An Analysis of Four Common Stream Restoration Techniques
Within the Chesapeake Bay Watershed

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May 3, 2019

Abstract

This paper explores four techniques of stream restoration commonly used within the Chesapeake Bay Watershed (CBW). The Chesapeake Bay receives flow from six states and is the largest transition zone between fresh water and salt water in the United States. As the east coast was settled and developed throughout history the water quality of the Bay decreased due to landscape changes and metropolitan growth. The Environmental Protection Agency (EPA) along with state governments issued drivers and permitting to establish water quality guidelines for local governments and organizations. Stream restoration was implemented as a method of reaching permitting goals and many restoration techniques are currently used throughout the CBW. Four common techniques of stream restoration were compared and contrasted for optimal location, water quality efficiency, and cost efficiency: Legacy Sediment Removal (LSR), Natural Channel Design (NCD), Regenerative Stream Conveyance (RSC), and Threshold Channel Design (TCD). It was determined that LSR is optimal in areas with few lateral constraints to allow for floodplain establishment and re-connection. RSC and NCD use structures to establish vertical control and prevent erosion which can add additional integrity but also increase the cost. TCD is best used when minimal changes to the stream are allowed. Each restoration technique was found to have successfully improved water quality and ecological uplift by preventing further accumulation of nutrients and sediments downstream and in the Bay waters.

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Introduction

The Chesapeake Bay is the largest estuary in the United States, receiving flow from a watershed that stretches across six states (McConnell 1995). The Bay is home to countless plants and animals, provides support to over 16 million people (Ibid 1995), and has been a primary ecological region of the east coast since humans inhabited North America. The Chesapeake Bay Watershed (CBW) covers 172,000 square km and receives the majority of its flow from the Susquehanna and the Potomac rivers (Hagy et al. 2004). The greater part of the land within the watershed is covered by forest and the entire watershed contains a high ratio of land to water (Auckerman 2004). Despite holding 18 trillion gallons of water, the Chesapeake Bay is a shallow body of water which leaves it more susceptible to temperature fluctuations and wind than other deeper bodies of water (Ibid 2004). Overall the Bay has a mean depth of nine meters (Hagy et al. 2004). The Chesapeake Bay contains almost 6,000 square km of surface water and ranges from six km wide at the city of Annapolis to 48 km wide at the mouth of the Potomac River (Auckerman 2004).

The Chesapeake Bay has been decreasing notably in water quality and biological diversity throughout the twentieth century and is predicted to continue on this trend into the foreseeable future. Early Native American agriculture did not appear to have significant impacts on the water quality of the Bay as severe changes in environmental features were not noted until about 250-300 years ago – coinciding with European colonization of the Americas (Prasad et al. 2010). Changes in land use have contributed greatly to key changes in sediment and high levels of land-based pollution within the bay. These land use changes include the introduction and spread of new floral species, clearing and cultivating of land, and the increase of industrial areas and urbanization within the watershed (Auckerman 2004).

Years of land use change and development within the Chesapeake Bay Watershed resulted in signs of eutrophication and anoxia as early as the 1930's. Although smaller-scale research was carried out sporadically (Kemp et al. 2005), intensive study was not conducted until the 1970's followed by the production of the 1983 Chesapeake Bay Agreement by the Environmental Protection Agency (EPA) (McConnell 1995). This 1983 Agreement outlined three main areas of concern for the ecological welfare of the bay: nitrogen and phosphorus enrichment, toxic pollutants, and the decline of aquatic vegetation. A second Agreement in 1987 further outlined specific objectives and agreements between the six states within the watershed to improve the declining water quality and biodiversity within the Chesapeake Bay and the CBW. Most recently a third agreement was signed in 2000 to recommit businesses, organizations, and government throughout the CBW to working together to improve water quality and biodiversity.

Each of the three Chesapeake Bay Agreements encouraged state and local governments to repair the water quality and biodiversity of the Chesapeake Bay by improving the water quality and biodiversity of the streams within the watershed. The Clean Water Act of 1977 introduced different types of permitting to regulate ecosystems and reduce nutrient and sediments within stream water. These permits include National Pollutant Discharge Elimination System (NPDES), Municipal Separate Storm Sewer System (MS4), and Total Maximum Daily Load (TMDL) requirements throughout the CBW. Certain stream restoration techniques are implemented throughout the watershed to regulate stream water flowing into the bay; these techniques vary depending on land use and stream size. A few common stream restoration techniques include Legacy Sediment Removal (LSR), Natural Channel Design (NCD), Regenerative Stream Conveyance (RSC), and Threshold Channel Design (TCD). The purpose of this paper is to analyze some of these common restoration techniques used in streams throughout the watershed and determine which techniques are more suitable for increasing water quality and biodiversity in different locations of the CBW. From this analysis, a recommendation will be made for prioritizing stream restoration techniques within the Chesapeake Bay Watershed.

Drivers

As specified in the 1983 Chesapeake Bay Watershed Agreement, water quality in the bay had been decreasing significantly at the time of the Agreement. The CBW has a long history of publications and regulations for managing the quality of water in the bay, as water quality standards and criteria vary depending on the body of water. The EPA has assigned each body of water in the United States a designated use which indicates the intended function for the body of water (EPA 1998); the Code of Maryland Regulations (COMAR) in agreement with the EPA has assigned each body of water in Maryland a designated use. A designated use is sometimes referred to as the body of water's use class, but for the purpose of this paper the function of a body of water will be called the designated use. As seen in Table 1, the Chesapeake Bay has five designated uses due to the variety in habitat and functions found within such a large body of water (MDE n.d.). Based on the uses assigned to the Chesapeake Bay and the biological and chemical components of the water needed to maintain these uses, the EPA determined water quality criteria for the Chesapeake Bay (EPA 1994). Dissolved oxygen (DO), chlorophyll *a*, and water clarity are the criteria that must remain within recommended measures to preserve good water quality for the Chesapeake Bay.

Table 1. Designated Uses of the Chesapeake Bay as determined by the Maryland Department of the Environment and the Code of Maryland Regulations (COMAR 26.08.02.08). Reprinted from Maryland Department of Environment Frequently Asked Questions: Chesapeake Bay Water Quality Standards.

Designated Use	**What is Protected**	**Habitats and Locations**
1. Migratory Fish Spawning and Nursery	Migratory fish including striped bass, perch, shad, herring and sturgeon during the late winter/spring spawning and nursery season	In tidal freshwater to low-salinity habitats. This habitat zone is primarily found in the upper reaches of many Bay tidal rivers and creeks and the upper mainstem Chesapeake Bay.
2. Shallow-Water	Underwater bay grasses and the many fish and crab species that depend on this shallow-water habitat	Shallow waters provided by grass beds near the shoreline
3. Open-Water Fish and Shellfish	Water quality in the surface water habitats to protect diverse populations of sportfish, including striped bass, mackerel and seatrout, bait fish such as menhaden and silversides, as well as the shortnose sturgeon, and endangered species.	Species within tidal creeks, rivers, embayments and the mainstem Chesapeake Bay year-round
4. Deep-Water Seasonal Fish and Shellfish	The many bottom-feeding fish, crabs and oysters, and other important species such as the bay anchovy	Living resources inhabiting the deeper transitional water column and bottom habitats between the well-mixed surface waters and the very deep channels during the summer months. The deep-water designated use recognizes that low dissolved oxygen conditions prevail during the summer due to a water density gradient (pycnocline) formed by temperature and salinity that reduces re-oxygenation of waters below the upper portion of the gradient.
5. Deep-Channel Seasonal Refuge	Bottom sediment-dwelling worms and small clams that act as food for bottom-feeding fish and crabs in the very deep channel in summer	Deep-channel designated use recognizes that low dissolved oxygen conditions prevail in the deepest portions of this habitat zone and will naturally have very low to no oxygen during the summer.

