Urban stream restoration: An evaluation of material processing and conveyance channels

Madeline Berg

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Urban Stream Restoration:
An Evaluation of Material Processing and Conveyance Channels

Madeline Berg

A thesis submitted to the Graduate Faculty of
JAMES MADISON UNIVERSITY

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Abstract

Stream restoration is gaining popularity in the Mid-Atlantic region to offset impacts from urbanization. Increased levels of impervious surfaces, decreased vegetation along banks, and changes in water flow patterns make urban stream ecosystems flashy and result in high erosion rates, increasing the amount of nutrients entering the Chesapeake Bay. Different restoration practices can play a large role in the amount of nutrients and organic matter leaving a stream and the amount of habitat that is present in-stream.

Due to the recent interest in stream restoration as a tool to help the health of the Chesapeake Bay, this study was undertaken to evaluate the in-stream effectiveness of two restoration practices: conveyance channels and material processing channels. Ten streams, five of each restoration practice, were evaluated in terms of organic retention and macroinvertebrates. The upper and lower reaches of each stream were sampled with transects to measure organic retention percent cover and sampled with two methods for macroinvertebrates.

Despite each site being evaluated only once during the summer of 2018, which was the highest rainfall on record in Maryland, trends were still apparent. Material processing channels had significantly higher organic retention compared to conveyance channels, as they had a larger average hydraulic radius and a greater presence of woody debris. Focusing on macroinvertebrate sampling methods, traditional kick-net sampling and habitube sampling collected similar richness. Abundance varied greatly, though habitubes collected higher average abundance compared to traditional sampling in conveyance channels.
Results from this study suggest that urban stream restoration practices can impact the amount of organic retention within streams as well as the ability to provide the best habitat for in-stream biota. When designing streams to reduce impacts to downstream waterbodies, material processing channels should be considered as they retain more organic matter and work to provide greater habitat potential, without an artificial substrate. Due to similar richness collections across all reaches, habitubes have the potential to be a valid future sampling technique. This or a similar study should be continued over multiple years through different seasons to see if the trends persist or get stronger as the site ages.
Introduction

Ecosystem restoration is best defined as the reestablishment of pre-disturbance functions, processes, and related chemical, physical, and biological links between aquatic and riparian ecosystems (Kauffman et al. 1997). Disturbances are usually caused by human activities and are most often through the means of urbanization or agriculture (Fischenich et al. 2000; Walter et al. 2008; Teels et al. 2006; Hassett et al. 2005). Re-creating an ecosystem to function exactly how it previously functioned is not possible. Instead, the process of restoration works to re-establish a general function, structure, and dynamic ecosystem that is self-sustaining (Kauffman et al. 1997). Thus, when conducting a restoration project, a holistic approach and watershed scale consideration is necessary. This ensures that all the natural and ecological processes are included within the ecosystem, since each system is different (Kauffman et al. 1997, Thompson et al. 2018, Violin et al. 2011). In order to successfully restore urban streams, the practice of urban stream ecology needs to broaden to include behavioral, social, and economic research, since humans dominate these environments (Walsh et al. 2005).

Urban Streams

Urban regions are continuously growing and changing, impacting freshwater ecosystems (Violin et al. 2011, Kaushal et al. 2012). Within the next two decades, at least 60 percent of the world’s population will live in cites, resulting in increased impervious surfaces, increased runoff and altered levels of organic matter and nutrients entering the streams, impacting reaches downstream. Low levels of impervious surfaces (around three percent), ten percent and above especially, can result in degradation of stream systems
Urbanization often increases water temperatures due to lack of canopy cover and increased impervious surface runoff. Most urban streams are hydrologically disconnected, impacting organic retention potential, especially in streams that are channelized or incised (Kaushal et al. 2012).

Urban stream syndrome describes the observed degradation of ecological characteristics of streams that are draining urban land. Urban streams have flashier hydrographs decreasing bank and bed stability, while often changing the channel morphology. This results in increased nutrient levels and contaminants, which together with increased velocity, reduce intolerant stream biota richness and increase tolerant taxa (Sudduth et al. 2006, Walsh et al. 2005). Flashy streams impact the amount of organic retention between storms, often creating “hot spots” (Kaushal et al. 2012). Urban streams have decreased base flow, reduced nutrient uptake due to disconnected riparian zones and streambeds, and an increase of suspended solids. The largest water source of urban streams is urban storm water runoff from drainage systems. These waters can often be impacted by sewer and sanitary systems, waste water plants, and legacy pollutants. The unstable hydrology consisting of frequent, short duration high peak floods, work to alter the channel, often resulting in incision and simplification of the stream channel (Violin et al. 2011). These urban streams play an important role due to their position in the landscape, making them vulnerable to impacts associated with land cover change (Walsh et al. 2005). Urban streams and storm water runoff is currently the fastest growing source of pollution to the Chesapeake Bay creating coastal hypoxia or “dead zones” (Kaushal et al. 2012). Restoring these streams and identifying the “hot spots” will help to reduce the pollutants entering the bay (Kaushal et al. 2012).
**Degraded Stream versus Healthy Stream**

Degraded streams have low to no base flow due to low groundwater tables and dehydrated soils. They often have restricted channel width, due to surrounding infrastructure, creating channel incision and erosion, transporting excessive sediment and nutrients downstream, or they have overly wide eroded channels due to increased flow through the stream. Nutrient pollution is the third largest source of water degradation in streams, according to the Environmental Protection Agency (Lammers et al. 2017). Degraded streams often have increased water temperature, impacting instream biota and are dominated by invasive or tolerant species, ultimately decreasing diversity. Restoration works to reverse these impacts to create a more functioning ecosystem. Healthy stream ecosystems have base flow, since they are connected to the groundwater supply. The input of woody debris works to dissipate energy and creates a dynamic equilibrium. They support diverse native flora on stable banks, due to the proper soil conditions, and support instream biota due to cooler water temperatures, higher oxygen levels, increased food and habitat sources, and the breakdown of instream nutrients (An 2018).

**Urban Stream Restoration**

Historically, urban stream potential was not realized as most urban streams were piped to protect urban populations from floods, disease, and so additional infrastructure (e.g., roads, homes) could be built (Walsh et al. 2005). Piped streams can increase the amount of organic matter and nutrients that eventually end up in stream channels, as all of the leaf matter and pollutants that are present along urban streets ends up getting washed into storm drains and is eventually scoured out of the pipe during high flow
events (Kaushal et al. 2012). Many restoration projects are working to open piped streams, stream daylighting, in order for the streams to provide ecological benefits to the environment (Walsh et al. 2005). This is challenging as practitioners have to engage surrounding communities to achieve understanding of the importance of restoration (Walsh et al. 2005).

