ENHANCING STREAM FUNCTION IN WESTERN NORTH CAROLINA PASTURES

By

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(Under the Direction of Jon Calabria)

ABSTRACT

This thesis evaluated the application of Natural Channel Design (NCD) and Best Management Practices (BMPs) in enhancing stream function on a cattle pasture in Buncombe County, North Carolina. Potential reductions in sediment, nutrient, and E. coli specific enhancement measures were quantified. Applying NCD principles and Rosgen's stream classification, the study addresses impacts from cattle access and historical land modifications, offering a scalable model for sustainable agriculture and ecological health. Key measures, including exclusion fencing, riparian buffers, bank stabilization, and alternative water sources, were implemented to reduce erosion and pollutants. Adaptive strategies tailored to each stream section integrate BMPs with NCD techniques, balancing stream health and pasture use. The results suggest improvements in water quality and stream stability, with implications for extending this BMP-NCD approach across Western North Carolina to support water quality in the French Broad River Basin.

INDEX WORDS: Stream Enhancement, Western North Carolina, Best Management Practices, Riparian Buffer, Pasture Management

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DEDICATION

This thesis is dedicated to my family. To name you all individually would be the length of the paper itself, but know I have a special place in my heart for all of you and the support you have given me throughout the years. An especially important thank you goes to my loving husband, my amazing and supportive parents, my impressive little brother, and to Lady and Cleo for all of the late-night, emotional support snuggles. To the amazing team of individuals I have worked with in the freshwater aquatic biology community of North Carolina, please know that y'all's guidance and love have saved me more times than I can count. And to the people of Western North Carolina- we are as strong and resilient as the mountains and rivers themselves; never forget that.

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CHAPTER 1

INTRODUCTION

Agriculture and Stream Function

The intersection of agricultural practices with stream health often leads to water quality issues, characterized by the presence of pollutants such as *E. coli*, nitrogen, phosphorus, and sediment (U.S. Environmental Protection Agency 2023a; 2023b). The U.S. Environmental Protection Agency (EPA) describes water quality in terms of its appropriateness for irrigation and livestock, emphasizing the importance of maintaining clean water not just for human use but for agricultural activities as well (US EPA 2023c). Agriculture contributes to Nonpoint Source (NPS) pollution, a widespread problem stemming from varied sources which include pesticides, bacteria from manure runoff, and sediment from eroding streambanks (US EPA 2023a; 2023b). Despite the clear impact of agricultural activities on water quality, provisions in the Clean Water Act present challenges in addressing these issues directly (US EPA 2022a; 2023b). Since the 1970s, the Clean Water Act has exempted agriculture from its regulations; this stance was reaffirmed by the Clean Water Rule in 2015, keeping agricultural activities largely unregulated, leaving many US waterways exposed to NPS pollution (US EPA 2022a; 2023b).

In the context of agriculture's broader effects on stream health, cattle farming emerges as a notable factor in water quality degradation. The management practices of cattle, particularly allowing grazing in proximity to stream corridors without sufficient barriers, are directly implicated in the pollution of these waterways (US EPA 2003; 2023a; 2023b). These actions result in increased levels of sediment, nutrient runoff, and bacterial contamination, notably from livestock waste (US EPA 2003; 2023a; 2023b). This direct contribution of cattle to the challenges facing water bodies not only makes clear the complexity of agricultural runoff as a primary source of water quality issues but also highlights the necessity of maintaining a balance between agricultural productivity and the preservation of stream function (US EPA 2023a; 2023b).

Agriculture in Western North Carolina: French Broad River Basin

Western North Carolina (WNC) is home to several major watersheds including the Hiawassee, Little Tennessee, French Broad, Watauga, and the New (N.C. Wildlife Resources Commission 2020). Most notable of these river basins is the French Broad which spans 7 of 23 counties in WNC, including Transylvania, Henderson, Buncombe, Madison, Haywood, Yancey, and Mitchell, serving as an integral part of the region's ecological and economic landscape (N.C. Department of Environmental Quality 2018; Parlier 2023a). The French Broad River provides a habitat for over ten rare fish species and three rare mussels, including notable species such as the freshwater drum, mooneye, and the federally endangered Appalachian elktoe mussel, identifying it as a vital ecological zone (NC DEQ 2018; NCWRC 2020). Additionally, the French Broad River attracts 6.9 million visitors annually, bolstering the local economy through recreational activities like fishing and rafting, and supports a population of over 500,000 as per the 2020 census (Parlier 2023). This underscores the river's crucial role in both sustaining environmental health and fostering economic prosperity in Western North Carolina, thereby highlighting the importance of maintaining its stream function for ecological integrity and community livelihood.

Despite the French Broad River's ecological significance and its role in supporting a vast array of recreational activities that boost the local economy, water quality issues, particularly concerning *E. coli* contamination, pose a threat to its function (NC DEQ 2019; Jones 2022). A significant indicator of this growing problem was the classification of a 19-mile section of the river on the N.C. Department of Environmental Quality’s impaired list in 2022, attributed to an overabundance of bacteria, including *E. coli*, indicative of contamination from human and animal feces (Jones 2022). To pinpoint the origins of *E. coli* contamination, the Buncombe County-based environmental conservation group MountainTrue conducted DNA tests from water samples taken at 30 sites along the French Broad River (Harris 2021). Analysis of 55 water samples collected from 30 sites identified *E. coli* contamination primarily originating from cow, human, and dog sources (Harris 2021). Among these, 44 samples showed cow-derived *E. coli*, establishing cattle as the leading contributor to *E. coli* pollution in the river (Harris 2021; NC DEQ 2019; Jones 2022). The large presence of cow-derived *E. coli* in the French Broad River underscores the impact of agricultural activities on water quality, highlighting the critical need for effective cattle and pasture management practices to mitigate these effects and preserve stream function.

Best Management Practices for Stream Function

Effective management practices for stream function, specifically focusing on the reduction of agricultural nutrient and sedimentation runoff as well as *E. coli* removal, are paramount for enhancing water quality in agricultural regions. The Natural Resources Conservation Service (NRCS) specifies several Best Management Practices (BMPs) tailored to address these issues directly. These BMPs include the implementation of riparian buffer zones, controlled livestock access to streams, nutrient management plans, and cover cropping techniques (NRCS 2023a).

Riparian buffer zones, vegetated areas between agricultural land and waterways, are critical in filtering out nutrients, sediment, and pathogens before they reach the stream(King et al. 2016; NC DEQ 2016; D. L. Osmond 2023). These buffers not only prevent direct access of livestock to streambanks, thereby reducing the risk of erosion and sedimentation, but also mitigate the runoff of nutrients and *E. coli* from manure (NC DEQ 2016; D. L. Osmond 2023). Controlled livestock access through fencing or alternative water supplies reduces the direct deposit of waste into water bodies and minimizes bank erosion (NC DEQ 2016). Nutrient management plans are essential for determining the appropriate amount, timing, and method of fertilizer and manure application to crops to minimize nutrient runoff into streams (US EPA 2003; NC DEQ 2016). Lastly, the practice of cover cropping can significantly reduce soil erosion and nutrient loss during off-seasons by keeping the soil covered and absorbing excess nutrients, which might otherwise leach into waterways(NRCS 2023a).

Implementing these NRCS-specified BMPs can greatly contribute to maintaining and enhancing stream function by reducing the inputs of sediment, nutrients, and pathogens like *E. coli* from agricultural activities. Not only do these practices support the ecological integrity of waterways, but they also sustain the agricultural productivity and environmental health necessary for community livelihood and the preservation of biodiversity within agricultural landscapes (NRCS 2023a).

Case Study Overview: WNC Cattle Farm Stream Enhancement Design

Situated in the northern part of Buncombe County, North Carolina, encompassing a 29-acre pastureland at the headwaters of a tributary to the French Broad River, this study presents a design aimed at enhancing stream function within a privately-owned, small family farm. This property, steeped in over 200 years of agricultural history, currently supports beef cattle farming practices that have contributed to notable on-site stream degradation, including erosion, sedimentation, and contamination with *E. coli* from cattle waste.

The selection of this site for enhancing stream function is founded on its representation of broader environmental challenges within Western North Carolina's pasturelands. Its location, adjacent to public, residential, and agricultural lands, including proximity to the Pisgah National Forest, underscores its potential impact on regional biodiversity and water quality. The stream has been modified for agricultural purposes, leading to pollution issues, including direct cattle access and historical land alterations. Furthermore, the site features a notable elevation gradient, from approximately 2,500 to 3,000 feet, spanning diverse habitats from an alluvial floodplain to steep mountainside pastures. This topographical diversity, while typical of the region, introduces additional complexities to devising a comprehensive plan for stream enhancement.

This research outlines a design framework utilizing Best Management Practices (BMPs) recommended by the Natural Resources Conservation Service (NRCS), targeting stream enhancement. For specific interventions such as streambank stabilization and riparian buffer establishment, guidelines from Natural Channel Design (NCD) are applied. Proposed BMPs for the design include livestock exclusion fencing, streambank stabilization, riparian buffer establishment, and an alternative livestock watering system. These practices are not only aimed at restoring stream function and reducing pollutants but also serve as a scalable model for similar landscapes across the region. The effectiveness of these BMPs will be assessed using the PLET tool from the EPA, providing quantifiable metrics on pollutant reduction and function enhancement (US EPA 2021)

Significance and Goals

The purpose of this study is to design a plan leveraging Best Management Practices (BMPs), informed by Natural Channel Design (NCD) principles, to enhance stream function within pasturelands in Western North Carolina. This initiative aims to address prevalent water quality issues, including the reduction of cow-derived *E. coli*, by integrating sustainable agricultural practices with stream conservation efforts.

The methods of enhancement explored in this research are grounded in specific standards set by the Natural Resources Conservation Service (NRCS) BMPs. While certain practices, such as streambank stabilization, necessitate professional intervention, others, including livestock exclusion fencing and the implementation of an alternative water supply, can be undertaken directly by landowners with or without the consultation of the NRCS. Moreover, the NRCS offers potential cost-sharing opportunities to facilitate the adoption of these practices. While specific to a singular project site, the principles and practices it employs are scalable and could, if implemented across pasturelands throughout Western North Carolina, significantly improve stream function and water quality across the entire region.

Delimitations

The scope of the project focusing on stream function enhancement within a cattle farming context in Western North Carolina (WNC) is bound by several delimitations that specify its focus and limitations. Firstly, the project centers exclusively on agricultural practices, particularly those related to cattle farming, and their impact on stream function and water quality, with an emphasis on reducing sedimentation, nutrient runoff, and *E. coli* contamination. The application of Best Management Practices (BMPs) as specified by the Natural Resources Conservation Service (NRCS) and informed by Natural Channel Design (NCD) principles is central to the project's methodology. This means that while the project aims to address water quality issues through specific, targeted interventions such as livestock exclusion, riparian buffer establishment, and streambank stabilization, it does not encompass broader agricultural practices outside of those that directly affect stream health.

Moreover, the project is geographically delimited to the northern part of Buncombe County, focusing on a 29-acre pastureland at the headwaters of a tributary to the French Broad

River. The choice of location highlights the project's intent to address stream function within a specific ecological and agricultural setting, thus not directly addressing other areas in WNC or different types of land use that might also impact stream health. The project's emphasis on cattle-derived *E. coli* as a primary pollutant, with nutrient load and sedimentation rates as secondary pollutants, limits the exploration of other potential sources of contamination or environmental stressors not directly related to cattle farming. Furthermore, while the project proposes scalable BMPs that could potentially be applied across WNC, the initial implementation and findings are confined to the selected study site, with broader applicability to be determined based on the outcomes of this localized effort.

Lastly, the reliance on NRCS guidelines and EPA tools like the STEPL for assessing the effectiveness of the implemented BMPs introduces a methodological delimitation, basing success metrics and project evaluation on frameworks and tools specific to these organizations. This approach assumes the adequacy of these methods for the project's goals but does not incorporate alternative or novel evaluation methodologies that might also be relevant. This specificity in methodology and focus ensures a clear project direction but also delineates the boundaries of what the project aims to achieve and evaluate.

CHAPTER 2

LITERATURE REVIEW

Stream Restoration

Importance of Stream Health

Stream health is fundamental to the integrity of local ecosystems, serving as a crucial habitat for a wide range of species, including fish, birds, amphibians, and plants ^onal Geographic Society 2023). The unique environmental conditions within streams support species that have evolved specific adaptations, such as mussels, crayfish, and fish species, creating significant biodiversity (National Geographic Society 2023). Healthy streams play a vital role in natural processes that sustain these ecosystems, particularly through the filtration of pollutants, which helps protect downstream waters from contamination and maintains ecological balance (US EPA 2013; Smithsonian 2024). This filtration capability is essential for preventing the spread of harmful pollutants that can lead to ecological disruptions, which pose significant threats to aquatic life (US EPA 2013). Additionally, the health of upstream streams directly influences the condition of larger water bodies like rivers, lakes, and coastal waters, demonstrating the interconnectedness of aquatic ecosystems (US EPA 2017; 2013).

The condition of streams is directly linked to human health, especially through their role in providing clean drinking water. In the continental United States, 357,000 miles of streams provide water for public drinking water, underscoring the necessity of maintaining the cleanliness and flow of these water sources (US EPA 2013). Beyond surface water, streams contribute to the recharge of underground aquifers, which ensures a continuous supply of water, particularly during dry periods (US EPA 2013). By filtering pollutants and controlling the quality of water before it reaches larger bodies of water, healthy streams reduce the risk of waterborne diseases and contamination, which are critical public health concerns (Smithsonian 2024; US EPA 2013). Furthermore, streams support recreational activities such as swimming and fishing, which are essential not only for physical well-being but also for the overall quality of life in communities (National Geographic Society 2023; US EPA 2017). The relationship between stream health and human health is therefore multifaceted, extending beyond direct consumption to encompass broader health and lifestyle benefits.

Streams are vital to various sectors of the economy, including agriculture, manufacturing, tourism, and recreation. Healthy streams provide essential services like irrigation, which is crucial for agricultural productivity and food security (US EPA 2023c). The fishing industry, both commercial and recreational, is heavily dependent on the cleanliness and ecological health of streams, with millions of anglers contributing billions of dollars annually to the economy through related activities (US EPA 2024). Additionally, they play a significant role in tourism, where activities such as boating, hiking, and nature viewing generate substantial economic benefits (National Geographic Society 2023; US EPA 2024). The economic significance of streams is further highlighted by their role in mitigating flood damage, which can prevent billions of dollars in property and crop losses each year (US EPA 2013). Thus, the economic value of healthy streams is extensive, providing both direct benefits to industries such as agriculture, manufacturing, and tourism, and indirect benefits by supporting community resilience and overall well-being (National Oceanic and Atmospheric Administration 2024; US EPA 2017).

Stream Degradation

Stream degradation is a significant environmental issue, often exacerbated by urbanization and poor land management practices. Due to urbanization, impervious surfaces, such as roads and buildings, increase stormwater runoff, which alters natural streamflow patterns and carries pollutants into water bodies. These changes lead to channel instability, increased erosion, and the loss of habitat for aquatic species (Utz et al. 2022). Moreover, the combination of pollutants, such as microplastics and road salts, further degrades water quality, creating complex ecological problems (Guasch et al. 2022).

However, agricultural practices are one of the leading contributors to stream degradation globally (David Allan 2004; US EPA 2023b). The overuse of fertilizers, improper land management, and livestock grazing have significant impacts on water quality, hydrology, and aquatic habitats (US EPA 2003; 2023a; 2023b; Schafer, van den Brink, and Liess 2011). While urbanization plays a role in stream degradation, agricultural runoff often results in nutrient loading, sediment deposition, and contamination from pesticides and herbicides, leading to long-term ecological consequences (US EPA 2023b; D. Osmond et al. 2012; Conley et al. 2009).

Nutrient runoff from fertilizers and/or animal manure is a critical issue in agricultural landscapes. Phosphorus and nitrogen, commonly found in these substances, are transported by surface runoff into nearby streams and rivers, resulting in eutrophication, which leads to algal blooms and oxygen depletion in aquatic ecosystems (Carpenter et al. 1998; Conley et al. 2009; Ranells et al. 2001). This nutrient loading disrupts the balance of aquatic environments, reducing biodiversity and altering food webs (Dodds and Smith 2016; Sharpley et al. 2011). Moreover, excess nutrients foster conditions that degrade stream health by encouraging the growth of invasive aquatic plants and algae, which can suppress the growth of native species and alter stream morphology.

Sediment transport is another major issue in agricultural areas, particularly due to soil erosion caused by tilling, deforestation, animal access to streams, and inadequate riparian buffer zones. The increased sediment loads in streams decrease water clarity, reduce light penetration, and smother benthic habitats, which are essential for many aquatic organisms(Bilotta and Brazier 2008). Excessive sedimentation also affects stream hydrology by changing channel morphology and increasing the frequency of flooding and bank erosion (Rosgen 2001; Doll et al. 2003). The loss of riparian vegetation, which serves as a buffer for streams, further exacerbates sediment transport into aquatic systems (Allan 2004).

Pesticides and herbicides from agricultural runoff also play a significant role in degrading stream ecosystems. These chemicals can be highly toxic to aquatic species, affecting fish, invertebrates, and plants. Long-term exposure to these contaminants can lead to population declines and disrupt the reproductive cycles of sensitive species (Schafer, van den Brink, and Liess 2011). Additionally, these contaminants often persist in the environment, leading to bioaccumulation in aquatic organisms and entering food webs, causing significant, long-term ecological and human health issues (Sibley and Hanson 2011).

Livestock grazing near streams adds another layer of degradation by increasing nutrient loads through manure runoff and contributing to streambank erosion due to trampling (Agouridis et al. 2005; Trimble and Mendel 1995). Studies have shown that livestock exclusion from riparian zones can significantly improve water quality and reduce erosion rates (Ranells et al. 2001; D. Osmond et al. 2012). However, in many agricultural landscapes, livestock, particularly cattle, continue to directly access streams, contributing to nutrient pollution and physical degradation of stream channels.

Agricultural best management practices (BMPs), such as riparian buffers, conservation tillage, and controlled grazing, are widely recognized for reducing the negative impacts of livestock on stream ecosystems. However, the successful implementation of these practices often depends on private farmers' voluntary decisions to adopt them (Sharpley et al. 2011). When small-scale farmers implement BMPs, such as rotational grazing and livestock exclusion zones, nutrient and sediment runoff into waterways is significantly reduced, improving water quality (Agouridis et al. 2005; D. L. Osmond 2023). Riparian buffers, in particular, are highly effective in filtering runoff from pastures and reducing nutrient loads, such as nitrogen and phosphorus, that enter streams (D. Osmond et al. 2012; Sharpley et al. 2011).

Although BMPs are effective, nutrient and sediment control measures require a coordinated approach to landscape management and a long-term commitment. Comprehensive strategies, including stream restoration, rehabilitation, or enhancement, are essential for sustained ecological health. Short-term solutions frequently fail to provide the long-term stability necessary to support resilient ecosystems (David Allan 2004; Carpenter et al. 1998).

Stream restoration efforts that emphasize long-term ecological sustainability, rather than short-term erosion or flood mitigation, offer more lasting benefits. For small agricultural operations, natural channel design can help restore stream function by addressing sediment transport, bank erosion, and water quality issues (Agouridis et al. 2005). Restoration projects, especially in small streams, are critical for rebuilding natural habitats, improving water quality, and supporting the ecological balance required for both environmental health and agricultural productivity (Fripp, Robinson, and Bernard 2007c; D. Osmond et al. 2012; Rosgen 1996).

Additionally, small farmers can further promote ecosystem longevity by planting native vegetation along streams to stabilize streambanks and naturally filter agricultural runoff (Agouridis et al. 2005; Sharpley et al. 2011; D. Osmond et al. 2012).

Stream Restoration, Rehabilitation, and Enhancement Overview

Stream restoration, rehabilitation, and enhancement are integral components of environmental management, aiming to improve ecological integrity and ecosystem services. In the literature on ecological restoration and related activities, several terms such as restoration, rehabilitation, enhancement, and reclamation are often used interchangeably, yet they represent distinct approaches and goals for their respective projects (Clewell and Aronson 2013). Restoration is broadly defined as the re-establishment of the structure and function of ecosystems to approximate pre-disturbance conditions, encompassing a wide range of river management and engineering activities, from structural to ecosystem process modifications, typically on a larger scale (Clewell and Aronson 2013; Wohl, Lane, and Wilcox 2015). It focuses on bringing ecosystems as close as possible to their original state, although the practicality of achieving true restoration is often debated (Wohl, Lane, and Wilcox 2015; Yochum and Reynolds 2020).

Rehabilitation, on the other hand, emphasizes the recovery of ecosystem processes and services without necessarily restoring the original species composition or community structure. This approach is often applied in landscapes heavily influenced by human activities, where the goal is to make the land useful again, typically by enhancing productivity (Fripp, Robinson, and Bernard 2007a). Reclamation is an older term focused on converting economically unproductive land, such as wetlands or shallow seas, into productive use, with the primary goal of recovering productivity rather than restoring historical ecosystems (Clewell and Aronson 2013). Finally, enhancement often refers to the intentional greening or revegetation of degraded land, which may involve non-native species and does not necessarily aim to restore original ecological conditions (Clewell and Aronson 2013). These distinctions highlight the varying objectives and methodologies applied across different ecological restoration practices.

While the term "stream restoration" in scientific literature is used to describe the re-establishment of streams and rivers to their pre-disturbance conditions, in practice achieving true restoration is increasingly challenging due to factors like climate change, altered land use within watersheds, and growing human populations (Fripp, Robinson, and Bernard 2007a). These changes have made it difficult, if not impossible, to fully restore ecosystems to their original state. Consequently, many stream design projects now prioritize "rehabilitation," which focuses on recovering stream ecosystem functions and services rather than attempting to recreate exact historical conditions (Clewell and Aronson 2013; Yochum and Reynolds 2020).

Despite this shift toward rehabilitation, the term "restoration" remains prevalent in public discourse and government communications. This is largely due to the general public's understanding of "stream restoration" as the overall improvement of a stream system's physical, chemical, and biological functions (San Antonio River Authority, n.d.). As a result, government agencies like the United States Department of Agriculture and the Natural Resources Conservation Service often label any project that enhances a stream or river as "restoration" for the sake of simplicity, even when "rehabilitation," "reclamation," or "enhancement" might be more accurate descriptors (Fripp, Robinson, and Bernard 2007a; Yochum and Reynolds 2020).

Primary Objectives of Stream Restoration

The primary objectives of stream restoration are to enhance key ecosystem services such as flood mitigation, water quality improvement, and habitat provision. By restoring the natural functions and processes of a stream, these efforts aim to mitigate floods through the re-establishment of floodplains and the improvement of natural water flow patterns. Such measures are crucial for managing sediment, stabilizing banks, and increasing the stream's capacity to handle floodwaters effectively (Fripp, Robinson, and Bernard 2007a).

Water quality improvement is another critical objective of stream restoration. Projects are designed to enhance the stream's chemical functions, such as increasing the removal of impurities and reducing contaminants as water flows through the system. This, in turn, boosts the overall ecological health of the stream (San Antonio River Authority, n.d.; Fripp, Robinson, and Bernard 2007a)

Equally important is the enhancement of habitats for diverse species, including fish, aquatic insects, and other wildlife. By improving the physical and biological functions of the stream, restoration projects create healthier and more diverse ecosystems (Wohl, Lane, and Wilcox 2015). This is achieved through measures like reshaping unstable stream reaches, planting native vegetation, and stabilizing banks, which together foster a robust and sustainable environment capable of supporting a wide range of species (San Antonio River Authority, n.d.; Wohl, Lane, and Wilcox 2015). These efforts not only benefit biodiversity but also contribute to the long-term resilience and sustainability of the stream, ensuring it continues to provide essential ecosystem services (Doll et al. 2003; Yochum and Reynolds 2020).

Stream Restoration on Agricultural Land

Stream restoration on agricultural lands is a critical component of improving water quality, reducing erosion, and enhancing riparian ecosystems, especially in regions where agricultural practices, such as cattle grazing, are prevalent. Unrestricted livestock access to streams leads to sedimentation, nutrient pollution, and streambank degradation, all of which compromise aquatic habitats and water quality (Agouridis et al. 2005; Trimble and Mendel 1995; Ranells et al. 2001). In areas like Western North Carolina's French Broad River Basin, these concerns are particularly severe due to the significant agricultural activities and livestock farming (Daniel E Line, Osmond, and Childres 2016; Tutwiler and Clark 2011).

Livestock exclusion, combined with the establishment of riparian buffers, significantly reduces sediment and nutrient inputs into streams (Daniel E Line, Osmond, and Childres 2016). Riparian buffers, act as natural filters, capturing pollutants like phosphorus and nitrogen before they reach waterways. Studies have shown that buffer zones of 25 to 50 feet can reduce pollutant loads effectively, with wider buffers providing greater protection depending on the level of erosion in the area (Daniel E Line, Osmond, and Childres 2016; Johnson et al. 2013). For example, pastures where cattle have access to streams benefit from buffers that range from 15 to 25 feet in width, which reduce nitrogen and phosphorus loads by approximately 25% or more (D. L. Osmond 2023).

In the French Broad River Basin, sedimentation and bacterial contamination remain significant challenges, particularly in tributaries that flow through agricultural lands (Harris 2021; Jones 2022). Projects that have been implemented by the Natural Resources Conservation Service (NRCS) and local conservation organizations, such as Conserving Carolina, have demonstrated the benefits of fencing cattle out of streams and restoring riparian zones with native vegetation (Agouridis et al. 2005; Barcas 2021; Trimble and Mendel 1995). These efforts not only improve water quality by reducing sedimentation but also restore streambank stability and enhance wildlife habitats (Agouridis et al. 2005; Barcas 2021; D. L. Osmond 2023). The French Broad River, which flows through several counties in Western North Carolina, is a vital water resource for agriculture, recreation, and local ecosystems. Sediment and nutrient loads from agricultural runoff pose a long-term threat to this important watershed, making stream restoration efforts essential (French Broad River Partnership 2021; Tutwiler and Clark 2011; Jones 2022).

One of the major challenges identified in these restoration efforts is balancing agricultural economic productivity with environmental protection. Many small farmers in Western North Carolina rely on their livestock for income, making cattle exclusion from water sources and large areas of potentially fertile land a controversial issue. However, programs through the USDA and NRCS such as the Agricultural Management Assistance Program (AMA), Conservation Stewardship Program (CSP), Environmental Quality Incentives Program (EQIP), and the Conservation Reserve Program (CRP), have provided financial aid and incentives to farmers to encourage them to implement conservation practices on their land ("USDA-NRCS Cost-Share Programs" 2024). These efforts include projects like stream restorations where cattle are excluded from streams, helping to protect water quality and promote healthier ecosystems, while mitigating the economic impact. This has been imperative in promoting the adoption of best management practices (BMPs) for water quality improvement ("USDA-NRCS Cost-Share Programs" 2024; Tutwiler and Clark 2011).

Stream Restoration Techniques

Process-Based versus Function-Based versus Form-based Restoration Techniques

Stream restoration techniques offer a variety of strategies for addressing stream degradation, depending on the specific goals of the project. These approaches are generally divided into three categories: process-based, function-based, and form-based, each focusing on a different approach of achieving restoration (Fripp et al. 2009). Selecting the most suitable method relies on understanding these distinctions and how each approach targets different restoration needs, from reestablishing natural processes to enhancing ecosystem functions or modifying physical structures.

Process-Based Restoration

Process-based restoration (PBR) focuses on restoring the natural hydrological and geomorphological processes that sustain healthy ecosystems (Beechie et al. 2010; Ciotti et al. 2021; Corday 2024). The goal is to restore the natural interactions between water flow, sediment transport, and riparian vegetation that maintain a stream's form and ecological functions over time (Beechie et al. 2010; Ciotti et al. 2021). This approach prioritizes the natural dynamic equilibrium of streams, minimizing engineering interventions and allowing streams to evolve naturally back to a stable state.

Common PBR techniques include using low-tech interventions such as Beaver Dam Analogs (BDAs), Post-Assisted Log Structures (PALS), placement of Large Woody Debris (LWD), and rock detention structures (RDS) which are installed with minimal use of heavy equipment and are relatively inexpensive (Beechie et al. 2010; Corday 2024). These structures are created to mimic natural processes like beaver damming, helping to slow water flow, raise groundwater levels, and improve riparian vegetation (Beechie et al. 2010; Ciotti et al. 2021). By promoting the natural buildup of sediment and organic material, these interventions work to reconnect floodplains and create conditions for a range of aquatic and riparian habitats to thrive. Moreover, PBR techniques provide long-term benefits by allowing ecosystems to become self-sustaining. Once established, these systems require minimal maintenance, as natural processes such as wood recruitment and sediment deposition continue to form habitats and promote ecosystem recovery, leading to the creation of both aquatic and terrestrial species diversity (Ciotti et al. 2021; Corday 2024).

However, not all streams are suitable for PBR techniques. The success of PBR depends greatly on selecting appropriate sites, as streams in highly altered environments, such as those with profound changes to their natural water or sediment levels, may lack the necessary conditions for natural processes to reestablish themselves (Corday 2024). Suitable locations for PBR are defined as "first to third-order 'wadeable' streams with a gradient of 3% or less located on rural public or private lands where there is room for the stream to utilize its full floodplain without causing infrastructure or water use conflicts" (Corday 2024). Only when restoration sites provide sufficient space for the stream to interact with its floodplain, allowing natural processes like sediment deposition and vegetation growth to occur, can PBR facilitate long-term ecosystem restoration.

Function-Based Restoration

Function-based stream restoration focuses on the recovery of a stream's natural processes that sustain its ecological and hydrological functions . By focusing on reconnecting specific biological, hydrological, and chemical processes, this method not only aims to stabilize stream channels but also restore their ability to support aquatic life, maintain water quality, and integrate with floodplains (Starr et al. 2012).

One of the core methodologies of function-based restoration is the Stream Functions Pyramid Framework (SFP), which organizes stream functions into hierarchical levels that build upon one another (Starr et al. 2012). These levels include five functional categories: hydrology, hydraulics, geomorphology, physicochemical, and biology (Starr et al. 2012). For instance, the restoration of biological functions depends on the proper functioning of geomorphological and physicochemical processes. This framework emphasizes a bottom-up approach to restoration, addressing foundational functions first to provide support for more complex ecological outcomes (Starr et al. 2012).

In function-based stream restoration, reference reaches are critical as they serve as the baseline or target condition for assessing and designing restoration projects. A reference reach is typically a section of stream that exhibits stable physical, chemical, and biological functions, acting as a natural benchmark against which degraded streams are compared. These reference sites are essential for setting realistic restoration goals which relies on reference conditions to define performance standards across hydrological, geomorphological, and biological functions (Starr et al. 2012).

Within this framework, the Stream Quantification Tool (SQT) was developed to measure the "functional lift," which refers to the improvement in a stream's ecological and hydrological processes resulting from restoration efforts (W. A. Harman and Jones 2017; Starr et al. 2012). The SQT quantifies this improvement by comparing the stream's conditions before and after the restoration work. This tool evaluates several parameters within the pyramid framework, including water flow, sediment transport, and biological diversity (W. A. Harman and Jones 2017; StreamMechanics 2017; Starr et al. 2012). The SQT can be adapted to regional reference standards making it key to standardizing restoration projects and ensure measurable ecological improvements (W. A. Harman and Jones 2017; StreamMechanics 2017).

While function-based stream restoration has proven effective in many cases, there are challenges and limitations to its application. One issue is the complexity and cost of accurately assessing and restoring multiple interrelated functions. The framework requires detailed, multidisciplinary data collection to measure hydrological, geomorphological, and biological functions, which can make projects more expensive and time-consuming compared to simpler, form-based methods (Starr et al. 2012).

In more dynamic systems, the static nature of function-based assessments, which often capture a "snapshot in time," might not fully account for the ongoing or future impacts of development or climate change (Starr et al. 2012). Furthermore, the framework is predominantly designed for simpler, single-thread stream systems and may struggle to fully capture the complexity of braided or multi-thread systems, where hydrological and geomorphological processes are more complex (Starr et al. 2012; W. A. Harman and Jones 2017). Therefore, while highly effective in many less-developed watersheds, function-based stream restoration may need adaptations or additional tools to be fully effective in heavily modified environments.

Form-Based Restoration

Form-based stream restoration is a widely used technique in the U.S. that emphasizes restoring the physical structure or form of a stream channel to improve its ecological functions. This approach often involves mimicking natural stream channel shapes and processes to stabilize banks, manage sediment transport, and enhance habitat quality (Fripp et al. 2009; Hey 2006; Rosgen 1996).

Form-based stream restoration draws on the foundational work of fluvial geomorphologists such as Luna Leopold, M. Gordon Wolman, and Thomas Dunne, who introduced key concepts in river behavior and hydraulic geometry. Their research highlighted the importance of balancing water flow and sediment transport in natural rivers, establishing the idea that restoring stream form could help stabilize degraded channels (Dunne and Leopold 1980). Building from this knowledge, modern form-based restoration is grounded in established geomorphological principles, with a focus on critical elements like channel geometry, bank stabilization, meander development, riffle-pool sequences, and floodplain connectivity (Bennett et al. 2011; Rosgen 1996).

Traditional form-based restoration methods, including hydraulic geometry-based techniques and conventional engineering strategies, often prioritize physical stability and the control of specific outcomes, such as flood mitigation or erosion prevention (Bennett et al. 2011; Kasprak et al. 2016). These methods typically rely on rigid structures like riprap and channel straightening (Fripp et al. 2009). While these techniques can be effective in certain scenarios, they can also lead to negative environmental impacts, such as reduced habitat diversity, increased water velocity and downstream flood risks, and diminished long-term stability (Bennett et al. 2011; Hey 2006; Kasprak et al. 2016; Rosgen 1996).

However, the most widely adopted method of form-based restoration in the U.S. is Natural Channel Design (NCD), developed by Dave Rosgen in the 1990s, which provides a practical methodology to form-based restoration by providing parameters to aid in replicating stable, naturally functioning stream forms (Rosgen 1996). Unlike other form-based techniques, NCD emphasizes the natural processes of sediment transport, streamflow, and channel morphology, rather than attempting to restore historical or "pristine" conditions, which may no longer be feasible due to changes in watershed characteristics(Fripp et al. 2009; Doll et al. 2003; Rosgen 1996; 2011). It integrates geomorphological and hydrological principles to design river systems that function effectively under current environmental conditions. Additionally, NCD relies on in-stream structures such as riffles, pools, and large woody debris, rather than manmade materials, such as concrete, to enhance habitats by creating diverse flow velocities, depths, and substrate types, promoting a more diverse and resilient stream ecosystem (Doll et al. 2003; Rosgen 1996; 2011).

In general, form-based restoration techniques, both NCD and traditional, have shown success in stabilizing streambanks and improving aquatic habitats, particularly in areas prone to high erosion and sedimentation (Kasprak et al. 2016). However, these techniques require careful planning and consideration of local geomorphology and hydrology to avoid future instability (Kasprak et al. 2016; Rosgen 1996; 2011). The success of form-based restoration depends on site-specific conditions, including sediment load, stream flow, and vegetation type (Hey 2006). Misalignment between the restored stream form and the natural stream processes can lead to long-term instability (Kasprak et al. 2016; Rosgen 1996; 2011).

Natural Channel Design in Stream Restoration

Natural Channel Design Overview

Natural Channel Design (NCD) aims to restore the form and function of degraded river systems by replicating stable, natural stream conditions. This approach is closely associated with Rosgen, who developed a widely recognized methodology rooted in his stream classification system and applied morphological design (Rosgen 1994; 1996; 2011). Rosgen's method focuses on creating stable stream channels by mimicking natural forms and processes, while acknowledging that designing to historical or pristine conditions may not always be feasible due to human-induced changes in watersheds and climate (Rosgen 1996; 2011). His structured approach, which has been widely adopted in stream restoration, integrates physical, biological, and geomorphological processes through a multidisciplinary framework. By drawing on hydrology, geomorphology, ecology, and engineering, NCD seeks to restore and sustain healthy stream dynamics (Wohl, Lane, and Wilcox 2015; Rosgen 2011; Yochum and Reynolds 2020).

Core Principles of Natural Channel Design

The Natural Channel Design (NCD) approach differs from traditional river engineering methods, which have often resulted in environmental damage and river instability (A Simon et al. 2007; Lave 2009). Instead of attempting to restore rivers to an idealized, pre-disturbance condition, NCD focuses on using fluvial processes over various temporal and spatial scales to rehabilitate degraded systems (Doll et al. 2003; Rosgen 2011; Yochum and Reynolds 2020). The goal is to create channels that are self-sustaining under current environmental conditions (Doll et al. 2003; Rosgen 1996; 2011). A key component of NCD is its emphasis on understanding the interactions between river form and processes, allowing for the prediction and restoration of stable channels modeled after naturally stable river reaches(Rosgen 2011; Yochum and Reynolds 2020).

NCD methodology involves utilizing a blend of empirical, analog, and analytical methods to restore river channels (Doll et al. 2003; Harman W. A. and Starr 2011; Rosgen 1996; 2011). An essential aspect of NCD is comparing the "existing reach," "reference reach," and "proposed design reach" (Doll et al. 2003; Rosgen 1996; 2011; Harman W. A. and Starr 2011; Yochum and Reynolds 2020). The existing reach reflects the current impaired state, while the reference reach serves as a stable counterpart under similar environmental conditions. The proposed design reach is then crafted by modeling key attributes from the reference reach (Doll et al. 2003; Rosgen 1996; 2011; Harman W. A. and Starr 2011; Rosgen 1994). Traditionally, NCD relied on the reference reach to guide restoration efforts, but advances in hydraulic modeling and the use of regional reference curves now allow for the creation of a proposed design reach without the need for a direct reference (Harman W. A. and Starr 2011; Yochum and Reynolds 2020). Instead, model-based predictions of channel form and function are utilized (Harman W. A. and Starr 2011; Yochum and Reynolds 2020).

Although model-based predictions can create the proposed design reach, the inputs for these models rely heavily on accurate field measurements of the existing reach. NCD requires the evaluation of over 67 dependent form variables related to the river's dimension, pattern, and profile (Rosgen 2011). These variables are influenced by independent driving factors, such as sediment load, boundary conditions, and riparian vegetation, all of which must be quantified and applied to the restoration effort (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020). By combining field assessments, reference data, and hydraulic modeling, restoration practitioners can propose design reaches that ensure the restored channel will remain stable and functional under current conditions.

Reference Curves for NCD in WNC

Regional reference curves, often referred to as bankfull hydraulic geometry relationships, are essential tools in stream restoration, as they provide a relationship between channel dimensions and drainage area (Harman W. A. and Starr 2011; W. A. Harman et al. 2000; Rosgen 1994; 2011). These relationships help predict the dimensions of a stream at bankfull discharge. In Western North Carolina, several studies have been performed to develop these reference curves, each employing distinct methodologies. Collectively, they provide valuable insights into stream morphology, helping them establish restoration guidelines based on natural stream conditions.

The studies on regional reference curves for stream restoration in Western North Carolina offer varied approaches, each focusing on different methods and variables to examine stream morphology. Henson, Kolawole, and Ayeni (2014) and W. A. Harman et al. (2000) emphasize the development of bankfull hydraulic geometry relationships using field data from gauged and ungauged watersheds, with a focus on predicting natural stream dimensions through regression models based on drainage area. Henson, Kolawole, and Ayeni (2014) included data from both small USDA Forest Service sites and larger USGS stations, highlighting the unique geomorphology of temperate rainforests in the Southern Appalachian Mountains. W. A. Harman et al. (2000), however, found challenges in identifying the bankfull stage due to dense vegetation and historical channel modifications, providing a more generalized model for the North Carolina mountainous regions. Both studies underscore the importance of localized data for stream restoration (Harman et al. 2000; Henson, Kolawole, and Ayeni 2014).

In contrast, Zink, Jennings, and Alexander Price (2012) and Leigh (2010) focus on the influence of land use and forest conditions on stream morphology. Zink, Jennings, and Alexander Price (2012) examined streams in largely undisturbed wilderness areas, such as the Joyce Kilmer and Slickrock Wilderness, and identified correlations between bankfull cross-sectional dimensions and drainage area, while also considering the impact of slope and bed morphology. This study emphasizes the stability of streams in old-growth forests, suggesting that these environments maintain high-quality aquatic habitats. Leigh (2010), on the other hand, highlights the effects of deforestation, noting that forested stream reaches tend to be much wider than those in grassland areas. Leigh's findings underscore the importance of riparian forest restoration in stream management, as deforestation significantly reduces in-stream habitat (Leigh 2010; Zink, Jennings, and Alexander Price 2012).

Despite the different focuses, these studies converge on the need for region-specific data in stream restoration efforts. Henson, Kolawole, and Ayeni (2014) and Zink, Jennings, and Alexander Price (2012) both emphasize the complexity of the Southern Appalachian region's geomorphology, with Henson, Kolawole, and Ayeni (2014) focusing on high-precipitation areas and Zink, Jennings, and Alexander Price (2012) addressing the unique conditions of wilderness streams. W. A. Harman et al. (2000) provides more generalizable models but acknowledges the difficulties in applying them across varied terrains. Bieger et al. (2015) extends these findings by comparing regional and nationwide curves, concluding that region-specific models offer more accurate predictions for stream restoration across physiographic regions, reinforcing the conclusions drawn by earlier studies (Bieger et al. 2015).