The different designated uses have varying measurement requirements for each of the criteria. For example, COMAR 26.08.02.03-3 Section C.(8)(b.)(i-iii) states that the dissolved oxygen concentrations for the Chesapeake Bay should be: greater than or equal to six mg/L for a seven-day averaging period from February 1 through May 21; greater than or equal to five mg/L as an instantaneous minimum from February 1 through May 31; and applicable to the open-water fish and shellfish subcategory criteria from June 1 to January 31. Criteria can change depending on the time of year. Listing the different criteria for each of the Chesapeake Bay designated uses is beyond the scope of this paper. For a full explanation and description of the required criteria measurements for each of the designated uses please see COMAR 26.08.02.03-3.

The Chesapeake Bay is home to many living resources for both recreational and commercial use; the designated uses for the Bay were assigned to protect these resources. Water quality is lessened when biological or chemical components prevent the body of water from fulfilling its designated use. Several processes that are degrading the water quality of the Bay have been determined over time including: land-use changes generating pollution, increased sewage volume from growing populations, dam construction inhibiting fish migration, industrial waste, and overharvesting of aquatic organisms, among others (McConnell 1995). As seen in Figure 1, a primary driver in degradation of the Bay’s ecosystem and water quality is eutrophication caused by nutrient enrichment, excessive sedimentation, and toxic pollutants (EPA 1994, Kemp et al. 2005, Lung 1986).

The Chesapeake Bay receives nutrients from over 80 industrial discharge areas and between 230 and 240 municipal wastewater treatment plants as well as runoff from 49,000 square km of agricultural land (Carter 1983, Auckerman 2004). The nutrients that have been shown to contribute the most to eutrophication are nitrogen and phosphorus. Runoff, especially from agricultural locations, and other non-point sources are the major contributors of nitrogen (Carter 1983). The major contributors of phosphorous are discharges from municipalities, industrial areas, and other point sources (Ryberg et al. 2018, Lung 1986); phosphorous can also be found attached to sediment particles (Joshi et al 2015). It has been shown that the high nutrient levels in the bay result in excessive algal blooms.

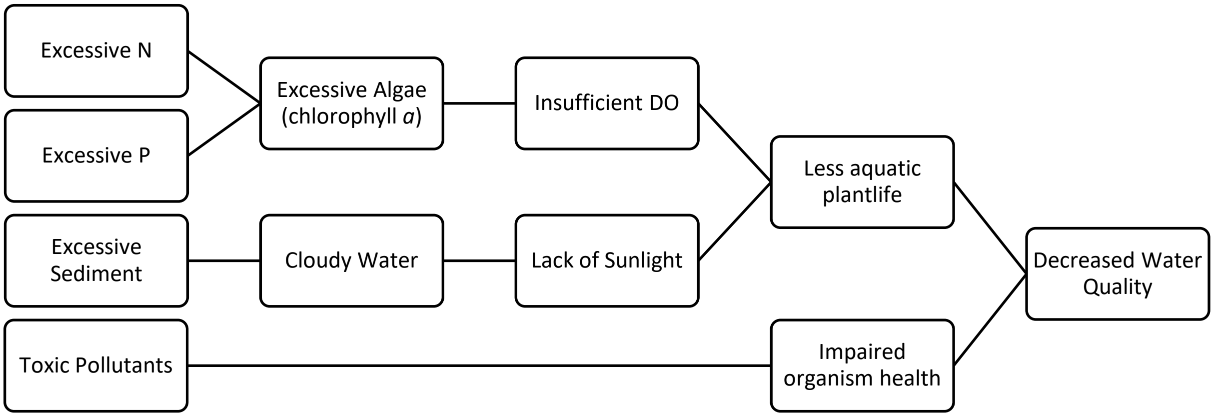


Figure 1. Flowchart summing how excessive nitrogen, excessive phosphorus, excessive sediment, and toxic pollutants reduce the water quality of the Chesapeake Bay. Original figure developed with information from CPB 1992, EPA 1994, Jones 2013, Joshi et al. 2015, Kemp et al. 2005, Lung 1986, McConnell 1995, and Werdell et al. 2009.

Not only can the algal blooms appear and smell unattractive, they also are the primary cause of low levels of dissolved oxygen and undesirable levels of chlorophyll *a* in the Bay. Dissolved oxygen – which is crucial to aquatic life – is being significantly reduced by the bacteria that decomposes dead algae (CBP 1992). This loss of oxygen can result in hypoxic or even anoxic conditions. Chlorophyll *a* is a measure of phytoplankton pigment and serves as an indicator of excessive nutrients in bodies of water (Werdell et al. 2009). Increased levels of chlorophyll *a* can contribute to loss of clarity and large quantities of decomposing phytoplankton can contribute to the decrease in DO within the bay (Jones 2013). A loss of aquatic flora due to reduction in DO by nutrient eutrophication negatively affects any organisms depending on the aquatic vegetation for food or shelter or other resource.

Sediment is particles of silt, clay, or sand pulled into the stream by overland flow or stream bank erosion. When too much sediment is brought into the bay from farther upstream in the watershed it can create cloudy and murky waters as well as contribute to the total phosphorus in the Bay. Excessive levels of sediment transportation can result in enough murkiness that crucial sunlight is not able to reach the aquatic vegetation below (CBP 2018). This is another instance where a loss of aquatic vegetation negatively affects the environment for fish, shellfish, or aquatic life that depend on the vegetation.

Section 307(a)1 of the CWA indicates that a list of toxic pollutants would be drawn up by a House of Representatives’ committee to determine which substances were considered toxic and should be removed from waters of the U.S. A list of 65 toxic pollutants was published soon after passage of the CWA and it has since been updated by the EPA (General Provisions 1981). Toxic pollutants in dangerous amounts negatively affect organisms on all tiers of the food chain and significantly reduce the biological and chemical quality of a body of water. Reducing the excessive amounts of nutrients, sediments, and toxic pollutants discharged from the CBW is crucial to the improvement of water quality in the Chesapeake Bay. For the purpose of this paper, the discussed techniques used to improve water quality of the CBW will focus on regulating excessive amounts of nutrients and sediments. Reduction and removal of toxic pollutants in the CBW is a related but separate topic as toxic pollutant levels in water are often altered by additional structures and techniques (Dushenkov et al. 1995).

Permitting

Specific permitting was introduced through The Clean Water Act of 1977 to regulate the reduction of nutrients and sediments within stream ecosystems. Local government bodies are encouraged to participate in improving water quality through pollutant control actions implemented by the Environmental Protection Agency. Nutrient and pollutant reduction in many places are often measured in “credits” with a credit being a specified amount of pollutants per period of time: pounds per day, month, year, etc. (Hall & Raffini 2005). A common method of reducing nutrients and pollution – especially from non-point sources – is stream restoration. Restoring streams that have degraded from erosion often returns the riparian environment to a functioning ecosystem where excessive sediments and nutrients are being dropped out of the water in specific areas of the channel. This allows riparian vegetation to absorb the nutrients and use them to the environment’s benefit, enriching soil and flora. For the purpose of managing stream restoration techniques and pollutant removal credits, NPDES, MS4, and TMDL permitting requirements were created.

National Pollutant Discharge Elimination System (NPDES) Permits were created to regulate pollutants and nutrients being moved through a point source. While remaining broadly defined over the three Chesapeake Bay Agreements, a point source is generally understood to indicate water flowing through a discernable conveyance within the Chesapeake Bay Watershed; i.e. industrial locations, pipes, and containers that eventually flow into the Bay. (EPA 2018a). The requirements found under a NPDES permit vary based on the structures discharging water, nutrients, or pollutants; however, this should not discourage owners of point source locations from obtaining a permit. Owners who fail to obtain a permit when one is required can be penalized on a federal, state, and agency level for not following regulations (Zorc et al. 1988).

