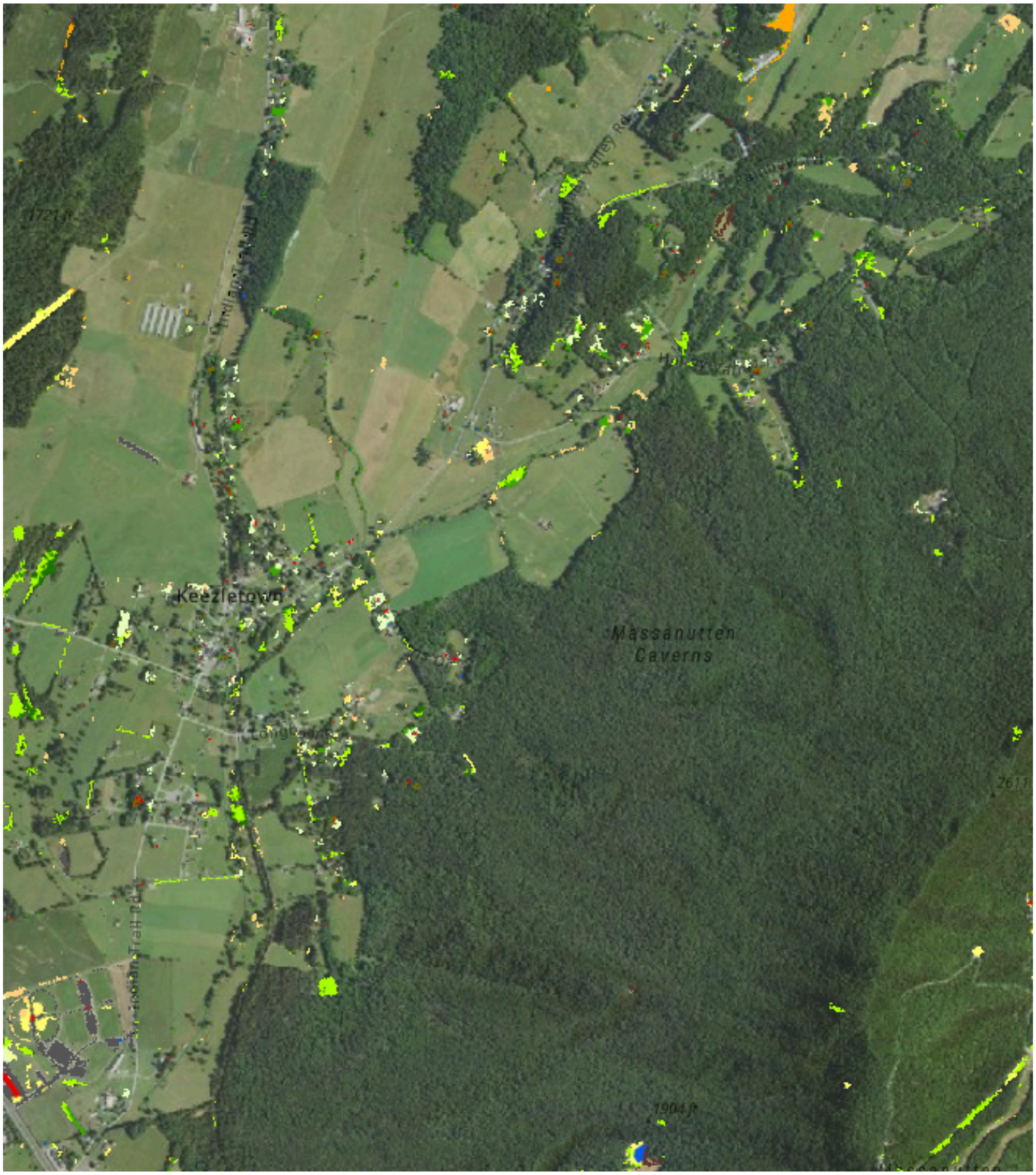

Figure 17: Land-use change along Cub Run between 2013-2022. ("CBP Land Use/Land Cover Data Project," 2024).

In this area, impervious additions are miniscule at scale of the Cub Run watershed, with most development attributed to outbuildings and sheds. Larger developed areas are all primarily classified as a gain in low vegetation. The one exception is Rockingham Park in the lower left next to the project site, which is classified as "barren gain," with some amount of low vegetation gain and one impervious structure. This affects the seasonal inlet to Cub Run just above the erosion site. Very little urban development has occurred in this area over the last decade, and most of the development indicates vegetation gain – a positive change for the watershed.

4.3.2 Discussion

Overall, this land-use study shows that, although urban development is happening on the outskirts of this watershed (Penn Laird, Massanutten), upper Cub Run remains a relatively quiet landscape in terms of development. Its use is primarily agriculture, with much of its headwater still forested land. As such, risks around stormwater surges and flooding are not as high (no significant areas of impervious surfaces), but the presence and legacy of agriculture in the area highlight the importance of maintaining and promoting a strong riparian buffer to regulate the quantity and quality of runoff, particularly considering how much land-area immediately adjacent to the stream appears to have been cleared of forest.

4.4 Process-Informed Restoration

In Chapter 2, four process-based principles were outlined for sustainable restoration. Restoration should target the root cause of degradation, it should be consistent with the physical (and biological) potential of the site, it should be proportional to the environmental problem, and outcomes for the ecosystem should be clearly determined (Beechie et al, 2010). For this project, only physical potential will be discussed; since a biological assessment was not within the scope of the methods, this remains a limitation of the project, and no actions can be recommended with respect to biological potential.

4.4.1 Root cause of degradation

Degradation here is defined as stream channelization and active bank erosion. The root cause of degradation is a combination of factors, creating a complex system response over time. Natural channel protection efforts were likely taken to mitigate an early erosion issue (the cause of disturbance is unknown) which, in combination with later upstream disturbances at the mill race, over time caused the stream to scour behind boulders into the bank. As new obstruction in the path of flow, this caused the stream to experience an insufficient channel width, prompting it to cut into the bank even deeper. This cycle created current conditions wherein the stream has lost access with its floodplain on the right bank and is unable to laterally adjust its width during perennial flow change. Two exacerbating factors are the position of the footbridge and the lack of buffer vegetation in this area.

Considering these factors, it is apparent that the basic function which the stream is attempting to achieve is growth and recession with the pace of annual flow variance. To reference an earlier discussion in Chapter 2 – "freedom space." Therefore, restoration efforts should aim to facilitate this motion through floodplain reconnection which would allow space for water to disperse its energy.

4.4.2 Physical potential of the site

Restoration actions must be identified within the potential of the local site; this may include topography, riparian conditions, climate, or any processes that could determine the restoration outcome. There are three main constraints for this site, pertaining to the topography, vegetation, and land-use respectively.

First, the eroded bank is in the middle of a bend in the stream, which means it is naturally at risk of ongoing erosion due to increased velocities along the outside edge. Any regrading effort will need to ensure that the new profile throughout the bend is as uniform as possible, and sized to a hydraulically appropriate width, to prevent the development of new concentrated shear forces elsewhere in the bend.

Second, there are very few established trees or shrubs within this area. Restoring the area may require relocating established trees, but their scarcity makes it a high priority to disturb the existing, mature trees as little as possible.

Third, if current land-use habits persist after restoration actions, a new, graded streambank may have difficulty establishing and maintaining its vegetation. Vehicles are periodically driven through the narrow gap between the stream and the hillside to the west, including over the wetland area adjacent to the stream. This practice could disrupt the development of new seedlings in the area. Persistent use of the footbridge could also prove detrimental to restoration, given the unsustainable flow dynamics that it creates. These risks must be carefully communicated to the landowner before commencing work, as an unwillingness or inability to adjust land-use practices may counteract restoration activities.

4.4.3 Environmental Scale

This principle addresses whether the degradation is experienced merely within a reach-scale, or more broadly at a watershed level. If it is a reach-scale problem, then often restoration actions within the reach can address the root-cause. However, if it is a watershed-scale problem, it may require multiple site-specific interventions to address the larger issue.