A relationship between the physical features and the habitats in restored streams needs to be established in regard to biotic communities. These biotic communities are used as indicators of stream health. The relationships can then be used for designing, monitoring, and assessment purposes in future restoration projects (Doll et al. 2016). Small urban streams are important for the surrounding ecosystem to sustain the biotic, chemical, and physical integrity of waters, in order to receive full benefits to the ecosystem (Teels et al. 2006).

**Urban Stream Restoration History**

Recognizing the value streams could provide, the United States is moving towards reservation of floodplains, creating parks and open spaces, especially in urban locations, while avoiding channelization in order to preserve a more natural environment (Wolman 1967). When working with any stream, a combination of economics, aesthetics, and physical limitations need to be considered as streams vary from location to location. Urban locations have higher exposure to construction, which can produce over 100 thousand tons per square mile per year of sediment that then enters streams, more than agriculture creates (Wolman 1967). This increase in runoff interrupts the conditions of the watershed by changing the channel formation, increasing erosion and flooding rates, and impacting plant growth. Depending on the channel design the stream might convey
the sediment downstream into tidal water, possibly creating a state of eutrophication (Wolman 1967). Ecologists need to play a large role in the science of restoration so engineering based processes can shift to more ecological based processes that are more sustainable (Palmer 2008).

*Piped Urban Streams*

Stream daylighting is the process of removing streams from underground pipes and opening them to the air. This provides improved riparian habitat, water quality, and habitat for instream biota. Daylighted streams can also reduce flooding by storing water and not conveying it through pipes. Property values are increased if a stream is daylighted as the stream adds intrinsically valuable public open land to urban communities. Often daylighting streams is a cheaper option than designing and replacing a failed pipe. Daylighting allows neighborhoods to be linked to their historic streams, which makes them more connected to the site. Daylighting of streams has historically resulted in channelized streams, conveyance streams, or naturalized streams (material processing) (Strickland et al. 2018).

*Stream Restoration with Channelization*

In the 1970’s, stream channelization gained popularity as a way to promote urbanization along water systems. Some prefer channelization as they have low maintenance costs and rapid dispersal of storm drainage (Wolman 1967).
Channelization is considered a hard engineering practice, as it is the process of straightening streams that traditionally meander, resulting in increased water velocities (Figure 1) (Vought et al. 1994). Increased water velocities convey instream sediment downstream to the Chesapeake Bay, as there is no wood, vegetation, or other obstructions that exist to catch sediment and prevent it from flushing out of the system (Wohl et al. 2016; Bukaveckas 2007). An example of a channelized stream is Jones Falls in Baltimore County and Baltimore City, Maryland, the channel structure of this stream did not change over four years due to the increased water flow and decreased retention rates (Wolman 1967).

The previously mentioned increase in velocity results in exacerbated flooding downstream while increasing erosion at the ends of the concrete structures (Vought et al. 1994). The increase in velocity reduces the levels of organic matter that can be retained in the stream channel (Quinn et al. 2007). Channelization works to convey rainwater and snowmelt quickly, taking nutrients to the bay (Vought et al. 1994). Lastly, channelization often results in little to no habitat for fish and wildlife species. The lack of fish and wildlife is due to increased water velocities, poor water quality, reduced food sources, and the lack of natural habitat (Bukaveckas 2007; Wolman 2018).

Channelizing a stream is expensive, as large equipment is required to straighten a stream. Most water tables are lowered, forcing the subsurface flow to occur through drainage tiles (Vought et al. 1994). This prevents the water from contacting the riparian soil, which allows nutrients such as nitrogen to enter the stream at high levels (Vought et al. 1994).
Citizens often do not favor this approach as it provides poor habitat, is an expensive temporary structure, not aesthetically pleasing, and can result in increased flooding (Bukaveckas 2007). As channelization has few benefits compared to other practices, it is no longer a commonly used technique.

Stream Restoration with Conveyance Channels

Around the 1990’s conveyance channels (Figure 2), often constructed with rock structures, evolved from the previous practice of channelization to create a more ecological based restoration practice. These streams are often constructed by the process of natural channel design (Rosgen 1997; Yochum 2017). Natural channel design practices may not increase geomorphic complexity and residence time (McMillan et al. 2014, Violin et al. 2011).

This stream restoration practice promotes fish and wildlife habitat and provides areas for vegetative growth. The vegetative growth provides bank stabilization as well as nutrient retention due to the interstitial spaces available slowing the water flow (Bukaveckas 2007). These structures are developed to correct grade control, reduce bank and bed erosion, allow sediment transport, and provide in-stream biota habitat. They are visually appealing and maintain channel structure (width / depth ratio). Rock structures may dissipate energy but most commonly protect more erodible bank and bed materials from erosion associated with storm water runoff velocities and help withstand large floods. (Rosgen 2001).
Rock structures used in conveyance channels, often convey organic matter due to the flat surfaces having no way to decrease water flow and retain high levels of organic matter, especially during high flow events. This is a poor feature for stream restoration as other projects work to decrease the amount of organic matter ending up in the Chesapeake Bay. Conveyance restoration practices can result in erosion at the end of the restored reach due to an increase in near-bank velocity, shear stress, and stream power (Sudduth et al. 2006). This is potentially harmful for fish and macroinvertebrates as well as the success of the restoration at the site and in upstream and downstream locations (Rosgen 2001).

Conveyance channel restoration practices are expensive, as purchasing and transporting mined materials to site locations and rock placement requires large equipment. The use of heavy equipment can be detrimental to the stream’s surroundings, leading to tree removal, soil compaction, and increased pollution (Carah et al. 2014; McMillan et al. 2014).

**Stream Restoration with Material Processing Channels**

A relatively new approach for urban stream restoration in the Mid-Atlantic region is incorporating wood as the main instream structure, creating a restoration project that works to create floodplain reconnection and process in-stream material. This design approach works to increase residence time and geomorphic complexity by development of multi thread channel restoration using

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*Figure 3: A stream restored as a material processing channel. Photograph: Severn Riverkeeper Program.*
wood and rock structures (McMillan et al. 2014). Using wood in stream restoration is considered an ecological or soft engineering practice, in comparison to using concrete or large rock. Switching from hard engineering practices to ecologically based practices (Rosgen 2001) allows streams to increase or maintain ecosystem goods and services while protecting downstream and coastal ecosystems (Flores et al. 2017). Wood improves the hydro-morphological and ecological status of stream ecosystems, but variation occurs depending on stream size and hydrology (Kail et al. 2007). The use of wood results in increased stream stability and structural complexity, allowing floodplain reconnection within the stream ecosystem. There are positive effects on many in-stream biota species due to the use of wood, instream habitat complexity, and increased water tables. Wood results in increased macroinvertebrates, increased levels of organic matter retention, and more pools within the stream (Law et al. 2017). Organic habitats result in higher abundance and taxon richness of macroinvertebrates compared to inorganic habitats (Sudduth et al. 2006). In-stream wood provides food for in-stream biota, as well as providing habitat for their different life cycle stages (Piegay et al. 2005) and during high flow events (Sudduth et al. 2006).