Municipal Separate Storm Sewer System (MS4) is a permit implemented by the CWA to regulate water quality in certain conveyance systems. An MS4 is a system for transporting stormwater or runoff to a stream or riparian system, and is specifically not a sewer or any part of a sewage treatment area (Dunn & Burchmore 2007). When the EPA initially established permitting legislation for water treatment, stormwater systems were omitted. NPDES permitting was created to cover industrial discharge areas but permitting for municipal systems was necessary as they contribute significant nutrient discharge (EPA 2018c). There has been much legal dispute over the MS4 permits as the requirements do not always list concrete numeric values that must be met. Instead most permits encourage best management practices based on the particular system and surrounding land. Some bodies of government have disagreed with that method of permitting and several cases have been brought to court to try and amend this legislation for MS4 permits (Dunn & Burchmore 2007). While this history has caused MS4s to remain somewhat controversial, it has also allowed cities and municipalities to use innovative and creative measures to improve water quality. Whether this is considered a good or a bad thing, MS4s have proved crucial to storm water and runoff discharge in urban environments.

TMDL permitting is a specific numeric limit that determines the maximum pollutant and nutrient levels allowed to enter a body of water. Point sources are assigned a wasteload allocation (WLA) and non-point sources are assigned a load allocation (LA) (Murphy 2010). A margin of safety (MOS) must also be determined to take into consideration any uncertainty or unawareness of impacts to water quality (Mowrey 2000). From a general perspective, the TMDL is determined by combining the total WLA, total LA, and MOS for a particular body of water;

however, more than one TMDL can be assigned to a body of water based on the different nutrients or pollutants being discharged (EPA 2018b). It has been argued that TMDLs are especially important to water quality because they are often the determining factor for the issuing of and the severity of other permits. As such, the pollutant and nutrient limits must be calculated to consider current and future sources of water quality impacts (Murphy 2010). Table 2 gives an example of TMDL limits allocated for bodies of water flowing to the Chesapeake Bay from within the watershed. The EPA issued TMDL limits in annual numbers and allocated by stream segments within the watershed (EPA 2010). This table is retyped from the table that was issued in 2009 and shows how the existing Total Nitrogen (TN) compares to the proposed TMDL TN. Similar tables for TMDL of phosphorus and sediment have also been produced and compared to existing conditions. This document remains the current guide for Chesapeake Bay TMDL limits.

Table 2. Example of Total Maximum Daily Load annual allocations in lbs per year for total nitrogen in the Chesapeake Bay. Reprinted from EPA 2010.

Example of Chesapeake Bay TMDL Total Nitrogen (TN)						
Segment ID	**Jurisdiction**	**CB 303(d) Segment**	**TN WLA (lbs/yr)**	**TN LA (lbs/yr)**	**TN TMDL (lbs/yr)**	**TN 2009 Existing (lbs/yr)**
GUNOH	MD	Gunpower River	255,714	792,403	1,048,117	1,305,958
NORTF	PA	Northeast River	1,324	33,132	34,456	55,984

The various permits issued to bodies of water carrying excessive nutrients and pollutants to the Chesapeake Bay are often interdependent on each other. TMDL permits are oftentimes influenced by and issued with NPDES permits (EPA 2018b); MS4 permits can be issued to follow the limits determined by a TMDL permit, as well as being monitored through NPDES permit regulations (Dunn & Burchmore 2007). Permitting for nutrient and pollutant limits entering a body of water have proved crucial to the Chesapeake Bay Watershed due to the guidelines put in place for water quality maintenance and monitoring.

Stream Restoration

While the implementation of permit regulations helped establish goals and boundaries for nutrient and sediment reduction in the CBW, certain practices must be put into place to make sure these permit limits are being met. A popular but brief definition of restoration is: “establishing natural stability and proper function of rivers” (Rosgen 1997). For the purpose of this paper, restoration will indicate: “the manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions to a former or degraded aquatic resource” (Law et al. 2015). Stream restoration is yet another method in which local governments can receive TMDL credits for improving water quality within the Chesapeake Bay Watershed by reducing erosion (Hamlin 2011).

Stream restoration is still a developing practice; however, an early example of stream restoration exists as far back as 1871 when an order to repair a river polluted by discharge from wool factories was issued by the British Parliament (Royal Commission, 1871 as cited in Cockerill & Anderson 2013). In the 1940’s a project was carried out to remove organic debris and improve flood control along the Schuylkill River (Cockerill & Anderson 2013). Closer to the recent turn of the century, the practice of stream restoration became more popular as a method of improving game and fishing habitats (Hamlin 2011) and later on as a method of water quality and ecosystem improvement (Sudduth et al. 2007).

Stream channel morphology is a complex process in which a stream moves in response to sediment supply and a changing environment. Scour and fill caused by storm events results in movement or deposition of sediment, bed, and bank materials (Niezgoda & Johnson 2005). The scale of this movement is dependent on the stream channel velocity: higher stream velocity results in movement of larger particles. Incoming sediment supply from the surrounding watershed and the sediment transport capacity of the water are direct factors in long-term erosion and deposition of stream bed and bank materials (Ibid 2005). Many different schools of thought exist on channel morphology and evolution. For the purpose of this paper, Andrew Simon's channel evolution model will be used as the primary study for how a stream channel's physical characteristics change after a disturbance (Simon 1989 as cited in Doll 1999), see Figure 3 for an example of Simon's channel evolution process.

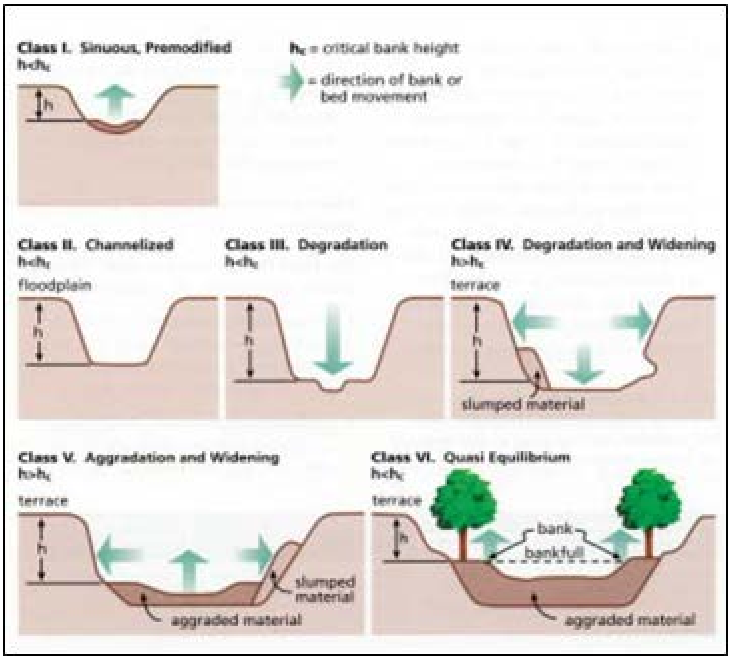


Figure 3. A. Simon's channel evolution model showing how channels degrade and aggregate in a cycle over time. This model applies generally to all pre-restoration projects. Reprinted from Doll 1999.

Many different techniques of stream restoration are applied throughout the United States. Four stream restoration practices that are used within the CBW among other and will be analyzed in this paper are: Legacy Sediment Removal (LSR), Natural Channel Design (NCD), Regenerative Stream Conveyance (RSC), and Threshold Channel Design (TCD). These different stream restoration techniques often use similar features, structures, and processes to reduce erosion and improve water quality.

Legacy Sediment Removal

Legacy sediment refers to a thick layer of fine sand, silt, and clay that has been established on top of historic gravel and sediment layers (Walter & Merritts 2008). It is generally believed that this thick layer of sediment in areas of the Eastern U.S. and especially the CBW was caused by extensive damming from the late 1600’s until the early 1900’s. Dams and their corresponding races were established to help power forges, furnaces, mining operations, and mills during the pioneer and colonial days of early America (Ibid 2008). Damming of a river resulted in sediment aggradation that oftentimes buried pre-settlement streams, wetlands, and valleys upstream of the dams. High-activity land use associated with settlement such as clearing, plowing, mining, etc. would cause large sediment movement and result in aggradation further downstream. Breaching or removal of these dams years later would result in the newly release water tearing through the accumulated sediments. This created heavily-incised stream channels as erosion cut down through the thick layer of fine sediment to the original valley bottom (James 2013).