10 Phases of the NCD Process

Rosgen (2011) outlines ten distinct phases in the NCD methodology, which guide practitioners from setting initial objectives to implementing and monitoring a completed restoration. Each phase builds upon field data, geomorphic assessments, and hydraulic models to ensure the restored stream is self-sustaining.

Phase one is defining the restoration objectives, which involves collaborating with stakeholders and regulatory agencies to set clear and measurable goals for the project (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020). These objectives may focus on improving ecological function, stabilizing channel form, or enhancing water quality. The definition of these goals must be rooted in a thorough understanding of the stream's context within the watershed while ensuring the restoration meets the needs of both the environment and the stakeholders(Doll et al. 2003; Clewell and Aronson 2013; Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020).

Phase two involves conducting a field-based assessment of the existing stream reach, including collecting geomorphic, hydrologic, and ecological data (Doll et al. 2003; Rosgen 2011; Harman W. A. and Starr 2011; Yochum and Reynolds 2020). The information gathered is essential for developing a comprehensive understanding of the stream's current condition, including its sediment transport capacity, bank stability, and riparian vegetation health (Doll et al. 2003; Fripp, Robinson, and Bernard 2007b; Rosgen 2011; Yochum and Reynolds 2020).

Phase three involves conducting a comprehensive watershed and river assessment, which is essential for identifying the underlying causes of stream degradation. This assessment ensures that restoration efforts tackle both reach-specific and watershed-wide issues (Fripp, Robinson, and Bernard 2007b; Harman W. A. and Starr 2011; Rosgen 2011). Additionally, it aims to address upstream and downstream factors that may affect the project's success while aligning restoration efforts with broader hydrologic and geomorphic patterns (Fripp, Robinson, and Bernard 2007b; Yochum and Reynolds 2020).

Phase four focuses on identifying a reference reach, if one is available. An ideal reference reach should demonstrate the characteristics that the restoration project aims to replicate (Doll et al. 2003; Fripp, Robinson, and Bernard 2007b; Rosgen 2011; Yochum and Reynolds 2020). These reference reaches act as blueprints for designing the proposed reach, enabling practitioners to model stable channel dimensions, patterns, and profiles. If a direct reference reach is unavailable, regional hydraulic geometry curves derived from multiple reference sites can be utilized as an alternative (Harman W. A. and Starr 2011; Yochum and Reynolds 2020).

Phase five involves the collection of essential field data to support the design of the proposed reach. This includes measurements of channel dimensions, flow data, sediment loads, and vegetation types. A total of over 67 variables must be gathered to provide a comprehensive understanding of various geomorphic and ecological parameters (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020). These measurements are critical and must be detailed to ensure that the proposed reach will function similarly to the reference reach (Doll et al. 2003; Harman W. A. and Starr 2011; Rosgen 1996; 2011; Yochum and Reynolds 2020).

In phase six, the proposed design reach is developed by applying data from the reference reach or regional curves, ensuring that the restored stream will remain stable under both current and future conditions (Rosgen 2011). During this design stage, key techniques from NCD will be considered, advocating for the use of natural materials in bank stabilization efforts instead of engineered solutions (Beechie et al. 2010; Doll et al. 2003; Harman W. A. and Starr 2011). This approach promotes a more organic integration with the surrounding environment. Stream patterns and movements will be delineated based on stream typology, allowing for customization to the inherent characteristics of each waterway (Doll et al. 2003; Harman W. A. and Starr 2011; Rosgen 1996; 2011). Additionally, the reconnection of floodplains will be emphasized as a crucial element, enabling streams to overflow into their floodplains during peak flows, which aids in flood mitigation, water quality enhancement, and habitat connectivity (Beechie et al. 2010; Rosgen 2011; Yochum and Reynolds 2020). Hydraulic and sediment transport models will also be employed to assess the design's hydrologic and geomorphic stability across a range of flow conditions (Harman W. A. and Starr 2011; Rosgen 1996; 2011).

Phase seven marks the final design and approval process following the validation of the initial design through modeling (Rosgen 2011). This phase includes the creation of detailed engineering drawings, cost estimates, and construction plans. Through interdisciplinary collaboration, it integrates the geomorphic, hydraulic, and ecological functions of the stream to ensure its long-term success (Doll et al. 2003; Harman W. A. and Starr 2011; Yochum and Reynolds 2020).

Phase eight is the construction and implementation of the design (Rosgen 2011). This includes installing in-stream structures, such as J-hooks, vanes, and other features designed to enhance channel stability and habitat diversity (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020).

Phase nine focuses on post-project monitoring, which is crucial for confirming that the restored stream is functioning as intended (Rosgen 2011). This monitoring includes the evaluation of key indicators such as bank stability, sediment transport, and habitat quality. Implementing adaptive management strategies is essential during this phase, allowing for real-time modifications and adjustments to enhance the performance of the restored stream (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020).

Phase ten, the final phase of NCD, involves long-term monitoring to ensure the restored reach remains stable and ecologically functional (Rosgen 2011). This phase may involve periodic evaluations of sediment dynamics, vegetation growth, and channel stability over years or decades (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020). Long-term monitoring also helps build the knowledge base for future NCD projects by providing valuable data on the long-term success of restoration designs (Rosgen 2011; Yochum and Reynolds 2020).

Ecological Benefits of Natural Channel Design

Natural Channel Design (NCD) offers significant ecological benefits by prioritizing the use of natural materials in bank stabilization and promoting a holistic integration with the surrounding environment. By employing techniques that align with the fundamental characteristics of each waterway, NCD helps preserve and enhance natural stream patterns and movements, which are critical for maintaining ecological integrity (Fripp, Robinson, and Bernard 2007b; Rosgen 1996; 2011). One of the key strategies of NCD is reconnecting floodplains, allowing streams to overflow into these areas during peak flows. This reconnection not only aids in flood mitigation but also enhances water quality and promotes habitat connectivity, ultimately supporting diverse aquatic and terrestrial ecosystems (Beechie et al. 2010; Fripp, Robinson, and Bernard 2007b).

Furthermore, NCD emphasizes the customization of restoration efforts based on stream typology, ensuring that interventions are tailored to the specific ecological needs of each site (Harman W. A. and Starr 2011; Rosgen 1996; 2011; Yochum and Reynolds 2020). This approach fosters the resilience of aquatic habitats and improves the overall health of riverine ecosystems by restoring natural processes and functions (Harman W. A. and Starr 2011; Rosgen 2011). As a result, NCD not only addresses immediate environmental concerns but also contributes to long-term ecological stability and biodiversity within the landscape.

Economic Benefits of Natural Channel Design

Natural Channel Design (NCD) presents significant economic benefits alongside its ecological advantages. By restoring stream stability and preventing future degradation, NCD projects can reduce long-term maintenance costs, protect infrastructure, and enhance property values (Rosgen 2011; Yochum and Reynolds 2020). The method's emphasis on sustainable design contributes to vital ecosystem services that yield long-term economic returns, such as flood mitigation and water quality improvement (Rosgen 1996; Wohl, Lane, and Wilcox 2015).

One of the primary economic advantages of NCD is its capacity to create self-sustaining systems that minimize the need for ongoing maintenance (Doll et al. 2003; Yochum and

Reynolds 2020). Unlike traditional engineered solutions, which often require frequent repairs due to erosion or sediment buildup, NCD designs mimic natural processes, leading to stable channels that adapt to changing hydrologic conditions (Doll et al. 2003; Rosgen 1996; 2011; Harman W. A. and Starr 2011). This results in significant cost savings for municipalities and landowners. Additionally, by stabilizing streambanks and enhancing floodplain connectivity, NCD protects infrastructure from flood damage, while techniques like vanes and grade-control structures direct flow away from vulnerable areas, contributing to the longevity of public and private investments (Yochum and Reynolds 2020).

Moreover, NCD can enhance the economic value of properties adjacent to restored waterways by improving landscape aesthetics and increasing recreational opportunities (Fripp et al. 2009). The stabilization of streambanks and reduction of flood risks further contribute to the desirability of these properties. NCD also provides valuable ecosystem services, such as mitigating flood risks and improving water quality, which can lead to long-term economic benefits for communities reliant on clean waterways (Wohl, Lane, and Wilcox 2015). By focusing on restoring natural processes, NCD projects create sustainable solutions that provide both immediate and long-term economic returns.

Criticism of NCD

Although Natural Channel Design (NCD) is widely used for stream restoration projects, its methodology has not been without criticism. Despite its ecological and economic benefits, many researchers and practitioners have expressed concerns about its reliance on form-based models, lack of process-based analysis, and broad application across diverse geomorphological contexts.

One of the central criticisms of NCD is its focus on restoring the physical form of streams, such as dimensions, pattern, and profile, without adequately addressing the dynamic processes that shape stream behavior over time (Lave 2009; A Simon et al. 2007). By prioritizing form over function, critics argue that NCD simplifies complex fluvial systems and overlooks critical elements like sediment transport dynamics, changing flow regimes, and feedback loops between the stream and its watershed (Lave 2009; A Simon et al. 2007). This form-based approach can lead to designs that are not resilient to environmental changes, particularly in systems experiencing rapid land-use changes or climatic variability (Wohl, Lane, and Wilcox 2015).

In a related critique, researchers argue that NCD's methodology often focuses on restoring a static snapshot of a stable reference reach, rather than accommodating the processes that drive channel evolution over time (Kasprak et al. 2016; A Simon et al. 2007). Rivers, by nature, are dynamic systems that respond to changes in sediment supply, flow patterns, and watershed characteristics. Because of this, NCD's form-based models may not fully capture how these systems will respond to future disturbances. This limitation is made worse by NCD's heavy reliance on selecting an appropriate reference reach. Poor selection can lead to channel degradation and ecological imbalances (Hey 2006; Rosgen 2008; A Simon et al. 2007; Wohl, Lane, and Wilcox 2015). A failure to account for future changes in land use, sediment loads, and hydrology, may lead to NCD restorations becoming misaligned with the dynamic nature of river systems (A Simon et al. 2007; Wohl, Lane, and Wilcox 2015).

Another concern involves the broad application of NCD across various geomorphological contexts. While Rosgen's classification system, which forms the foundation of NCD, is designed to be universally applicable, some researchers argue that it oversimplifies complex stream systems. In regions where natural stream processes don't align with these classifications, restoration projects may be at a higher risk of failure (A Simon et al. 2007). This is especially true in heavily modified landscapes, where the assumptions underpinning NCD don't always hold, leading to inconsistent success rates (Lave 2009). Numerous cases have shown NCD projects failing to achieve long-term stability or ecological success, especially when the reference reach approach was misapplied or watershed conditions weren't adequately considered (A Simon et al. 2007).

In light of growing environmental challenges, NCD has been criticized for not adequately preparing restoration projects for future climate changes or shifts in surrounding ecosystems (A Simon et al. 2007; Wohl, Lane, and Wilcox 2015). Its reliance on static models and historical reference reaches often leaves designs vulnerable to the unpredictable nature of climate variability, land use changes, and evolving watershed conditions(Kasprak et al. 2016; A Simon et al. 2007). However, phase 10 of NCD, which focuses on adaptive management, offers a critical opportunity to address these concerns (Wohl, Lane, and Wilcox 2015). By actively monitoring and adjusting restoration strategies as new environmental data emerges, this phase provides the flexibility needed to ensure that NCD projects can remain resilient in the face of future uncertainties (Yochum and Reynolds 2020).

Best Management Practices for Pastureland and Streams

Overview

Effective management of cattle pastureland and stream ecosystems is essential for maintaining soil integrity, water quality, and livestock productivity (Agouridis et al. 2005; NRCS 2023a; D. L. Osmond 2023). Best management practices (BMPs) focus on balancing productive grazing with environmental conservation. Rotational grazing systems support forage regrowth, maintain soil structure, and mitigate erosion, while buffer strips positioned between pastureland and streams serve to capture runoff and provide additional ecological benefits, such as maintaining cooler water temperatures (Agouridis et al. 2005; NRCS 2009b; 2023a).

In terms of stream and riparian zone management, fencing livestock away from streams and providing alternative watering systems are key strategies for preventing erosion and contamination (Daniel E Line, Osmond, and Childres 2016; D. L. Osmond 2023). Riparian buffers, comprising trees and shrubs, stabilize streambanks and absorb excess nutrients before they can degrade water quality (King et al. 2016; NC DEQ 2016; D. L. Osmond 2023). While BMPs offer clear advantages for both the environment and livestock production, their adoption can be challenging due to the financial and logistical demands, particularly for small farms. To offset these challenges, the U.S. Department of Agriculture (USDA) and the Natural Resources Conservation Service (NRCS) offer several programs to support farmers in implementing sustainable practices (NRCS 2022c).

U.S. Department of Agriculture (USDA) and Natural Resources Conservation Service (NRCS) Overview

The U.S. Department of Agriculture (USDA) and the Natural Resources Conservation Service (NRCS) play a key role in helping farmers restore streams on pasturelands, including those used for cattle operations. They offer a mix of financial assistance, technical advice, and conservation planning to help farmers balance agricultural productivity with protecting the environment (NRCS 2022b; 2009a). Their efforts aim to protect streams and riparian ecosystems from damage while still allowing farmers to keep their lands productive (NRCS 2009a; 2022b).

In 1935, the NRCS was created by the USDA in response to the dustbowl to address widespread soil erosion (NRCS 2022a). The NRCS operates as a branch of the USDA, with a focus on sustainable agricultural practices and land stewardship (Moore 2023). Both agencies work closely to provide financial and technical support to farmers, particularly in the area of conservation and environmental management. While the USDA oversees a broad range of agricultural services, the NRCS specializes in conservation, offering smaller-scale, targeted programs to help small farms with land improvements, including stream restorations. The key difference lies in their scope as the USDA has a wider agricultural authority, while NRCS is more focused on natural resource conservation, particularly soil, water, and ecosystems (NRCS 2022b).

USDA and NRCS Programs for Pastureland and Stream Restorations

Through the funding of the USDA, the NRCS offers several programs for farmers that provide financial incentives to participate in sustainable farming practices. While these programs may vary by state to address specific agricultural needs, local agricultural extensions collaborate with the NRCS to ensure that the programs effectively meet the needs of their communities (Moore 2023). In North Carolina, the N.C. Cooperative Extension serves farmers across the state, including those in the Western North Carolina region (Moore 2023). Farmers can participate in a variety of federally funded, voluntary programs aimed at pastureland management and stream restoration, such as the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP) (NRCS 2009a). Additionally, state-funded initiatives are available for North Carolina farmers through the North Carolina Department of Agriculture and Consumer Services. These programs include the Agriculture Cost Share Program (ACSP) and the Agricultural Water Resources Assistance Program (AgWRAP), which not only help farmers improve water quality on their land but also contribute to broader efforts to enhance water quality across the state (N.C. Division of Soil and Water Conservation: 2023).

Each of these programs, both state and federal, assists farmers in establishing Best Management Practices (BMPs) on their land, designed to the specific needs of each farm. The NRCS provides Conservation Practice Standards (CPS) to ensure that each BMP is implemented consistently and aligns with federal environmental goals. These standards are science-based guidelines designed to address key resource concerns such as soil health, water conservation, and biodiversity. To account for regional variations, they are localized through Field Office Technical Guides (FOTGs), which adapt the standards to local environmental conditions and agricultural practices (NRCS 2020a).

To qualify for funding, farmers must develop a conservation plan in collaboration with local NRCS staff. During this process, they identify environmental challenges on the property and outline the necessary practices to address them. Specific BMPs are selected to address these challenges, then each BMP is further detailed through CPS to ensure all aspects are being addressed (NRCS 2020a). Once the necessary standards are confirmed, the plan can be submitted to programs such as the Environmental Quality Incentives Program (EQIP) and Agricultural Cost Share Program (ACSP) which can fund up to 75% of the upfront costs (NRCS 2009a). However, the plan then goes through an application process where the NRCS uses the Conservation Assessment Ranking Tool (CART) to evaluate applications based on environmental benefits, resource concerns, and project feasibility. Applications are ranked competitively, and only the highest-scoring projects receive funding (NRCS 2020a).

NRCS BMPs for Stream Restoration on Cattle Pastureland

NRCS BMPs for stream restoration on cattle pastureland focus on reducing sediment and nutrient runoff, stabilizing streambanks, and protecting water quality through measures like exclusion fencing, riparian buffer restoration, and in-stream enhancements(NRCS 2009b; 2023a). Each of these BMPs correlates with specific CPS and their subsequent FOTGs. The primary NRCS BMPs and CPS for stream restoration on pasturelands include:

- Livestock exclusion fencing (NRCS CPS 382 – *Fence*) which prevents cattle from accessing streams thereby reducing bank erosion, sediment deposition, and the transfer of pathogens and nutrients like nitrogen and phosphorus, while allowing vegetation regrowth along streambanks (NRCS 2021b).
- Riparian Buffer Establishment (NRCS CPS 391 - *Riparian Forest Buffer*) is instrumental in filtering runoff, stabilizing streambanks, and providing wildlife habitat by planting native tree and shrub species selected based on site conditions, with buffers designed to reduce pollutant load, including up to 50% reductions in nitrogen and phosphorus (NRCS 2020c).
- Streambank Stabilization (NRCS CPS 580 - *Streambank and Shoreline Protection*) uses bioengineering techniques and structural measures like log vanes, cross vanes, and rock sills to stabilize eroding streambanks by considering the stream's hydrological and geomorphological characteristics, managing sediment transport, reducing erosion, and improving habitat diversity (NRCS 2020e).
- In-Stream Restoration (NRCS CPS 584 - *Channel Bed Stabilization*) involves reshaping degraded stream channels using form-based processes, incorporating structural elements

to dissipate energy, improve sediment transport, and manage stream flow, particularly in areas where cattle have caused significant channel degradation (NRCS 2021a).

- Stream Crossing (NRCS CPS 578- *Stream Crossing*) provides guidelines for creating stable, low-impact crossings in pastures, using structures like culverts or reinforced rock crossings to prevent streambank damage, reduce erosion, and minimize sedimentation while allowing livestock passage (NRCS 2022e).
- Access Control (NRCS CPS 472- *Access Control*) limits livestock access to sensitive areas like riparian zones and streambanks, preventing overgrazing, minimizing soil compaction and erosion, and enhancing stream restoration efforts when combined with exclusion fencing (NRCS 2017a).
- Watering Facility (NRCS CPS 614- *Watering Facility*) provides alternative water sources, such as tanks, troughs, or ponds, to ensure livestock have clean, accessible water away from streams, reducing cattle access to waterways and protecting water quality (NRCS 2023c).
- Filter Strips (NRCS CPS 393- F*ilter Strips*) are areas of herbaceous vegetation planted between pastureland and streams to trap sediment, nutrients, and pollutants, reducing runoff and nutrient loading from manure while complementing riparian buffer zones (NRCS 2016b).

The aforementioned NRCS BMPs are among the most frequently applied in stream restoration on cattle pastureland, though they do not represent the full range of possible practices. However, their consistent and widespread use has provided a foundation for understanding their impact on stream health in this setting. As these methods are implemented and evaluated, they present an opportunity to assess their effectiveness on long-term stream viability and water quality.

Watershed and Hydrologic Modeling Tools to Evaluate Stream Restorations

Overview

Watershed and hydrologic modeling tools such as Soil and Water Assessment Tool (SWAT), Revised Universal Soil Loss Equation (RUSLE), Hydrologic Engineering Center's River Analysis System (HEC-RAS), Pollutant Load Estimation Tool (PLET), and Spreadsheet Tool for Estimating Pollutant Load (STEPL) are integral to the NRCS and USDA's mission of managing water resources and promoting sustainable agricultural practices. These tools are often used in evaluating the potential efficacy of stream restoration projects to determine whether the project should be prioritized for funding via the NRCS Conservation Assessment Ranking Tool (CART).

Watershed Modeling Tools Comparison

Although each of these models aims to manage watersheds and water quality by assessing the impacts of land use, conservation practices, and hydrological processes on water resources, they differ in complexity, scale, and specific functions. SWAT is a comprehensive, physically based model that simulates the effects of land management on water, sediment, and agricultural chemical yields in complex watersheds, integrating processes like runoff, evapotranspiration, and groundwater flow for versatile long-term simulations (Arnold et al. 1998; Gassman et al. 2007; USDA 2024). RUSLE is an empirical model for estimating soil erosion by water, improving on the original USLE with more advanced calculations for factors like rainfall intensity, soil properties, topography, and land cover, with its latest upgrade, RUSLE2, offering further enhancements in accuracy and usability (USDA and NRCS 2024).

HEC-RAS is a hydraulic model that simulates water flow in both natural and man-made channels, specializing in river hydraulics, including flow profiles, floodplain mapping, and sediment transport (Brunner 2016). PLET and STEPL are user-friendly, empirical modeling tools used to calculate nutrient, and sediment loads from different land uses and the load reductions resulting from implementing various BMPs (US EPA 2021; 2022b; 2022c). However, with STEPL set to retire in 2024 and fully replaced by PLET as a more accessible and accurate modeling system, this review will exclude STEPL from comparisons of modeling tools for stream analysis, as its approaching phase-out lessens its relevance in the current context (US EPA 2021; 2022b).

Selecting Watershed Modeling Tools

Selecting the right model to determine the efficacy of various projects, such as watershed restoration, soil conservation, or pollutant reduction, depends on several key factors including project scale, type of outcomes desired, complexity of the system, and data availability.

One of the key considerations when selecting a model is the scale of the project. SWAT is a widely preferred option for large-scale watershed initiatives requiring detailed simulations of hydrology, pollutant transport, and long-term water quality impacts (Arnold et al. 1998; Gassman et al. 2007). In contrast, for smaller-scale projects centered on soil conservation, RUSLE2 is more appropriate, as it predicts soil erosion at the field level and helps design conservation practices (USDA and NRCS 2024).

For small to medium-sized watersheds, PLET offers a simple, user-friendly tool for estimating sediment and nutrient loads, as well as modeling pollutant transport across diverse landscapes at a regional scale, making it ideal for BMP-focused projects (US EPA 2022b). Finally, HEC-RAS is suited for projects requiring detailed hydraulic analysis, such as flood control or river restoration, due to its capability to simulate river flow and floodplain dynamics (Brunner 2016).

The desired outcomes of a project, whether improving water quality, reducing flood risk, or conserving soil, are key factors in model selection. For projects focused on reducing pollutant loads, PLET is effective in estimating pollutant loads from various land-use practices and evaluating the impact of BMPs on reducing nutrient and sediment pollution (US EPA 2022b). For flood risk mitigation, HEC-RAS excels due to its ability to simulate detailed water levels, flow velocities, and flood extents, while SWAT is better suited for larger-scale runoff analysis (Brunner 2016; Arnold et al. 1998; USDA 2024). For soil conservation, RUSLE2 is the preferred model, as it quantifies soil erosion and informs conservation practices aimed at reducing erosion (USDA and NRCS 2024).

Other considerations for selecting a model are data requirements and model complexity. SWAT, for instance, requires extensive inputs like weather, soil properties, topography, and land-use data, making it suitable for projects with significant data resources (Arnold et al. 1998; Gassman et al. 2007). In contrast, simpler models like PLET and RUSLE2 require less input data. PLET uses readily available data and simplified assumptions for pollutant load estimations, while RUSLE2 relies mainly on local soil, rainfall, and topography data, making them accessible for projects with limited data availability (US EPA 2022b; USDA and NRCS 2024). PLET, as an empirical model, is user-friendly and ideal for projects focused on cost-effective pollutant load reductions at a local level (US EPA 2022b).

Comparing Watershed Modeling Tools for Agricultural Runoff Management

In the context of agricultural runoff management, choosing the right modeling tool is critical to accurately assess the impact of land-use practices, predict pollutant loads, and implement effective restoration measures. For projects addressing non-point source pollution from large agricultural areas, SWAT excels at quantifying runoff, sediment loss, and nutrient loading under varying land use and climate conditions (USDA 2024). However, its high data requirements and complexity can be a limitation for small-scale or resource-constrained projects (Arnold et al. 1998; Gassman et al. 2007). In contrast, RUSLE2 offers a more straightforward, empirical approach for estimating soil erosion, making it ideal for field or plot-level conservation planning where soil loss due to runoff is the primary concern (USDA and NRCS 2024). While RUSLE2 is limited to erosion prediction and lacks the comprehensive water quality modeling of SWAT, it is easier to apply in smaller, targeted agricultural restoration contexts and is extensively used by the NRCS for soil conservation planning (USDA 2024; USDA and NRCS 2024).

For projects focused on floodplain restoration or hydraulic flow modeling, HEC-RAS is the preferred tool due to its precision in simulating river dynamics and flood risks, though its focus on hydraulic analysis limits its broader watershed management applications (Brunner 2016). For estimating pollutant loads from agricultural runoff, PLET is a well-suited, simplified model. It effectively assesses watershed-specific nutrient and sediment loads, helping to identify critical pollutant source areas and allowing non-specialist users to evaluate BMPs quickly (US EPA 2022b; 2022c). However, its simplicity limits its precision and applicability to more complex hydrological projects (US EPA 2022b). Ultimately, the choice of model depends on the project's scale and focus, from SWAT's comprehensive analysis to more targeted and accessible options like RUSLE2 and PLET.

Literature Gaps

Despite the growing body of research on agricultural impacts on stream health, small-scale, family-owned cattle farms remain underrepresented in studies focused on stream restoration. These farms face unique challenges, including limited resources and infrastructure, which can intensify water quality issues and hinder the implementation of effective restoration practices (Bracmort et al. 2004). Furthermore, the adoption of Best Management Practices (BMPs) is often inconsistent due to social and economic barriers, particularly for small farmers who may lack access to financial assistance or knowledge of available support programs (Rhodes, Leland, and Niven 2002). Addressing these gaps is fundamental to improving water quality and promoting sustainable farming practices in regions like Western North Carolina.

While extensive research exists on the impact of large-scale agricultural practices on stream degradation, there is a significant gap in the literature regarding small-scale, family-owned cattle farms and their role in stream restoration. Most studies focus on either urban restoration efforts or large-scale agricultural operations, often overlooking the unique challenges and contributions of smaller farms, particularly in regions like Western North Carolina. Small farms may lack the resources and infrastructure that larger farms possess, leading to more water quality issues and environmental degradation. These farms often operate on tighter budgets, often with limited access to government support or technical expertise, which can hinder the implementation of Best Management Practices (BMPs) such as riparian buffer zones, controlled livestock access, and nutrient management plans (Agouridis et al. 2005; D. L. Osmond 2023). Given that small farms comprise a substantial portion of agricultural activity in areas like the French Broad River Basin, further research is needed to understand how BMPs can be tailored and implemented effectively on these smaller, family-run operations.

Another critical gap in the literature is the inconsistent adoption of BMPs due to social and economic barriers faced by these small-scale farmers. While BMPs, such as riparian buffers and livestock exclusion, have been widely recognized for their effectiveness in improving water quality and reducing sedimentation, their adoption remains voluntary and is often further undermined by financial constraints (Bracmort et al. 2004; Rhodes, Leland, and Niven 2002). Programs through the USDA and NRCS, like the Environmental Quality Incentives Program (EQIP) and Conservation Stewardship Program (CSP), offer financial incentives to implement these practices (NRCS 2009a; USDA 2023). However, small farmers may lack awareness about or access to these programs, and even when they do, the initial costs of measures such as fencing or streambank stabilization can remain prohibitive, despite the financial assistance (Bracmort et al. 2004). Additionally, while many farmers may recognize the long-term economic benefits of BMPs, such as improved pasture productivity and reduced erosion, the delayed return on investment often makes it difficult for them to prioritize these practices, as they face immediate pressures to maintain current yields (Bracmort et al. 2004; Liu, Bruins, and Heberling 2018; D. L. Osmond 2023). Ultimately, there is a need for more research into how educational outreach, economic incentives, and policy adjustments can address these barriers and promote wider BMP adoption among small-scale cattle farmers.

CHAPTER 3

METHODS AND PRELIMINARY RESULTS

Overview

This thesis integrates the principles of Natural Channel Design (NCD), following the 10 phases outlined by Rosgen (1996), and the Natural Resource Conservation Service (NRCS) Best Management Practices (BMPs) in a case study for a small cattle farm in Western North Carolina to develop a comprehensive stream restoration plan. The primary goal of this plan was to provide a proposal design to enhance stream function and improve water quality by reducing sedimentation, nutrient runoff, and streambank erosion caused by cattle access. The methodology involved detailed site assessment, geomorphic and hydrological data collection, and the application of both structural and non-structural BMPs to stabilize the stream and restore its ecological function. The project specifically followed NRCS Conservation Practice Standards (CPS) to guide the implementation of these BMPs in tandem with NCD techniques to ensure a sustainable and effective restoration process.

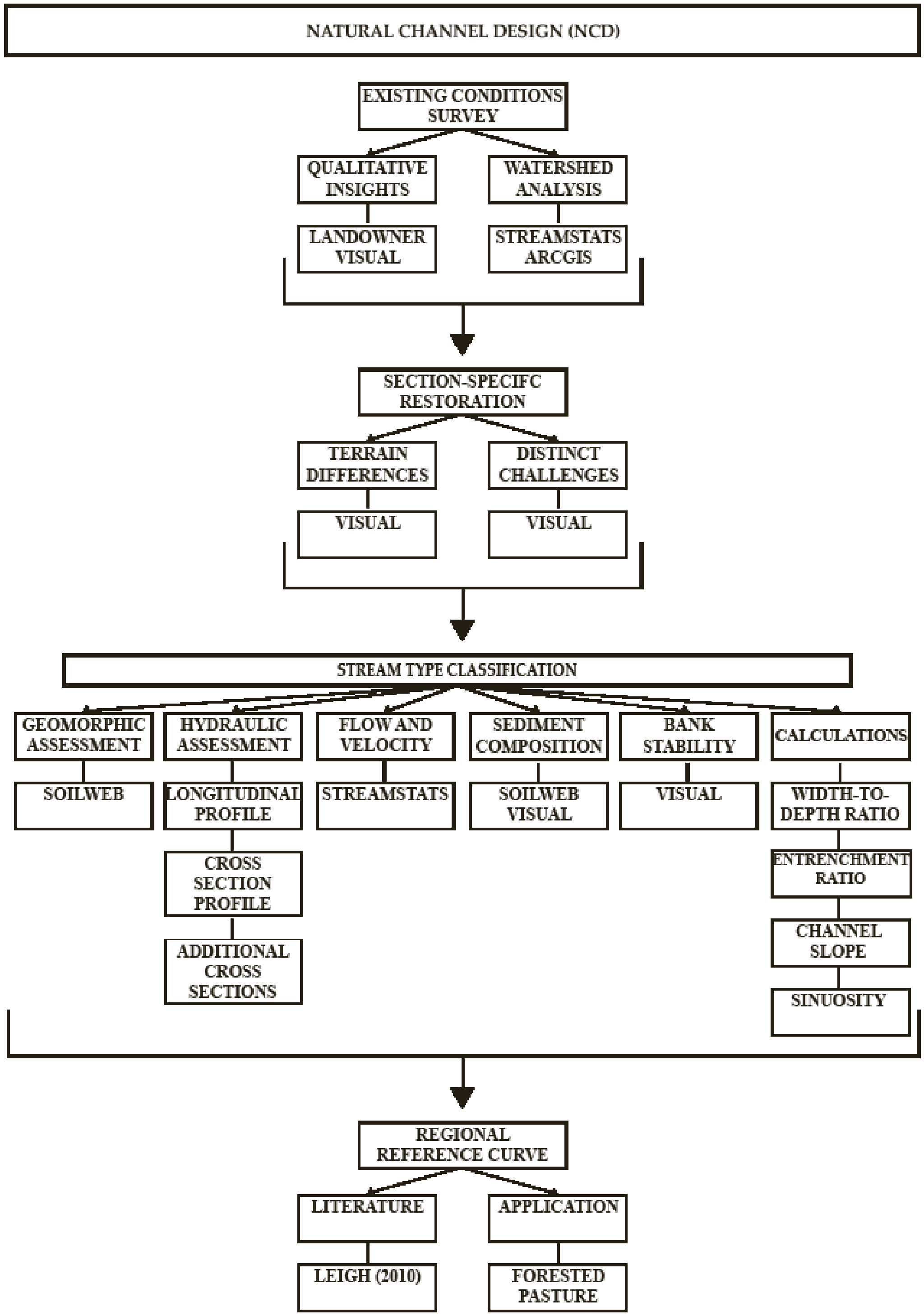


Figure 1. Flow chart of methods used to determine Natural Channel Design parameters for stream restoration. Chart by author.

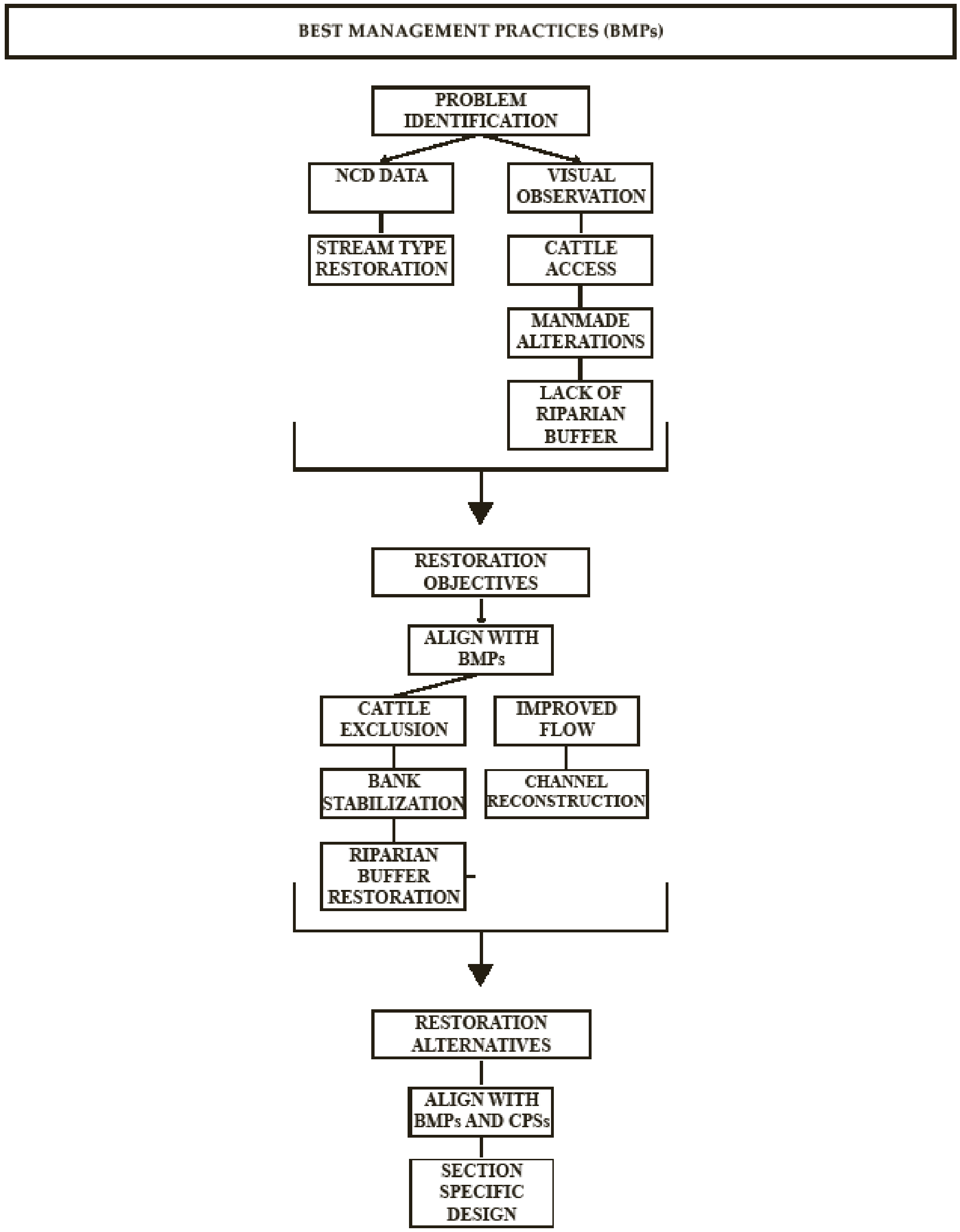


Figure 2. Flow chart of methods used to determine Best Management Practices for farm design. Chart by author.

Figures 1 and 2are flow charts that illustrate a structured, data-driven approach to stream restoration on agricultural land, providing an overview of the methods used in this project and detailing both the NCD and BMP frameworks. The NCD chart outlines a step-by-step process, starting with the primary stages of Existing Conditions Survey, Section-Specific Restoration, Stream Type Classification, and Regional Reference Curve Application. Each stage is further broken down into focus areas, supported by specific techniques or tools, demonstrating a progression from broad goals to detailed methods. This layered structure provides a clear and logical flow, showing how each primary stage is systematically supported by increasingly focused steps and methodologies.

The BMP chart complements this by presenting the restoration approach in a three-tiered format. The primary steps, Problem Identification, Restoration Objectives, and Restoration Alternatives, represent the main stages of the BMP framework. Each stage is then broken down into specific factors and objectives, such as identifying degradation causes and establishing objectives like Cattle Exclusion and Channel Reconstruction. The final level details the techniques, standards, and alignments that guide these objectives, including assessment tools and adherence to BMPs and CPS for section-specific design solutions. This layered structure ensures each restoration step is both problem-focused and standards-driven, creating a comprehensive and systematic approach to stream restoration.

Existing Conditions Survey

Overview

The initial phase of the project involved a comprehensive existing-conditions survey, an essential process in both NCD and NRCS guidelines. This process involved a combination of qualitative insights, direct field observations, and quantitative data collection through mapping tools like StreamStats and ArcGIS. Following both NCD and NRCS BMPs, the survey focused on understanding the human-induced impacts on the stream and identifying key areas of concern for the proposed restoration (NRCS 2020a; Rosgen 1996; 2011). Engaging local knowledge from the landowner and using both qualitative and quantitative data collection ensured a well-rounded assessment of the stream and its surrounding environment, in line with both NCD and NRCS recommendations (Doll et al. 2003; Fripp, Robinson, and Bernard 2007c; Harman W. A. and Starr 2011; Rosgen 1996; 2011; Yochum and Reynolds 2020).

Landowner Insights and Visual Site Observations

Gathering the landowner's insights through informal interviews and site walks was essential to the survey process, as recommended by both NCD and NRCS. Stakeholder engagement is emphasized in both frameworks, offering critical historical context and ensuring that restoration efforts align with practical land use needs (Harman W. A. and Starr 2011; Rosgen 2011; Yochum and Reynolds 2020). The landowner's observations about structural changes which included the straightening of the stream channel, the introduction of obstructions such as logs, boulders, and outdated equipment, and the installation of 36-inch corrugated pipes for crossings, were key to understanding how the stream has evolved over time. This aligns with Rosgen's NCD process, which highlights the importance of recognizing past human modifications when assessing stream morphology (Doll et al. 2003; Harman W. A. and Starr 2011; Rosgen 1996; 2011; Yochum and Reynolds 2020). The landowner also shared insights into the property's history, noting that it transitioned from a homestead to a cattle farm in the 1970s (Landowner 2022). This background is critical for understanding current sediment and nutrient loading, especially given that the land was clear-cut to create pasture, often a primary cause of erosion and riparian zone degradation, which NRCS guidelines aim to address with targeted BMPs (Doll et al. 2003; Fripp, Robinson, and Bernard 2007c; Harman W. A. and Starr 2011; Rosgen 2011).

To complement these insights, visual observations were conducted to assess the stream's physical condition and its surroundings. This hands-on approach, recommended by both NCD and NRCS, allowed for the direct identification of degradation indicators like bank erosion, sedimentation, and loss of riparian vegetation (Doll et al. 2003; Fripp, Robinson, and Bernard 2007c). Specific attention was paid to signs of heavy livestock use, such as trampled vegetation, cattle trails, and waste found within 5-10 feet of the stream. These observations are consistent with NRCS guidelines, which stress the importance of identifying areas impacted by livestock when planning BMPs like exclusion fencing and riparian buffer zones (NRCS 2020a; Fripp, Robinson, and Bernard 2007c; Yochum and Reynolds 2020). The upper portion of the stream is in moderately a forested area, while the lower section is fully exposed to sunlight and lacking riparian buffer. This absence of vegetation increased the vulnerability to erosion and nutrient loading, in line with NCD's focus on maintaining stable riparian zones to enhance water quality and streambank stability (Doll et al. 2003; Harman W. A. and Starr 2011; Fripp, Robinson, and Bernard 2007c; Rosgen 1996; 2011; Yochum and Reynolds 2020). These visual assessments reinforced the need for interventions like vegetative buffers, which are strongly recommended in both frameworks.