Floodplain reconnection restoration projects are more successful if the wood structures mimic natural wood assemblages (Roni et al. 2015; Harvey et al. 2017). The use of multiple small wood structures upstream and downstream within the restored reach helps to prevent one structure from having all the water force, organic load, and habitat responsibility (Bureau of Reclamation et al. 2015; Kauffman et al. 1997). As stream restoration projects age, the structures collect woody debris allowing them to continuously build (Wellnitz et al. 2014), creating a longer lasting structure. This
provides sustainable habitat and benefits to the environment (Roni et al. 2015). Streams eventually become self-sustaining as re-vegetated stream banks continue to deliver wood to streams (Moore et al. 2017).

Material processing streams that are designed with wood structures are more cost effective and result in a more natural channel formation (Bolton 2014; Roni et al. 2015; Carah et al. 2014). Wood can potentially be found onsite, decreasing the amount of materials transported to the site. Decreased transportation results in less fuel consumption, air pollution, onsite damage, soil compaction, and habitat alteration (Abbe et al. 1997).

A concern for citizens and professionals is that wood used in-stream will decay quickly. In reality, wood that remains saturated decays slowly (Roni et al. 2015; Wohl 2017). Other factors that influence wood decay include temperature, species of tree, presence of oxygen, and dissolved nutrients that are present in the water. Biotic communities that impact the rates of decay include fungi, microbes, insects, and fish (Wohl 2016). Public science education is needed to help citizens understand the benefits using wood in material processing restoration projects to create floodplain reconnection and provide ecosystem benefits, in order for them to understand why this approach is necessary (Piegay et al. 2005).

**Restoration Approaches**

Common restoration approaches in the Mid–Atlantic region include: natural channel design and a variety of approaches developed to increase material processing and restoration of historic stream functions (e.g., base-flow channel design, Regenerative Stream Channel, and integrated stream and wetland design).
Natural channel design attempts to restore degraded streams to match the geomorphic form of a nearby reference reach. This is often problematic as they do not account for differences in watershed conditions. Most natural channel design streams focus on stability, instead of ecological improvement (Lammers et al. 2017).

On the other hand, Regenerative Stream Channel and other material processing practices are an approach to reestablish robust ecosystems. They are designed and built using a variety of techniques based on project conditions to create a stable stream. This is a relatively new approach so some of the benefits have not yet been seen, but recent research is starting to show trends and benefits in terms of nutrient retention (An 2018, Thompson et al. 2018). Most Regenerative Stream Channel streams are constructed from the bottom to the top within the stream channel, so the surrounding tree populations / riparian areas are not impacted to the same degree as other methods, reducing the tree removal numbers and soil compaction.

**Restoration Practices**

**Non-Construction**

Non-construction practices, also known as passive restoration, focus on letting the ecosystem correct itself without instream work. These projects take longer to establish, but often receive the same results as in-stream construction practices in terms of increased habitat. Non-construction practices include: Conservation Reserve Enhancement Program (CREP) or Conservation Reserve Program (CRP) and revegetating. CREP / CRP programs, implemented in most of the Mid - Atlantic region, work to create buffers, by planting trees along streams in agricultural areas (Teels et al. 2006). CREP / CRP offers financial incentives through the United States Department of
Agriculture to farmers who voluntarily restore streams or include buffers using CREP / CRP approved non-point source best management practices (Sweeney et al. 2004; Teels et al. 2006). The best management practice technique is intended to improve wildlife habitat and help the Chesapeake Bay’s regulated communities to meet the Total Maximum Daily Load requirements (Hoornbeek et al. 2013; Hassett et al. 2005).

Riparian buffers along streams provide many benefits which include stream shading, bank stabilization, increased habitat for fish and wildlife, reduced nutrient transport, and provide an energy source for the stream (Vought et al. 1994). Stream shading will reduce water temperatures during the summer, resulting in increased in-stream biota. Lower temperatures prevent vegetation from growing in the streams and indicates a healthier system. The vegetation roots stabilize the banks, resulting in less bank erosion (Vought et al. 1994). When vegetation is present, it helps to reduce the degrading effects that are caused by non-point sources of pollution.

Many benefits of riparian vegetation vary based on the scale. Local scale vegetation provides shade, wood and organic matter, and works to stabilize the banks (Teels et al. 1973). At a larger scale, vegetation influences the overall stream sediment and nutrient inputs, other energy sources, as well as temperature of the system and the flow regime (Teels et al. 1973). For urban streams, providing vegetation along the banks is not enough to correct the degraded ecosystem, but is often necessary to help the stream restoration project succeed (Walsh et al. 2005).

**Construction**

Construction practices, also known as active restoration, are often needed to complete a successful urban stream restoration project. Construction practices are
designed to reinforce / re-stabilize banks of a degraded stream. These practices can be destructive to the stream ecosystem and take years for the impacts to resolve, but are often the only way to restore a degraded urban stream (Hassett et al. 2005). Construction practices use rock, wood, beavers, or bioengineering to create in-stream structures that work to retain organic matter, improve water quality, decrease erosion rates, and improve wildlife and in-stream biota habitat (Wellnitz et al. 2014; Gerhard et al. 2000; Wohl et al. 2016). Construction practices are used in combination with riparian buffer plantings, as mentioned above.

**Rock Structures / Wood Structures**

Rock structures work to protect banks from erosion or potential failure and are often used for banks along public or private land (Li et al. 2002; Yochum 2017). The placement of rock is an important consideration as rock can result in reduced vegetation growth, reduced sediment retention, and less wood input into the stream (Li et al. 2002; Yochum 2017). These rock structures can potentially cause erosion and reduced hyporheic exchange, but can also provide habitat for certain species that need little ecosystem complexity (Li et al. 2002). One rock structure can impact the hydro-morphodynamics of the stream (Kang et al. 2015). Several structures create scour pools providing instream biota habitat (Wohl et al. 2016), and prevent the amount of bank erosion due to the deflection of water away from the banks.

On the other hand, wood structures are considered a softer and more ecologically based restoration technique. Wood structures often are not cabled down but are unbound and strategically placed. They also work to direct incoming high velocity water toward the center of the stream creating scour pools that provide habitat for in-stream biota while
decreasing bank erosion (Roni et al. 2015; Wohl et al. 2016). Wood results in slower water velocity and increased organic matter and nutrient retention, and is often used to create floodplain reconnection, and provide in-stream biota habitat (Craig et al. 2008; Roni et al. 2015).

