Evaluating the Long-Term Morphological Response of a Headwater Stream to Three Restoration Techniques

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Scholarly Abstract

The stream restoration industry has been growing since the addition and modification of Section 404 to the Clean Water Act. Many projects follow the guidelines of Natural Channel Design and use in-stream structures to stabilize stream channels. Post-project monitoring rarely exceeds 3-5 years, and the lack of guidance, funding, and pre-restoration data prevents meaningful post-project assessment of the design techniques. The Virginia Tech Stream Research, Education, and Management (StREAM) Lab is a research facility where a stream restoration project was completed along 1.3 km of Stroubles Creek in 2010. The study site provides a unique opportunity to compare the use of three restoration treatments with different intensities of restoration actions. Following exclusion of cattle from all three sites, the first treatment reach was left to naturally revegetate (Treatment 1) and along Treatment 2 the streambanks were re-graded to a 3:1 slope and replanted. An additional inset floodplain was constructed within the active channel of Treatment 3. Pre-restoration data, including topographic surveys and erosion pin measurements, provided a baseline for quantification of morphological response 11 years post-restoration. This project utilized as-built survey data from 2010 and a follow-up survey in 2021. The spatial data were analyzed to quantify important stream metrics: cross-sectional area, width, maximum depth, hydraulic depth, and width-to-depth ratio. Overall, the percent change per year of each metric decreased substantially following the restoration, indicating an increase in stability. While Treatment 3 continues to show minor erosion on average (+3.3% in area, +3.2% in width, and +11.2% in maximum depth), Treatments 1 (excluding cross section 5) and 2 decreased on average in area (-3.4% and -18.6%) and hydraulic depth (-13.3% and -10.8%).

Treatment 1 eroded by an average of 11.7% in width compared to a decrease of -13.4% in Treatment 2 and an increase in 3.2% in Treatment 3. Comparisons of each treatment to Virginia Mitigation Banking Standards indicated Treatment 1 met the fewest number of criteria, followed by Treatment 2 and then Treatment 3, indicating that hard structures are not necessary to meet mitigation bank standards, even in urban watersheds. In an urban, incised channel with cattle impacts, re-grading the streambanks, actively planting woody riparian vegetation, and incorporating an inset floodplain will accelerate the establishment of channel stability, as compared to the more passive approach of simply removing cattle access to the channel.

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General Abstract

The stream restoration industry has been growing since the addition and modification of Section 404 to the Clean Water Act. Specific design models, such as Natural Channel Design which focuses heavily on preventing the stream from moving using stone and wood structures, guide many projects. Post-project monitoring rarely exceeds 3-5 years, and the lack of guidance, funding, and pre-restoration data prevents meaningful post-project assessment of the design techniques. The Virginia Tech Stream Research, Education, and Management (StREAM) Lab is a research facility in which human interactions in the Stroubles Creek Watershed can be evaluated. A stream restoration project was completed on Stroubles Creek at the StREAM Lab property in 2010. This project provides a unique opportunity to compare three different intensities of restoration actions. Following exclusion of cattle from all three sites, plants were left to naturally regrow in the first treatment reach and Treatment 2 re-shaped the banks to a gentler slope and replanted. Like Treatment 2, an additional inset floodplain was constructed within the active channel of Treatment 3. Pre-restoration data, including topographic surveys and bank erosion measurements provided a baseline for quantification of physical response 11 years post-restoration. This project utilized survey data from immediately post-restoration in 2010, and a follow-up survey in 2021. The surveys were analyzed using AutoCAD Civil3D and cross-sectional area, width, maximum depth, hydraulic depth (area/top width), and width-to-depth ratio were calculated. Overall, the percent change per year of each metric decreased substantially following the restoration, indicating an increase in stability. While Treatment 3 continues to show minor erosion (+3.3% in area, +3.2% in width, and +11.2% in maximum depth), Treatments 1 (excluding cross section 5) and 2 decreased on average in area (-3.4% and -18.6%) and hydraulic depth (-13.3% and -10.8%). Treatment 1 eroded by an average of 11.7% in width compared to a decrease of -13.4% in Treatment 2 and an increase in 3.2% in Treatment 3. Comparisons of each treatment to Virginia Mitigation Banking Standards indicated Treatment 3 met the highest number of criteria, followed by Treatment 2 and then Treatment 1, indicating that hard structures are not necessary to meet mitigation bank standards, even in urban watersheds. In an urban, incised channel with cattle impacts, regrading the streambanks, actively planting woody riparian vegetation, and incorporating an inset floodplain will accelerate the establishment of channel stability, as compared to the more passive approach of simply removing cattle access to the channel.

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Contents

List of Figures

List of Tables

1 Introduction

Stream ecosystems have been disturbed by humans since the beginning of civilization. Some of the modern examples of disturbance seen today are sediment and pollutant loading, watershed urbanization, dams, and habitat loss. Stream restoration aims to provide ecological uplift and improve physical function. Specific goals vary by location but can include stormwater pollution reduction, improvement of aquatic organism habitat, or protection of infrastructure (Wheeler, 2020). Protecting infrastructure is particularly important in urban ecosystems where bank erosion is more likely and streams may migrate near buildings, sewer lines, or other man-made structures. As of October 2020, 340 miles of streams in the Chesapeake Bay Watershed had been re-engineered in some way, with plans to complete 900 miles of restoration by 2025 for Total Maximum Daily Load (TMDL) compliance. The estimated cost of these projects is $500 million (Wheeler, 2020). In many regions of the U.S., impacts to streams account for at least 50% of the individual permits issued by the Army Corps of Engineers each year (Lave et al., 2008).

Stream restoration projects are being completed because of the requirements put forth by the Federal Water Pollution Control Act amendments of 1972, commonly known as the Clean Water Act (CWA). The objective of the CWA is to restore and maintain the chemical, physical, and biological integrity of the nation’s waters. This requires mitigation to occur when protected ecosystems are damaged to compensate for the damage. Section 303 of the CWA outlines water quality standards and implementation plans, specifically pointing to TMDL plans to provide methods to improve impaired waters. The United States Environmental Protection Agency (US EPA) defines TMDLs as the maximum amount of a pollutant that can enter a waterbody without causing impairment and exceeding limits of water quality standards for that particular pollutant (US EPA, 2021). Also driven by section 404 of the CWA are mitigation projects, which are restoration projects that are completed to offset or compensate for loss or destruction of the ecosystem due to unavoidable development (Lave, 2018).

This recent push for stream restoration has been met with criticism. For example, a study completed in 2014 evaluated the effectiveness of stream restoration, specifically looking at streams that were impacted by coal mining in Southern Appalachia (Palmer and Hondula, 2014). This study was critical of the stream restoration being done because it found that often, the streams most impacted were ephemeral while the streams being restored were perennial systems. Thus, the lost functions of the ephemeral systems were not being restored. Additionally, the restored streams were often impaired under biological and water quality standards, but only geomorphic work was done on the systems, leaving the biology and water quality unaddressed. This study also found that in 97% of the streams, the habitat improvement five years after restoration was marginal or suboptimal (Palmer and Hondula, 2014). Rob Schnabel with the Chesapeake Bay Foundation argued that disregarding the runoff problems created by impervious surfaces and only focusing on stream channel restoration is like “putting in a temporary Band-Aid” on the problem (Wheeler, 2020, para. 42). In addition to the lack of biological improvement, some researchers think that the efforts of many restoration projects in the Eastern U.S. may be misguided. Using macrofossil analysis on floodplain areas in the Eastern U.S., researchers have found that major portions of the valley bottoms were historically covered in wetland vegetation. They suggest that restoring the systems to natural riparian wetlands may be more effective at improving biodiversity and ecosystem function than stream restoration or similar actions. (Voli et al., 2009)

Stream mitigation banks have also been criticized, with critics claiming that projects that require more effort are typically more highly rewarded, even if that means destruction of pre-existing high-quality habitat (Lave, 2018). Additionally, scientists note that stream restoration should not be the first action taken over protection of functional systems because maintenance is much easier and more effective than restoration (Roni et al., 2002); however, there is no financial incentive for preservation (Lave et al., 2008). Mitigation credits are bought and sold in terms of linear feet of stream, which becomes problematic when each linear foot of stream is expected or claimed to provide a “consistent quantity of stream function” (Lave et al., 2008).

Another criticism of stream restoration is that the projects typically undergo a one-time evaluation and are not monitored for long periods of time, typically a maximum of three years. The exception to this monitoring length are projects completed for mitigation banks which are monitored for 3-10 years (Lave, 2018) (USACE and VA DEQ, 2018). There are several challenges that make evaluation difficult, and it can be difficult to produce measurable results. Evaluation is difficult due to “insufficient baseline data, inadequate funds, and no guidance on how to proceed with an evaluation” (Kondolf and Micheli, 1995, p.2). In a study completed in Washington State, project managers were surveyed regarding monitoring for their projects. Out of the respondents, 51% reported that they had collected baseline data of some kind, and only 18% reported that monitoring was being required by another authority. The respondents also noted the barriers that prevented them from monitoring, which included cost, time, and lack of personnel (Bash and Ryan, 2002). Some parameters are not practical to monitor in the short term; for example, to detect a statistically significant change in turbidity on the Latrobe River in Australia, 80 years of monitoring data would be required (Kondolf and Micheli, 1995).

Given the current lack of formal project evaluation, the goal of this research is to evaluate the morphological changes of Stroubles Creek 11 years post-restoration and to determine if different levels of restoration effort (cattle access removal, sloping banks, and/or inset floodplains and vegetation plantings) influenced the channel morphological response. Additionally, this data will be compared to the migration criteria that must be met by projects that are completed for mitigation banks to determine if the heavy use of stream restoration structures typically seen in mitigation bank sites was necessary at this site.

2. Literature Review

2.1 Definition of Stream Restoration

Stream restoration involves ecological engineering to restore structure and function to an impacted stream habitat. A full return of structure and function is frequently impossible however, so the goal of modern stream restoration projects is to restore the pre-disturbance conditions as much as possible (Shields et al., 2003). Some alternative terms used include stream rehabilitation, naturalization, enhancement, or reclamation, all which vary slightly in definition (Shields et al., 2003). The definition of stream restoration differs with discipline and is a widely used term to describe a variety of actions. Environmental engineers, ecologists, geomorphologists, and hydrologists all use the term to describe their management actions and goals, which are not consistent across disciplines (Bennett et al., 2011).

2.2 Drivers of Stream Restoration

Stream restoration projects in the United States are typically motivated by federal legislation including the Clean Water Act and the United States Endangered Species Act. The Clean Water Act requires compensatory mitigation and Total Maximum Daily Load (TMDL) plans for Waters of the United States (WOTUS) which are impacted by human activity or pollution. TMDLs aim to reduce pollution and improve water quality on the watershed scale while restoration or mitigation does not typically address upstream pollution, but instead creates stable channels and habitat in the riparian system (Cook et al., 2015). The United States Endangered Species Act names species that are threatened or endangered which can increase funding allocated towards protection of those species through habitat revitalization.

Section 404(b)(1) of the Clean Water Act defines compensatory mitigation as the process of offsetting unavoidable impacts to waters of the United States through prevention of impacts, enhancement of unimpacted systems, restoration of impacted systems, and creation of new systems. It is generally preferred that mitigation occur within the same watershed as the impacted site; however, that is not a requirement. When an unavoidable impact occurs, the responsible party must acquire mitigation credits to offset their impact. Credits can be obtained through mitigation banks, in-lieu fee programs, or permittee-responsible mitigation. Mitigation banks must meet specific requirements before the credits can be released and used for compensation. Mitigation plans must meet performance standards that are defined on an individual project basis. All specific performance standards and monitoring requirements are determined by the district engineer for the specific project. More specific standards and specifications are often outlined at the state level. Mitigation is often criticized because of the lack of defined standards and the fact that credits are given on a metric of stream length rather than stream function (Doyle and Shields, 2012). The number of credits bought and sold through stream mitigation banking in some states, particularly in the southeast United States, has recently surpassed wetlands banking.

Monitoring of mitigation sites is required by the Clean Water Act, but overarching standards are not specified due to the individual nature of each project. Since monitoring requirements listed by the Clean Water Act are so generalized, states often go into more detail for their mitigation bank requirements. In Virginia, as outlined by the 2018 Virginia Mitigation Banking Instrument Template, monitoring must occur for ten years and monitoring reports must be prepared during years one, two, three, five, seven, and ten; additional years can be requested. If standards are not met, “Adaptive Management” may be required for approval and release of credits.

Performance standards for Virginia stream mitigation banks focus on attaining dynamic equilibrium. Biological standards listed depend on the type of landscape and vegetation present, but most require a riparian buffer of at least 400 woody stems per acre and a 30% canopy cover be achieved by the end of the first growing season.

Standards listed under “stream performance” are related to the physical form of the channel, including variables such as width/depth ratio, bank height ratio, entrenchment ratio (ER) and cross-sectional area. The width/depth ratio and bank height ratio standards are dependent on the pre-restoration values; however, the ER must be appropriate for the designed channel type within the Rosgen classification system. The cross-sectional area must not increase or decrease from the as-built area by more than 25%. To meet lateral stability/bank migration standards, four out of nine criteria must be met. One required criterion is that the Bank Erosion Hazard Index (BEHI) must meet a “Moderate” score by year three of monitoring. Other criteria options involve limits on the change in width to depth ratio, bankfull cross-sectional area, sinuosity, and radius of curvature. (USACE and VA DEQ, 2018)

Under the CWA, state environmental agencies are required to develop Total Maximum Daily Load (TMDL) plans which state the total amount of a given pollutant a water body can process and still meet water quality standards. TMDLs aim to improve water quality by reducing pollution loading on a watershed-scale (Cook et al., 2015). Before water quality standards can be set, “designated uses” such as navigation, public water supply, or recreation are established which state the main intended use of the water body (Blumm and Smith, 2021). Standards are then set under state-specific metrics (Cook et al., 2015) based on the defined uses. Water bodies that do not met the water quality standards are considered impaired and projects are completed to clean up and restore them to non-impaired conditions. TMDLs are used by the EPA as a mechanism to address both point and non-point sources of pollution (Blumm and Smith, 2021). TMDL development and implementation are both prioritized by states, but there is no set prioritization method outlined by the EPA (Norton et al., 2009). Therefore, many TMDLs that are developed, sit untouched, waiting “in line” to be implemented (Norton et al., 2009), and implementation is not always mandatory (Cook et al., 2015).

Some projects are not driven by regulation but are instead completed for protection or revitalization of a specific species. Projects with these goals are commonly administered in the western United States where economically significant fish species like Pacific salmon (*Oncorhynchus sp.*) and steelheads (*Oncorhynchus mykiss*) are populous. Funding for these projects increased when the fish species were deemed threatened or endangered under the United States Endangered Species Act (Roni et al., 2002). A large threat to salmon populations in the western United States is damming of rivers for hydroelectric power production which increases water temperatures. Hydroelectric dam operators are exempt from permitting under the Clean Water Act because they are not considered point source dischargers, so they are only subject to water quality standards. Occasionally, temperature TMDLs will be created in rivers which experience temperature changes due to hydroelectric power production. However, there are rarely regulatory reasons for stream restoration projects whose main goals are production or rehabilitation of fish habitat. (Blumm and Smith, 2021)

2.3 Stream Impacts

When studying streams in the mid-Atlantic United States, the historical presence of mill dams must be considered. Mill dams were constructed throughout the region from the late 1600s to the early 1900s with peak development between 1780 and 1860 (Walter and Merritts, 2008). It was estimated in 2006 that only 2% of US river kilometers were not affected by flow regulation from dams (Graf, 2001, 2006). Poor farming practices and land clearing in the 18th century through the early 20th century caused massive amounts of sediment to be eroded from uplands and transported to streams and floodplains in the eastern U.S. (Gutshall and Oberholtzer, 2011). The mill dams in the region caused ponding which trapped the sediment and caused it to be deposited upstream of the dams (Gutshall and Oberholtzer, 2011). The trapped sediments are referred to as legacy sediments which are broadly defined as "those for which the location, volume, and/or presence of contaminants result from past and contemporary human activities" (Wohl, 2015, p. 31). Dams have multiple effects on stream sediment dynamics, by enhancing sedimentation upstream while reducing sedimentation downstream (Wohl, 2015). This formation of legacy sediments impacts both the geomorphology and the hydrology of the ecosystem (Gutshall and Oberholtzer, 2011). As more sustainable farming practices were adopted in the mid-20th century (Gutshall and Oberholtzer, 2011), and dams were breached, streams began to cut down and incise through the legacy milldam sediments that had accumulated, creating the locally steep and high streambanks seen today (Walter and Merritts, 2008). Streams with high and steep streambanks experience significant bank erosion due to undercutting which increases turbidity and fine sediment supply to the stream. The build-up of sediment due to runoff from agricultural practices does not require the presence of a milldam, but can also be due to any cause of widespread deposition (McMahon et al., 2021), such as a sudden slope decrease.

Legacy sediments can also be deposited on the floodplain naturally through aggradation-degradation episodes (ADEs). An ADE involves channel response in the vertical dimension following elevated sediment deliveries. During an ADE, equilibrium is interrupted, and the channel aggrades with increased sediment. Channel incision typically occurs when sediment sources decrease or return to normal. Sources of increased sediment delivery can include land use changes such as mining, deforestation, plowing or long-term events such as glaciation, volcanic eruptions, or tectonic events (James, 2010).

Cattle have been studied over approximately the last 50 years as a major destructive force in the riparian community. Davis (1982) goes as far as to say that the long-term impact of overgrazing by cattle is one of the most destructive forces in riparian ecosystems. In the climate of the western United States, livestock seeking shade and water will congregate in riparian zones where those resources are available (Kondolf, 1993).

Livestock grazing and overgrazing in the riparian zone impact streamside vegetation, stream channel morphology, and the shape and quality of the water column, as well as the structure of the soil portion of the streambank. The effects of cattle on streamside vegetation include compaction of soil which increases runoff and decreases the water available to vegetation. Additionally, the herbage removal reduces the shading on the ground and allows the soil surface temperature to rise, which in turn increases the evaporation of water from the soil and further reduces plant available water. Finally, the vegetation is damaged physically by the livestock from trampling, rubbing, and browsing (Kauffman and Krueger, 1984). Degradation of vegetation in the riparian zone allows for fluvial erosion of alluvial material below the root zone to occur more easily which advances channel widening and instability (Beschta and Ripple, 2008). However, compared to channel morphology, vegetation is capable of faster recovery after cattle removal (Kondolf, 1993). Cattle impacts on channel morphology include the loss of bank overhang and subsequently fish habitat, as well as overall channel widening (Kauffman et al., 1983).

There is little research and documentation on the impacts of excluding cattle on channel morphology (Kondolf, 1993). However, the exclusion of cattle can be related to the trophic cascade effects that have been recorded after the reintroduction of predator species in several United States National Parks. As the predators in National Park areas were extirpated by hunting, the ungulate populations were able to rise significantly. An ungulate is a large, hoofed mammal such as elk, deer, bison, or cattle. The impact of increased ungulate grazing in riparian zones of National Parks resembles the grazing of cattle in agricultural environments. In Olympic National Park it was found that elk tended to utilize riparian zones inside the park where hunting was forbidden rather than outside of the park. Because of this behavioral response to the lack of a predator species, channel reaches inside and outside of the park could be compared and differences in channel characteristics attributed to the elk population. Inside the park, where elk populations were concentrated, the channels were steeper and wider with significantly more braiding than outside the park. Where herbivory was increased, erosion of the riverbanks was also expected to increase (Beschta and Ripple, 2008).

Since recent periods of high development and urbanization, there have been marked changes in the stream ecosystems. These changes have recently been labeled as the urban stream syndrome. Streams characterized by the urban stream syndrome typically have altered hydrology, morphology, water quality, and deteriorated habitats. This paper will focus primarily on the impacts on hydrology and morphology. Urban streams typically experience decreased baseflows and increased maximal flows due to increased impervious surfaces in the watershed.

Because water cannot infiltrate to the aquifers, the baseflow in the stream is reduced. Maximal flows are increased during storms because of the decreased infiltration and increased runoff. These maximal flows also occur more quickly, causing a flashier hydrograph. The increased surface runoff volume also shows itself in the recurrence interval of flood events. Flood periodicity can increase from 1.2-2.4 yr in natural systems to several times per year in urban systems (Komínková, 2012). This increase in flood events causes more erosion and the enlargement of stream channels, which reduces water quality and destroys bank habitat for aquatic biota (Komínková, 2012).

2.4 Stream Restoration Techniques

Stream restoration most often refers to the design and construction of functional streams and associated floodplains using practices such as installation of structures and planting of vegetation to stabilize the stream and removing disturbances that cause instability (Doll et al., 2003). Stable channels are designed using habitat structures and encouraging healthy riparian zones (Cook et al., 2015). The two most common stream restoration design techniques are Natural Channel Design (Rosgen, 1996) and Valley Restoration Design.

Developed by Rosgen, Natural Channel Design (NCD) consists of three components: 1.) a classification system; 2.) a set of design guidelines; and 3.) structures. There has been great debate in the United States over NCD for over two decades; however, the classification system is the least debated and most widely used component. The classification system aims to predict river behavior from physical features, such as “slope, planform, level of entrenchment, width/depth ratio, and bed material” (Lave, 2009). The classification system is designed to be easy to use for those without an extensive understanding of geomorphology (Small and Doyle, 2012). Most of the NCD controversy is sparked when use of the classification system is then taken to the design stage by those with limited background on fluvial systems (Simon et al., 2007). Rosgen's design guidelines are an eight-phase, 40-step process, utilizing regional curves, reference reaches and dimensionless ratios (Lave, 2009). Rosgen recommends stabilizing the channel to prevent downcutting and lateral migration (Lave, 2009) to reduce the threat of channel migration to surrounding land use and nearby infrastructure (Doll et al., 2003). This goal is also known as "locking in place", which is where the use of structures comes in (Lave, 2009, p. 1522). Channel locking maintains the width-to-depth ratio, the sediment transport capacity, and the channel capacity while decreasing stream power, near-bank velocity, and shear stress. To reach this goal, Rosgen suggests employing the use of traditional hydraulic engineering structures, but designs them using boulders and logs, giving a more natural appearance than a concrete structure. The structures should be placed intentionally to not only divert flow in a particular direction, but to also create scour pools and other channel features that are characteristic of a similar natural channel. (Lave, 2009)

Many people are critical of the focus that NCD places on stability, claiming that the channel cannot be considered "natural" if it is locked in place and unable to migrate (Lave, 2009). Others say that designing a stabilized channel in this way completely lacks a "coupled understanding of physical and biological processes" in a stream (Small and Doyle, 2012, p. 144). Additionally, while use of the classification system is helpful for identification and communication, it is a very generalized and simplified view of the fluvial system (Small and Doyle, 2012).Viewing the stream in this simplified way allows those with limited and possibly insufficient training to design and modify streams based on the classification system (Simon et al., 2007).

Valley Restoration Design (VRD) or Integrated Valley and Wetland Restoration was originally developed by Art Parola. Unlike Rosgen's Natural Channel Design, VRD does not use reference reaches, but instead requires an “understanding of the valley groundwater and surface water hydrologic systems and the characteristics of sediment loads to predict the likely channel forms and floodplain topography” (Starr and Harman, 2015, p. 3). This approach aims to restore the floodplain and stream channel processes that existed before human influence. Because this method focuses on restoring process rather than form, it is self-sustaining and not constricted to a fixed form. These restorations are designed to evolve as the landscape evolves through vegetative succession and the potential for beaver repopulation (Starr and Harman, 2015). Valley Restoration Design is typically more costly and time-consuming than NCD because of the amount of data required. However, this method has an advantage in utilization of models that have been developed over decades to represent and describe the processes occurring (Small and Doyle, 2012). This restoration technique aims to combine the ecological and engineering design viewpoints (Shields et al., 2003).

A common non-structural stream restoration practice is regrading of streambanks to improve bank stabilization. This practice is commonly used in conjunction with planting of native vegetative species to prevent further erosion. Regrading involves sloping steep banks to angles with a 2:1 (H:V) slope or flatter. The banks can then either be planted with native vegetation or the pre-existing vegetation can be allowed to repopulate. Regrading is the desired method of bank stabilization where the boundaries of the stream are not limited by infrastructure. Regrading and replanting have the potential to improve bank stability over time as species grow larger and the roots continue to enhance stability. The largest source of potential failure for streambank stabilization by regrading banks is the occurrence of a large flow event before vegetation can reestablish. Planting of larger species will decrease the likelihood of failure. Regrading and replanting also allows for the development of naturally undercut banks which provide habitat for aquatic species (RHAA Landscape Architects, 2000).

If a bank is already relatively stable, vegetative-only practices can be used and regrading is not necessary. Several studies have examined the roles of riparian vegetation on stream morphology and sediment storage. Hey and Thorne (1986) developed equations for the width of a channel relative to the type of riparian vegetation present along the floodplain. They found that wider streams typically have herbaceous vegetation surrounding them and narrower streams have woody vegetation. However, this is for large watersheds. A 2004 study (Anderson, Bledsoe, & Hession, 2004) reviewed the Hey and Thorne data and compared it to small watersheds (less than about 20 km) and found that forested reaches have wider channels than grassy reaches. So, the impact of the vegetation on the width of the stream, depends on the size of the watershed that is being studied. Another 2022 study (Gurnell & Bertoldi, 2022) conducted an analysis on the storage of sediment within river channels, specifically measuring the effects of vegetated surfaces. Comparing bare riverbed to submerged aquatic vegetation, emergent aquatic vegetation, and vegetated emergent bedforms such as bars and benches gave insight into the effects of these forms of vegetation on the storage of fine sediment in the channel. Results indicated that each vegetated surface is capable of capturing and retaining large amounts of fine sediment, but the vegetated emergent bedforms perform the best (Gurnell & Bertoldi, 2022).

Vegetative-only practices involve removing non-native species and replacing them with native species. Replanting the bank should be done carefully as to not leave the bank exposed and unprotected for extended periods of time. It should also be taken into consideration that large extensive vegetation can significantly reduce flow velocities and can cause adverse effects if the amount of vegetation is more than what is necessary for natural flow conditions. This is especially true for typically arid and semi-arid areas where streams naturally dry during part of the year (RHAA Landscape Architects, 2000).

2.5 Stream Restoration Project Assessment

Monitoring and project assessment must occur under the Clean Water Act, but specific standards are not laid out by the legislation. The CWA Section 404(b)(1) states that the monitoring period for mitigation projects must be long enough to demonstrate that standards have been met and must not be less than five years ("Federal Water Pollution Control Act"). However, district engineers may waive monitoring requirements once the project standards appear to have been met or they may extend the length until deemed successful ("Federal Water Pollution Control Act"). Most often, monitoring standards apply to the stability of the channel physical form and standards lack reference to biological health and water quality (Lave, 2018) due to the significant challenge of monitoring biota (Roni et al., 2002). Currently, presence of riparian vegetation is the only criteria related to water quality and biology in almost all Corps of Engineers districts in the United States (Lave, 2018).

Stream restoration projects are often evaluated in terms of "success" and "failure", where a system must be stable to be deemed successful. The industry lacks a set of defined metrics for "success" or "failure", and many practitioners are against creating one due to the individual nature of each project (Bennett et al., 2011). Additionally, professionals from a variety of disciplines participate in restoration work and all have different focuses for their project goals (Bennett et al., 2011). Others argue that a national monitoring system is necessary to further the field of stream restoration. However, they recognize that it is likely not feasible to monitor every project implemented each year, so an in depth review of a statistical sample of the population of projects is suggested. (Bernhardt et al., 2007). There is also a disconnect between practitioners and scholars, so results from projects, especially those that are deemed “failures”, are not widely shared or well communicated (Bennett et al., 2011). Some studies have found that practitioners have a will and desire to implement monitoring but lack resources to do so (Bernhardt et al., 2007).

2.6 Channel Evolution Models

Channel evolution models (CEMs) in their simplest forms are linear models that suggest that following a disturbance, a channel exists in an unstable state and adjusts in a predictable manner until it reaches a new state of equilibrium, different from that of pre-disturbance conditions (Phillips, 2013). Historically, CEMs were primarily applicable to channelized single-thread channels (Booth and Fischenich, 2015), specifically in the southeastern United States (Van Dyke, 2013). The classic six-stage evolution model depicted in Figure 1 begins with an unaltered channel that is close to equilibrium. During this stage, some migration may occur through bank retreat and advancement. Stage two is channelization, or another disturbance. Other disturbances can be urbanization, dam removal, etc. The channelization causes a knickpoint which is used to track the following stages of evolution through space and time. Disturbances often cause changes in hydrology, morphology, and vegetation. Channelization specifically causes an increase in slope through straightening of meander bends, and a loss of vegetation. In response to the disturbance, the stream incises to reduce the slope, which is stage three. In stage four, downcutting continues, but is coupled with channel widening due to the steep banks created in stage three, causing bank failure. As bank failure ensues, sediment is added to the channel which aggrades downstream and reduces stream energy, further contributing to aggradation. The combination of aggradation and mass wasting results in a widened channel in stage five. Vegetation also begins to colonize the aggraded areas as energy dissipates. Vegetation growth increases roughness, further encouraging deposition and stabilizes banks. As vegetation grows and banks become more stable, the channel settles into stage six where the stream exists in a new channel formed of aggraded material with a terraced floodplain. The new main channel is at a lower elevation than the pre-disturbed channel. (Van Dyke, 2013)

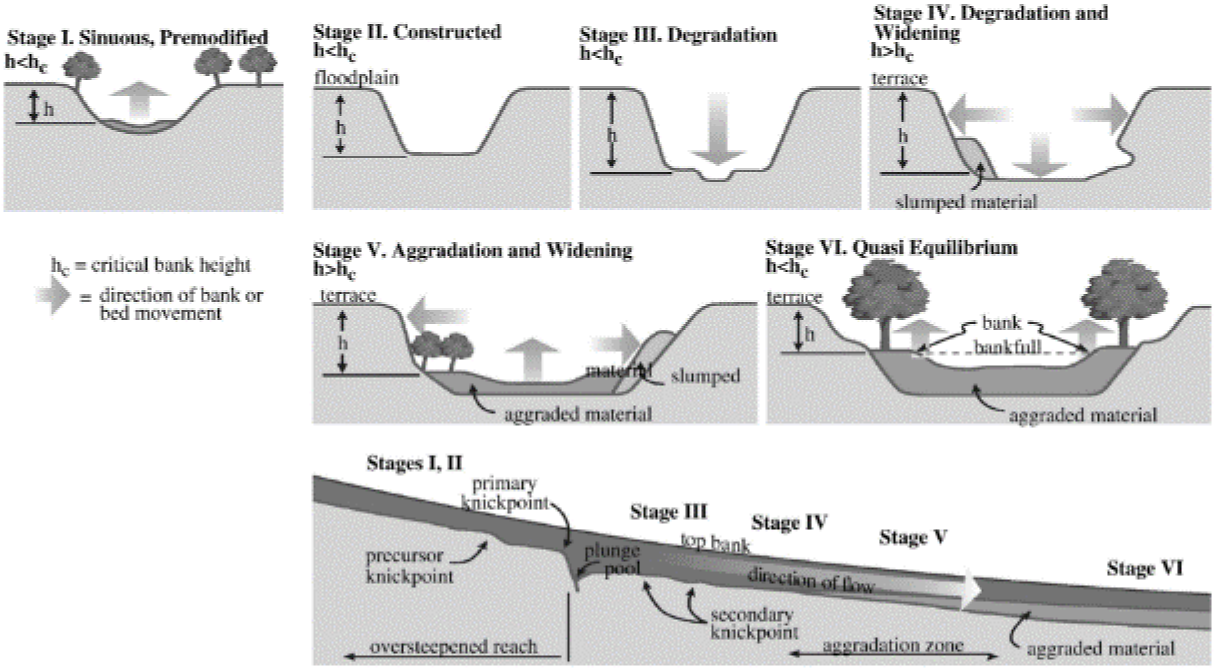


Figure 1: Stages of channel evolution (from Simon and Rinaldi, 2006*).*

3 Methods

The stream restoration project for this research is on Stroubles Creek, a freshwater tributary to the New River. Located in southwestern, Virginia, USA (Figure 2), the project watershed (15.3 km^2) drains much of the Town of Blacksburg and the Virginia Tech campus (Figure 3). It is situated in the EPA Ecoregion 67f which has Southern Limestone/Dolomite Valleys and Low Rolling Hills (Level IV Ecoregion) in the Ridge and Valley Level III Ecoregion (US EPA, 2003). The area is surrounded by the Appalachian Mountains, which are believed to be one of the oldest mountain ranges in the U.S. (Friends of the Blue Ridge Mountains, 2022). The drainage area of the project watershed is 15.3 km^2 and land cover was classified in 2011 as 87% developed with 36% impervious surfaces (Figure 4). About 10% of the land is covered in pasture and 3% is forested (StreamStats, 2022). The study location is in the lower portion of the project watershed which contains the agricultural and forested land cover while the upper portion of the project watershed is mostly developed low to high density residential. Directly adjacent to the stream channel in the study reach is pasture (Multi-Resolution Land Characteristics Consortium, 2019) and prior to the stream restoration project in 2009 was grazed by cattle with full access to the stream. The region experienced an average total precipitation of 108 cm annually between 1991 and 2020 (NOAA NCEI U.S. Climate Normals Quick Access, 2022). Precipitation is relatively even across each season with the spring and summer each receiving an average of 30 cm annually and the fall and winter each experiencing about 23 cm (NOAA NCEI U.S. Climate Normals Quick Access, 2022). Snowfall is recorded in every season except summer but is highest in the winter and spring. The annual average temperature is 11ºC, which ranges from an average of 0.56ºC in the winter to 21ºC degrees in the summer (NOAA NCEI U.S. Climate Normals Quick Access, 2022). Elevation in the watershed ranges from 606 m to 701 m above sea level and the watershed relief at the study location is just over 91 m. (StreamStats, 2022).