Watershed Analysis

The watershed analysis was conducted using StreamStats and ArcGIS, both tools recommended by NRCS for assessing watershed characteristics and drainage area size (Fripp, Robinson, and Bernard 2007b; 2007c). StreamStats, developed by the USGS, provided critical flow statistics and hydrological data, helping to delineate the watershed and calculate flow dynamics (U.S. Geological Survey 2019). Using these tools allowed for a more precise understanding of the stream's potential for sediment transport and nutrient loading, which aligns with NRCS's emphasis on incorporating hydrologic assessments into BMP planning (Fripp, Robinson, and Bernard 2007c; Rosgen 2011).

ArcGIS enabled a detailed overlay of the farm boundaries with the watershed data, offering a clearer view of how land use within the farm affected the stream (ESRI 2023). The analysis showed that the watershed and farm boundaries were largely consistent, except for a small section of the watershed extending into the neighboring Pisgah National Forest (ESRI 2023). Using data from the USDA's SSURGO (2019) database, a LiDAR vegetation cover index and slope map were generated through ArcGIS to further analyze the watershed (ESRI 2023). These datasets were vital for identifying areas with steep slopes and reduced vegetation cover which are common contributors to increased runoff and erosion in pasture-dominated landscapes (ESRI 2023; Fripp, Robinson, and Bernard 2007c; Yochum and Reynolds 2020).

Focusing on watershed characteristics like drainage area size, slope, and vegetation cover is in line with NRCS and NCD guidelines, both of which emphasize the need to understand these factors when designing effective restoration strategies (Doll et al. 2003; Fripp, Robinson, and Bernard 2007c; Rosgen 2011; Yochum and Reynolds 2020). These analyses provided the necessary baseline data to guide the proposed design of the stream restoration with NCD and NRCS principles in mind.

Stream Classification

Overview

In line with Rosgen's NCD methodology, I classified the stream into four distinct sections, W, X, Y, and Z, based on initial observations during the existing conditions survey. Rosgen's stream classification system provides a structured approach for assessing stream geomorphology by categorizing streams based on entrenchment ratio, width-to-depth ratio, sinuosity, and slope (Rosgen 1996; 2011). This classification system informed the division of the stream, allowing each section's unique characteristics to guide tailored restoration efforts (Rosgen 2011).

Sectioning the stream in this manner follows NCD's core principles of stream succession and acknowledges that streams may shift types due to disturbances such as sediment load or streambank erosion (Rosgen 2011). By identifying these distinct sections, the restoration strategy accounts for the natural variations in slope, vegetation cover, channel morphology, and sediment composition. The specific geomorphic features of each section guided the specific strategies needed to address issues like erosion, sedimentation, and degraded riparian zones. This approach adheres to both Rosgen's multi-stage restoration framework and NRCS's focus on addressing site-specific conditions (Doll et al. 2003; Fripp, Robinson, and Bernard 2007c; Rosgen 2011; Yochum and Reynolds 2020).

This classification enabled focused data collection and analysis, ensuring that the restoration strategies addressed the unique conditions of each section. It also facilitated the alignment of restoration goals, including reducing sediment loads, enhancing streambank stability, and improving overall stream function, with both NCD and NRCS guidelines.

Geomorphic Assessment

Building on the initial stream section distinctions, each section underwent a detailed geomorphic assessment using Rosgen's Level I and Level II classifications. This assessment focused on identifying key physical characteristics such as slope, valley type, sediment composition, and evidence of anthropogenic modifications (Rosgen 1996; 2011). By examining these features, I was able to better understand the current stability of the stream and the specific restoration needs of each section. The following descriptions provide an in-depth look at how these classifications informed the identification of distinct geomorphic traits in Sections W, X, Y, and Z.

Each section was classified using Rosgen's Level I and Level II classifications:

- Section W was characterized by a colluvial valley type confirmed by SoilWeb data from the USGS (UC Davis California Soil Resource Lab. 2023). This section had a mixed landscape, with forest on one side and pasture on the other. It began at a spring and featured ponding caused by a road built without an outlet, where cattle often stood. The streambed in this section was composed of mud, silt, and small debris, with some rocks scattered throughout.
- Section X had the steepest slope and was fully forested, with bedrock boulders embedded in the surrounding valley. The streambed in this section contained numerous rocks and pebbles, and another spring fed into the stream here. This section was visually distinct from the others due to its rocky streambed and forested surroundings.
- Section Y exhibited clear anthropogenic modifications, as confirmed by the landowner (Landowner 2022). It began after the stream passed through a 36" corrugated pipe and continued in a straight line without a riparian buffer. Cattle had direct access to the stream, and evidence of erosion and bank degradation was widespread. Large logs and other debris were also present, and the streambed consisted mainly of cobble and sand, marking a shift from the boulders and pebbles found in section X.
- Section Z, located in a floodplain, had a very low slope compared to the other sections and followed the road. This section had been straightened and deepened to maximize the adjacent pastureland. There were signs of a small wetland nearby, as indicated by a

change in vegetation and standing water. This section was primarily analyzed using ArcGIS and StreamStats due to time constraints, as it appeared visually consistent and heavily altered by human activities.

Hydraulic Assessment

For the hydraulic assessment, I followed Rosgen's NCD methodology, along with guidelines from Doll et al. (2003). This process involved determining the bankfull stage and measuring channel dimensions for sections W, X, and Y of the stream. Rosgen's principles for identifying bankfull indicators, such as scour lines, changes in vegetation, and terraces, were key to assessing stream stability and understanding flow dynamics (Rosgen 1996; 2011; W. Harman 2000). These methods ensured a more accurate classification of the stream's hydraulic characteristics.

For each section, I measured the length along the thalweg, following the guideline from Doll et al. (2003) that recommends a minimum length of 20 times the approximate bankfull width. In Section Y, the largest of the three, the bankfull width was approximately 5.6 feet, requiring a minimum length of 112 feet. However, to capture more topographical changes, I increased the measured length to 180 feet for each section. This increased length ensured that a comprehensive assessment of stream morphology was included.

Using an engineering tape measure, I laid the tape along the thalweg, securing it with rocks where necessary to maintain accuracy, as recommended by Doll et al. (2003). This approach allowed for consistent and precise measurements of stream length and the identification of key hydraulic features, such as riffles, to take cross-section measurements. After positioning the tape measure, I located prominent riffles within the section, which I used as locations for cross-sectional measurements. According to Doll et al. (2003), riffles are a reliable place to measure cross-sections, as they represent hydraulic controls within the stream system. However, due to the steep gradient of the stream and low flow conditions, no true pools were present in the surveyed sections, apart from the large pool at the end of Section W. Instead, I identified riffles based on noticeable shifts in water velocity and stream gradient, which corresponded to changes in the geomorphic structure of the stream. While Rosgen and Doll's methods encourage the use of riffle-pool sequences for identifying cross-section points, I adapted this methodology to fit the stream's physical limitations by marking clear changes in gradient or velocity as a new hydraulic feature (Doll et al. 2003; Rosgen 1996; 2011).

After marking the riffles, I continued with bankfull verification, primarily using physical indicators such as scour lines, bench markers, and vegetation lines, as recommended by Doll et al. (2003), Rosgen (2011), and W. Harman (2000). This process, however, was complicated by cattle access, which caused disturbances like trampling and erosion, creating false indicators that resembled natural bankfull markers. These false indicators posed a significant challenge in verifying bankfull stage in the field. Although these issues limited field verification, I successfully flagged bankfull stage at multiple points along the stream, and any inconsistencies were later addressed during the stream restoration design process.

For more detailed measurements, I employed a Leica Sprinter 150M Digital Level and a barcode leveling staff, following the procedures outlined in Doll et al. (2003) for channel slope determination This equipment enabled me to capture precise elevations along the thalweg, documenting channel slope at all marked riffles and other significant terrain changes, providing a comprehensive longitudinal profile of the stream channel.

In addition to measuring the longitudinal profile, one representative cross-section was selected in each section for detailed measurement, chosen for its typical stream characteristics rather than any exaggerated or narrowed features (Doll et al. 2003; Harman W. A. and Starr 2011; Rosgen 1996; 2011). At this representative cross-section, measurements were taken from past the top of the bank on one side to the other, capturing as many variations in topography as possible to accurately represent the full channel dimensions (Doll et al. 2003). Special attention was given to marking the top of bank, bankfull stage, top of water, and thalweg, with the thalweg measured as a single point at the deepest part of the channel (Doll et al. 2003). This approach follows Doll et al. (2003) guidelines for collecting cross-sectional data. For the remaining marked riffle cross-sections, measurements of the top of bank, top of water, and thalweg were taken to maintain consistent data across all points.

Section Z was analyzed remotely rather than through direct field measurements, a decision determined by both logistical constraints and the section’s unique characteristics (ESRI 2023). In contrast to Sections W, X, and Y, where field measurements were essential for refining restoration plans, Section Z’s heavily modified channel and absence of natural features made remote assessment through ArcGIS a practical, time-efficient choice. Initial visual evaluation indicated that Section Z would require significant modification, potentially even full relocation and redesign, due to its extensive anthropogenic alterations. Additionally, its consistent slope and bankfull width, combined with straightforward topography in an open alluvial plain, made accurate remote measurement feasible. This remote approach enabled comprehensive data collection without compromising methodological rigor, efficiently addressing the logistical challenges associated with field-based assessment in this altered section.

Flow and Velocity

Due to time constraints and a lack of appropriate equipment, flow and velocity measurements were not directly collected in the field. Instead, I utilized StreamStats to assess flow conditions by identifying the watershed area contributing to each section of the stream (U.S. Geological Survey 2019). StreamStats' Peak-Flow Statistics Flow Report provided discharge estimates for different flood events, categorized by annual exceedance probabilities (AEP), which offered a useful proxy for understanding the hydraulic capacity of the stream at each section (U.S. Geological Survey 2019). While this approach lacked the detail that field measurements could provide, it allowed me to develop an informed understanding of flow dynamics within the stream based on watershed size and land use characteristics.

Sediment Composition

Due to time constraints and limited access to the necessary equipment, I was unable to conduct a formal sediment survey, such as the Wolman pebble count method or other bedload and suspended sediment sampling techniques, which are often recommended in stream restoration protocols (Doll et al. 2003; Harman W. A. and Starr 2011; Rosgen 1996; 2011). However, a visual assessment of the streambed was conducted for each section of the stream to estimate sediment composition, supplemented by soil data from SoilWeb to better understand the dominant substrate types in each section (UC Davis California Soil Resource Lab. 2023).

Based on visual observations, the sediment composition for each section was as follows:

- Section W was predominantly composed of silt and clay, with occasional boulders that influenced the course of the stream. These larger boulders created areas where the stream altered its flow direction and velocity.
- Section X exhibited a mix of boulders, pebbles, gravel, and sand, with gravel being the dominant sediment type. The presence of boulders also contributed to changes in stream

flow, but the majority of the streambed was comprised of gravel and smaller particles, indicating a high-energy environment that can transport larger sediment loads.

- In Section Y, the sediment consisted of a combination of boulders, pebbles, gravel, and sand, with a notable shift towards a gravel-sand mix. The reduced presence of larger particles in comparison to section X is potentially due to anthropogenic modifications and cattle access affecting the stream's natural flow patterns.
- The streambed in Section Z was primarily composed of sand and silt, with occasional cobbles. The sandy and silty nature of this section suggests slower-moving water and potential deposition areas, which are consistent with its location in a floodplain and proximity to wetland vegetation.

This qualitative assessment provided a baseline understanding of the stream's sediment dynamics, despite the absence of a formal survey. These observations helped inform the restoration strategy, as the varying sediment types across sections indicated different levels of sediment transport potential and erosion risk.

Stream Stability and Erosion

Due to limitations in time and equipment, I opted for a visual assessment of erosion throughout the stream sections rather than implementing specialized techniques or tools, such as Rosgen's methods for measuring erosion rates (Rosgen 1996; 2011). To document erosion impacts, I relied on photo documentation and direct visual observation during the site visits. This approach allowed me to capture and evaluate the extent of erosion, particularly focusing on the influence of cattle access on streambank conditions. Although quantitative erosion measurements were not taken, qualitative observations provided important insights into the stream's overall stability and erosion-related challenges.

The primary signs of erosion I noted were related to livestock presence, particularly from cattle trails and streambank disturbance in close proximity to the water. In areas with the most direct cattle access, such as sections Y and Z, bank degradation was evident. Additionally, I observed areas where the stream appeared to undercut the banks, particularly in section Y, where the stream was highly entrenched.

Stream Type Calculations

To complete the stream type assessment, I calculated several key parameters for each of the four sections (W, X, Y, and Z): the width-to-depth ratio, entrenchment ratio, channel slope, and sinuosity (Doll et al. 2003; Rosgen 1996; 2011). These parameters are critical in identifying the Rosgen stream type and diagnosing stream stability.

- Width-to-Depth Ratio: I calculated this by measuring the bankfull width and the mean bankfull depth across a representative cross-section for each stream section (Dunne and Leopold 1980). The bankfull width was measured as the distance between the top of the bankfull indicators on each side of the stream. The mean depth was determined by averaging multiple depth measurements across the bankfull channel at evenly spaced intervals. By dividing the bankfull width by the average depth, I obtained the width-to-depth ratio for each section (Rosgen 1996).
- Entrenchment Ratio: To assess how confined each stream section was within its valley, I calculated the entrenchment ratio, which is the ratio of the floodplain width to the bankfull channel width. I measured the width of the floodplain at twice the bankfull depth and compared it to the bankfull width. An entrenchment ratio of less than 1.4 indicated a highly entrenched stream, while higher values suggested broader floodplains, following Rosgen's classification system (Doll et al. 2003; Rosgen 1996).

- Channel Slope (Gradient): The slope of each section was calculated by measuring the change in elevation over the length of the section, following the procedure outlined by Doll et al. (2003). I used the Leica Sprinter 150M Digital Level to measure elevation differences along the thalweg and calculated slope as the change in elevation divided by the total stream length for each section. This slope calculation is crucial for determining the energy of the stream and its ability to transport sediment, with steeper gradients generally indicating higher energy systems (Rosgen 1996).
- Sinuosity: The sinuosity of each section was determined by measuring the stream's length along its thalweg and dividing it by the valley length. This value helps categorize the stream's meandering pattern. A value of 1 indicates a straight stream, while higher values reflect increased meandering (Rosgen 1996).

Initial Stream Classification

Based on the field data and calculations, I classified each stream section according to Rosgen's stream type classification system (Rosgen 1996; 2011). The most influential factor in this classification was the channel slope, followed by entrenchment ratio, width-to-depth ratio, and sinuosity.

- Section W: Field data initially indicated it was between a Type A and B stream, but further analysis confirmed it as Type B. Although the slope of 0.11 aligns more with Type A, the colluvial valley setting and high width-to-depth ratio are more consistent with Type B criteria.

- Section X: Classified as a Type A stream due to its very steep channel slope, the section will remain a Type A post-restoration. The high slope combined with the presence of boulders and forested surroundings fits the characteristics of this stream type.
- Section Y: Though impacted by anthropogenic modifications, this section was classified as Type A due to its steep slope and entrenched nature. It will remain a Type A post-restoration with interventions focused on bank stabilization and cattle exclusion.
- Section Z: Lack of full-field measurements required reliance on ArcGIS and visual assessments, which indicated this section should be a Type E stream due to its low gradient and location within a floodplain. The restoration will aim to restore it to a meandering, low-gradient channel typical of Type E streams.

Regional Reference Curve Selection and Application

The application of regional reference curves is critical for developing accurate stream restoration designs tailored to the geomorphological and land-use conditions of a specific area (Zink, Jennings, and Alexander Price 2012). In stream restoration projects, these curves provide essential baseline data regarding channel dimensions, hydraulic geometry relationships, and stream functions (Rosgen 1996; 2011). For this restoration project, the forested and agricultural reference curves developed by Leigh (2010) were used because they provide guidance on stream sections of varying land uses and watershed sizes. These curves, derived from small streams in the Southern Blue Ridge Mountains, take into account the unique dynamics of both forested and agricultural land uses, making them relevant for the mixed conditions found within the project area (Leigh 2010).

Leigh (2010) emphasizes the importance of using separate hydraulic geometry equations for forested and agricultural stream reaches, noting that management, planning, and restoration efforts must consider these differences. In this project, both the forested and pasture/grassland regional reference curves were utilized to address the mixed land-use context, which includes both forested upper sections and agricultural lower sections. Other regional curves, such as those developed by NCSU, were excluded because they primarily reflect larger, fully forested streams that do not match the project's smaller watershed size and land-use variability (W. A. Harman et al. 2000; Leigh 2010).

The flexibility of Leigh's (2010) forested and pastureland reference curves allowed for the application of different stream restoration targets based on the specific conditions of each section, such as the forested upper sections versus the more agricultural lower sections. The following is a breakdown of a case-by-case basis for the use of these curves:

- For Section W, a spring-fed headwater stream (0.53 square miles) in a moderately forested area, I compared my field data to the forested regional reference curve, which suggested a bankfull width of 5.53 feet and a cross-sectional area of 3.03 square feet. However, my data indicated a narrower channel with a width of 4.661 feet and a cross-sectional area of 0.691 square feet. After further research on spring-fed systems, which typically have smaller channels due to distinct hydrologic processes, I determined that relying on field data, rather than strictly following the reference curve, would prevent over-widening the stream and disrupting natural sediment transport (Griffiths et al., 2008; Leigh, 2013). This decision, along with the recommendation to lower the stream slope, supported the stream's classification as a Type B system.
- In Section X, which is characterized by its steep gradient and fully forested setting, I used Leigh's forested reference curve, which closely aligned with my field measurements. The width-to-depth ratio was slightly higher than expected, but the reference curve provided

appropriate guidance for high-gradient streams, reinforcing the section’s classification as Type A.

- For Section Y, located in open pastureland with no riparian buffer, I applied the agricultural reference curve from Leigh’s study. My field data revealed significant widening and narrowing throughout the stream. The reference curve helped me assess the appropriate bankfull dimensions for a more stable stream, consistent with its Type A classification.
- For Section Z, I applied the agricultural reference curve. Field data indicated a low-gradient system, and using the curve’s guidance for agricultural land use, I confirmed that this section should be classified as a Type E stream. The curve provided key baseline values for evaluating the width-to-depth ratio, ensuring the stream would reconnect with the wetland and maintain the natural dynamics expected for a Type E stream.

The reference curve data provided a valuable cross-check, confirming the accuracy of my initial stream type assessments before moving forward with design alternatives. By comparing field data with the guidance from the curves, I ensured that each section's classification aligned with its actual geomorphological characteristics. This process allowed for a solid foundation upon which to develop restoration strategies tailored to each section's unique conditions

Problem Identification and Restoration Objectives

Problem Identification

Based on the geomorphic, hydraulic, and sediment data collected, several critical issues were identified across the four sections (W, X, Y, and Z) of the stream, particularly relating to cattle access, lack of riparian buffers, and anthropogenic alterations. These issues are consistent with challenges commonly found in small agricultural streams (Agouridis et al. 2005; David Allan 2004). The main problems identified were:

1. Cattle Access and Stream Degradation: In all sections, but especially in Section Y, unrestricted cattle access caused significant bank erosion and destabilization. Cattle trails were evident within 5-10 feet of the stream, and hoofprints and fecal matter were prevalent, contributing to sediment and nutrient loading into the stream.
2. Erosion and Streambank Instability: Sections Y and Z showed the most signs of active bank erosion, particularly where the banks were degraded by cattle access. In section Y, the stream was highly entrenched, and in certain areas, undercutting of the banks was visible, leading to vegetation loss.
3. Anthropogenic Modifications: Sections Y and Z have been heavily altered by human activities. In Section Y, the straightened channel and lack of riparian buffer significantly disrupted natural stream processes, leading to widened banks and increased sediment deposition. In Section Z, the channel was straightened to maximize pastureland, eliminating any natural meanders and reducing overall stream resilience.
4. Lack of Riparian Buffer: In Sections Y and Z, there was no significant riparian vegetation, leaving the stream fully exposed to direct sunlight and increasing the potential for erosion and water temperature fluctuations, which can negatively impact water quality.
5. Obstructions and Flow Impediments: In Section W, an old farm road lacking adequate drainage caused ponding and disrupted water flow. Similarly, in Section Y, logs and other debris hindered the stream's flow.

Restoration Objectives

Based on these identified problems, several key restoration goals were established to guide the development of a comprehensive restoration plan. These goals were designed to align with both Natural Channel Design (NCD) principles and NRCS Best Management Practices (BMPs), ensuring the restoration process addresses the stream's ecological and hydrological needs while also considering the surrounding agricultural land use.

1. Cattle Exclusion: Implement exclusion fencing around sensitive sections of the stream to prevent direct cattle access, particularly in Sections Y and Z, where cattle presence is most disruptive. This will reduce bank erosion and nutrient loading, in line with NRCS BMP standards for streambank protection (NRCS 2021b; D E Line et al. 2000)
2. Bank Stabilization: Restore eroded streambanks using a combination of vegetative plantings and structural stabilization techniques such as live staking or root wads in areas of severe degradation. This will enhance bank stability and reduce further erosion (NRCS 2021a; Rosgen 1996; 2011)
3. Riparian Buffer Restoration: Establish riparian buffer zones in Sections Y and Z, where vegetation has been depleted. Planting native vegetation will help reduce runoff, provide shade to regulate water temperature, and enhance wildlife habitat, all while improving overall stream function (NRCS 2020c).
4. Channel Reconstruction: In Section Z, redesign the stream channel to restore natural meanders where possible, allowing the stream to reconnect with its floodplain and improve sediment transport capacity. This will help to mimic natural stream processes, which have been altered by anthropogenic modifications (NRCS 2021a; 2020e; Rosgen 1996; 2011)

5. Improved Water Flow and Drainage: Address the ponding issue in Section W by installing a drainage pipe beneath the farm road to allow water to flow naturally and prevent future buildup of debris and waste. This will restore natural hydrological function in the upper section of the stream. (NRCS 2017a; 2022e; Rosgen 1996; 2011)

Determining Restoration Alternatives Overview

After completing the existing conditions assessment and setting restoration goals, a range of restoration alternatives was considered to address the identified problems in line with both Natural Channel Design (NCD) and Natural Resource Conservation Service (NRCS) guidelines. These alternatives were evaluated with the two primary objectives of restoring stream function and ensuring the long-term viability of the site as agricultural land. Restoration strategies were tailored to each section of the stream based on its specific geomorphic characteristics and the severity of degradation observed during the assessment phase.

Livestock exclusion, bank stabilization, riparian buffer restoration, and channel re-establishment were considered the primary techniques for improving water quality, reducing erosion, and reestablishing natural hydrological processes. Each alternative was carefully explored to ensure a balance between ecological integrity and the practical needs of the landowner’s farming operation. The final set of recommendations reflects a combination of NCD principles and NRCS Best Management Practices (BMPs), designed to offer sustainable, long-term solutions for stream restoration.

Section W Design

Overview

The restoration plan for Section W follows a comprehensive approach that integrates structural improvements, such as the installation of a culvert and streambank stabilization, with bioengineering techniques, including coir log placement and live staking. Native vegetation is also reintroduced to enhance stream stability, restore natural flow beneath the road, and protect the riparian buffer. These efforts ensure long-term ecological health while maintaining landowner access and supporting continued agricultural use of the surrounding land.

Channel Stabilization and Pipe Installation

The channel stabilization design for Section W focused on addressing ponding and preventing erosion by restoring stream flow beneath the road while ensuring long-term bank stability. The solution involved installing a 19-inch by 30-inch elliptical corrugated pipe to reconnect the streambed, restore proper hydrology, and maintain the road's function for landowner access.

Based on the project’s needs for durability, flexibility, and cost-effectiveness in a rural agricultural setting, I selected corrugated metal pipe. This material is well-suited for managing variable flow conditions while maintaining structural integrity, especially in areas prone to erosion (Gubernick et al. 2008; Forest Service and Wiest 1998; NRCS 2022e). Corrugated pipes are more flexible than other materials, allowing for easier installation in uneven terrain, which was a key consideration for this project (N.C. Department of Transportation 2022). Additionally, corrugated pipes are cost-effective, making them an ideal choice for agricultural applications where budget constraints are often present. Importantly, the pipe’s higher roughness coefficient slows water velocity, which helps reduce sedimentation (Gubernick et al. 2008; NC DOT 2022).

To estimate the appropriate pipe size, I used the NRCS Curve Number Method, which is well-suited for assessing total storm runoff in rural watersheds (NC DOT 2022). This method considers both land use and soil absorption over the entire storm, providing a more accurate estimate of the total runoff that needs to be managed, rather than focusing solely on peak storm intensity (NC DOT 2022). The calculation incorporated a 25-year, 24-hour storm event, land use coefficients for mixed forest and pastureland, and Hydrologic Soil Group B (NOAA 2024a; UC Davis California Soil Resource Lab. 2023). Based on these factors, I determined the runoff volume and converted it into a peak flow rate using a 3-hour drainage period, which was calculated from the watershed's time of concentration and slope (NC DOT 2022).

Utilizing the determined flow rate, I applied Manning's Equation, factoring in the roughness coefficient of the corrugated pipe material and the slope of the installation (NC DOT 2022). While the calculated pipe diameter was approximately 20 inches, I standardized it to a 24-inch round pipe to ensure sufficient capacity and reduce the risk of flooding. To minimize excavation depth and limit disruptions to the farm road, I opted for a 19-inch by 30-inch elliptical pipe, which provides the same hydraulic capacity as a 24-inch round pipe while still accommodating high-flow events (Hydrology Studio 2024).

The installation of the pipe beneath the road will reconnect the streambed on both sides, maintaining the flow of water while preserving the road's location and permeable dirt surface to meet the landowner's preferences. This approach also ensures that the road's topography will remain largely unchanged.

The pipe will be installed at a 9% slope, which aligns with the post-restoration classification of the stream as a Type B channel. The slope was carefully evaluated to ensure the pipe would effectively mimic natural stream conditions, control water velocity, and allow for the passage of aquatic organisms (Gubernick et al. 2008; NRCS and USDA 2022).

To prevent erosion and sedimentation, headwalls will be installed at both the inlet and outlet of the pipe. These headwalls will stabilize the surrounding soil, prevent washout, and reduce turbulence at the pipe ends (NRCS 2017b). By directing the flow smoothly, the headwalls will minimize scour and erosion, while managing runoff from the road and protecting nearby streambanks.

Finally, the road embankments will be regraded to gentler slopes, less than 2:1, to improve stability and reduce erosion from runoff (NC DOT 2022). This comprehensive approach addresses both hydraulic and structural needs, ensuring the long-term functionality of the road while enhancing stream health.

Pond Remediation, Stream Reconnection, and Riparian Buffer Establishment

The ponded area upstream of the road, which has accumulated mud and sediment due to the road blockage, will require remediation to restore natural stream function. Following NRCS guidelines and best practices from stream restoration literature, the area will need to be dewatered, and accumulated sediment and mud will need to be carefully excavated to restore the streambed to its original elevation (Doll et al. 2003). Material similar to the native substrate will be used to reconstruct the streambed, ensuring the natural channel dimensions match upstream and downstream sections (Doll et al. 2003; Yochum and Reynolds 2020). The reconstructed streambed will be graded to a consistent slope of 9%, allowing smooth water flow through the newly installed pipe.

Downstream of the pipe, the streambed will require slight elevation adjustments to align with the pipe outlet and prevent erosion from the drop in elevation. The streambed will be raised using natural substrate materials to match the invert elevation of the pipe outlet, ensuring a smooth transition of flow. This adjustment will prevent the formation of scour pools and minimize downstream erosion, which can occur when water exits the pipe at a higher velocity (Yochum and Reynolds 2020).

To stabilize the streambanks, biodegradable coir logs will be installed along the bank toe to provide immediate erosion control and support, while coir mats will be placed on exposed surfaces to protect against erosion from rainfall and flowing water. These materials will gradually biodegrade as planted vegetation establishes, eventually taking over the stabilization role (Yochum and Reynolds 2020). Vegetative restoration will include live staking with native species like ninebark (*Physocarpus opulifolius*) and spicebush (*Lindera benzoin*), chosen for their robust root systems and ability to stabilize banks (Doll et al. 2003; Jon Calabria 2023). Additionally, a mix of native sedges (*Carex spp.*), rushes (*Juncus spp.*), and other herbaceous plants will be planted to provide ground cover, enhance soil stability, and improve habitat diversity (Doll et al. 2003; Jon Calabria 2023). These plant selections will be made based on NRCS recommendations for the North Carolina mountain region, with careful consideration for the site's specific conditions (Hall, n.d.).

Cattle Exclusion Fencing and Riparian BMPs

Cattle exclusion fencing will be installed along the stream to prevent livestock from entering the riparian zone, protecting vegetation and reducing direct bank erosion. A 35-foot riparian forest buffer will be established on the left side of the stream, adjacent to the current cattle grazing area, while a 90-foot buffer will be created on the right side, which follows the slope of the mountain where cattle use has already been minimal. This approach promotes a healthy riparian buffer, meeting the minimum BMP standards, while still maximizing available pastureland. The fencing will extend continuously along the stream, with varying distances and BMPs applied based on site-specific stream characteristics, ensuring effective protection and restoration throughout the entire area.

Applicable NRCS Conservation Practice Standards

- CPS 584: Channel Bed Stabilization
    - Application: Stabilizing the streambed where ponding has occurred and downstream of the pipe installation to prevent erosion and maintain flow continuity.
    - Standard Quote: “Stabilize the bed of a stream or other watercourse to prevent erosion and control sedimentation” (NRCS 2021a).
- CPS 395: Stream Habitat Improvement and Management
    - Application: Enhancing in-stream habitat for aquatic organisms through channel design improvements or bioengineering techniques.
    - Standard Quote: “Enhance stream habitat for aquatic organisms by improving channel structure and water flow” (NRCS 2019).
- CPS 580: Streambank and Shoreline Protection
    - Application: Coir logs and live staking stabilize the streambanks and prevent erosion.
    - Standard Quote: “Protect against the loss of soil along shorelines and streambanks from water or wind erosion” (NRCS 2020e).
- CPS 574: Spring Development

  - Application: Protects spring-fed water sources upstream of the road to maintain consistent flow and stream health.
  - Standard Quote: “Maintains or improves the quantity and quality of spring water” (NRCS 2020d).
- CPS 587: Structure for Water Control
  - Application: Installation of the elliptical corrugated pipe and headwalls controls water flow beneath the road, preventing erosion and washout.
  - Standard Quote: “Control the rate of water flow to minimize erosion and sedimentation” (NRCS 2017b).
- CPS 560: Access Road
  - Application: The road is stabilized and designed to minimize impact on the stream and surrounding area while maintaining landowner access.
  - Standard Quote: “Minimize erosion and sedimentation by designing roads to manage surface water and prevent soil loss” (NRCS 2017a).
- CPS 578: Stream Crossing
  - Application: Stream crossing added for livestock or machinery, ensuring streambed protection and water quality.
  - Standard Quote: “Provide stable areas for livestock or machinery to cross streams without damaging the streambed or banks” (NRCS 2022e).
- CPS 393: Filter Strip
  - Application: Establishing a 35-foot and 90-foot riparian buffer traps sediment and filters runoff before it reaches the stream.

  - Standard Quote: "Reduce pollutants in runoff and manage erosion" (NRCS 2016b).
- CPS 612: Tree/Shrub Establishment
  - Application: Planting native species (e.g., ninebark, spicebush) along the riparian buffer promotes long-term bank stabilization and habitat diversity.
  - Standard Quote: "Stabilize streambanks, reduce erosion, and enhance wildlife habitat" (NRCS 2023b).
- CPS 561: Heavy Use Area Protection
  - Application: Stabilizing areas heavily used by livestock near crossings and exclusion fences to prevent soil degradation.
  - Standard Quote: "Protect heavily used areas from erosion and soil degradation due to livestock or other traffic" (NRCS 2020b).
- CPS 382: Fence
  - Application: Cattle exclusion fencing along the stream prevents livestock from entering the riparian zone, protecting vegetation and reducing direct bank erosion.
  - Standard Quote: "Use fencing to manage livestock access and prevent overgrazing in sensitive areas such as riparian zones" (NRCS 2021b).

Section X Design

Overview

For Section X, the proposed design centers on creating a stable channel form while sustaining wetland functionality downstream. The restoration approach focuses on reshaping the channel to achieve the ideal width-to-depth and entrenchment ratios characteristic of a Rosgen Type A stream. To accomplish this, targeted excavation and fill will stabilize the channel profile, manage flow velocity, and mitigate incision risk. To promote both stability and ecological function, native riparian buffers of grasses, sedges, and shrubs will be established along the banks and at the stream-wetland transition zone. These buffers will help trap sediment, filter runoff, and support wetland continuity.

Channel Stabilization

A combination of bioengineering methods will be used along the banks to support bank stabilization and encourage vegetation growth. Toe wood will be installed along sections of the bank that require stronger, more durable stabilization. Toe wood involves positioning tree root wads and logs at the base of the bank, where they anchor the soil and deflect water flow away from the banks, mimicking natural wood structures in undisturbed streams (Jon Calabria 2023; Yochum and Reynolds 2020). This method not only provides long-term stabilization but also enhances habitat diversity by creating hiding spaces and shelter for fish and aquatic invertebrates. The addition of toe wood along high-stress bank areas is an effective strategy for providing sustainable, natural bank protection (Yochum and Reynolds 2020).

For areas of the bank that require lighter stabilization, coir logs and biodegradable mats will be used just as in Section W. The coir logs and mats will provide a quickly established yet temporary structural support for the banks while creating an ideal environment for vegetation to take root (Yochum and Reynolds 2020). As the coir decomposes over time, it will be replaced by the growing roots of the riparian vegetation, effectively transitioning from temporary to permanent stabilization (Yochum and Reynolds 2020). This method is particularly effective in low-flow sections, where bank protection is still needed but does not require the durability that toe wood offers. Moreover, coir logs and mats are compatible with native plant growth, promoting a seamless integration of structural support and vegetation (Doll et al. 2003).

Wetland Maintenance

Using toe wood and coir logs in the upstream section of the wetland offers a low-impact approach that aligns well with the hydrological needs of the wetland system. These bioengineering methods mimic natural wood and fiber structures, enhancing soil stability and minimizing bank erosion without requiring disruptive interventions (Somers et al. 2000). By reinforcing banks in this manner, sediment and nutrient transport are controlled, preventing excess deposition in the downstream wetland while maintaining a natural hydrologic flow crucial for wetland function. This low-impact strategy ensures that the delicate balance of wetland hydrology is preserved effectively (Somers et al. 2000).

The wetland itself appears to be in good ecological condition and requires minimal intervention, aside from establishing a stable riparian buffer to support runoff filtration and habitat continuity. Implementing this buffer with native species will contribute to long-term stability while preserving the wetland's unique hydrological regime. By focusing on protective buffer zones rather than extensive modification, this approach promotes a naturally resilient wetland system capable of sustaining local biodiversity and hydrological function.

Cattle Exclusion Fencing and Riparian BMPs

Cattle exclusion fencing will continue to be installed along the stream to keep livestock out of the stream and riparian zone, protecting vegetation and reducing direct bank erosion. A 35-foot riparian forest buffer will be established on the stream’s left side, followed by an additional 35-foot grass buffer. On the right side, a 35-foot riparian forest buffer will be planted, with a 90-foot grass buffer extending into the steep mountain slopes, where cattle access has already been limited by the terrain. This approach supports a healthy riparian buffer that meets minimum BMP standards while maximizing available pastureland.

Applicable NRCS Conservation Practice Standards

- CPS 580: Streambank and Shoreline Protection
    - Application: Bioengineering methods, such as the use of toe wood, coir logs, and biodegradable mats, will stabilize banks, manage flow velocity, and minimize erosion, supporting the bank's structural integrity.
    - Standard Quote: "Streambank protection measures prevent erosion, protect water quality, and support bank stability through natural and structural methods" (NRCS 2020e).
- CPS 584: Channel Bed Stabilization
    - Application: Targeted excavation and fill will reshape the channel, helping to control flow velocity, prevent incision, and maintain a stable bed profile. This practice ensures long-term channel stability and prevents sediment transport issues.
    - Standard Quote: "Stabilize channel beds to control degradation, maintain hydrology, and protect aquatic habitats"(NRCS 2021a).
- CPS 395: Stream Habitat Improvement and Management
    - Application: Toe wood and other bioengineering methods enhance bank stability while creating habitat diversity for fish and aquatic invertebrates, adding ecological value to stabilization efforts.
    - Standard Quote: "Stream habitat improvements promote biodiversity and enhance ecological functions within aquatic systems" (NRCS 2019).
- CPS 656: Constructed Wetland

    - Application: Minimal intervention will be applied to the existing wetland, aside from riparian buffer establishment, to maintain its ecological integrity and filter nutrients while preserving hydrology.
    - Standard Quote: “Constructed wetlands support water quality improvement, flood control, and habitat diversity” (NRCS 2022a).
- CPS 391: Riparian Forest Buffer
    - Application: A 35-foot riparian forest buffer will be established on both sides of the stream to trap sediment, filter runoff, and support habitat continuity for wetland species.
    - Standard Quote: “Riparian forest buffers are used to intercept pollutants, reduce erosion, and protect aquatic habitats” (NRCS 2020c).
- CPS 390: Riparian Herbaceous Cover
    - Application: Adjacent to the riparian forest buffer, an additional grass buffer (35 feet on the left, 90 feet on the right) will enhance sediment trapping and runoff filtration, especially on the right where slopes are steep.
    - Standard Quote: “Herbaceous cover within riparian zones enhances sediment filtration and nutrient absorption, reducing runoff impacts” (NRCS 2022d).
- CPS 393: Filter Strip
    - Application: Establishing a 35-foot and 90-foot riparian buffer traps sediment and filters runoff before it reaches the stream.
    - Standard Quote: “Reduce pollutants in runoff and manage erosion” (NRCS 2016b).
- CPS 612: Tree/Shrub Establishment

    - Application: Planting native species (e.g., ninebark, spicebush) along the riparian buffer promotes long-term bank stabilization and habitat diversity.
    - Standard Quote: “Stabilize streambanks, reduce erosion, and enhance wildlife habitat” (NRCS 2023b).
- CPS 382: Fence
    - Application: Cattle exclusion fencing will be placed along the stream to prevent livestock from entering the riparian zone, safeguarding vegetation and reducing direct bank erosion.
    - Standard Quote: “Use fencing to manage livestock access and prevent overgrazing in sensitive areas such as riparian zones” (NRCS 2021b).

Section Y Design

Overview

To address the impact of cattle and human activity in section Y, a comprehensive redesign is required to stabilize the stream channels and achieve the characteristics of a Type A stream. The thalweg will remain in its current position to keep the stream within its existing alignment, avoiding further encroachment into the pasture. This approach allows the pastureland to remain productive by preserving its usable area, ensuring that the redesign stabilizes the stream without reducing the available agricultural land. However, the stream channel will be adjusted to a uniform width of 2 feet 10 inches to correct areas that are either too wide or too narrow. Additionally, the longitudinal profile of the channel will be re-evaluated and modified to follow the step-pool sequence required for the Type A stream designation.

Channel Stabilization

Channel stabilization for Section Y primarily requires managing energy along the 13% slope. To address this, a step-pool structure is proposed to balance effective energy dissipation with a straightforward design. Step spacing is recommended to range from 0.3 to 0.5 times the bankfull width (2.937 feet), approximately 0.9 to 1.5 feet between each step (Rosgen 1996; 2011). However, to avoid excessive structure density, the design proposes expanding this interval to 3 to 6 feet along the 180-foot reach. This layout will yield approximately 30 to 40 steps, providing an effective balance between energy management and construction feasibility.

The design further specifies a step height of 0.5 feet, calculated as 0.2 to 0.5 times the bankfull width (Rosgen 1996; 2011). This height allows for habitat continuity while still facilitating controlled energy dissipation (Rosgen, NRCS). Pools are to be established immediately downstream of each step with a depth between 1.5 and 2.5 times the mean stream depth of 0.451 feet, which translates to approximately 0.7 feet for optimal performance in slowing flows and minimizing erosion risk.

Materials for constructing the steps include locally available boulders, large rocks, and toe wood. Boulders will serve as anchors at each step, embedded into the substrate to enhance stability (Yochum and Reynolds 2020). Logs will function as cross vanes, strategically placed across the channel at each step and angled slightly upstream to focus flow centrally and support bank integrity (Yochum and Reynolds 2020). Toe wood wads are included in the design at select bank locations to reinforce areas prone to erosion (Yochum and Reynolds 2020).

The construction plan involves marking step locations at 3- to 6-foot intervals along the channel, with boulders and logs placed across the channel width to achieve a consistent 0.5-foot height above each downstream step. Pools will be shaped downstream of each step to a depth of

0.7 feet, facilitating energy dissipation within these deeper sections. Toe wood will be placed strategically along vulnerable banks to enhance stability and minimize erosion, particularly during high-flow events. This proposed approach provides a stable and ecologically sensitive design to effectively manage slope energy while maintaining habitat connectivity.

Cattle Exclusion Fencing and Riparian BMPs

Cattle exclusion fencing will continue to be installed along the stream to prevent livestock from entering the stream and riparian areas, which will help protect vegetation and minimize bank erosion. A riparian buffer zone will be established on both sides of the stream. On the left side, a 15-foot-wide forested buffer will be planted, followed by a 35-foot grass buffer extending outward. On the right side, there will be a similar 15-foot forest buffer, followed by a 15 to 35-foot grass buffer that extends to the existing fence line bordering the gravel road. This design aims to enhance riparian health while maintaining effective separation between livestock and the stream.