Within the scope of this project, the erosion trouble is a reach-scale problem. It may be a piece of a larger dynamic within the watershed (e.g. legacy soils, development change), but the area is small enough that it could not be argued to be significantly altering watershed-level problems such as TMDL loads within the Chesapeake.

However, it is within the scope of this project to address as many stakeholder interests as possible. Despite how insignificant the scope of this site is to the broader Chesapeake Bay Watershed, performing a bank stabilization project would simultaneously contribute to the broader goal of absolving a watershed-scale environmental problem of high nitrogen, phosphorous and sediment loads.

4.4.4 Articulated Outcomes

This is a critical step in the planning process, but one which can only be fully developed once applicable BMPs are discussed in Chapter 5. Process-based restoration requires long-term planning (Beechie et al., 2010), and it is important to clearly define what the goals are and how long it will take to achieve them. The primary goals of this restoration are to reduce stream erosion while maintaining usability of the land, and to restore the riparian zone. Specific metrics pertaining to how and how long this will take, are a function of which BMPs are used.

4.5 BMP Guidance and Regulatory Framework

Based on the field data gathered, the following guidance was gathered from local regulating authorities – primarily Virginia Department of Environmental Quality (VDEQ) and Virginia Department of Conservation and Resources (VDCR) – as was deemed most applicable to on-the-ground conditions.

4.5.1 Dealing with Incised Channels

Incised channels are typically a consequence of past land development efforts that have confined or degraded the dynamic function of the stream and reduced its ability to dissipate energy. Streambank stabilization guidance in Virginia states that the goal of restoration should foremost be to re-establish floodplain connectivity, to allow the stream to perform important floodplain functions (Department of Conservation and Recreation, 2004). In general, it is recommended to re-connect the stream to its historic floodplain elevation, though in some cases – particularly urban areas – this is no longer possible.

The state standard for prioritizing restoration strategy by channel type is adopted from the Rosgen (1997) geomorphic methodology. As applied to this project, the applicable option outlined is to "Change channel type along existing channel" (Department of Conservation and Recreation, 2004). This option requires converting the channel in-place to a more stable stream profile and dimension, primarily through grade controls. This is for areas that have physical restraints preventing the stream from being re-routed within the floodplain to its historic floodplain elevation, so a lower floodplain is connected and the channel widened with supporting bank stabilization methods to dissipate energy and lower shear stresses.

It is noted within the guidance that low-gradient incised channels within the Mid-Atlantic should only be re-graded if they are still actively incising (as is the case with this project).

4.5.2 Bank Stabilization and Restoring the Buffer Zone

Virginia guidance for any streambed or streambank stabilization aims to mimic natural structures and processes as much as possible, employing soft engineering practices as opposed to hard engineered solutions (Department of Conservation and Recreation, 2004) which have a tendency to become problematic over longer temporal periods, such as was described in the channel incision scenario.

Most stream projects employ a combination of BMPs to provide a holistic treatment and diversify natural structures and processes to make the system function more resilient and more likely to become self-sustaining over time. Often these BMPs are broken up according to the applicable buffer management zone (*Figure 18*) as a means of classifying different levels of protection and their functions (Virginia Department of Environmental Quality, 2024b). Within the streamside zone, there are additional BMPs that address individual vegetation zones (*Figure 19*) corresponding to the stream's mean water, mean high water, and mean low water levels (Virginia Department of Environmental Quality, 2024a).

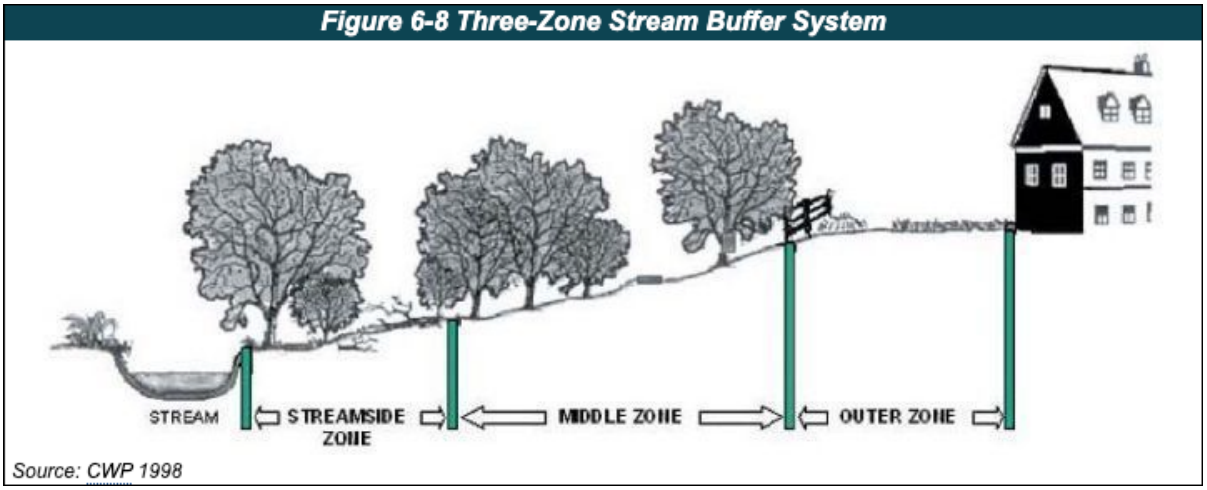

Figure 18: Stream buffer zones. (Virginia Department of Environmental Quality, 2024b).

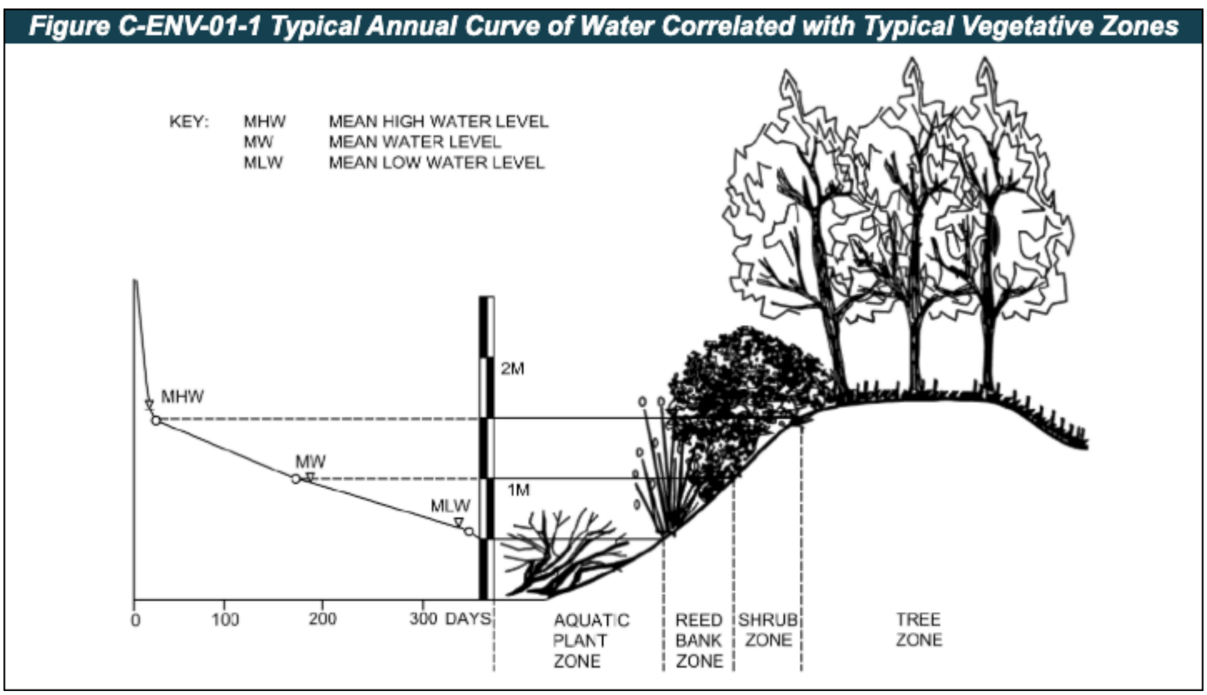

Figure 19: Vegetative Zones. (Virginia Department of Environmental Quality, 2024a).