Areas of legacy sediment build up are often recognizable by the stratigraphic profile of layers in a stream bank (Walter & Merritts 2008). As seen in Figure 4, The bottom layer is composed of bedrock or the original valley bottom; next is a layer of mixed gravel and quartz, usually indicative of long-term erosion in the pre-settlement valley as gravels and quartz were moved over time from hillslopes to lower elevations. On top of that is a dark layer of silt loam, indicative of buried wetland soils; this layer is often rich with preserved organic matter found throughout. Finally, the legacy sediments extend anywhere from one to five meters up from the silt loam, detailing how sediment was accumulated through the valley from upland erosion and damming practices (Ibid 2008). Some scientists in the field of stream restoration believe that removing this thick layer of legacy sediment can restore an incised channel back to the pre-European settlement (sometimes called ‘natural’) condition (Palmer 2009). Legacy sediment removal (LSR) follows the idea that by removing the accumulated layer of sediment that has been eroded to an incised channel, the stream can be restored to smaller, shallower, intertwining

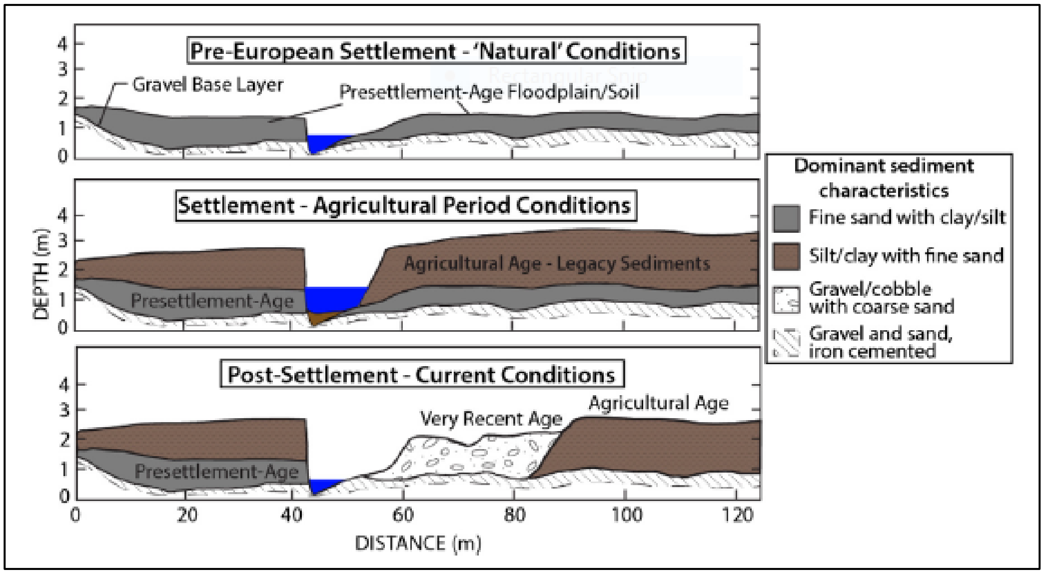


Figure 4. Evolution of valley conditions within the Eastern United States. A lack of legacy sediments can be observed in the pre-colonial period (top), the growth of legacy sediments during the agricultural area (middle), and the current incised channel and eroded legacy sediments (bottom). Reprinted from Donovan et al. 2015.

channels surrounded by wetlands (Walter & Merritts 2008). A shallower stream bank will allow for more floodplain connectivity; wetlands and flourishing riparian vegetation within the floodplain will help reduce erosion and higher stream velocity during storm events (Niezgoda & Johnson 2005) as well as reestablish a thriving riparian ecosystem.

Legacy sediments have been shown to hold considerable amounts of nutrients and sediments. Studies in southeast Pennsylvania show that legacy sediments make up a majority of suspended sediments found in the mouth of the Conestoga River (Donovan et al. 2015), a significant contributor to the Susquehanna River. The erosion of stream banks containing legacy sediments within the CBW contributes to the nutrients and sediments transported to and found within the Bay (Noe & Hupp 2009). In metropolitan areas with high square km of impervious surfaces and structures, removing several meters of sediment buildup to establish a meandering channel with floodplain connection is not always possible. This kind of stream restoration project seems to work best in areas that have minimal channel constraints and sufficient land for floodplain connection.

Rothenberger et al. (2017) conducted a risk assessment on the potential removal of several dams along the lower Bushkill Creek in eastern Pennsylvania. Three of these dams were located in urban areas of Easton, PA. As part of the risk assessment, the legacy sediments that had accumulated due to damming were sampled for contamination and heavy metals. In the event that the dams are cleared for removal, not only could significant geomorphic and ecological disturbance occur, but there is the possibility of the releasing of heavy metals and contaminated sediments into the surrounding ecosystem. This is a risk specific to legacy sediments located in urban and industrial areas (Rothenberger et al. 2017). In this type of instance where legacy sediments are to be removed along with a dam removal, it is recommended that full or partial sediment excavation be implemented to remove some if not the majority of the legacy sediments (Ibid 2017).

Natural Channel Design

Natural Channel Design (NCD) is a type of restoration that follows a stream classification and oftentimes a reference reach to return a stream to a stable system or type. Stream classification categorizes different types of streams based on physical characteristics and relationships with each other (Kasprak et al. 2016). There are several different schools of thought concerning stream classification (Ibid 2016). However, NCD is very commonly associated with the Rosgen Classification system (Sudduth et al. 2011) founded by David Rosgen. The Rosgen Classification involves four levels of detail in which at least nine major stream types are classified (Rosgen 1994). Different aspects of these nine stream types are defined, including: cross-sectional configuration, entrenchment ratios, slopes, meander width ratios, sinuosity, and channel bed material – among others. The level of detail and sheer amount of information available to students of the Rosgen Classification is enough to fill textbooks as this particular school of thought has been in practice for over 40 years (Rosgen 2006). The Natural Channel Design stream restoration practice analyzed in this paper will follow the Rosgen Classification “brand” of Natural Channel Design, but Rosgen’s stream classifications will not be explored in great detail. For further information about this school of stream classification, readers are encouraged to turn to several textbooks and papers written and published by David L. Rosgen.

Natural Channel Design is a method of stream restoration that uses a geomorphic approach to determine the cause of instability in a stream and the best practices to return the stream to a more stable state (Rosgen 2006). As part of a geomorphic approach, a reference reach or a similarly formed stream in a better state of stability are often used to determine what the final restored product should resemble (Sudduth et al. 2011). An important aspect of Natural Channel Design is the use of structures to stabilize the stream bed or banks, mitigate current erosion, and prevent future erosion. Geomorphic measurements of the currently-eroding system are used to determine appropriate material types for the restored system. Introducing a new material that is too small will be carried away downstream. A new material that is too large may slow water velocity to a detrimental rate or create blockages that incur damming and erosion (Rosgen 2003). Two common types of structures are log and rock structures (Doll 1999) with the idea that materials taken from the native environment are considered slightly more optimal than materials brought in from elsewhere (Gillilan et al. 2005).