Applicable NRCS Conservation Practice Standards

- CPS 584: Channel Bed Stabilization
    - Application: To prevent degradation and excessive erosion, the step-pool structure with strategically placed boulders and logs stabilizes the channel bed, controls energy, and prevents sediment loss.
    - Standard Quote: “Channel bed stabilization practices are used to prevent erosion, control grade, and enhance structural stability in flowing water systems” (NRCS 2021a).
- CPS 580: Streambank and Shoreline Protection

    - Application: To stabilize banks along the 180-foot reach, toe wood, large boulders, and logs are used to reinforce areas prone to erosion, providing stability during high-flow events. This practice mitigates bank erosion and sediment deposition within the stream.
    - Standard Quote: “Streambank and shoreline protection involves the use of vegetation, structures, or other treatments to stabilize banks and protect water quality” (NRCS 2020e).
- CPS 395: Stream Habitat Improvement and Management
    - Application: Implementing a step-pool structure along the stream length, with spaced steps and habitat-enhancing pools, aims to maintain habitat connectivity and improve in-stream habitat for aquatic species. The step-pool sequence helps dissipate energy along the slope while providing various depths for habitat complexity.
    - Standard Quote: “Stream habitat improvement practices are designed to enhance aquatic habitats, support biodiversity, and stabilize stream channels” (NRCS 2019).
- CPS 390: Riparian Herbaceous Cover
    - Application: A 35-foot-wide grass buffer is established on both sides of the stream to trap sediment and filter agricultural runoff, supporting riparian health and improving water quality.
    - Standard Quote: “Riparian herbaceous buffers improve water quality by trapping sediment, filtering runoff, and providing a protective buffer to water bodies” (NRCS 2022d).

- CPS 391: Riparian Forest Buffer
  - Application: On each side of the stream, a 15-foot forest buffer is installed to support bank stability, reduce erosion, and protect aquatic habitats through improved shade and organic matter input.
  - Standard Quote: “Riparian forest buffers are used to intercept pollutants, reduce erosion, and protect aquatic habitats” (NRCS 2020c).
- CPS 393: Filter Strip
  - Application: Establishing a 15 to 35-foot riparian buffer traps sediment and filters runoff before it reaches the stream.
  - Standard Quote: “Reduce pollutants in runoff and manage erosion” (NRCS 2016b).
- CPS 612: Tree/Shrub Establishment
  - Application: Planting native species (e.g., ninebark, spicebush) along the riparian buffer promotes long-term bank stabilization and habitat diversity.
  - Standard Quote: “Stabilize streambanks, reduce erosion, and enhance wildlife habitat” (NRCS 2023b).
- CPS 382: Fence
  - Application: The cattle exclusion fencing along the stream prevents livestock access to sensitive riparian zones, protecting vegetation and minimizing erosion caused by animal disturbance.
  - Standard Quote: “Fencing is used to exclude livestock from riparian zones, protecting sensitive vegetation and water quality” (NRCS 2021b).

Section Z Design

Overview

To address severe bank erosion, instability, and excessive channel incision caused by historical modifications, I developed a comprehensive stabilization plan for Section Z, incorporating a critical wetland integration component to restore connectivity between the channel and the adjacent wetland. Following Rosgen’s Type E channel guidelines, the design introduces meanders to control flow velocity and minimize erosion, using root wads and coir logs to reinforce bank stability. A widened transition zone facilitates wetland integration by diffusing water flow, encouraging sediment deposition, and distributing water gradually across the wetland area. The plan also includes cattle exclusion fencing and a dual-layer riparian buffer, combining forested and grassed sections to enhance water quality and protect bank integrity. This method integrates hydraulic stability with ecological connectivity to support long-term environmental health.

Channel Stabilization

Channel stabilization for Section Z requires a comprehensive reconfiguration strategy, which includes channel relocation and realignment. The methodology for this process includes channel excavation, in-stream structures, bank reinforcement, and floodplain connectivity. This approach aims to effectively manage energy dissipation, prevent erosion, and enhance habitat connectivity, following Rosgen’s guidelines for stream stability and bioengineering (Harman W. A. and Starr 2011; Rosgen 1996; 2011; Yochum and Reynolds 2020).

The channel’s meandering planform is a key aspect of this design, specifically constructed to control flow velocity and dissipate energy, thereby reducing bank erosion risks. With a sinuosity set at 1.5, as recommended for Type E channels (Rosgen 1996; 2011). I calculated the meander wavelength and radius of curvature based on bankfull width and target sinuosity, using empirical relationships. This approach avoids over-widening and keeps the channel dimensions stable across each curve to support natural sediment transport without compromising the channel's integrity(NOAA 2024a; Rosgen 1996; 2011; Yochum and Reynolds 2020).

In addition to channel geometry, root wads will be incorporated as the primary in-stream structures for energy dissipation, strategically placed along the meander bends to stabilize banks and direct flow toward the thalweg. By positioning one to two root wads per bend with root masses oriented downstream, the design will maximize flow deflection, reducing scouring potential on the banks and supporting consistent energy dissipation across the reach (NOAA 2024a; Rosgen 1996; 2011; Yochum and Reynolds 2020). For areas not stabilized with root wads, coir logs and mats will be applied as temporary erosion controls to reinforce the banks until full stabilization is achieved.

Floodplain connectivity is another critical element of Section Z's stabilization plan, allowing high flows to spill over naturally and deposit sediment across a designated floodprone area adjacent to the channel. This process is essential to ensuring the channel can effectively handle excess flow without excessive erosion or alteration to its shape (Harman W. A. and Starr 2011; Rosgen 1996; 2011; Yochum and Reynolds 2020). This design equips Section Z to manage high-flow events effectively, balancing energy dissipation, bank stability, and habitat connectivity for a resilient, natural channel stabilization solution.

Wetland and Stream Integration

I designed a proposed integration plan for a Rosgen Type E stream to enter and distribute water throughout a wetland system, aiming to create diffuse flow and balanced hydrological conditions to support wetland stability and biodiversity. The wetland’s 4% slope supports gradual, natural flow distribution without causing excess erosion, making a Type E stream, with its low gradient, high sinuosity, and stable banks, an ideal candidate for effective integration and water distribution within the wetland (Rosgen 1996). For optimal placement, I positioned the stream’s entry near the wetland’s upper third. This location enables water to flow naturally across the wetland, distributing moisture evenly across a larger surface area by allowing gravity to facilitate a gradual, fan-like spread (Somers et al. 2000). The goal of this positioning was to ensure that water could flow across the entire wetland area without requiring artificial control structures.

To support a smooth transition from the stream to the wetland, I designed a slightly widened channel section at the entry point, creating a shallow “transition pool” that slows water flow and reduces entry-point erosion. The width of this entry section is approximately 1.5 to 2 times the natural width of the stream channel, which allows water to spread out gradually into the wetland (Somers et al. 2000). This configuration not only helps manage water velocity but also promotes sediment deposition near the entry, reducing sediment transfer into the main wetland area (Somers et al. 2000).

To further enhance water quality and stabilize the wetland ecosystem, I implemented a multi-layered buffering strategy designed to filter runoff and manage sediment before it enters the main wetland area. I extended a 35-foot riparian forest buffer surrounding the outer boundaries of the wetland, providing a robust layer of native trees and shrubs to stabilize the banks and slow the flow. Around this, I established an additional 35-foot grass riparian buffer to further capture sediment and nutrients before they reach the wetland. Within the wetland itself, I planted a diverse mix of native wetland species, including sedges and rushes, to enhance biodiversity and improve soil stability. Together, these buffers act as natural filters, capturing sediment and nutrients while providing structural support to the banks and protecting against erosion (Somers et al. 2000). By selecting species adapted to saturated soils, I aimed to create a self-sustaining filtration system that promotes a balanced, biodiverse wetland ecosystem (Somers et al. 2000).

As the water flows through and disperses across the wetland, it eventually exits through a designated outlet point where the Type E channel characteristics are re-established. To transition smoothly back to the original stream form, I tapered the exit channel gradually over a 10–20 foot section to match the original Type E stream's depth and width, helping to maintain stable, narrow, and sinuous flow (Rosgen 1996; 2011; Somers et al. 2000). I added natural stabilizers such as logs and stones near the exit, along with native vegetation along the banks, to prevent erosion, maintain channel stability, and help the stream resume its natural Type E form downstream of the wetland (Rosgen 1996; 2011; Somers et al. 2000; Yochum and Reynolds 2020).

Through this design approach, I aimed to establish a seamless connection between the stream and wetland, facilitating diffuse water distribution across the wetland while preserving the natural characteristics of the Type E stream as it enters and exits the area. By combining strategic entry positioning, widened transition zones, micro-basins, and natural stabilizers, this proposed design provides a balanced and ecologically supportive integration of the stream within the wetland system.

Cattle Exclusion and Riparian Buffer Installation

Cattle exclusion fencing will continue to be installed along the stream to prevent livestock from accessing the stream and riparian areas, protecting vegetation and reducing bank erosion. A riparian buffer will be established on both sides of the stream, consisting of a 35-foot-wide forested buffer directly adjacent to the stream, followed by a 35-foot grass buffer. This design promotes riparian health and maintains a clear separation between livestock and the stream.

Applicable NRCS Conservation Practice Standards

- CPS 584: Channel Bed Stabilization
    - Application: To prevent bank erosion and enhance stability, root wads and coir logs are applied along the meander bends and critical areas, stabilizing banks, directing flow, and managing energy dissipation.
    - Standard Quote: “Channel bank stabilization practices are used to control erosion, maintain streambank stability, and protect water quality in channelized water systems” (NRCS 2021a).
- CPS 395: Stream Habitat Improvement and Management
    - Application: The addition of root wads improves habitat complexity and flow dynamics, promoting aquatic species’ habitat by supporting consistent energy dissipation and minimizing scouring potential.
    - Standard Quote: “Stream habitat improvement and management practices enhance stream function and provide favorable conditions for aquatic organisms” (NRCS 2019).
- CPS 391: Riparian Forest Buffer
    - Application: A 35-foot forested buffer stabilizes banks, filters runoff, and enhances biodiversity, protecting the riparian zone from erosion and nutrient loading.

    - Standard Quote: “Riparian forest buffers are used to intercept pollutants, provide habitat, and stabilize streambanks with native vegetation” (NRCS 2020c).
- CPS 390: Riparian Herbaceous Cover
    - Application: A 35-foot grass buffer supplements the forested zone, capturing sediment and nutrients before reaching the wetland area and enhancing sediment trapping along the riparian corridor.
    - Standard Quote: “Riparian herbaceous cover establishes dense vegetation to filter runoff, trap sediment, and improve water quality near water bodies” (NRCS 2022d).
- CPS 612: Tree and Shrub Establishment
    - Application: Native trees and shrubs planted in the riparian buffer stabilize soil, provide habitat, and enhance riparian resilience over the long term.
    - Standard Quote: “Tree and shrub establishment improves vegetative cover, stabilizes soil, and enhances habitat diversity in riparian areas” (NRCS 2023b).
- CPS 342: Critical Area Planting
    - Application: For rapid vegetative establishment in erosion-prone areas, such as newly stabilized banks, native plantings secure the soil, preventing further erosion.
    - Standard Quote: “Critical area planting involves establishing vegetation in erodible areas to protect soil, reduce erosion, and stabilize critical areas” (NRCS 2016a).
- CPS 659: Wetland Enhancement

  - Application: Enhancing wetland areas with buffers and natural structures supports biodiversity and improves water quality by diffusing flow across a natural gradient.
  - Standard Quote: "Wetland enhancement practices focus on improving existing wetlands to increase water quality, wildlife habitat, and hydrological function" (NRCS 2022f).
- CPS 472: Access Control
  - Application: Access control restricts entry to riparian and wetland areas, protecting vegetation and preventing disturbance in sensitive zones.
  - Standard Quote: "Access control is implemented to protect sensitive areas from disturbance, maintain vegetation, and support habitat conservation" (NRCS 2017a).
- CPS 382: Fence
  - Application: Fencing along riparian and wetland areas restricts livestock, preventing degradation of vegetated buffers and enhancing bank stability.
  - Standard Quote: "Fences are used to control livestock movement, protect sensitive areas, and maintain soil and water quality" (NRCS 2021b).

Watershed Modeling

PLET

To assess the effectiveness of best management practices (BMPs) for mitigating cattle-related impacts on a small watershed within the Dillingham Creek HUC 12 (060101050801), the North Fork weather station in Buncombe County was selected to provide localized climate data (US EPA 2022b; NOAA 2024a). The property was categorized into two primary land uses: 2.06

acres designated as urban for the farmhouses and 27.8 acres designated as pastureland. Soil within the area was identified as hydrologic soil group B, characterized by moderate infiltration rates, which informed the baseline pollutant loading potential and BMP effectiveness calculations (US EPA 2022b; UC Davis California Soil Resource Lab. 2023). Standard pollutant load coefficients were applied to both land use categories, focusing specifically on typical nutrient and sediment loading associated with livestock.

For the BMP configurations, the approach centered on isolating cattle-specific contributions by removing all non-cattle-related elements from the watershed, enabling a focused assessment of BMP performance on typical watershed dynamics with the 15 cattle currently maintained by the farmer (Landowner 2022). The BMPs included a cattle exclusion fencing overlay across the riparian zone, established as a parallel BMP to prevent direct livestock access to the stream and riparian buffers. Within the exclusion zone, BMPs were applied in series, beginning with a 4.2-acre grass buffer, followed by a 2.6-acre forest buffer, and concluding with 0.2 acres of streambank stabilization along the stream edge. Each BMP in the series was configured to reduce pollutant loads progressively as runoff passed through each treatment zone, while the cattle exclusion overlay reduced livestock access across the entire riparian buffer area. Additionally, an alternative watering system was set up across the remaining 20.8 acres of pastureland as a parallel BMP to further minimize cattle’s impact on the stream by providing off-stream water access.

To evaluate the cumulative impact of these BMPs on pollutant loading, PLET was used to calculate baseline loads and the resulting reductions attributed to each BMP. This approach allowed for specific analysis of nutrient, nitrogen, phosphorus, and sediment reductions achieved through each BMP configuration. The effectiveness of each BMP was assessed individually and cumulatively at the final node, providing a comprehensive view of their role in addressing cattle-related pollutant loading within this specific watershed.

E. coli Reduction Calculation

Reducing *E. coli* concentrations in agricultural runoff is a primary objective in managing water quality on grazing lands. While the PLET modeling system does not directly calculate *E. coli* reductions from NRCS BMPs, additional resources offer a framework for estimating these reductions (NC DEQ 2016). These calculations evaluate BMP effectiveness, particularly riparian buffers, in filtering contaminants before they reach water bodies. Implementing these targeted BMPs allows for the assessment of potential *E. coli* reductions, considering site-specific factors such as soil type, land use, and grazing intensity, and aligns with USDA NRCS guidelines (NC DEQ 2016).

This calculation is applicable on the farm due to the installation of the riparian buffer BMP, where runoff flows through a grass buffer followed by a forested riparian buffer surrounding the stream, enabling an assessment of the buffer system's efficacy in reducing *E. coli* concentrations. To calculate this effectiveness, a baseline assessment classified the year-round grazed pasture in “fair” condition, noting grazing impacts such as moderate vegetative cover, minor bare soil patches, and erosion (Ogles et al. 2020). This classification aligns with USDA NRCS guidelines for grazing land conditions, assigning it a Curve Number of 69, reflecting both soil group characteristics and grazing impacts (NC DEQ 2016; Ogles et al. 2020). To estimate runoff volume, a typical 24-hour, 1-year rainfall event of 2.60 inches was selected based on precipitation frequency data for Barnardsville, North Carolina (NOAA 2024a). The Curve Number was used to compute potential runoff, taking into account the maximum retention capacity of the soil, which was adjusted for pastureland with fair vegetative cover. This calculation provided an approximate runoff volume in gallons, giving a basis for determining the initial fecal coliform load entering the buffer.

A standard concentration value was used for year-round grazing, setting the fecal coliform level in runoff at 1.894×10^6 col/gal, a rate observed in pastures under continuous grazing pressure (NC DEQ 2016). This value, combined with the calculated runoff, provided a baseline fecal coliform load before filtration. The estimated effectiveness of the riparian buffer was then applied, with an efficiency rate of 85%, reflecting typical reductions observed in vegetative buffers that filter fecal coliforms under similar grazing conditions (NC DEQ 2016).

This approach offered a conservative, realistic estimate of fecal coliform reduction achievable through the implementation of riparian buffers alongside grazed pastures.

CHAPTER 4

RESULTS

Watershed and Farmland Overview

Watershed Location and Context within Farmland

The Dillingham Creek watershed (HUC12 code 060101050801) encompasses 18,361.77 acres, with 16,762.99 acres primarily forested, most of which fall within the Big Ivy area of Pisgah National Forest (US EPA 2022b). In the watershed's lower sections, there are 825.08 acres of pastureland and 67.39 acres of cropland, creating diverse land-use conditions and influencing hydrology and sediment transport within the HUC 12 area.

Within the larger Dillingham Creek watershed, the farm's stream drains a smaller 0.12-square-mile sub-watershed, which serves as the basis for this analysis. The lower one-third of this sub-watershed lies within the farm's boundaries, where it shifts from forested upper areas to predominantly pastureland. This agricultural influence directly impacts local hydrology and sediment transport, aligning with the project's overall goal of enhancing stream stability and restoring natural flow patterns in agricultural landscapes.

Farmland Overview and Historical Context

Figure 3. View of farm from below including pasture, farm equipment, and outbuildings. Photo by author, September 12, 2023.

The farm, located in Buncombe County, North Carolina, shares its northern boundary with Pisgah National Forest and is bordered on all other sides by rural and agricultural lands. Established nearly 200 years ago as a self-sustaining homestead, it once supported a family with gardens, chickens, a dairy cow, and various crops. Over time, however, its focus shifted solely to cattle, transitioning fully into a beef operation by the 1970s which is a legacy that continues today, with cattle farming still shaping the landscape. The farm's primary focus remains cattle grazing, supporting between 15 to 20 beef cattle at any given time. Aside from pastureland, the property includes outbuildings used mainly for storage, reflecting its evolution into a dedicated cattle operation that continues to define its ecological and operational character.

Reflecting the varied landscapes of the region, the farm’s terrain transitions from steep hillsides to open, flood-prone lowlands. A spring-fed stream originates on the property, flowing through the farm’s varied terrain before joining a tributary of Ivy Creek, which then travels for about 20 miles before reaching the French Broad River.

Topography and Terrain Analysis

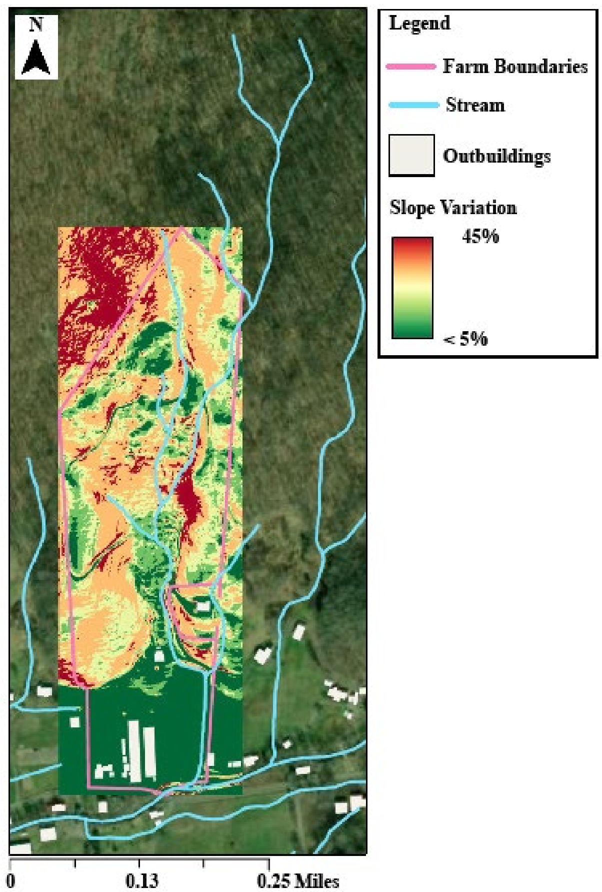


Figure 4. Map of slope variation on the farm. Data sourced from ESRI. Map created using ArcGIS Pro.

The farm's terrain exhibits significant variation between the upper and lower sections. In the upper areas, slopes surpass 45%, as shown by the red zones on the slope map in Figure 2, while the lower floodplain, marked in green, has slopes of less than 5%. This change in slope corresponds to the transition from steep, rugged conditions in a boulder-strewn colluvial valley in the upper pasture to more level terrain, with soil composed mainly of cobble and sand, in the lower floodplain. The stream mirrors this gradient, with the changing slopes affecting its characteristics along its course.

Stream Hydrology

The stream's hydrology is notably influenced by steep slopes in its upper reaches and flatter floodplain areas downstream. Flow patterns varied with geomorphic features and surrounding vegetation, where areas with minimal vegetation experienced higher runoff and erosion. Hydrological disruptions included increased water velocity in straightened and entrenched sections, where the lack of meanders and floodplain connection concentrated flow energy, leading to accelerated erosion. Additionally, impoundments from road crossings and heavy livestock access led to ponding and reduced water flow in other areas. These varied hydrological conditions underscored the need for interventions to stabilize flow patterns, reduce velocity where entrenchment is high, and reconnect the floodplain to allow for natural dispersal of high flows.

Stream Characteristics and Vegetation

Figure 5. The stream surrounded by rocky terrain and sparse brush, with the absence of typical riparian vegetation contributing to the destabilization of streambanks. Note the steep gradient visible in the background.

Figure 6. Streamside vegetation in the upper pasture, with blackberry bushes and scattered brush, with little to no typical riparian vegetation contributing to streambank destabilization. Photo by author, April 29, 2023.

Figure 7. The stream running through the lower pasture, surrounded by grasses and minimal brush. The lack of dense riparian vegetation and the steep gradient in the background contribute to erosion and streambank instability. Photo by author, July 29, 2023.

The farmland watershed presents diverse stream characteristics shaped by varying slopes, vegetation cover, and historical modifications. Originating from a spring, the stream flows through a landscape that transitions from steep, forested areas to open, low-gradient floodplains. While moderate forest cover in the upper reaches offers some natural stabilization and shade, an adequate riparian buffer is missing along the entire stream. In the lower areas, vegetation is sparse, limited to scattered brush like blackberry bushes and pasture grasses, providing minimal protection. Without the stabilizing influence of a riparian buffer, the stream is highly vulnerable to erosion, with increased sediment and nutrient loads as a result.

Figure 8. Stream section showing human modifications, including a log obstruction and a plastic corrugated pipe directing water into the stream. Photo by author, April 29, 2023.

Figure 9. Cattle grazing above stream with full access to waterway. Photo by author, April 19, 2024.

Figure 10. Cattle grazing in pasture with foreground showing erosion above stream from heavy use due to cattle crossing and access road. Photo by author, April 29, 2023.

Human modifications have further altered the stream's structure and flow, including channel straightening, the installation of corrugated pipes for crossings, and the presence of large debris such as logs and remnants of farm equipment. Additionally, unrestricted cattle access across both forested and open pasture areas has destabilized the banks, contributing to erosion and vegetation loss throughout. Together, these changes have disrupted the stream's natural dynamics, leading to sedimentation issues and reducing its resilience in managing nutrient and sediment loads across the watershed.

Environmental Challenges and Restoration Strategies

Table 1. Summary of Environmental Parameters and Proposed Modifications for Farm Stream. Data collected by author.

Problems	Causes	Solutions	NCD Guidelines / NRCS CPS
Streambank Erosion and Sedimentation	Unrestricted livestock access, soil compaction	Install livestock exclusion fencing along streambanks to prevent cattle access	CPS 382: Fence for Livestock Exclusion, CPS 580: Streambank Protection
Nutrient Runoff and Water Quality Degradation	Nutrient inputs from cattle manure	Establish riparian buffers with native vegetation to intercept runoff before entering stream	CPS 391: Riparian Forest Buffer, CPS 612: Tree/Shrub Establishment
Altered Flow Patterns and Floodplain Disconnection	Channel straightening, road crossings altering flow	Increase sinuosity in stream channel, install elliptical culvert for hydrological connectivity	NCD Phase 6: Restore Natural Flow, CPS 587: Structure for Water Control
Insufficient Riparian Vegetation	Lack of vegetation along streambanks due to cattle access	Plant native trees, shrubs, and grasses to establish a protective riparian buffer	CPS 391: Riparian Forest Buffer, CPS 612: Tree/Shrub Establishment
Channel Stability	High flow velocity due to entrenchment, bank erosion	Use biodegradable coir logs and mats along banks for erosion control, reinforced [illegible]	CPS 580: Streambank and Shoreline Protection, CPS 395: Stream Habitat Improvement
Degraded Habitat for Aquatic Organisms	Erosion and sedimentation, altered flow	Redesign stream channel to improve in-stream habitat conditions for aquatic species	CPS 395: Stream Habitat Improvement and Management

The farm's stream faces a range of environmental challenges, primarily driven by historical modifications and current agricultural practices. Streambank erosion and sedimentation emerge as significant issues due to unrestricted livestock access and soil compaction along the banks. To mitigate these effects, Fence for Livestock Exclusion (CPS 382) and Streambank Protection (CPS 580) are recommended to install fencing along streambanks, preventing cattle access and reducing further erosion and sediment deposition.

Nutrient runoff and water quality degradation are also prevalent due to nutrient inputs from cattle manure. To address these issues, the establishment of riparian buffers with native vegetation is recommended to intercept runoff before it reaches the stream, following Riparian Forest Buffer (CPS 391) and Tree/Shrub Establishment (CPS 612) guidelines. The absence of a sufficient riparian buffer throughout the stream, compounded by vegetation loss from cattle access, leaves the stream vulnerable to further erosion and nutrient loading. Planting native trees, shrubs, and grasses along the banks will reestablish a protective buffer, providing essential streambank stability and filtration of pollutants.

Altered flow patterns and floodplain disconnection due to channel straightening and road crossings have further disrupted hydrological processes and habitat connectivity. To restore a more natural flow and reconnect the floodplain, the strategy involves increasing the sinuosity of the stream channel and installing an elliptical culvert for improved hydrological connectivity, as per Structure for Water Control (CPS 587) guidelines.

Channel stability is further compromised by high flow velocity in entrenched areas, leading to increased bank erosion. The use of biodegradable coir logs and mats along the banks, reinforced with live staking, is recommended to control erosion and improve stability, in alignment with Streambank and Shoreline Protection (CPS 580) and Stream Habitat Improvement (CPS 395) standards.

Finally, degraded habitat for aquatic organisms is a concern due to erosion, sedimentation, and altered flow conditions. To enhance in-stream habitat for aquatic species, the strategy recommends redesigning the stream channel to promote favorable habitat conditions, following Stream Habitat Improvement and Management (CPS 395) guidelines.

Together, these restoration strategies aim to restore ecological stability and resilience within the watershed by addressing the interconnected issues of erosion, nutrient management, habitat connectivity, and stream structure, ultimately promoting a healthier and more sustainable watershed ecosystem.

Section W

Overview

Section W lies in the upper reaches of a small headwater stream that originates from a spring in a forested area and is bordered by mixed land use. The landscape shows notable impacts from human modifications and cattle activity, including ponding due to road impoundment and livestock access. Positioned on steep slopes with moderate runoff potential, Section W presents challenges for vegetation establishment and slope stabilization. These factors collectively highlight the need for targeted restoration efforts to enhance stream stability and ecological resilience in this area.

Visual Observations

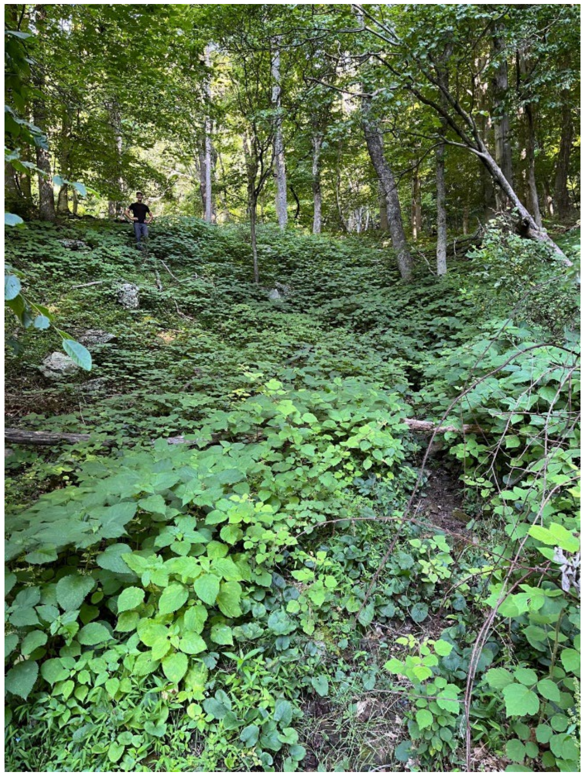


Figure 11. Headwaters of the stream where the spring emerges from the ground. Photo by author, July 12, 2023.

Figure 12. Vegetation and debris accumulating in the stream channel, with a deciduous forest floor visible on the left side and pastureland on the right. Photo by author, July 12, 2023.

Figure 9 and Figure 10 capture the natural features and land use influences in Section W's upper reaches. Figure 9 shows the stream's headwaters emerging from a spring in a forested area, while Figure 10 highlights vegetation and debris within the channel, bordered by a deciduous forest on one side and pastureland on the other. These images illustrate the contrasting environments around the stream that impact its condition and flow.

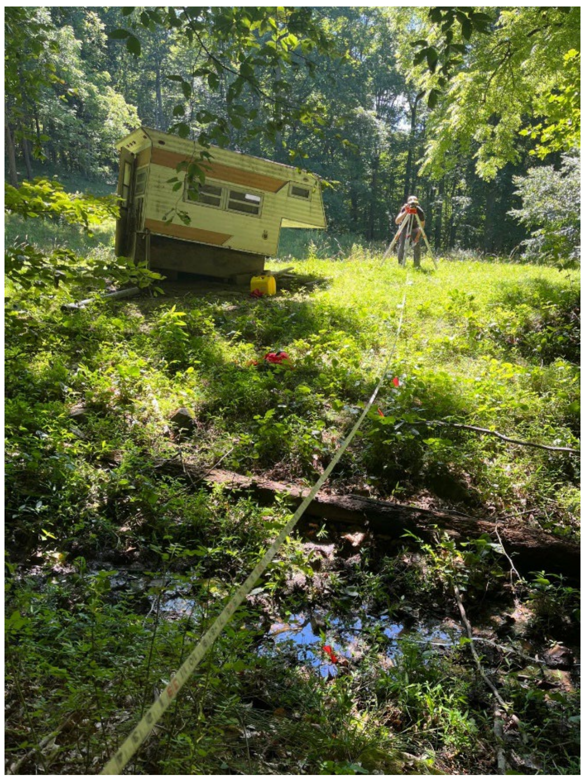


Figure 13. Pastureland on the right streambank. The camper, removed shortly after this photo was taken, was not included in the analysis due to its brief presence. Photo by author, July 12, 2023.

Figure 14. Mud pond formed due to cattle activity and road impoundment, with a view of deciduous forest on the right side of the stream and pastureland on the left. Photo by author, July 12, 2023.

Figure 15. Evidence of iron-oxide bacteria likely from excess nutrient load from cattle manure. Photo by author, July 12, 2023.

Figure 11Figure 12,Figure 13 illustrate various impacts of land use and livestock activity on Section W. Figure 11 shows pastureland along the right streambank, with a camper that was removed shortly after the photo was taken and therefore excluded from the analysis. Figure 13 highlights the presence of iron-oxide bacteria, likely resulting from excess nutrient load from cattle manure, indicating nutrient enrichment in the stream. Figure 12 depicts a mud pond formed due to cattle activity and road impoundment, with deciduous forest on the right side of the stream and pastureland on the left. Together, these images capture the influence of livestock and land use on the stream's ecological condition.

Geomorphic Assessment and Sediment Composition

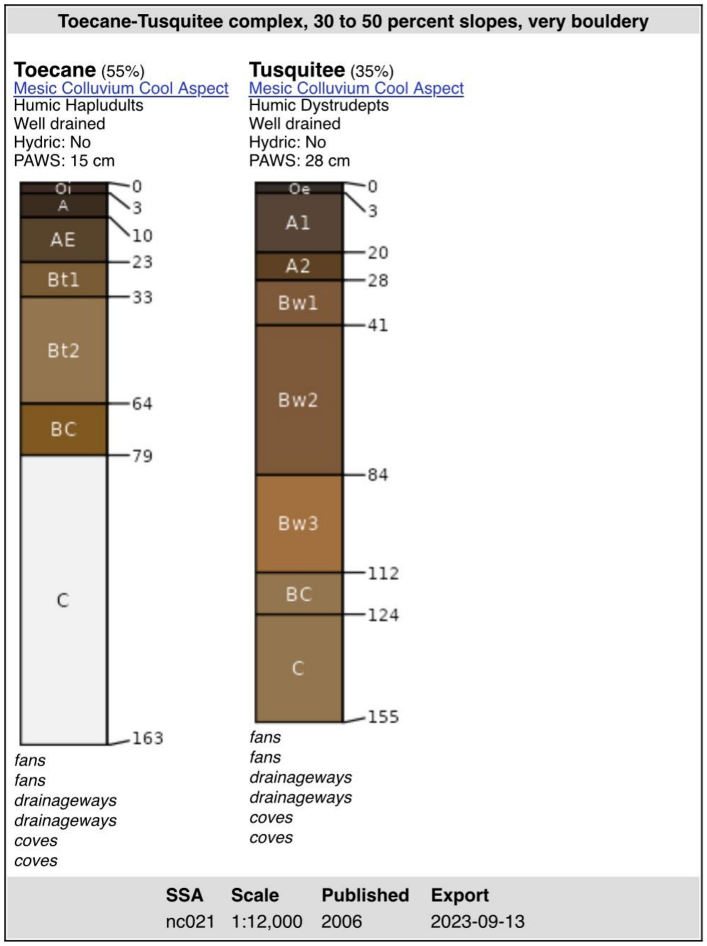


Figure 16. Soil Composition in Section W. (UC Davis California Soil Resource Lab, 2023).

Section W soil composition is classified as a Toecane-Tusquitee complex, as illustrated by the soil profile in Figure 14. This complex consists of two primary soils: Toecane (55%) and Tusquitee (35%), characterized by 30 to 50 percent slopes. The Toecane soil reaches a depth of 163 cm, while the Tusquitee soil extends to 155 cm. These soils are formed from cobbly and stony colluvium derived from igneous and metamorphic rock, contributing to medium runoff and limited water retention in the landscape. As classified by the USGS, this soil complex is not considered prime farmland, indicating challenges for vegetation establishment and slope stabilization efforts necessary in this bouldery environment.

Field Measurements and Calculations

Table 2. Section W Existing Conditions and Field Calculations. Data collected by the author.

	Section W
Watershed Area (sq mi)	0.05
Stream Classification	B
Channel Pattern	Single-thread
Bankfull Cross-Sectional Area (sq ft)	0.69
Bankfull Width (ft)	4.66
Bankfull Mean Depth (ft)	0.15
Bankfull Max Depth (ft)	0.31
Entrenchment Ratio (ft/ft)	1.69
W/D Ratio (ft/ft)	31.46
Sinuosity (ft/ft)	1.22
Stream Slope	0.11

Table 2 presents baseline measurements and calculated values for Section W, including metrics for stream width, depth, bank height, and slope. These values inform the subsequent analysis of longitudinal and cross-sectional profiles and guide interpretations related to stream morphology and stability.

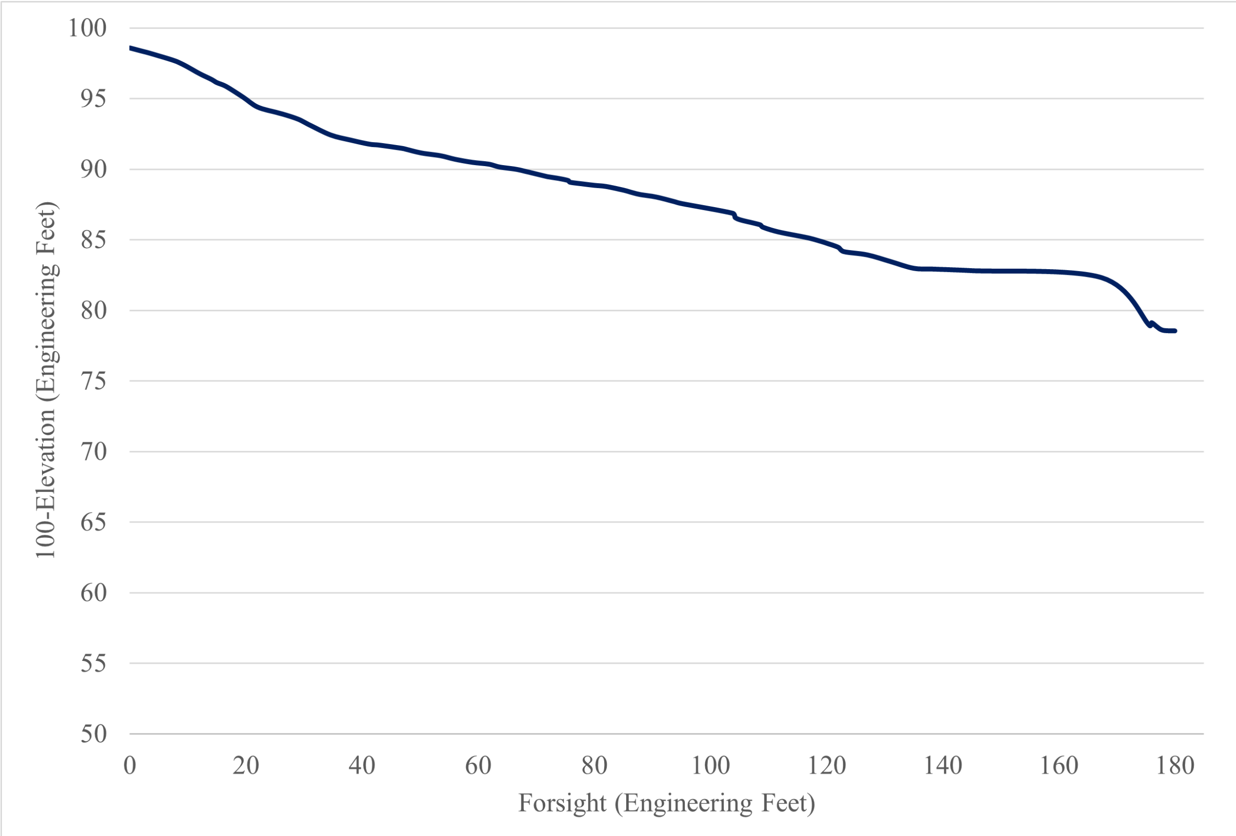


Figure 17. Longitudinal Profile of Section W. Data collected by the author.

Figure 15 provides a longitudinal profile of Section W, illustrating elevation changes along a 180-foot stretch of the stream reach. The foresight measurements begin at an elevation of 98.59 feet, with a gradual descent of approximately 15 feet before reaching a 10-foot-long ponded area adjacent to the farm access road. This transition features a level slope at the road crossing, followed by a distinct 5-foot drop from the top of the road into the dry streambed below. The initial slope from the beginning of the profile to the end of the streambed measured 11%; however, when factoring in the manmade modifications around the road crossing, the effective streambed slope aligns more closely with 9%.

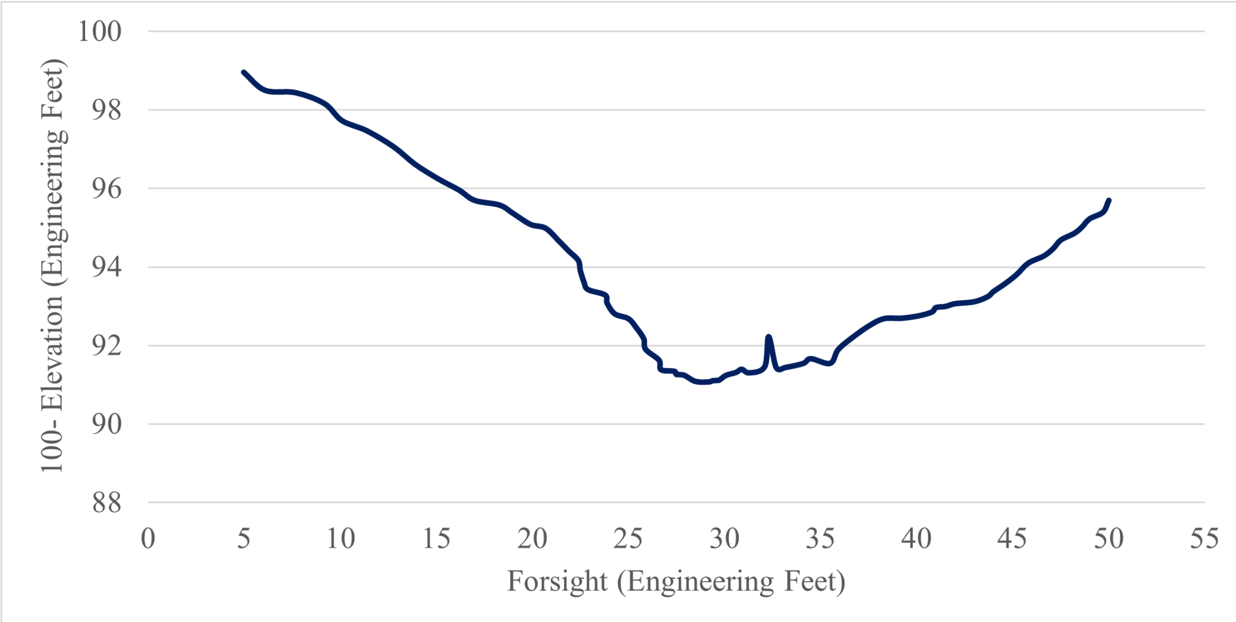


Figure 18. Cross-Section of Section W. Data collected by the author.