Buffer Management and Vegetative Zones

BMP guidance suggests that extra care be taken in managing headwater streams due to their important ecological functions. Vegetation, stream width, and development within the stream's buffer zone, are all managed to maximize ecosystem services and economic benefits. The recommended minimum width for the *streamside zone* shown in *Figure 9* is 25 feet (plus wetlands) for perennial streams, though a buffer of more than 50 feet is optimal (Virginia Department of Environmental Quality, 2024b). Full functions of riparian buffers, such as pollutant and runoff reduction, require large uninterrupted forested areas; Virginia law §9 VAC 10-20-130.3.a. states that: "The 100-foot wide buffer area shall be deemed to achieve a 75% reduction of sediments and a 40% reduction of nutrients." (Virginia Department of Conservation and Recreation, 2006.)

Buffer extents of this proportion are unrealistic within the scope of the Cub Run project, but the legal framework underscores the importance of providing as much buffer area as the project can possibly allow. Locally, agricultural-zoned properties are allowed to encroach this 100-foot buffer up to 25 feet from the stream, provided they employ BMPs to satisfy water quality and quantity controls (Virginia Department of Conservation and Recreation, 2006). Clearly, this is not enforced.

Within the streamside zone, allowable anthropogenic use is considered very restricted, with priority allotted to the vegetation remaining undisturbed and mature (Virginia Department of Environmental Quality, 2024b). The streamside zone is subdivided into vegetative zones, shown in *Figure 19.* These relate to levels of BMP protections, as outlined in the discussion of *C-ENV-01* below. The aquatic plant zone remains underwater for most perennial flow, whereas the reed bank and shrub zones may experience seasonal water submersion and high shear stresses (Virginia Department of Environmental Quality, 2024a). Tree zones are higher, and more likely to submerge in the ten-year or hundred-year storms. When reestablishing a buffer area, it is important to design the placement of new vegetation within appropriate zones that accommodate for varying shear forces and storm events that each species of plant/tree is capable of withstanding.

Soil and Erosion

The potential for soil erosion is primarily a function of four factors: soil characteristics, vegetative cover, topography, and climate (Virginia Department of Environmental Quality, 2024b). Sands and silt may easily erode, whereas clays and organic matter tend to hold their structure or repel water. Good soil maintains a balance of structural integrity, while still being loose enough to allow infiltration. Organic material and vegetation are particularly conducive to positive soil qualities; organic matter is highly supportive of soil structure, and vegetation protects from exposure (evaporation) and the erosive impacts of rainfall. On the ground, vegetation provides surface obstructions, increasing friction and reducing the water's energy along its fall path.

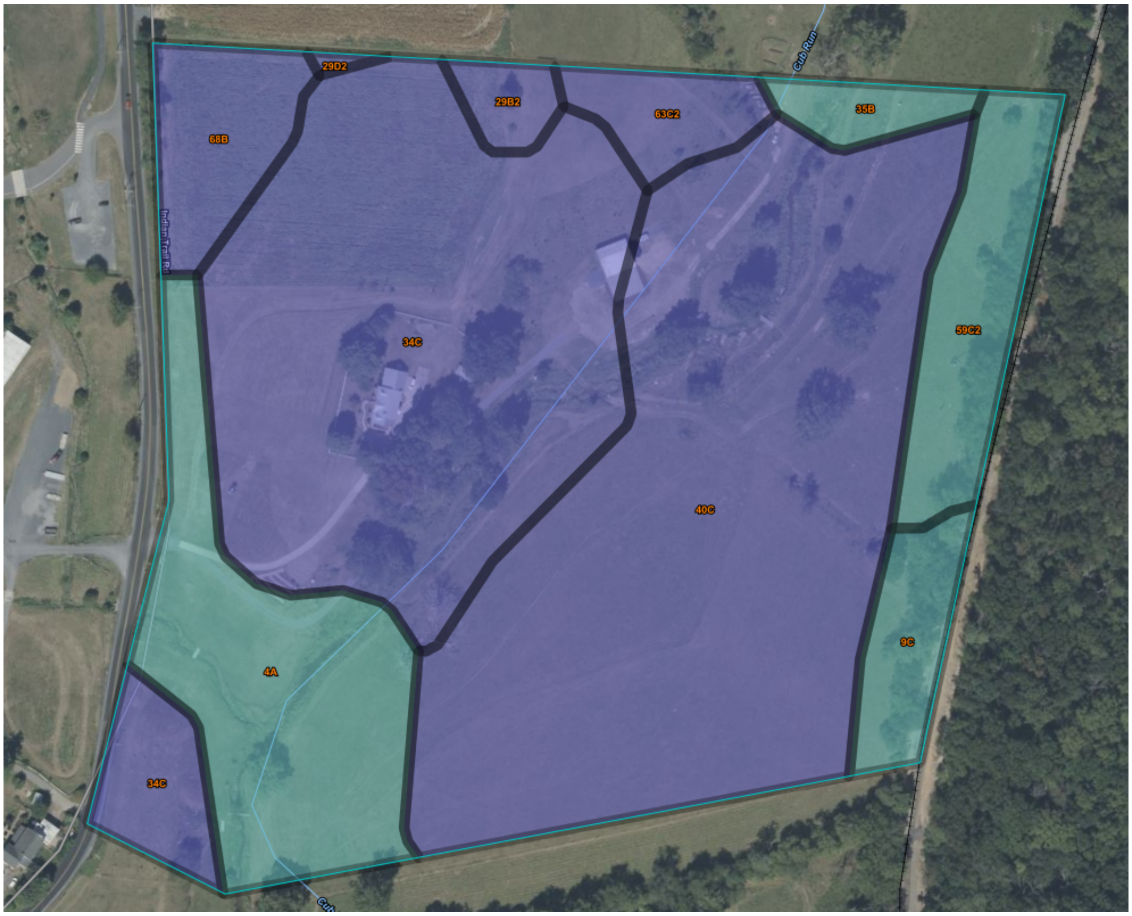

Figure 20: Hydrologic Soil Groups (HSG) for the site. Erosion is within area 4A. (USDA Web Soil Survey, 2025).

Tables — Hydrologic Soil Group — Summary By Map Unit

Summary by Map Unit — Rockingham County, Virginia (VA165)

Summary by Map Unit — Rockingham County, Virginia (VA165)

Map unit symbol	Map unit name	Rating	Acres in AOI	Percent of AOI
4A	Aquic Udifluvents, nearly level	C	3.8	12.5%
9C	Buchanan fine sandy loam, 7 to 15 percent slopes, very stony	C	0.9	3.1%
29B2	Frederick and Lodi silt loams, 2 to 7 percent slopes, eroded	B	0.4	1.2%
29D2	Frederick and Lodi silt loams, 15 to 25 percent slopes, eroded	B	0.0	0.2%
34C	Frederick-Rock outcrop complex, 3 to 15 percent slopes	B	9.7	31.6%
35B	Guernsey silt loam, 2 to 7 percent slopes	C	0.5	1.6%
40C	Laidig cobbly fine sandy loam, 7 to 15 percent slopes	B	11.5	37.6%
59C2	Sequoia-Berks silt loams, 7 to 15 percent slopes, eroded	C	1.8	5.8%
63C2	Shenval loam, 7 to 15 percent slopes, eroded	B	0.8	2.5%
68B	Timberville variant silt loam, 0 to 7 percent slopes, frequently flooded	B	1.2	4.0%
Totals for Area of Interest			**30.7**	**100.0%**

Figure 21: HSG reference table. (USDA Web Soil Survey, 2025).

Topography can affect erosion, both in its grade and spatial orientation. For example, south facing slopes may be dryer. Climate also has the potential for significant impacts over time, as it can affect frequency and intensity of storm events.