**Beaver Dam Analogs / Beaver Dams**

Beavers, *Castor canadensis*, are termed ecosystem engineers as they have historically worked to create floodplain reconnection in many stream ecosystems with the use of their dams (Yochum 2017; Thompson 2016). The construction of dams within the stream channel results in increased deadwood, influencing the hydrology. The dams continue to catch other woody material that enters the stream channel as the dam ages, allowing it to grow (Weber et al. 2017). Beaver dams work to store surface and ground water flow, improve stream complexity, modify nutrient cycling and store sediments (decreasing the suspended sediment), increase biodiversity, increase recreational opportunities, and create a broader array of plant species creating a more stable bank.

In urban locations, beavers work to attenuate storm events and encourage overbank flow, to create secondary channels and provide a sink for nutrient rich sediments. As human populations grow, beaver ponds will work to retain all the extra sediment and nutrients that enter the stream in anthropogenic landscapes. Streams with more dams are more complex and less likely to fail and flood during high flow events. Beaver dams could be a great method to protect downstream ecosystems, like the Chesapeake Bay, from eutrophication in a cost-effective way (Puttock et al. 2017).

As a result of the benefits beavers create for stream ecosystems, Beaver Dam Analogs, a stream restoration design technique, has been developed to mimic the habitat
that they create (Castro 2017; Yochum 2017; Weber et al. 2017). Many believe that beavers could be the missing ingredient for stream restoration design (Law et al. 2017). Beavers have been used to restore multi-channel streams without the use of construction, but this technique takes a long time to establish. If floods occur and dams are removed, beavers often abandon the stream, jeopardizing the longtime condition of the site (Castro 2017). Beaver dam analogs work to fill the cross section of the stream and help to improve small channels by increasing sediment and organic retention. These structures often require historic or future presence of beavers and the site needs an open and sunny environment (Castro 2017).

Concerns about beavers in urban areas have been presented as they can have direct and indirect impacts on the built environment. Examples include beavers backwatering streams, blocking culverts, and flooding nearby roads. Urban populations are growing and human and wildlife interactions are inevitable, meaning that the movement towards non-lethal management needs to be considered. The benefits of using beavers for stream restoration could outweigh the risks. They provide the opportunity for cost effective, ecologically compatible, and successful restoration, even in urban streams, since they constantly respond to their environment. The risks and benefits of beavers for urban stream restoration should be considered, and if the benefits outweigh the risks then beavers should be considered for stream management (Castro 2017, Chapter 7).

**Bioengineered Structures**

Bioengineered structures refer to the combination of engineering practices with ecological practices in order to design, construct, and maintain a vegetative system. When used alone, bioengineered structures are a patch for the problem, which means they
need to be used in combination with other methods. The benefits of bioengineered structures are directly correlated to the amount of wood and roots that are present within the stream (Sudduth et al. 2006).

**Monitoring of Stream Restoration Projects**

Traditional monitoring of completed restoration projects is lacking, as most restoration projects are not evaluated in any form, which results in a paucity of data available to validate the success of a stream restoration project (Bernhardt et al. 2005, Rubin et al. 2017). This makes it difficult to assess if the site is functioning properly, and inform future projects (Moore et al. 2017, Rubin et al. 2017). Arrangements and investments need to be made in order to ensure maintenance is conducted and comprehensive monitoring is implemented (Hassett et al. 2005; Moore et al. 2017). There is also a lag time between restoration and recovery, so most monitoring occurs too soon to see the potential results (Violin et al. 2011). For maintenance and monitoring to occur, reliable funding and an agency responsible for the maintenance must be secured prior to restoration (Moore et al. 2017).

Information that has been collected from monitoring of completed restoration projects is often not readily available and often is not linked to project goals. Data that is available is considered “piecemealed”, since only portions of the data are available to others (Bernhardt et al. 2005, Rubin et al. 2017). Only about ten percent of completed restoration projects have available data from monitoring, varying by region (Bernhardt et al. 2005). In the Chesapeake Bay Watershed, many stream or river restoration projects have occurred costing over 400 million dollars since 1990 and only about five percent of the recorded projects indicated any monitoring was conducted (Hassett et al. 2005). If
restoration projects were designed with specific, realistic goals and were monitored based on the goals, it would help to reduce uncertainty and increase our knowledge of how stream restoration projects function (Lammers et al. 2017, Bond et al. 2003).

Documenting failures of restoration is just as important as documenting stream restoration success in order to inform practitioners and support design / construction improvement.

The type of restoration practice completed plays a role in the monitoring conducted. In the Chesapeake Bay watershed, floodplain reconnection projects were more likely to be monitored over storm water management and riparian management projects (Hassett et al. 2005). Most of the monitoring completed is focused on determining if the stream restoration project stays intact. This type of monitoring occurs anywhere from a month up to five years after the project is completed. Monitoring should be completed in small numbers so the projects will be evaluated well, instead of many projects being evaluated poorly (Rubin et al. 2017).

A good way to monitor stream restoration sites is with the BACI (Before - After - Control - Impact) monitoring plan that assesses the status and trends of biological and physical responses of stream restoration projects. Before refers to sampling sites prior to restoration. After refers to post restoration monitoring. Before and after monitoring allows the changes of the site to be seen. Even if differences can be seen, there is a chance that the variability is naturally high (Rubin et al. 2017). Control refers to a reference site; these sites are not identical to the stream being restored but are a nearby stream that is not impacted. Impact refers to the restoration site. Control and impact sites
allow the effects of restoration actions to be discerned from natural variability, stochastic events, and other trends (Smith et al. 1994).

**Metrics for Evaluating Stream Restoration Success**

*Benthic Macroinvertebrates*

Benthic macroinvertebrates are insects found in their immature forms that lack a backbone, live on the bottom of streams, and are visible without a microscope, making them an easy way to assess stream health (McDonald et al. 1991, Sallenave 2015). Benthic macroinvertebrates are commonly used to evaluate a stream's health in terms of water quality and are used as bio-indicators of restoration success (Palmer et al. 2005). That being said, macroinvertebrates presence or absence could be due to habitat stressors as well as water quality (Sallenave 2015). They are also impacted by land use, for example a high level of impervious surface in a watershed is often associated with decreased macroinvertebrate richness and tolerant taxa abundance increases. Macroinvertebrates take time to recover after being present in a degraded stream, even after restoration occurs, due to their relatively long-life cycle (McDonald et al. 1991).