The general idea for the use of natural material structures in an NCD stream restoration project are to control the grade of the stream and protect the banks (Doll 1999) as seen in Figure 5. Several types of structures are commonly used throughout NCD projects. Cross-

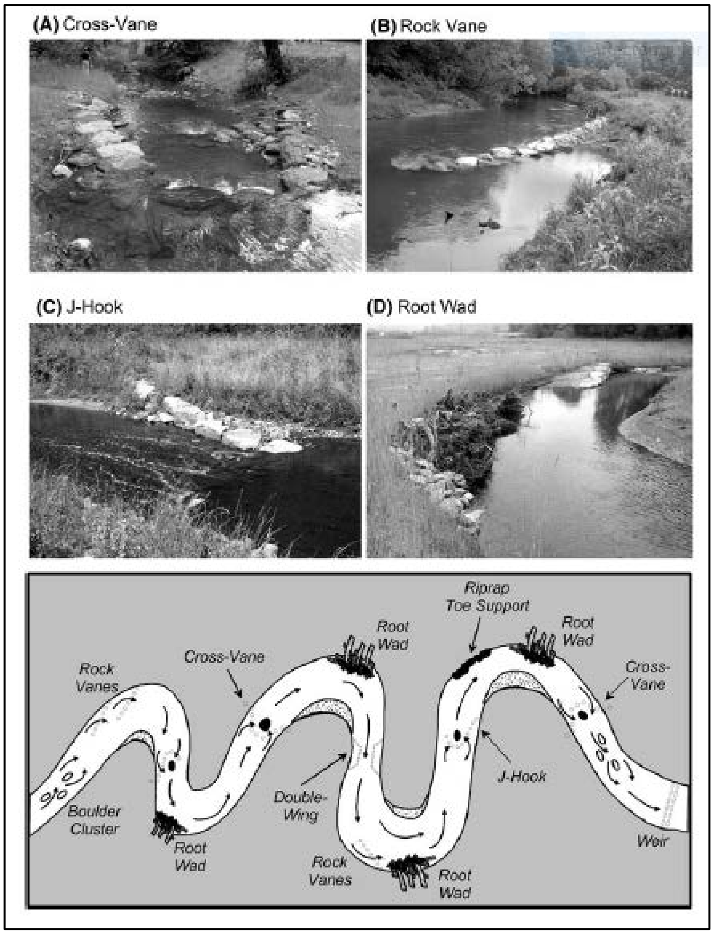


Figure 5. Field photos of stream stabilization structures commonly used in Natural Channel Design practices. Mentioned in this paper are cross-vanes, j-hook vanes, and rootwad structures. Diagram at the bottom shows an example of where these structures would be located along a newly restored stream. Reprinted from Miller & Kochel 2010.

vane structures are a series of boulders or logs placed across a stream to direct flow away from the banks and more towards the center of the stream (Rosgen 2001). J-hook vane structures are a curved series of boulders or logs placed around a pool to direct flow away from the outer bank and prevent erosion along a stream meander (Ibid 2001). Both of these vane structures are implemented for the purpose of preventing future bank erosion. Rootwads are large root balls set into a stream bank to help create aquatic habitat while a boulder revetment is a harder type of bank protection using large stone to prevent future erosion (Hamlin 2011).

A common critique of the NCD method is that building and implementing structures that were not initially in the stream is just another opportunity for erosion by poor structural integrity or improper structure selection (Simon et al. 2007). A study conducted by Hamlin (2011) on the durability of several stream restoration structures provides valuable insight on the lifespan of some of these structures. Cross vanes were determined to have a half-life of approximately 6.5 years and were seen to start decreasing in durability after about nine years. J-hook vane structures had a half-life of approximately 15.6 years. Rootwad installations had a half-life on average of about 4.5 years and boulder revetments had a half-life of approximately 24.3 years.

Durability problems were similar in the vane structures: Hamlin’s study discovered most of the vanes fell apart due to poor installation. Incorrect boulder sizes were picked or boulders were not fit together well and the structure washed out. The J-hook vane structures in particular are installed next to a pool and many of the failed structures were scoured or washed out into the pool. Rootwad structures are less of a protective structure and more meant to provide habitat and encourage biodiversity, because of this they are more prone to erosion and scour after the restoration has been finished. Boulder revetments on the other hand, had the longest half-life and seemed to experience the least amount of durability and integrity problems. This is most likely due to the simplicity of this type of structure, but they are not without their problems. Boulder revetments that failed had been undermined by bed and bank erosion or had been washed out due to improper boulder size (Hamlin 2011). Any process that involves structures is bound to experience structural integrity. Natural Channel Design is still a widely used and highly-lauded method of stream design and is a crucial practice of stream restoration within the Chesapeake Bay Watershed.

A study by Tullos et al. (2009) compared a restored reach of stream with a control reach of stream in rural, urban, and agricultural settings. The streams had been restored or reconfigured using NCD with the purpose of restoring channel geomorphology and habitat complexity in areas that had been constrained or simplified by development. The control reaches were located immediately upstream of the restored area, allowing the original or undisturbed characteristics of each reach to be measured for this study. Urban channels that underwent NCD had been previously altered by channelization, armoring, loss of floodplain access, and loss of habitat complexity. Rural channels that had been restored with NCD had previously been altered by cattle access and realignment. In the study Tullos and team analyzed and measured indicators of habitat quality and biodiversity and compared each restored reach with the corresponding control reach. Across the board, both urban and rural reaches that had been restored using NCD had certain measures of habitat complexity, stability, and biodiversity that did not differ from the control reaches. It was discovered, however, that both rural and urban control reaches had much higher percent vegetation cover than restored reaches – this is most likely due to the fact that riparian vegetation often has to be removed and replaced during a restoration project. In rural projects specifically, habitat complexity variables were significantly lower in restored reaches.

Urban reaches also had significantly lower habitat complexity variables except for variables associated with channel flow (Tullos et al. 2009).

Further analysis showed that rural reaches had a greater difference in taxonomic composition between control and restored reaches, while urban reaches did not have a significant difference. For rural control and restored reaches, the similarities in biodiversity factors and the differences in taxonomic factors indicate that taxonomic factors respond quicker to restoration in rural settings. On the other hand, urban control and restoration reaches had similar biodiversity factors and similar taxonomic factors. This indicates that certain factors do not respond more quickly to restoration in urban settings and biodiversity and taxonomic aspects are more likely to respond at the same rate in urban settings – most likely due to modifications and constraints caused by urbanization. From this study it could be argued that NCD works well in both rural and urban situations, but the system's response to the restoration will be different depending on the location (Tullos et al. 2009).

Regenerative Stream Conveyance

Regenerative Stream Conveyance (RSC) is a method of restoration using alternating pool and weir structures. RSC is also known as Regenerative Stormwater Conveyance for its use restoring channel incisions at stormwater outfalls (Thompson et al. 2018), or Regenerative Step Pool Storm Conveyance (SPSC) (Anne Arundel County 2012). An RSC system consists of a series of alternating shallow pools and riffle weirs, native riparian vegetation, and an underlaying media layer (Brown et al. 2010). The media layer is usually composed of a bed material that promotes infiltration, usually a sand and mulch matrix (Koryto et al. 2017; Thompson et al. 2018; Williams et al. 2016; Williams et al. 2017). This mix is porous, carbon rich, and has high hydrologic conductivity (Hayes 2016). Fungal and microbial communities within the pool feed off the carbon media as well as nutrients caught in the system. Soil micro- and macro-invertebrates feed off these communities which contributes to the porosity of the media – creating a self-improving feedback (Ibid 2016, Brown et al. 2010). Water collected in the RSC system percolates through the channel bed matrix and is dissipated into the environment instead of contributing to flows downstream while the carbon-rich media assists with filtering sediments and denitrification (Koryto et al. 2017).

Riffle weirs are created using appropriately sized boulders and are set at the downstream end of each pool to help control grade (Thompson et al. 2018). During relatively small storm events water is collected in the pools and infiltrated back into the groundwater table; during larger storm events the RSC system dissipates energy, preventing erosion in the form of further bed and bank degradation. The weirs help enforce shallow and slow movement of water which in turn allows for more water to seep into the channel bed media and disperse as groundwater (Burke & Dunn 2010). The layout of the riffle weirs and pools allows steep, incised channels to be restored to systems with gentler slopes (Thompson et al. 2018). Natural vegetation is also a crucial component to the RSC system. Native riparian and wetland vegetation planting in and around the pools and riffle weirs can assist in the uptake of nutrients, microbial attachment, contaminant adsorption, and long-term sequestration (Brown et al. 2010). Vegetation also contributes to biodiversity as well as the aesthetics of the RSC system (Hayes 2016). Woody debris including rootwads can be placed strategically in the pools to promote aquatic habitat and provide additional carbon substrate (Williams et al. 2016).