The soils in the watershed primarily consist of the Groseclose series which is formed from weathered limestone, shale, siltstone, and sandstone. The soils are well drained but exist on moderate slopes of 2-7%, so the runoff class is high. (USDA, 2021) Directly along the stream channel are McGary and Purdy soils which exist on lower slopes of 0-2% and are somewhat poorly drained. These soils contain high amounts of silt and clay (USDA, 2021). Blacksburg, Virginia was first settled in 1740 and Virginia Tech was founded in 1872, which caused expansion of the town and land development. Following settlement, sediments which are still

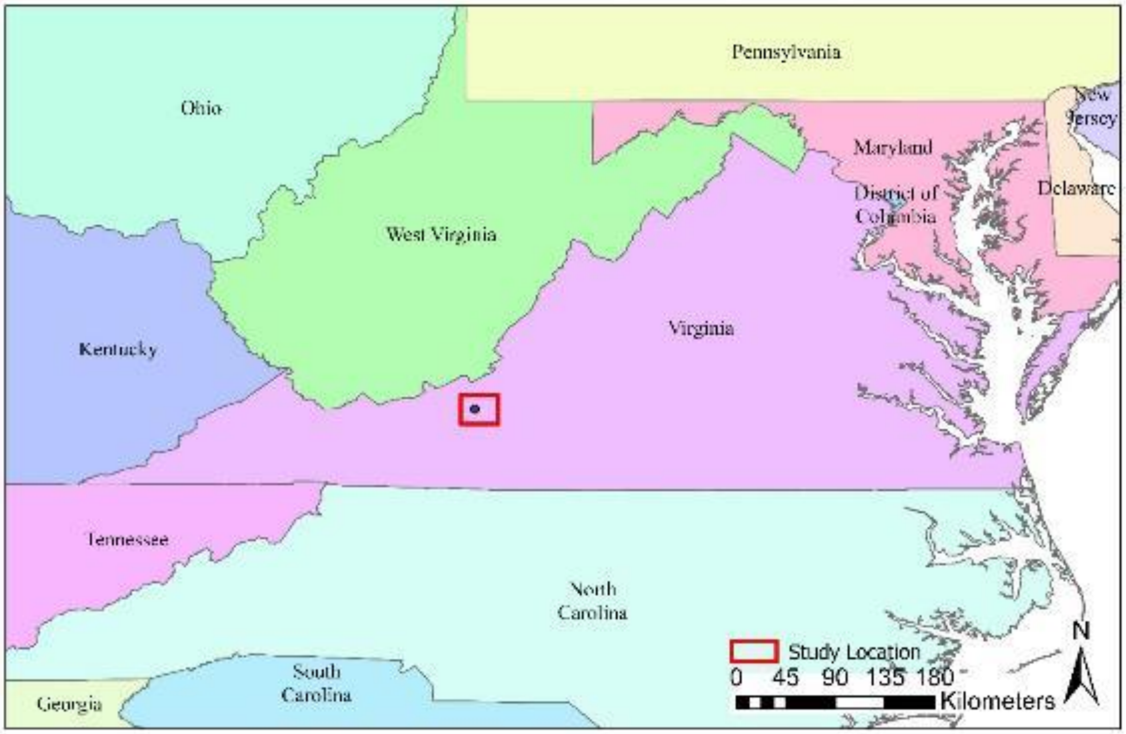


Figure 2: Location of study

present in the soil profile today were deposited on the floodplain as legacy sediments, covering the original gravel streambed. Figure 5 depicts the sedimentological history of the Stroubles Creek floodplain.

Stroubles Creek is a gravel-bed, riffle-pool channel at a slope of 0.022 with weakly formed riffles and point bars. The D50 currently ranges from about 11 to 22 mm but is embedded due to fine sediment loading from streambank retreat and upstream construction. Around 1937, the main branch of Stroubles Creek was buried under what is now the Virginia Tech Drillfield (Parece et al., 2010). Around the same time, a dam was constructed to form a recreational pond just downstream of the Drillfield which is now known as the Duck Pond. The Duck Pond is currently trapping sediment but is not an official stormwater retention pond, which has trapped coarse sediment from the increasingly urbanized upstream portion of the watershed. Because

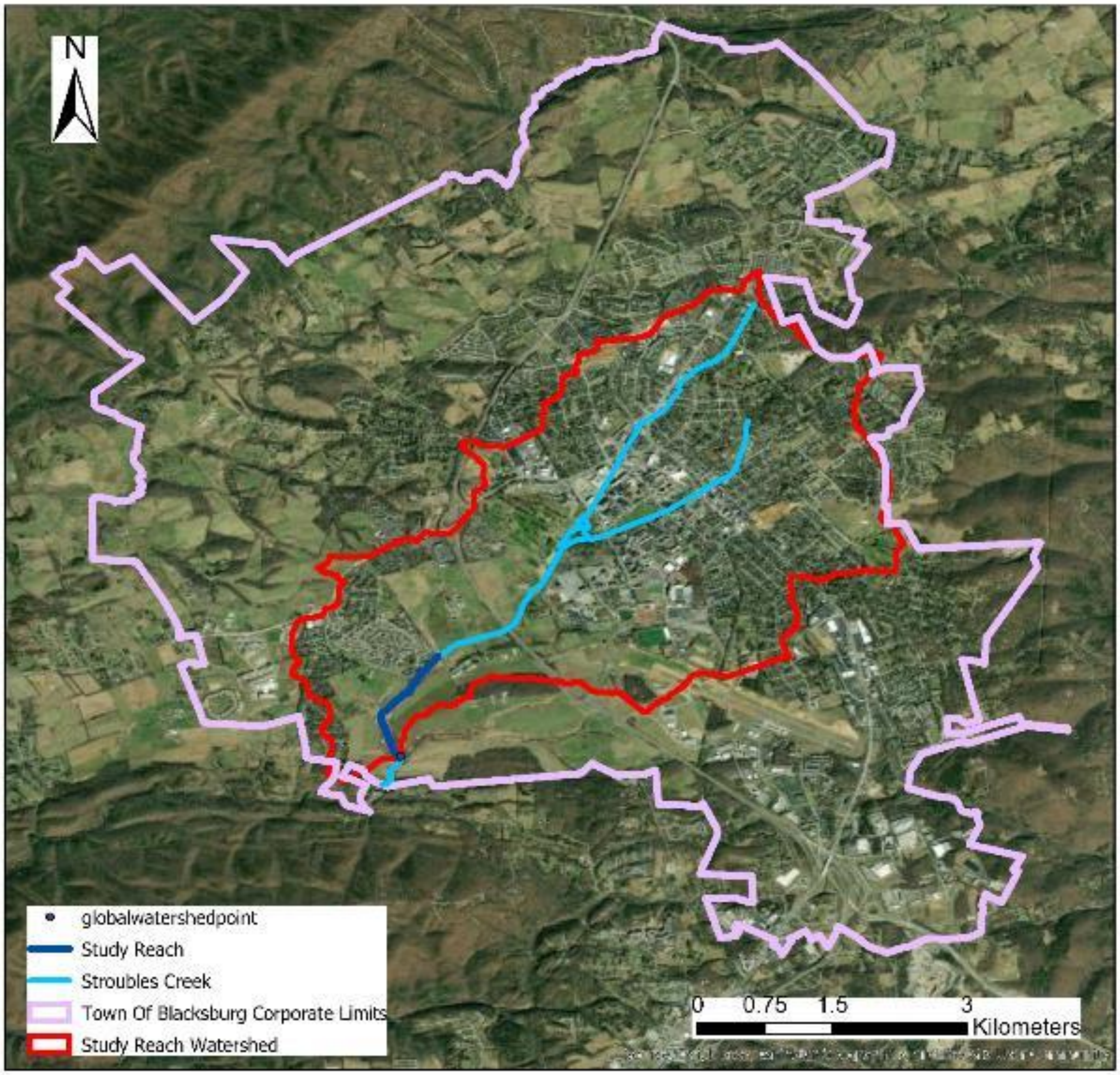


Figure 3: Stroubles Creek and the Stroubles Creek watershed in the town of Blacksburg.

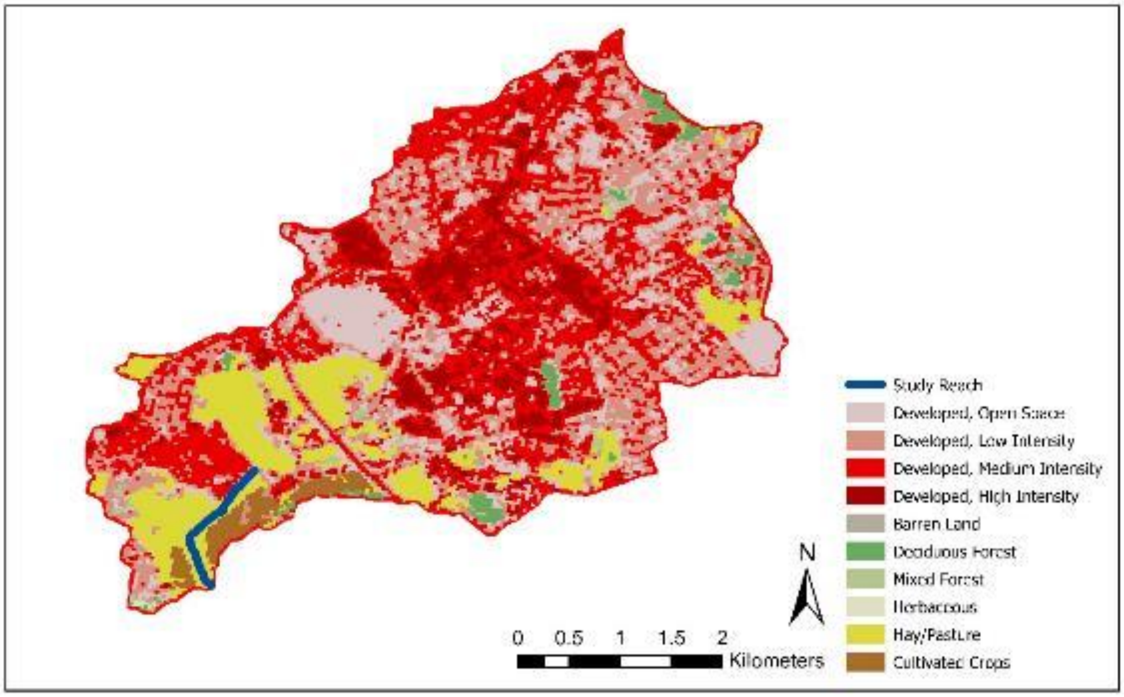
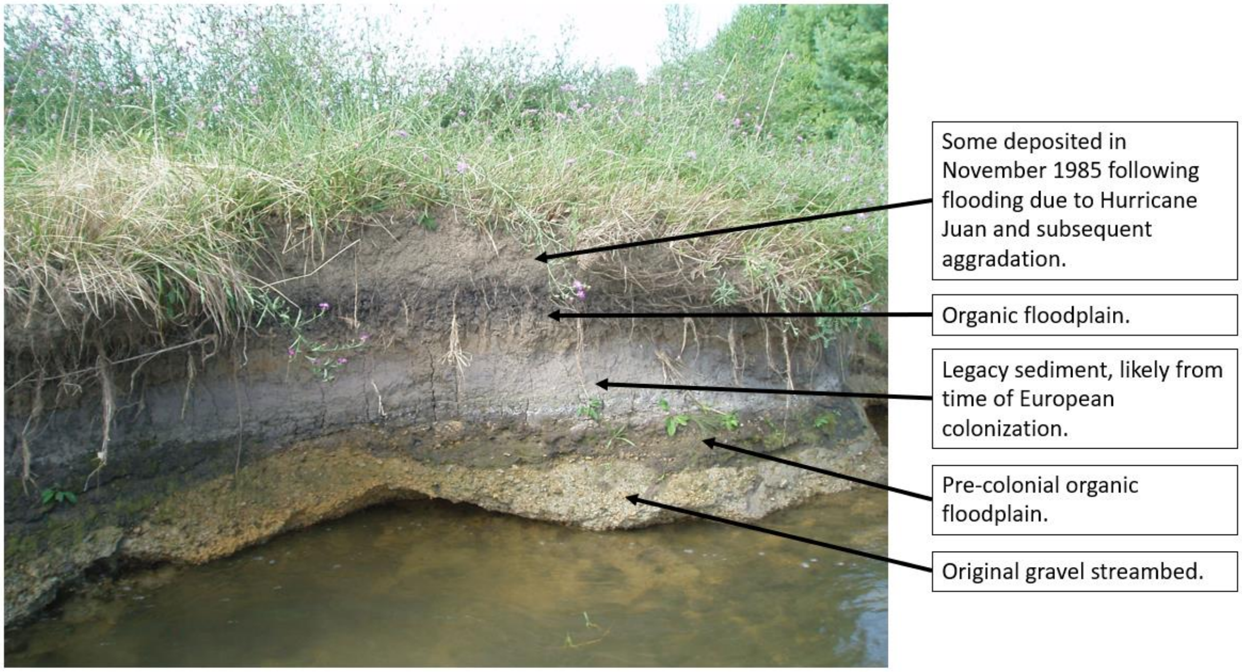


Figure 4: Watershed of study reach and 2011 land use.



Some deposited in November 1985 following flooding due to Hurricane Juan and subsequent aggradation.

Organic floodplain.

Legacy sediment, likely from time of European colonization.

Pre-colonial organic floodplain.

Original gravel streambed.

Figure 5: Stroubles Creek streambank (image was taken in Treatment 1).

sediment deposition in the pond has been an ongoing issue, dredging of the Duck Pond occurred in 1950, 1960, and 1986, and is planned for the summer of 2023. The headwaters upstream of the Drillfield are primarily piped or contained in rectangular channels lined by either concrete or gabion baskets. All sections of the stream have portions that have been straightened. Due to the straightening, channelizing, and legacy sediments, the channel in the project reach is highly incised with an average bank height of 1.17 m measured in 2021. Additionally, because of the amount of incision and stream burial, the presence of the Duck Pond, and the geologic age of the landscape, the supply of coarse material to the stream is limited and the study reach is sediment-starved. The primary source of sediment to the channel is from the streambanks and bedrock outcrops in the channel bed.

Stroubles Creek was first listed in 1996 on the 303(d) TMDL priority list due to low Virginia Stream Condition Index (VSCI) scores for the benthic macroinvertebrate community (Benham et al., 2003) and was again included on the 1998 and 2003 lists. Possible stressors identified were organic matter, nutrients, and sediment. A watershed assessment identified sediment as the main stressor and both a total maximum daily load (TMDL) plan (Benham et al., 2003) and TMDL implementation plan (Yagow et al., 2006) were developed. Channel and streambank erosion caused by a lack of riparian cover, increased runoff rates, and animal grazing were identified as major sediment sources. The recommended TMDL called for a 77% reduction in sediment loads from agricultural sources and channel erosion, and stream restoration was recommended as the most effective method for sediment load reduction. (Benham et al., 2003; Yagow et al., 2006).

StREAM Lab History

The portion of Stroubles Creek where the study site is located is the Virginia Tech Stream Research, Education, and Management (StREAM) Lab (Figures 6, 7, 8). Located on a former dairy farm, the StREAM Lab property was purchased by the Virginia Tech Foundation in 2001 and a 1.3-km long restoration was designed and implemented during 2009-2010 as part of the TMDL implementation plan for Stroubles Creek (Wynn et al., 2010). Pre-restoration data from 2006 and 2007 indicated ongoing erosion. In 2007, the banks were high due to legacy sediment deposition on the floodplain and channel incision. In 2007 bank heights averaged 0.93 m, and channel width averaged 6.93 m. Cantilever bank failures were common, contributing fine sediment to the channel (Figure 9).

Prior to the restoration project, Stroubles Creek was in stage four of the channel evolution model, with pre-restoration measurements exhibiting evidence of incision and widening (Appendix A Table A-1). Banks were steep due to prolonged incision and mass wasting was causing widening. The disturbance on Stroubles Creek was channelization coupled with urbanization, so excessive fine sediment was being added to the channel from the streambanks as well as construction during the expansion of the town pre-dating stormwater and erosion and sediment control legislation. The majority of that sediment likely passed through the system due to the high stream energy from channelization.

When the stream restoration was designed, the main goal was to help remove Stroubles Creek from the impaired waters list for excess sediments. More specific objectives to help reach that goal included improvement of the Virginia Stream Condition Index to a score greater than 60 for the benthic macroinvertebrate community. This score prior to the restoration averaged 45.3. Since the sediment was identified as the main stressor and the streambanks were identified as a major source of sediment, a second goal was to reduce sediment loading to the stream by physically modifying the banks using the three treatments described previously. Removing cattle access, which is one of the three restoration treatments used for physical modification, was also intended to reduce bacterial loadings to the stream. The final two goals involved assessing the effectiveness of the three treatment methods and developing an education and outreach program about the project.

During restoration design, the 1.3. km length of Stroubles Creek on the StREAM Lab property was divided into three sections for evaluation of different restoration techniques (Figure 10). Cattle were excluded from the entire project reach in 2009. The lowest level of restoration was completed in the furthest upstream section, named Treatment 1 and the highest level of restoration was completed in the furthest downstream section, named Treatment 3. In Treatment 1 (0.5 km), the streambanks were left to naturally stabilize while the floodplain re-vegetated. In the middle section, Treatment 2 (0.5 km) was completed. This Priority 4 restoration involved reshaping the banks to a 3:1 slope and replanting with native vegetation (Wynn et al., 2010). Treatment 3 (0.3 km) used a Priority 2 restoration in which the banks were reshaped to include an inset floodplain and replanted with native vegetation (Wynn et al., 2010) (Figure 11). The elevation of the inset floodplains was designed to contain a 2.5-yr flood (8.5 m^3/s) and to minimize movement of particles at or above the 84th percentile (21 mm) (Wynn et al., 2010) at this discharge. The existing channel slope and baseflow channel width were maintained because the existing sinuosity was similar to a nearby reference reach (Thompson et al., 2012).

Prior to the restoration, turbidity was measured at different locations along the stream. Following the restoration, stage and YSI meters were installed at the downstream end of each treatment. Additionally, topographic surveying of the channel was repeated prior to and following the restoration. The stage data from the monitoring stations was used in this project to analyze the hydrology from November 2012 to March 2022.

Figure 6: 2009 Aerial imagery of the StREAM Lab property at Stroubles Creek.

Figure 7: 2011 Aerial imagery of the StREAM Lab property at Stroubles Creek.

Prior to the restoration, surveys were conducted in 2006 and 2007 and included nine repeated cross section measurements. It is likely that both surveys were conducted using a Topcon GR-3 (Tokyo, Japan) survey unit, but the specific unit was not recorded at the time of surveying and cannot be confirmed. A total of 30 cross sections were selected for surveying with a Topcon GR-3 (Tokyo, Japan) survey unit immediately after restoration construction was completed in 2010; the section ends were monumented using rebar, and the cross sections were then re-surveyed in 2021 with a Trimble R10 GNSS (Sunnyvale, California) system, which has a maximum

Figure 8: 2019 Aerial imagery of the StREAM Lab property at Stroubles Creek

precision of 8 mm horizontally and 15 mm vertically. When first established in 2010, Treatments 1, 2, and 3 had five, thirteen, and twelve cross sections, respectively. Fewer cross sections were established in Treatment 1, due to the presence of two stormwater outfalls in this reach. When the project site was surveyed again in 2021, a total of 20 cross sections were found, including four in Treatment 1, ten in Treatment 2, and six in Treatment 3 (Table 1). Once the 2021 survey was completed, the cross-sectional area, width, maximum depth, hydraulic depth, and width-to-

Figure 9: Images of StREAM Lab property prior to restoration

depth ratio (Table 2) were computed using Autodesk Civil3D 2022 (San Rafael, California) for each cross section that was surveyed in 2010 and 2021. The top boundary used to calculate these metrics was defined using a constant top-of-bank for each cross section across the two time points. The top-of-bank line was chosen where the clearest change in slope occurred on the lower bank, which represents the first elevation at which flows spill onto the floodplain (Figure 12).

Maximum depth was measured from the thalweg elevation to the top-of-bank line. Width was measured across the top-of-bank line. The same method of measurement was used for all years, including pre-restoration and post-restoration data. Hydraulic depth was calculated as the cross-sectional area divided by the top width.

Herbaceous vegetation measurements were completed in 2003 as part of a separate study. For that study, all herbaceous vegetation was cut at ground level in a 1-m^2 quadrat and air dried at 60°C (Wynn et al., 2004). At that time, vegetation along the entire study reach was uniform due to cattle grazing pressure and no trees or woody vegetation were present. Additionally, the stream was characterized as having either one sloping bank and one vertical bank or vertical banks on both sides. Three vegetation samples from vertical banks and three samples from sloped banks were averaged.

To quantify differences in vegetative success among the three restoration treatments, woody stem density and herbaceous biomass in each treatment area were quantified in 2021. Herbaceous biomass was sampled using, ten, 1-m^2 quadrats in each treatment reach, for a total of 30 samples. The location of each quadrat sample was selected using stratified random sampling across the length of each reach. In the field, the quadrat was placed parallel to the streambank at each sampling point. Then, all the herbaceous vegetation rooted within the 1-m^2 quadrat was cut

Figure 10: Treatments 2 and 3 during construction. a) Treatment 2 with banks regraded, gravel bars forming; b) Treatment 3 gravel bars forming; c) Treatment 3 with constructed inset floodplain.

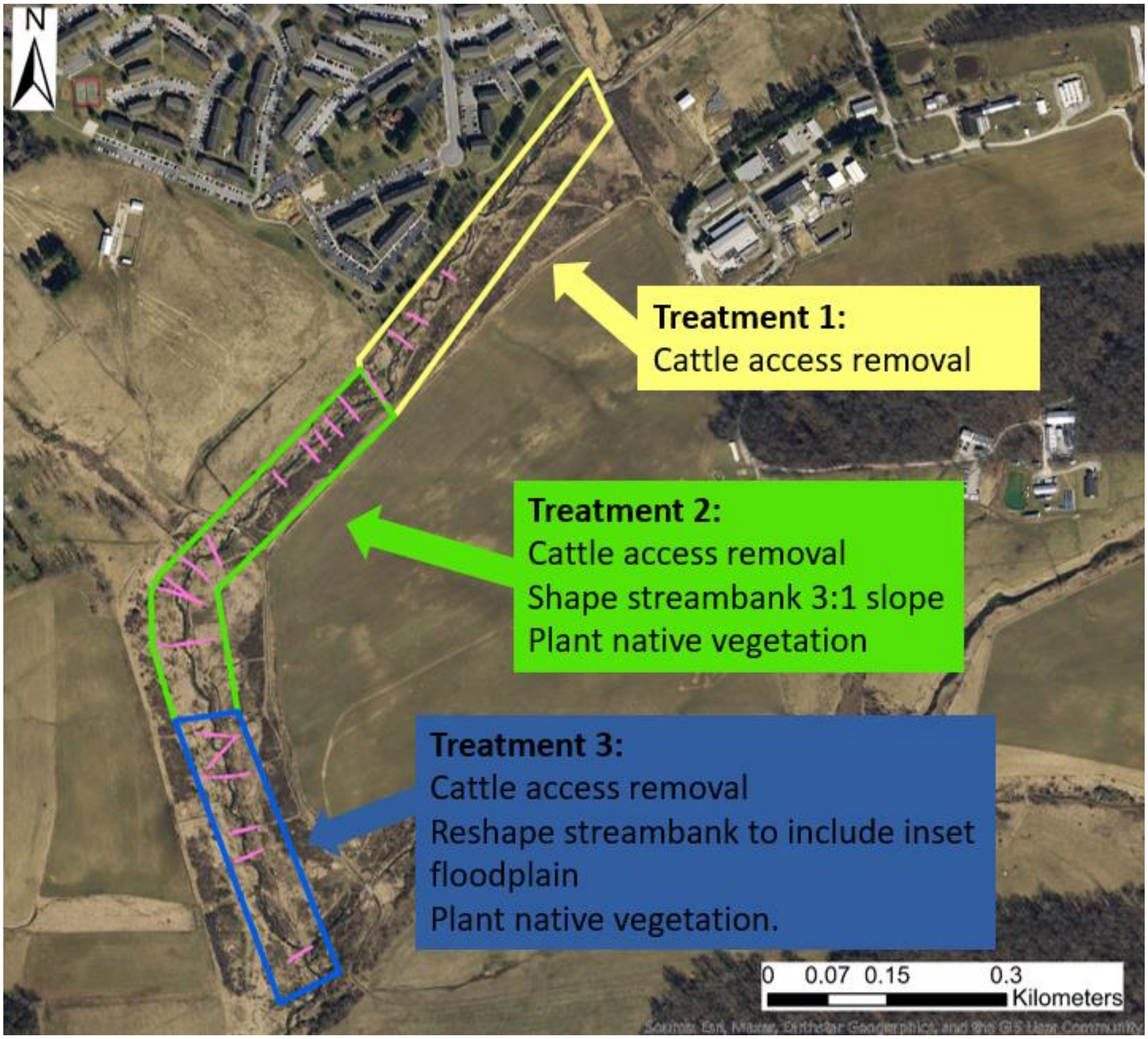


Figure 11: Location of cross sections and Treatments on Stroubles Creek.

at ground level and collected. Following collection, the samples were stored in a cooler at 4°C for a maximum of seven days prior to drying. Samples were dried at 60°C and weighed to determine dry herbaceous biomass in each treatment reach.

Woody stem counts were completed using three, 100-m^2 quadrants in each treatment reach, for a total of nine samples. Sample locations were again chosen using random sampling. At each predetermined location, a 10 m x10 m quadrant was created adjacent to the channel, and all stems with an average diameter greater than 2.5 cm at ground level were counted.

Table 1: Number of cross sections established in 2010 and surveyed again in 2021 for each treatment.

Treatment	Number of cross sections established in 2010	Number of cross sections found and re-surveyed in 2021
1. Cattle Removal	5	4
2. Cattle removal, banks sloped 3:1, native vegetation planted	13	10
3. Cattle removal, inset floodplain constructed, native vegetation planted	12	6

Table 2: Values measured for each cross section.

Measurement	Calculation Method
Cross-Sectional Area	Area underneath top-of-bank line
Width	Length of top-of-bank line
Maximum Depth	Distance from thalweg to top-of-bank line
Hydraulic Depth	Area / Top Width
Width-to-Depth Ratio	Width / Hydraulic Depth

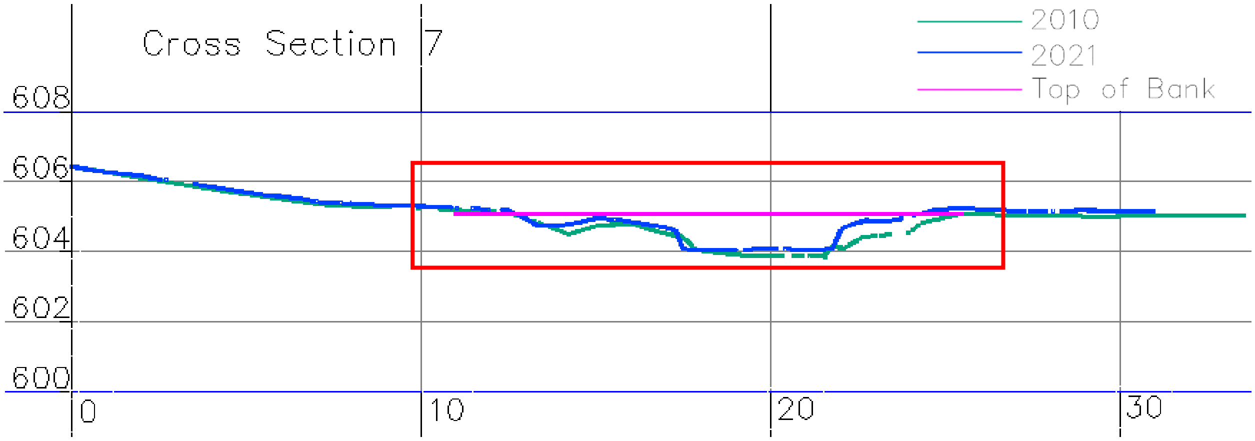


Figure 12A: Example of top-of-bank line used for maximum depth and top width measurement. Area was measured between the top-of-bank line and the cross section boundary. This example is from Cross Section 7.

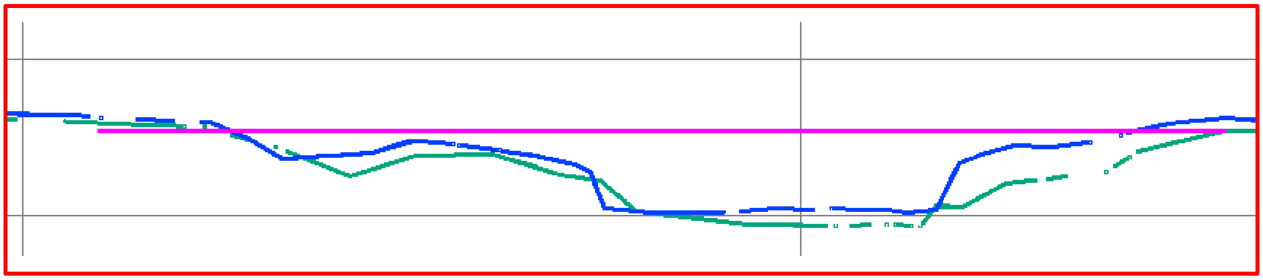


Figure 12B: Closer view of active channel in Cross Section 7. For this cross section, the top of bank line was chosen on the right bank.

3.1 Statistical Analysis

A two-way analysis of variance (ANOVA) statistical test was performed on each channel geometry and vegetation metric to determine if there were significant differences in the means between the treatments. This test was followed by a Tukey's HSD analysis to determine which values were significantly different from each other. Additionally, a non-parametric Kruskal-Wallis test was conducted, followed by a multiple comparisons test on significant results from the Kruskal-Wallis test. All tests were conducted at a 95% confidence level. Each analysis was also repeated to measure effects of geomorphic units and planform locations on each of the metrics. Geomorphic units were grouped by pool, riffle, and run. In this case, runs were identified as transitional areas between the pools and riffles (Doll et al., 2003). Cross Section 5 was left out of all averaging and statistical analyses due to its position under a sampling bridge at the interface of Treatments 1 and 2 and because it was an outlier. P-values less than 0.05 indicate significant differences between treatments, geomorphic units, or planform locations are significant for area, width, maximum depth, hydraulic depth, or width-to-depth ratio.

4 Results

4.1 Qualitative Results

Upon visual inspection of the three restoration treatments on Stroubles Creek, there is a notable difference between the vegetation in each treatment (Figure 13). Following cattle exclusion from the StREAM Lab property in July 2009, the herbaceous vegetation grew rapidly, increasing the channel roughness on the streambanks that had more gentle slopes. Increased roughness allowed for sediment deposition along the channel margins to occur even as the restoration was ongoing. Specifically in Treatment 2, gravel bars were visibly forming during construction (Figure 10A). Since the completion of the restoration, the presence of vegetation, both herbaceous and woody, has visibly increased and the channel width has visibly narrowed in general. Banks that were not regraded remain vertical and continue to retreat via toe scour and cantilever failure (T. Thompson, personal communication, July 9, 2022).