At the project site, soil directly surrounding the erosion site is listed under USDA Hydrologic Soil Group (HSG) C (*Figure 20* and *Figure 21*), where group A has the highest infiltration and lowest runoff potential, and D the lowest infiltration and highest runoff potential (USDA NRCS, 2009). Group C is considered to have slower infiltration rates, so it is important to manage it for erosion and sedimentation particularly during construction efforts. The surrounding property is a mixture of Groups C and B, indicating moderate infiltration ability. The classification of soil as *Aquic Udifluvents* indicates that it was formed as a fluvial deposit and likely experiences frequent flooding, thereby making it vulnerable to erosion when paired with the added risks of steep slopes, lack of vegetation, or changes in land use. Behind the toe BMP, common practices are to apply live staking: sapling stakes planted during the dormant season to take root and become bushes/trees over time, or a brush mattress which essentially provides a grid cover of live stakes supported and anchored by dead stakes and string.

Reestablishing Riparian Buffer

Most information from Virginia DEQ regarding riparian buffer comes from the C-ENV-01 Vegetative Streambank Stabilization guidance document (Virginia Department of Environmental Quality, 2024a). For the shrub zone, there are a few BMP options, including seeding grass (with straw, mulch, or soil stabilization blanket cover), fascine rolls, or willow mattresses. Fascines are an effective method to protect the toe of the bank from erosion; these are long bundles of live cuttings tied with rope into bundles at intervals of 2 feet and staked every 2-3 feet. The live cuttings are intended to root overtime and be permanent buffer.

Virginia DCR published a manual which gives specific guidance into the management and re-establishment of buffers, as relates to the Chesapeake Bay Preservation Act (Virginia Department of Conservation and Recreation, 2006). This manual describes the most effective buffer as an area which aims to mimic surrounding, natural and forested landscapes. VDCR includes a specific table land-to-vegetation ratios for trees and shrubs (Figure 6), as well as guidance to promote soil permeability, such as bank slopes less than 5% and velocities (sheet flow) less than 1.5 ft/s. According to the Chesapeake Bay Preservation (Section 9 VAC 10-20-130-5), existing trees may be moved or replaced, provided that the post-development condition is able to equally provide the buffer services of the pre-development condition.

RESTORATION/ESTABLISHMENT TABLE A

A. ¼ acre or less of buffer

(Up to 10,890 square feet or less of buffer area.)

For every 400 square-foot unit (20'x20') or fraction thereof, plant:

one (1) canopy tree @ 1½" - 2" caliper or large evergreen @ 6'
two (2) understory trees @ ¾" – 1 ½" caliper or evergreen @ 4'
or *one* (1) understory tree and *two* (2) large shrubs @ 3'-4'
three (3) small shrubs or woody groundcover @ 15" – 18"

Example:
A 100-foot wide lot x 100-foot wide buffer is 10,000 square feet.
Divide by 400 square feet (20'x20' unit) to get:
25 units

Units	x	plant/unit	Number of plants
25 units	x	1 canopy tree	25 canopy trees
		2 understory trees	50 understory trees
		3 small shrubs	75 small shrubs
			150 plants

Figure 22: Ratios for restoring buffer (Virginia Department of Conservation and Recreation, 2006).

4.5.3 Nationwide Permit 13 - Army Corps of Engineers

This nationwide permit outlines permissible exemptions for small-scale streambank stabilization operations. The permit states that bank stabilization activities may be undertaken without additional permitting provided that (specifications summarized as most applicable to this project):

1. Activity is less than 500 linear feet.
2. Activity moves less than one cubic yard per running foot below ordinary high water mark.
3. Flow is unimpaired
4. Native plants are utilized for stabilization.
5. New materials (or vegetation) is designed for current erosion stressors.
6. Proper maintenance is observed.

Additional protections are included for fish and wildlife populations, such as spawning, bird migration and endangered species accommodations, none of which apply to Cub Run in its headwaters. Appropriate measures must be taken during construction to minimize soil disturbance with equipment (particularly around wetlands), and E&S controls must be observed (Army Corps of Engineers, 2022).

Even if a landowner is reasonably confident their work falls within this exemption, it is always advisable to request that a representative from the local DEQ office visit the site and confirm that it meets all these requirements before assuming work.

Chapter 5: Recommendations and Conclusion

5.1 Developing a Management Strategy

A successful restoration plan must always look holistically at the problem; this often requires the consideration of conflicting agendas – ecological, anthropogenic use, financial and temporal costs, longevity of intervention, or interests from stakeholders yet unknown. With such a wide spectrum of stakeholders for any given project, the accomplishment of all stakeholder objectives is rarely achievable. However, this is the heart of environmental management: with as much data as can possibly be made available, management must navigate a discrete decision process around which actions to pursue that will balance the interests of the most critical stakeholders.

To tackle this management challenge, first a concise summary of the current hydraulic and erosive conditions (discussed in Sections 4.1 and 4.2) should be compared against the theoretical framework for process-informed restoration to identify critical interventions for the site. Second, key stakeholder interests and objectives should be stated as they relate to the management of the stream's current condition. Finally, conditions and objectives should be evaluated under Virginia's regulatory framework to identify BMPs and inform a full restoration plan to best accomplish stakeholder objectives.

5.1.1 Summary of Hydraulic and Erosion Findings / Critical Interventions

The first finding is that the streambank is actively receding. Based on historic imagery, it has been eroding the right bank away for many years, although evidence suggests it is eroding at a faster rate in in the last 4 years. The critical intervention for this finding is to stabilize the streambank and restore a buffer zone.

The second finding is that the right floodplain has become isolated in this area. The bank does not have adequate full-bank width here (identified as approximately 23 feet), and during high-water events, concentrated velocities and high shear stresses are experienced along the eroded bank. The critical intervention for this finding is to reconnect the floodplain by re-grading the bank.

The third finding is that man-made structures and interventions are causing adverse hydraulic effects in high-water conditions. The bridge downstream of the eroded bank is too low and acts as a dam, as well as creates a lateral pinch-points on either side of the stream. In the center of the stream, large boulders placed a rock toe have aggravated erosion issues by braiding the stream and rerouting high-velocity water which scours behind the rock. Critical interventions for these findings are to remove the bridge and ideally remove the largest boulders from the stream – but this second impact could be mitigated through careful implementation of the first 2 interventions for regrading and stabilization, since they would improve hydrologic connectivity. Proposing in-stream channel work introduces complexity and cost to the landowner, since this work requires additional permitting – something that would be difficult to navigate without hiring a consultant. While it is advisable to remove the rocky island, the stream would still benefit greatly from a simple regrading project, if that were all that the landowner could afford. Leaving the boulders would maintain a reduced wetted width of the stream, maintaining risk of future erosive patterns. However, connecting the floodplain through re-grading would provide opportunity for flows to disperse energy laterally into the floodplain, which is not possible in the current configuration.

When comparing these findings against the process-based framework, the root cause of degradation may be tied to insufficient freedom-space of the stream. Re-grading the right bank is a viable restoration option in this area since it is within the physical potential of the site (there is room to re-connect the floodplain), and the environmental scale of the problem is known to be localized and not systemic.

5.1.2 Summary of Key Stakeholder Interests

The primary stakeholder for this project is Church of the Lamb. The church seeks to restore the land from decades of ecological stress due to old agricultural practices. Priorities for this restoration are to promote biodiversity, plant native tree species, and protect water quality – all the while landscaping for beauty and not compromising utility of the land for small crops, husbandry, and community engagement.

The secondary stakeholder is the broader Keezletown community, which has goals to protect rural areas, primarily through the preservation of natural landscapes and the restoration of the riparian buffer zone along Cub Run.

Tertiary stakeholders are the state of Virginia, and other macro-regulating authorities such as the Chesapeake Bay Foundation. These all place a heavy emphasis on buffer restoration as a means of reducing unwelcome sediment and nutrient loads in the watershed and the Chesapeake Bay.

These three categories of stakeholders form a series of interests that are aligned – although with varying levels of specificity – in their goals: restore riparian buffer, stabilize streambanks, plant native species, promote biodiversity and clean water.

5.4 Restoration Recommendation

Recommendation 1: *Adjust current land-use and land management practices*

Several key areas would benefit from better management practices:

- Vegetated buffer width
- Footbridge placement
- Wetland promotion

While these are not the root cause of degradation within the project area, they are all supporting factors for promoting stream health and resilience which can be easily addressed by the landowner. Failure to adjust these land management practices could render any other restoration efforts ineffective.