Due to their common use at stormwater outfalls, RSC structures have more restrictive guidelines than the previous restoration techniques. RSC's are often installed following the native drainage patterns to minimize construction and alterations within the surrounding drainage area (Anne Arundel County 2012). Appropriate structures and designs should be used to ensure against head-cut formation or weir and pool instability as tying into the surrounding system is also a crucial aspect of this technique (Ibid 2012). Three different types of RSC system can be constructed based on the design needs and constraints. A "classic" RSC consists of riffle weirs and pools as described above, see Figure 6 for a representation of this method. This is used most often to restore eroded stormwater outfalls as well as carry and infiltrate surface runoff (Hayes 2016). A "wetland seepage" RSC consists of the same structures as the classic, but also uses riffle grade controls to direct flow into the floodplain, starting and supplying riparian wetlands (Ibid 2016). An "instream riffle" RSC uses the same structures as the classic and includes riffle grade controls, but instead of encouraging wetland establishment, the riffle structure is used to establish floodplain connection with the stream channel (Ibid 2016).

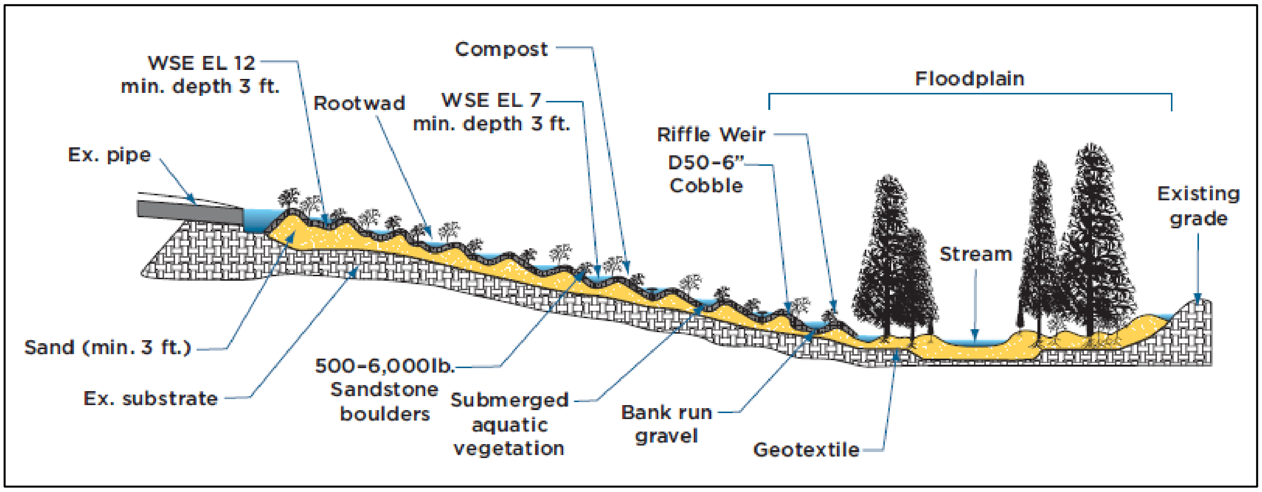


Figure 6. Example of a Regenerative Stormwater Conveyance system. Notice the variety in the depths and lengths of the pools as well as the vegetation growing in and around the structures. Reprinted from Burke & Dunne 2010.

Threshold Channel Design

Threshold channel design is a method of stream restoration that involves creating or restoring channels with very rigid boundaries. Also called artificial channel design, this type of restored channel is often composed of heavily armored or heavily stabilized stream banks and bed (Zhou & Chang 2018). This method of stream restoration is designed in such a way that a very small fraction of channel bed material will be at the threshold of movement based on the discharge, flow, and velocity of the water moving through the system (Shields et al. 2003). In this type of system either the flow of water is at or below the threshold of movement or the channel material is too coarse to be picked up and moved further downstream. Threshold channels are used in scenarios where movement of bed material is negligible and proposed channel boundaries are meant to be immobile, compared to other techniques of channel design where bed and bank material can be transported and dropped further downstream – contributing to the creation of stream features – and channel boundaries are allowed to change in response to the environment (USDA 2007).

According to the NRSC’s National Engineering Handbook (2007) there are four categories of threshold channel design: allowable velocity approach, allowable sheer stress approach, tractive power approach, and grass-lined channel approach. The allowable velocity approach is typically used with meandering channels lined with sand or earth. The proposed channel is designed so that the velocity of the water remains at or below the velocity that is required to move substantial sand or earth particles from the channel bed or banks. The allowable sheer stress approach is typically used with channels lined with rock, gravel, or cobble – slightly bigger material than the allowable velocity approach. Due to the size and shape of these larger materials an allowable sheer stress variable is used as the limit instead of an allowable velocity.

Sheer stress is a measurement that factors in the velocity of the waters as well as the hydraulic radius and boundary roughness of the bed and bank materials. The tractive power approach is used to design channels with cemented or hardened soils. The grass-lined channel approach is used in channels where permanent vegetation can be supported. Certain grasses must be used for these kinds of channels as specific grass types are better for concentrating bed flow or protecting steep slopes from erosion (USDA 2007). General guidelines for selecting the appropriate threshold channel design category can be found in Table 4. Alluvial channel design techniques refer to other less rigid channel designs such as NCD that allow channel and bed material changes in response to changes in the environment. Alluvial channel design is included in this table in contrast to the different threshold channel design techniques.

Table 4. General guidelines to help determine which category of threshold channel design to use based on the desired stream bed and bank material. Reprinted from Natural Resources Conservation Service (2007.)

Technique	**Significant sediment load and movable channel boundaries**	**Boundary material smaller than sand size**	**Boundary material larger than sand size**	**Boundary material does not act as discrete particles**	**No baseflow in channel. Climate can support permanent vegetation**
Allowable velocity		**X**			
Allowable sheer stress			**X**		
Tractive power				**X**	
Grass lined/tractive stress					**X**
Alluvial channel design techniques	**X**				

Nutrient and Sediment Removal

One of the over-arching goals of stream restoration is the removal of excessive nutrients and sediments from waters flowing into the Chesapeake Bay. Reducing eutrophication and turbidity results in a healthier ecosystem and thriving aquatic organisms within the bay. Studies have shown that nutrients and sediments are carried to streams more quickly via runoff and interflow – as opposed to groundwater flow – and larger streams with larger drainage areas can receive and carry more nutrients than streams of a smaller order (Craig et al. 2008). Dams and other structures that reduce water velocity as well as connected watersheds and floodplains have been shown to act as “hotspots” for nutrient removal in healthy systems (Ibid 2008). The stream restoration techniques discussed and analyzed within this paper have had varying degrees of success in removing or reducing excess nutrients and sediments from stream systems.

An LSR stream restoration project near Lancaster, PA was considered a success by the EPA (Hartranft et al. 2011). The project consisted of 3,000 linear feet of Big Spring Run located in West Lampeter Township, PA and required the removal of approximately 22,000 tons of legacy sediment containing more than 50,000 pounds of phosphorous. Riparian vegetation was replanted using seeds found within the silt loam layer buried underneath the legacy sediments. Floodplain reconnection and wetlands were established to help disperse nutrients and sediments. The EPA in collaboration with several universities estimated that the restored system prevented 100 tons of sediment and 230 pounds of phosphorous from entering downstream systems – including the Bay – each year (EPA 2017).

Stony Run, located in the northern area of Baltimore City, was a small urban NCD restoration project completed in 2007 (Burke & Dunn 2010). During the early expansion of the city of Baltimore, the watershed of Stony Run had slowly been altered as the surrounding area over time became over 30% impervious surface. This led to increased runoff transporting more nutrients and sediment to the stream, resulting in heavier flows and excessive nutrient and sediments being moved through the stream system. Due to the constraints present in urban stream restoration, an NCD method was determined to be the best option. Two thousand seven hundred linear feet of stream was restored and erosion reduced using cross-vane, j-hook, and imbricated riprap structures to protect the banks and reduce stream velocity (Ibid 2010). Pre- and post-restoration monitoring determined that average N (measured in milligrams per liter) was reduced from 3.11 mg/L upstream of the restoration to 2.81 mg/L downstream of the restoration. These numbers translate to a baseflow removal efficiency of 0.58 lbs/ft/yr, compared to the Chesapeake Bay Program Removal Efficiency standard of 0.02 lbs/ft/yr (Ibid 2010).