4.2 Quantification of Vegetative Success

Prior to the restoration, the entire stream reach (all three treatments) was in pasture dominated by herbaceous vegetation with little to no woody vegetation. Dry herbaceous biomass sample results from 2002 were 1,445 kg/acre on the steep banks and 2,133 kg/acre on the gradually sloped banks.

Herbaceous biomass and woody vegetation stem counts taken in 2022 showed that Treatment 2 had the most herbaceous biomass on average while Treatment 1 had the highest average woody stem counts (Table 3). However, Treatment 3 had the highest median value of woody vegetation, almost double that of Treatment 1. A diversity of native vegetation was planted in Treatments 2 and 3, but willow (*Salix sp.*) and American sycamore (*Platanus occidentalis*) now dominate the riparian vegetation (Figure 14). Treatment 1 was not replanted with native vegetation, so an

Figure 13: Images of StREAM Lab property 12 years after restoration in 2022. A) Treatment 1; B and C) Treatment 2; D) Treatment 3

Table 3: 2021 Vegetation counts for Stroubles Creek, Blacksburg, VA.

Treatment	**1**	**2**	**3**
Herbaceous (kg/acre)	1665	1773	1560
Woody - Mean (stems/acre)	836	580	769
Woody - Median (stems/acre)	405	202	809

invasive species, autumn olive (*Elaeagnus umbellata*), dominates in that section. The autumn olive (*Elaeagnus umbellate*) stems were included in the woody stem count to ensure an accurate representation of the amount of woody vegetation in the floodplains. Autumn olive (*Elaeagnus umbellate*) is characterized by many stems protruding from a single base at the ground surface (Figure 14A), so many stems are counted for each individual plant, which inflated the number of woody stems counted in Treatment 1.

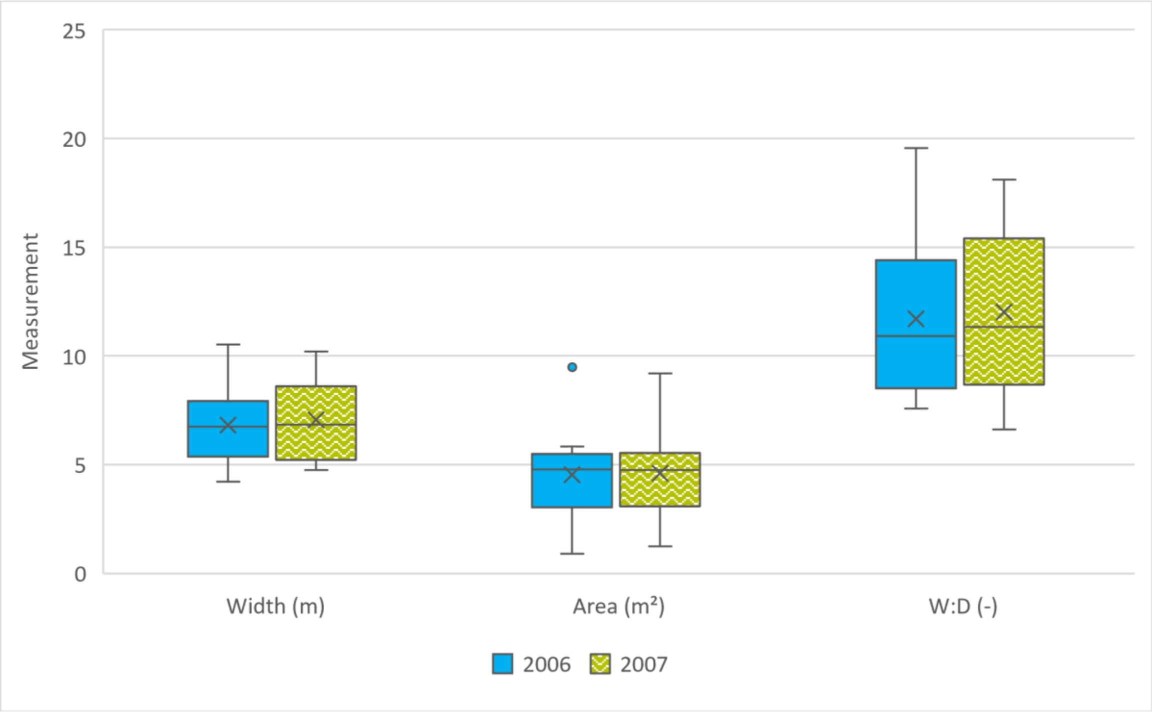
4.3 Planform Measurements

Sinuosity was measured on aerial photographs for 2011 and 2019. In 2011 the average overall sinuosity was 1.071 and in 2019 the average sinuosity was 1.065 indicating a negligible decrease (-0.53%) over 8 years. The existing sinuosity was similar to that of a nearby reference reach, so the sinuosity was not changed during the restoration (Wynn et al., 2010). However, because of the lack of structures used in the design, the channel can migrate, and sinuosity appears to be slightly increasing.

4.4 Pre-Restoration Geomorphic Measurements and Hydrology

Prior to the restoration, in 2007, bank heights ranged from 0.4 m to 1.2 m and channel widths ranged from 4.7 m to 10.2 m (Figure 15; Appendix A Table A-1). From 2006 to 2007, the average area, width and depth of the stream increased between 3.8% and 10% per year,

Figure 14: Vegetation on Stroubles Creek. A) Treatment 1, Autumn olive (Elaegnus Umbellata); B) Treatment 2; C) Treatment 3



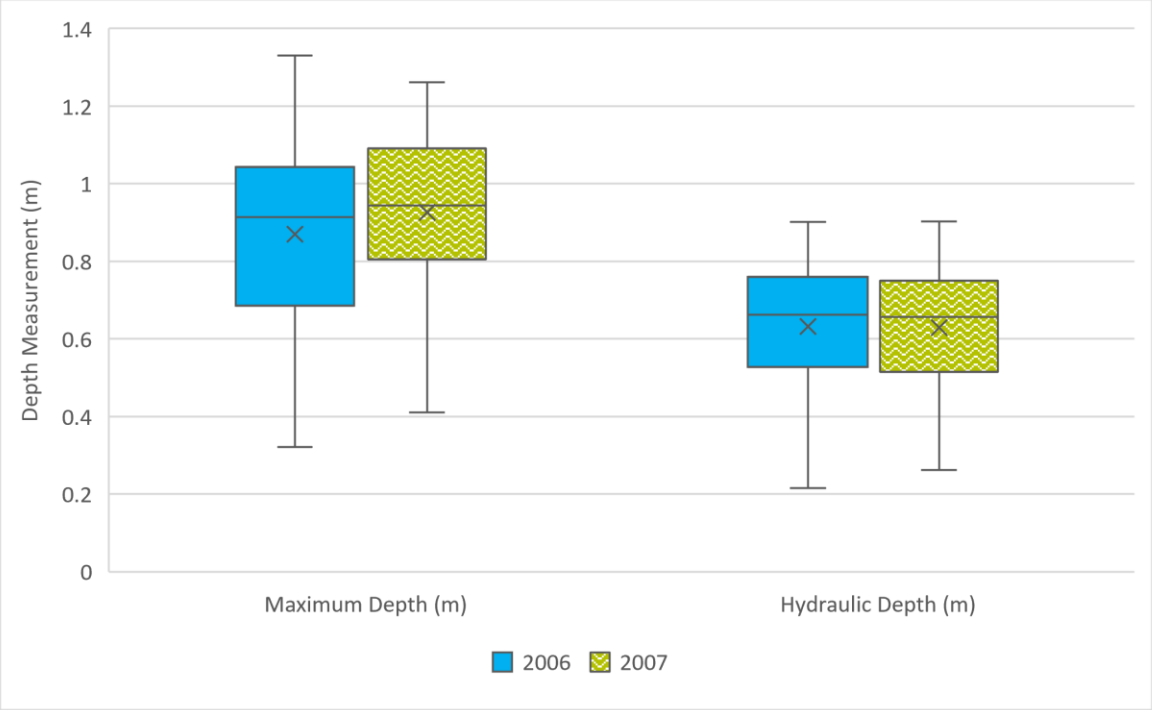


Figure 15: Pre-restoration values of width, maximum depth, area, hydraulic depth and width-to-depth ratio on the Stroubles Creek, Blacksburg, Virginia.

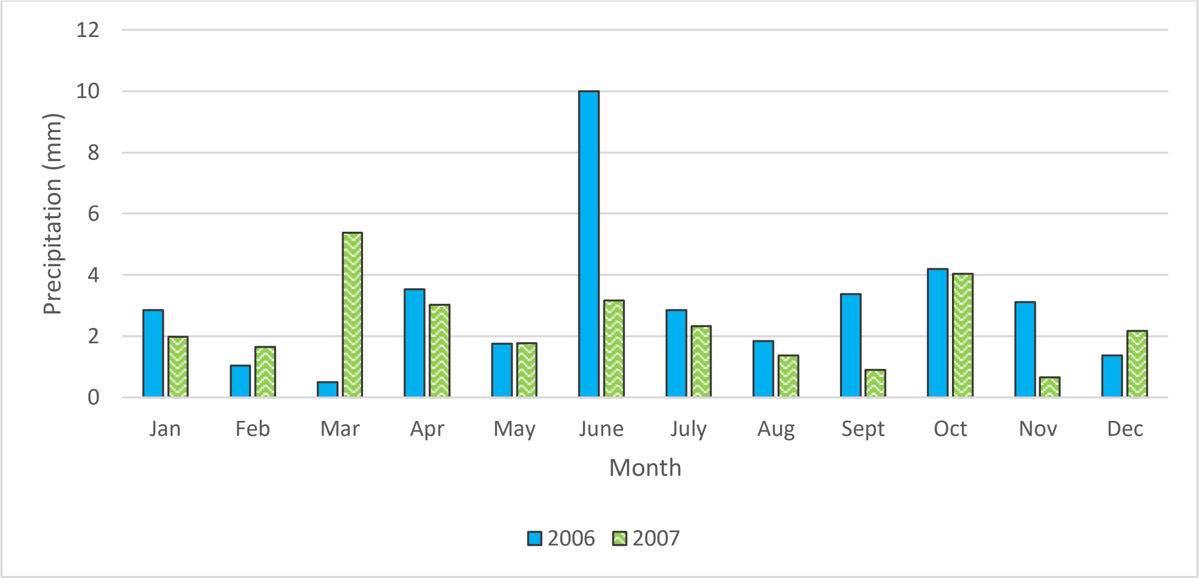


Figure 16: Average monthly precipitation data for2006 and 2007 in Blacksburg, Virginia.

respectively (Appendix A Table A-3). The change in depth was greater than the change in width resulting in a decrease in the width-to-depth ratio. The specific date of the 2006 survey is unknown, but as seen in Figure 16, there was a large storm event in June 2006, which could be inflating the rates of change between 2006 and 2007. Figure 17 depicts the flows in 2007.

4.5 Study Period Hydrology

Beginning in November 2011, stage was recorded every 10 min at the first sampling bridge (Bridge 1) at the StREAM Lab. Stroubles Creek overtops the banks at Bridge 1 at a stage of approximately 0.9 m. The stage data were evaluated and the number of days with a bank overtopping event for each year from 2012 to 2021 were counted. NOAA precipitation data was used to calculate the total precipitation during each year of the study period (NOAA NCEI U.S. Climate Normals Quick Access, 2022). As seen in Figure 18, the precipitation was around the

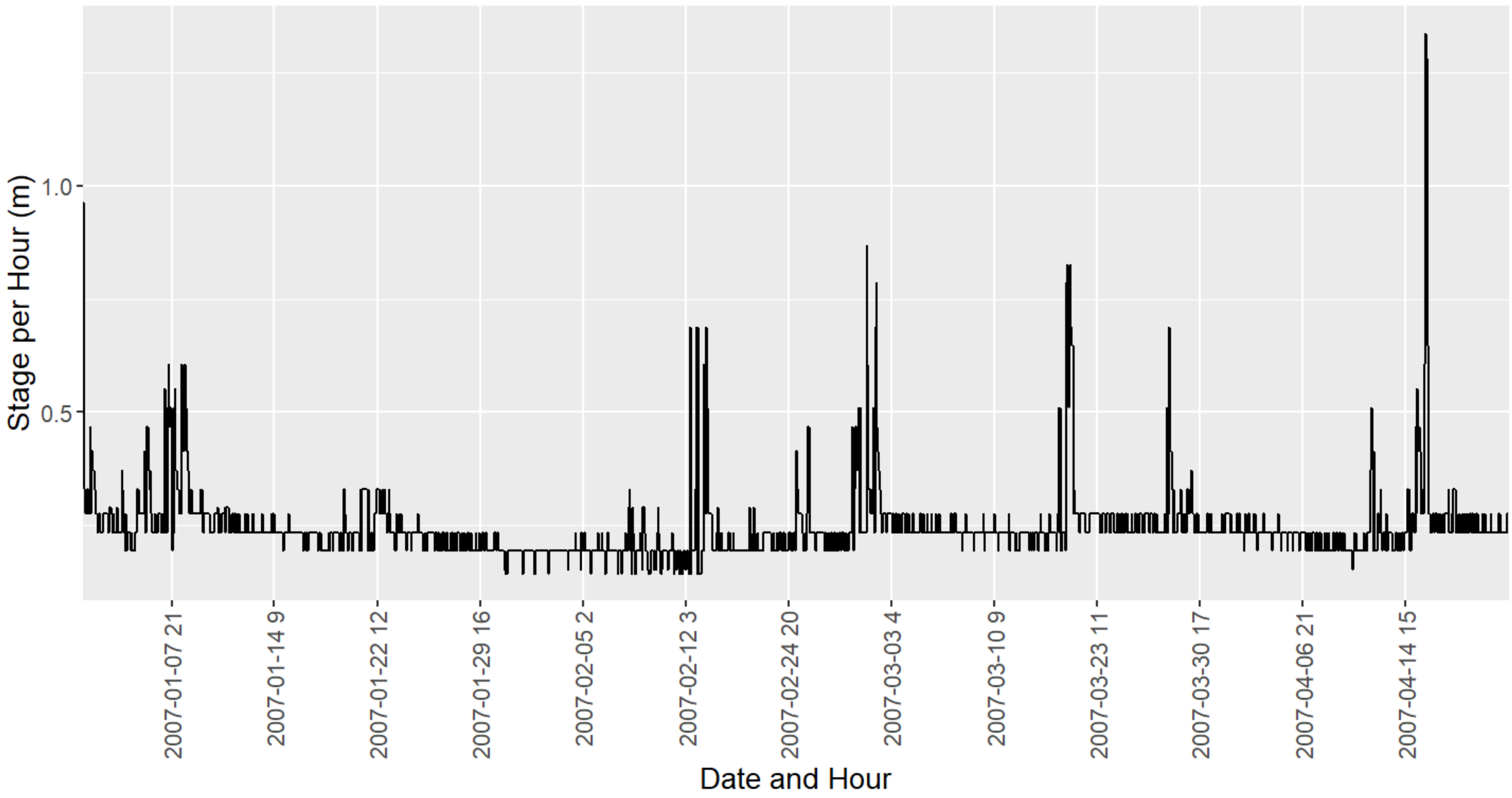


Figure 17: Historic stage hydrograph for Stroubles Creek from January to May 2007. Values shown are averages per hour each day. The date and hour are shown on the x-axis with the hours given in 24-hour time. Data are not available for 2006.

Figure 18: Hydrology data for Stroubles Creek during the study period (2010-2021). Data to calculate overtopping events was not available until November 2011.

30-yr average, with 5 yr exceeding the average value, 4 yr under the average value, and 3 yr at the average value. Figure 19 depicts the daily flow hydrograph from November 2011 to March 2022.

4.6 Treatment Response to Restoration

4.6.1 Treatment 1

Treatment 1 included four total cross sections, all of which were runs. Two of the cross sections were in straight sections, one was in a slight meander bend, and the last was at the end of a meander bend, just under the downstream edge of a sampling bridge (Figure 20). The sampling bridge does not have abutments in the channel and has minimum impact on in-channel and floodplain flows. The bridge serves as the separator between Treatments 1 and 2. The change in cross-sectional area for Treatment 1 cross sections ranged from -44.7% to +2.6%

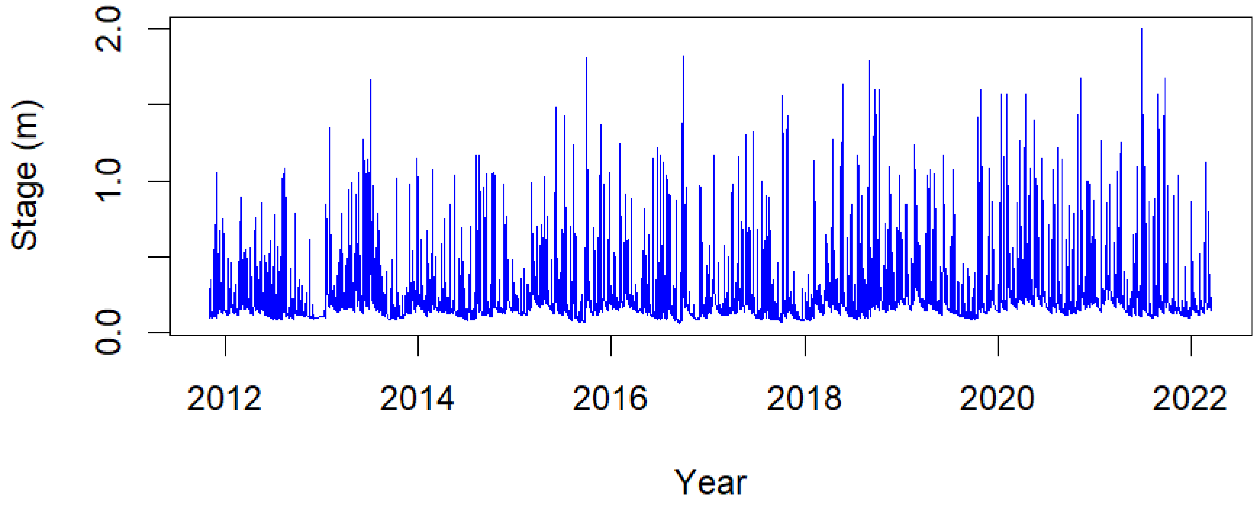


Figure 19: Recent stage hydrograph for Stroubles Creek from November 2011 to March 2022. Values shown are averages per day.

(Appendix A Table A-4). Change in width ranged from -45.2% to +5.2% (Figure 21), while depth ranged from -3.8% to +3.4% for maximum depth and -18.8% to +0.9% for hydraulic depth. Finally, change in W:D ranged from -45.7% to +37.8%. Of the four cross sections in Treatment 1, cross sections 3, 4, and 5 decreased in area and cross sections 1, 3, and 4 increased in width, maximum depth, and W:D but decreased in hydraulic depth. The cross section located under the sampling bridge, cross section 5 (Appendix B-4), increased very slightly in hydraulic depth (0.9%), decreased in width (-45%), maximum depth (-3.8%), W:D (-43%), and area (45%). This was the greatest reduction in area of any cross section in the study. The change around this area can be seen in aerial photographs (Figures 22, 23). It is evident that the pool upstream of the cross section has filled in substantially since the restoration. In the 2009 aerial photograph, there are lines in the vegetation which show where the cattle frequently walked near and through the stream. Additionally, the pool just upstream of Cross Section 5 was a cattle wallow. It should also be noted that between Cross Section 4 and 5 there is a stormwater inlet from a neighboring apartment complex which supplies additional flow and sediment downstream of Cross Section 4.

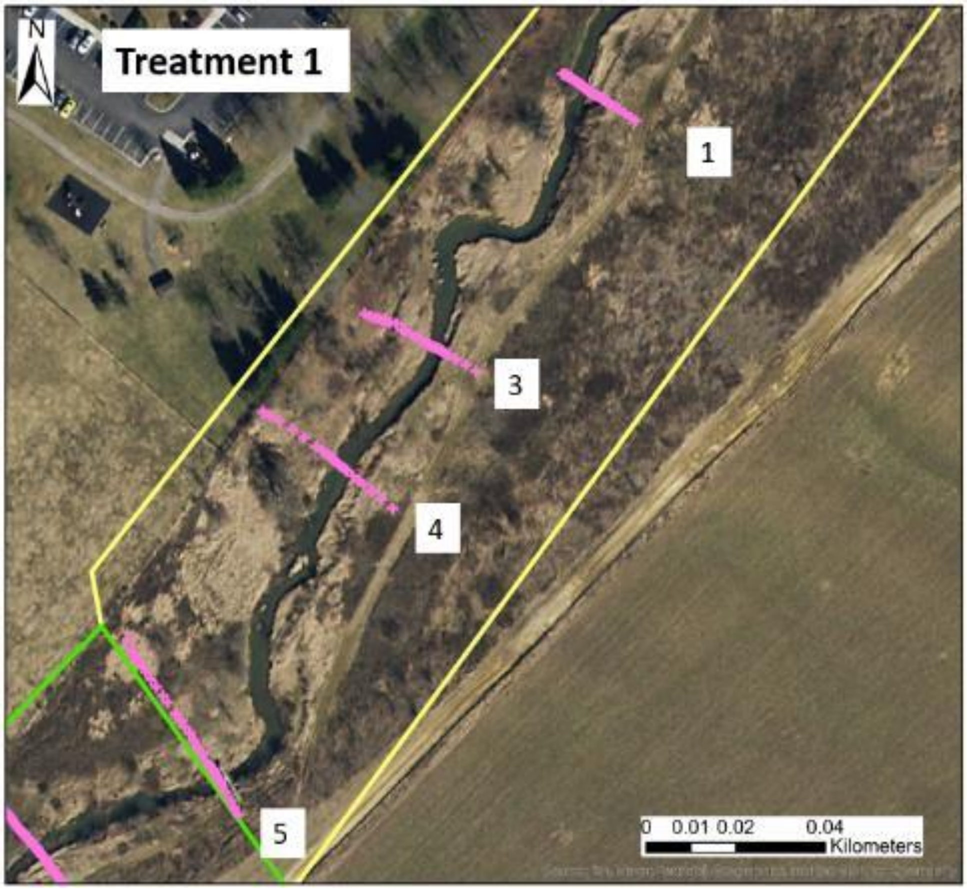


Figure 20: Cross section locations in Treatment 1 in 2019. The yellow line is the extent of Treatment 1, and the green line is the extent of Treatment 2.

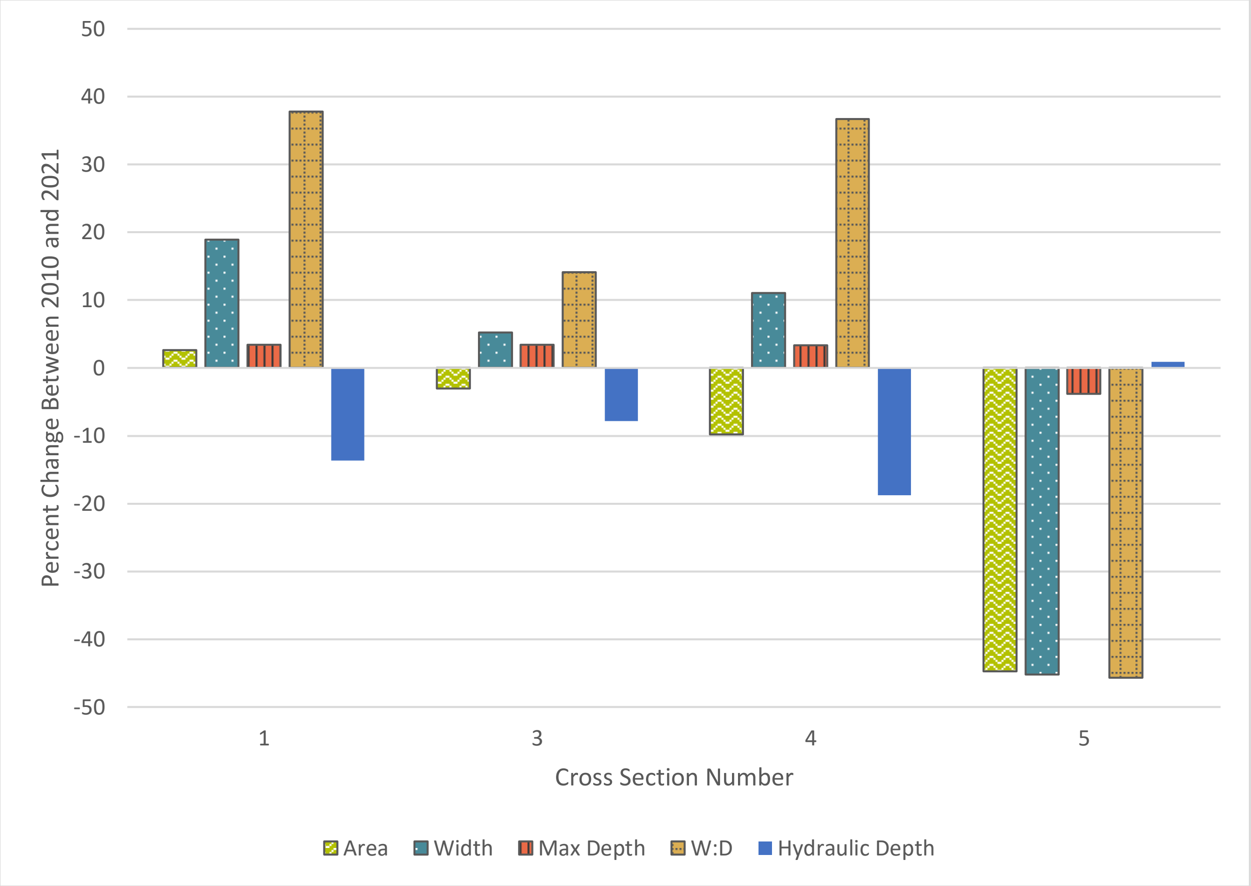


Figure 21: Percent changes in area, width, maximum depth, hydraulic depth, and W:D for Treatment 1 on Stroubles Creek, Blacksburg, VA.

4.6.2 Treatment 2

Treatment 2 (Appendix A Table A-2) consisted of 10 cross sections including six runs, three riffles, and one pool (Figure 24). The change in cross-sectional area ranged from -36.7% to -4.0% (Appendix A Table A-4). Change in width ranged from -20.0% to -0.6% (Figure 25). No cross sections increased in cross-sectional area or width in Treatment 2 (Figure 25). Four of the 10 cross sections (numbers 8, 12, 14, and 16) increased in maximum depth, with changes ranging from -14.0% to +4.8% (Figure 25). However all but one cross section (number 14) decreased in hydraulic depth ranging from -3.4% to -27.3% (Figure 25). Cross section 14 (Appendix B-13) showed an increase of +17.7% (Figure 25) for hydraulic depth. Eight of the cross sections with decreases in both width and hydraulic depth showed positive changes in width-to-depth ratio because the magnitude of change in hydraulic depth was greater than the magnitude of change in width (Appendix A Table A-4). W:D changed between -32.0% to +19.7% through the study period (Figure 25). Out of all the treatments, Treatment 2 was the only one to decrease across all metrics on average, indicating aggradation on the stream bed and narrowing of the channel. Since the roughness increases drastically between Treatments 1 and 2, reduced flow velocities may be encouraging deposition, causing the aggradation observed in Treatment 2.

4.6.3 Treatment 3

Treatment 3 (Appendix A Table A-2) had six cross sections including two runs, two riffles, and two pools (Figure 26). The pools and runs increased in area, indicating erosion, while the riffles aggraded (Figure 27), with changes falling between -18.4% and +15.9%. Half of the cross sections increased in width and half decreased, ranging from -5.4% to +9.9%. Coconut coir fiber logs were placed along all regraded banks and were present on the banks during the 2010 survey but had washed away by the time of the 2021 survey. These coir fiber logs are approximately 30 cm in diameter, so the loss of the logs could be impacting the changes in width, area, or hydraulic depth. All but one cross section increased in maximum depth between +1.0% and +28.0% and the two most upstream cross sections (numbers 19 and 21; Appendix B-15 and B-16) had the greatest positive change in maximum depth for the entire study. Increases in maximum depth in cross sections 19 and 21 indicate pool development, as cross section 19 is a pool in a straight section and cross section 21 is in a meander bend. Cross section 22 (Appendix B-17) was the only cross section to decrease in maximum depth, with a change of -4.8%. Only one of the six cross sections (number 19) decreased in W:D (-16.3%) (Appendix A Table A-4). All others increased by 2.0% to 18.2%. Hydraulic depth changed between -13.7% and +17.7%

Figure 22: Area around Cross Section 5 in 2009. Pink line is the location of Cross Section 5.

Figure 23: Area around Cross Section 5 in 2019. Pink line is the location of Cross Section 5.

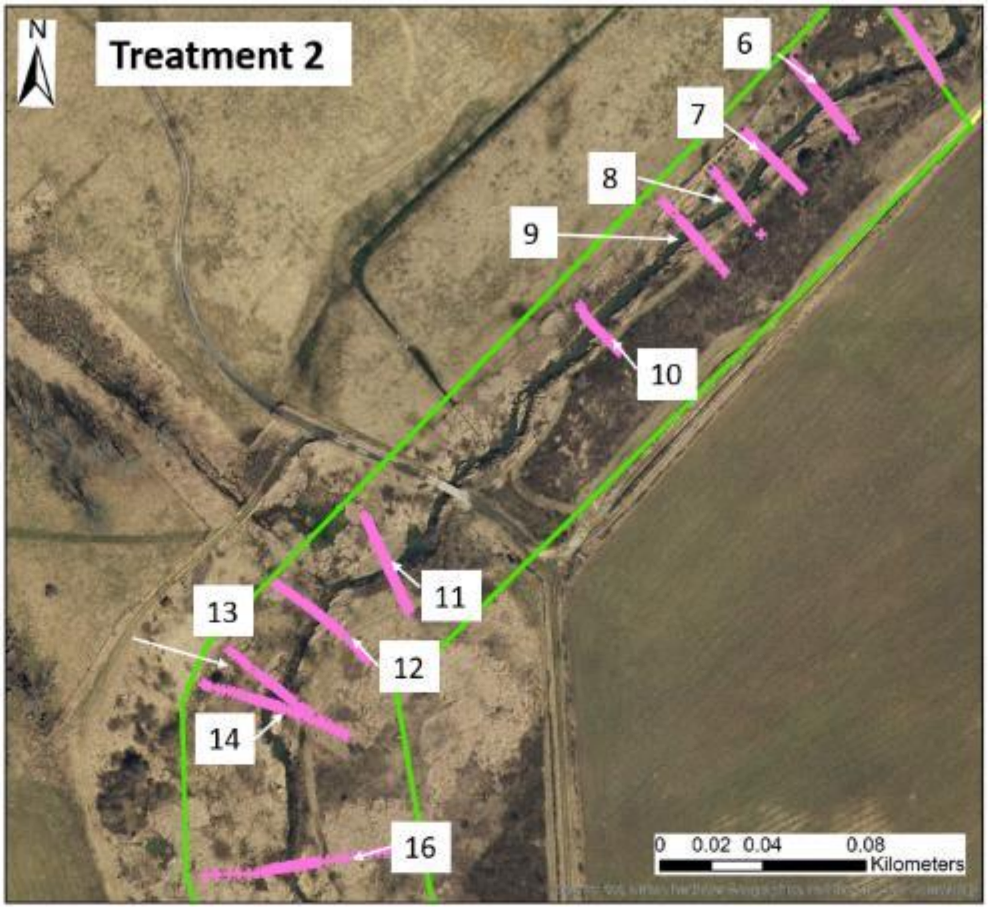


Figure 24: Cross section locations in Treatment 2 in 2019. The green line indicates the extents of Treatment 2.

with half the cross sections increasing and half the cross sections decreasing. Both riffles decreased, both runs increased, and the pools were split. Both runs in Treatment 3 increased across all the metrics. Channel morphology in Treatment 3 is heavily influenced by willows (*Salix sp.)* hanging into the channel. In general, in Treatment 3, the pools are widening and deepening.