Environmental Protection Agency as well as several other agencies have created protocols to assess macroinvertebrate populations. Macroinvertebrates are easy to collect, as they require minimal equipment, and they are present in even the small order streams (Sallenave 2015). Macroinvertebrates are traditionally collected using a D-frame kick net over a segment of the stream. Riffles, vegetation, and instream wood or other structures are often the most reliable places to sample for macroinvertebrates since they have low flow, and high levels of dissolved oxygen, habitat, and food sources all year long (McDonald et al. 1991, Wohl et al. 2016). Macroinvertebrates are divided into three
groups: pollution intolerant (1), wide tolerance range for water quality (2), and tolerant of water degradation (3). When the number of groups one and two decreases, group three often increases, due to poor water quality (McDonald et al. 1991).

Seasonality impacts which macroinvertebrates will be collected. Macroinvertebrates can be very difficult to identify to species level, especially depending on the life stage when they are collected (Sallenave 2015). The highest rates of macroinvertebrates are collected in autumn, due to the increased organic matter present in the streams (Westveer et al. 2018). As stream restoration projects age, the number of shredders, filter-feeders, and burrowers should increase. Macroinvertebrates are most often dispersed after restoration by water flow, which means they are impacted by the distance between new habitat and old habitat, as well as the presence of available habitat and dispersal capacity. There are still a lot of knowledge gaps in macroinvertebrate recolonization after stream restoration (Westveer et al. 2018).

Stream restoration results in increased structural heterogeneity creating habitats at different scales. This should provide habitat for a diverse macroinvertebrate community, often a goal of stream restoration projects. To achieve this goal, attention has to be paid to the practices that are used to prevent extreme disturbance to the stream system during construction (Spanhoff et al. 2007). Streams with a healthy macroinvertebrate community also provide a food source for many fish, which impacts the food web (Sallenave 2015).

There are several different functional feeding groups of macroinvertebrates: shredders, collectors, scrapers, filterers, and predators (Voshell 2003). The idea of different macroinvertebrates dominating an area of the stream based on the available food source was initiated by the River Continuum Concept (Vannote et al. 1979). This concept
stated that headwater streams are very influenced by riparian vegetation and as water systems became larger they are more influenced by material coming from upstream sources. Thus, the stream size causes a shift in what macroinvertebrates are present. Shredders are found on the bottom of the stream channel and eat coarse particulate organic matter that has fallen into the water (> 1 mm). They have mouth parts that allow them to rip and shred leaves as they feed. Collectors wander along the stream bottoms and scavenge for dead organisms and other food particles that are found in-between rocks and in pools (fine particulate organic matter). Scrapers shear algae from surfaces, such as rocks and woody debris. Filterers are filter feeders that swim through the water or sit sessile and filter out particles from the water that passes by in the current. Most of the vegetation that they eat are particles of leaves that were shredded earlier by shredders (fine particulate organic matter). Predators exist in larval and adult stages, and they often swim under the water or fly above the surface and collect prey (Voshell 2003 & Vannote et al. 1979).

Urban streams are reported to have disturbance tolerant taxa present, due to increased storm water runoff from roadways and poor water quality from the increased amounts of nutrients and toxins. This means that the richness of sensitive macroinvertebrates is low. Most often the shredder functional feeding group of macroinvertebrates are less abundant in urban streams, compared to rural streams. This is often due to the increased flow rates, especially during storm events, that results in decreased organic retention (Walsh et al. 2005).

Many restored streams are assessed by a benthic index of biotic integrity indices (BIBI), as well as richness, abundance, diversity, and composition of the
macroinvertebrates present to see if restoration was successful. Higher abundance and diversity of macroinvertebrates does not necessarily mean that the stream is functioning better after restoration. BIBI’s use the macroinvertebrates present to assess the water quality (Rubin et al. 2017). Some stream restoration projects work to increase the potential habitat as the primary goal and water quality improvement as a secondary goal. This means that the indices based on pollution sensitivity of macroinvertebrate taxa may not be the best way to assess if restoration projects are successful. Depending on the goal of restoration, for example to reduce erosion, BIBI’s could be warranted (Rubin et al. 2017).

**Artificial Substrate Sampling versus Traditional Sampling**

Artificial substrates are often used to sample streams either in place of other sampling techniques (e.g., kick net samples) or in combination with other methods. Artificial substrates are beneficial because they work to standardize the sampling area and reduce inter replicate variation of physical habitats between sites. This results in increased precision and power for the samples and works to eliminate cofounding effects before colonization (Rinella et al. 2005 & Erin Letovsky et al. 2012). Sampling different sites can be complicated by the availability or lack thereof of similar natural substrates in each site. Artificial sampling techniques are used as a way to standardize the substrate between sites, so comparisons can occur (Phillips et al. 2017). One downside to artificial substrates as a sampling technique is the extended incubation time before sample collection, creating an environment that would not ordinarily be in the stream channel (Letovsky et al. 2012). Most artificial substrates peak in diversity, in number of individuals, and in taxa after two to four weeks of being placed in the stream. High flow
events can impact the number of organisms collected in the artificial substrate samples (Roby et al. 1978).

One potential artificial substrate sampling technique is the use of habitubes (Figure 4), coconut fiber mesh bags containing coconut fiber mats, about 20 by 25 centimeters in size. Habitubes were created to mimic natural leaf packs and can be placed into the stream channel to colonize macroinvertebrates. Patrick Barber created habitubes in 2013 to help restored streams gain macroinvertebrate populations by transplanting the habitubes from a stream with a diverse macroinvertebrate community to a recently restored stream (Barber 2017). These have not been evaluated as potential macroinvertebrate sampling techniques, but were donated for evaluation as a potential sampling technique.

**Organic Retention**

Retention refers to a stream’s process of removing organic matter from transport, allowing the matter to be used by in-stream biota (Speaker et al. 1984). Retention provides a link between input and storage of organic matter. Higher retention potential occurs when increased obstacles are present (Speaker et al. 1984). Leaves are often retained at uniform rates, unless wood debris jams are present in the stream segment. The presence of wood debris jams results in higher retention rates and shorter travel distances before retention (Speaker et al. 1984; Quinn et al. 2007; Brookshire et al. 2003). Wood that spans the stream cross section eventually results in an increased channel width, side channel development, and the creation of pools, which help to accumulate organic matter.
Vegetation around the stream should enhance instream organic matter by increasing the input of instream wood. Although vegetation is important in organic retention, detritus and substrate of the bank and bed also play a large role (Quinn et al. 2007).

Factors that impact organic retention include the size and depth of the stream, in-stream velocity, number of storms, and abundance of retention structures (Webster et al. 1994). Larger streams with a higher velocity often have an increased probability of transporting a particle further (Brookshire 2003). Practices such as logging have traditionally resulted in less in-stream wood and lower retention rates. Disturbances, such as storms, can increase the amount of wood in streams and increase retention (Webster et al. 1994).