Current practices prioritize mowing and clearing of brush as close as 10 feet from the streambank. However native grasses can function as a highly effective buffer, and persistent mowing will deter larger brush and saplings from establishing and developing deep root systems near the stream. Widening this buffer zone to a minimum of 25-30 feet (per official guidelines), would allow a more diverse portfolio of vegetation to establish and facilitate ecosystem resilience in high-water events and storm cycles.

Second, the footbridge is placed too low within the floodplain and impedes water flow during storm events. It is exacerbating the current erosion issue and could lead to unwanted erosion around bridge through routine storm events, and in the event of a two-year or ten-year storm may become displaced or cause flooding. If a new bridge is constructed in its stead, it should be designed to place a minimal footprint at its foundation within the flood zone and ensure that its horizontal span is at a height well above ordinary high-water.

Small wetland areas were observed near the project site but appeared to be sand-filled and regularly disturbed. Allowing this wetland to heal and revegetate would facilitate restoration of hydrologic connectivity with the stream and promote biodiversity.

Recommendation 2: *Regrade the eroded bank*

To re-establish floodplain connectivity, approximately 70 linear feet of the streambank should be regraded. The regraded area should be a maximum of 12.5 feet wide at the crux of the bend, and at its extents be graded to match the natural slopes of upstream and downstream termini (see *Figure 24*). At its center – the widest point – it should aim to mimic the slope of the reference reach, shown in *Figure 15.* This comparison shows that 12.5-13 horizontal feet are needed to achieve a vertical rise of 4.5 feet; approximately a 1:3 rise-over-run ratio.

The regraded slope should also mimic the non-linear profile of the reference cross-section, resembling a flattened S-curve shape: lower slopes nearest to the water's toe in a concave-up profile, steeper slopes in the middle and more linear grade, and lower slopes near the crest in a concave-down profile (*Figure 23*). Shear stresses are greater in the lower third of a streambank (Department of Conservation and Recreation, 2004), so creating a more relaxed slope in this section will help facilitate energy dispersion and reduce erosion.

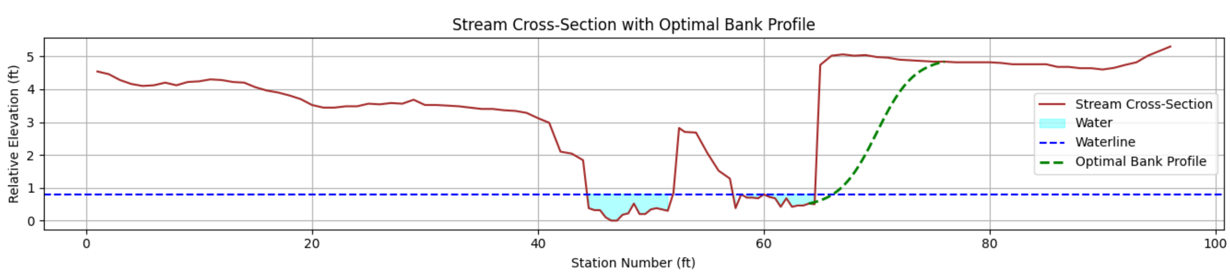

Figure 23: Visualization of an S-shaped streambank profile.

Prior to starting work, a silt fence should be placed between the bank and the stream to protect the stream from undue amounts of sediment deposition during construction. Regrading should be done with bucketed equipment, such as a mini excavator, so that the equipment can stay up on the bank and pull back soil. Equipment should *not* excavate from streamside, as entering and disturbing the stream would be a violation of the legal parameters allowing landowner bank stabilization. Equipment should always use the same point of entry/exit to avoid unnecessary land disturbance. Any disturbed areas outside of the regraded area should be seeded and covered with straw post-construction, allowing grass to revegetate.

Figure 24: Proposed regrading shown on aerial image

Recommendation 3: *Restore the buffer zone.*

Once bank regrading construction is complete, the buffer zone must be restored as quickly as possible with native species. This requires that a collection of grasses, shrubs and trees be planted according to BMPs, to provide stabilization across varying timescales. Grasses may provide immediate soil protection, shrubs intermediate-to-long term cover and root protection, and trees ensure the long-term independence of this riparian system.

The regraded area is, with a conservative estimate, just under 400 square feet. According to the Virginia DCR manual, this area should have at least one canopy tree, two understory trees, and three small shrubs (Virginia Department of Conservation and Recreation). There are two existing trees within the work area that can be classified as both canopy or understory and remain undisturbed. A third tree is present which will need to be relocated. Although the relocated tree may qualify as a third tree for the buffer ratio recommendation, there is no guarantee that it will become established in its new location and not die.

To accommodate for this uncertainty, a fourth understory tree should be planted towards the top of the new regraded area. Additionally, live staking efforts should focus on planting shrub and grasses for the reed bank and shrub zones, as outlined in VDEQ C-ENV-01. Along Cub Run, willow trees were observed to do quite well in this environment.

At water level along the toe of the bank, a fascine should be placed to the extents of the construction zone. This will mitigate erosion early in the recovery process and help with the establishment of permanent buffer, as a first line of defense.

Behind this fascine and for the rest of the exposed, newly constructed bank, live staking should be practiced. It is commonly recommended that a geotextile or bio-mattress cover be applied to prevent surface runoff and provide intermediate protection of the soils until new plantings can take root. Live stakes should be planted during the dormant season (approximately November to April), and it is advisable to plant in the late winter/early spring to mitigate ground frost effects. Stakes can be sourced from the surrounding property and should be cut the same day as they are planted.

5.5 Limitations and Risk

As discussed in Section 3.2.3, lack of seasonal flow data is a limitation for this restoration strategy. At the time of survey, the stream velocity at the survey site was 1.3 ft/s, which is under the recommended 5 ft/s for DEQ streambank stabilization BMPs. The reference reach had a measured velocity of 0.5 ft/s. There is a risk that average velocities for routine storm events may exceed the recommended velocity and prevent stabilization techniques from being effective. There is also a risk that changes in climate patterns may increase storm intensity, duration, and frequency, also rendering BMPs ineffective.

Leaving the in-stream boulders undisturbed could continue to cause problems at this site. Relocating the boulders would calm many of the localized hydraulic forces, but for a small landowner is not the first recommended course of action, due to the added legal and paperwork complexities. In-channel work is not covered by the Nationwide 13 Permit and would require a more rigorous site evaluation that would be costly to the landowner. Re-grading the bank to allow floodplain access is a method of addressing the root cause of degradation (insufficient freedom space) while being less time- and cost-intensive and is therefore, a reasonable starting-point for restoration efforts.

5.6 Adaptive Management and Monitoring

The most unpredictable and time-dependent period of the restoration process is waiting for the riparian buffer zone to become established. Environmental factors such as storms and drought, and even human factors like poor planting technique, can affect whether live stakes take root, or whether a geotextile ground cover is able to protect seeding over time. To accommodate for this risk and any other unexpected changes that occur after project completion, the site should be continually monitored so that adaptive measures may be taken to rectify adverse changes. The goal is for the landscape to become self-sustaining over time and therefore monitoring and management should become less frequent and less intensive the more time elapses.

Within the first one-to-two years, regular monthly check-ins should be done to watch for signs of new life in the stakes, ensure natural riparian grasses are taking root and that the fascine has stayed in place and is effectively preventing erosion on the toe. Intermediate interventions may need to be taken to re-seed, or re-plant.

During these first few years and beyond (until the new riparian has become fully established), careful surveys should be taken after each large storm event, to ensure that surges in water volume and velocity haven't damaged or destroyed new work on the bank.

To revisit the process-informed restoration framework, specific outcomes must be articulated:

- Bank should be regraded in a way that does not introduce new areas of erosion.
- Bank slope should allow floodplain access in high-water.
- Buffer zone should be re-vegetated with native species, including grasses, shrubs, and trees.
- Buffer zone should become fully self-sustaining within a ten-year window.

Should any of these outcomes not materialize, or progress at a rate slower than expected, restoration techniques should be re-evaluated for their effectiveness and alternatives considered.