Figure 12 provides a cross-sectional profile of Section W, showing elevation changes across a 45-foot stretch of the stream width. The left bank exhibits an elevation drop of approximately 7 feet, while the right bank has a drop of around 4.5 feet. The profile displays a concave shape, with the lowest point at the center, indicating the primary flow path. Irregularities are present in the streambed, primarily due to debris such as a log within the channel. The cross-sectional shape reflects characteristics of a moderately entrenched channel, consistent with a Type B stream profile.

Reference Curve Calculations and Proposed Conditions

Table 3. A Comparison of Existing, Reference, and Proposed Calculations for Section W. Data collected by author.

	Section W		
	Existing	Reference	Proposed
Watershed Area (sq mi)	0.05	-	0.05
Stream Classification	B	-	B
Channel Pattern	Single-thread	-	Single-thread
Bankfull Cross-Sectional Area (sq ft)	0.69	N/A	0.77
Bankfull Width (ft)	4.66	N/A	3.80
Bankfull Mean Depth (ft)	0.15	N/A	0.20
Bankfull Max Depth (ft)	0.31	N/A	0.37
Entrenchment Ratio (ft/ft)	1.69	1.4-2.2	1.56
W/D Ratio (ft/ft)	31.46	>12	18.64
Sinuosity (ft/ft)	1.22	>1.2	1.22
Stream Slope	0.111	0.02-0.099	0.097

Table 3 presents field measurements, reference values based on NCD standards and reference curve calculations, and proposed calculations for design modifications for Section W. Key metrics include bankfull area, width-to-depth ratio, and slope.

Environmental Challenges and Restoration Strategies

Table 4. Summary of Environmental Parameters and Proposed Modifications for Section W. Data collected by author.

Section	Problems	Causes	Solutions	NCD Guidelines / NRCS CPS
W	Ponding near road	Road blocking natural water flow	Install 19-inch by 30-inch elliptical drainage pipe to reconnect flow and maintain hydrology beneath road	NCD Phase 6: Restore natural flow using hydraulic structures; CPS 587: Structure for Water Control
	Bank erosion from cattle access	Cattle standing near ponded water, trampling banks	Livestock exclusion fencing along riparian zone to prevent access	CPS 382: Fence for livestock exclusion
	Poor vegetation near banks	Cattle trampling, lack of riparian cover	Plant native riparian vegetation (e.g., ninebark, spicebush) to stabilize banks; establish a 35-foot buffer on one side and a 90-foot buffer on the other	CPS 391: Riparian Forest Buffer, CPS 612: Tree/Shrub Establishment, NCD Phase 6: Enhance vegetation cover
	Altered sediment deposition patterns	Cattle disturbance causing sediment buildup	Redirect cattle access away from stream and implement sediment management practices	CPS 580: Streambank Protection, CPS 561: Heavy Use Area Protection
	Narrower-than-expected bankfull width	Natural spring-fed conditions leading to smaller channel	Preserve current stream dimensions due to unique hydrological conditions	NCD Phase 5: Respect unique hydrological conditions
	Channel stability	Erosion and sedimentation near banks and streambed	Install biodegradable coir logs and coir mats along banks to provide erosion control, reinforced by live staking with native species	CPS 580: Streambank and Shoreline Protection, CPS 395: Stream Habitat Improvement and Management
	Road stability	Erosion from runoff and high-flow events	Regrade road embankments to less than a 2:1 slope, stabilizing the structure while minimizing erosion	CPS 560: Access Road
	Stream crossing for livestock/machinery	Need for stable crossing points	Construct stream crossing to prevent bank and bed damage while allowing controlled access	CPS 578: Stream Crossing
	Degraded habitat for aquatic organisms	Disrupted flow and sedimentation from road blockage	Improve habitat through channel design adjustments to enhance in-stream conditions	CPS 395: Stream Habitat Improvement and Management

Table 4 outlines the primary environmental challenges observed in Section W, their underlying causes, and the corresponding solutions proposed to address each issue. It includes interventions aimed at restoring natural flow, stabilizing streambanks, improving vegetation cover, managing sediment deposition, and enhancing habitat. Each solution aligns with relevant NCD guidelines and NRCS Conservation Practice Standards to support the ecological and structural stability of Section W.

Proposed Restoration Design

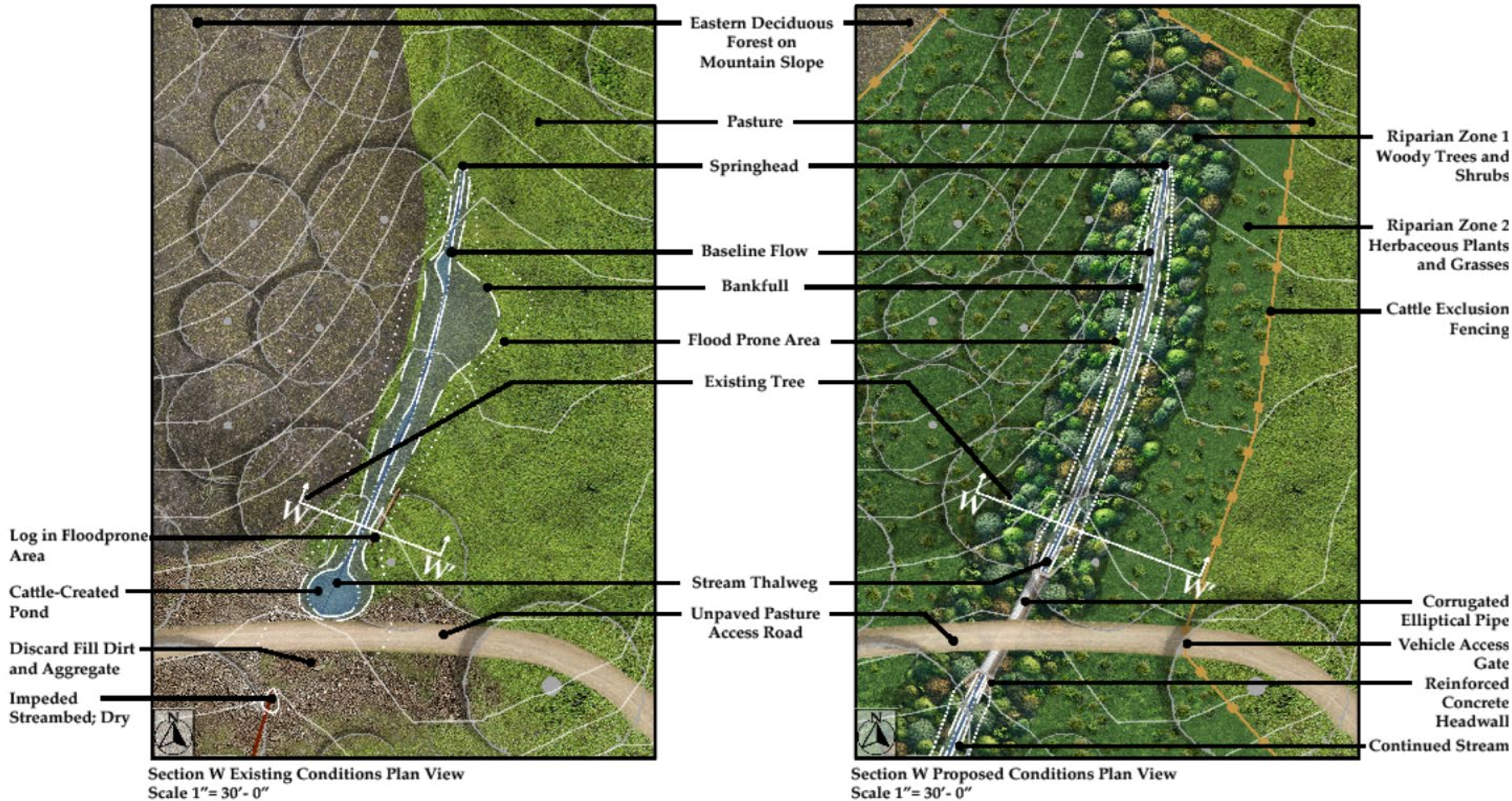


Figure 19. Master Plan Comparison of Existing and Proposed Stream Conditions for Section W. Illustrated by author.

Figure 17 presents a comparison of existing and proposed conditions for Section W in the stream restoration project. The Existing Conditions view (left) illustrates several impediments affecting the stream's natural flow, including a cattle-created pond, discarded fill dirt, and aggregate, as well as a log obstructing the flood-prone area. Additionally, the streambed shows signs of dryness and impeded flow, exacerbated by the close proximity of an unpaved pasture access road, which introduces risks of erosion and sediment deposition.

In the Proposed Conditions view (right), the design introduces a structured approach to stream stabilization and hydrological reconnection. A corrugated elliptical pipe is installed to maintain the 9% slope while passing under the pasture access road, reconnecting the streambed on the other side. Sized to handle a 25-year, 24-hour storm event at 21.33 cubic feet per second (cfs) per NC DOT (2022) standards, the pipe ensures adequate flow capacity without disrupting the landscape. Gradual, vegetated banks over the headwall will reduce erosion, with native grass plantings providing initial sediment interception.

The design also includes a two-zone riparian buffer: Riparian Zone 1 features trees and shrubs, such as Ninebark and Elderberry, to stabilize banks and provide canopy cover, while Riparian Zone 2 consists of herbaceous plants and graminoids like Christmas Fern and Jewelweed to capture sediment and prevent runoff. The fenced cattle exclusion zone further protects the stream from livestock impact, enhancing long-term bank stability and water quality.

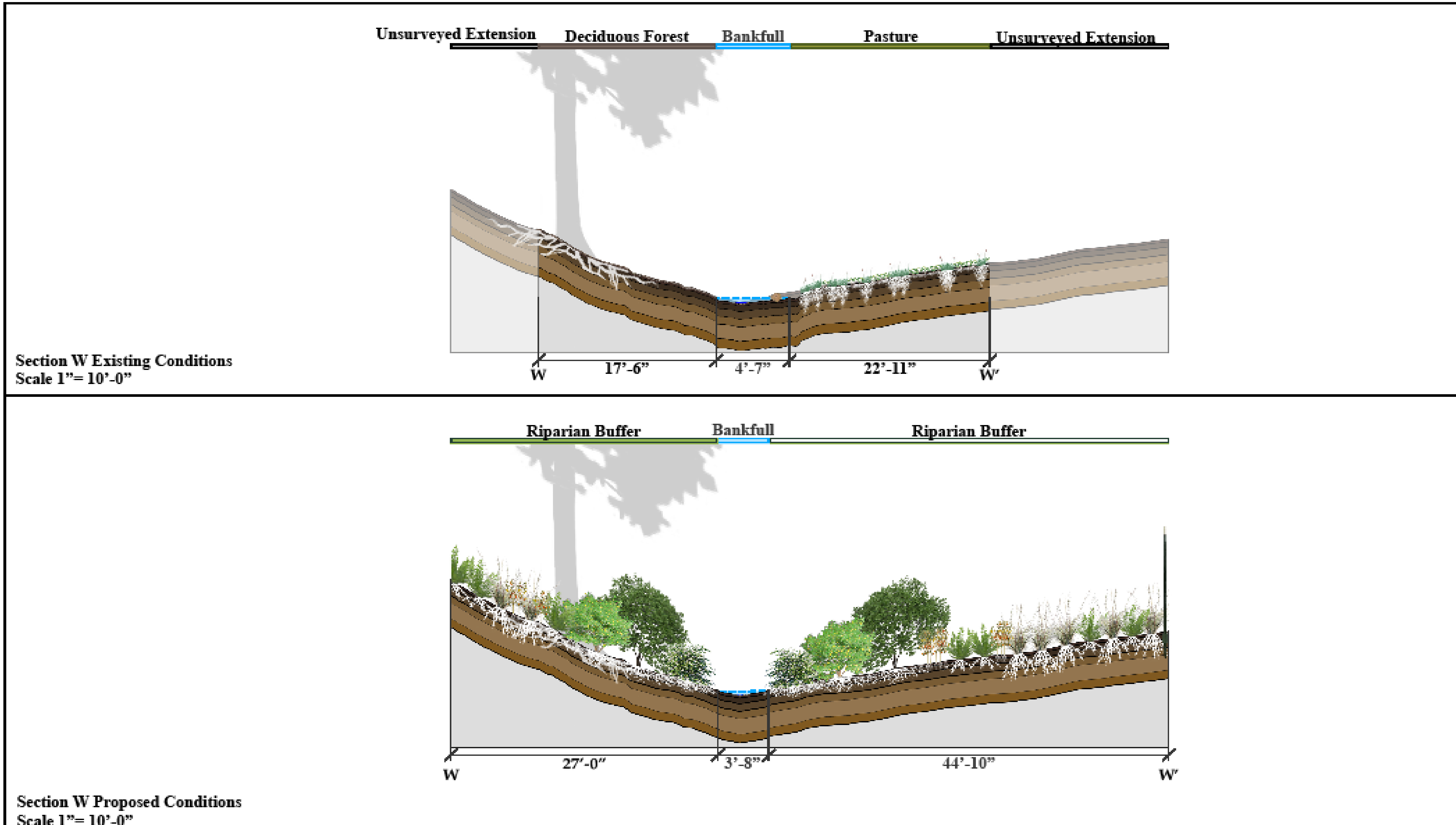


Figure 20. Section Cut Comparison of Existing and Proposed Stream Conditions for Section W. Illustrated by the author.

Figure 18 provides a cross-sectional view comparing Existing Conditions (top) and Proposed Conditions (bottom) for Section W.

In the Existing Conditions plan, the channel width at bankfull measures approximately 4'-7", bordered by a 17'-6" stretch of deciduous forest on the left and a 22'-11" pasture area on the right. The existing banks show minimal vegetation, particularly in the forested reach.

The Proposed Conditions plan broadens the bankfull width slightly to around 3'-8" while expanding the overall width of the stream corridor, creating a more gradual profile creating hydrological reconnection with the floodplain. The addition of riparian buffers on both sides incorporates native vegetation, including trees, shrubs, and grasses.

Section X

Overview

Section X is located on a steep, boulder-laden slope within a deciduous forest, marked by a rocky streambed with accumulated debris and erosion along its banks. This section experiences notable impacts from steep topography and lacks sufficient bank vegetation. As the stream flows downstream, it transitions into a wetland area characterized by herbaceous cover and grasses before rechanneling, necessitating targeted interventions to stabilize the banks, improve hydrological connectivity, and support wetland functionality. These conditions highlight the distinct interaction between steep topography and channel morphology, which together influence the stream's stability and its progression into the downstream wetland area.

Visual Assessment

Figure 21. Section X topography includes a steep slope and boulders. It is enclosed in a deciduous forest. Photo by author, July 12, 2023.

Figure 22. The stream shows signs of erosion and invasive species along its sides. The streambed is full of debris. Photo by author July 12, 2023.

Section X is situated on a steep, boulder-strewn slope within a deciduous forest, as seen in Figure 19. This rugged terrain contributes to erosion and poses challenges for stream stability. Observations, as seen in Figure 20, reveal signs of bank erosion and the presence of invasive species along the stream's edges, with debris accumulating in the streambed

Figure 23. The stream continues through a rocky and debris-filled channel before entering into a transition zone before reaching the wetland. Photo by author July 12, 2023.

Figure 24. Wetland area of the stream section passes through herbaceous cover and grasses before rechanneling downstream. Photo by author, September 3, 2023.

Section X transitions from a rocky, debris-filled stream channel into a wetland area, as illustrated in Figure 21Figure 22. In Figure 21, the stream flows through a channel laden with rocks and debris, leading into a transition zone before reaching the wetland. Figure 22 shows the wetland area, where the stream passes through dense herbaceous cover and grasses before rechanneling downstream. This transition highlights the need for careful management to support wetland function, control sediment, and maintain channel stability as the stream flows from upland areas into this sensitive zone.

Geomorphic Assessment

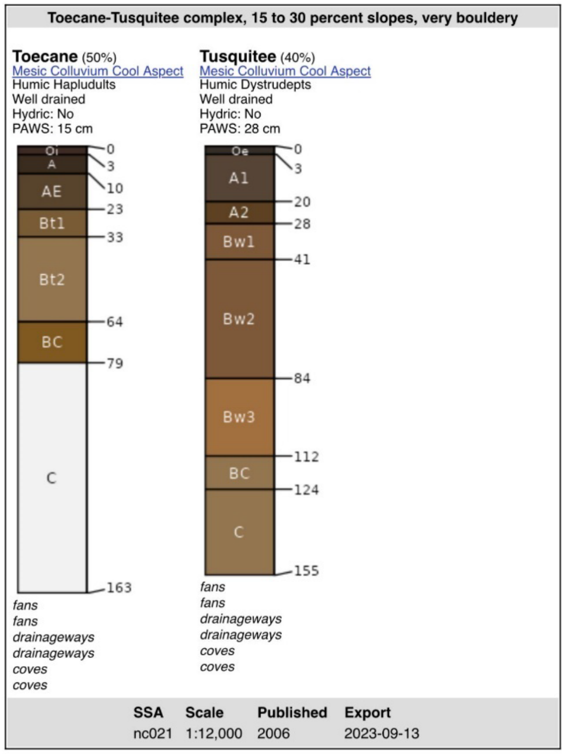


Figure 25. Soil Composition in Section X. (UC Davis California Soil Resource Lab, 2023).

Section X soil composition is classified as a Toecane-Tusquitee complex. This complex consists of two primary soils: Toecane (50%) and Tusquitee (40%), occurring on moderately steep slopes of 15 to 30 percent in a very bouldery landscape. These soils are well-drained and non-hydric, with Toecane reaching a depth of 163 cm and Tusquitee extending to 155 cm. This complex is commonly found in fans, drainageways, and coves, with a composition of cobbly and stony colluvium derived from igneous and metamorphic rock. They experience medium runoff and are not classified as prime farmland.

Field Measurements and Calculations

Table 5. Section X Existing Conditions and Field Calculations. Data collected by the author.

	Section X
Watershed Area (sq mi)	0.06
Stream Classification	A
Channel Pattern	Single-thread
Bankfull Cross-Sectional Area (sq ft)	1.20
Bankfull Width (ft)	3.94
Bankfull Mean Depth (ft)	0.31
Bankfull Max Depth (ft)	0.42
Entrenchment Ratio (ft/ft)	1.22
W/D Ratio (ft/ft)	12.89
Sinuosity (ft/ft)	1.18
Stream Slope	0.18

Table 5 presents baseline measurements and calculated values for Section X, including metrics for stream width, depth, bank height, and slope. These values inform the subsequent analysis of longitudinal and cross-sectional profiles and guide interpretations related to stream morphology and stability.

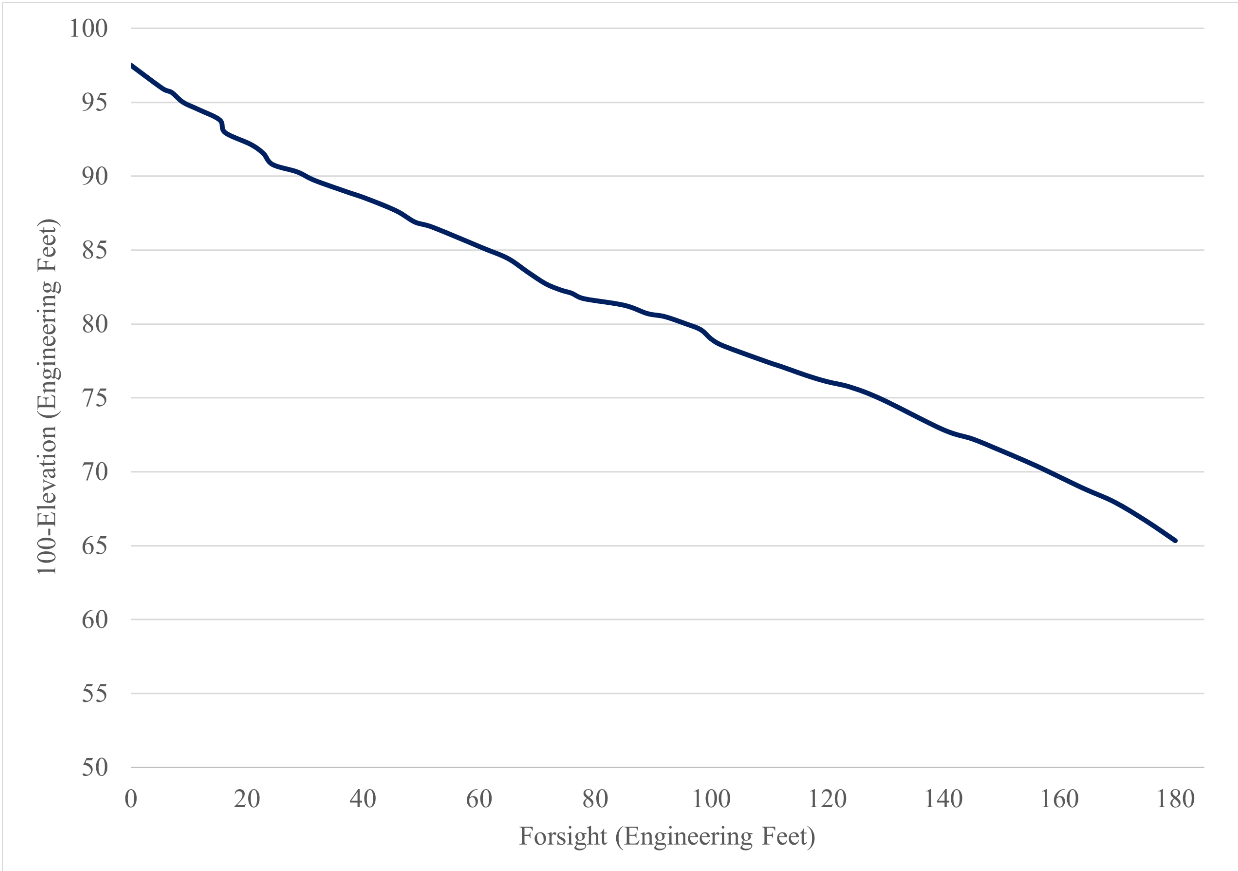


Figure 26. Longitudinal Profile of Section X. Data collected by the author.

Figure 24 illustrates the longitudinal profile of Section X, capturing elevation variations over a 180-foot stretch along the stream reach. The foresight readings start at an elevation of 97.51 feet, with a consistent descent of approximately 30 feet across the section. Section X displays a uniform slope without notable interruptions, maintaining a continuous grade of approximately 17% over the entire distance.

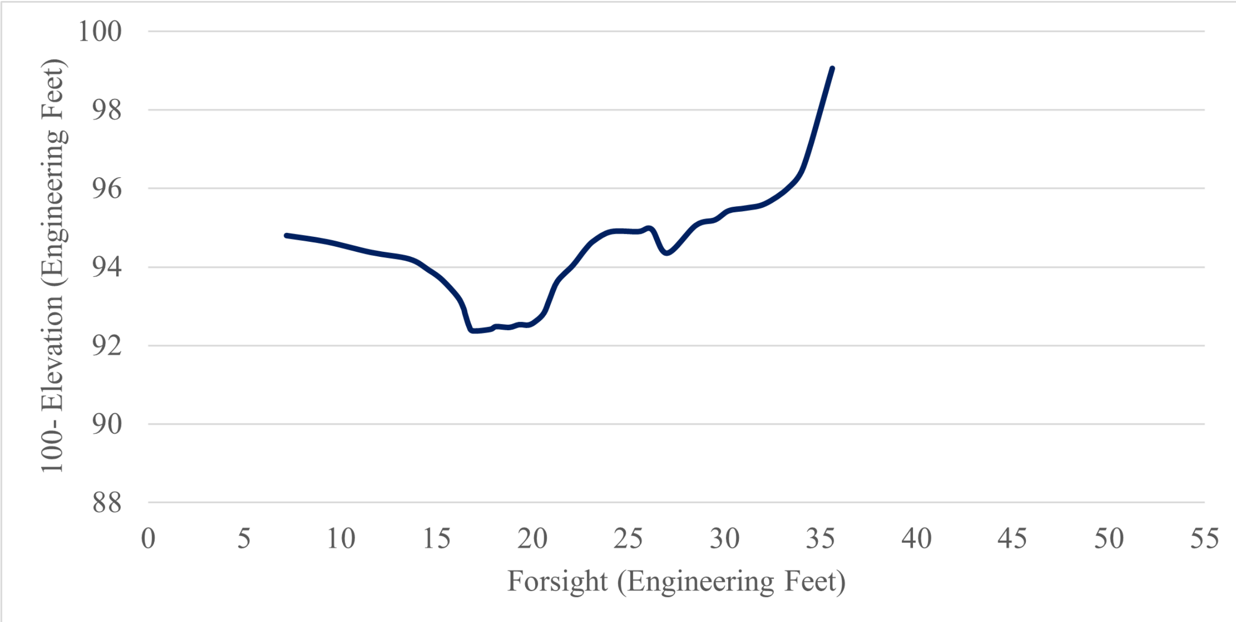


Figure 27. Cross-Section of Section X. Data collected by the author.

Figure 25 illustrates the cross-sectional profile of Section X, capturing elevation variations across an approximately 30-foot span of the stream width. The left bank shows a gentle slope, descending approximately 2 feet, while the right bank features a steep incline with a drop exceeding 6 feet. The profile reveals an asymmetrical cross-section shape, indicative of underlying geomorphic features potentially at play, especially when coupled with the knowledge of a large boulder ending measurements on the right side of the cross-section. The streambed shows moderate to high entrenchment, which is representative of a Type A stream profile.

Reference Curve Calculations and Proposed Conditions

Table 6. A Comparison of Existing, Reference, and Proposed Calculations for Section X. Data collected by author.

	Section X		
	Existing	Reference	Proposed
Watershed Area (sq mi)	0.06	-	0.06
Stream Classification	A	-	A
Channel Pattern	Single-thread	-	Single-thread
Bankfull Cross-Sectional Area (sq ft)	1.20	3.21	3.23
Bankfull Width (ft)	3.94	5.73	5.72
Bankfull Mean Depth (ft)	0.31	0.56	0.56
Bankfull Max Depth (ft)	0.42	N/A	0.89
Entrenchment Ratio (ft/ft)	1.22	<1.4	1.29
W/D Ratio (ft/ft)	12.89	<12	10.13
Sinuosity (ft/ft)	1.18	1-1.2	1.18
Stream Slope	0.179	0.04-0.10+	0.179

Table 6 presents field measurements, reference values based on NCD standards and reference curve calculations, and proposed calculations for design modifications for Section X. Key metrics include bankfull area, width-to-depth ratio, and slope.

Environmental Challenges and Restoration Strategies

Table 7. Summary of Environmental Parameters and Proposed Modifications for Section X. Data collected by author.

Section	Problems	Causes	Solutions	NCD Guidelines / NRCS CPS
X	Channel stability	Unstable channel profile due to erosion	Reshape channel using targeted excavation and fill to stabilize profile	NCD Phase 5: Maintain stable channel dimensions; CPS 584: Channel Bed Stabilization
	Bank stability in high-stress areas	Erosion in areas needing durable stabilization	Use bioengineering techniques like toe wood for durable stabilization	NCD Phase 6: Enhance bank stability with natural structures; CPS 580: Streambank and Shoreline Protection; CPS 580: Streambank and Shoreline Protection
	Temporary bank stabilization for low-flow sections	Need for lighter stabilization in low-flow sections	Apply coir logs and biodegradable mats for temporary support	NCD Phase 6: Establish temporary support; CPS 580: Streambank and Shoreline Protection
	Wetland maintenance	Maintaining natural hydrologic flow for wetland	Stabilize upstream channel through bioengineering techniques without disrupting hydrology; Install riparian transition strip between stream and wetland	NCD Phase 5: Maintain hydrological function; CPS 584: Channel Bed Stabilization; CPS 390: Riparian Herbaceous Cover; CPS 656: Constructed Wetland
	Cattle exclusion	Livestock access causing direct bank erosion	Install cattle exclusion fencing and establish riparian buffer	NCD Phase 6: Protect riparian areas from livestock access; CPS 382: Fence; CPS 391: Riparian Forest Buffer, CPS 390: Riparian Herbaceous Cover
	Runoff filtration and sediment trapping	Runoff from surrounding pastureland	Establish riparian forest and grass buffers on both sides of the stream	NCD Phase 6: Establish riparian buffers for filtration and stability; CPS 391: Riparian Forest Buffer, CPS 390: Riparian Herbaceous Cover

Table 7 outlines the primary environmental challenges identified in Section X, their underlying causes, and the proposed solutions tailored to address each issue. The interventions focus on achieving stable channel form, supporting wetland functionality, reinforcing bank stability, managing flow velocity, and establishing effective riparian buffers. Each solution is aligned with relevant NCD guidelines and NRCS Conservation Practice Standards to enhance both the ecological integrity and structural stability of Section X.

Proposed Restoration Design

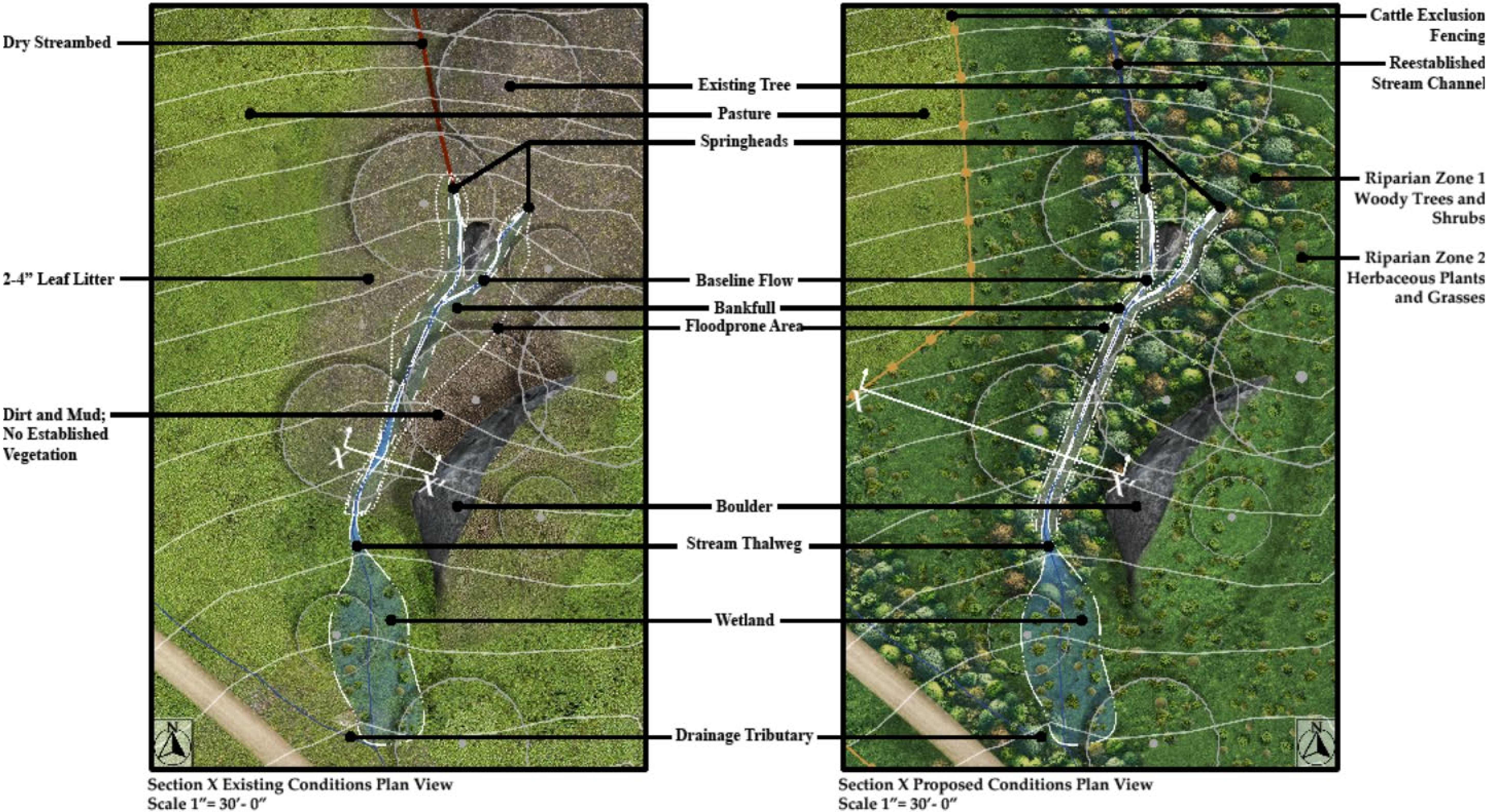


Figure 28. Master Plan Comparison of Existing and Proposed Stream Conditions for Section X. Illustrated by author.

Figure 26 presents a comparison of existing and proposed conditions for Section X in the stream restoration project. The Existing Conditions view (left) highlights a narrow channel with sections of dry streambed and areas of dirt and mud lacking established vegetation, contributing to exposed banks prone to erosion. Livestock have unrestricted access to the stream, resulting in degraded bank stability and increased sediment within the channel. Minimal vegetation along the banks allows for unfiltered runoff and extends the floodplain area.

In the Proposed Conditions view (right), the stream channel has been reshaped to achieve target width-to-depth and entrenchment ratios. High-stress areas along the bank are reinforced with toe wood and coir logs. Riparian Zone 1 contains woody trees and shrubs, while Riparian Zone 2 includes herbaceous plants and grasses. The buffer zones trap sediment, filter runoff, and support downstream wetland functionality. Cattle exclusion fencing lines both sides of the stream, preventing livestock access to the riparian area.

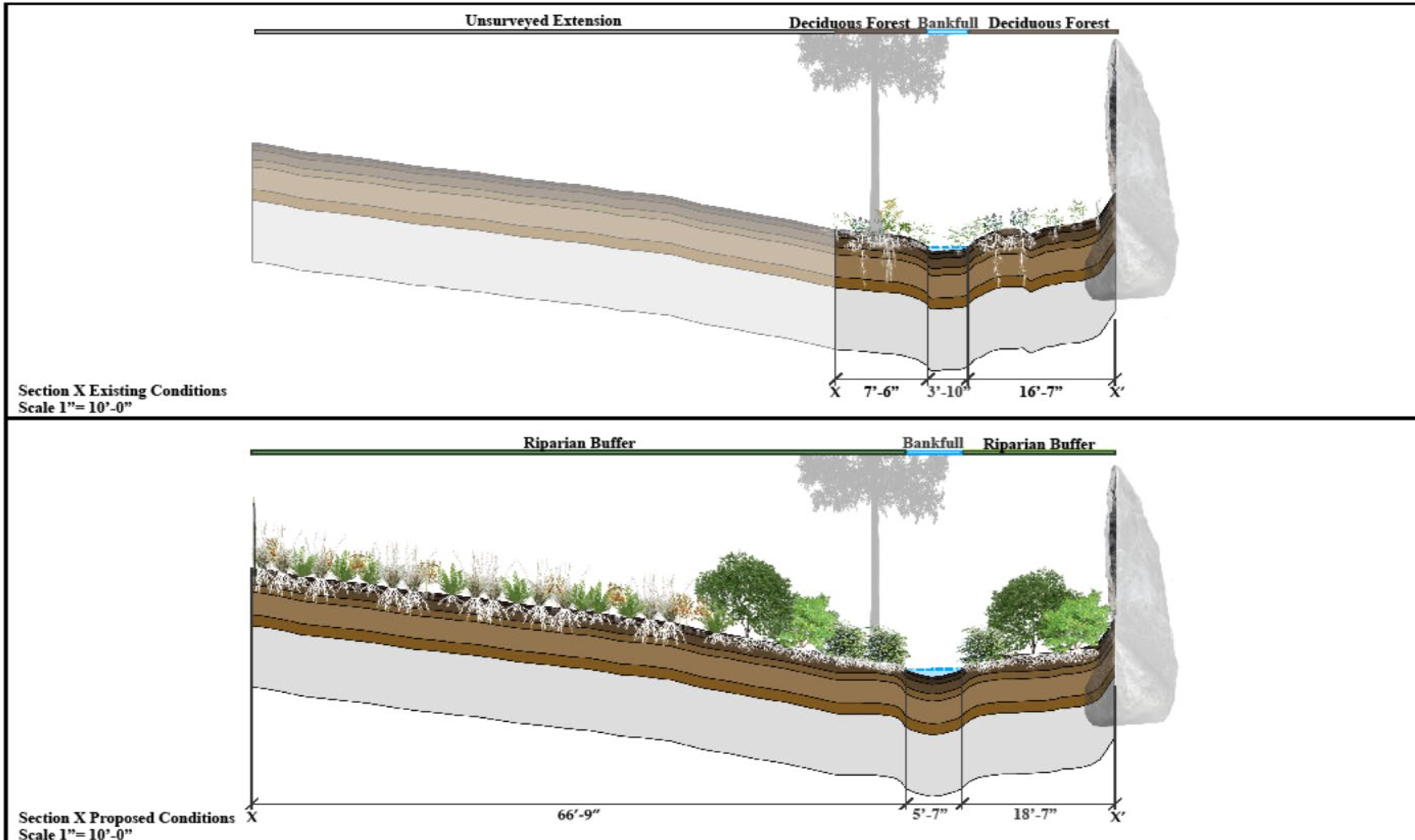


Figure 29. Section Cut Comparison of Existing and Proposed Stream Conditions for Section W. Illustrated by the author.

Figure 27 provides a cross-sectional view comparing Existing Conditions (top) and Proposed Conditions (bottom) for Section X.

In the Existing Conditions plan, the channel width at bankfull measures approximately 3'-10", bordered by a 7'-6" strip of deciduous forest on the left and a 16'-7" strip of deciduous forest on the right. The banks show limited vegetation, with visible erosion and exposed soil along the channel edges.

The Proposed Conditions plan adjusts the channel to resemble the characteristics of a Rosgen Type A stream while maintaining the thalweg in the same location. The bankfull width has been slightly increased to approximately 5'-7", and the total stream corridor width has been expanded to 66'-9" on the left and 18'-7" on the right. The redesigned profile incorporates a more gradual bank slope, improving hydrological connectivity with the surrounding riparian zone. Riparian buffers are established on both sides, introducing native grasses, shrubs, and trees to stabilize the banks and enhance ecological functionality.

Section Y

Overview

Section Y is located in an open pasture area where the stream flows along a steep slope and is heavily affected by livestock access and human modifications. These impacts have led to streambank erosion, sediment deposition, and limited riparian vegetation. The channel shows signs of instability, with irregular width and depth, and lacks structural features necessary for energy dissipation along the slope. Without a riparian buffer, this section also experiences elevated sediment and nutrient runoff from pastureland, further affecting water quality. These conditions underscore the need for comprehensive restoration measures to stabilize the channel, control flow energy, and improve ecological health in Section Y.

Visual Assessment

Figure 30. Section Y begins at a 36” culvert beneath the pasture access road. Fencing lines the left side of the stream, adjacent to a gravel road. Photo by author, July 13, 2023.

Figure 31, Section Y ends approximately 60 feet before the barn, with cattle having full access to the stream. Trampled vegetation and heavily used access points are evident throughout. Photo by author, July 13, 2023.

Figure 32. Heavy-use access area indicated by uneven banks and dried manure. The stream channel features rocks and cobble but is primarily sand. Photo by author, July 13, 2023.

Figure 28 through Figure 30 provide a visual overview of Section Y, highlighting the impacts of livestock access and the surrounding infrastructure on the stream. Figure 28 shows the beginning of Section Y at a 36” culvert beneath the pasture access road, with fencing along the left side adjacent to a gravel road. Moving downstream, Figure 29 illustrates the end of Section Y, located about 60 feet before the barn, where cattle have unrestricted access, resulting in trampled vegetation and well-worn access points. Figure 30 captures a heavy-use area marked by uneven banks and dried manure. The stream channel throughout Section Y contains rocks and cobble but primarily consists of sand, illustrating the combined effects of cattle activity and natural sediment composition on stream stability.