The stream placement relative to urban locations can impact the amount of organic retention that occurs. Streams that come from storm drain runoff pipes often have leaves and other debris collected from trees along roads washed into the channel. This results in a larger amount of organic matter than can be retained within the stream channel. When evaluating stream restoration projects, the origination of organic matter, either catchment sources or riparian sources, should be considered (Walsh et al. 2005).

**Vegetation**

Dense vegetation along the stream bank is a reliable indicator of a healthy stream. Roots from the vegetation help to bind soil together, reducing erosion and increasing bank stability (Violin et al. 2011). Vegetation along the bank helps to increase bank and floodplain flow resistance, which results in reduced velocities near the bank and any erosive material. Larger vegetation helps provide shade to the stream. This shade decreases stream temperatures, decreases solar radiation, and provides cover for hiding
opportunities (Palmer et al. 2011). Vegetation along stream banks provides leaves, and other organic matter, creating food inputs for macroinvertebrates (Allan et al. 2003). Lastly, vegetation helps to induce sediment deposition to support stabilizing fluvial processes (Kui et al. 2016). Eventually the vegetation will be able to provide sources of in-stream wood (Roni et al. 2015).

Objectives

The first objective of this study was to compare organic retention between streams restored as material processing channels and conveyance channels in the upper and lower reaches of the restoration project.

Hypothesis: Streams restored as material processing channels would have increased organic retention over conveyance channels because the use of wood and other instream structures working to retain organic matter and continuing to grow over time.

Material processing restored channels tend to have increased large woody debris and channel width that works to slow the flow of water by increasing the surface area thus increasing the ability of the stream to retain organic matter in the stream channel, especially during high flow events. Conveyance restored channels work to facilitate the flow of water out of urban locations quickly, while reducing bed and bank erosion within the project boundaries but often reduces the amount of organic retention.

The second objective of this study was to compare material processing channels and conveyance channels by observing macroinvertebrate richness, abundance, and diversity in the upper and lower reaches of the restoration project.

Hypothesis: Streams restored as material processing channels would have an increased richness, abundance, and diversity of macroinvertebrates over conveyance channels
because the use of wood and other instream structures providing a greater diversity of physical and hydraulic habitats as well as food sources.

The increased stream channel complexity and organic retention in material processing restored channels should work to provide more habitat and food sources for in-stream biota. Meanwhile, conveyance restored channels often have faster flowing water, and less in-stream complexity reducing the amount of organic retention as well as often providing poor biotic habitat.

A secondary objective of this study was to compare traditional macroinvertebrate sampling methods to habitube sampling in the upper and lower reaches of restored channels (material processing channels and conveyance channels) to evaluate habitubes as a potential sampling technique in the future.

Hypothesis: Habitubes would provide a representative sample of the macroinvertebrates in the stream compared to traditional sampling because they were placed in the stream for about a month allowing a community to develop prior to collection.

Artificial substrates have an extended duration compared to traditional sampling methods and potentially provide a habitat that would not normally be in the stream channel. Comparing habitube samples to traditional samples in each stream allows a comparison of the two methods to see if they sample similarly or not. Looking at the different families that are collected is another way to evaluate them. It is assumed that if both sampling methods collect similar richness and abundance between each site and across all sites that they have the potential to be a sampling technique in the future.
Methods

Study Streams

To allow for an evaluation of two stream restoration practices, ten field sites in urban locations of Maryland and Washington, D.C. within the Chesapeake Bay watershed (Chesapeake Bay Program) and within the Mid-Atlantic region (National Wildlife Federation), were investigated (Figure 5). Five of the sites were material processing restored channels and five were conveyance restored channels.

The Mid-Atlantic region was selected for this study due to the impact the streams and stream restoration projects have on the Chesapeake Bay. As previously mentioned, the Chesapeake Bay is in a state of eutrophication, which emphasizes the importance of stream restoration practices to implement designs to increase nutrient and organic matter retention and create habitat for in-stream biota. Material processing channel and conveyance channel site locations were selected based on considerations of
independent variables including the age of the stream restoration, length of restored reach, physiographic province, percent of impervious area of the watershed, upstream reach, and drainage area of the watershed. All sites had to have at least 10% impervious area, to be considered urban streams, less than 10 years since construction so they were all relatively recent, at least 0.3 km long, and within the piedmont and coastal plain physiographic regions. Sites were originally to be selected based on having an upstream unrestored reach, this however was difficult to obtain in the urban locations, so many of the sites had an upstream reach that was located within a pipe. Drainage areas were restricted as much as possible to reduce variation, but other variables had increased focus. This allowed variation between the independent variables to be minimized so the focus was on testing the dependent variables, the restoration practices. Ten sites were selected so fewer projects could be evaluated well, instead of many projects evaluated poorly (Rubin et al. 2017). Six of the study streams were located in the piedmont physiographic province and four in the coastal plain physiographic province (Figure 6).
Figure 6: Physiographic provinces and site locations within Maryland and Washington, D.C.
All of the study streams were located in urban environments, surrounded by streets and houses and not by farm land (Table 1). The percent impervious ranged between 10 - 76% (Table 1), as some of the channels were more central to Washington, DC or Annapolis, MD than others (Figure 6). The material processing restored channels were Linnean Park, Davis Branch, Hawkins Cove, Spa Creek, and Alger Park. The conveyance restored channels were Jones Falls, Muddy Creek BGE, Brampton Hills, Moore’s Branch, and Plumtree Run. The order of the sites listed in this document is based on sampling dates within each restoration practice.

Table 1: General site characteristics for all ten sites, which helped in the selection of sites.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Restoration Practice</th>
<th>Year Restored</th>
<th>Physiographic Province</th>
<th>Upstream From Pipe?</th>
<th>Length (km)</th>
<th>Percent Impervious Surface</th>
<th>Drainage Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linnean Park</td>
<td>Material Processing</td>
<td>2015</td>
<td>piedmont</td>
<td>yes</td>
<td>0.26</td>
<td>34</td>
<td>0.26</td>
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<td>Davis Branch</td>
<td>Material Processing</td>
<td>2016</td>
<td>piedmont</td>
<td>yes</td>
<td>0.67</td>
<td>27</td>
<td>2.08</td>
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<tr>
<td>Hawkins Cove</td>
<td>Material Processing</td>
<td>2018</td>
<td>coastal plain</td>
<td>yes</td>
<td>0.49</td>
<td>47</td>
<td>0.31</td>
</tr>
<tr>
<td>Spa Creek</td>
<td>Material Processing</td>
<td>2017</td>
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<td>yes</td>
<td>1.52</td>
<td>76</td>
<td>1.85</td>
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<td>Alger Park</td>
<td>Material Processing</td>
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<td>yes</td>
<td>0.48</td>
<td>32</td>
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<tr>
<td>Jones Falls</td>
<td>Conveyance</td>
<td>2017</td>
<td>piedmont</td>
<td>no</td>
<td>0.24</td>
<td>18</td>
<td>59</td>
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<tr>
<td>Muddy Creek BGE</td>
<td>Conveyance</td>
<td>2016</td>
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<td>Moore’s Branch</td>
<td>Conveyance</td>
<td>2011</td>
<td>piedmont</td>
<td>no</td>
<td>0.32</td>
<td>34</td>
<td>2.38</td>
</tr>
<tr>
<td>Plumtree Run</td>
<td>Conveyance</td>
<td>2017</td>
<td>piedmont</td>
<td>yes</td>
<td>0.38</td>
<td>57</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Site Descriptions