4.6.4 Comparison of Treatments

Treatment 1 decreased in area and hydraulic depth but increased in width, width-to-depth ratio and maximum depth. Treatment 2 decreased in all metrics excluding W:D and

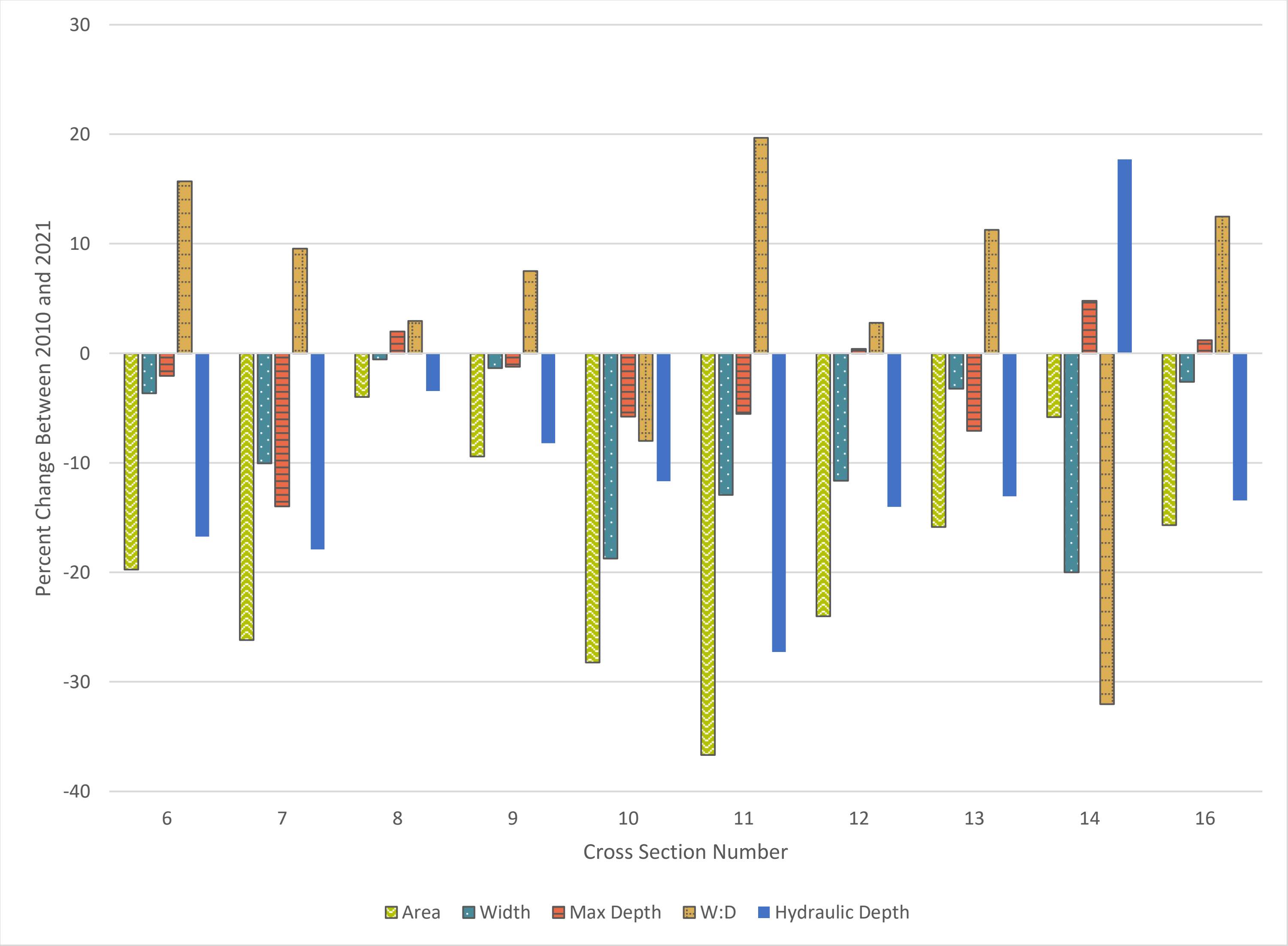


Figure 25: Percent change in area, width, maximum depth, hydraulic depth, and W:D in Treatment 2 on Stroubles Creek, Blacksburg, VA.

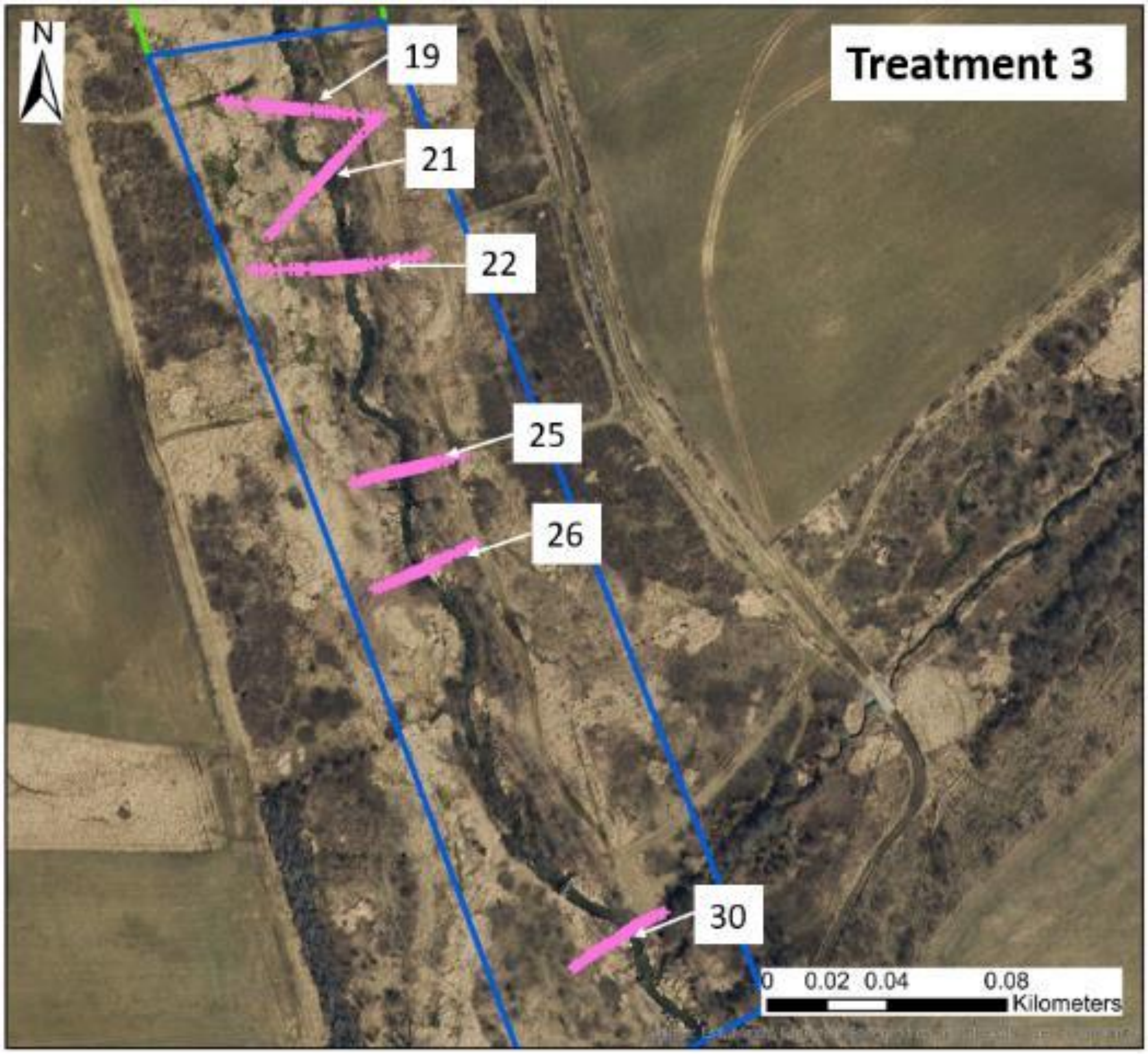


Figure 26: Cross section locations in Treatment 3 in 2019. The blue line indicates the extent of Treatment 3.

showed the greatest magnitude of change in area, width, and hydraulic depth. Cross sections in Treatment 3 increased in all metrics on average, indicating overall erosion throughout that reach. Treatment 3 showed the greatest magnitude of change in maximum depth. While the average change in hydraulic depth across treatments was statistically equivalent (Figure 28), there were significant differences among treatments for the average change in W:D ratio, width, cross-sectional area and maximum depth. A non-parametric Kruskal-Wallis test supported the results from the ANOVA. The Tukey HSD analysis showed that changes in cross-sectional area, width and maximum depth were greater for Treatment 2 as compared to Treatment 3. Changes in width and W:D were significantly greater in Treatment 1 than in Treatment 2. The Kruskal-Wallis multiple comparisons test supports the Tukey analysis for area and maximum depth, but for width, it only supports the difference between Treatments 1 and 2. The non-parametric multiple comparisons test did not match the ANOVA for W:D.

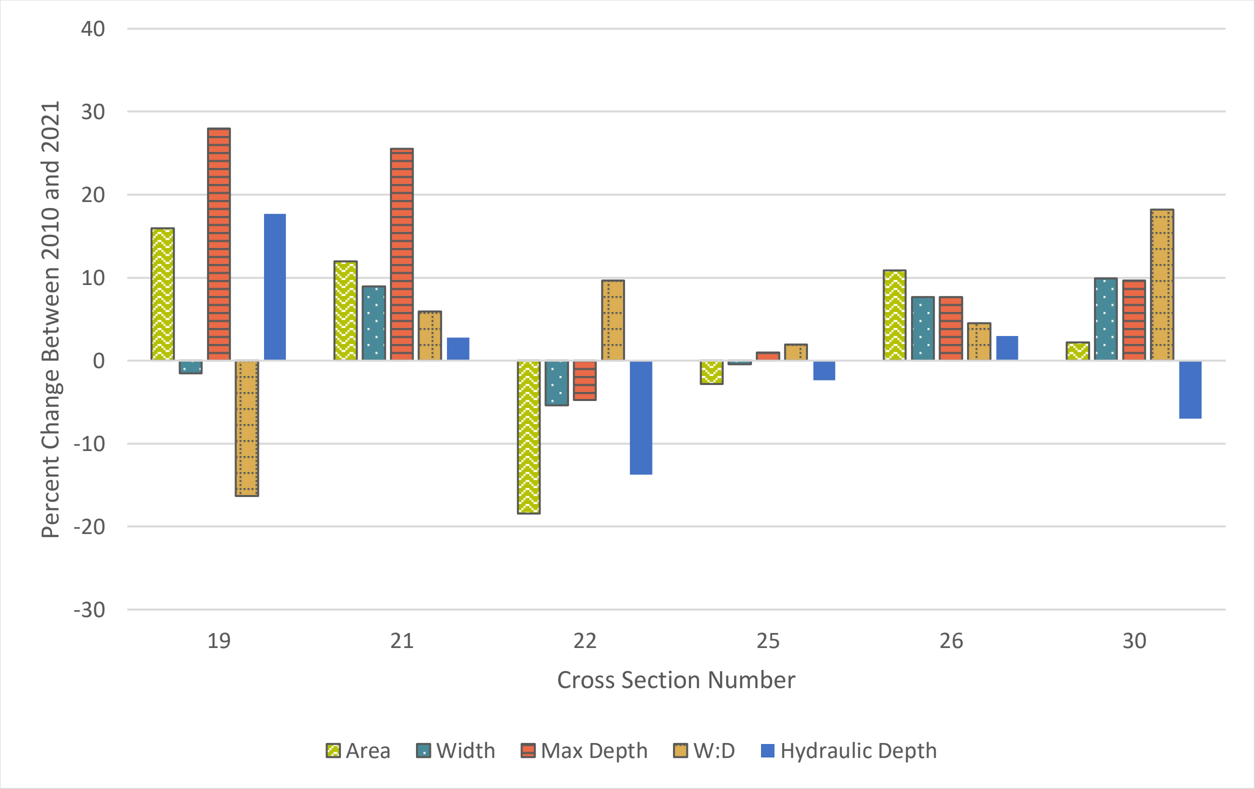


Figure 27: Percent change in area, width, maximum depth, hydraulic depth, and W:D in Treatment 3 on Stroubles Creek, Blacksburg, VA.

Figure 28: Measured values for area, width, maximum depth, hydraulic depth, and W:D ratio for 2010 and 2021 separated by treatment. Cross Section 5 was removed from the analysis. The first p-value indicates the ANOVA statistical significance of differences in the average percent change among treatments and the second p-value is the result from the Kruskal-Wallis test. A star next to the p-value indicates statistical significance.

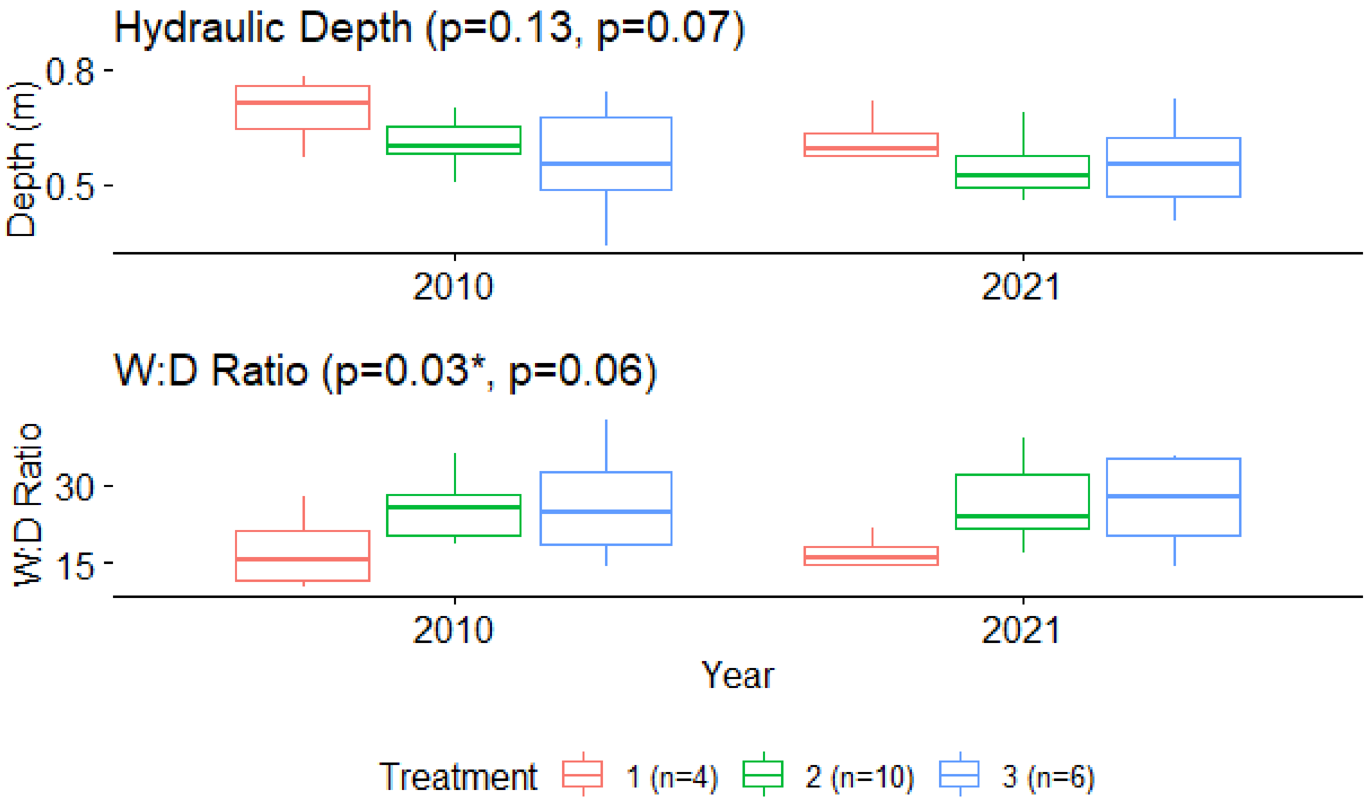


Figure 28, cont: Measured values for area, width, maximum depth, hydraulic depth, and W:D ratio for 2010 and 2021 separated by treatment. Cross Section 5 was removed from the analysis. The first p-value indicates the ANOVA statistical significance of differences in the average percent change among treatments and the second p-value is the result from the Kruskal-Wallis test. A star next to the p-value indicates statistical significance.

It is likely that the location and intensity of each treatment impacted the others, specifically that upstream treatments impacted the results of downstream treatments. However, this interaction cannot be statistically isolated.

4.7 Comparison Between Geomorphic Units

When averaging by geomorphic unit (Figure 29), riffles are the only channel form that aggraded across all metrics. Pools experienced the greatest amount of cross section change, with maximum pool depth increasing 1.3% per year on average. The runs aggraded on average. Channel width decreased slightly on average in riffles and pools (-4.9% and -3.9% respectively)

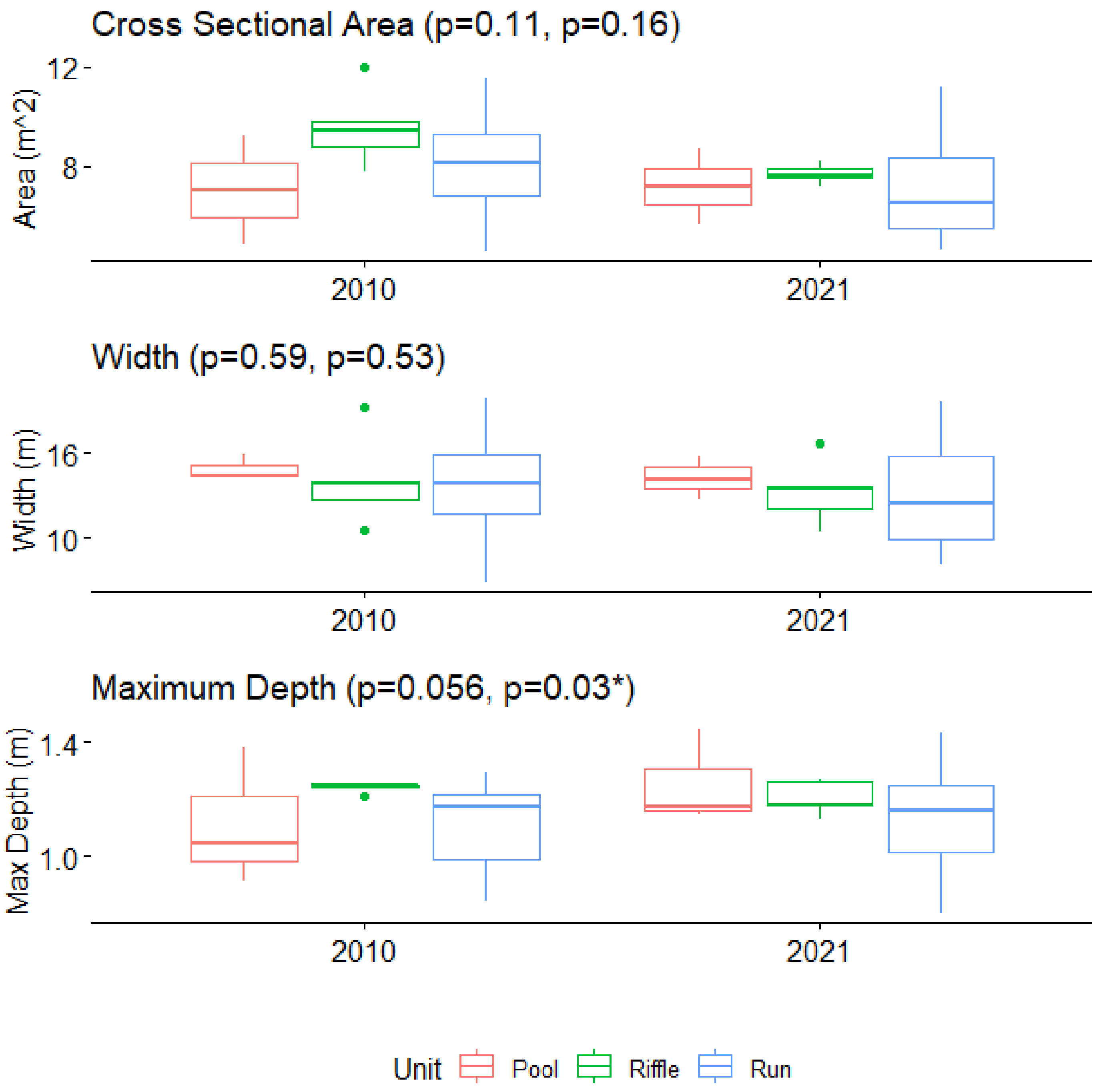


Figure 29: Measured values for area, width, maximum depth, hydraulic depth, and W:D ratio for 2010 and 2021 separated by geomorphic unit. Cross Section 5 was removed from the analysis. The first p-value indicates the ANOVA statistical significance of differences in the average percent change among geomorphic features and the second p-value is the result from the Kruskal-Wallis test. A star next to the p-value indicates statistical significance.

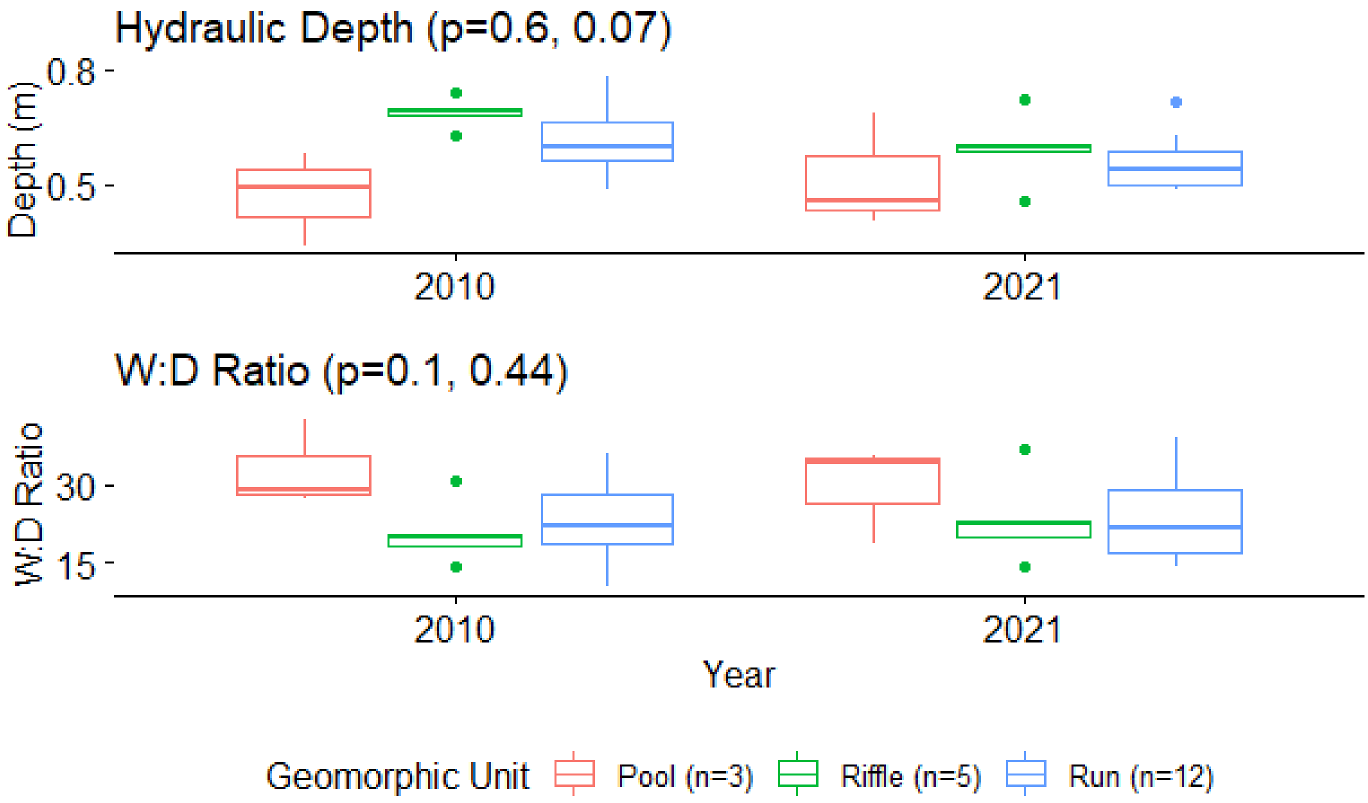


Figure 29, cont: Measured values for area, width, maximum depth, hydraulic depth, and W:D ratio for 2010 and 2021 separated by geomorphic unit. Cross Section 5 was removed from the analysis. The first p-value indicates the ANOVA statistical significance of differences in the average percent change among geomorphic features and the second p-value is the result from the Kruskal-Wallis test. A star next to the p-value indicates statistical significance.

and increased by a negligible amount in runs (+0.52%). The increase in maximum depth was significant based on the Kruskal-Wallis test (p=0.03) but not the ANOVA (p=0.056).

In this project, it was found that the pools deepened substantially (1.3% per year on average), the runs deepened slightly (0.2% per year on average), and the riffles aggraded slightly more than the eroding runs (-0.3% per year on average). Research studies using tracer particles have found that in streams over extended periods of time, particles tend to erode from the center of pools and are deposited on bars (Papangelakis and Macvicar, 2020). The data measured for pools deepened yet narrowed which could be explained by the motion of particles described by the previously mentioned study. Additionally, it was found that tracer particles originally located in riffles traveled short distances if they traveled at all and tended to remain within their original unit (Papangelakis and Macvicar, 2020). This is consistent with the data for this project where the riffles show a small amount of aggradation each year (Figure 29).

All results from the ANOVA were not statistically significant. Maximum depth was significant under the Kruskal-Wallis test (p=0.03) with pools having a greater maximum depth than riffles. The changes in width were all similar between riffles and pools (-0.45% and -0.35% per year respectively) but was negligible on average for runs (+0.05% per year). Changes in area and hydraulic depth follow the same pattern where pools erode (+4.1% and +9.5% respectively) and riffles (-17.9% and -14.0%) and runs aggrade (-9.0% and -9.7%).

4.8 Comparison of Planform Location

To compare results by planform location, the cross sections were grouped according to whether they were in a meander bend, in a slight bend, or in a straight section (Figure 30).

On average, cross sections in meander bends decreased in width (-0.6 m) twice as fast as those in straight sections (-0.3 m). Cross sections in slight bends increased in width (+0.2 m) at a third of the rate of meander bends decrease. Average changes in maximum depth and hydraulic depth were minimal, although changes in maximum depth were positive and hydraulic depth were negative (+0.1 m and -0.1 m for meander bends, +0.0 m and -0.1 m for slight bends, +0.0 and -0.0 m for straight sections). All planform locations aggraded in cross-sectional area on average, with meander bends (-1.2 m^2) showing the most aggradation followed by slight bends (-0.9 m^2) and then straight sections (-0.8 m^2). Finally, W:D increased by about 30% more on average in straight sections (+0.9) than it did in meander bends (+0.3) or slight bends (+0.3).

While all three planform locations aggraded, there were no significant differences. If the only designations used are "straight" and "meander bend" (encompasses "slight bend" and "meander bend"), there are no significant differences detected by the ANOVA test. The Kruskal-Wallis test confirmed the result from the generalized ANOVA test, as there were no significant differences detected. This was the case for both designation groups (using generalized "meander bend" and more specific characterization) under the Kruskal-Wallis test.

5 Discussion

5.1 Comparison of Treatments

Gurnell and Bertoldi (2022) found that vegetated emergent bedforms were highly capable of storing large amounts of sediment that passes through a stream system. They hypothesize that the abundance of sediment storage on vegetated bars and benches is especially true for streams recovering from an impact. They suspect that the bars form a new floodplain within the previously enlarged channel (Gurnell and Bertoldi, 2022), following the path of the channel evolution model (Van Dyke, 2013) discussed previously. The inset floodplains in Treatment 3 on Stroubles Creek mimic the bars in the Gurnell and Bertoldi study (2022), which states that almost all fine sediment should be trapped in the system by vegetated surfaces. However, significant sediment trapping is not seen across the board in Treatment 3 but is instead mostly present in Treatment 2. Treatments 1 and 2 have high herbaceous vegetation amounts, and since the banks in Treatment 2 are sloped, the water has a higher chance of encountering the vegetated surfaces at all flood flows. The limited sediment supply to Stroubles and the increased roughness in Treatment 2 could be limiting the amount of fine sediment reaching Treatment 3. However, the impact of one treatment on another cannot be easily isolated.

Results from this study indicate that overall, the stream restoration project moved Stroubles Creek from stage four to stage five of the channel evolution model. As expected from the channel evolution model, rates of bank erosion have significantly slowed on average in Treatment 3 (Appendix A Table A-2) and Treatment 2 is now narrowing. Measurements also indicate that hydraulic depth has stabilized (Treatment 3) or aggraded (Treatments 1 and 2) during the last 11 years. The area and width are also relatively stable with 3.3% and 3.2% changes respectively in Treatment 3 over the 11-year study period. Treatment 3 appears to be the most stable of all the Treatments, with the least average change across all metrics. Treatments 1 and 2 are exhibiting the correct trends of decreases in hydraulic depth but are also beginning to narrow in some cross sections. However, Treatment 1 widened in all cross sections excluding Cross Section 5 indicating that removal of cattle is insufficient in this case for restoring and stabilizing the stream. Overall, the channel has followed the channel evolution model as expected but narrowed more at earlier stages due to the removal of cattle as part of the restoration.

5.2 Review of Original Goals of the Stroubles Creek Stream Restoration Project

The original goals of the Stroubles Creek stream restoration design were outlined in the methods section of this paper and were evaluated by this project. The primary objective was to remove Stroubles Creek from the impaired waters list. To do this, specific goals were listed relating to the Virginia Stream Condition Index, sediment load reduction from the streambanks, reduction in bacterial loading, educational and outreach programs, and evaluation of the three restoration treatments.

Figure 30: Measured values for area, width, maximum depth, hydraulic depth, and W:D ratio for 2010 and 2021 separated by planform location. Cross Section 5 was removed from the analysis. The first p-value indicates the ANOVA statistical significance of differences in the average percent change among planform locations and the second p-value is the result from the Kruskal-Wallis test. A star next to the p-value indicates statistical significance.

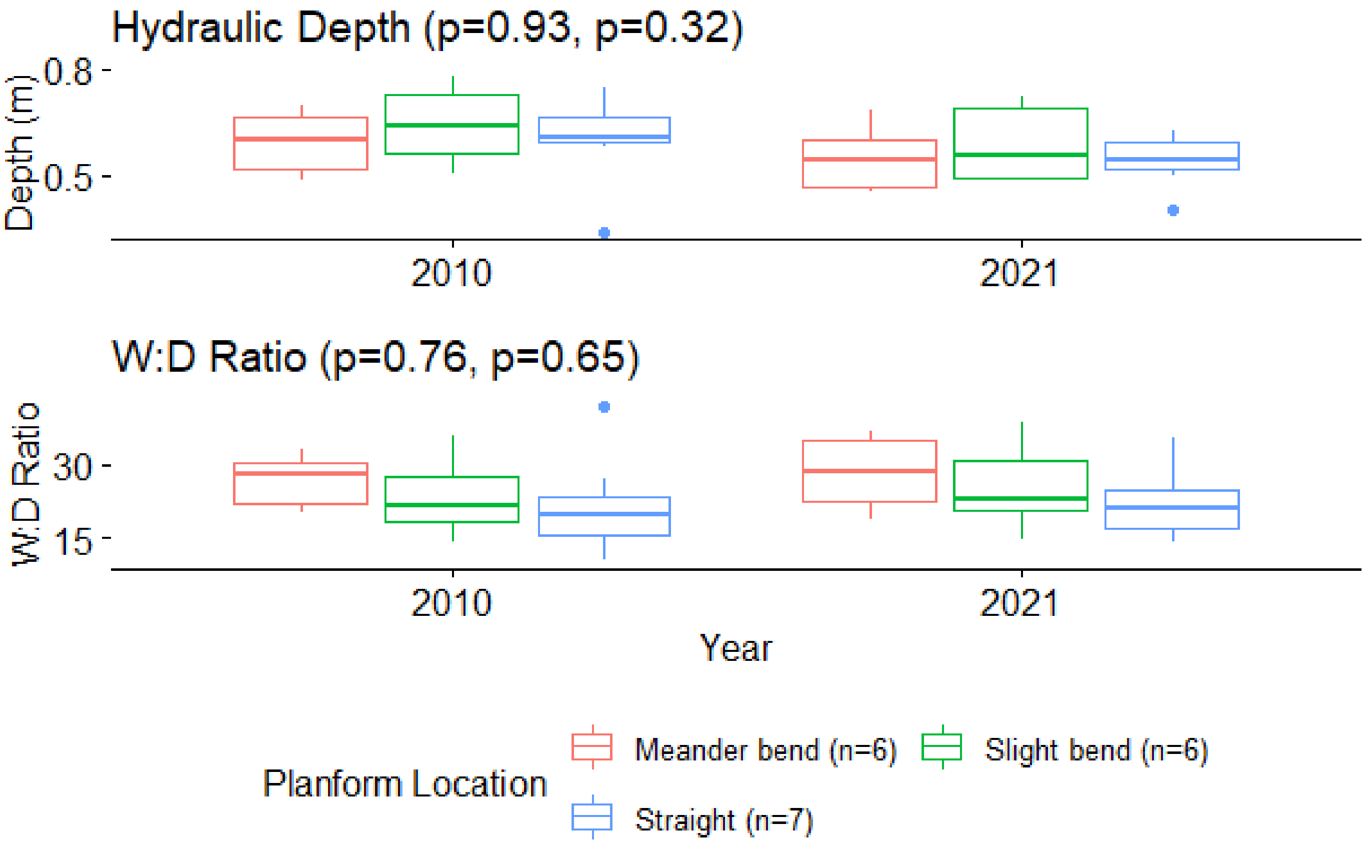


Figure 30, cont: Measured values for area, width, maximum depth, hydraulic depth, and W:D ratio for 2010 and 2021 separated by planform location. Cross Section 5 was removed from the analysis. The first p-value indicates the ANOVA statistical significance of differences in the average percent change among planform locations and the second p-value is the result from the Kruskal-Wallis test. A star next to the p-value indicates statistical significance.