Geomorphic Assessment

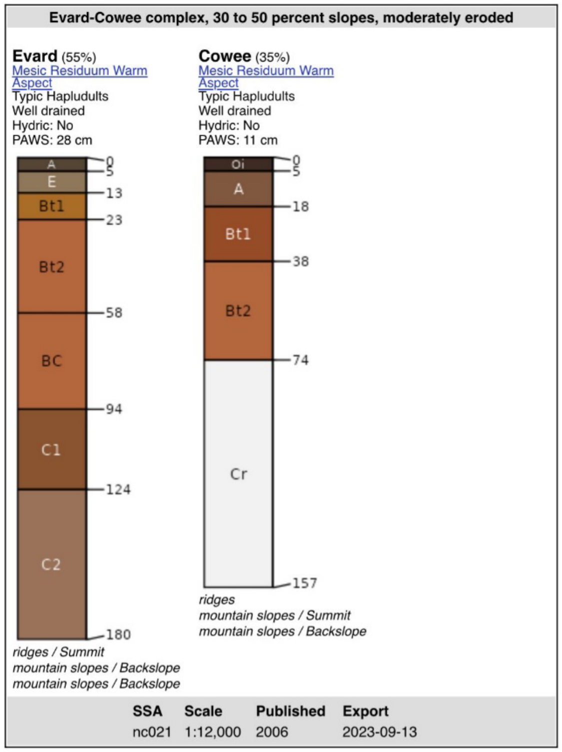


Figure 33. Illustration of Section Y soil composition based on the soil profile and classification of an Evard-Cowee complex. (UC Davis California Soil Resource Lab, 2023).

Section Y soil composition is classified as a Evard-Cowee complex. This complex consists of two primary soils: Evard (55%) and Cowee (35%). Both soils occur on steep 30 to 50 percent slopes with moderate erosion. This complex is typically found on ridges, summits, and mountain backslopes, with a composition of residuum derived from metamorphic materials. The soils are well-drained and non-hydric, with Evard reaching a depth of 180 cm and Cowee extending to 157 cm. They have high runoff potential and are classified by the USGS as not prime farmland.

Field Measurements and Calculations

Table 8. Section Y Existing Conditions and Field Calculations. Data collected by the author.

	Section Y
Watershed Area (sq mi)	0.11
Stream Classification	A
Channel Pattern	Single-thread
Bankfull Cross-Sectional Area (sq ft)	1.69
Bankfull Width (ft)	5.60
Bankfull Mean Depth (ft)	0.30
Bankfull Max Depth (ft)	0.64
Entrenchment Ratio (ft/ft)	1.61
W/D Ratio (ft/ft)	18.53
Sinuosity (ft/ft)	1.05
Stream Slope	0.13

Table 8 presents baseline measurements and calculated values for Section Y, including metrics for stream width, depth, bank height, and slope. These values inform the subsequent analysis of longitudinal and cross-sectional profiles and guide interpretations related to stream morphology and stability.

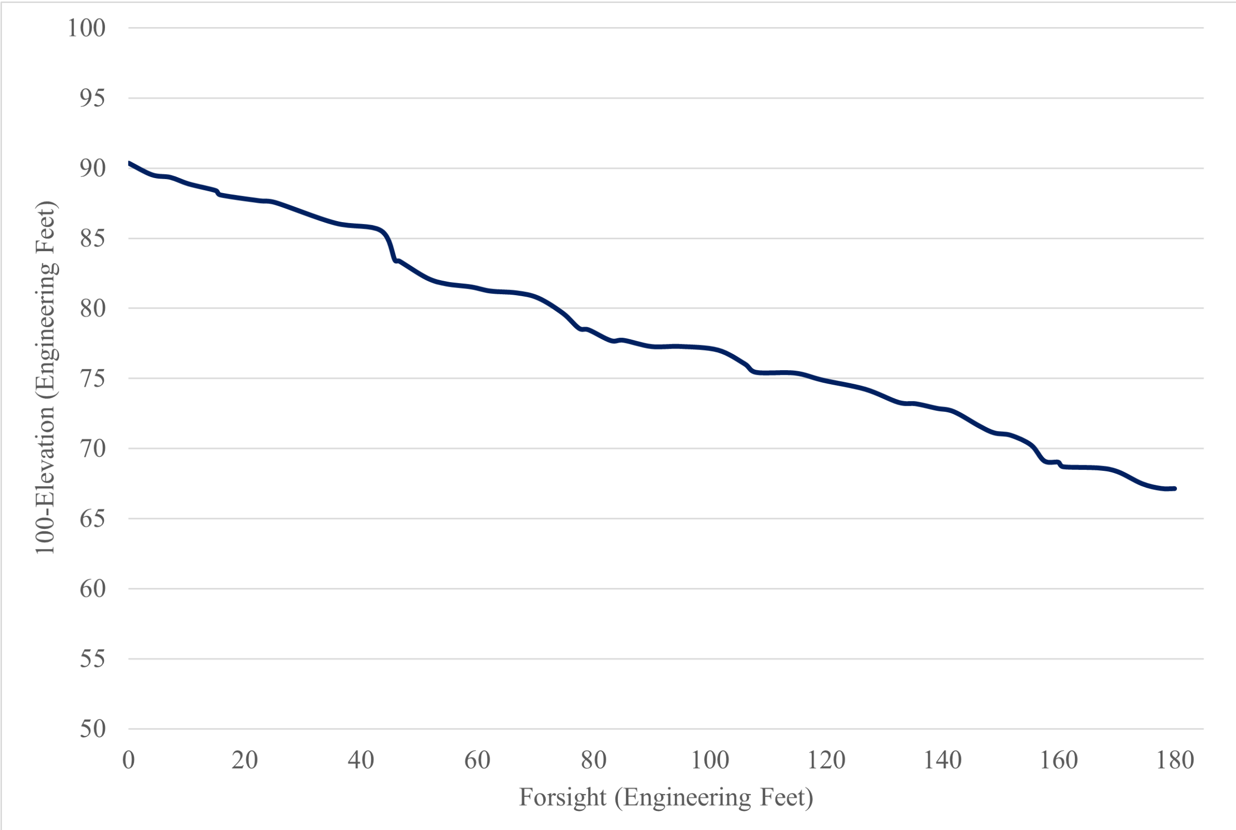


Figure 34. Longitudinal Profile of Section Y. Data collected by the author.

Figure 32 displays the longitudinal profile of Section Y, with foresight measurements recorded along a 180-foot reach. The profile shows a gradual elevation decrease of about 25 feet, with a generally continuous slope interspersed with subtle undulations that highlight minor variations in the streambed gradient, characteristic of a step-pool stream type. The overall 13% gradient aligns with the classification of a Type A stream.

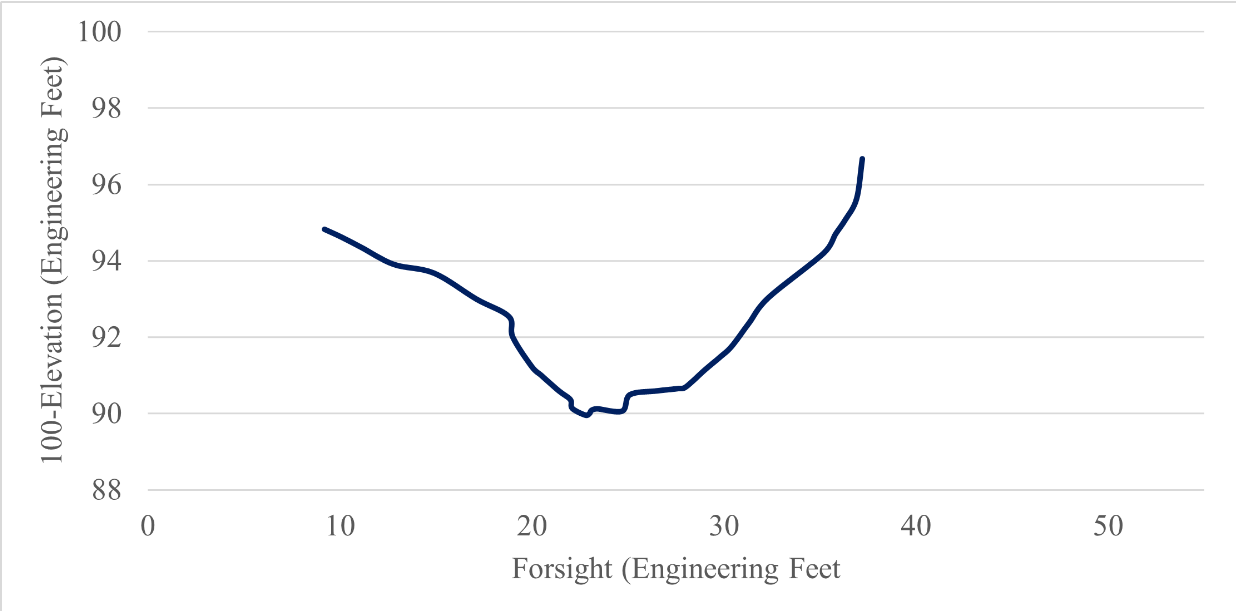


Figure 35. Cross-Section of Section Y. Data collected by the author.

Figure 33 presents the cross-sectional profile of Section Y, showing elevation changes across a 30-foot span of the stream width. The left bank descends gently, leveling out near the center of the channel, before rising steeply along the right bank to form a V-shaped cross-section. This profile suggests moderate entrenchment, typical of confined stream types.

Reference Curve Calculations and Proposed Conditions

Table 9. A Comparison of Existing, Reference, and Proposed Calculations for Section Y. Data collected by author.

	Section Y		
	Existing	Reference	Proposed
Watershed Area (sq mi)	0.110	-	0.110
Stream Classification	A	-	A
Channel Pattern	Single-thread	-	Single-thread
Bankfull Cross-Sectional Area (sq ft)	1.69	1.39	1.324
Bankfull Width (ft)	5.60	2.54	2.937
Bankfull Mean Depth (ft)	0.30	0.55	0.451
Bankfull Max Depth (ft)	0.640		0.790
Entrenchment Ratio (ft/ft)	1.607	<1.4	1.286
W/D Ratio (ft/ft)	18.534	<12	6.515
Sinuosity (ft/ft)	1.047	1-1.2	1.047
Stream Slope	0.129	0.04-0.1+	0.129

Table 9 presents field measurements, reference values based on NCD standards and reference curve calculations, and proposed calculations for design modifications for Section Y. Key metrics include bankfull area, width-to-depth ratio, and slope.

Environmental Challenges and Restoration Strategies

Table 10. Summary of Environmental Parameters and Proposed Modifications for Section Y. Data collected by author.

Section	Problems	Causes	Solutions	NCD Guidelines / NRCS CPS
Y	Stream channel instability	Irregular channel width	Reshape the channel to more uniform width	NCD Phase 6: Re-naturalize channel geometry; CPS 584, CPS 580
	Excessive energy along slope	Steep slope without energy control measures	Add step-pools for energy dissipation	CPS 584: Channel Bed Stabilization
	Severe bank erosion	Cattle access, lack of riparian buffer, straightened channel	Exclusion fencing, riparian buffer restoration	NCD Phase 6: Protect riparian areas from livestock access; CPS 382: Fence; CPS 391: Riparian Forest Buffer, CPS 390: Riparian Herbaceous Cover
	Undercutting of banks, vegetation loss	Minimal riparian buffer between stream and pasture	Stabilize banks by re-establishing forest and grass riparian buffer zones	NCD Phase 6: Establish riparian buffers for filtration and stability; CPS 391: Riparian Forest Buffer, CPS 390: Riparian Herbaceous Cover

Table 10 outlines the primary environmental challenges identified in Section Y, their underlying causes, and the proposed solutions designed to address each issue. The interventions aim to stabilize the channel, manage slope energy, reinforce bank stability, control sediment deposition, and establish protective riparian buffers. Each solution aligns with relevant NCD guidelines and NRCS Conservation Practice Standards, enhancing both the ecological health and structural stability of Section Y's proposed restoration design.

Proposed Restoration Design

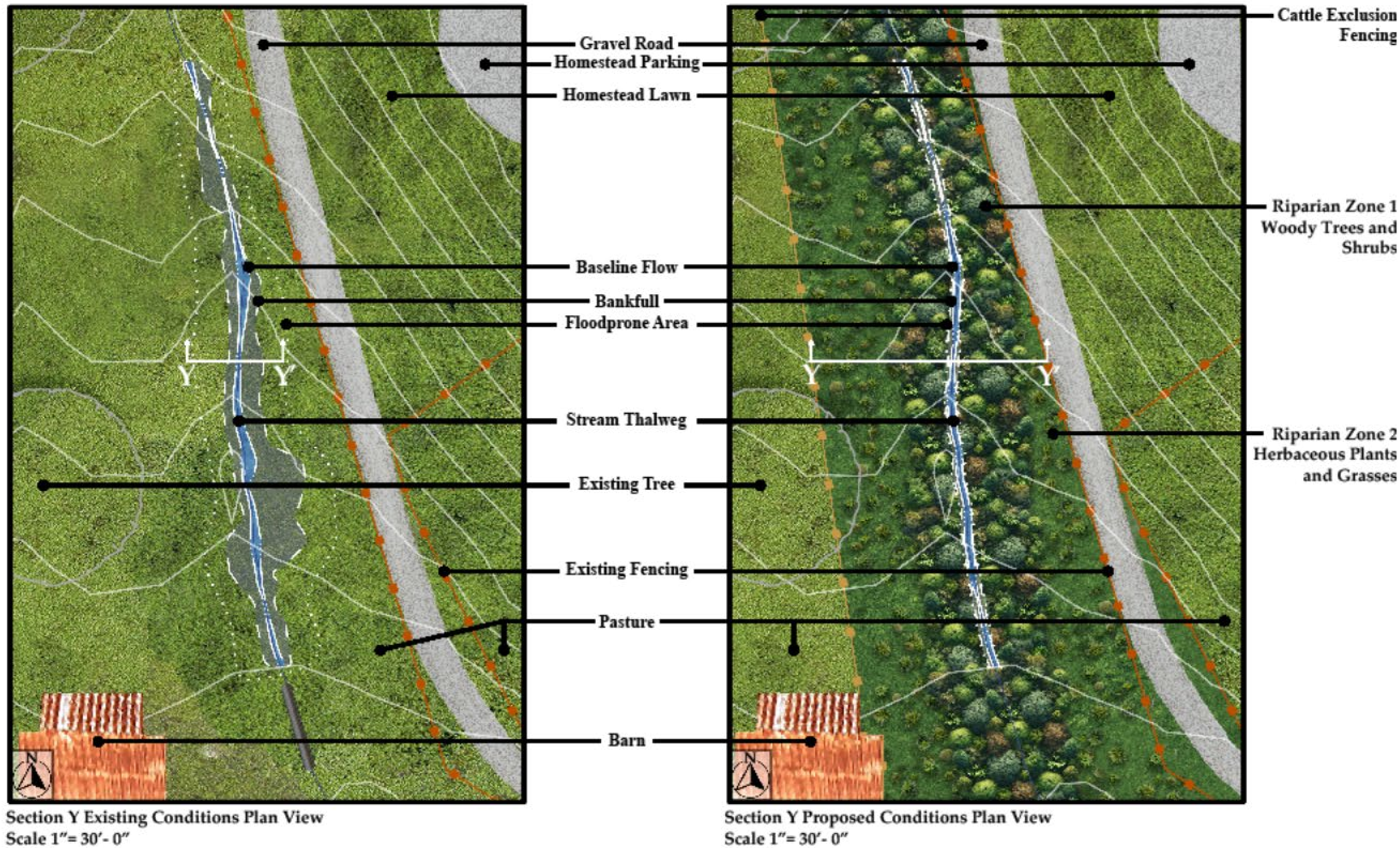
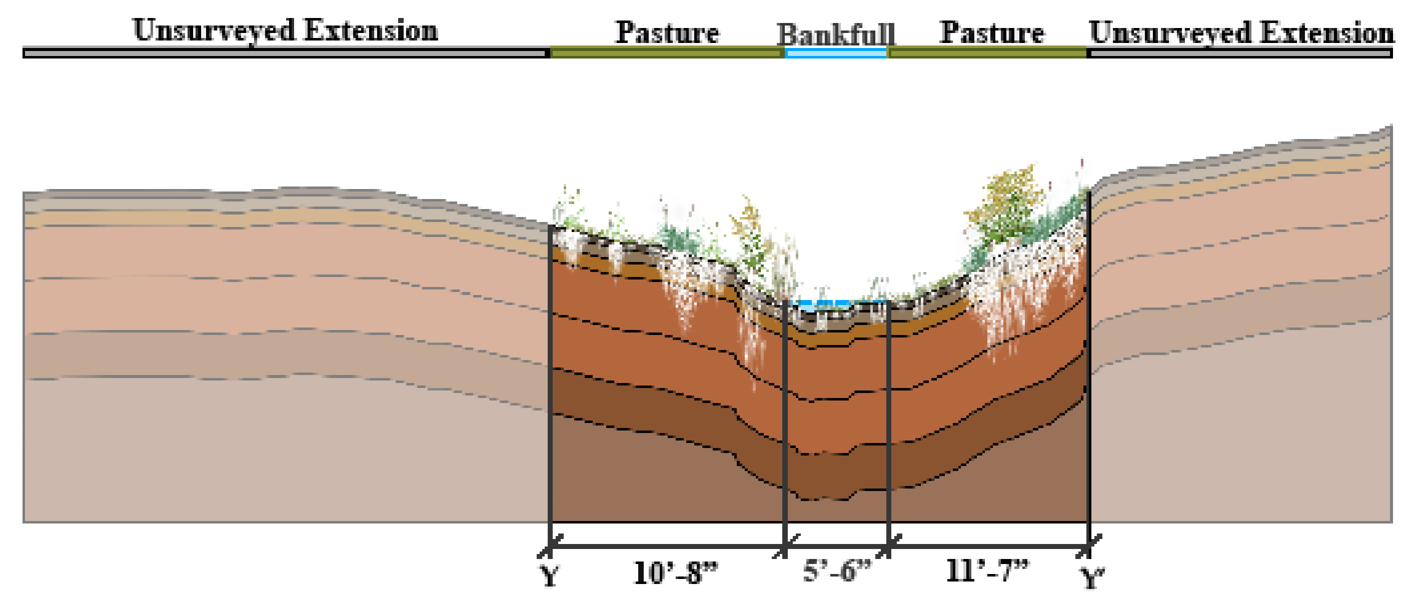


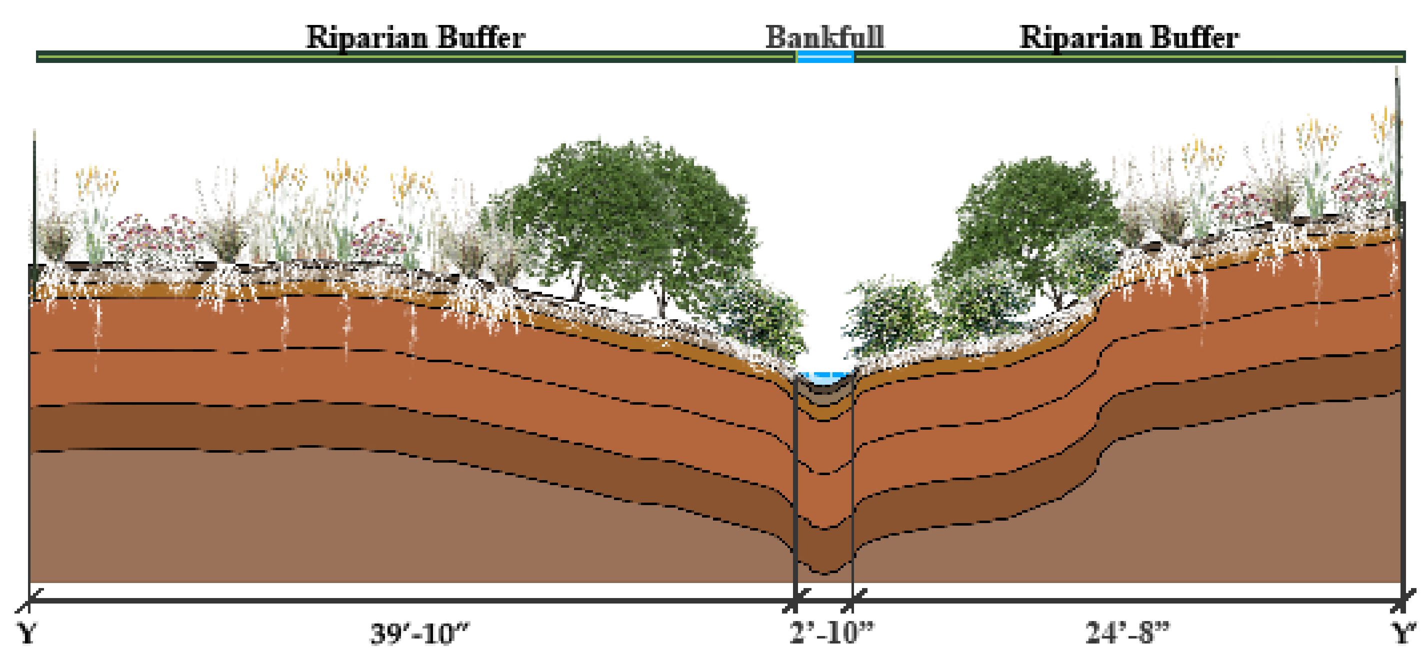
Figure 36. Master Plan Comparison of Existing and Proposed Stream Conditions for Section X. Illustrated by author.

Figure 34 provides a comparison of existing and proposed conditions for Section Y in the stream restoration project. The Existing Conditions view (left) shows the proximity of a gravel road and homestead parking area, minimal fencing for cattle exclusion, and open pastureland encroaching on the stream banks. The flood-prone area has limited vegetation, with exposed stream banks prone to erosion.

The design adds a two-zone riparian buffer in the Proposed Conditions view (right). Riparian Zone 1, adjacent to the stream, contains woody trees and shrubs, while Riparian Zone 2 includes herbaceous plants and grasses. Additionally, a cattle exclusion fence is installed to create a protected buffer, preventing livestock from accessing the stream and disturbing the banks. The proposed design also reestablishes a defined flood-prone area to help disperse high flows and reduce erosive pressure on the stream banks.



Section Y Existing Conditions
Scale 1”= 10’-0”



Section Y Proposed Conditions
Scale 1”= 10’-0”

Figure 37. Section Cut Comparison of Existing and Proposed Stream Conditions for Section Y. Illustrated by the author.

Figure 35 provides a cross-sectional view comparing Existing Conditions (top) and Proposed Conditions (bottom) for Section Y.

In the Existing Conditions plan, the channel at bankfull measures approximately 5'-6" in width, bordered by a 10'-8" section of pasture on the left and an 11'-7" section of pasture on the right. The stream banks are steep, with minimal vegetation and visible erosion along the channel edges, indicating significant instability and a lack of riparian buffer.

The Proposed Conditions plan restructures the channel to resemble the characteristics of a Rosgen Type A stream while maintaining the thalweg in the same location. The bankfull width is narrowed to approximately 2'-10", with the total stream corridor expanded to include a 39'-10" riparian buffer on the left and a 24'-8" riparian buffer on the right. The redesigned banks have a gentler slope, enhancing connectivity with the riparian areas and reducing erosion potential. The riparian buffers on both sides feature a mix of native grasses, shrubs, and trees.

Section Z

Overview

Section Z is located alongside a road in an open pasture area, where anthropogenic alterations have significantly impacted the stream's natural flow and stability. The channel has been straightened, leading to increased water velocity and entrenchment, which has contributed to streambank erosion and destabilization, particularly following rain events. Livestock has unrestricted access to both the stream and adjacent wetland areas, resulting in poor vegetation along the banks and increased sediment deposition. The lack of protective riparian cover and channel instability has reduced habitat quality and further exacerbated erosion. These conditions highlight the need for targeted restoration efforts to restore natural flow patterns, reconnect the stream to its floodplain, manage sediment deposition, and improve the ecological health and resilience of Section Z.

Visual Assessment

Figure 38. Section Z runs alongside the road, showing clear anthropogenic alterations from the straightening of the stream channel. Photo by author, September 3, 2023.

Figure 39. Stream on the left next to road, with wetland indicators in the pastureland shown by a shift from pasture grasses to rushes and other water-tolerant species. Cattle have direct access to both the stream and wetland areas. Photo by author, September 3, 2023.

Figure 40. The stream channel in Section Z is highly entrenched, with increased water velocity from channel straightening, evidenced by fallen streamside vegetation following a recent rain event. Photo by author, September 3, 2023.

Figure 36 through Figure 38 provide a visual assessment of Section Z, illustrating the impacts of anthropogenic modifications and livestock access on the stream and surrounding pastureland. Figure 36 shows the straightened stream channel running alongside the road, highlighting the clear anthropogenic changes in this section. Figure 37 reveals wetland characteristics in the pasture, where vegetation shifts from pasture grasses to water-tolerant species like rushes, with cattle having unrestricted access to both the stream and wetland areas. In Figure 38, the entrenched stream channel in Section Z demonstrates increased water velocity due to straightening, with fallen streamside vegetation following a recent rain event underscoring the impacts of this channel modification on stream stability and bank resilience.

Geomorphic Assessment

Section Z differs from the preceding sections due to its clear transition from soil types throughout its length from the upper to the lower parts of the section. The upper portion contains Tate loam, a well-drained soil on slopes ranging from 15 to 30 percent. The middle part of the section features a Dellwood-Reddies complex, characterized by moderately well-drained soils on 0 to 3 percent slopes, with occasional flooding. The lower portion transitions into Reddies sandy loam, a moderately well-drained soil also on 0 to 3 percent slopes, located in the floodplain.

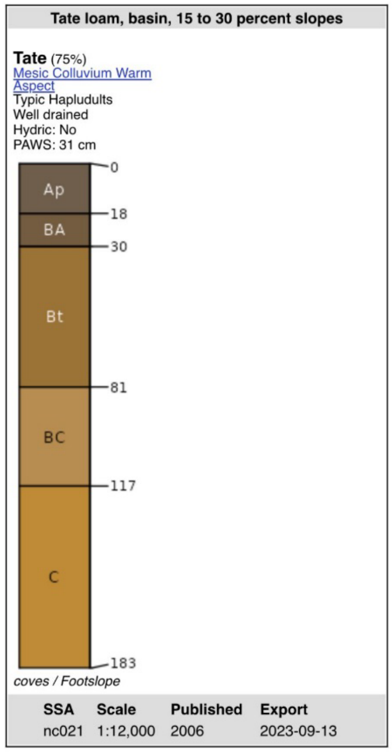


Figure 41. Illustration Section Z upper soil composition based on the soil profile and a Tate loam consociation classification. (UC Davis California Soil Resource Lab, 2023).

Section Z upper soil composition is classified as a Tate-loam consociation (75%). This soil occurs on 15 to 30 percent slopes. This complex is typically found in coves with a composition of residuum derived from metamorphic materials. The soil is well-drained and non-hydric, reaching a depth of 183cm. It has high runoff potential but is classified by the USGS as farmland of local importance.

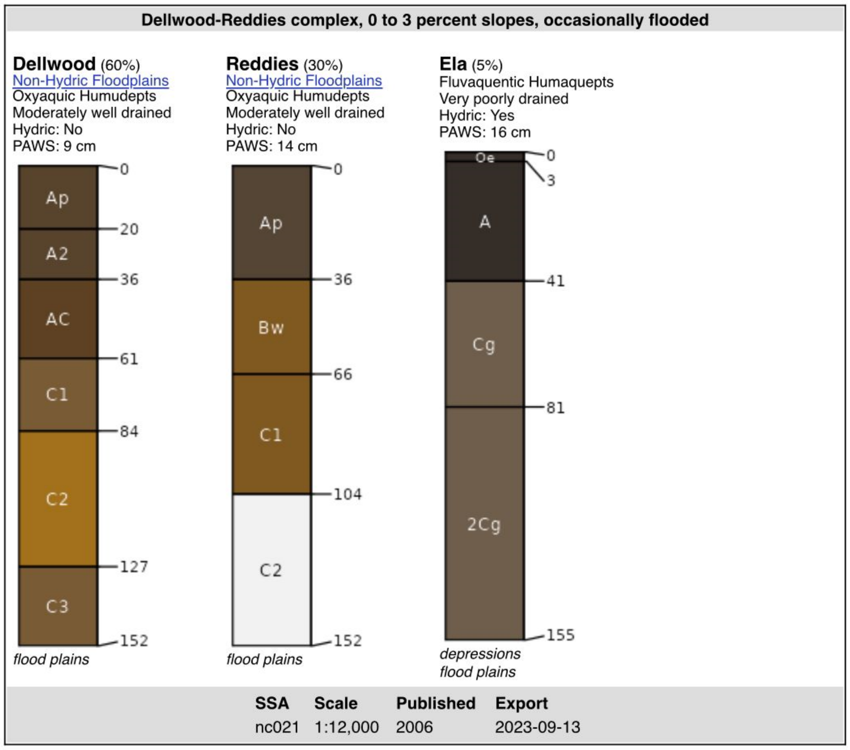


Figure 42. Illustration Section Z middle soil composition based on the soil profile and classification of a Dellwood-Reddies complex. (UC Davis California Soil Resource Lab, 2023)

Section Z middle soil composition is classified as a Dellwood-Reddies complex. This complex consists of three primary soils: Dellwood (60%), Reddies (30%), and Ela (5%). These soils occur on nearly flat slopes of 0 to 3 percent and are occasionally flooded. Dellwood and Reddies soils are found on non-hydric floodplains, with Dellwood having a moderately well-drained profile extending to 152 cm and Reddies extending to 152 cm as well. Ela soil is found in depressions and floodplains, is very poorly drained, and is hydric, extending to 155 cm. This complex has a very low to negligible runoff rate and is considered farmland of statewide importance.

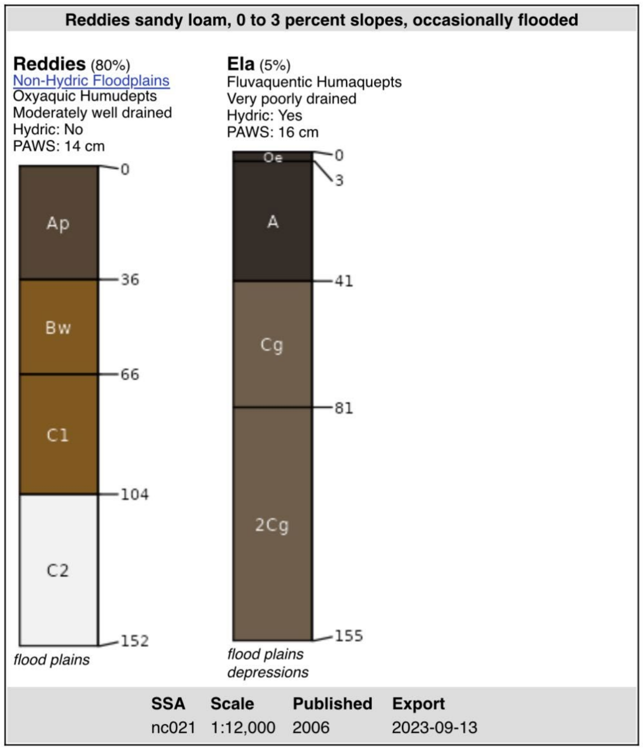


Figure 43. Illustration Section Z lower soil composition based on the soil profile and classification of a Reddies sandy loam consociation. (UC Davis California Soil Resource Lab, 2023)

Section Z lower soil composition is classified as Reddies sandy loam consociation, consisting of two primary soils: Reddies (80%) and Ela (5%). These soils occur on nearly level slopes of 0 to 3 percent and are occasionally flooded. Reddies soil is found on non-hydric floodplains, is moderately well-drained, and extends to a depth of 152 cm. Ela soil, located in floodplains and depressions, is very poorly drained and hydric, with a profile depth of 155 cm. This complex has a very low to negligible runoff rate and is considered prime farmland.

Field Measurements and Calculations

Table 11. Section Z Existing Conditions and Field Calculations. Data collected by the author.

	Section Z
Watershed Area (sq mi)	0.11
Stream Classification	-
Channel Pattern	Single-thread
Bankfull Cross-Sectional Area (sq ft)	-
Bankfull Width (ft)	-
Bankfull Mean Depth (ft)	-
Bankfull Max Depth (ft)	-
Entrenchment Ratio (ft/ft)	-
W/D Ratio (ft/ft)	-
Sinuosity (ft/ft)	1.02
Stream Slope	0.04

Table 11 presents baseline measurements and calculated values for Section Z, including watershed area, sinuosity, and slope. Several parameters, such as Bankfull Cross-Sectional Area, Bankfull Width, Bankfull Mean Depth, Bankfull Max Depth, Entrenchment Ratio, and Width-to-Depth Ratio, could not be measured remotely and typically require on-site field assessments. However, due to the significant anthropogenic changes in Section Z, including a straightened channel and modified landscape, on-site measurements were not deemed essential. These alterations would likely have influenced representative values, making remote assessment through ArcGIS and StreamStats an effective approach for obtaining baseline characteristics.

Reference Curve Calculations and Proposed Conditions

Table 12. A Comparison of Existing, Reference, and Proposed Calculations for Section Z. Data collected by author.

	Section Z		
	Existing	Reference	Proposed
Watershed Area (sq mi)	0.11	-	0.11
Stream Classification	-	-	E
Channel Pattern	Single-thread	-	Single-thread
Bankfull Cross-Sectional Area (sq ft)	-	1.39	1.40
Bankfull Width (ft)	-	2.54	2.56
Bankfull Mean Depth (ft)	-	0.55	0.55
Bankfull Max Depth (ft)	-	N/A	0.77
Entrenchment Ratio (ft/ft)	-	>2.2	17.71
W/D Ratio (ft/ft)	-	<12	4.69
Sinuosity (ft/ft)	1.02	>1.5	1.50
Stream Slope	0.040	<0.02-0.039	0.040

Table 12 presents field measurements, reference values based on NCD standards and reference curve calculations, and proposed calculations for design modifications for Section Y. Key metrics include bankfull area, width-to-depth ratio, and slope.

Environmental Challenges and Restoration Strategies

Table 13. Summary of Environmental Parameters and Proposed Modifications for Section Z. Data collected by author.

Section	Problems	Causes	Solutions	NCD Guidelines / NRCS CPS
Z	Stream channel straightening	Anthropogenic alterations from road construction	Increase stream sinuosity from 1 to nearly 1.5 to restore a natural flow pattern	NCD Phase 6: Restore natural channel geometry
	Entrenched channel with increased water velocity	Channel straightening, lack of natural vegetation	Reconnect floodplain and establish a two-zone riparian buffer with native grasses, shrubs, and trees	NCD Phase 4: Floodplain reconnection, CPS 580: Streambank Protection, CPS 395: Stream Habitat Improvement and Management
	Poor vegetation along banks and floodplain	Cattle trampling and limited riparian cover	Plant native riparian vegetation and establish a multi-zone buffer to stabilize banks	CPS 391: Riparian Forest Buffer, CPS 612: Tree/Shrub Establishment
	Altered sediment deposition	Increased flow velocity from straightened channel	Introduce erosion control structures to stabilize banks and reintroduce natural meanders to encourage sediment deposition	CPS 580: Streambank Protection
	Disconnected wetland area	Lack of integration with stream flow	Reinstate wetland connection to stream, allowing for natural water distribution and enhanced habitat quality	NCD Phase 6: Wetland integration; CPS 657: Wetland Restoration
	Unrestricted cattle access to stream and wetland	Lack of fencing along riparian areas	Install cattle exclusion fencing to protect stream and wetland from livestock access	CPS 382: Fence for livestock exclusion

Table 13 provides an overview of the main environmental challenges identified in Section Z, along with their causes and proposed restoration strategies. The solutions are designed to restore natural flow patterns, enhance bank stability, improve vegetation cover, and control sediment deposition, aligning with NCD and NRCS standards to support ecological resilience.

Proposed Restoration Design

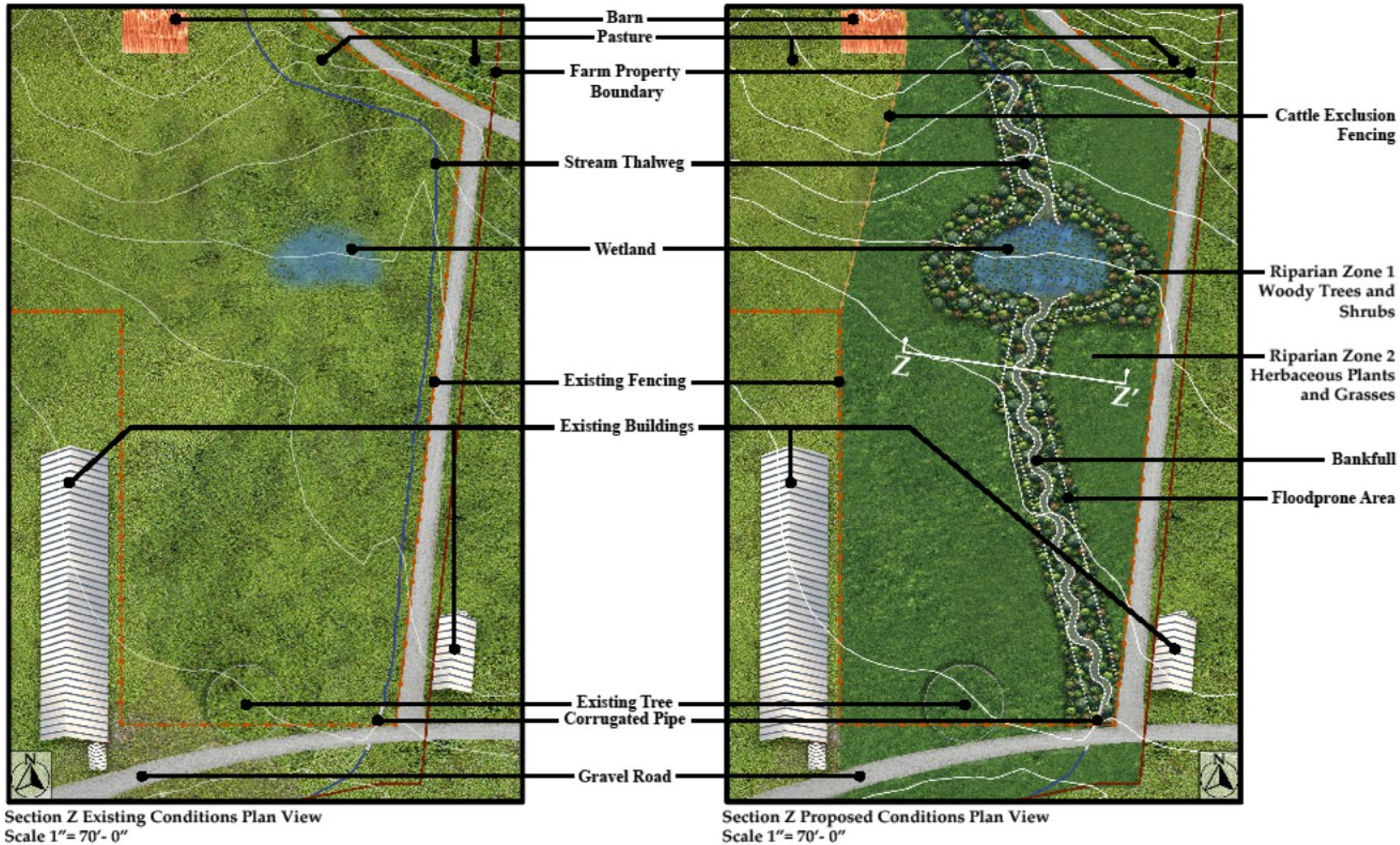


Figure 44. Master Plan Comparison of Existing and Proposed Stream Conditions for Section Z. Illustrated by author.

Figure 42 provides a comparison of existing and proposed conditions for Section Z in the stream restoration project. The Existing Conditions view (left) highlights the open pasture environment with minimal vegetation along the stream banks. With fencing only along the outer perimeter of the pasture, livestock has direct access to the stream, contributing to bank erosion and destabilization. A nearby gravel road and a corrugated pipe crossing indicate areas of human modification within the floodplain, further impacting the stream's natural flow and vegetation cover. Additionally, a wetland area near the stream remains largely unprotected, while the floodprone area lacks riparian buffer vegetation to mitigate erosion during high-flow events.

The Proposed Conditions view (right) presents the enhancements I designed to improve stream stability and ecological function. To slow water flow and reduce erosive forces, I increased the stream's sinuosity from 1 to nearly 1.5, allowing it to follow a more natural, winding path through the alluvial plain. I also directed the stream flow into the wetland area, enabling moisture to spread evenly across the surface through gravity, without relying on artificial control structures. As the stream exits the wetland, it re-channelizes to flow through the alluvial plain toward the established corrugated pipe outlet beneath the road, which then continues into Dillingham Creek.

Along the stream and wetland perimeters, I added a two-zone riparian buffer. Riparian Zone 1, adjacent to the stream, is planted with woody trees and shrubs, while Riparian Zone 2, set further back, includes herbaceous plants and grasses. I also installed a cattle exclusion fence to create a protected buffer, preventing livestock from disturbing the stream and banks. Additionally, I re-established a defined flood-prone area to allow high flows to spread out, reconnecting the floodplain and reducing bank erosion. This proposed design aims to enhance the stream's resilience against erosion and improve its ecological health.