Material Processing Channels

1. Linnean Park

Linnean Park is located in Washington, D.C. within the piedmont physiographic province and was restored in 2015. The length of the restored stream reach is 259 meters (850 LF) and runs from an upstream storm water drain pipe to a downstream pipe (Figure 7). The drainage area of the site is 0.26 km$^2$, and the stream is surrounded by 34% impervious area (Linnean Park Design Report). No monitoring has occurred post restoration.

![Image of Linnean Park](image)

**Figure 7:** The left shows the upper reach, the middle shows the lower reach, and the right shows the pipe that the stream goes flows into at the end of the reach.

This project was designed by Biohabitats, Inc. working closely with the contractor Underwood and Associates. The District Department of the Environment provided the funding and initiation of the project. Prior to restoration, this was a highly degraded urban stream that had been heavily eroded resulting in exposure of sanitary sewer lines. This stream provided poor habitat to in-stream and out of stream biota, due to poor water
quality and excessive sediment as well as an understory of invasive species. This stream was restored using the Regenerative Stream Water Conveyance method, which works to reconnect the stream with its floodplain and allows storm water to support surface and hyporheic flows through surface storage and infiltration of storm water runoff. While this site was being constructed, there were minimal disturbances to the surrounding trees, so cover would be present after project completion, increasing the organic retention potential and helping to keep the water from direct sunlight. This restoration project created a public park for the surrounding neighborhood, as well as providing habitat and cleaner water.

2. Davis Branch

Davis Branch is located in Woodstock, MD within the piedmont physiographic province and was restored in 2016. The restored stream reach is 671 meters (2,200 LF) and runs from an upstream reach through a pipe to a downstream unrestored reach (Figure 8). The drainage area for this site is 2.08 km², and the stream is surrounded by 27% impervious area (Davis Branch Design Report). No monitoring has occurred since restoration completion; however, there was some pre-restoration monitoring. After construction completion, beavers moved in and built several dams in the upper reach of the stream, down from the bridge.
This project was designed by Biohabitats, Inc. and was constructed by Ecotone, Inc. Davis Branch is located next to the Howard County Nature Conservancy, but is in a rapidly developing watershed, receiving water from surrounding developments and fields. Prior to restoration, this site was severely eroded by unsustainable land management practices and manipulation of upstream hydrology. Restoration worked to support water quality improvement under the NPDES MS4 permit. The design of this project was to create floodplain reconnection, providing habitat for terrestrial and aquatic organisms, as well as enhancing the diversity of plants. Limited tree cover exists at this site after construction as the trees that were untouched during construction have been cut down by beavers, leaving only the young planted trees behind. The proximity of Davis Branch to the Nature Conservancy allows for education and outreach opportunities.

3. Hawkins Cove

Hawkins Cove is located in Annapolis, MD within the coastal plain (fall zone region) physiographic province and was restored in 2018. The restored stream reach is 488 meters (1,600 LF) and runs from an upstream pipe to downstream tidal waters.
(Figure 9). The drainage area is 0.31 km², and the stream is surrounded by 47% impervious area (Hawkins Cove Design Report and Streamstats respectively). No monitoring has occurred since restoration completion. There was macroinvertebrate sampling conducted in the Spring of 2017, prior to restoration.

Hawkins Cove was designed by Biohabitats, Inc. and was constructed by Meadville Land Service, Inc. Urbanization adjacent to the stream resulted in increased nutrients, decreased bank stability, and an understory of invasive species prior to restoration. Thus, the goals of restoration were to reduce nutrients and pollutants entering the Chesapeake Bay by connecting the stream to its floodplain and stabilizing the stream banks while protecting existing infrastructure and trees. As a result, dense tree cover exists, increasing the organic retention potential, and helping to keep the water from direct sunlight.
4. Spa Creek

Spa Creek is located in Annapolis, MD within the coastal plain (fall zone region) physiographic province and was restored in 2017. The length of the restored stream reach is 1,524 meters (5,000 LF) and runs from an upstream pipe to downstream tidal waters (Figure 10). The middle of this restoration project has beaver dam analogs working to create a wetland environment. This was not evaluated, as it was outside of the upper and lower 80 meter reaches. The drainage area is 1.85 km², and the stream reach is surrounded by 76% impervious area (Spa Creek Design Report and Streamstats respectively). No monitoring has occurred since restoration completion.

Figure 10: Left shows the upper reach and the right shows the downstream reach of the restoration project.

This project was designed by Biohabitats, Inc. and was constructed by Meadville Land Service, Inc. Prior to restoration, urbanization of surrounding locations resulted in erosion of the banks and increased pollutants and sediment entering downstream tidal waters, the Chesapeake Bay. The upper reach had been previously lined with gabion baskets resulting in erosion at the end of the structures. Thus, restoration was conducted to help the Chesapeake Bay community meet its pollution reduction goals. The goal of this restoration project was to raise the channel bed and reconnect the stream with its
floodplain. Tree cover exists at this site, increasing the organic retention potential, and helping to keep the water from direct sunlight. The upper reach had fewer trees along the stream (more spaced out) than the lower reach, due to the presence of increased infrastructure.

5. Alger Park

Alger Park is located in Washington, DC within the coastal plain physiographic province and was restored in 2015. The length of the restored stream reach is 476 meters (1,560 LF) and runs from an upstream pipe to a downstream drain allowing the stream to enter another pipe to go under the road (Figure 11). The drainage area is 0.13 km², and the stream is surrounded by 32% impervious area within a 0.03 km² park (Alger Park Design Report). Since restoration has been completed, post-restoration monitoring, to see if the project goals were met, has occurred. Prior to restoration, one year of pre-restoration monitoring occurred.