A stream restoration project carried out in Anne Arundel County, MD utilized the second type of RSC system (Burke & Dunn 2010) listed earlier in this paper. Wilelinor Stream was targeted as a degraded stream that contributed to excessive sediments and nutrients further downstream. A wetland seepage system was designed, utilizing RSC's to reduce water velocity as well as promote wetland establishment in the nearby floodplain. Approximately 1,300 linear feet of stream was restored with RSC structures; seepage reservoirs and off-line ponds were created nearby to collect water from higher storm events and help dissipate energy and the appropriate berms and bars were created to promote correct flow of water throughout the system (Ibid 2010). Data gathered during monitoring of the new site determined that in-stream nitrogen processing, sediment uptake, and water quality improvement were all occurring at significant rates – indicating the project was a success. The structural integrity of the restoration was confirmed when the RSC structure and the surrounding system survived a 100-year storm event (Ibid 2010).

In the early 1970's a large portion of the Ohio University campus – and the surrounding area of Athens, Ohio – was consistently flooded by the Hocking River. In an effort to establish flood control measures, an 8 km portion of the river near the campus was replaced with an artificial channel (Zhou & Chang 2018). While this helped reducing the flooding and any corresponding economic or structural problems associated with the flooding, many people were questioning the environmental impacts of the long artificial channel. Although threshold channels by definition cannot pull material from the stream bed, it is a common concern that nutrients and sediment from surface runoff will essentially be funneled down the artificial channel and contribute to eutrophication or sedimentation further downstream (NRCS 2007). Not many threshold channels have the ability to absorb nutrients back into the ecosystem, unlike streams with natural beds and banks. In a study conducted several decades later, it was determined that the surface erosion in areas upstream of the Hocking River were very similar to surface erosion in downstream areas; in addition, it was determined that the Hocking River watershed was contributing sediments in a ratio similar to nearby watersheds. This indicates that the artificial portion of the Hocking River was not accelerating the movement of sediments through the watershed any more that adjacent watersheds with natural stream channels (Zhou & Chang 2018).

Costs of Stream Restoration

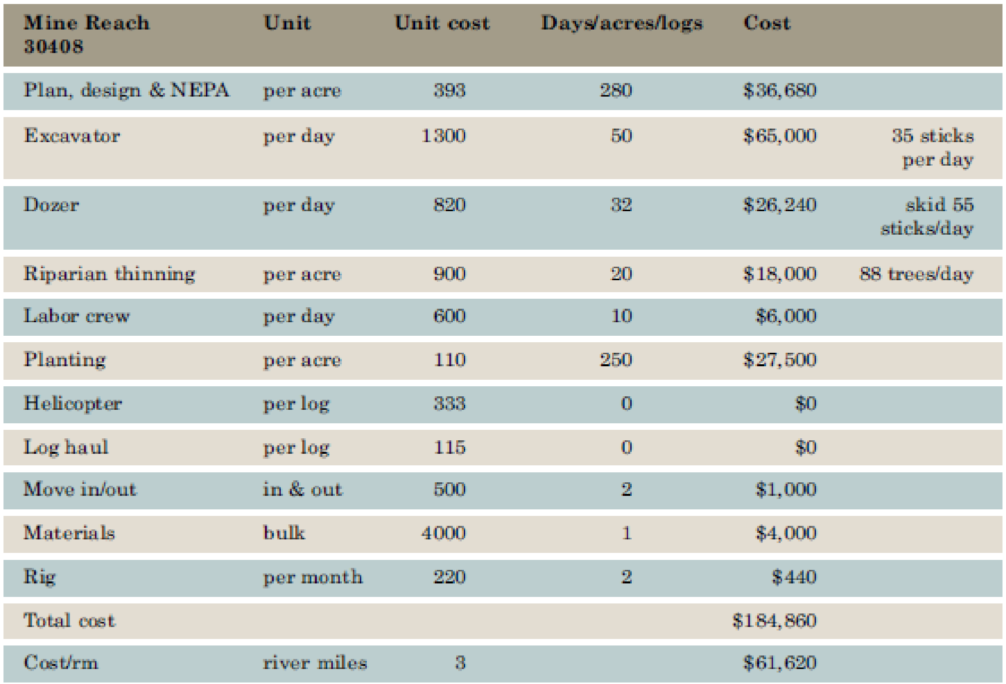
Stream restoration within the Chesapeake Bay Watershed is not an inexpensive endeavor. Project budgets vary greatly based on the stream restoration technique and the size of the project. Stream projects within the United States are quantified in linear feet (LF) and in order to be consistent with current projects, this paper will use LF as the unit for length of stream restoration projects. Stream restoration project costs are often divided into several categories that added together produce the total cost of the project. These cost reports are incredibly detailed for the contractors and designers of the project, but can be listed in varying detail as cost analysis for the general public. Some cost analyses list only costs for pre-construction, construction, post construction, and the total cost (Bonham & Stephenson 2004). Other reports divide the categories up further and include costs for survey, modeling, design, and permitting among other activities (LeBoon 2007). See Tables 5 and 6 for an example of a general cost analysis versus a more detailed cost analysis for stream restoration projects.

Table 5. An example of a generalized list of stream restoration costs. A cost for site acquisition is not necessary for projects that were donated or in cases where data could not be found. These costs and their corresponding projects were reprinted from Bonham & Stephenson 2004

Project Size	Pre-Construction Cost	Site Acquisition Cost	Construction Cost	Post Construction Cost	Total Cost
Small (<3,001 LF)	$26.14	$5.65	$68.35	$18.81	$118.96
Medium (3,001 - 10,000 LF)	$21.25	$4.21	$57.28	$10.01	$92.74
Large (> 10,000 LF)	$13.04	-	$45.82	$6.37	$65.22

Note: A cost for site acquisition is not necessary for projects that were donated or in cases where data could not be found.

Table 6. An example of a more detailed list of stream restoration costs. Line items include different construction and tools needed and materials are priced in bulk. Costs and their corresponding projects were reprinted from Bair 2004.



Mine Reach 30408	Unit	Unit cost	Days/acres/logs	Cost	
Plan, design & NEPA	per acre	393	280	$36,680	
Excavator	per day	1300	50	$65,000	35 sticks per day
Dozer	per day	820	32	$26,240	skid 55 sticks/day
Riparian thinning	per acre	900	20	$18,000	88 trees/day
Labor crew	per day	600	10	$6,000	
Planting	per acre	110	250	$27,500	
Helicopter	per log	333	0	$0	
Log haul	per log	115	0	$0	
Move in/out	in & out	500	2	$1,000	
Materials	bulk	4000	1	$4,000	
Rig	per month	220	2	$440	
Total cost				$184,860	
Cost/rm	river miles	3		$61,620	

There is no exact formula for quantifying and comparing stream restoration project costs especially across a wide range of states and geographies as the Chesapeake Bay Watershed. Excluding legacy sediment removal, several examples of cost per linear foot of stream restoration can be obtained for the different stream restoration techniques discussed in this paper. Costs for legacy sediment removal are often listed as a single number (EPA 2015). The three other types of stream restoration can be priced on materials used and given a cost per linear foot. Many states have guidelines in place to help determine pricing of a restoration structure or material; these can be used to quantify the overall cost of the project or cost/linear foot (MDE 2000, Virginia DCR 2004).

Prices can range for a multitude of reasons; however, it has been shown that urban stream restoration projects are often more expensive than projects in rural areas (Kenney et al. 2012). Projects in urban areas often have more constraints due to urban growth and impervious surfaces used in metropolitan areas. This results in more severe stream conditions (higher velocity, lack of sinuosity, etc.) which in turn result in higher degrees of degradation and erosion. In order to restore the stream to a functioning system, structures made with more expensive materials such as riprap and timber are required. Projects in rural areas often require less expensive materials and have the added benefit of using nearby natural materials – such as trees and salvaged stream bed material – as stream restoration structures (King et al. 1994).