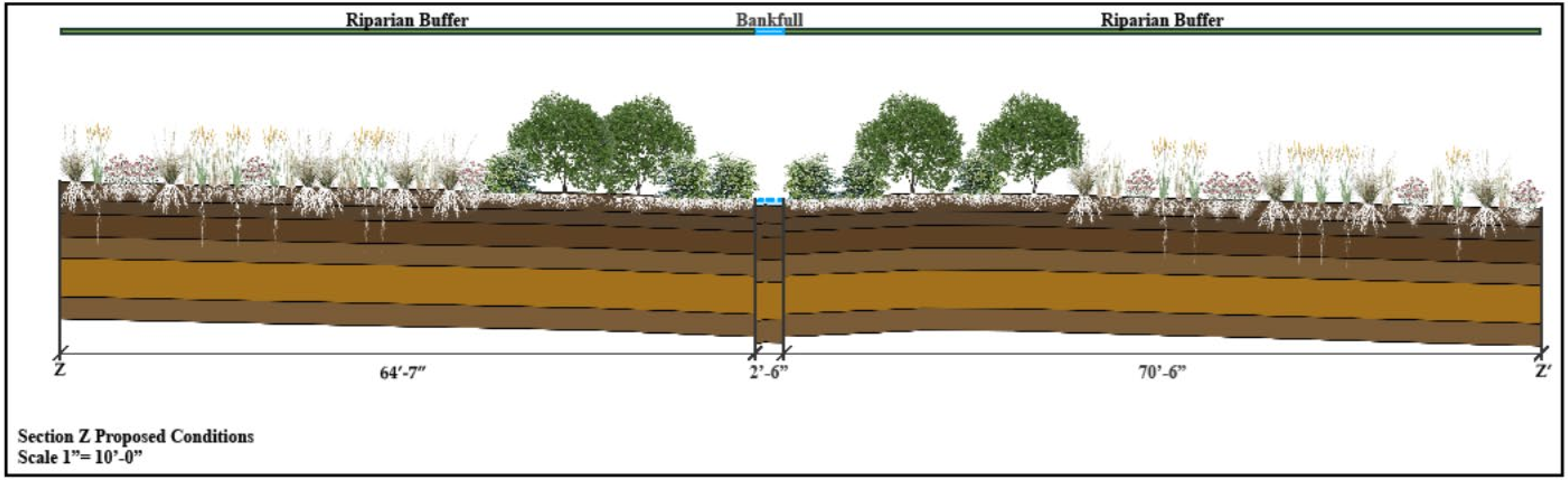


Figure 45. Section Cut Proposed Stream Conditions for Section Z. Illustrated by the author

Figure 43 provides a cross-sectional view of the Proposed Conditions Rendering for Section Z. This section does not have an existing conditions rendering due to the decision to analyze this section remotely instead of through direct field measurements.

The Proposed Conditions rendering for Section Z showcases the redesigned stream channel, structured to mimic the characteristics of a Rosgen Type E stream. This redesign includes a narrower channel with a bankfull width of approximately 2'-6", along with a high entrenchment ratio that allows the stream to readily reconnect with its floodplain during high flows. The channel is bordered by substantial riparian buffers with a 64'-7" buffer on the left and a 70'-6" buffer on the right. These buffers are densely planted with native vegetation, including a mix of grasses, shrubs, and trees, forming a layered structure that enhances bank stability and habitat diversity.

PLET Watershed Model Results

Overview

The PLET model results for the Dillingham Creek watershed indicate that the applied BMPs significantly reduced pollutant loads associated with cattle impacts. Nitrogen, phosphorus, biochemical oxygen demand (BOD), and sediment loads all decreased following BMP implementation, with reductions of over 30% observed for nitrogen, phosphorus, and sediment. These findings highlight the effectiveness of BMPs such as cattle exclusion, buffer zones, and alternative watering systems in mitigating nutrient and sediment runoff, contributing to improved water quality in the watershed.

Pollutant Reduction Rates

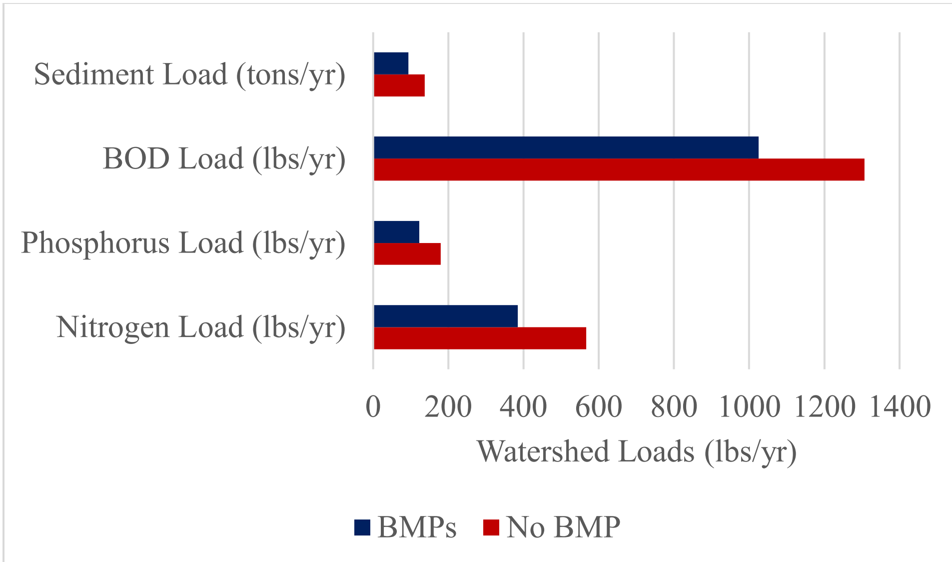


Figure 46. Comparison of watershed loads with and without BMPs applied. (PLET, 2024).

Figure 44 demonstrates that implementing BMPs in the Dillingham Creek watershed led to significant reductions in pollutant loads across all categories. Nitrogen load decreased from 566.77 lbs/year without BMPs to 384.27 lbs/year with BMPs, representing a 32.2% reduction. Phosphorus load was reduced by 31.74%, from 179.64 lbs/year to 122.63 lbs/year. BOD load dropped from 1306.68 lbs/year to 1025.25 lbs/year, a 21.54% reduction. Sediment load, measured in tons per year, declined from 137.37 tons/year to 93.4 tons/year, marking a reduction of 32.01%. These results indicate that the BMP configurations implemented within the watershed effectively reduced pollutant loads, particularly for nitrogen, phosphorus, and sediment.

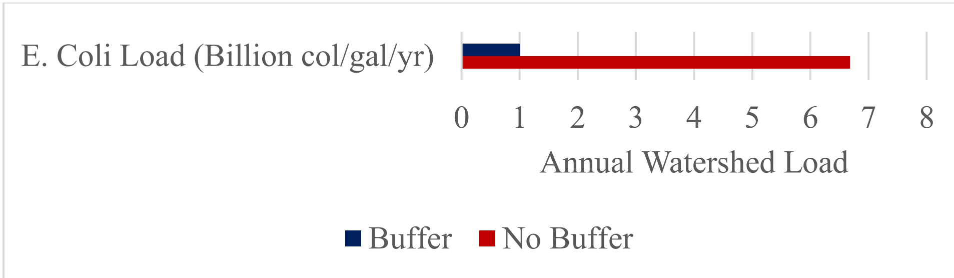


Figure 47. Comparison of *E. coli* watershed load with and without riparian buffer applied. (PLET, 2024).

Figure 45 illustrates that implementing a riparian buffer in the Dillingham Creek watershed yielded significant reductions in *E. coli* load, demonstrating the buffer's efficiency in improving water quality. The *E. coli* load decreased from 6.68 billion colonies per gallon per year without a riparian buffer to 1 billion colonies per gallon per year. This substantial decrease highlights the riparian buffer's effectiveness in filtering and reducing bacterial contamination, which is crucial for safeguarding water quality in agricultural watersheds.

CHAPTER 5

DISCUSSION

Case Study Findings

Overview

The findings from this case study underscore the effectiveness of integrating Best Management Practices (BMPs) with Natural Channel Design (NCD) principles to enhance water quality and restore stream functionality in a small Western North Carolina cattle farm. By addressing issues like sedimentation, nutrient runoff, and erosion through tailored, section-specific strategies, this approach promotes stream stability and habitat diversity while reducing pollutant levels. The integration of BMPs with NRCS Conservation Practice Standards (CPS) adds structure and scalability, making it suitable for similar farms across the region. Implementing this framework throughout the French Broad River Basin could lead to widespread water quality improvements, supporting both environmental sustainability and the economic value of clean waterways for the surrounding communities.

Integration of Natural Channel Design and Best Management Practices

The integration of NRCS Conservation Practice Standards (CPS), targeted agricultural BMPs, and Natural Channel Design (NCD) principles in this thesis project establishes a comprehensive approach to restoring and enhancing stream function on a small Western North Carolina cattle farm. These components are applied to mitigate specific agricultural impacts such as sedimentation, nutrient runoff, and erosion from livestock access, and they foster long-term resilience within the stream ecosystem. By aligning with NRCS guidelines and employing NCD methods, the project not only aims to restore ecological stability to the stream but also models scalable practices that could benefit similar pasturelands across the region.

The NCD framework in this project provides a foundation for achieving stability across the stream system, creating a resilient base that enhances the longevity of the restoration. By first implementing NCD principles to ensure channel stability and hydrologic connectivity, the design supports sustainable conditions essential for applying further improvements. Building upon this stable framework, NRCS BMPs are integrated to elevate the plan's effectiveness, specifically using CPS parameters to optimize BMPs such as erosion control, riparian restoration, and floodplain redefinition. This alignment with CPS standards not only strengthens the overall ecological functionality but also positions the project to qualify for government funding programs like EQIP, supporting its viability and scalability across similar agricultural settings (NRCS 2009a).

In this thesis, BMPs set by the NRCS play a central role in enhancing stream restoration by addressing the direct impacts of agricultural runoff, erosion, and vegetation loss. These BMPs, such as livestock exclusion, riparian buffers, and erosion control, are designed to improve water quality and support soil retention, helping the stream system build resilience. Aligned with these BMPs, the NRCS also provides CPS guidelines that add structured, technical standards for bank stabilization, nutrient filtering, and livestock management. Because the NRCS develops both BMPs and CPS, they are intentionally aligned, creating a cohesive framework that maximizes the effectiveness of BMPs while meeting funding criteria for conservation programs (NRCS 2020a). This alignment not only strengthens the restoration approach but also makes it cost-effective by ensuring eligibility for government funding options, adding practical and financial viability to the project's long-term design.

In this way, the project leverages the strengths of CPS and BMPs within the NCD framework to create a balanced, adaptable model for agricultural stream restoration. This approach demonstrates how well-implemented agricultural practices can integrate with natural channel dynamics, achieving mutual benefits for agricultural productivity and environmental restoration within a single, unified design.

Overall, the integrated approach of combining NCD principles, NRCS BMPs, and CPS guidelines establishes a comprehensive framework for restoring stream function on agricultural land. This layered method first builds a stable foundation with NCD, enabling BMPs to address specific impacts such as erosion and runoff, while CPS guidelines provide the structured, technical standards to enhance ecological effectiveness and secure funding support. Together, these elements not only strengthen the restoration strategy as a whole but also allow for the development of tailored techniques that are precisely suited to the unique conditions of each stream section. This integration serves as the basis for a nuanced, adaptable approach to restoration that meets both ecological and practical goals.

Stream Restoration Design Outcomes Overview

The outcomes from implementing a design plan integrating Best Management Practices (BMPs) and Natural Channel Design (NCD) demonstrate promising potential for improving stream function and water quality in Western North Carolina (WNC) pasturelands. These results underscore the value of section-specific restoration methods tailored to varied stream characteristics, including slope, sediment composition, and vegetation cover, across the sections W, X, Y, and Z. The observed reductions in pollutants and enhancements in bank stability and habitat diversity confirm that well-planned BMP applications can substantially mitigate the impacts of cattle farming on small stream ecosystems.

Section-Specific Stream Restoration

The distinctive geomorphic and hydrologic characteristics of each stream section guided specific restoration interventions, resulting in improvements in stability and function. Restoration methods were adapted section by section, responding to challenges such as impoundment, erosion, flow dynamics, and sediment management, which are issues commonly encountered in the diverse topography and elevations of WNC. This approach emphasizes the need for section-specific strategies to meet the varying demands of streams across WNC's mountainous terrain, especially on farmland where human alterations and land use needs must also be considered.

Section W required modifications to address impoundment and continuity issues caused by an access road crossing that blocked flow, resulting in upstream pooling and downstream erosion. Initially classified as a Type A stream with an 11% slope, Section W was reclassified to Type B to better fit its unique geomorphic and hydrologic features. The stream's spring-fed source provides a steady base flow, minimizing seasonal fluctuations and high-energy discharges, which aligns with the sediment transport balance of a Type B stream (NRCS 2020d; Rosgen 1996). Installing a pipe reduced the slope to 9%, restored flow continuity, mitigated downstream erosion, and supported a stable, moderately entrenched channel profile.

In Section X, with its steep slope, dense boulder presence, and fully forested location, NCD techniques were specifically tailored to stabilize the banks while maintaining downstream wetland connectivity. The use of toe wood and coir logs provides robust structural support, essential for stabilizing banks against high flow velocities while preserving ecological continuity to the wetland. This strategy underscores the importance of adapting restoration practices to fit section-specific conditions to promote resilience and function for all ecological habitats.

In Section Y, significant degradation from direct cattle access required reshaping the straightened channel to restore natural flow dynamics. Although bank stabilization and cattle exclusion fencing were implemented across all sections, Section Y's design prioritized preserving adjacent productive pastureland. To manage water energy within the existing stream area, a step-pool sequence was added to help disperse energy without using additional pastureland. Additionally, minimum riparian buffer requirements were used here, in contrast to the larger buffers in upper sections without prime pastureland.

In Section Z, situated within a low-gradient floodplain, reintroducing meanders to transform the section into a Type E stream enhanced its floodplain connection and improved sediment deposition control. This approach leveraged the area's natural flood-prone hydrology to better distribute flows during peak events, reducing bank erosion and promoting stability. The specific interventions in each section illustrate how distinctive features, such as slope, flow regime, and landscape position, require customized strategies to achieve sustainable restoration.

This section-based approach enabled the use of regionally appropriate reference curves, ensuring stability across diverse sections with distinct geomorphic and hydrologic characteristics. For this project, both forested and agricultural reference curves from Leigh's (2010) study were applied to accommodate the mixed conditions observed across Sections W, X, Y, and Z. These curves, tailored for small streams in the Southern Blue Ridge Mountains, were critical for establishing accurate baseline dimensions, hydraulic geometry relationships, and stream function targets. Leigh (2010) emphasized that using separate curves for forested and agricultural reaches helps in stream management, as forested areas generally yield different stream dimensions than those in pastureland due to differences in sediment transport dynamics and vegetation influence.

This difference in reference curve selection is especially relevant for Sections Y and Z, which, despite the addition of riparian buffers, will continue to exhibit pastureland characteristics for some time. Although these buffers are intended to encourage gradual forested growth, the areas will still function more like pastureland, especially in terms of sediment yield and vegetation structure, due to ongoing cattle grazing nearby. Given this extended establishment period, the agricultural reference curve was more appropriate for Sections Y and Z, as it better aligns with current conditions and anticipated land use.

The results and findings from this project emphasize the critical need for section-specific stream restoration, not only on this property but across Western North Carolina. Each section's unique geomorphic and hydrologic characteristics, whether impoundment from road crossings, steep slopes, pasture proximity, or low-gradient floodplains, require tailored interventions to improve stability, function, and resilience. These findings underscore that a one-size-fits-all approach would overlook essential site-specific factors that influence long-term restoration success. By adapting strategies to align with the diverse topography, land use, and environmental conditions typical of WNC, this project demonstrates how restoration can be optimized to address both ecological goals and land management needs. This approach serves as a model for future restoration efforts across the region, where varied elevations, land uses, and historic modifications require thoughtful, targeted methods to achieve sustainable and resilient outcomes.

Pollutant Load Reductions

The outcomes observed in this study underscore the potential effectiveness of Best Management Practices (BMPs) in reducing agricultural pollutant loads, as primarily estimated by the Pollutant Load Estimation Tool (PLET). PLET modeling estimated reductions exceeding 30% for nitrogen, phosphorus, and sediment loads, and over 20% for biochemical oxygen demand. The estimated reduction rates align closely with existing literature emphasizing BMP efficacy in mitigating non-point source pollution from livestock-heavy agricultural areas (Line, Osmond, & Childres, 2016).

The study estimated *E. coli* reduction separately through calculations rather than using PLET, as the model does not include *E. coli* reduction in its pollutant modeling capabilities. This calculation aligns with findings in the literature that vegetated buffers serve as natural filtration systems, reducing the passage of bacterial contaminants from manure-laden runoff before it reaches waterways (D. L. Osmond 2023). The calculated reductions suggest the effectiveness of combined forest and grass buffers in cattle pastures for lowering *E. coli* loads which is particularly relevant in regions like the French Broad River Basin, where *E. coli* from agricultural sources remains a critical water quality concern (Harris 2021; Jones 2022).

The findings from this study underscore the potential of BMPs to reduce agricultural pollutants effectively in erosion-prone, livestock-intensive settings. Modeling results indicate that BMPs, especially combined vegetated buffers, could be highly effective in mitigating nutrient and bacterial loads. In regions like the French Broad River Basin, where agricultural runoff remains a major concern, this approach offers a viable strategy for enhancing water quality. This study reinforces the value of BMPs, paired with targeted modeling tools, as a guide for sustainable pasture management and improved stream health across similar agricultural landscapes.

Scalability of an Integrated Natural Channel Design and Best Management Practice Framework in Western North Carolina

By applying a Best Management Practices (BMPs) and Natural Channel Design (NCD) framework on a farm typical of the French Broad River Basin's agricultural landscape, this study illustrates a scalable model for improving water quality across similar cattle farms in the region. In Buncombe County alone, pastureland spans 16,316 acres out of the county's 78,245 total farmland acres, highlighting the prevalence of livestock farming (USDA 2022). With 14,004 cattle countywide and 206 cows within the Dillingham Creek watershed in the French Broad River Basin, where this study is based, mitigating cattle-related runoff and erosion on small- to mid-sized farms is essential to enhance the basin's water quality (USDA 2022).

The 29-acre farm in this study, which reflects 43% of farms in Buncombe County that are between 10 and 49 acres, exemplifies the widespread applicability of this BMP-NCD approach across Western North Carolina (USDA 2022). Its success at this scale indicates the framework's feasibility and effectiveness for similar small- to medium-sized farms that dominate the region. As these farms collectively contribute to the region's water quality, scaling up this framework could generate cumulative environmental benefits in the French Broad River Basin.

In fact, implementing BMPs on cattle farms of this size throughout the French Broad River Basin is essential for improving water quality on a large scale. The French Broad River Basin faces ongoing environmental challenges primarily due to agricultural runoff, which contributes to elevated levels of sediment, nutrients, and bacterial contamination, particularly *E. coli* (Harris 2021). The 19-mile section of the river that was designated as impaired had E. coli concentrations in some areas reaching nearly eight times the EPA's safe limit for recreational waters (Jones 2022). DNA analysis of samples identified cattle as the most significant contributor to this contamination, highlighting the urgent need for targeted, sustainable practices to on agricultural land to address these issues at their source (Harris 2021).

Improving water quality throughout the French Broad River Basin would bring both ecological and economic gains. The French Broad River supports a thriving recreation-based economy, drawing 6.9 million visitors annually for activities like fishing and boating, which directly benefit local businesses (Parlier 2023). By reducing sediment and bacterial loads, the BMP-NCD framework not only enhances water quality but also bolsters the river's recreational value, strengthening economic resilience across the region.

The BMP-NCD framework implemented in this study offers a scalable, targeted solution to some of the French Broad River Basin's most pressing environmental challenges. By reducing pollutants from cattle farms throughout the basin, this model can significantly improve water quality, benefiting both local ecosystems and the regional economy. With broad implementation, this approach has the potential to secure the health of the French Broad River Basin for future generations.

Study Limitations

Time Constraints and Reliance on Remote Assessment

Due to time constraints, certain areas of the study site, particularly Section Z, could not be assessed through direct field measurements. Instead, remote assessment tools like ArcGIS and StreamStats were utilized to estimate key characteristics, such as slope and geomorphic attributes. While these tools provide valuable insights, they lack the precision and depth of information that on-site observations would offer. The reliance on remote assessment could introduce inaccuracies in the data, affecting the design's ability to fully capture the unique attributes of Section Z. This limitation suggests that future studies should prioritize comprehensive field assessments to improve data accuracy, especially in sections where remote assessments may overlook critical geomorphic or hydrological details.

Data Constraints on Reference Curves

The use of regional reference curves in this study introduced certain limitations due to potential discrepancies between the generalized data and the unique characteristics of the study site. While regional reference curves offer a valuable baseline for estimating natural stream dimensions, they may not fully capture local variability, particularly given the specific topography, mixed land use, and hydrological dynamics of Western North Carolina. As a result, the design's ability to accurately model natural stream conditions in sections with atypical slopes, sediment loads, or vegetation could be limited. This constraint suggests that while regional data provides a foundational estimate, site-specific adjustments may be necessary to achieve the highest degree of precision if the design were to be implemented.

Budget and Practicality for Small-Scale Farmers

The reliance on NRCS BMP standards assumes that landowners can access financial assistance and resources, such as those provided by the USDA and NRCS cost-share programs. However, small-scale farmers may face barriers in securing the funds or technical support needed to implement these BMPs, even if cost-sharing programs are available. This financial constraint could limit the design's applicability in real-world settings, particularly in cases where landowners must bear the costs independently. The practicality of the proposed design is thus contingent on the availability of funding and support mechanisms, which, if absent, could hinder small-scale farmers from achieving the intended ecological benefits.

Lack of Experimental Validation

This thesis presents a theoretical design without field implementation, meaning the proposed pollutant reduction, bank stability, and habitat enhancement measures have not been empirically validated. Without experimental data, the anticipated improvements remain speculative, relying on established literature values and BMP efficacy reported in comparable studies. This introduces uncertainty regarding how effectively the design would function under the actual conditions and constraints of the study site. Experimental validation would help confirm the design's performance and adaptability and provide insights into any adjustments needed to address unforeseen challenges that could arise during implementation.

Future Research

Future research could explore innovative, integrated land management practices to support agricultural productivity alongside stream restoration. Investigating the socioeconomic impacts of stream restoration on agricultural landowners would provide insights into the costs, benefits, and barriers they encounter, including productivity impacts, cost-sharing program accessibility, and perceptions of ecological benefits. Rotational grazing and alternative grazing systems could be evaluated as complementary BMPs, reducing erosion and runoff while improving soil health, water retention, and forage regrowth, which could potentially offset land lost to riparian buffers. Additionally, integrating agroforestry within riparian buffers could provide income through tree crops, such as fruit, nuts, or timber, while preserving ecological functions; studies could assess suitable tree species and the market potential for these agroforestry products. Silvopasture in adjacent areas, which combines trees, forage, and livestock, offers a dual approach to maintaining productive land use near buffer zones while promoting soil stability and water quality. Research into these multi-functional approaches would provide farmers with sustainable, economically viable options that align conservation efforts with their agricultural goals.

CHAPTER 6

CONCLUSION

The overall objective of this thesis was to develop and propose a comprehensive stream restoration design using Best Management Practices (BMPs) and Natural Channel Design (NCD) methods to address water quality and ecological challenges on a cattle farm in Western North Carolina. The proposed design strategically incorporates interventions such as livestock exclusion fencing, riparian buffer establishment, and bank reinforcement to address specific issues of erosion, sedimentation, and *E. coli* contamination in the study area. Key findings demonstrate that tailored combinations of NCD and BMPs can significantly reduce these water quality stressors, offering a viable approach to enhancing stream function and ecological stability while maintaining agricultural productivity.

This study contributes a replicable model for small- to medium-sized farms across the region, showcasing the potential of BMP-driven strategies to align agricultural practices with environmental conservation objectives. By achieving modeled reductions in sediment, nutrient, and bacterial loads, the project not only enhances stream stability but also underscores the financial viability of these practices, as they align with NRCS Conservation Practice Standards (CPS), which support cost-sharing opportunities for farmers. Through quantifiable pollutant reductions and improved channel stability, the research illustrates the scalability of its methods within similar agricultural landscapes, providing valuable insights for regional water quality management and sustainable land use practices.

While the research demonstrates promising results, several limitations warrant consideration. The design remains a theoretical proposal, not implemented in practice, and thus requires further study to validate the observed benefits under real-world conditions. Additionally, the project focuses on a specific agricultural setting; varying land uses or larger-scale operations may require adaptations to the BMP and NCD framework presented here. Despite these limitations, the findings offer a foundational approach that can be refined and adjusted for diverse agricultural and environmental contexts, with scalability for broader applications within the French Broad River Basin.

The proposed framework sets a basis for future research in sustainable agriculture and watershed management. Future studies could evaluate the socioeconomic impacts of adopting BMP and NCD frameworks, particularly regarding farm productivity, cost-sharing participation, and landowner attitudes toward ecological benefits. Further exploration of complementary BMPs, such as rotational grazing, agroforestry, and silvopasture, could enhance the model by incorporating soil health and productivity benefits. As a whole, this thesis contributes a practical framework that suggests how sustainable agricultural practices may harmonize ecological and economic goals, providing a model for future restoration and conservation initiatives in agricultural landscapes.

APPENDIX

A Longitudinal Profile Field Measurements

Section W					
Longitudinal-Profile Survey					
Data Collected: 7.13.23					
Weather Conditions: Partly Cloudy 85°					
Data Collected by: Morgan Burchfiel, Noah Cleveland					
Data Entered: 8.4.23					
Data Entered by: Morgan Burchfiel					
Point Number	Tape Measure (Engineering Feet)	Elevation (Engineering Feet)	100-Elevation (Engineering Feet)	Head of Riffle #	Notes
1	0.00	1.41	98.59		
2	1.67	1.59	98.41		
3	3.50	1.79	98.21		
4	7.00	2.22	97.78		
5	8.33	2.42	97.58	1	
6	9.83	2.73	97.27		
7	12.00	3.23	96.77		
8	14.00	3.63	96.37		
9	15.00	3.87	96.13		
10	16.58	4.14	95.86	2	
11	19.50	4.9	95.1		
12	22.00	5.6	94.4		
13	25.33	5.99	94.01		
14	26.67	6.14	93.86	3	
15	29.00	6.46	93.54		
16	31.00	6.88	93.12	4	
17	34.58	7.58	92.42		
18	38.00	7.94	92.06		
19	41.25	8.23	91.77		
20	43.00	8.3	91.7		
21	46.92	8.53	91.47		
22	47.83	8.62	91.38	5	
23	50.25	8.86	91.14		
24	53.50	9.05	90.95		
25	56.00	9.3	90.7		
26	59.00	9.52	90.48		

27	61.83	9.65	90.35		
28	63.67	9.85	90.15		
29	66.50	10.01	89.99	6	
30	68.33	10.18	89.82		
31	71.17	10.46	89.54		
32	72.00	10.54	89.46		
33	74.00	10.67	89.33		
34	75.50	10.81	89.19	7	
35	75.83	10.93	89.07		
36	78.00	11.05	88.95		
37	80.00	11.15	88.85		
38	82.00	11.23	88.77		
39	85.00	11.49	88.51	8	
40	86.67	11.68	88.32		
41	88.00	11.81	88.19		
42	90.67	11.98	88.02		
43	93.83	12.31	87.69		
44	95.00	12.44	87.56		
45	103.83	13.13	86.87		
46	104.25	13.43	86.57		
47	105.25	13.61	86.39		
48	108.50	13.94	86.06		
49	109.00	14.11	85.89		
50	111.67	14.45	85.55		
51	116.67	14.86	85.14	9	
52	119.00	15.12	84.88		
53	120.00	15.25	84.75		
54	122.00	15.54	84.46	10	Detailed Cross-Section
55	123.00	15.85	84.15		
56	127.00	16.08	83.92		
57	131.00	16.55	83.45	11	
58	135.00	17.03	82.97		Beginning of Pool
59	138.50	17.09	82.91		
60	145.00	17.2	82.8		End of Pool/Beginning of Road
61	167.42	17.7	82.3		End of Road
62	175.67	21.1	78.9		
63	176.00	20.89	79.11		
64	177.75	21.4	78.6		Dry Streambed
65	180.00	21.47	78.53		End of Measurement

Section X					
Longitudinal-Profile Survey					
Data Collected: 7.13.23					
Weather Conditions: Partly Cloudy 85°					
Data Collected by: Morgan Burchfiel, Noah Cleveland					
Data Entered: 8.4.23					
Data Entered by: Morgan Burchfiel					
Point Number	Tape Measure (Engineering Feet)	Elevation (Engineering Feet)	100-Elevation (Engineering Feet)	Head of Riffle #	Notes
1	0.00	2.49	97.51		
2	5.50	4.08	95.92	1	
3	7.00	4.32	95.68		
4	9.00	5	95		
5	11.67	5.49	94.51		
6	15.33	6.2	93.8	2	
7	16.25	7.05	92.95		
8	20.67	7.85	92.15		
9	22.83	8.46	91.54	3	
10	24.42	9.21	90.79		
11	28.67	9.71	90.29		
12	31.58	10.27	89.73	4	
13	37.00	11.03	88.97		
14	40.50	11.5	88.5	5	
15	45.67	12.33	87.67		
16	49.00	13.11	86.89		
17	52.00	13.45	86.55	6	
18	60.50	14.83	85.17		
19	65.00	15.57	84.43	7	
20	68.33	16.47	83.53		
21	71.42	17.26	82.74		
22	74.00	17.69	82.31		
23	76.00	17.92	82.08		
24	78.00	18.28	81.72		
25	85.00	18.73	81.27		
26	89.00	19.29	80.71	8	Detailed Cross-Section
27	92.00	19.5	80.5		
28	95.67	19.99	80.01		
29	98.25	20.39	79.61	9	
30	100.00	21.01	78.99		

31	102.00	21.46	78.54		
32	109.50	22.54	77.46	10	
33	112.17	22.89	77.11		
34	116.58	23.5	76.5		
35	120.00	23.9	76.1		
36	124.00	24.27	75.73		
37	129.33	25.08	74.92		Top of Wetland
38	140.00	27.15	72.85		
39	145.00	27.77	72.23		
40	149.33	28.46	71.54		
41	156.00	29.59	70.41		
42	164.00	31.09	68.91		
43	169.50	32.04	67.96		
44	175.00	33.33	66.67		
45	180.00	34.66	65.34		End of Wetland

Section Y					
Longitudinal-Profile Survey					
Data Collected: 7.5.23					
Weather Conditions: Partly Cloudy 75°					
Data Collected by: Morgan Burchfiel, Noah Cleveland					
Data Entered: 7.26.23					
Data Entered by: Noah Cleveland					
Point Number	Tape Measure (Engineering Feet)	Elevation (Engineering Feet)	100-Elevation (Engineering Feet)	Head of Riffle #	Notes
1	0.00	9.65	90.35	1	
2	4.00	10.48	89.52		
3	7.17	10.66	89.34	2	
4	10.33	11.13	88.87		
5	15.00	11.61	88.39		
6	15.75	11.91	88.09		
7	22.50	12.33	87.67		
8	25.25	12.46	87.54	3	
9	35.50	13.92	86.08		
10	43.42	14.46	85.54	4	
11	45.83	16.58	83.42		
12	46.58	16.64	83.36	5	

13	51.33	17.84	82.16		
14	54.67	18.26	81.74		
15	59.00	18.48	81.52	6	
16	62.25	18.77	81.23		
17	66.75	18.9	81.1	7	
18	70.50	19.27	80.73		
19	74.75	20.36	79.64		
20	77.50	21.43	78.57		
21	79.17	21.54	78.46	8	
22	83.00	22.31	77.69		
23	85.17	22.28	77.72	9	
24	90.00	22.73	77.27	10	
25	95.00	22.72	77.28		
26	101.41	22.98	77.02	11	
27	106.00	23.96	76.04		
28	108.00	24.57	75.43		
29	114.66	24.62	75.38	12	
30	119.50	25.13	74.87	13	
31	126.75	25.77	74.23	14	
32	132.50	26.71	73.29		
33	135.50	26.81	73.19	15	
34	139.00	27.13	72.87		
35	142.00	27.37	72.63	16	
36	146.50	28.42	71.58		
37	149.00	28.89	71.11		
38	151.83	29.06	70.94	17	
39	155.33	29.76	70.24	18	
40	157.58	30.89	69.11		
41	160.00	30.98	69.02	19	
42	160.83	31.3	68.7		
43	167.00	31.39	68.61	20	
44	170.25	31.66	68.34		
45	174.41	32.51	67.49		
46	177.66	32.85	67.15		
47	180.00	32.86	67.14		

B Detailed Cross-Section Field Measurements

Section W				
Detailed Cross-Section Survey				
Data Collected: 6.29.23				
Weather Conditions: Sunny 80°				
Data Collected by: Morgan Burchfiel, Eddie Burchfiel				
Data Entered: 8.4.23				
Data Entered by: Morgan Burchfiel				
Point Number	Forsight (Engineering Feet)	Elevation (Engineering Feet)	100-Elevation (Engineering Feet)	Notes
1	4.99	1.04	98.96	
2	6.1	1.5	98.5	
3	7.7	1.56	98.44	
4	9.2	1.84	98.16	
5	10.1	2.27	97.73	
6	11.4	2.53	97.47	
7	12.8	2.94	97.06	
8	13.9	3.38	96.62	
9	15.1	3.75	96.25	
10	16.2	4.04	95.96	
11	17	4.3	95.7	
12	18.3	4.42	95.58	
13	19	4.63	95.37	
14	19.9	4.91	95.09	
15	20.7	5.01	94.99	
16	21.4	5.34	94.66	
17	21.9	5.59	94.41	
18	22.4	5.83	94.17	
19	22.5	6.08	93.92	
20	22.7	6.39	93.61	
21	22.9	6.57	93.43	
22	23.8	6.71	93.29	
23	23.9	6.92	93.08	
24	24.3	7.19	92.81	
25	25	7.31	92.69	
26	25.4	7.53	92.47	
27	25.8	7.82	92.18	
28	25.9	8.09	91.91	

29	26.6	8.37	91.63	
30	26.7	8.61	91.39	
31	27.4	8.65	91.35	
32	27.5	8.73	91.27	
33	27.9	8.75	91.25	
34	28.5	8.91	91.09	
35	29.2	8.92	91.08	
36	29.4	8.89	91.11	
37	29.7	8.88	91.12	
38	29.8	8.85	91.15	
39	30.1	8.75	91.25	
40	30.6	8.68	91.32	
41	30.9	8.6	91.4	
42	31.3	8.69	91.31	
43	32.1	8.53	91.47	
44	32.3	7.77	92.23	
45	32.7	8.56	91.44	
46	33.2	8.55	91.45	
47	34.1	8.45	91.55	
48	34.5	8.33	91.67	
49	35.5	8.45	91.55	
50	35.9	8.11	91.89	
51	36.5	7.85	92.15	
52	37.5	7.5	92.5	
53	38.3	7.31	92.69	
54	39.2	7.3	92.7	
55	40.1	7.24	92.76	
56	40.8	7.14	92.86	
57	41	7.03	92.97	
58	41.5	7	93	
59	42	6.93	93.07	
60	43	6.88	93.12	
61	43.7	6.75	93.25	
62	44	6.62	93.38	
63	44.6	6.42	93.58	
64	45.2	6.19	93.81	
65	45.8	5.9	94.1	
66	46.6	5.72	94.28	
67	47.1	5.53	94.47	

68	47.5	5.31	94.69	
69	48.2	5.14	94.86	
70	48.6	4.98	95.02	
71	49	4.77	95.23	
72	49.7	4.6	95.4	
73	50	4.3	95.7	

Section X				
Detailed Cross-Section Survey				
Data Collected: 6.29.23				
Weather Conditions: Sunny 80°				
Data Collected by: Morgan Burchfiel, Eddie Burchfiel				
Data Entered: 8.4.23				
Data Entered by: Morgan Burchfiel				
Point Number	Forsight (Engineering Feet)	Elevation (Engineering Feet)	100-Elevation (Engineering Feet)	Notes
1	7.2	5.2	94.8	Right Bank
2	9.3	5.36	94.64	
3	11.6	5.63	94.37	
4	13.6	5.8	94.2	
5	14.6	6.08	93.92	Top of Right Bank
6	15.3	6.33	93.67	
7	16.1	6.76	93.24	
8	16.4	7.04	92.96	
9	16.5	7.21	92.79	Right Bankfull
10	16.7	7.51	92.49	Right Top of Water
11	16.9	7.63	92.37	Thalweg
12	17.8	7.59	92.41	
13	18.1	7.52	92.48	
14	18.8	7.54	92.46	
15	19.3	7.47	92.53	
16	19.8	7.48	92.52	
17	20.2	7.37	92.63	Left Top of Water
18	20.6	7.17	92.83	Left Bankfull
19	20.9	6.81	93.19	
20	21.3	6.36	93.64	
21	22.1	5.96	94.04	

22	22.7	5.58	94.42	Top of Left Bank
23	23.2	5.33	94.67	
24	24.1	5.1	94.9	ROCK
25	25.5	5.1	94.9	END OF ROCK
26	26.2	5.04	94.96	
27	27	5.65	94.35	
28	28.5	4.94	95.06	
29	29.5	4.8	95.2	
30	30.2	4.57	95.43	
31	31.1	4.5	95.5	
32	32.1	4.39	95.61	
33	33.3	3.99	96.01	
34	34.1	3.45	96.55	
35	35.6	0.94	99.06	Left Bank

Section Y				
Detailed Cross-Section Survey				
Data Collected: 6.29.23				
Weather Conditions: Sunny 80°				
Data Collected by: Morgan Burchfiel, Eddie Burchfiel				
Data Entered: 8.4.23				
Data Entered by: Morgan Burchfiel				
Point Number	Forsight (Engineering Feet)	Elevation (Engineering Feet)	100-Elevation (Engineering Feet)	Notes
1	9.2	5.17	94.83	
2	10.1	5.38	94.62	
3	11.1	5.64	94.36	
4	12.8	6.09	93.91	
5	14.9	6.32	93.68	
6	17.1	7	93	
7	18.8	7.46	92.54	
8	19	8	92	
9	20	8.78	91.22	
10	20.5	9.01	90.99	
11	21.4	9.41	90.59	Right Bankfull
12	22	9.64	90.36	
13	22.1	9.87	90.13	Right Top of Water

14	22.8	10.05	89.95	Thalweg
15	23	10	90	
17	23.1	9.92	90.08	Left Top of Water
18	23.4	9.88	90.12	
19	24.7	9.94	90.06	
20	25.1	9.51	90.49	
21	26.5	9.41	90.59	Left Bankfull
22	27.6	9.35	90.65	
23	28	9.31	90.69	
24	29	8.86	91.14	
25	29.8	8.52	91.48	
26	30.4	8.24	91.76	
27	31.3	7.63	92.37	
28	32.3	6.97	93.03	
30	35.2	5.79	94.21	
31	35.8	5.3	94.7	
32	36.3	4.93	95.07	
33	36.9	4.37	95.63	
34	37.2	3.32	96.68	

C Additional Cross-Section Field Measurements

Section W					
Additional Riffle Cross Sections					
Data Collected: 7.12.23					
Weather Conditions: Partly Cloudy 85°					
Data Collected by: Morgan Burchfiel, Eddie Burchfiel, Noah Cleveland					
Data Entered: 8.4.23					
Data Entered by: Morgan Burchfiel					
Riffle #	Point #	Forsight (Engineering Feet)	Station (Engineering Feet)	100-Station (Engineering Feet)	Notes
Beginning of Measurement	1	7	4.95	95.05	Right Bankfull
Beginning of Measurement	2	8.2	6.01	93.99	Right Top of Water
Beginning of Measurement	3	9.2	6.19	93.81	Thalwag
Beginning of Measurement	4	10.5	6.1	93.9	Left Top of Water
Beginning of Measurement	5	12.7	5.08	94.92	Left Bankfull