The goal of improving the Virginia Stream Condition Index score on Stroubles Creek to a score greater than 60 (Wynn et al., 2010) has not yet been met. The most recent score reported by the DEQ water quality monitoring fact sheets for impaired waters in 2020 was 57.9. This score isan improvement from the pre-restoration score of 45.3. ("Fact Sheets for Impaired (Category 4 or 5) Waters in 2020 New River Basin", 2020) The improvement could be attributed to the cattle removal from the stream channel, increased stormwater management upstream, and/or improved erosion and sediment control practices in the watershed.

Because sediment was identified as the main cause of impaired benthic habitat, another objective of the project was to reduce sediment loading from the streambanks of Stroubles Creek by implementing three different restoration treatments at the StREAM Lab property (Wynn et al., 2010). Prior to the restoration, the cross-sectional area along the channel was eroding at an average rate of 5% per year (Appendix A Table A-3), adding more fine sediment into the stream system and causing unhealthy aquatic habitat conditions. Since the restoration, each reach which received a different restoration treatment has responded differently (Appendix A Table A-2 and A-4).

The final goal was to assess the effectiveness of each stream restoration method, determining whether the goal of reducing streambank erosion was met for each treatment and overall. Treatment 1 increased on average in width, depth, and W:D while decreasing in area and hydraulic depth. Treatment 2 decreased on average in most of the metrics (area, width, maximum depth, and hydraulic depth). Treatment 3 eroded on average in all categories, however it had the lowest magnitude of change of all the treatments. The only aggradation in Treatment 1 was in cross section 5 which was due to increased sediment load from a stormwater outfall, an initially overly wide channel and a change in bank roughness at that location. Upstream of cross section 5, the cross sections eroded. On average, the entire channel decreased in area (-11.0%), width (-3.8%), and hydraulic depth (-7.4%). The average increase in W:D ratio overall is a result of the decrease in hydraulic depth, not an increase in width. Kauffman and Krueger (1984) indicate that proper livestock management which limits the ability of livestock to access stream bottoms is effective in reducing streambank erosion and protecting floodplains. Therefore, the narrowing of the entire project reach is an expected response to the removal of cattle access along the channel. The data measured confirms that this goal is being met and not only has streambank erosion been reduced overall by the restoration, but aggradation has been occurring. Overall, the average channel changes indicated successful reduction of streambank erosion, however results from Treatment 1 indicate that cattle removal alone is not sufficient for reducing widening on an incised stream with urbanized headwaters.

5.3 Comparison to Virginia Mitigation Bank Criteria

In addition to the original goals listed above, the current conditions of each reach were compared to the Virginia Mitigation Banking Criteria. The criteria chosen include evaluation of the riparian buffer performance, W/D Ratio Stability Rating, and cross-sectional area change. This assessment does not encompass the entirety of the Virginia Mitigation Banking Requirements, but rather what could be quantified for this project. The Bank Erosion Hazard Index (BEHI) rating and bank height ratio are additional standards that were not measured post-restoration.

5.3.1 Evaluation of Riparian or Upland Buffer Performance Standards

One requirement for riparian or upland buffers is that they must have at least 400 woody stems of native tree or shrub species per acre. The vegetation in the buffer area must be monitored each year until a 30% canopy cover is achieved and maintained. Before the canopy cover reaches 30%, the average height of all established and surviving trees must be at least 5 feet in years 5 and 10 of monitoring (USACE and VA DEQ, 2018). Canopy cover was not evaluated in this project so only stem counts will be considered.

Although native plantings were only done in Treatment 2 and Treatment 3 (Wynn et al., 2010) the mean number of woody stems in all three treatments meets the 400 woody stems per acre requirement (Table 3).

Treatment 1 was not actively planted during the restoration, so the herbaceous vegetation was very dense, and the woody vegetation was young and dominated by autumn olive (*Elaeagnus umbellate*), a non-native woody species. The mean and median stem counts were 836 and 405, respectively, so while Treatment 1 meets the required number of stems, it did not meet the mitigation bank requirements because the stems counted were non-native. Treatment 1 had the highest mean value of woody stems due to the physical properties of autumn olive (*Elaeagnus umbellate*) which has many woody stems protruding from a single base, many of which exceed the 1-in diameter limit and are therefore counted toward the stem count. In comparison, Treatment 2 exhibits a median value of only 202 stems per acre, therefore not meeting the requirement when considering the median rather than the mean (580 stems/acre). Treatment 2 had the lowest number of woody stems out of the reaches when looking at both the median and mean values. Low woody stem count in Treatment 2 could be the result of an early frost shortly after planting followed by several out of bank flood flows which washed away the plantings. Additionally, there is a large amount of bedrock on the upper portion of Treatment 2 and subsequent plantings have not been successful (C. Hession, personal communication, July 7, 2022). Treatment 3 was planted at double the density of Treatment 2 and survived at a much higher rate than Treatment 2. The vegetation in Treatment 3 is older, more developed trees, primarily willow (*Salix sp.*) and American sycamore (*Platanus occidentalis*), which have one single, larger stem or trunk which was counted toward the stem count. These trees are at a higher density than the clumps of woody vegetation in Treatment 1 where each clump is distributed more widely. Studies have found that tree density in younger forests can be double that which is found in old-growth forests (Spies and Franklin, 1991) which could be a cause for the differences we see along Stroubles Creek.

5.3.2 W/D Ratio Stability Rating

The width-to-depth ratio requirements for VA mitigation banks are based on the as-built channel dimensions. A metric called the W/D Ratio Stability Rating is used which compares the current measured W:D ratio to the as-built W:D ratio. The value of the W/D Ratio Stability Rating must not exceed 1.3 and must not be less than 0.7 if the channel was originally incising (USACE and VA DEQ, 2018). The W/D Ratio Stability Ratings are shown in Figure 31. Three cross sections did not meet this requirement, which are cross sections 1, 4, and 5 highlighted in red on Figure 31. Two were above the upper limit of 1.3 (cross sections 1 and 4) and one was below the lower limit of 0.7 (cross section 5). Cross section 14 (Appendix B-13) is also highlighted in red on Figure 31 because it has a stability rating that is equivalent to the limit of 0.7.

Cross section 5 (Appendix B-4) had a significantly lower W:D stability rating of 0.5 and is the only cross section to be below the lower limit. It should be noted that cross section 5 is directly under a sampling bridge, but there are no bridge piers or parts of the bridge in the active channel. All supports for the bridge are in the floodplain. The bridge is used to separate Treatment 1, where the banks are largely vertical, from Treatment 2, where the banks are gradually sloped. As more vegetation can grow on the gradually sloped banks and vegetation was actively re-established as part of Treatment 2, the roughness along the banks of Treatment 2 is higher than that of Treatment 1. This means that the flow velocity likely decreases at the transition between Treatment 1 and Treatment 2, causing sediment deposition at the bridge. Another potential

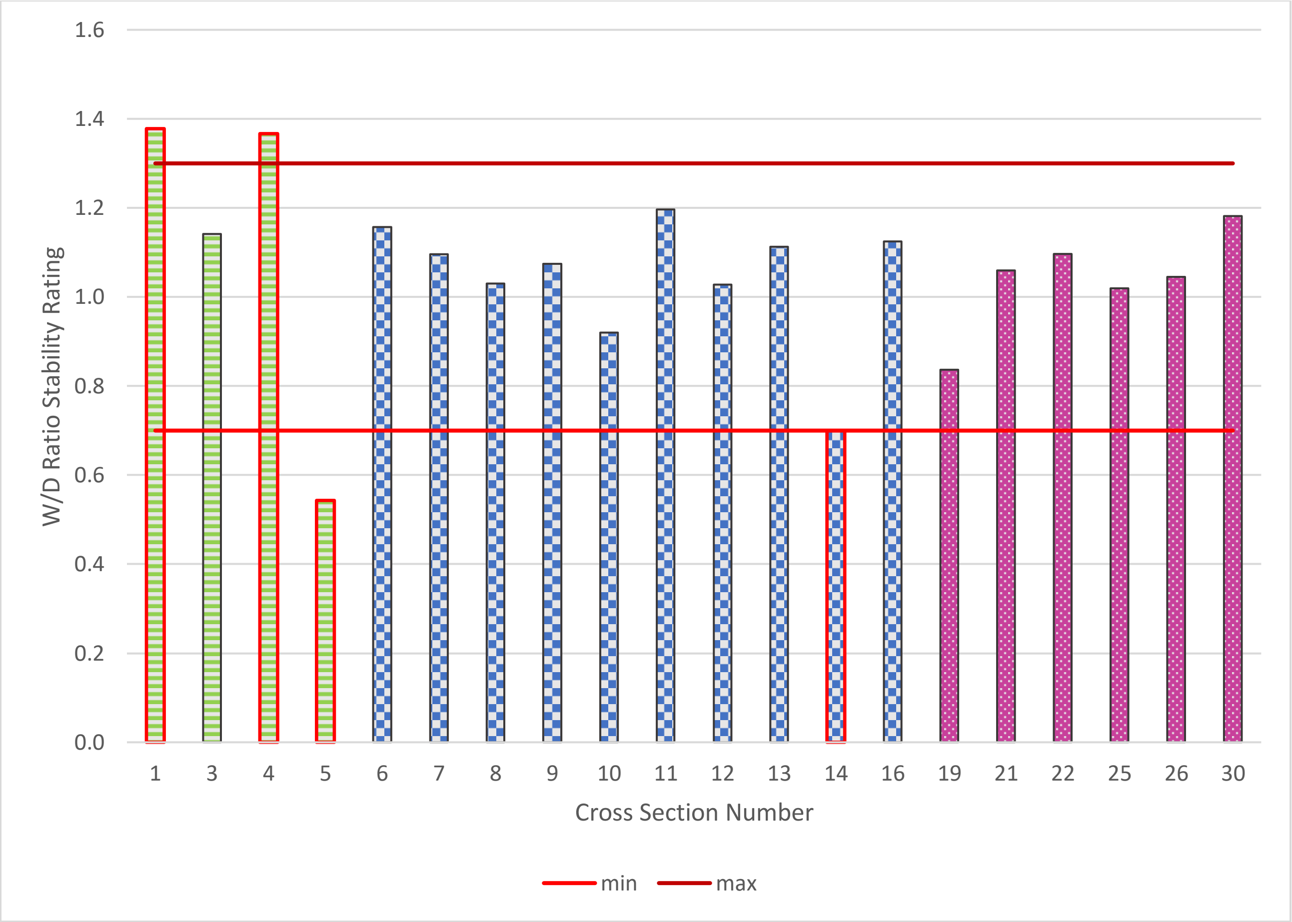


Figure 31: W/D Ratio Stability Rating for Stroubles Creek, Blacksburg, VA.

reason for the deposition could be a quick change in slope from steep to shallow at this location (Appendix D Figure D-1) which would cause the water to slow and the sediment to drop out.

The two cross sections that exceed the higher limit are cross sections 1 and 4 which are both just over the limit at a stability rating of 1.4. These two cross sections have the highest positive percent change in W:D (37.8% and 26.7% respectively) and the highest positive percent changes in width (18.9% and 11.0% respectively) of all cross sections in the study. The changes in hydraulic depth for both cross sections are slightly above the 75th percentile for all cross sections in the study. These results reflect the ongoing channel degradation that is occurring in Treatment

1 and indicate that cattle exclusion is insufficient to stabilize streambanks in incised channels. Cross section 14 (Appendix B-13) which is at the lower limit, had the second highest negative change in width of all cross sections (-20.0%). Changes in hydraulic depth were about the same as that of cross sections 1 and 4 mentioned above which are just above the 75th percentile value. Overall, the low post-restoration W:D is a result of a decrease in width rather than an increase in depth, which is a positive response to the restoration which aimed to decrease sediment loading. However, due to high variability in all the data and a small sample size, there is no significance in the W:D or the W:D stability rating between treatments. Averaging for each treatment gives stability ratings of 1.1, 1.0 and 1.0 respectively, so differences are negligible, and all treatments fall within the required bounds.

It should be noted that the limits from the MBI template on W/D ratio stability rating discourage channel narrowing in over-widened channels. This is counter-active to many stream restoration projects completed to meet TMDL goals of reducing sediment loading to streams.

5.3.3 Cross-Sectional Area Change

The cross-sectional area using the bankfull depth must not increase or decrease by more than 25% of the as-built area (USACE and VA DEQ, 2018). However, the bankfull depth cannot be determined on this reach because it is an unstable stream located in an urban setting and the banks were manually re-shaped during the restoration in 2010 on Treatments 2 and 3, so the top-of-bank depth was used instead. The percent changes in Figure 32 are the total changes across the 11 years since completion of the restoration project. There are four cross sections which do not meet the requirements in this case, highlighted in red. The data shown in Figure 32 indicates that four of the cross sections exceed the allowed change of 25% in cross-sectional area. All four aggraded, decreasing in cross-sectional area. Cross section 5 (Treatment 1) (Appendix B-4) was one of the four exceeding this limit and was the cross section with the highest percent change in area over the 11 years at just under 45%. The other three cross sections exceeding the 25% limit include cross sections 7, 10, and 11, all of which are in Treatment 2.

When averaged, channel widening is seen in Treatments 1 and 3 and narrowing is seen in Treatment 2. A 2004 study (Anderson et al., 2004) found that reaches with forested riparian areas are wider than grassy reaches in small watersheds, explaining why Treatment 3, which is vegetated by American sycamore (*Platanus occidentalis*) and willow (*Salix sp.*) trees, increased in width while Treatment 2, which is dominated by herbaceous vegetation decreased. Treatment 1, which is vegetated almost entirely by grass, experienced the greatest rate of change in width of all the treatments through cantilever failures due to toe erosion of the steep banks. These findings are further supported by recent erosion pin data which measured 13.0 cm of erosion per year in Treatment 1 (Gamble, 2021). Historic erosion pin data from 2005-2008 on Stroubles Creek documented pre-restoration erosion rates of about 11.4 cm/yr in sampling locations from what are now Treatments 2 and 3. Calculations of the volumetric erosion rates show that the streambanks in what is now Treatment 2 eroded less than those in what is now Treatment 3 (Gamble, 2021).

The bank height increased slightly for Treatment 1 (+3.4%), decreased for Treatment 2 (-2.7), and increased for Treatment 3 (+11.2), but all remained within the required limits. Bank heights in Treatment 1 remained relatively steady throughout the 11 years post-restoration, because the maximum depth changes were minimal for all the cross sections. All cross sections measured in this reach were runs which had the least amount of vertical change of any geomorphic units in the study. Treatment 2 decreased in bank height because the majority of the cross sections aggraded. Treatment 1 was likely a sediment source for Treatment 2, as the banks in Treatment 1 eroded through mass wasting. The only pool in Treatment 2 was the cross section which enlarged the most in that reach. Treatment 3 was the only one to increase in bank height, because five of the six cross sections incised. The two that eroded the most were the two most upstream in the reach, numbers 19 and 21 (Appendix B-15 and B-16). These two cross sections increased the most in maximum depth of all cross sections in the study. Cross section 19 is in a straight section with a pool and cross section 21 is in a meander bend characterized by a run. Stroubles Creek lacks a good source of coarse sediment, and is considered to be sediment-starved (T. Thompson, personal communication, July 9, 2022). This could be a potential cause for the high erosion in Treatment 3 as the sediment that is supplied to the channel is stored in Treatment 2 before it is able to reach Treatment 3. This is further supported by cross section 22 (Appendix B-17), which is directly downstream of cross section 21. Cross section 22 decreased in depth, which could be attributed to the deposition of sediment that was eroded from the two cross sections above it. The remaining three downstream cross sections eroded, at a slower rate than cross sections 19 and 21.

As seen in the analyses of width, and depth, it appears that most of the aggradation occurred in Treatment 2, although only the difference in depth is statistically significant. However, since we see the most aggradation in Treatment 2, the higher decrease in area is expected in that treatment. Overall, the cross-sectional area decreased, which was desired for this project. So, although four cross sections failed to meet the mitigation bank criteria, they acted as expected and were successful given the restoration design goals.

5.3.4 Stability

Goals for projects completed under mitigation banks often focus heavily on stability. Comparisons to pre-restoration data prove that this project did improve stability (Figure 33).

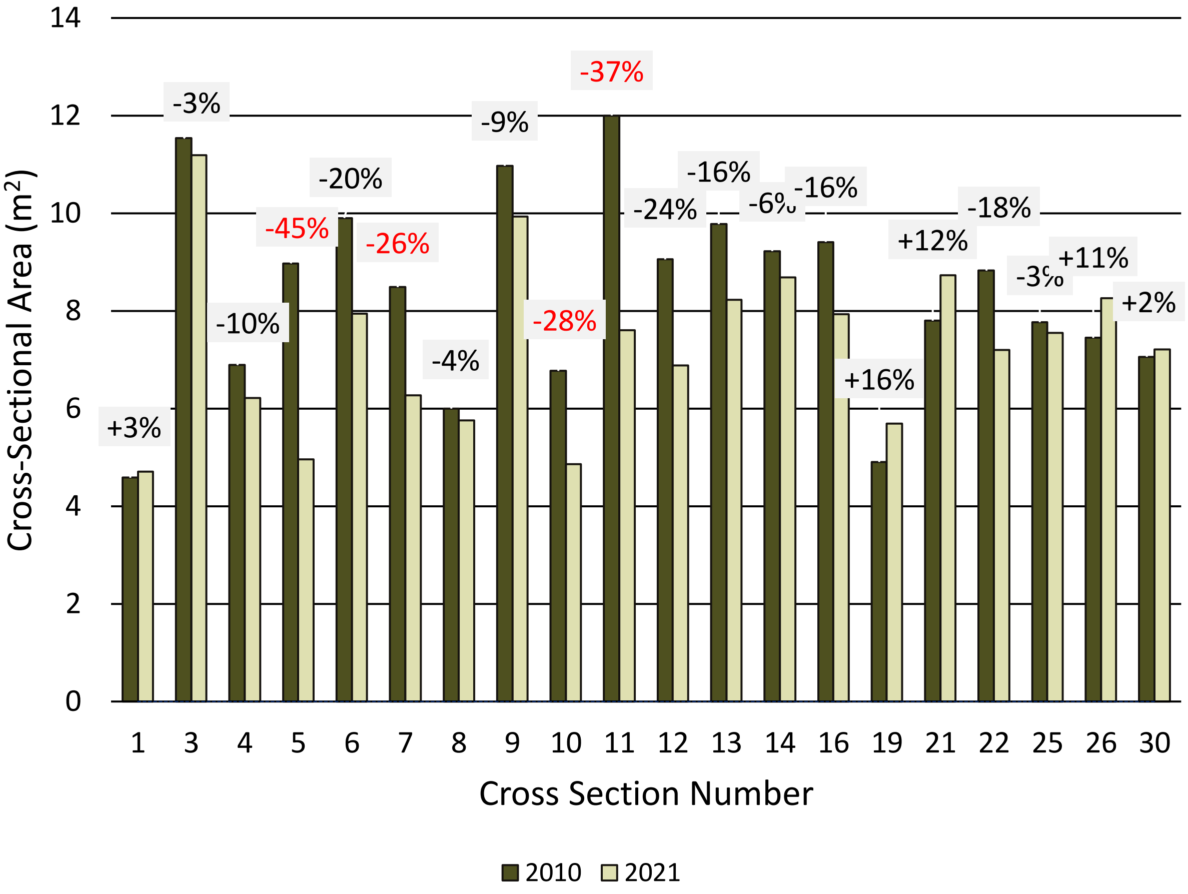


Figure 32: 2010 and 2021 Cross-sectional area on Stroubles Creek, Blacksburg, VA. Percent change is indicated above the bars for each cross section. The numbers in red font indicate cross sections that do not meet the mitigation bank criteria.

What was previously erosion in width and depth prior to the restoration is now aggradation. Area still eroded on average but the amount per year decreased significantly, indicating an increase in stability. This was true for all the measured values, which decreased in rate of percent change after the restoration. The variability in change also decreased significantly, indicating an overall improvement in stability, compared to prior to the restoration (Figure 34). However, it should be noted that pre-restoration measurements are across only one year, and a large storm event occurred during that time.

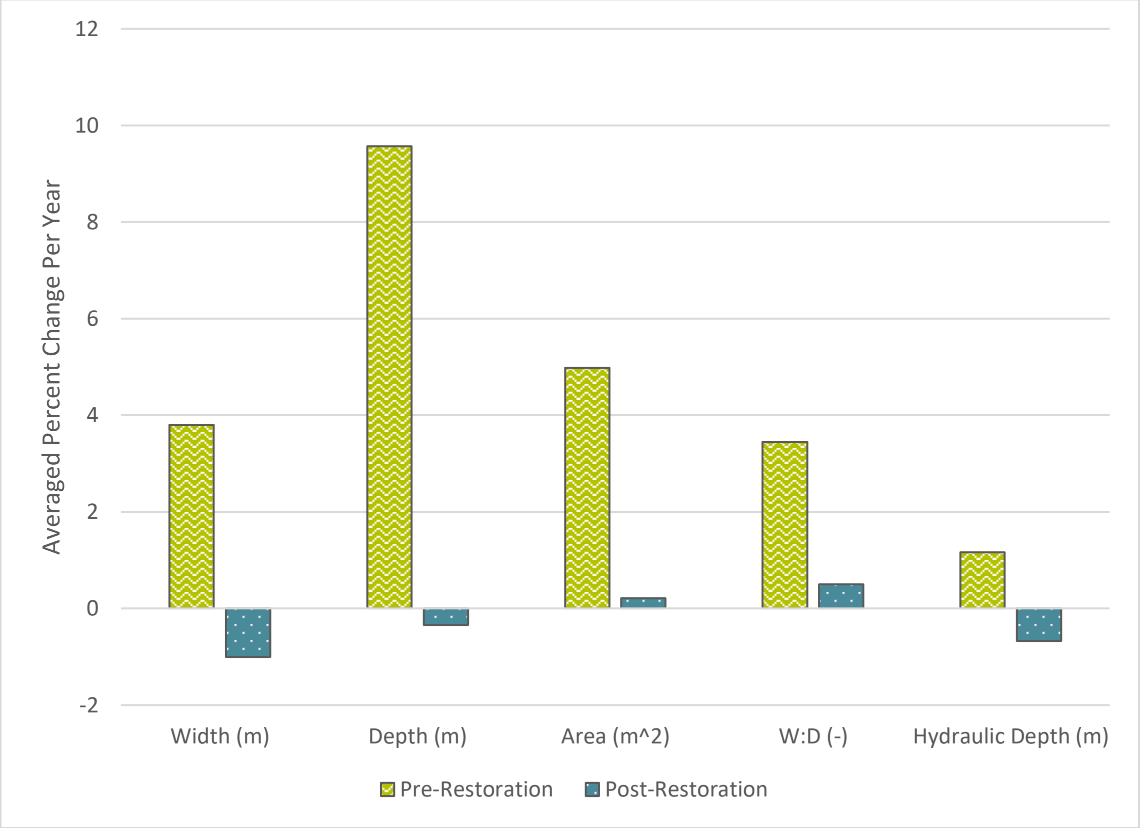


Figure 33: Averaged percent change per year in width, maximum depth, hydraulic depth, area, and W:D for pre-restoration and post restoration.

5.3.5 Evaluation of Each Treatment Under Mitigation Banking Standards

Treatment 3 met the most mitigation banking standards, followed by Treatment 2 and then Treatment 1 (Table 4), indicating that as the intensity of the design increased, the rate of success increased, as defined by the MBIs. Treatment 3 met all the criteria evaluated in this project. Treatment 2 met one of the three criterion and Treatment 1 did not meet any of the criteria. However, as discussed previously in this paper, success under mitigation standards may not be

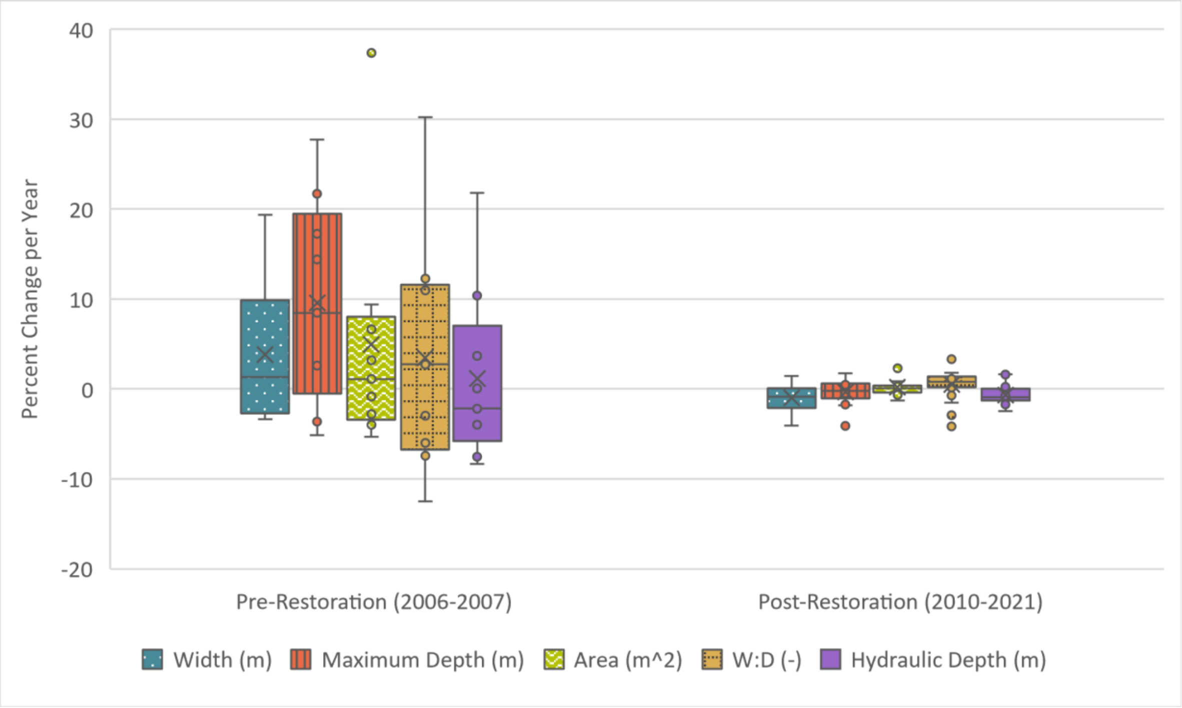


Figure 34: Percent changes per year for pre-restoration and post-restoration.

equivalent to success under design standards. For example, a main focus of this restoration project was to encourage aggradation. Several cross sections received failing scores for their change in cross-sectional area as well as the W:D ratio stability rating, but all aggraded as expected by the project designers. The limits on change in W/D ratio stability rating and cross-sectional area limit the use of less intensive restoration techniques that allow and encourage the channel to self-form.

5.4 Comparison to Similar Projects

5.4.1 Beaver Creek, Knox County, Tennessee

A project similar to the Stroubles Creek restoration (Schwartz et al., 2015) was completed on Beaver Creek in Knox County, East Tennessee in 2012. The study reach is in the Ridge and Valley physiographic province of Tennessee, and the watershed was 14.2% urban developed lands, most of which occurred in the upper portion of the watershed which intersects with a

Table 4: Evaluation of each treatment under Virginia Mitigation Banking Criteria.

VA Mitigation Banking Criteria	Treatment 1	Treatment 2	Treatment 3
Riparian buffer of at least 400 native woody stems per acre and at least 30% canopy cover by the end of the first growing season.	✗	✗	✓
Cross-sectional area must not increase or decrease by more than 25% of as-built area.	✗	✗	✓
The value of the W:D Ratio stability rating must be between 0.7 and 1.3.	✗	✓	✓

portion of the city of Knoxville. There is evidence of channelization in the 1930s and the channel was incising for the decade prior to the restoration. Prior to the restoration, the stream lacked riffle-pool morphology and bank soils had high cohesive properties, similar to Stroubles Creek.

In contrast to Stroubles Creek, the Beaver Creek study reach was lined with trees prior to the restoration. The goal of the restoration project was to create a model to determine the best locations for riffle and pool structures to be located longitudinally along the channel, and then to complete the restoration work to do so and evaluate the success of the restoration as well as the model performance.

Data were collected for one year following restoration and included geomorphic surveys, hydrology studies, and biological surveys. The geomorphic surveys measured cross sections at both riffles and pools that were constructed during the restoration. Comparison of the cross sections did not indicate any apparent aggradation or erosion over the one year of data. However, hydrology studies showed that there were eight bankfull events during this time period, indicating that this reach was particularly stable across both riffles and pools. (Schwartz et al., 2015) Geometric surveys of Stroubles Creek showed much lower stability as some cross sections changed as much as 4% in a year. However, the goal of the Stroubles Creek restoration was to utilize that lack of stability to decrease the cross-sectional area, particularly by narrowing the stream to recover from cattle impacts prior to the restoration. Riffles and pools were not created during the construction of the Stroubles Creek project but are weakly formed now.

Two biological surveys were conducted including the Tennessee Macroinvertebrate Index (TMI) and the Index of Biological Integrity. Both improved following the restoration, however, neither metric improved enough to move out of the impaired designation. Stroubles Creek showed the same response, with habitat improvement but still falling in the impaired designation. Another study by Schwartz and Herricks found that restoration which focuses on habitat improvements but not water quality improvements will increase the number of species present, but the species will primarily be pollution tolerant (Schwartz and Herricks, 2007).

5.4.2 North Carolina

A research project conducted by researchers at the University of North Carolina, North Carolina State University, and Duke University monitored twelve different streams to compare characteristics between urban degraded streams, urban restored, and forested streams. Four of each category located in the Piedmont region of North Carolina were included in the study. The projects selected in the “restored” category were those that represented best-case-scenario projects. (Violin et al., 2011)

The researchers conducted habitat surveys, hydrologic analyses, and macroinvertebrate sampling. Results found that the urban restored streams were indistinguishable from urban degraded streams in all habitat metrics excluding canopy cover, where restored streams had a significantly lower value than urban degraded. Since plantings were conducted on sections of Stroubles Creek following the removal of heavy machinery used in the restoration construction, the trees planted were able to grow and develop a significant canopy cover in the planted sections. The sections that were not planted have minimal canopy cover. Stream velocities and flow heterogeneity varied widely within categories in the North Carolina study; however the overall hydrologic characteristics were consistent across all stream types.

Biologic studies indicated that the forested streams had higher mean EPT (Ephemeroptera, Plecoptera, Trichoptera) richness than urban restored and degraded in both the summer and winter. The biotic index was found to correlate with the imperviousness in the watershed, indicating that higher imperviousness led to a higher biotic index. However, the EPT richness decreased significantly with increasing imperviousness. Biotic index and EPT richness were not measured on Stroubles Creek, but the habitat for species and the water quality have both indicated improvement from pre-restoration values.