Cost per linear foot is calculated based on the total project cost. This can vary from state to state within the CBW. It should be noted that all dollar amounts have been calculated for inflation from their original year and are shown in 2018 dollars in this paper. In a report on several stream restoration projects it was determined that projects with shorter lengths tend to have a higher cost per linear foot than longer stream projects (King et al. 1994). Another pattern found throughout stream project reports indicates that streams restoration in urban areas have a higher cost per linear foot than projects in rural areas. This appears to be confirmed in certain reports as three different projects under 500 linear feet utilizing NCD techniques in an urban area of Pennsylvania all cost over $300 per linear foot (LeBoon 2007). Stream restoration projects in Baltimore County average at $300/LF (EPA 2006) while stream restoration projects in Baltimore City average at closer to $800/LF (Kenney et al. 2012). Stream projects utilizing RSC techniques tend to run a little more expensive than NCD stream projects. Two similarly sized projects in Maryland help confirm this as the project utilizing step pool systems cost close to $300/LF while the NCD projects cost per linear foot was less than 10% of the first project's cost per linear foot (EPA 2006). This is most likely due to the fact that step pool systems require a large amount of expensive materials to be brought from off-site and natural channel designs can reuse materials from on-site. Despite lacking an exact formula to predict stream restoration costs it can be postulated that projects in urban areas requiring structural materials to be brought in will be more expensive per linear foot than rural projects that use local materials.

Discussion

Project reports on restorations utilizing Legacy Sediment Removal indicate that this method appears to work best in rural locations. The removal of significant amounts of sediment for the purpose of reverting the stream to a shallower and more meandering channel requires an area that can serve a system with ample floodplain connection. This type of restoration project is more likely to be found in more rural areas with less lateral constraints as opposed to confined urban areas. Removing large amounts of sediment prevents that sediment from ending up in the Chesapeake Bay and allows the stream channel to reconnect with the floodplain. Determining the cost of an LSR project is different compared to other restoration techniques, but it is ultimately a large price for the removal and disposal of significant amounts of sediment. From analysis carried out throughout this paper, it can be determined that Legacy Sediment Removal projects are most cost-efficient and increase water quality efficiently in rural locations (EPA 2015; Rothenberger et al. 2017; Walter & Merritts 2008).

The Natural Channel Design method of stream restoration is applicable to either landscape. While floodplain connection is not as necessary as the previous method, the ability to support a meandering channel is a necessity for a project using NCD. Structures are a well-known part of Natural Channel Design and while improper structure installation remains one of the largest critiques of this method, adding structures to improve channel and bed stabilization and habitat creation remains a crucial aspect. Bringing materials from off-site can drastically affect the cost of the project as opposed to reusing local materials. Projects carried out in rural locations have shown an increase in biodiversity after the restoration is complete compared to projects in urban locations. It can be determined that the Natural Channel Design method of stream restoration is extremely efficient in urban landscapes, but is most cost-efficient in rural landscapes where materials can be reused and biodiversity has a greater chance of improving (Hamlin 2011; Rosgen 2003; Rosgen 2006; Tullos et al. 2009).

Regenerative Stream Conveyance is a restoration method that also uses significant structures in its design. The pool and weir system utilized in this method is crucial to reducing water velocity and allowing water, sediments, and nutrients to settle and be infiltrated back into the ecosystem to increase biodiversity as opposed to continuing further downstream. Materials for this method can be reused from the altered landscape; due to the numerous pools and weirs created for these kinds of restorations it is more likely that materials will have to be purchased and brought from off-site resulting in a higher cost. Regenerative Stream Conveyance restoration projects do not always require room for meandering channels and while floodplain connection is optimal it is not necessary as the goal for this kind of project is to decrease the channel slope and water velocity. Due to the lack of these limitations, it can be determined that the RSC method can be used to improve water quality and biodiversity equally in urban and rural locations under specific site conditions (Anne Arundel County 2012; Hayes 2016; Thompson et al. 2018).

The restoration method of Threshold Channel Design is useful in very specific scenarios. The purpose of the TCD method is establish a stream with no lateral movement of the channel and minimal material transportation. The threshold of movement must be calculated for these channels and then the appropriate material chosen to line the channel bed and banks. Cost for TCD restoration projects vary based on the material needed to stabilize the channel but there is little chance for materials to be reused from the original stream as specific stone sizes or grass types are needed for these channels. From various studies it can be determined that TCD can be used in both urban and rural landscapes, the material used for the channel should be appropriate for the restoration project's surrounding ecosystem and purposes (USDA 2007; Shields et al. 2003).

Conclusion

Stream restoration is a field of study that has been used in modern environmental engineering for the greater part of a century, but is also a relatively young scientific practice with plenty of opportunity for development as techniques are tested and adjusted to produce the best results. While varying techniques of stream restoration exist and are implemented successfully, this paper compares and contrasts four specific techniques commonly used throughout the Chesapeake Bay Watershed. Location and channel constraints have shown to be a deciding factor with certain techniques such as Legacy Sediment Removal or Natural Channel Design requiring ample space for floodplain reconnection or wetland establishment. However, techniques do exist and are used in areas with constrained channels or minimal room for sinuosity. Threshold Channel Design has been shown to reduce erosion and flooding without accelerating the flow of nutrients and sediments that cause eutrophication further downstream.

Materials required can also greatly affect which method is selected as Regenerative Stream Conveyance and Natural Channel Design both significantly use stone and log structures and materials that are gathered and reused from on-site can help cost effectiveness of restoration projects. The different techniques analyzed in this paper produce varying results but research indicates that when the techniques are selected and installed appropriately, the surrounding ecosystem and by extension the Bay benefit. See Table 7 for a compilation of the analysis conducted in this paper on the four stream restoration techniques, their efficiency in urban and rural landscapes, nutrient and sediment reduction, and cost.

The development of the surrounding landscape, the changing of the stream’s ecosystem by human or natural interference, and the existing channel conditions help determine which method of stream restoration would produce the best results. This paper examined various examples and reports of different stream restoration projects across the six states within the Chesapeake Bay Watershed for the purpose of determining the most efficient system for increasing water quality and biodiversity. These analyses and recommendations are not concrete and further research can and should be continued on this topic, but based on the information gathered in this paper the prioritization seen in Table 7 has been shown to produce favorable results for stream restoration in the Chesapeake Bay Watershed.

Table 7. A summary of the analysis of four stream restoration techniques used within the Chesapeake Bay Watershed.

Summary Table of Analysis of Stream Restoration Techniques				
Restoration Method	**Urban Locations**	**Rural Locations**	**Nutrient & Sediment Removal**	**Cost Efficiency**
Legacy Sediment Removal	Less efficient due to lateral constraints	Most efficient, ample room for sediment removal and floodplain connections	Removes large quantities of nutrients and sediments with removal of legacy sediments	Removing and disposing of large quantities of nutrients and sediments is expensive
Natural Channel Design	Efficient, less likely to find ample room	Most efficient, rural restorations have shown a higher increase in biodiversity	Successfully reduces nutrients from continuing downstream and produces a higher baseflow removal efficiency than the current standard	Stone and log structures are more expensive if bought from off-site, but can cost less if reused from on-site
Regenerative Stream Conveyance	Improves biodiversity and water quality in urban locations	Improves biodiversity and water quality in rural locations	Extremely successful at nutrient reduction and water quality improvement	Requires expensive materials to be installed with less chance of recycling on-site materials
Threshold Channel Design	Very efficient due to minimal materials and footprint needed but does not greatly improve water quality	Very efficient due to minimal materials and footprint needed but does not greatly improve water quality	Does not remove nutrients and sediments from the system but also does not accelerate their movement through the system	Efficient due to few materials required but very expensive

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