Riffle 1	6	7.6	4.95	95.05	Right Bankfull
Riffle 1	7	10	5.49	94.51	Right Top of Water
Riffle 1	8	10.8	5.53	94.47	Thalweg
Riffle 1	9	11	5.44	94.56	Left Top of Water
Riffle 1	10	12.8	4.74	95.26	Left Bankfull
Riffle 2	11	12	5.22	94.78	Right Bankfull
Riffle 2	12	13.9	6.11	93.89	Right Top of Water
Riffle 2	13	14.4	6.15	93.85	Thalweg
Riffle 2	14	15.2	6.09	93.91	Left Top of Water
Riffle 2	15	17.4	5.27	94.73	Left Bankfull
Riffle 3	17	10.9	7.08	92.92	Right Bankfull
Riffle 3	18	12.6	7.54	92.46	Right Top of Water
Riffle 3	19	13.7	7.59	92.41	Thalweg
Riffle 3	20	14.2	7.51	92.49	Left Top of Water
Riffle 3	21	16	6.96	93.04	Left Bankfull
Riffle 4	23	7.1	7.2	92.8	Right Bankfull
Riffle 4	24	10.3	8.33	91.67	Right Top of Water
Riffle 4	25	15	8.54	91.46	Thalweg
Riffle 4	26	15.2	8.52	91.48	Left Top of Water
Riffle 4	27	17.2	7.67	92.33	Left Bankfull
Riffle 5	28	7.5	8.3	91.7	Right Bankfull
Riffle 5	29	13.7	9.77	90.23	Right Top of Water
Riffle 5	30	14.2	9.82	90.18	Thalweg
Riffle 5	31	14.6	9.76	90.24	Left Top of Water
Riffle 6	34	9.1	8.32	91.68	Right Bankfull
Riffle 6	36	15.2	10.03	89.97	Right Top of Water
Riffle 6	37	15.9	10.07	89.93	Thalweg
Riffle 6	38	16.7	10.08	89.92	Left Top of Water
Riffle 7	41	8.2	7.52	92.48	Right Bankfull
Riffle 7	42	14	9.07	90.93	Right Top of Water

Riffle 7	43	14.2	9.07	90.93	Thalweg
Riffle 7	44	14.5	8.94	91.06	Left Top of Water
Riffle 7	45	21.9	7.89	92.11	Left Bankfull
Riffle 8	46	7.6	7.48	92.52	Right Bankfull
Riffle 8	47	13.8	8.99	91.01	Right Top of Water
Riffle 8	48	15.7	9.03	90.97	Thalweg
Riffle 8	49	16.7	8.75	91.25	Left Top of Water
Riffle 8	50	24.3	7.85	92.15	Left Bankfull
Riffle 9	51	8.3	7.82	92.18	Right Bankfull
Riffle 9	52	15.4	9.25	90.75	Right Top of Water
Riffle 9	53	16.4	9.44	90.56	Thalweg
Riffle 9	54	16.9	9.25	90.75	Left Top of Water
Riffle 9	55	26.2	8.11	91.89	Right Bankfull
Riffle 10	CS 2	24	7.58	92.42	Left Bankfull
Riffle 10	CS 3	29.2	8.85	91.15	Left Top of Water
Riffle 10	CS 4	29.7	8.89	91.11	Thalweg
Riffle 10	CS 5	30.1	8.91	91.09	Right Top of Water
Riffle 10	CS 7	34.1	7.53	92.47	Right Bankfull
Riffle 11	56	9.4	8.68	91.32	Left Bankfull
Riffle 11	57	16.8	10.78	89.22	Left Top of Water
Riffle 11	58	17.9	10.93	89.07	Thalweg
Riffle 11	59	18.2	10	90	Left Top of Water
Riffle 11	60	25.3	8.86	91.14	Left Bankfull
Riffle 12	61	10.5	8.33	91.67	Right Bankfull
Riffle 12	62	15.3	10.21	89.79	Right Top of Water
Riffle 12	63	15.6	10.32	89.68	Thalweg
Riffle 12	64	16.3	10.24	89.76	Left Top of Water
Riffle 12	65	26.5	8.34	91.66	Left Bankfull
Riffle 13	66	12.4	4.97	95.03	Right Bankfull
Riffle 13	67	48.3	6.5	93.5	Right Top of Water
Riffle 13	68	49.6	6.63	93.37	Thalweg

Riffle 13	69	50.5	6.4	93.6	Left Top of Water
Riffle 13	70	64.1	4.91	95.09	Left Bankfull
End of Measurement	71	23.1	6.99	93.01	Right Bankfull
End of Measurement	72	24.2	7.71	92.29	Right Top of Water
End of Measurement	73	25.3	8.01	91.99	Thalweg
End of Measurement	74	26.1	7.91	92.09	Left Top of Water
End of Measurement	75	30	6.63	93.37	Left Bankfull

Section X					
Additional Riffle Cross Sections					
Data Collected: 7.13.23					
Weather Conditions: Partly Cloudy/Rain 80°					
Data Collected by: Morgan Burchfiel, Eddie Burchfiel, Noah Cleveland					
Data Entered: 8.4.23					
Data Entered by: Morgan Burchfiel					
Riffle #	Point #	Forsight (Engineering Feet)	Station (Engineering Feet)	100-Station (Engineering Feet)	Notes
Riffle 1	1	7.3	6.8	93.2	Right Bankfull
Riffle 1	2	9.1	7.96	92.04	Bottom of Right Bank
Riffle 1	3	16.8	8.3	91.7	Right Top of Water
Riffle 1	4	17.1	8.34	91.66	Thalweg
Riffle 1	5	17.3	8.29	91.71	Left Top of Water
Riffle 1	6	23.9	8.24	91.76	Bottom of Left Bank
Riffle 1	7	26.4	6.23	93.77	Left Bankfull
Riffle 2	8	6	5.86	94.14	Right Top of Bank
Riffle 2	9	10.2	7.27	92.73	Right Bottom of Bank
Riffle 2	10	10.5	7.23	92.77	Right Top of Water
Riffle 2	11	10.7	7.39	92.61	Thalweg
Riffle 2	12	11.1	7.29	92.71	Left Top of Water
Riffle 2	13	11.5	7.23	92.77	Left Bankfull
Riffle 3	15	8.6	18.5	91.4	Right Top of Bank
Riffle 3	16	8.85	23.5	91.15	Right Bottom of Bank
Riffle 3	17	8.77	28.1	91.23	Right Top of Water
Riffle 3	18	8.81	28.5	91.19	Thalweg
Riffle 3	19	8.72	28.9	91.28	Left Top of Water

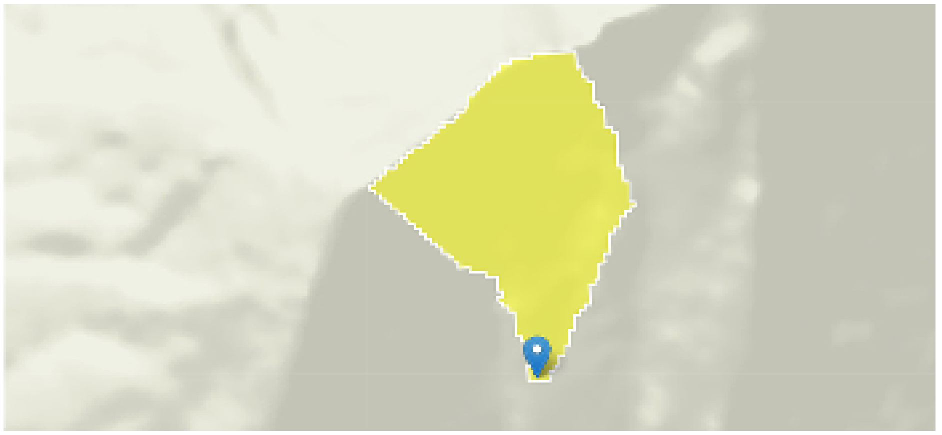
Riffle 3	20	8.3	32.3	91.7	Left Bankfull
Riffle 3	21	5.74	38.4	94.26	Left Top of Bank
Riffle 4	22	7.32	8.2	92.68	Right Bankfull
Riffle 4	23	8.17	10.7	91.83	Right Bottom of Bank
Riffle 4	24	8.15	13.9	91.85	Right Top of Water
Riffle 4	25	8.24	14.2	91.76	Thalweg
Riffle 4	26	7.6	21.5	92.4	Left Top of Water
Riffle 4	27	7.26	24.4	92.74	Left Bankfull
Riffle 5	29	3.49	32.5	96.51	Left Top of Bank
Riffle 5	30	5.7	4.2	94.3	Left Bankfull
Riffle 5	31	7.17	12.6	92.83	Left Top of Water
Riffle 5	32	7.19	12.5	92.81	Thalweg
Riffle 5	33	7.05	14	92.95	Right Top of Water
Riffle 5	34	5.81	23.3	94.19	Right Bankfull
Riffle 6	35	7.74	12.8	92.26	Right Bankfull
Riffle 6	36	8.63	21	91.37	Right Top of Water
Riffle 6	37	8.69	21.3	91.31	Thalweg
Riffle 6	38	8.61	21.9	91.39	Left Top of Water
Riffle 6	39	7.1	28.7	92.9	Left Bankfull
Riffle 7	41	9.21	13.7	90.79	Right Bankfull
Riffle 7	42	9.14	17.5	90.86	Right Top of Water
Riffle 7	43	9.18	17.6	90.82	Thalweg
Riffle 7	44	9.08	17.8	90.92	Left Top of Water
Riffle 7	45	7.69	30.7	92.31	Left Bankfull
Riffle 8	46	6.33	15.3	93.67	Right Bankfull
Riffle 8	47	7.51	16.7	92.49	Right Top of Water
Riffle 8	48	7.63	16.9	92.37	Thalweg
Riffle 8	49	7.37	20.2	92.63	Left Top of Water
Riffle 8	50	6.36	21.3	93.64	Left Bankfull
Riffle 9	51	5.22	12.3	94.78	Right Bankfull Rock
Riffle 9	52	6.7	15.2	93.3	Right Top of Water
Riffle 9	53	6.76	15.3	93.24	Thalweg
Riffle 9	54	6.76	15.8	93.24	Left Top of Water
Riffle 9	55	5.71	17.6	94.29	Left Bankfull
Riffle 10	56	4.71	7.1	95.29	Right Bankfull
Riffle 10	57	6.02	11.6	93.98	Right Top of Water
Riffle 10	58	6.16	12.1	93.84	Thalweg
Riffle 10	59	6.08	13	93.92	Left Top of Water
Riffle 10	60	4.64	15.7	95.36	Left Bankfull

Section Y					
Detailed Cross-Section Survey					
Data Collected: 6.29.23					
Weather Conditions: Sunny 80°					
Data Collected by: Morgan Burchfiel, Eddie Burchfiel					
Data Entered: 8.4.23					
Data Entered by: Morgan Burchfiel					
Riffle #	Point #	Forsight (Engineering Feet)	Station (Engineering Feet)	100-Station (Engineering Feet)	Notes
Riffle 1	1	10.6	5.41	92.97	Right Bankfull
Riffle 1	2	12.1	8.54	91.46	Right Top of Water
Riffle 1	3	12.4	8.5	91.5	Thalweg
Riffle 1	4	14.7	8.26	91.74	Left Top of Water
Riffle 1	5	15.3	5.34	93.22	Left Bankfull'
Riffle 2	6	11.1	6.08	93.92	Right Bankfull
Riffle 2	7	11.2	8.35	91.65	Right Top of Water
Riffle 2	8	11.9	8.42	91.58	Thalweg
Riffle 2	9	12.2	8.35	91.65	Left Top of Water
Riffle 2	10	16.8	6.03	93.97	Left Bankfull'
Riffle 3	11	13.5	5.84	93.43	Right Bankfull
Riffle 3	12	17.7	7.99	92.01	Right Top of Water
Riffle 3	13	18	8.06	91.94	Thalweg
Riffle 3	14	18.2	8.1	91.9	Left Top of Water
Riffle 3	15	18.1	5.61	93.24	Left Bankfull'
Riffle 4	16	11	6.1	93.9	Right Bankfull
Riffle 4	17	18.2	7.32	92.68	Right Top of Water
Riffle 4	18	18.3	7.45	92.55	Thalweg
Riffle 4	19	18.7	7.45	92.55	Left Top of Water
Riffle 4	20	21.7	6.09	93.91	Left Bankfull'
Riffle 5	21	18.3	7.38	92.62	Right Bankfull
Riffle 5	22	18.9	9.25	90.75	Right Top of Water
Riffle 5	23	19	9.34	90.66	Thalweg

Riffle 5	24	19.9	9.36	90.64	Left Top of Water
Riffle 5	25	21.3	7.4	92.6	Left Bankfull'
Riffle 6	26	12.6	7.46	92.54	Right Bankfull
Riffle 6	27	17.1	9.54	90.46	Right Top of Water
Riffle 6	28	18.3	9.58	90.42	Thalweg
Riffle 6	29	19.2	9.49	90.51	Left Top of Water
Riffle 6	30	19.6	7.92	92.08	Left Bankfull'
Riffle 7	31	11.6	7.04	92.96	Right Bankfull
Riffle 7	32	15.2	9.35	90.65	Right Top of Water
Riffle 7	33	16.9	9.4	90.6	Thalweg
Riffle 7	34	18.9	9.35	90.65	Left Top of Water
Riffle 7	35	22.5	7.53	92.47	Left Bankfull'
Riffle 7	36	15.9	8.04	91.96	Right Bankfull
Riffle 8	37	18.7	10.14	89.86	Right Top of Water
Riffle 8	38	18.9	10.24	89.76	Thalweg
Riffle 8	39	20.5	10.24	89.76	Left Top of Water
Riffle 8	40	23.4	8.1	91.9	Left Bankfull'
Riffle 9	41	16.8	8.43	91.57	Right Bankfull
Riffle 9	42	19.5	10.14	89.86	Right Top of Water
Riffle 9	43	19.6	10.19	89.81	Thalweg
Riffle 9	44	20.7	10.09	89.91	Left Top of Water
Riffle 9	45	25.5	8.38	91.62	Left Bankfull'
Riffle 10	46	20	8.78	91.22	Right Bankfull
Riffle 10	47	22.1	9.87	90.13	Right Top of Water
Riffle 10	48	22.8	10.05	89.95	Thalweg
Riffle 10	49	23.1	9.92	90.08	Left Top of Water
Riffle 10	50	30.4	8.24	91.76	Left Bankfull'

D Streamstats Data

SECTION W STREAMSTATS



Delineation of watershed draining to Section W

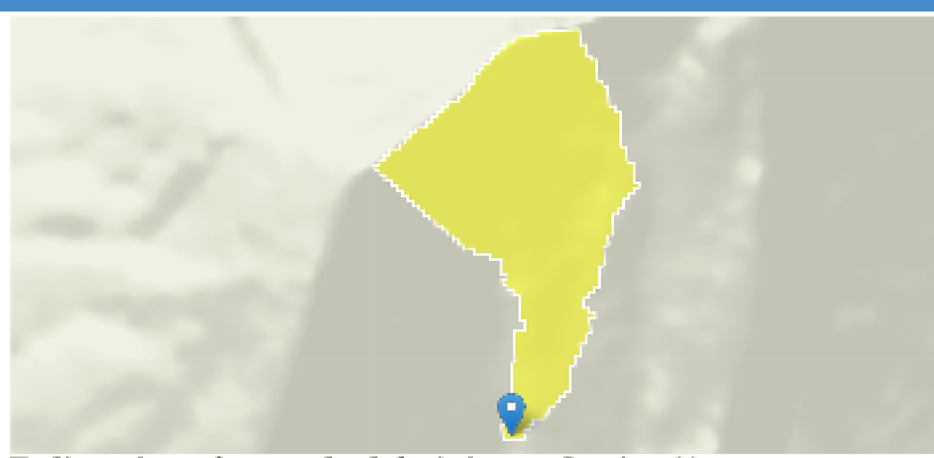
Parameter Description	Value	Unit
Area that drains to a point on a stream	0.0526	square miles
Percentage of drainage area located in Region 2 - Blue Ridge	100	percent

SECTION Y STREAMSTATS

Delineation of watershed draining to Section Y

Parameter Description	Value	Unit
Area that drains to a point on a stream	0.11	square miles
Percentage of drainage area located in Region 2 - Blue Ridge	100	percent

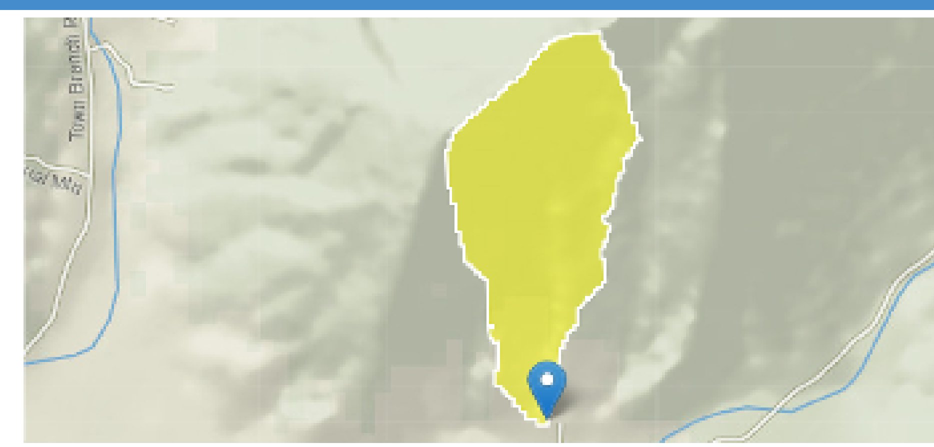
SECTION X STREAMSTATS



Delineation of watershed draining to Section X

Parameter Description	Value	Unit
Area that drains to a point on a stream	0.0586	square miles
Percentage of drainage area located in Region 2 - Blue Ridge	100	percent

SECTION Z STREAMSTATS



Delineation of watershed draining to Section Z

Parameter Description	Value	Unit
Area that drains to a point on a stream	0.11	square miles
Percentage of drainage area located in Region 2 - Blue Ridge	100	percent

E Natural Channel Design Equations

Parameter	Calculation	Calculation Variables
Cross-Sectional Area	$A_{bkf} = \sum(x_{i+1} - x_i)\left[\frac{(y_i - y_{i+1})}{2}\right]$	A_{bkf} = Cross-sectional area at bankfull stage x_i = The horizontal position from a starting point on the left bank x_{i+1} = The horizontal position of the next measurement point after x_i y_i = The depth of the stream at point i along the cross-section y_{i+1} = The depth at the next measurement point, just after y_i
Bankfull Width	$W_{bkf} = \Sigma(x_{i+1} - x_i)$	W_{bkf} = Bankfull Width x_i = The horizontal position from a starting point on the left bank x_{i+1} = The horizontal position of the next measurement point after x_i
Mean Depth	$D_{mean} = \frac{A_{bkf}}{W_{bkf}}$	D_{mean} = Mean depth at bankfull stage A_{bkf} = Cross-sectional area at bankfull stage W_{bkf} = Bankfull Width
Maximum Depth	$D_{max} = \max(y_1, y_2, y_3, \ldots, y_n)$	D_{max} = Maximum depth at bankfull stage y_i = Depth measurement at each point i across the stream, where i =1,2,3,...,n
Width-to-Depth Ratio	$WD_{ratio} = \frac{W_{bkf}}{D_{mean}}$	WD_{ratio} = Width-to-depth ratio at bankfull stage W_{bkf} = Bankfull Width D_{mean} = Mean depth at bankfull stage
Floodprone Width	$W_{fp} = Width\ of\ the\ Channel\ at\ (2 \times D_{max})$	W_{fp} = Floodprone width D_{max} = Maximum depth at bankfull stage
Entrenchment Ratio	$E_{ratio} = \frac{W_{fp}}{W_{bkf}}$	E_{ratio} = Entrenchment ratio W_{fp} = Floodprone width
Sinuosity	$S = \frac{L_{channel}}{L_{valley}}$	S = Sinuosity $L_{channel}$ = Channel length along thalweg from the start to the endpoint of the channel segment L_{valley} = Valley length in a straight line from the start to the endpoint of the channel segment
Stream Slope	$S_{stream} = \frac{\Delta h}{L_{channel}}$	S_{stream} = Stream slope Δh = Change in elevation between the start to the endpoint of the channel segment $L_{channel}$ = Channel length along thalweg from the start to the endpoint of the channel segment

Equations are from Leopold, Wolman, and Miller (1964) and Rosgen (1996).

Equations are from Leopold, Wolman, and Miller (1964) and Rosgen (1996).

F Section W Pipe Size Calculations

Calculation Step	Description	Value	Information Source
National forest (woods) and pasture area draining to buffer	60% woods and 40% pastureland	0.0526 square miles	Project data
Determine Curve Number (CN)	a. Curve Number based on poor condition* for grazing pasture, soil group HSG B b. Curve Number based on good condition** for woods c. Calculation for CN for combination of 60% woods and 40% pastureland	a. 69 b. 30 c. 45.6	(Brunner 2016; NRCS 1986)
Potential Maximum Retention (S)	Calculation of maximum retention for CN 45.6 utilizing equation: $S = \frac{1000}{CN} - 10$	11.93 inches	(Brunner 2016; NC DEQ 2016; NRCS 1986)
Precipitation (P)	25 year, 24-hour storm per NCDEQ design guidelines	5.53 inches	(NOAA 2024; NC DOT 2022)
Runoff Depth (Q_d)	Estimated runoff using SCS/NRCS method: $Q_d = \frac{(P - 0.2 \times S)^2}{(P + 0.8 \times S)}$	1.98 inches	(Brunner 2016; NC DEQ 2016; NRCS 1986)
Runoff Volume	Q (inches) × Watershed Area (acres) × 3630	230,702 cubic feet	(NC DOT 2022)
Time of Concentration (T_c)	Calculation of time of concentration where L is maximum flow path length (900 feet) and S is the average slope (0.3): $T_c = 0.0078 \times \left(\frac{L^{0.77}}{S^{0.385}}\right)$	2.33 hours rounded up to 3 hours based on NC DOT guidelines to ensure that peak flows are managed effectively	(NC DOT 2022)
Convert Time of Concentration to Seconds	Drainage Period in Seconds= 3 hours × 3600 seconds/hour	10,800 seconds	(NC DOT 2022)
Peak Flow Rate (Q_p)	$Q_p = \frac{Runoff\ Volume}{Drainage\ Period\ in\ Seconds}$	21.36 cubic feet per second	(NC DOT 2022)
Select Pipe Material	Corrugated metal chosen for durability, cost-effectiveness, and flexibility in rural settings	Roughness coefficient: 0.024	(NC DOT 2022)
Define Pipe Slope	Based on Rosgen's Type B Stream	0.09	(NC DOT 2022; Rosgen 1996; 2011)
Setup Manning's Equation	Setting up Manning's Equation to determine diameter of a pipe where Q_p = Peak flow rate, n = Manning's roughness coefficient, A = Cross-sectional area of the pipe, R = Hydraulic radius, and S=Slope of the pipe: $Q_p = \frac{1.49}{n} \times A \times R^{2/3} \times S^{1/2}$	-	(NC DOT 2022)

Calculate Cross-sectional Area (A)	For a circular pipe where D is the diameter: $$A = \frac{\pi \times D^2}{4}$$	-	(NC DOT 2022)
Hydraulic Radius (R)	For a circular pipe: $$R = \frac{D}{4}$$	-	(NC DOT 2022)
Solve Manning's Equation for Diameter (D)	$$D = \left(\frac{Q \times n}{1.49 \times \pi \times S^{1/2}}\right)^{3/8} \times 4^{5/8}$$	19.55 inches which I rounded up to 24 inches to standardize sizing to commercial pipe availability	(NC DOT 2022)
Convert to Elliptical Pipe	Selected a 19-inch by 30-inch elliptical pipe which has comparable hydraulic capacity to a 24-inch circular pipe to reduce excavation depth and minimize road disruption	19-inch by 30-inch elliptical pipe	(Hydrology Studio 2024)

*Poor condition for grazing pasture is considered <50% ground cover or heavily grazed with no mulch (Brunner 2016).

**Good condition for woods is when they protected from grazing, and litter and brush adequately cover the soil (Brunner 2016).

G Pollutant Load Estimation Tool Calculations

Inputs for PLET are based on project data and existing PLET values for Dillingham Creek Watershed (HUC 060101050801) (US EPA 2022a; 2022b).

▼ 1. Watershed Land Use Area (ac) and Precipitation (in)

Double-click on the "HSG" field to select a Hydrologic Soil Group category [NOTE: hover over the "HSG" column header for more information].

Watershed	HSG	Urban	Cropland	Pastureland	Forest	User Defined	Feedlots	Total	Feedlots Percent Paved	Annual Rainfall	Rain Days	Average Rain/Event
060101050801 - Dillingham Creek	B	2.07	0.00	27.88	0.00	0.00	0.00	29.95	0-24%	49.96	133.22	0.6582

2. Agricultural Animals (Animal Count)

Watershed	Beef Cattle	Young Beef	Dairy Cattle	Young Dairy Stock	Swine (Hog)	Feeder Pig	Sheep	Horse	Chicken	Turkey	Duck	# Of Months Manure Applied to Cropland	# Of Months Manure Applied to Pastureland
060101050801 - Dillingham Creek	15	0	0	0	0	0	0	0	0	0	0	0.00	0.00

3. Septic and Illegal Wastewater Discharge

Watershed	Number Of Septic Systems	Population Per Septic System	Septic Failure Rate, %	Waste Water Direct Discharge, # Of People	Direct Discharge Reduction, %
060101050801 - Dillingham Creek	0	0.00	0.00	0	0.00

4. Percent Nutrient in Soil

Watershed	Soil N conc.%	Soil P conc.%	Soil BOD conc.%
060101050801 - Dillingham Creek	0.08	0.0308	0.16

5. Revised Universal Soil Loss Equation Version 2 (RUSLE2) Factor Values *

** Please refer to the RUSLE2 Factor Updates document under the help materials for additional details.*

	Cropland					Pastureland					Forest					User Defined				
Watershed	R	K	LS	C	P	R	K	LS	C	P	R	K	LS	C	P	R	K	LS	C	P
060101050801 - Dillingham Creek	200	0.250	1.57	0.200	1.00	200	0.240	4.16	0.040	1.00	200	0.240	4.16	0.003	1.00	200	0.250	1.57	0.149	1.00

6. Reference Runoff Curve Number

SHG	A	B	C	D
Urban	83.00	89.00	92.00	93.00
Cropland	67.00	78.00	85.00	89.00
Pastureland	49.00	69.00	79.00	84.00
Forest	39.00	60.00	73.00	79.00
User Defined	0.00	0.00	0.00	0.00

7. Nutrient Concentration in Runoff (mg/L)

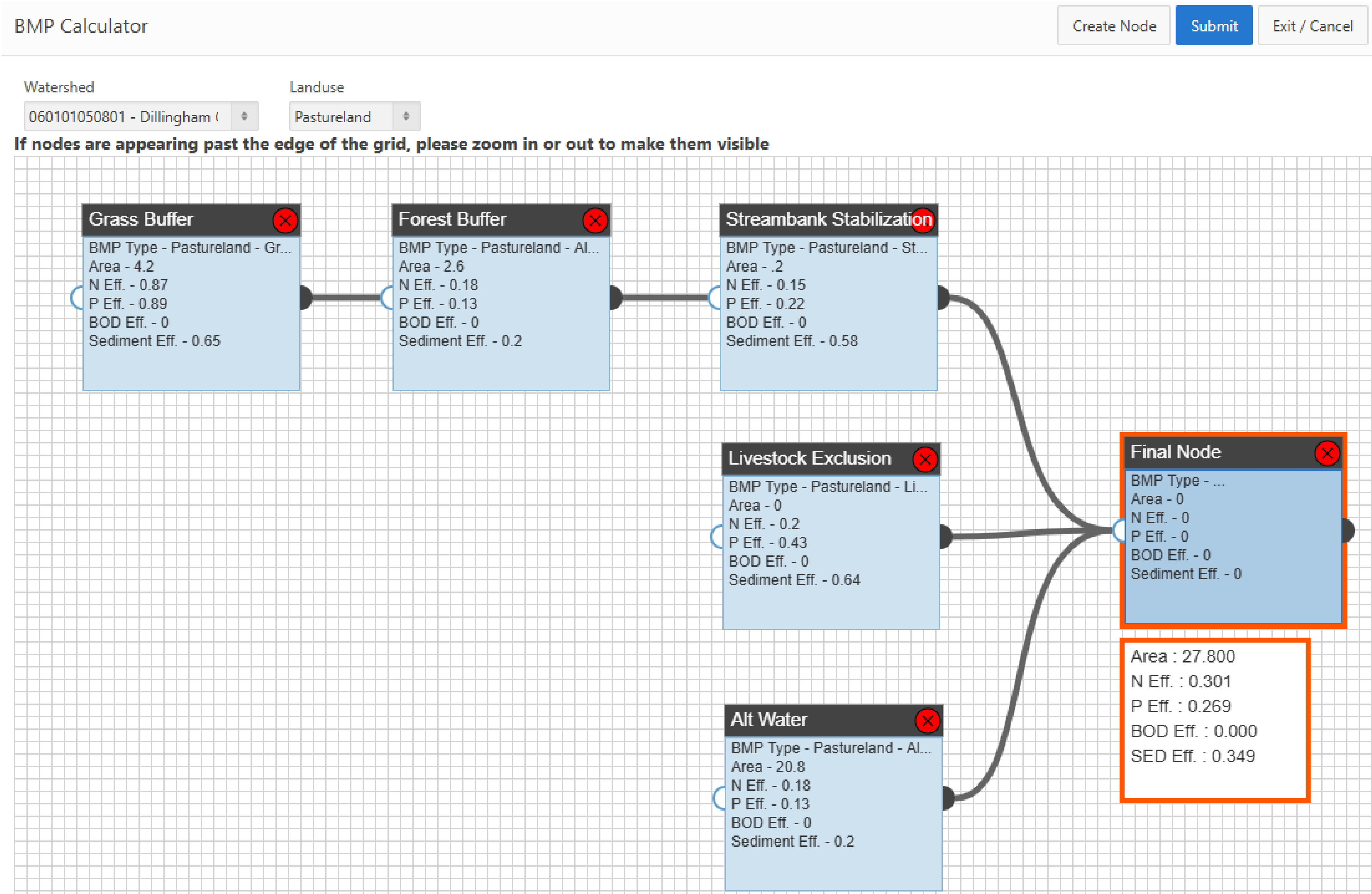
Landuse	N	P	BOD
1. L-Cropland	1.90	0.30	4.00
1a. w/ manure	8.10	2.00	12.30
2. M-Cropland	2.90	0.40	6.10
2a. w/ manure	12.20	3.00	18.50
3. H-Cropland	4.40	0.50	9.20
3a. w/ manure	18.30	4.00	24.60
4. L-Pastureland	4.00	0.30	13.00
4a. w/ manure	4.00	0.30	13.00
5. M-Pastureland	4.00	0.30	13.00
5a. w/ manure	4.00	0.30	13.00
6. H-Pastureland	4.00	0.30	13.00
6a. w/ manure	4.00	0.30	13.00
7. Forest	0.20	0.10	0.50
8. User Defined	0.00	0.00	0.00

Animal Weight

Beef Cattle	Dairy Cattle	Hog	Sheep	Horse	Chicken	Turkey	Duck	Goose	Deer	Beaver	Raccoon	Other
1000	1400	200	100	1000	4	10	4	6	40	15	7	0

Landuse Type	BMP Name	N	P	BOD	Sediment
Pastureland	30m Buffer with Optimal Grazing	0.16	0.65		
Pastureland	Alternative Water Supply	0.18	0.13		0.2
Pastureland	Critical Area Planting	0.18	0.2		0.42
Pastureland	Forest Buffer (minimum 35 feet wide)	0.45	0.4		0.53
Pastureland	Grass Buffer (minimum 35 feet wide)	0.87	0.89		0.65
Pastureland	Grazing Land Management (rotational grazing with fenced areas)	0.43	0.26		
Pastureland	Heavy Use Area Protection	0.18	0.19		0.33
Pastureland	Litter Storage and Management	0.14	0.14		0
Pastureland	Livestock Exclusion Fencing	0.2	0.43		0.64
Pastureland	Multiple Practices	0.25	0.2		0.22
Pastureland	Pasture and Hayland Planting (also called Forage Planting)	0.18	0.15		
Pastureland	Prescribed Grazing	0.41	0.23		0.33
Pastureland	Streambank Protection w/o Fencing	0.15	0.22		0.58
Pastureland	Streambank Stabilization and Fencing	0.75	0.75		0.75
Pastureland	Use Exclusion	0.43	0.08		0.51
Pastureland	Winter Feeding Facility	0.35	0.4		0.4

For the PLET BMP Calculator, I utilized project data and PLET input data for BMP efficiency in reducing Nitrogen, Phosphorus, Biochemical Oxygen Demand (BOD) and Sedimentation (US EPA 2022a; 2022b). In this PLET BMP Calculator model below, BMP nodes are primarily arranged in a series configuration, with runoff flowing sequentially through the Grass Buffer, Forest Buffer, and Streambank Stabilization, enabling cumulative pollutant reduction at each stage. Meanwhile, Livestock Exclusion and Alternative Water BMPs operate independently and converge at the Final Node, where their effects are combined with the sequential treatments. The Final Node aggregates the overall pollutant reduction from all BMPs, providing a comprehensive summary of the system's effectiveness before runoff exits. This setup effectively captures both sequential and independent BMP impacts on pollutant load reduction.


BMP Calculator
Create Node
Submit
Exit / Cancel
Watershed
060101050801 - Dillingham (
Landuse
Pastureland
If nodes are appearing past the edge of the grid, please zoom in or out to make them visible
Grass Buffer
BMP Type - Pastureland - Gr...
Area - 4.2
N Eff. - 0.87
P Eff. - 0.89
BOD Eff. - 0
Sediment Eff. - 0.65
Forest Buffer
BMP Type - Pastureland - Al...
Area - 2.6
N Eff. - 0.18
P Eff. - 0.13
BOD Eff. - 0
Sediment Eff. - 0.2
Streambank Stabilization
BMP Type - Pastureland - St...
Area - .2
N Eff. - 0.15
P Eff. - 0.22
BOD Eff. - 0
Sediment Eff. - 0.58
Livestock Exclusion
BMP Type - Pastureland - Li...
Area - 0
N Eff. - 0.2
P Eff. - 0.43
BOD Eff. - 0
Sediment Eff. - 0.64
Alt Water
BMP Type - Pastureland - Al...
Area - 20.8
N Eff. - 0.18
P Eff. - 0.13
BOD Eff. - 0
Sediment Eff. - 0.2
Final Node
BMP Type - ...
Area - 0
N Eff. - 0
P Eff. - 0
BOD Eff. - 0
Sediment Eff. - 0
Area : 27.800
N Eff. : 0.301
P Eff. : 0.269
BOD Eff. : 0.000
SED Eff. : 0.349

H E. coli Load Calculations

Calculation Step	Description	Value	Information Source
Pasture area draining to buffer	Total acreage of pasture draining into the riparian buffer	27.8 acres	Project data
Curve Number (CN)	Curve Number based on poor condition* for grazing pasture, soil group HSG B	69	(Brunner 2016; NRCS 1986)
Precipitation (P)	24-hour rainfall event with a 1-year frequency	2.60 inches	(Brunner 2016; NOAA 2024)
Potential Maximum Retention (S)	Calculation of maximum retention for CN 69 utilizing equation: $S = \frac{1000}{CN} - 10$	4.49 inches	(Brunner 2016; NC DEQ 2016; NRCS 1986)
Runoff Depth (Q)	Estimated runoff using SCS/NRCS method: $Q = \frac{(P - 0.2 \times S)^2}{(P + 0.8 \times S)}$	0.381 inches	(Brunner 2016; NC DEQ 2016; NRCS 1986)
Runoff Volume (gallons)	Q (inches) × Area (acre) × 27,154	352,802 gallons	
Fecal Coliform Concentration	Concentration for year-round grazing pasture	1.894×10^6 colonies/gallon	(NC DEQ 2016)
Initial Fecal Coliform Load (No BMP of riparian buffer applied)	Runoff volume × fecal coliform concentration	668 billion colonies	(NC DEQ 2016)
Buffer Filtration Efficiency	Efficiency of riparian buffer in reducing fecal coliform in runoff	85%	(NC DEQ 2016; Sullivan et al. 2007; NRCS 2020)
Reduced Fecal Coliform Load (With BMP of riparian buffer applied)	Initial fecal coliform load × filtration efficiency	568 billion colonies	(NC DEQ 2016)
Total Fecal Coliform Load After Reduction	Initial fecal coliform load – Reduced Fecal Coliform Load	100 billion colonies	(NC DEQ 2016)

*Poor condition for grazing pasture is considered <50% ground cover or heavily grazed with no mulch (Brunner 2016).

I Riparian Buffer Proposed Plant Lists

Section W	
Trees	
Acer negundo	Boxelder Maple
Betula lenta	Cherry Birch
Carya ovata	Shagbark Hickory
Halesia caroliniana	Silverbell
Nyssa sylvatica	Blackgum
Small Trees and Shrubs	
Hamamelis virginiana	Witch-hazel
Lindera benzoin	Spicebush

Xanthorhiza simplicissima	Yellow-root
Physocarpus opulifolius	Ninebark
Sambucus nigra spp. Canadensis	Elderberry
Herbaceous Plants	
Arisaema triphyllum	Jack-in-the-Pulpit
Chelone glabra	Turtlehead
Impatiens capensis	Jewelweed
Lobelia siphilitica	Great Blue Lobelia
Mimulus ringens	Monkeyflower
Physostegia virginiana	Obedient plant
Rudbeckia laciniata	Cutleaf Coneflower
Ferns	
Onoclea sensibillis	Sensitive Fern
Osmunda cinnamomea	Cinnamon Fern
Osmunda regalis	Royal Fern
Graminoids	
Carex crinita	Fringed Sedge
Carex intumescens	Bladder Sedge
Carex lurida	Lurid Sedge
Carex scoparia	Broom Sedge
Carex stricta	Tussock Sedge
Carex vulpinoidea	Fox Sedge
Juncus effusus	Soft Rush
Juncus tenuis	Poverty Rush
Cyperus strigosus	Umbrella Sedge
Juncus coriaceus	Leathery Rush

Section X	
Trees	
Acer negundo	Box Elder
Betula lenta	Cherry Birch
Carya ovata	Shagbark Hickory
Carya ovata	Shagbark Hickory
Halesia caroliniana	Silverbell

Nyssa sylvatica	Blackgum
Small Trees and Shrubs	
Hamamelis virginiana	Witch-Hazel
Xanthorhiza simplicissima	Yellowroot
Physocarpus opulifolius	Ninebark
Herbaceous Plants	
Arisaema triphyllum	Jack-in-the-Pulpit
Chelone glabra	Turtlehead
Impatiens capensis	Jewelweed
Lobelia siphilitica	Great Blue Lobelia
Ferns	
Onoclea sensibillis	Sensitive Fern
Osmunda cinnamomea	Cinnamon Fern
Osmunda regalis	Royal Fern
Graminoids	
Carex crinata	Fringed Sedge
Carex intumescens	Bladder Sedge
Carex lurida	Lurid Sedge
Carex scoparia	Broom Sedge
Carex stricta	Tussock Sedge
Carex vulpinoidea	Fox Sedge

Section Y	
Trees	
Acer negundo	Box Elder
Betula lenta	Cherry Birch
Carya ovata	Shagbark Hickory
Carya ovata	Shagbark Hickory
Halesia caroliniana	Silverbell
Nyssa sylvatica	Blackgum
Small Trees and Shrubs	
Magnolia tripetala	Umbrella Tree

Physocarpus opulifolius	Ninebark
Salix sericea	Silky Willow
Sambucus nigra spp. Canadensis	Elderberry
Spiraea alba	Meadowsweet
Spiraea tomentosa	Steeplebush
Viburnum nudum var. cassinoides	Withe-rod
Viburnum nudum var. nudum	Possumhaw
Viburnum dentatum	Southern Arrow-wood
Cornus amomum	Silky Dogwood
Herbaceous Plants	
Eupatorium fistulosum	Joe-Pye-Weed
Helenium flexuosum	Purplehead Sneezeweed
Helianthus angustifolius	Swamp Sunflower
Rudbeckia laciniata	Cutleaf Coneflower
Symphyotrichum novae-angliae	New England Aster
Vernonia noveboracensis	Ironweed
Graminoids	
Andropogon gerardii	Big Bluestem
Schizachyrium scoparium	Little Bluestem
Sorghastrum nutans	Indiangrass
Tripsacum dactyloides	Eastern Gamagrass
Elymus hystrix	Bottlebrush Grass
Carex crinata	Fringed Sedge
Carex intumescens	Bladder Sedge
Carex lurida	Lurid Sedge
Carex scoparia	Broom Sedge
Carex stricta	Tussock Sedge
Carex vulpinoidea	Fox Sedge
Juncus effusus	Soft Rush

Section Z	
Trees	
Acer negundo	Box Elder
Betula lenta	Cherry Birch

Carya ovata	Shagbark Hickory
Carya ovata	Shagbark Hickory
Halesia caroliniana	Silverbell
Nyssa sylvatica	Blackgum
Small Trees and Shrubs	
Physocarpus opulifolius	Ninebark
Salix sericea	Silky Willow
Sambucus nigra spp. Canadensis	Elderberry
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Vernonia noveboracensis	Ironweed
Graminoids	
Andropogon gerardii	Big Bluestem
Schizachyrium scoparium	Little Bluestem
Sorghastrum nutans	Indiangrass
Tripsacum dactyloides	Eastern Gamagrass
Elymus hystrix	Bottlebrush Grass
Carex crinata	Fringed Sedge
Carex intumescens	Bladder Sedge
Carex lurida	Lurid Sedge
Carex scoparia	Broom Sedge
Carex stricta	Tussock Sedge
Carex vulpinoidea	Fox Sedge
Juncus effusus	Soft Rush

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