5.4.3 Six Mile Creek, Slaterville Springs, New York

Six Mile Creek in Slaterville Springs, New York was restored using natural channel design in 2005 (Buchanan et al., 2014). The Six Mile watershed differs from Stroubles Creek and even Beaver Creek in Tennessee as it was primarily forested (83%) with a smaller portion designated as residential at the time of the study. Post-project monitoring was conducted 2.5 (2007), 5 (2010), and 7 (2012) years after construction was completed. A large storm occurred in the summer of 2006 which caused changes to the channel shape, which were then corrected back to the original design in 2007. This project also utilized structures and the primary goal was to stabilize the channel and prevent further incision and migration, which differs from the goals of the Stroubles Creek project. (Buchanan et al., 2014)

Geomorphic surveys of Six Mile Creek showed a reduction in cross section adjustment indicating an increase in stabilization. The as-built design increased the W:D ratio in an aim to reduce entrenchment. Immediately following restoration, the W:D decreased until 2007 when it remained relatively stable. Stroubles Creek similarly responds, as it shows relatively stable W:D ratios for the 11 years post-restoration for all but one cross section. Longitudinal adjustments and planform adjustments, which were not measured on Stroubles Creek, exhibited the same trends as the other metrics with an initial period of adjustment followed by long-term stabilization. (Buchanan et al., 2014)

6 Conclusions

Stroubles Creek showed different responses over time to each restoration treatment. There were significant differences in cross-sectional area and maximum depth between Treatments 2 and 3. With inspection of the data, it appeared that Treatment 2 is changing most favorably in the direction desired by the restoration designers. Cross sections in Treatment 2 were originally wider than in other sections, so that could be thre reason for the higher rate of adjustment. Also, since the treatment is still dominated by herbaceous vegetation, it is more likely to be narrower than Treatment 3 which has more woody riparian vegetation (Anderson et al., 2004). Treatment 3 were originally narrower on average than the other treatments, so less adjustment needed to take place. There is evidence that the locations of each treatment relative to each other can be impacting the results of the study. The urban nature of the upper portion of the watershed limits the availability of coarse sediment to the channel, and the stream lacks the supply needed to make the desired morphological changes within 11 years. Effects from treatment boundaries can also come into play, specifically between Treatments 1 and 2 where the bank slope was decreased. The decrease in bank slope and increase in bank vegetation between treatments appears to have caused a localized area of significant aggradation just upstream of the boundary in Cross Section 5.

Comparisons to Virginia Mitigation Banking Standards suggested that given a stream with incision, cattle impacts, and low coarse sediment loads, a restoration which involves only removing the cattle impacts will require significantly more time for recovery than using more active restoration techniques, including bank grading, creation of an inset floodplain, and restoration of a woody riparian buffer. Treatment 3 met the most criteria, followed by Treatments 2 and then 1. Treatment 3 met all the criteria evaluated in this project with respect to riparian buffer performance, W/D ratio stability rating and cross-sectional area change. While Treatments 1 and 2 failed under several criteria, they performed as expected by aggrading and proceeding naturally along the channel evolution model pathway. This project suggests that hard structures are not necessary to meet mitigation bank criteria, even for urbanized watersheds, contrary to what is suggested and implemented in Natural Channel Design.

The restoration has decreased streambank erosion and improved the condition of the stream. While habitat was not explicitly measured for this project, it is known that the Virginia Stream Condition Index has improved following the restoration. Additionally, streambank erosion was successfully reduced, with width, hydraulic depth, and area decreasing on average throughout the study area. W:D increased on average due to a decrease in hydraulic depth, not an increase in width. While Treatment 3 continues to erode, Treatments 1 and 2 have aggraded, successfully meeting the goal of the original stream restoration project which was to reduce streambank erosion. While narrowing of the channel caused some cross sections to fail under Virginia Mitigation Bank Standards, this response was encouraged by the removal of cattle from the reach.

6.1 Future Studies

This restoration project focused only on the physical form of the channel, so further improvements on habitat conditions are still needed. Some habitat improvements include continuation of pool development for habitat heterogeneity and increased woody streamside vegetation which can create cover for aquatic species and contribute large woody debris to the stream. Recommendations for future research include creating an in-depth sediment budget of the watershed, continuing evaluation of Treatments 1 and 2 to gain insight into the response times of less intensive treatments and completing a watershed-scale restoration or modeling which focuses on improving water quality. Additionally, since the coconut coir logs were in place on the bottom of the graded streambanks in 2010 and are now gone, the changes in channel dimensions may simply be due to the loss of the coir fiber logs rather than actual changes in cross section. A future recommended study would compare locations of coir fiber logs with cross section locations to determine if the changes in channel dimensions were sedimentation and erosion or from removal of coir fiber logs. Another project that could be similar to this one would be to conduct a flume study to evaluate different treatments on streams with the same conditions. Since it was assumed that the treatments impacted each other in this study, the only way to combat that impact is to conduct the same project on three identical streams. Since this is not possible in nature, a flume would be the only way to evaluate the treatments on similar systems.

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Appendix A – Raw Cross Section Measurements and Percent Changes

Table A - 1: Measured values for each cross section pre-restoration in 2006 and 2007.

	2006					2007				
Cross Section	Width (m)	Maximum Depth (m)	Area (m^2)	W:D (-)	HD (m)	Width (m)	Maximum Depth (m)	Area (m^2)	W:D (-)	HD (m)
A	10.51	1.33	9.472	11.662	0.901	10.206	1.262	9.206	11.315	0.902
B	8.596	0.92	5.843	12.646	0.680	8.925	0.944	5.610	14.199	0.629
C	6.746	0.553	2.818	16.149	0.418	6.655	0.673	2.669	16.594	0.401
D	7.231	0.913	4.786	10.925	0.662	7.329	0.937	4.745	11.320	0.647
E	4.969	0.879	3.259	7.576	0.656	4.801	1.031	3.476	6.631	0.724
F	4.205	0.321	0.904	19.560	0.215	4.742	0.41	1.242	18.105	0.262
G	5.767	0.818	3.668	9.067	0.636	5.623	0.936	3.709	8.525	0.660
H	6.958	1.026	4.988	9.706	0.717	8.306	0.989	5.457	12.642	0.657
I	6.403	1.061	5.146	7.967	0.804	6.852	1.151	5.311	8.840	0.775

Table A - 2: Measured values for each cross section post-restoration in 2010 and 2021.

Cross Section	Treatment	Planform Location	Geomorphic Unit	2010					2021				
				Width (m)	Max Depth (m)	Area (m^2)	W:D (-)	HD (m)	Width (m)	Max Depth (m)	Area (m^2)	W:D (-)	HD (m)
1	1	Straight	Run	6.86	0.97	4.58	10.26	0.67	8.16	1.00	4.71	14.14	0.58
3	1	Slight bend	Run	14.79	1.29	11.54	18.96	0.78	15.56	1.34	11.19	21.64	0.72
4	1	Straight	Run	9.23	0.96	6.89	12.36	0.75	10.25	0.99	6.21	16.89	0.61
5	1	End of Meander*	Run	15.76	1.15	8.98	27.68	0.57	8.63	1.11	4.96	15.03	0.57
6	2	Slight bend	Run	16.83	1.26	9.90	28.61	0.59	16.22	1.24	7.95	33.11	0.49
7	2	Straight	Run	12.90	1.21	8.49	19.61	0.66	11.60	1.04	6.27	21.49	0.54
8	2	Slight bend	Run	11.95	1.00	6.00	23.80	0.50	11.88	1.02	5.76	24.51	0.48
9	2	Slight bend	Run	19.87	1.23	10.97	35.98	0.55	19.61	1.22	9.94	38.68	0.51
10	2	Straight	Run	11.17	0.85	6.77	18.44	0.61	9.08	0.80	4.86	16.96	0.54
11	2	End of Meander	Riffle	19.19	1.25	12.00	30.69	0.63	16.71	1.18	7.60	36.73	0.45
12	2	Straight	Run	15.63	1.22	9.06	26.97	0.58	13.81	1.22	6.88	27.72	0.50
13	2	Meander bend	Riffle	14.02	1.21	9.78	20.10	0.70	13.56	1.13	8.22	22.37	0.61
14	2	Meander bend	Pool	15.88	1.38	9.22	27.34	0.58	12.70	1.45	8.69	18.58	0.68
16	2	Meander bend	Riffle	13.89	1.25	9.41	20.49	0.68	13.52	1.27	7.94	23.05	0.59
19	3	Straight	Pool	14.40	0.92	4.91	42.25	0.34	14.18	1.17	5.69	35.35	0.40
21	3	Meander bend	Run	16.11	1.14	7.80	33.27	0.48	17.55	1.44	8.74	35.26	0.50
22	3	Slight bend	Riffle	12.72	1.24	8.83	18.33	0.69	12.03	1.18	7.20	20.11	0.60
25	3	Slight bend	Riffle	10.52	1.25	7.77	14.24	0.74	10.47	1.26	7.55	14.52	0.72
26	3	Straight	Run	12.23	1.20	7.45	20.07	0.61	13.16	1.29	8.26	20.98	0.63
30	3	Meander bend	Pool	14.30	1.05	7.06	28.97	0.49	15.72	1.15	7.21	34.23	0.46

Table A - 3: Percent changes for pre-restoration from 2006 and 2007 on Stroubles Creek, Blacksburg, VA. For percent change, a red highlight indicates a decrease, a green highlight represents an increase, and a yellow highlight represents minimal change

Cross Section	**Percent Change**				
	Width (m)	**Max Depth (m)**	**Area (m^2)**	**W:D (-)**	**Hydraulic Depth (m)**
A	-2.89	-5.11	-2.81	-2.98	0.09
B	3.83	2.61	-3.99	12.28	-7.53
C	-1.35	21.70	-5.29	2.75	-3.99
D	1.36	2.63	-0.86	3.62	-2.18
E	-3.38	17.29	6.66	-12.48	10.39
F	12.77	27.73	37.39	-7.44	21.83
G	-2.50	14.43	1.12	-5.98	3.71
H	19.37	-3.61	9.40	30.25	-8.35
I	7.01	8.48	3.21	10.96	-3.56

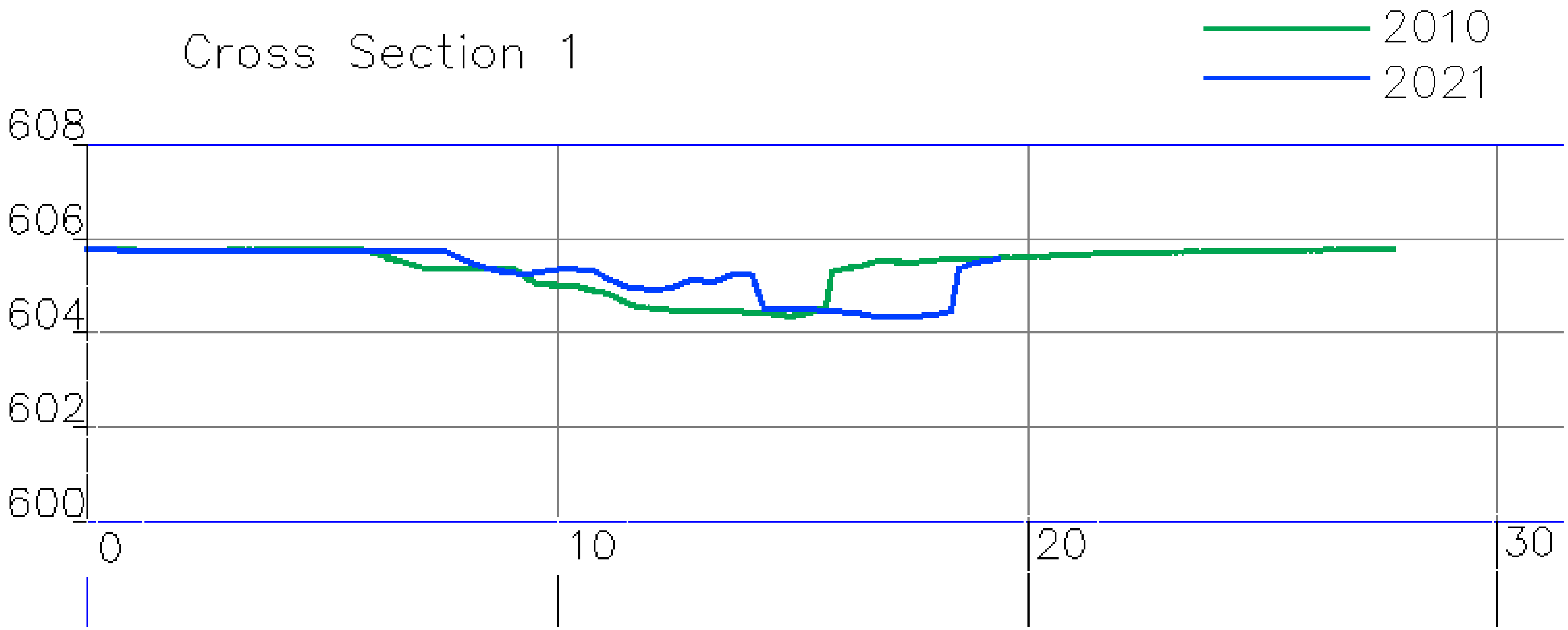
Table A - 4: Percent changes for area, width, depth, and W:D over the entire study period (2010 to 2021) for Stroubles Creek, Blacksburg, VA. For percent change, a red highlight indicates a decrease, a green highlight represents an increase, and a yellow highlight represents minimal change.

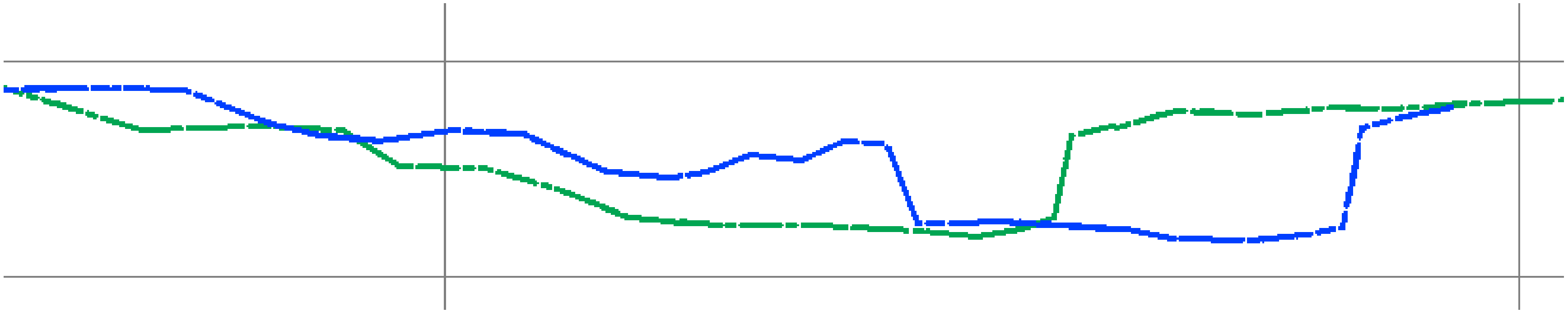
Cross Section	Treatment	Planform Location	Geomorphic Unit	11-Year Area % Change	11-Year Width % Change	11-Year Maximum Depth % Change	11-Year W:D % Change	11-Year HD % Change
1	1	Straight	Run	2.64	18.93	3.40	37.80	-13.70
3	1	Slight bend	Run	-3.03	5.21	3.41	14.15	-7.83
4	1	Straight	Run	-9.82	11.02	3.33	36.68	-18.78
5	1	End of meander, bridge	Run	-44.75	-45.22	-3.81	-45.69	0.86
6	2	Slight bend	Run	-19.75	-3.64	-2.06	15.71	-16.72
7	2	Straight	Run	-26.17	-10.06	-13.97	9.56	-17.91
8	2	Slight bend	Run	-3.98	-0.57	2.01	2.97	-3.43
9	2	Slight bend	Run	-9.43	-1.33	-1.22	7.49	-8.21
10	2	Straight	Run	-28.23	-18.74	-5.79	-7.99	-11.68
11	2	End of meander	Riffle	-36.66	-12.94	-5.52	19.68	-27.25
12	2	Straight	Run	-24.01	-11.63	0.41	2.77	-14.01
13	2	Meander bend	Riffle	-15.88	-3.25	-7.10	11.28	-13.05
14	2	Meander bend	Pool	-5.83	-19.99	4.78	-32.03	17.70
16	2	Meander bend	Riffle	-15.70	-2.63	1.20	12.47	-13.43
19	3	Straight	Pool	15.94	-1.51	27.98	-16.34	17.72
21	3	Meander bend	Run	11.99	8.93	25.55	5.96	2.80
22	3	Slight bend	Riffle	-18.40	-5.40	-4.75	9.67	-13.74
25	3	Slight bend	Riffle	-2.81	-0.46	0.96	1.95	-2.36
26	3	Straight	Run	10.88	7.65	7.67	4.51	3.00
30	3	Meander bend	Pool	2.18	9.89	9.66	18.17	-7.01