5.7 Conclusion

The challenge of this project was to explore land-use change in a small, rural watershed, to understand how generations of land-management decisions affected hydrogeomorphic change and use that knowledge to inform current land and stream management practices for local landowners. Through a study of Cub Run's historic imagery, ongoing lateral migrations were found throughout the project site. The stream made hydraulic adjustments to events such as the removal of an old mill-race, and a new footbridge being constructed below the high-water line. This imagery shows erosion at the site slightly accelerating over time, indicating that it may not be adapting well to developments in the vicinity.

However, land-use within the upper Cub Run watershed, although developed, still has high percentages of wooded and agricultural land, and hydrogeomorphic change throughout the property, at least over the last 80 years, is not substantial. This indicates that erosion trouble is not necessarily a watershed-level-source environmental problem and may be a reasonable candidate for local reference-reach solutions.

A process-based framework was applied to determine the root cause of degradation, the physical potential of the site and the environmental scale of the issue, and then specific outcomes were articulated. Every symptom of erosion at the site was connected to the stream's inability to handle flow fluctuations – a function of insufficient width and floodplain disconnection. Referencing both academic research and local regulatory guidance, reconnecting the floodplain should be a top priority for restoration efforts. BMP guidance is aligned with the physical potential of the site; there is space to re-grade the bank and re-establish a riparian buffer, and while there remain some areas of risk due to the natural topography, careful post-development monitoring and management could produce a successful result. Furthermore, the environmental scale was found to be complementary with this strategy, as demonstrated through the historical analysis. Success of the restoration may be evaluated by routine monitoring and occasional maintenance of the site to ensure that the articulated outcomes are being met.

Most importantly, these restoration efforts will accomplish complementary stakeholder goals within the community. For the landowner, it serves a dual purpose of both adding natural beauty to the property and further developing the land's potential for native plant pollination, forestry, agriculture, and a healthy river ecosystem. Within the community it promotes natural landscape protection while accomplishing broader goals of sediment and nutrient controls within the landscape. Re-grading the bank and establishing new riparian zones accomplishes floodplain connectivity, but it also fulfills broader stakeholder goals within the community, state and watershed, while creating a beautiful landscape for the parish community to enjoy.

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Appendices

Appendix I: Restoration Quick-sheet for Landowner

Specifics regarding buffer materials, riparian sourcing, and regrading techniques are detailed as recommended by a consulting restoration biologist (Louise Finger) with the Virginia Department of Wildlife Resources.

Recommendation 1

Changes in land-use and land management practices:

1) Allow a wider grass buffer along stream (25-35 feet).
2) Allow the downstream wetland to revegetate (no sand fill) and re-connect to the stream. Driving equipment or vehicles in this area is not recommended.
3) Remove the footbridge.

Justification:

Riparian buffer is critical to the long-term resilience of a watershed. Studies have found that even native grasses form a highly effective buffer, allowing carbon sequestration, erosion control, and habitat protection. The official recommended buffer for agricultural properties in Virginia is 100 feet, but a minimum of 25 feet is allowed in most contexts.

Wetlands are valuable ecosystems for promoting biodiversity and regulating climate effects for local biota; they're also disappearing at a rapid pace across the country. At this site, the wetland has been covered in sand and driven over, causing it to dry and to lose it partial connectivity to the stream. Letting this area rest would allow revegetation and restored connectivity.

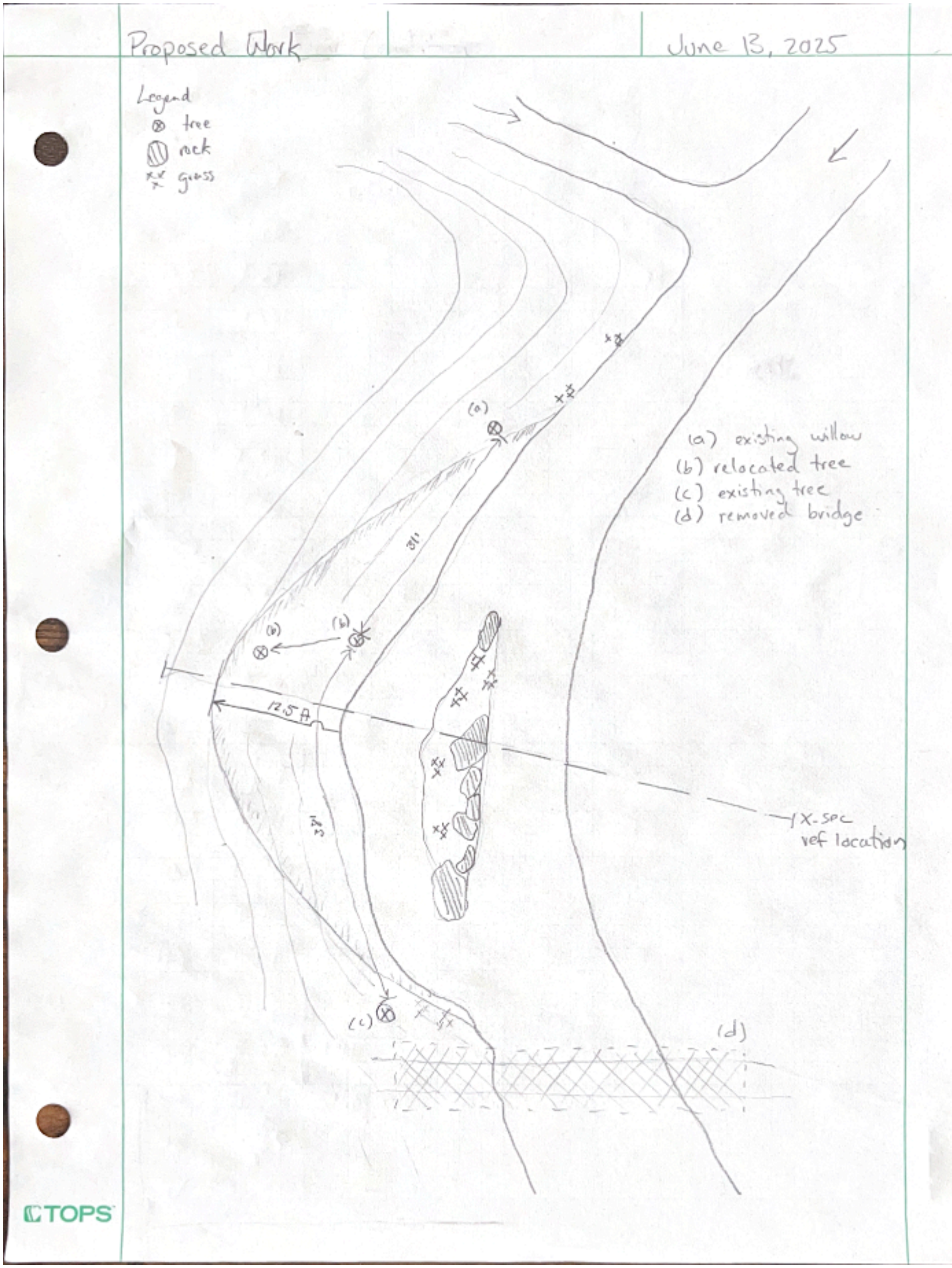
The footbridge was not built at an adequate height over the stream and has become an in-stream obstruction during routine high-water events. This will cause unwanted erosion, scouring and even flooding in larger storm events. If a new bridge is built, at least 3 additional vertical feet should be factored, and consider relocating the crossing to a more stable, upstream section of the stream.

Recommendation 2

Grade back 70 linear feet of the eroded bank to a maximum width of 12.5 feet (see drawing below) and reconnect to existing natural slopes on the north and south termini.

Justification:

The stream has lost connectivity with its floodplain on the western bank. This causes high velocities and shear stresses along the bank, eroding the soil and carrying sediment downstream. With a connected floodplain, this energy is allowed to disperse laterally into the floodplain, where slower velocities would allow water to infiltrate the soil for a longer residence time within the watershed.



Guidance:

Prior to starting work, a silt fence should be placed between the bank and the stream to protect the stream from undue amounts of sediment deposition during construction. Regrading should be done with bucketed equipment, such as a mini excavator, so that the equipment can stay up on the bank and pull back soil. Equipment should *not* excavate from streamside, as entering and disturbing the stream would be a violation of the legal parameters allowing landowner bank stabilization. Equipment should always use the same point of entry/exit to avoid unnecessary land disturbance. Any disturbed areas outside of the regraded area should be seeded and covered with straw post-construction, allowing grass to revegetate.

During regrading efforts, the young tree located in the middle of the regraded section should be dug and relocated back into the bank, as shown in the diagram (b).

Recommendation 3

Immediately following construction of the bank, the soil should be stabilized and buffer vegetation established. A mix of native grasses, shrubs, and trees should be planted in this area.

Justification:

The long-term success of regrading is contingent on establishing a self-sustaining buffer. This vegetation will help the soil maintain its structure and organic composition, slow runoff water and sediment transport, and slow the stream's flow through increased bed roughness. A mix of canopy and understory trees, shrubs, and grasses are all important to span different time intervals of vegetation establishment and storm peaks. Grasses root quickly and provide low-structure support within the soil over shorter periods of time, allowing shrubs time to establish, which in turn allow time for trees to establish. Sturdier vegetation will protect weaker vegetation over time, helping it weather periodic storm events or changing climate conditions.

Guidance:

Grasses should be spread throughout the graded area, while shrubs should start about 1/4 to 1/3 of the way up the slope. Trees can be located anywhere from the upper 2/3 to the top of the bank. This is not an exact science, but all plantings should be placed in a way that anticipates the frequency of full submersion and soil saturation with respect to their development time and provides the best chance of long-term vegetative success.

Sequence of replanting should be as follows: mix native riparian herbaceous seed with a cover crop, type dependent on time of year. Mixture can be 2/3 cover crop, 1/3 native mix. If planting before the winter, use wheat or rye; if planting before summer use a draught-hearty crop such as millet. Next, lay coir fiber matting, rolling it out parallel to water-flow, and stake across the whole area. Live staking should be done in a 2-foot grid across the whole area. Stakes can be sourced from the property, ideally from shrubs along the stream and a couple of understory trees (willow would be a good option). Stakes should be harvested the same day they are planted. Consider adding a fascine with live stakes along the water's edge.

Live staking should always be done in the dormant season (usually November – April), and it's recommended to stake in early spring to avoid ground frost effects over the winter.

Several helpful guidance documents are available for live staking:

Vermont DEC Guide:
https://dec.vermont.gov/sites/dec/files/wsm/lakes/docs/Shoreland/BioEngineeringManual_Live%20staking.pdf

Penn State:
https://extension.psu.edu/live-staking-for-stream-restoration

Virginia Working Landscapes:
https://www.vaworkinglandscapes.org/wp-content/uploads/Live-Staking-Guide.pdf

Material Sourcing:

Native riparian herbaceous seed mix: https://www.ernstseed.com/product/va-northern-ridge-valley-riparian-mix/ (Virginia Northern Ridge & Valley Mix).

Post-Construction Monitoring:

Project site should be carefully monitored for the first few months to the first year post-construction. If new areas of focused erosion are emerging, grasses not becoming established or live stakes not budding, additional planting efforts may need to be taken. Not all live stakes are expected to establish (a factor in planting so many), but over the first year signs of life should be seen in at least a small percentage of the stakes.

Legal Considerations:

So long as construction is limited to the 70 feet of streambank outlined in the plan, and stays outside of the streambed, no permitting should be necessary, as outlined by the Nationwide 13 Permit. However, it may be advisable to request that a local DEQ employee visit the site and review the restoration plan prior to construction, just to confirm.

Appendix II: Survey Plan

Field Survey Plan - Cub Run
Capstone Project
March 22, 2025

Data Collection Objectives:

1. Obtain a channel cross-section of the eroded site.
2. Obtain a longitudinal slope of the stream over a distance of roughly 500 feet upstream of site to 100 feet downstream of site.
3. Map the surrounding streambank terrain and identify pinch-points in the stream above and below the site.
4. Identify current riparian buffers that might be repurposed or preserved.
5. Identify man-made structures to preserve or move.
6. Measure the full-bank width throughout the property to establish baseline hydrologic requirements (freedom space) of the stream.
7. Identify a reference condition within the property, and obtain a channel cross-section.

Data Analysis Objectives:

1. Mapping: integrate collected data for terrain, buffers, structures and erosion locations to a comprehensive map of the area that can be used for decision-making and location reference. Indicate cross-section locations and document site observations from field study.

   Using this resource, identify potential areas to relocate the footbridge that would not overly constrain the stream's movement or conflict with erosion mitigation.

2. Graphs: use the cross-section data to create 2 graphs: 1 for the erosion site, and 1 for the reference condition. Overlay these outlines onto the same graph to visualize a healthier profile for the project location.

   Use the longitudinal elevation data to plot the channel slope and water slope along reach, and the profiles of the water line and streambed.

Equipment:

1. Laser Level / Receiver / Stadia rod
2. 100' tape
3. Notepad / Engineering Paper
4. GPS

The laser level survey is a 2-person job; one person needed to take the readings, and a second to document the reading. The bankfull width measurement also requires 2 people; 1 for either end of the tape.

Cross-section Sampling Method:

The laser level will be anchored next to the cross-section area, slightly above the floodplain on stream-right (R-L established as facing downstream). The tape will be fixed at the far end of the floodplain on stream-left, and stretched across the stream perpendicular to flow at the point of deepest erosion. The far side of the tape will be fixed at the opposite floodplain limit.

Readings will be taken across the entire extent of the tape. For each reading, document STA and FS; ELEV will be calculated post-survey. In the floodplain, readings can be taken every 1-foot. Once within the normal seasonal bankflow area, begin taking readings every 6". If significant drops or features are present, take additional measurements as seems necessary. The 6" grid is not necessary to take a usable cross-section, but aids in finer resolution when graphing during analysis.

Ensure that the receiver is as level as possible throughout the process (built-in level indicator).

Indicate on the datasheet the waterline level is reached.

Indicate on the datasheet when fullbank width location is reached.

Record coordinates of cross-section.

If possible, take a BS reading between the reference cross-section and the erosion cross-section.

Include relevant notes for each data entry.

Longitudinal Slope Method:

Identify a start location roughly 500 feet upstream of the cross-section site. Samples must be taken at stream thalweg (deepest centerline) and for every sample taken, obtain:

1. Coordinates (GPS).
2. Surface water elevation (laser level).
3. Stream bottom elevation (laser level).
4. Linear distance along thalweg from last sample location (tape).

Continue sampling at intervals of roughly 25-50 feet until approximately 100 longitudinal feet below cross-section site.

If possible, try to use the same laser level stand location as the cross-section measurements. If it must be moved, ensure that a reference reading is obtained between stands.

Site Documentation Method:

Engineering paper must be used for drawings and maps, to best capture a sense of scale. Coordinates will be logged using a GPS for all relevant landmarks, stations and sampling locations. There should be a minimum of 4 drawings:

1. Location of erosion cross-section with respect to reference reach location. Indicate approximate x-y distance and change in elevation (z). Document shared terrain and fluvial features between the two sites, and their differences.
2. Cross-section drawing of the erosion site.
3. Cross-section drawing of the reference site.
4. Area around the erosion site. Using the 100' tape, document in linear feet the length of erosion along the streambank, approximate location of all trees (and species if known), grass buffers, and man-made structures. Indicate location of cross-section.