Appendix B – Cross Section Images and Profiles

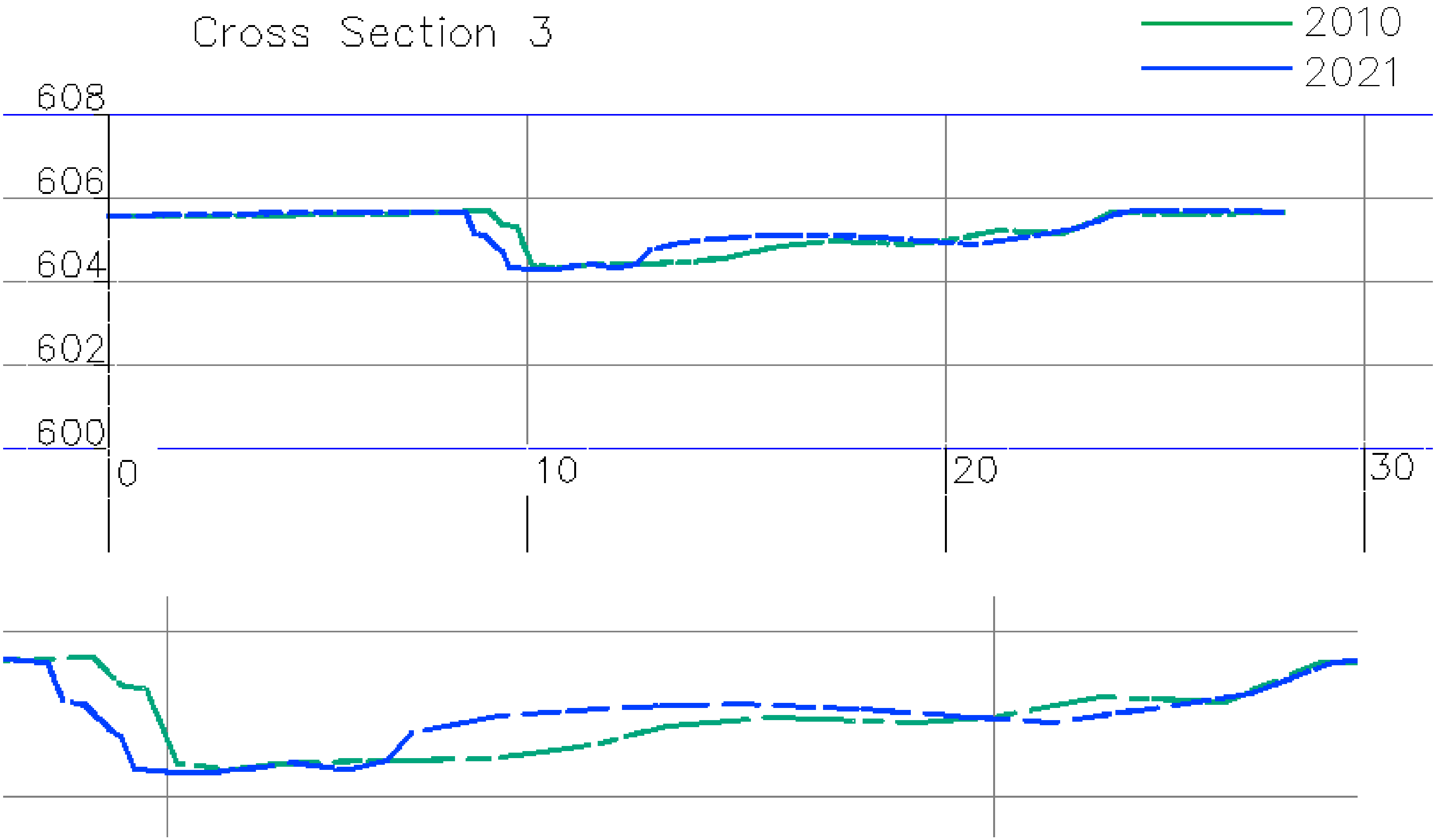
Treatment 1

Appendix B-1: Cross Section #1 – Run

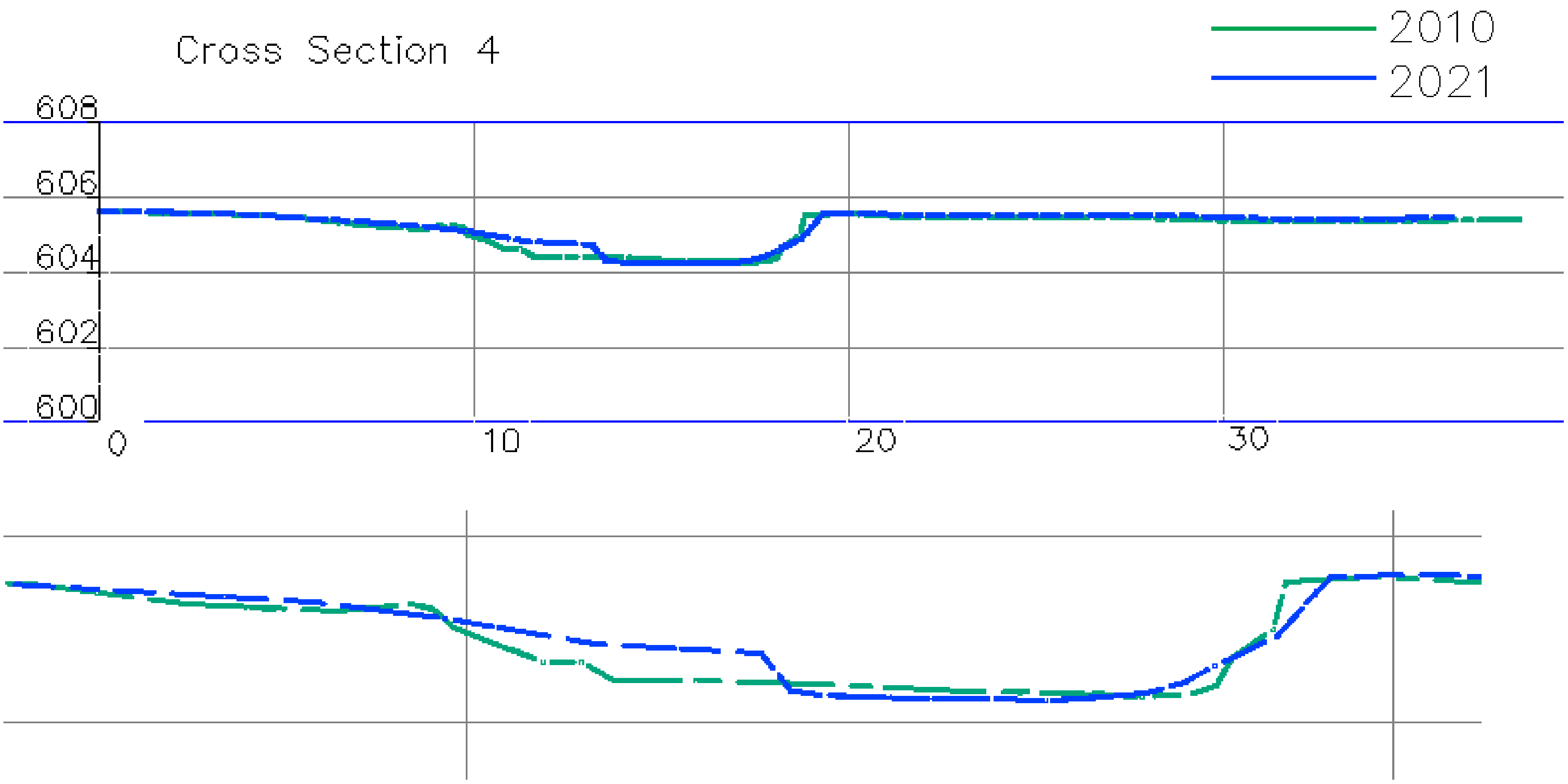

Cross Section 1
2010
2021
608
606
604
602
600
0
10
20
30



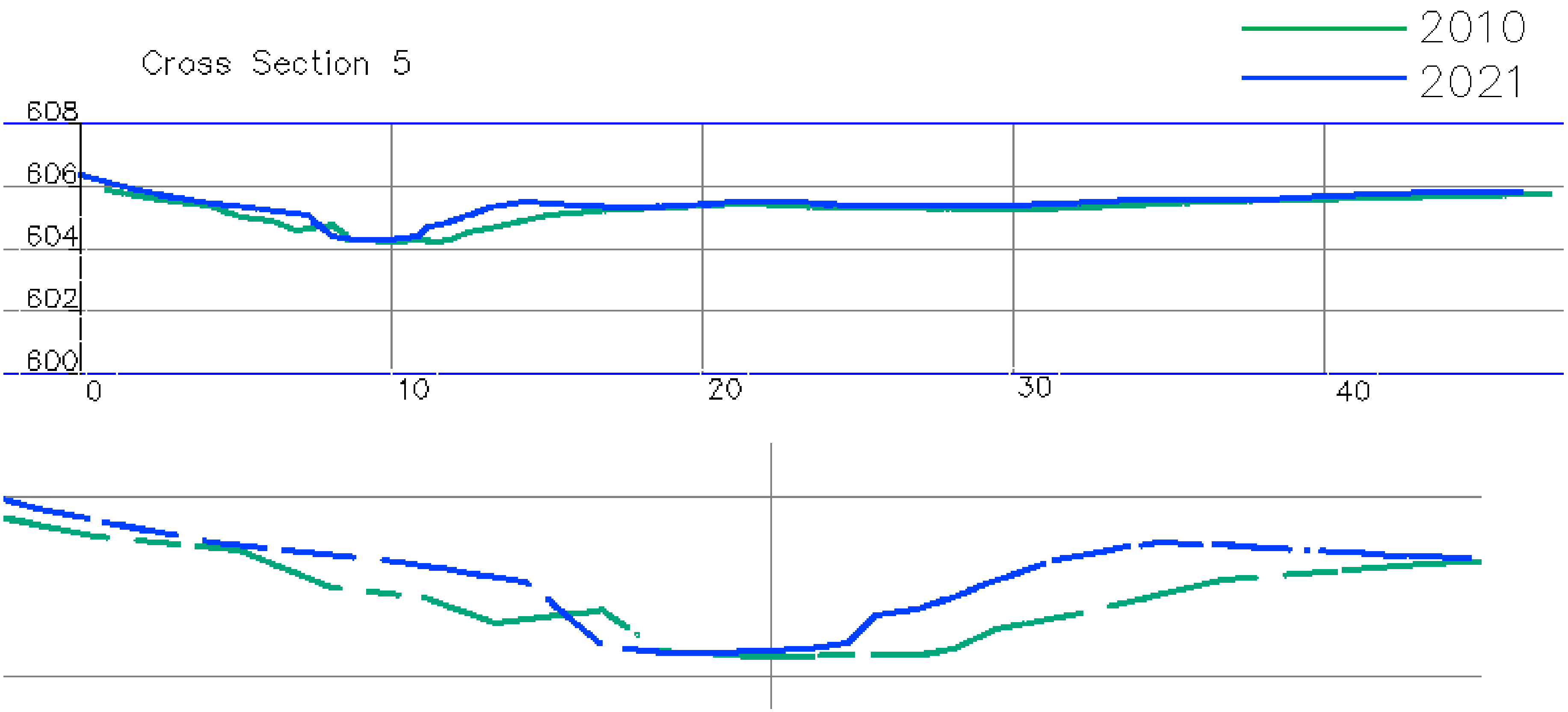
Appendix B-2: Cross Section #3 – Run


Cross Section 3
2010
2021
608
606
604
602
600
0
10
20
30

Appendix B-3: Cross Section #4 – Run

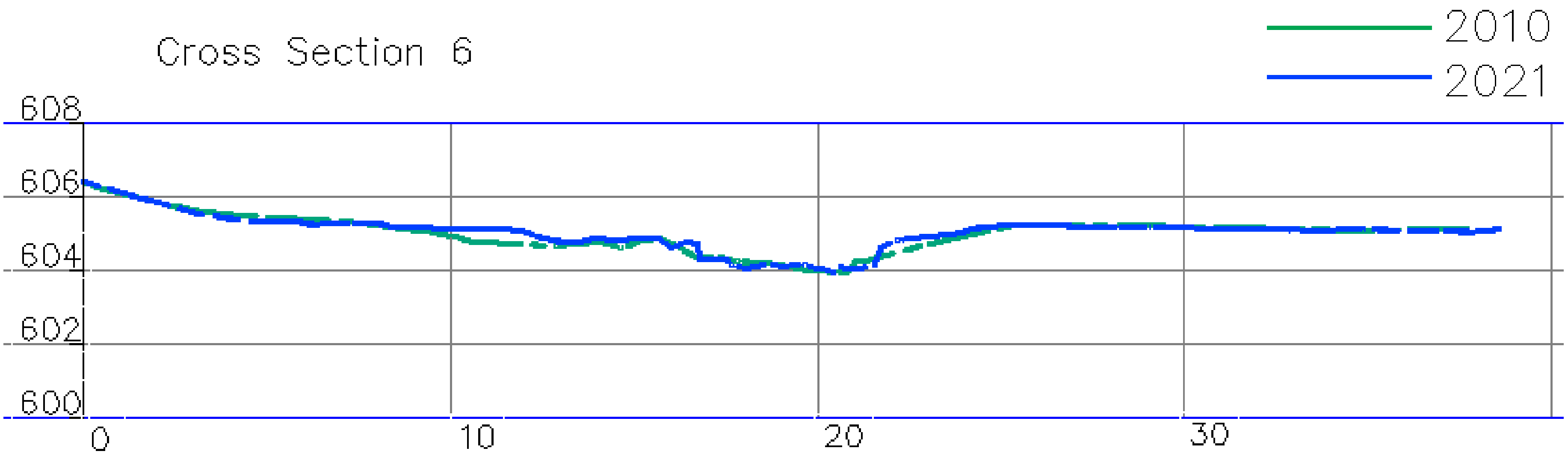

Cross Section 4
2010
2021
608
606
604
602
600
0
10
20
30

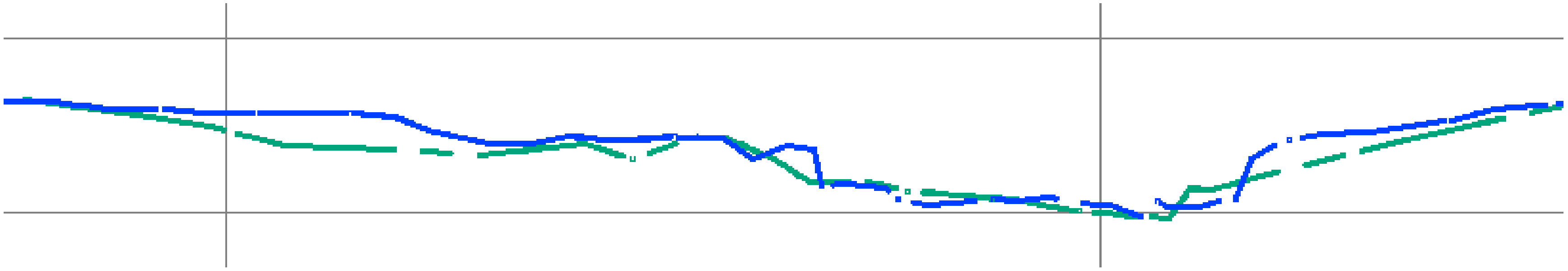
Appendix B-4: Cross Section #5 – Run


Cross Section 5
2010
2021
608
606
604
602
600
0
10
20
30
40

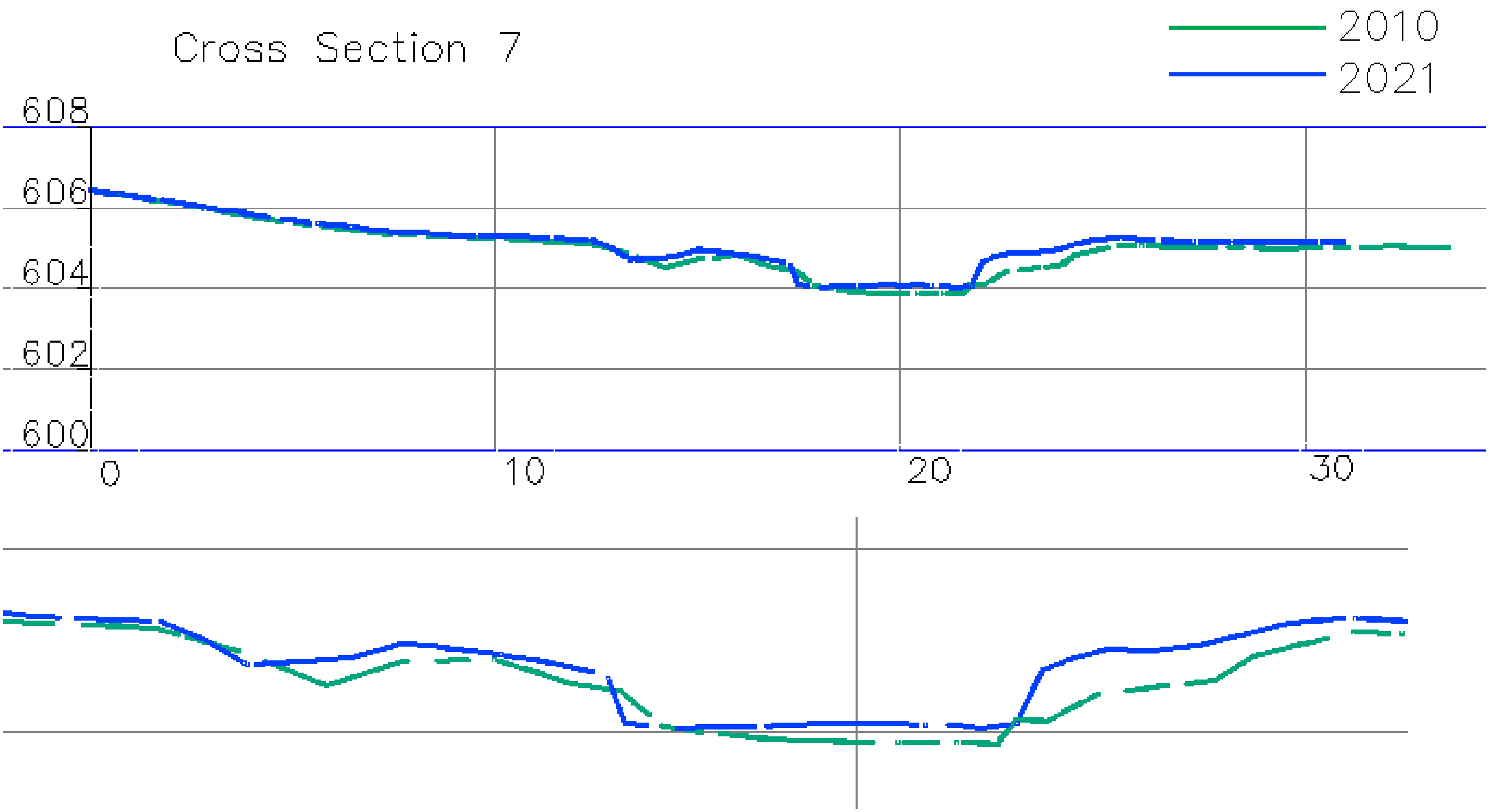
<u>*Treatment 2*</u>

Appendix B-5: Cross Section #6 – Run

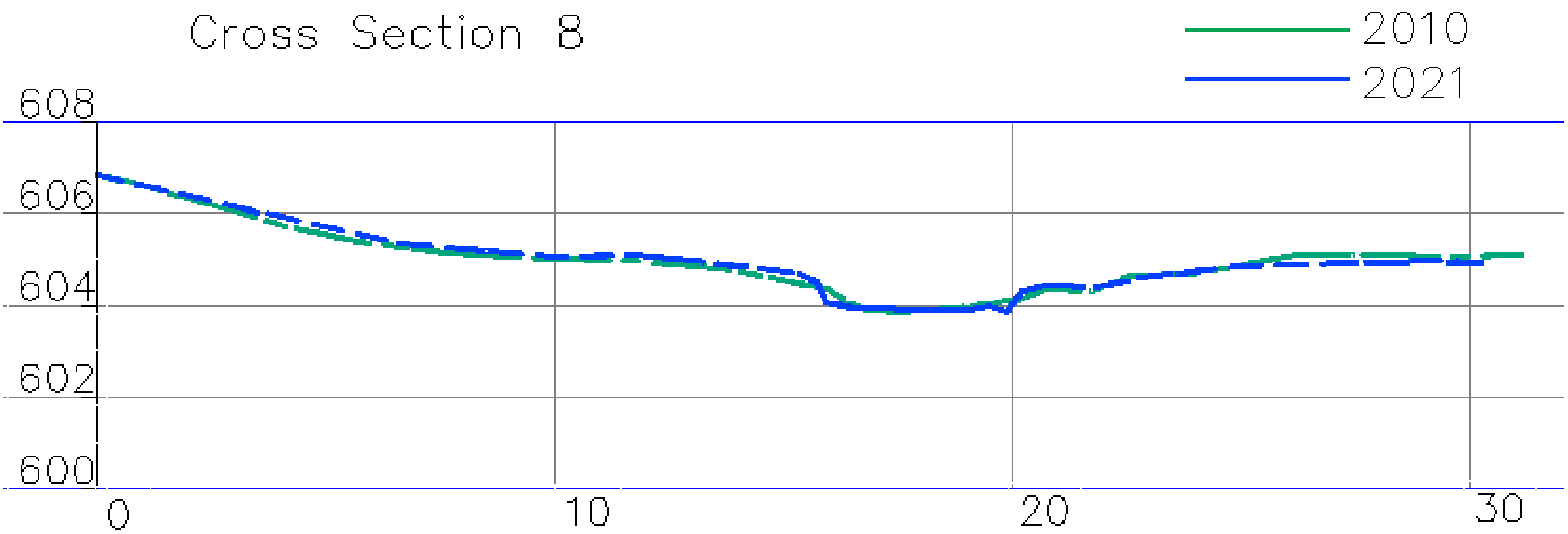

Cross Section 6
2010
2021
608
606
604
602
600
0
10
20
30



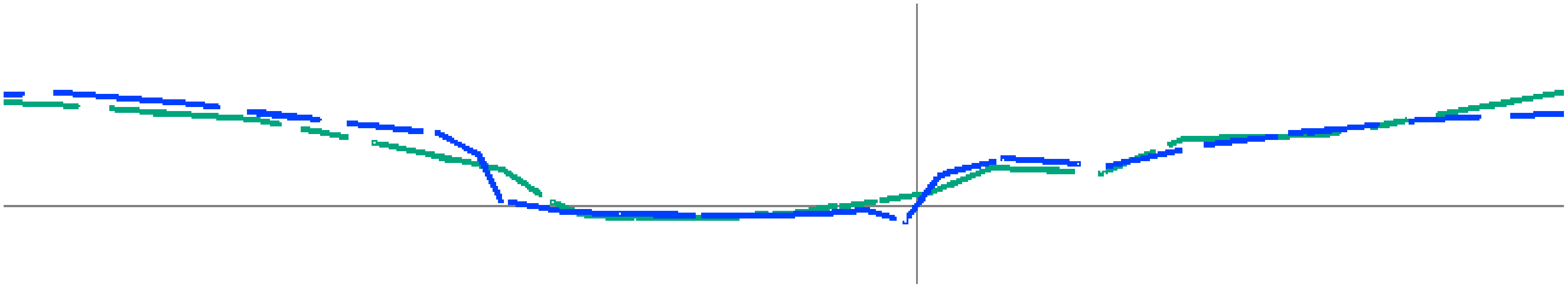
Appendix B-6: Cross Section #7 – Run


Cross Section 7
2010
2021
608
606
604
602
600
0
10
20
30

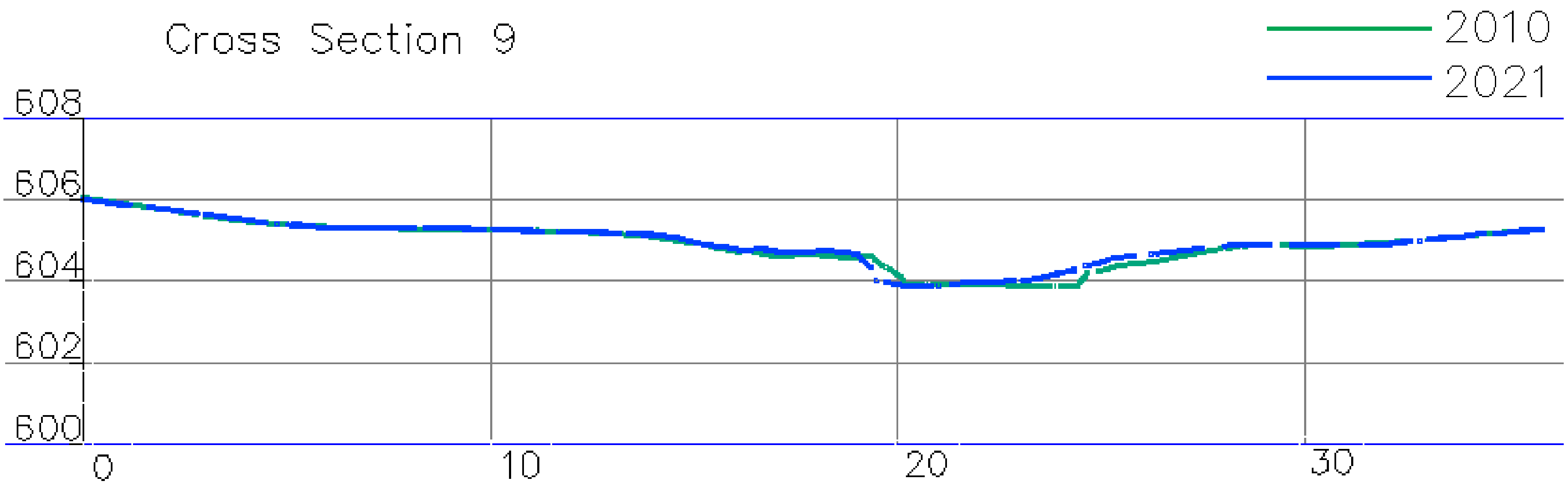
Appendix B-7: Cross Section #8 – Run

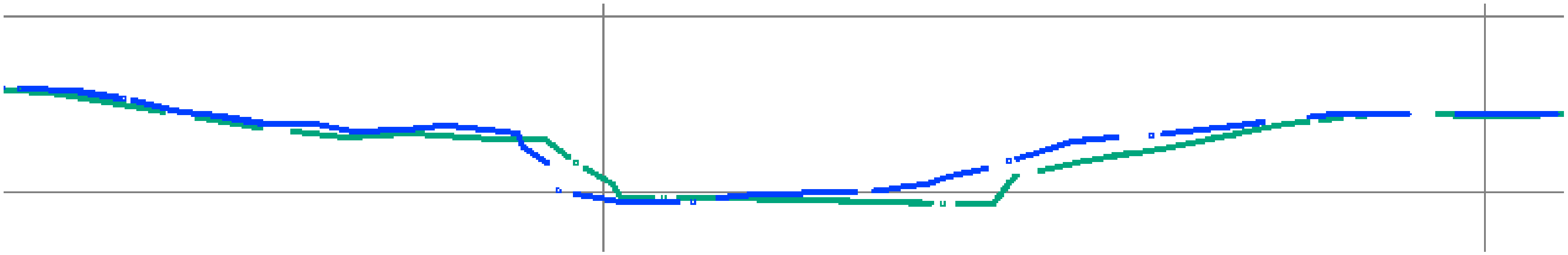


Cross Section 8

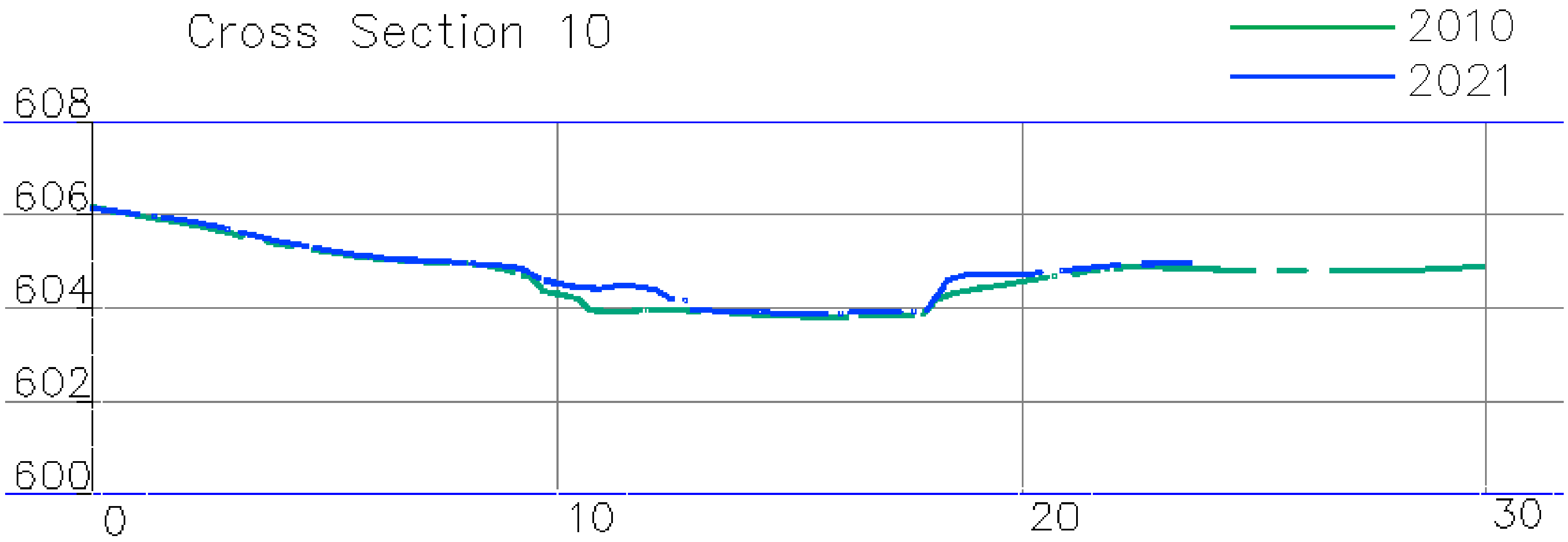


Appendix B-8: Cross Section #9 – Run

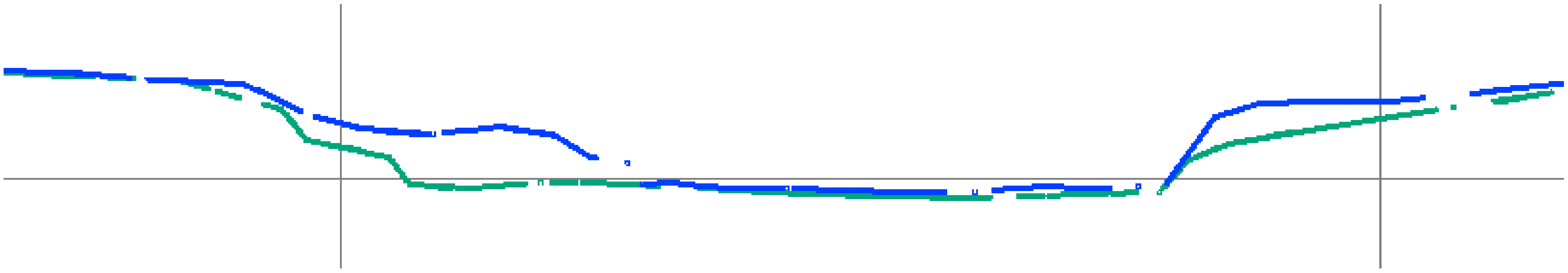

Cross Section 9
2010
2021
608
606
604
602
600
0
10
20
30



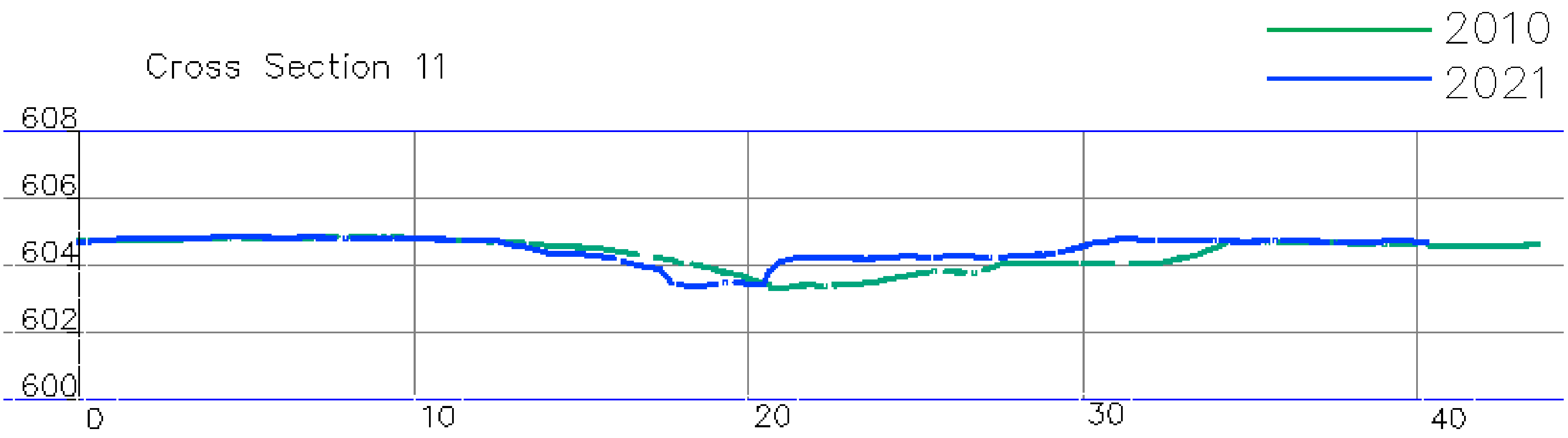
Appendix B-9: Cross Section #10 – Run

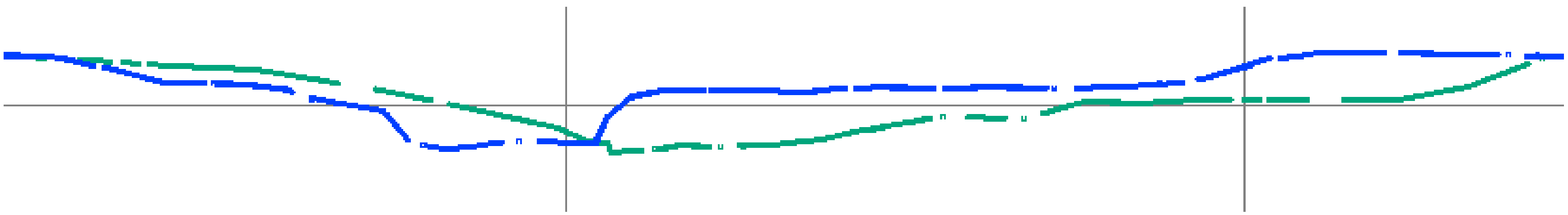


Cross Section 10

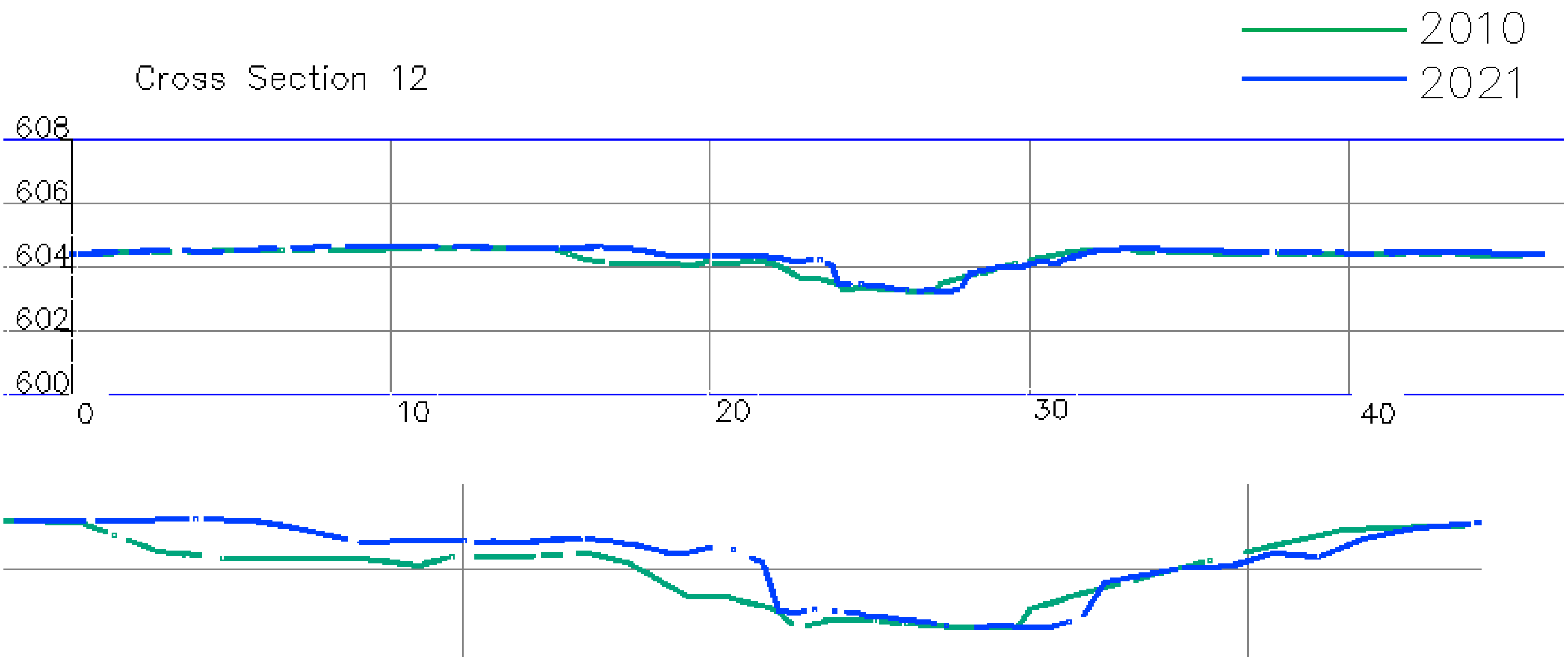


Appendix B-10: Cross Section #11 – Riffle

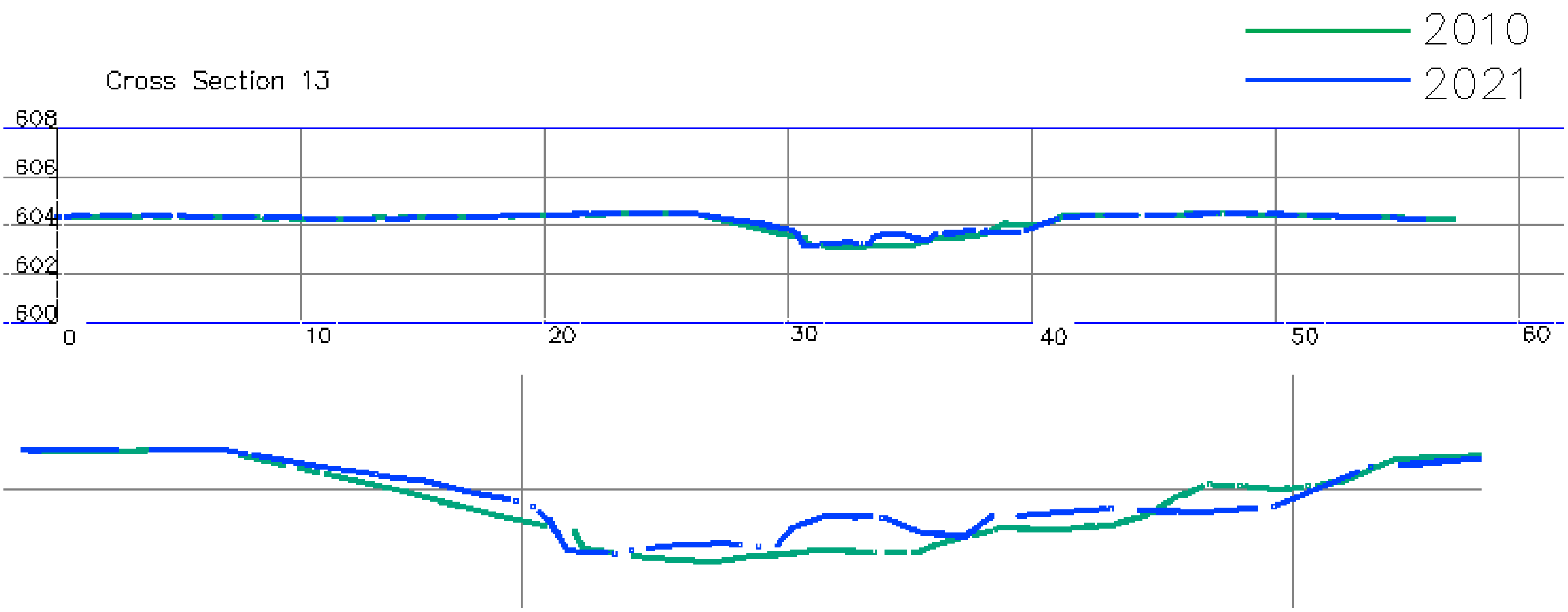

Cross Section 11
2010
2021
608
606
604
602
600
0
10
20
30
40



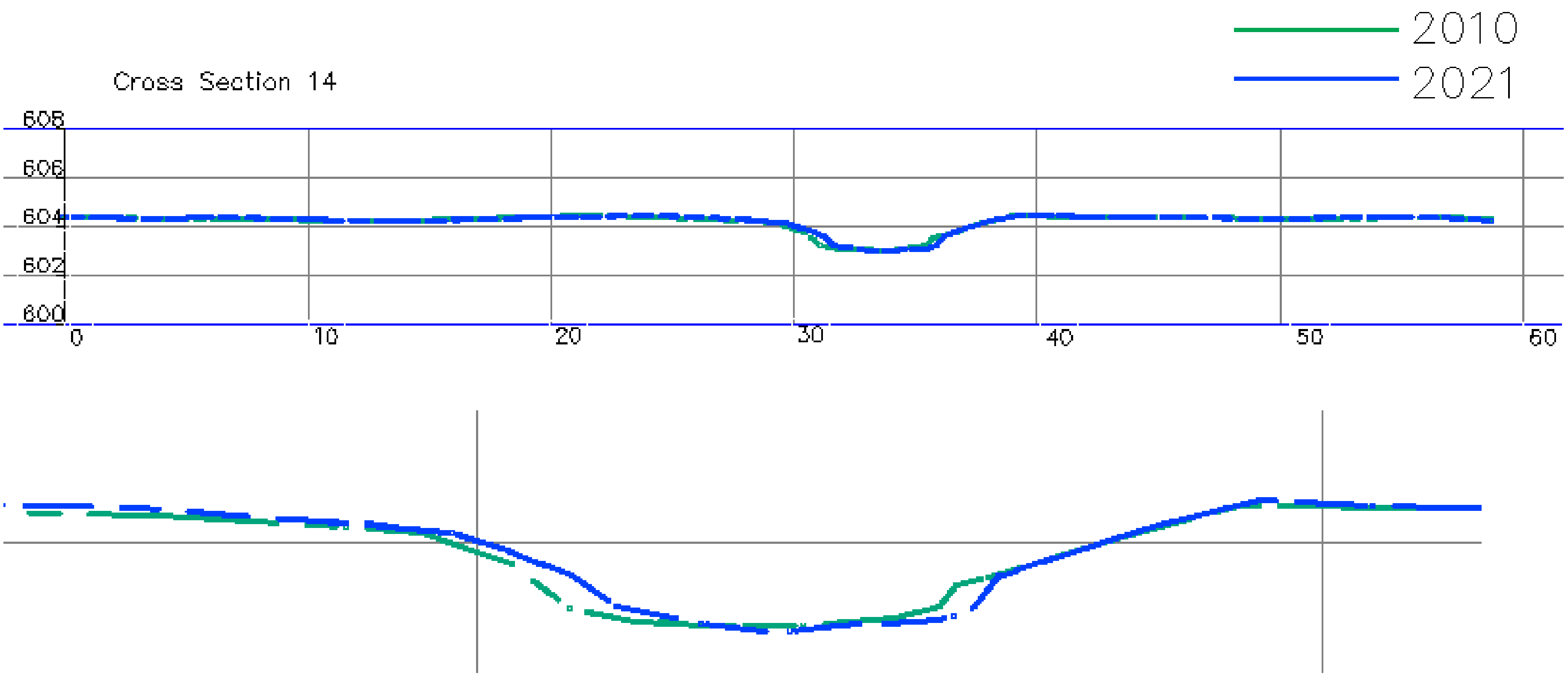
Appendix B-11: Cross Section #12 – Run


Cross Section 12
2010
2021
608
606
604
602
600
0
10
20
30
40

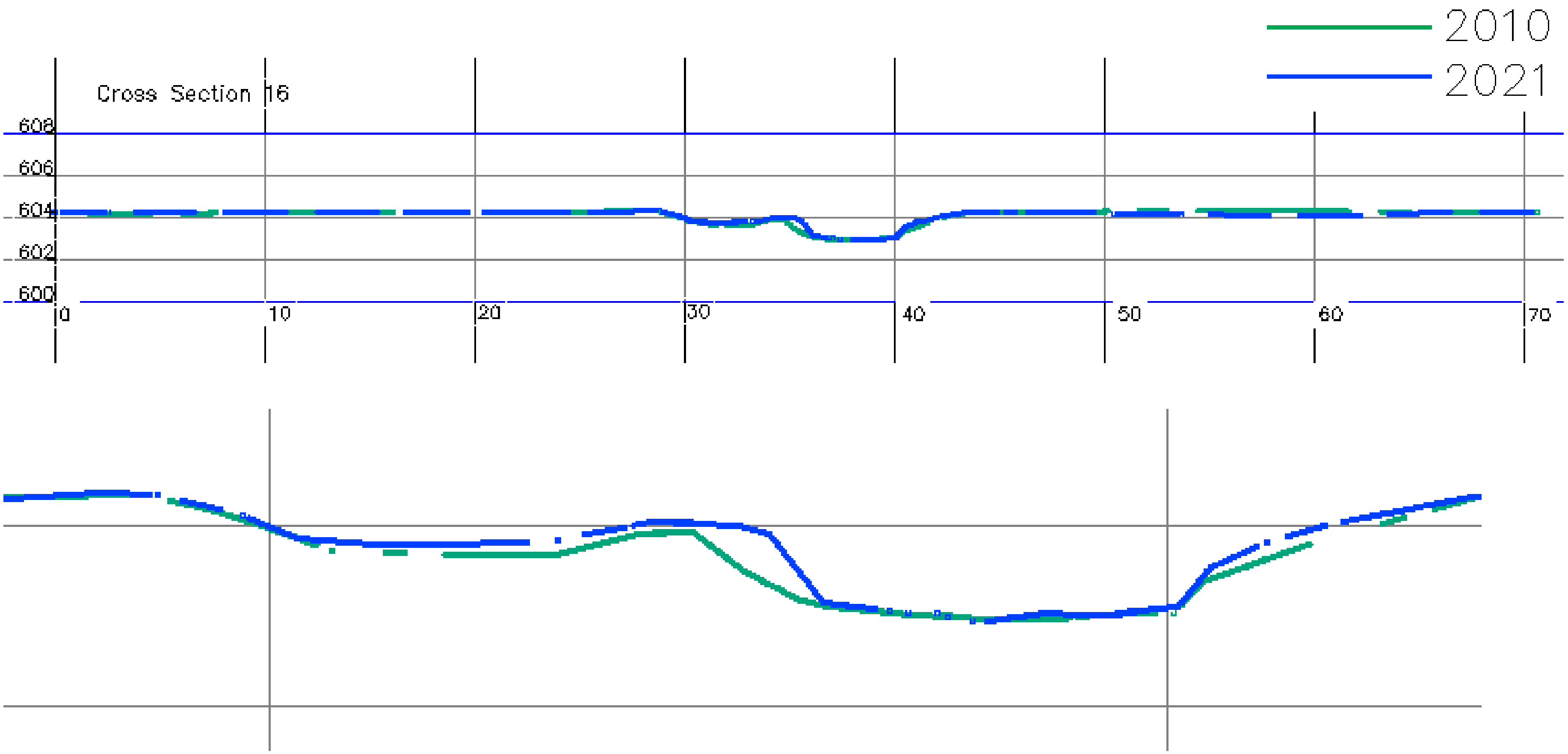
Appendix B-12: Cross Section #13 – Riffle