Bankfull Width Method:

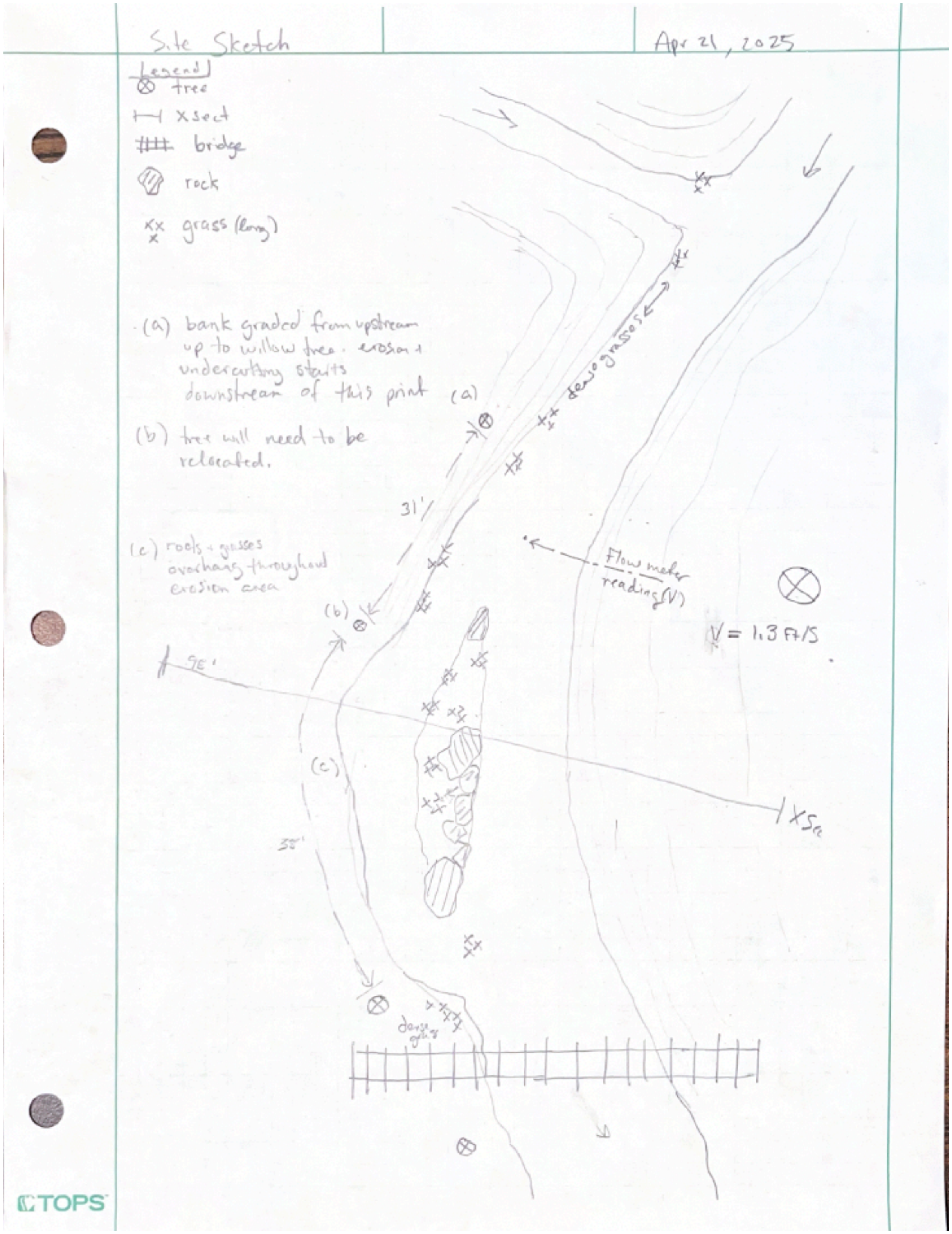
Bankfull width helps establish flow seasonality within a stream by determining the max volume of flow it receives at a given time within the 1.5-2 year interval. The measurement is straightforward and requires only a tape to be stretched across the stream to the bankfull mark; however, determining that mark is a flexible and less obvious process.

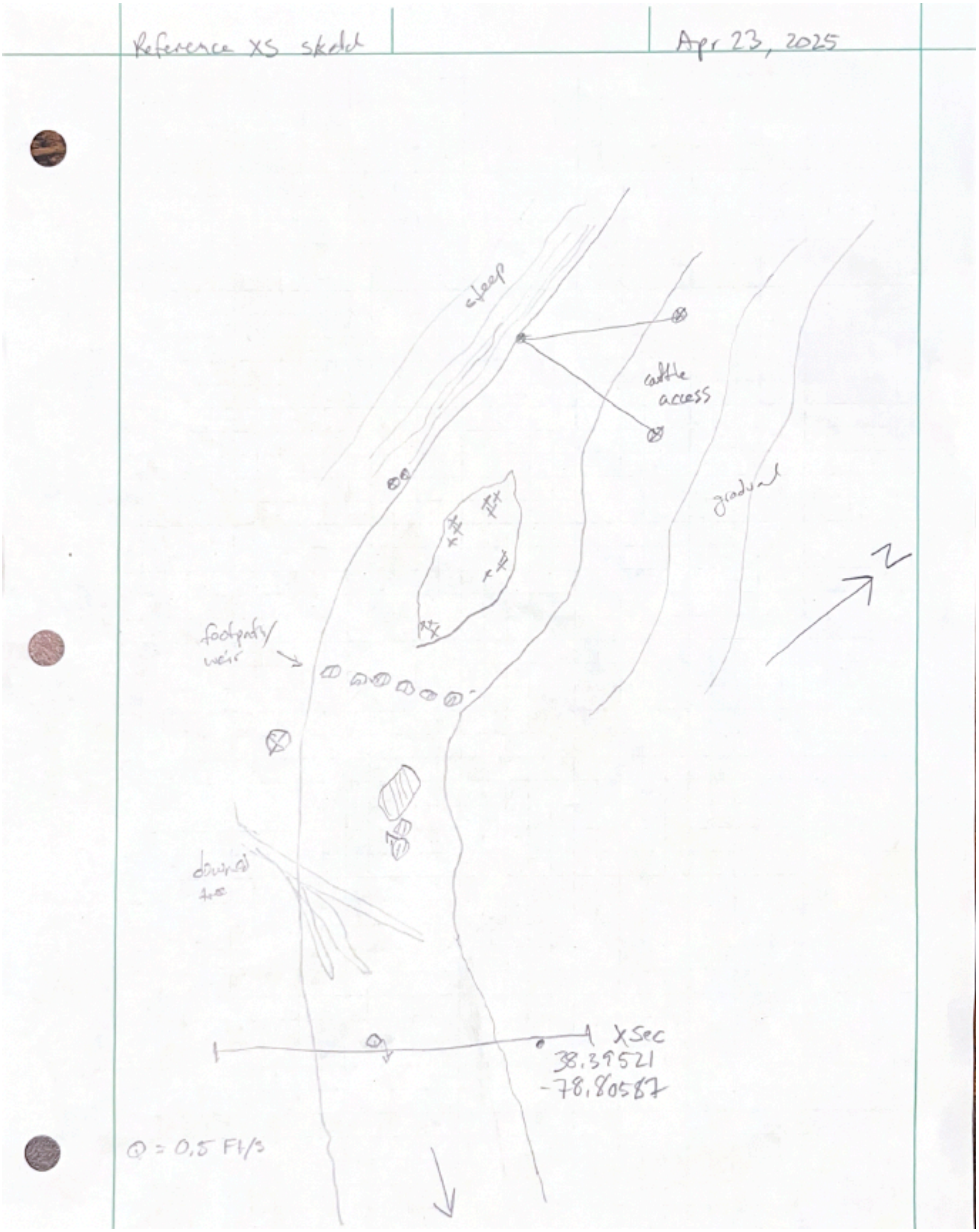
Using Penn State's Bankfull-Guidance document (Penn State Center for Dirt and Gravel Road Studies, 2022), look for the following indicators to determine bankfull width, ordered from most-to-least reliable:

1. Change in bank slope - look for benches and obvious changes in the bank slope to indicate a transition from the floodplain.
2. Depositional features - check tops of bars and bank for debris or deposition clues
3. Changes in particle size - streams drop more sediment once they start to access their floodplains.
4. Vegetation cover - particularly after a recent rain, grass may be laid down along the bank from high-water flow.
5. Scour features

For Cub Run, identify at least 5-7 good measurement points upstream of the site, without significant bedrock or braiding constraints. Avoid areas with logjams, noticeable human impacts, or hard bends where the stream is moving laterally. Calculate the average of these measurements to determine bankfull width.

Appendix III: Survey Data

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