2010
2021
Cross Section 13
608
606
604
602
600
0
10
20
30
40
50
60

Appendix B-13: Cross Section #14 – Pool

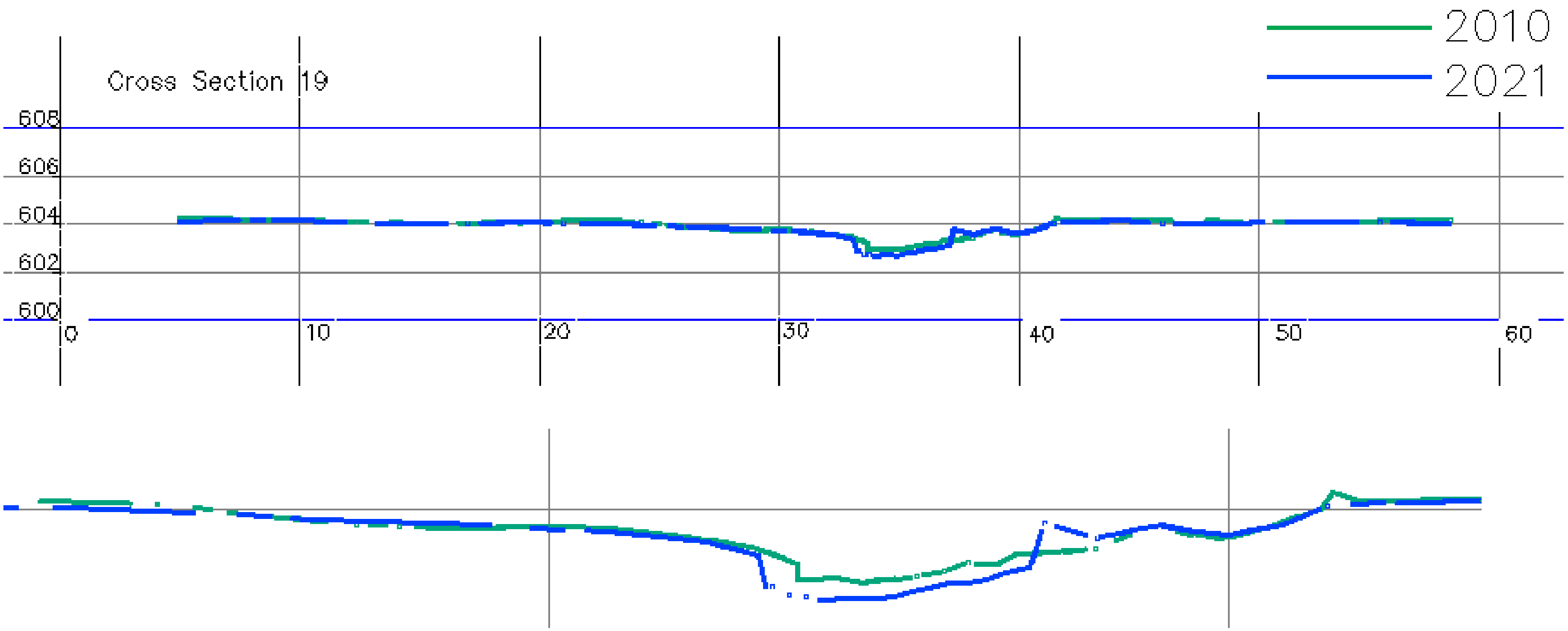

2010
2021
Cross Section 14
608
606
604
602
600
0
10
20
30
40
50
60

Appendix B-14: Cross Section #16 – Riffle

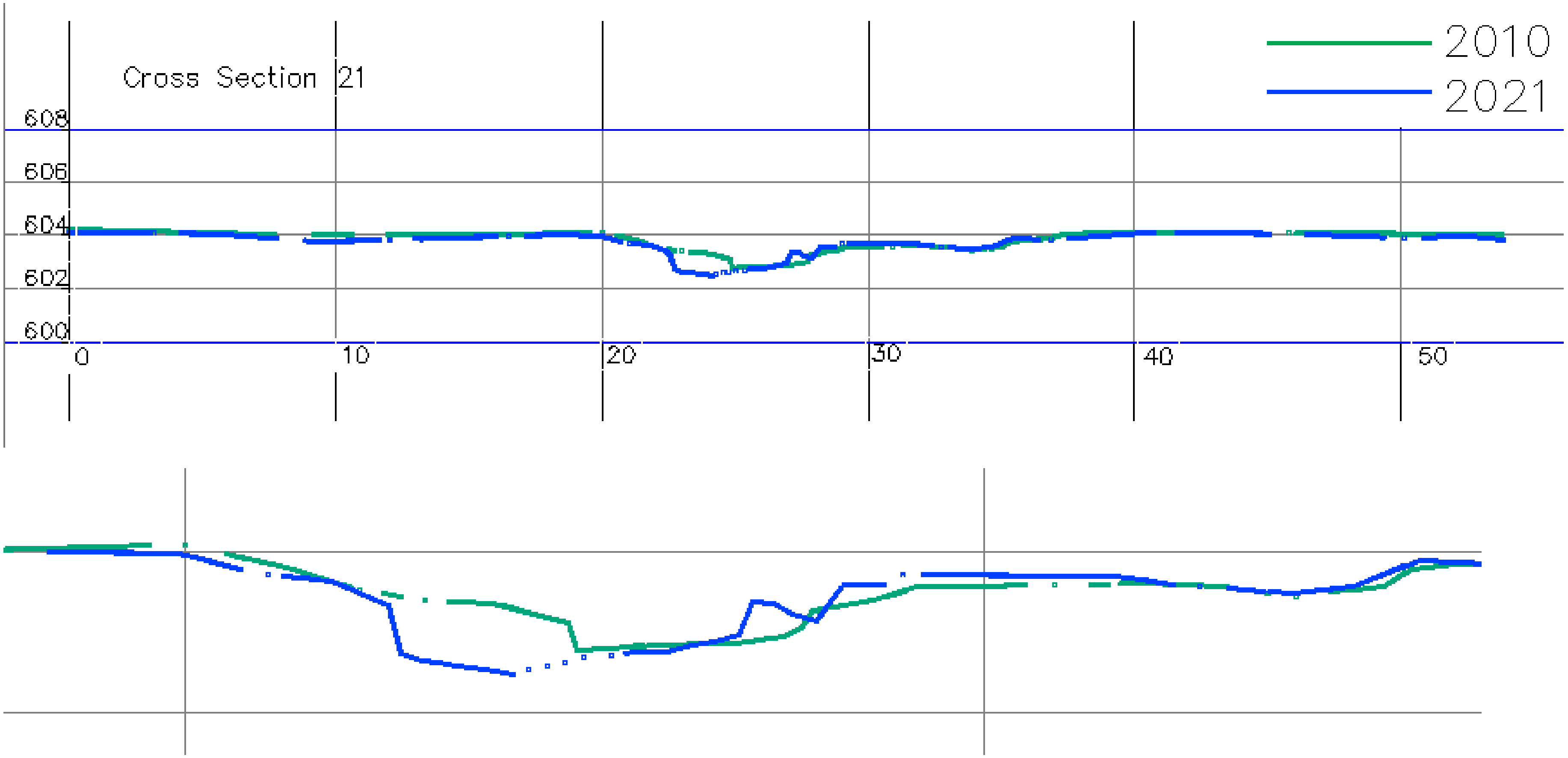

2010
2021
Cross Section 16
608
606
604
602
600
0
10
20
30
40
50
60
70

Treatment 3

Appendix B-15: Cross Section #19 – Pool

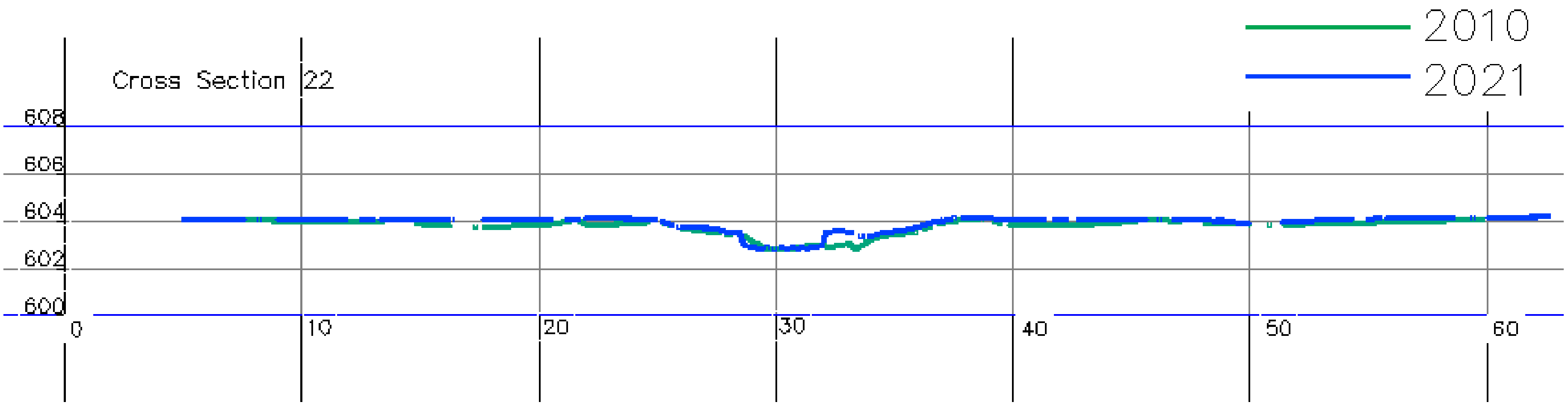

2010
2021
Cross Section 19
608
606
604
602
600
0
10
20
30
40
50
60

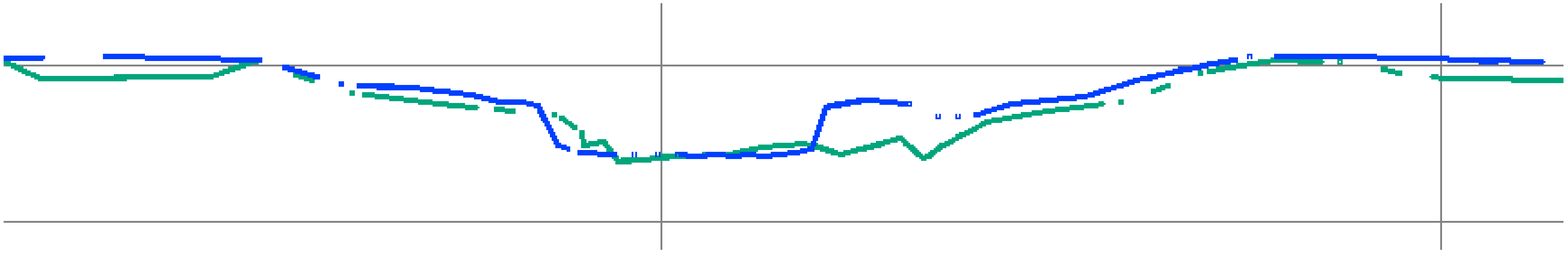
Appendix B-16: Cross Section #21 – Run



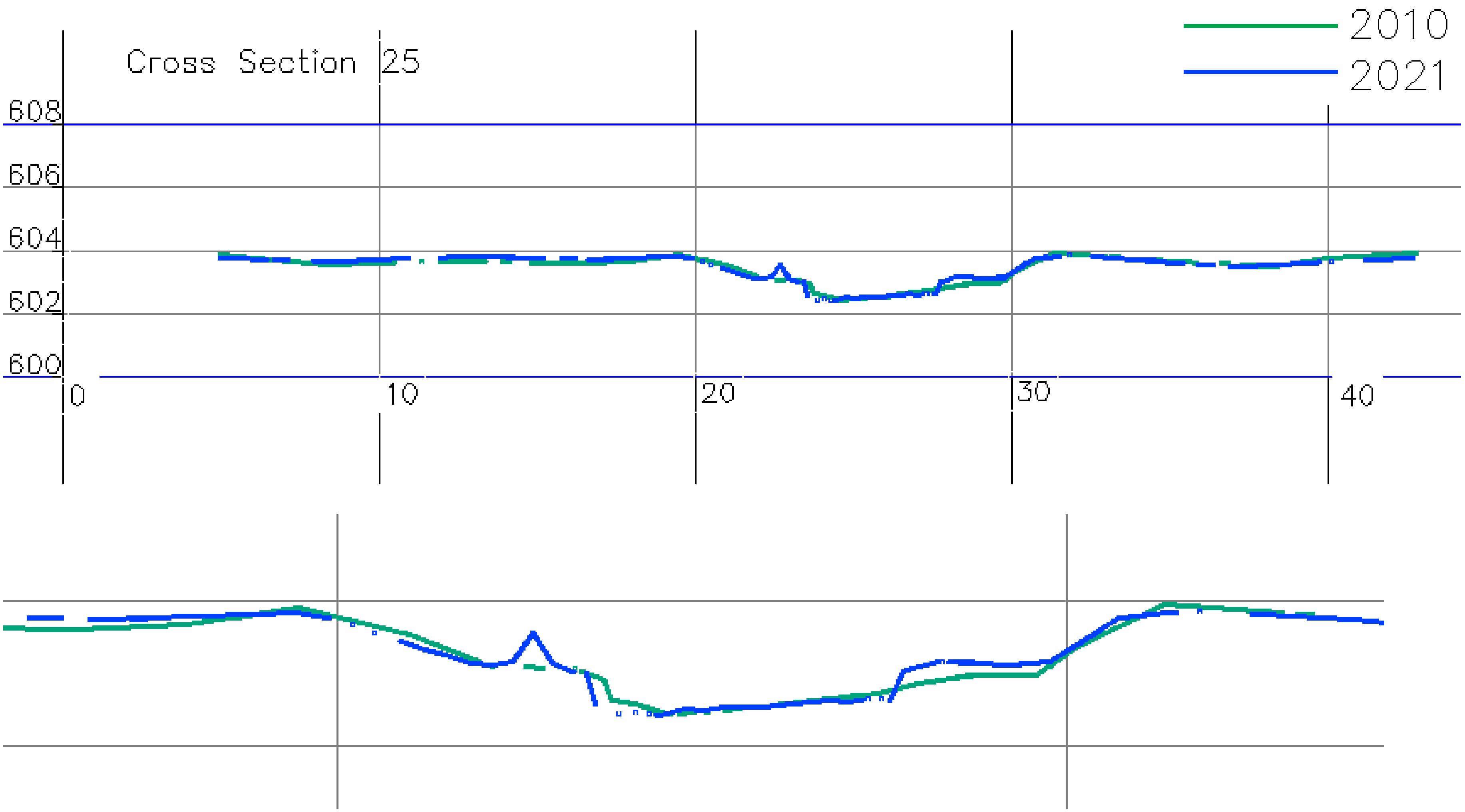
Cross Section 21
2010
2021
608
606
604
602
600
0
10
20
30
40
50

Appendix B-17: Cross Section #22 – Riffle

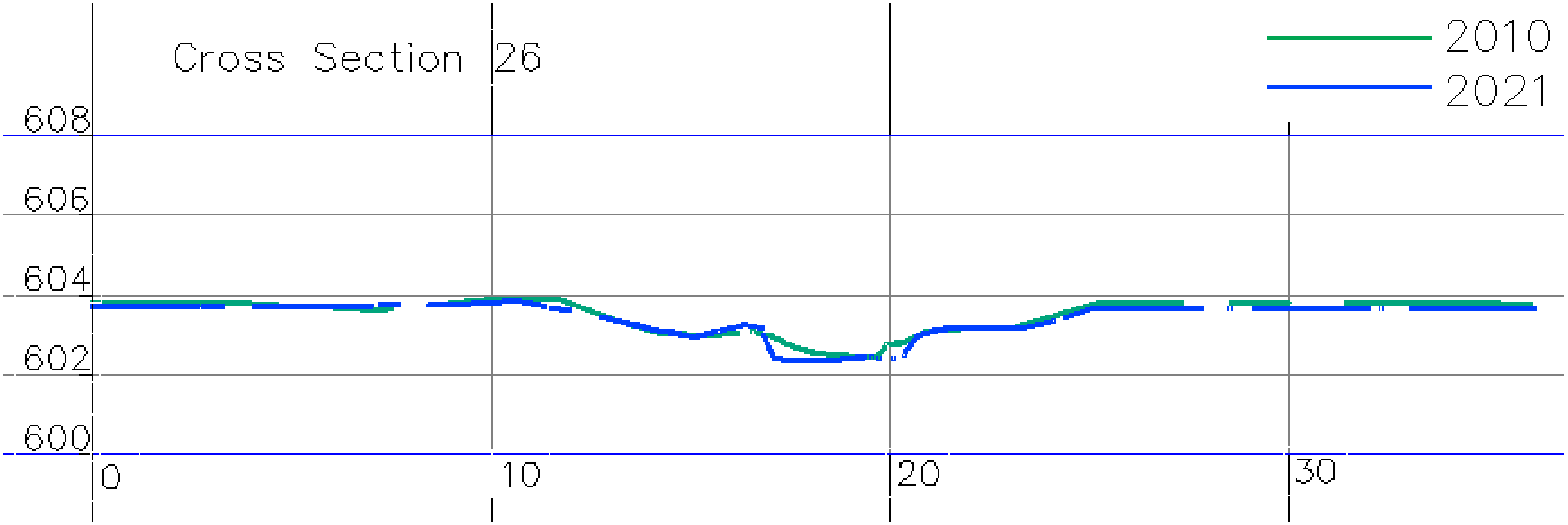

2010
2021
Cross Section 22
608
606
604
602
600
0
10
20
30
40
50
60

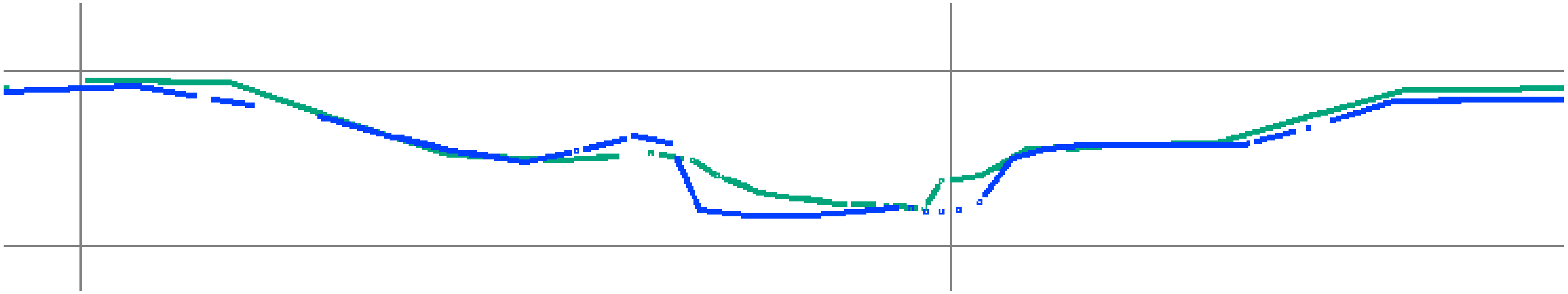


Appendix B-18: Cross Section #25 – Riffle

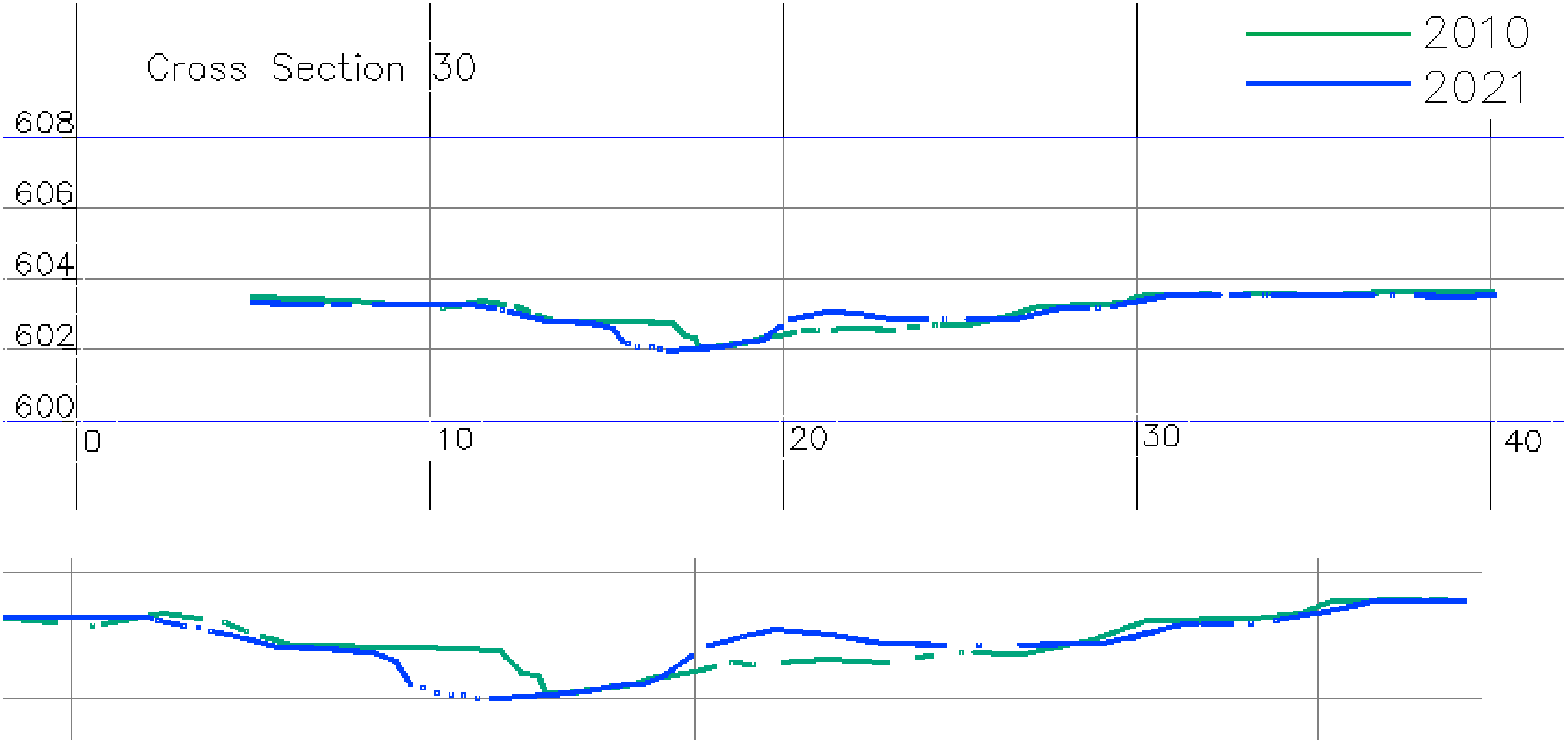

Cross Section 25
2010
2021
608
606
604
602
600
0
10
20
30
40

Appendix B-19: Cross Section #26 – Run


Cross Section 26
2010
2021
608
606
604
602
600
0
10
20
30



Appendix B-20: Cross Section #30 – Pool


Cross Section 30
2010
2021
608
606
604
602
600
0
10
20
30
40

Appendix C – Treatment Images

Treatment 1

Treatment 2

__Treatment 3__

Appendix D – Longitudinal Profile 2011

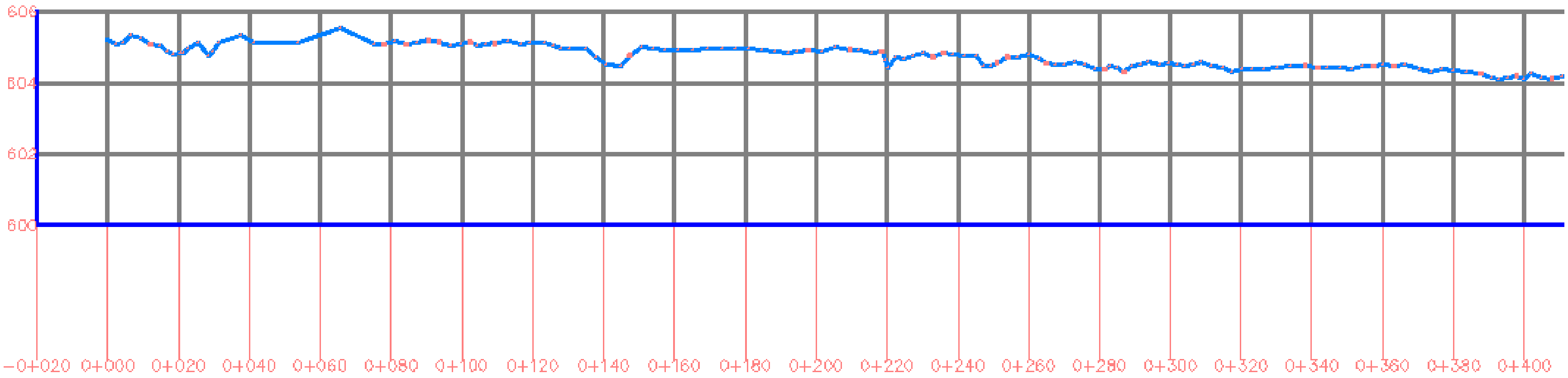


Figure D 1A: Longitudinal profile of Stroubles Creek in 2011.

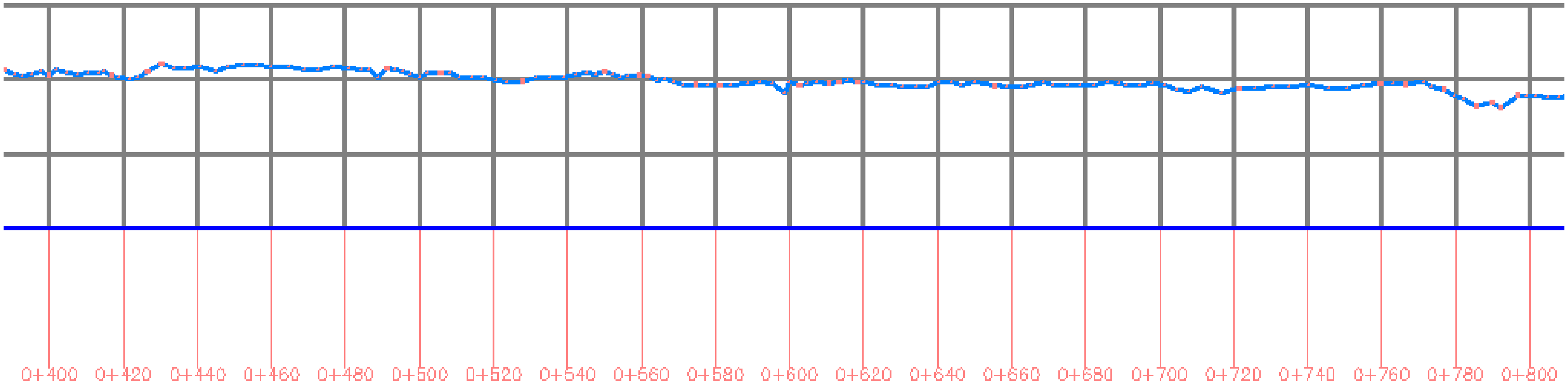


Figure D 1B: Longitudinal profile of Stroubles Creek in 2011.

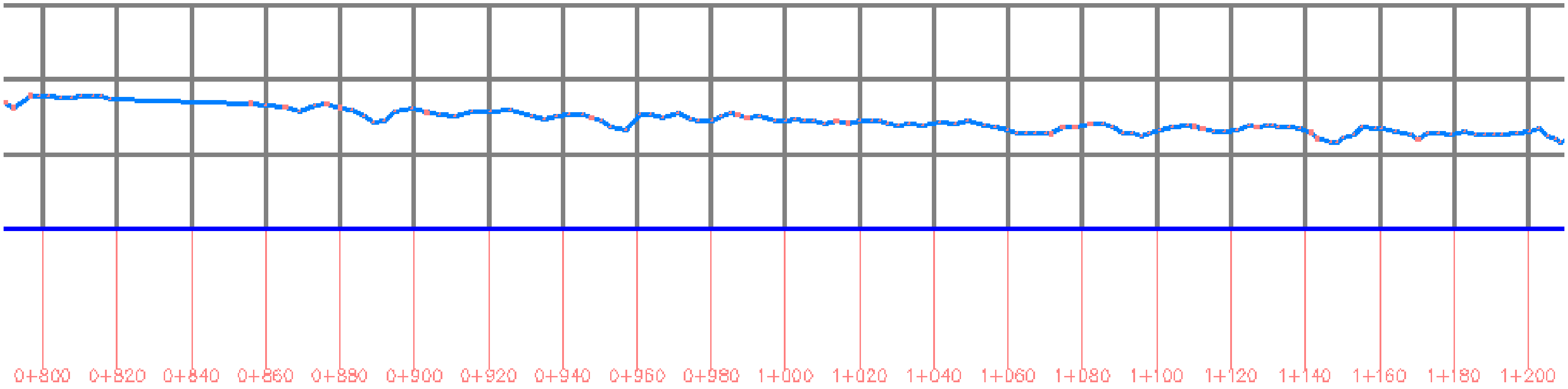


Figure D 1C: Longitudinal profile of Stroubles Creek in 2011.

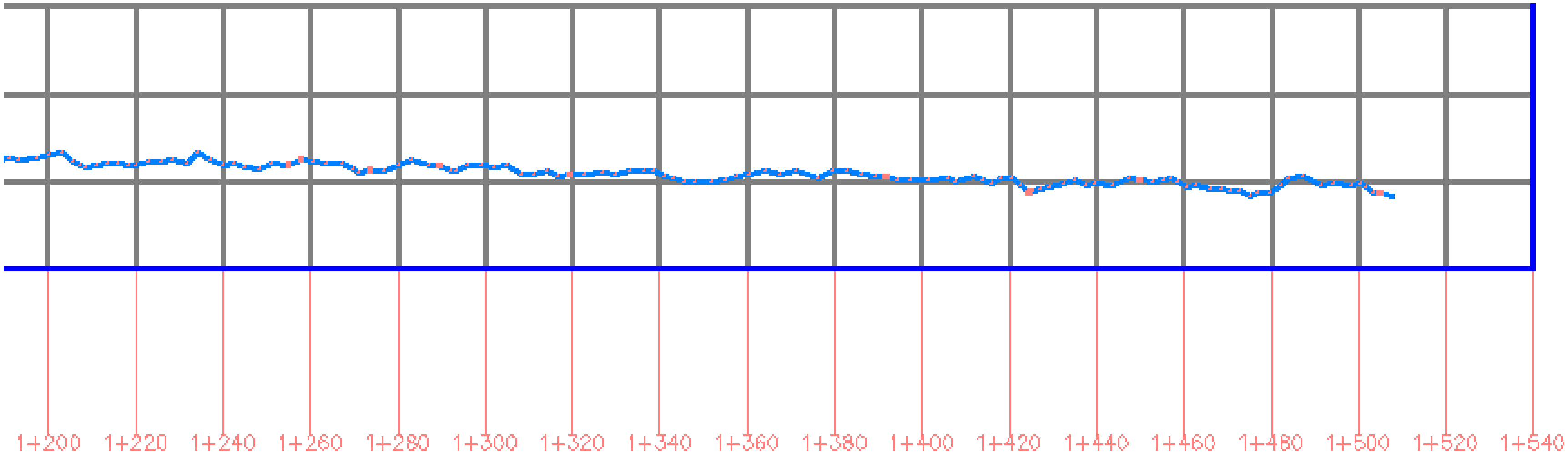


Figure D 1D: Longitudinal profile of Stroubles Creek in 2011.