![Figure 11: Left shows the stream reach from the top to the bottom, the middle shows the lower reach, the right shows the drain at the lower reach that leads the stream back into a pipe.](image)

This project was designed by Biohabitats, Inc. and LimnoTech for District Department of the Environment and was constructed by Environmental Quality
Resources. The goals of this project were to provide habitat, increase bank / bed stability, and improve water quality of an eroded stream gully, through Regenerative Stream Channel restoration. The project was designed to create floodplain reconnection and to restore the channel bed to provide a reconnection with geomorphic surfaces, that were deeply eroded prior to restoration. This allows base flow to persist through summer months, helping aquatic biota populations. The more consistent water flow will work to keep a strong native plant community and keep invasive plants from taking over. Tree cover exists at this site, increasing the organic retention potential and helping to keep the water from direct sunlight. This stream is located near a very popular neighborhood park and is fed through groundwater seeps, overland flow, and piped storm water discharge.

Conveyance Channels

6. Jones Falls

Jones Falls is located in Baltimore County, MD within the piedmont physiographic province and was restored in 2017. The length of the restored stream reach is 243 meters (800 LF) and runs from an upstream unrestored reach to a small downstream channelized reach. The drainage area is 59 km², and the stream reach is surrounded by 18% impervious area (Streamstats and GIS). No monitoring has occurred post-restoration.
This project was designed by Brightwater, Inc. and was constructed by Environmental Quality Resources. Jones Falls was channelized over 30 years ago to prevent flooding (remnants seen in Figure 12). The channelized stretch was disrupting brown trout (Salmo trutta) in other stretches of the Jones Falls watershed, resulting in the restoration project goals of removing a majority of the concrete, allowing fish passage, and preventing pollutants and sediment from passing downstream. This was hoped to be a prototype for other concrete and pavement removal projects throughout urban areas. Due to the previous channelization, little tree cover exists, but there is a grass buffer that could reduce the amount of organic matter that can enter the stream, within the restored reach. This could also result in increased water temperatures, especially during summer months.
7. Muddy Creek BGE

Muddy Creek BGE is located in Anne Arundel County, MD within the coastal plain physiographic province and was restored in 2016. The length of the restored stream reach is 366 meters (1,200 LF) and runs from an upstream unrestored reach to a downstream unrestored reach (Figure 13). The drainage area is 1.56 km², and the stream reach is surrounded by 10% impervious area (Muddy Creek Design Report and Streamstats respectively). Since restoration has been completed there has not been any monitoring, though there were snapshot measurements taken prior to restoration.

Figure 13: Left shows the middle reach, the middle shows the rocks placed along the banks to prevent erosion, and right shows the power lines that ran above the site.

This site was designed by Bray Hill, LLC for the West Rhode Riverkeeper and Maryland Department of the Environment. This stream flows under the BGE transmission right-of-way and during rain events turned into a flashy stream that eroded the banks and conveyed large sediment loads to the Chesapeake Bay. This site was restored in order to help correct the negative impacts to the environment as well as to protect electric transmission towers. During restoration, meander curves were added and lined with rock to slow the flow of water and keep the banks from eroding. This site has no tree cover due to the power lines above, resulting in less organic retention potential,
but there is a wildflower garden surrounding the stream on both sides. The lack of tree cover could result in increased water temperature, especially during summer months.

8. Brampton Hills

Brampton Hills is located in Howard County, MD within the piedmont physiographic province and was restored in 2012. The length of the restored stream is 610 meters (2,000 LF) and runs from an upstream storm drain outfall to a downstream confluence with Red Hill Branch. There has been monitoring at this site since restoration occurred, as seen by the monitoring equipment placed in the stream channel (Figure 14).

![Figure 14: Left shows the upper reach pipe, the middle shows one of the pieces of equipment present to monitor after restoration, the right shows the lower reach of the stream.](image)

This project was designed by KCI Technologies, Inc. for Howard County. Prior to restoration, the banks of this stream were highly eroded resulting in transport of excess sediment to downstream reaches. The goal of this restoration project was to stabilize the stream by creating step pool sequences, adding stone toe protection and imbricated wall, as well as riffle grade controls. During restoration, the stream was raised and bank full benches were created for high flow events. Tree cover exists at this site, increasing the organic retention potential, and helping to keep the water from direct sunlight.
9. **Moore’s Branch**

Moore’s Branch is located in Baltimore County, MD within the piedmont physiographic province and was restored in 2011. The length of the restored stream is 828 meters (2,715 LF) and runs from an upstream pond to a downstream unrestored reach (Figure 15). The drainage area is 2.38 km², and the stream reach is surrounded by 34% impervious area (Moore’s Branch Design Report / Rob Ryan). Since restoration completion, no monitoring has been conducted.

This site was designed by Chesapeake Environmental Management and constructed by Meadville Land Services, Inc. and Ecotone, Inc. Prior to restoration, this site had eroded banks and was not providing good fish habitat, one of the restoration goals. The restored stream reach had cold water temperatures, as the upstream water source is coming from the bottom of Quarry Lake. Tree cover does exist allowing the stream to be protected from the sun as well as having a high organic matter retention potential.
10. Plumtree Run

Plumtree Run is located in Bel Air, MD within the piedmont physiographic province and was restored in 2017. The length of the restored stream is 378 meters (1,240 LF) and runs from a small upstream unrestored reach into a pipe, and the downstream reach goes through a pipe into an unrestored reach (Figure 16). This unrestored reach is currently in the design phase for restoration in 2019. The drainage area from this site is 0.91 km², and the stream reach is surrounded by 57% impervious area (Plumtree Run Design Report). No post restoration monitoring has occurred.

This site was designed and constructed by Ecotone, Inc. This stream reach used to be piped and was daylighted a few years ago. Prior to restoration, this stream reach would flood often and the banks would erode and not slow water flow, working to channel it all into the Chesapeake Bay. The goals of this project were to slow down erosion and prevent nutrients and sediment from washing into the Chesapeake Bay. Some tree cover exists near the stream, but not directly next to the channel, as there is a large grass buffer. This buffer reduces the amount of organic matter entering the stream and could also result in increased water temperature.
Extra Component

11. Edith J. Carrier Arboretum

This stream restoration project was included as an extra component due to its proximity to James Madison University. This site is outside of the physiographic provinces of the Maryland sites so it could not be evaluated with the other sites but it provides potential for continuous sampling and a project for undergraduates in the following years as it was just recently restored.

The Edith J. Carrier Arboretum stream restoration project is located in Harrisonburg, VA within the valley and ridge physiographic province and was restored in 2017. This stream restoration runs through the 0.51 km² urban botanical garden at James Madison University. The length of the restored stream is 329 meters (1,080 LF) and runs from an upstream pipe to a downstream storm water pond (Figure 17). The drainage area from this site is about 1.32 km², and the stream is surrounded by 73% impervious area. Hydrologic and water quality monitoring has occurred since restoration completion.

Figure 17: The left and middle show the middle reaches of the stream and the right shows the pond at the downstream end of the stream.
**Study Design**

All sites were sampled once between Mid-May to Mid-June 2018 (Table 0-2A). Upon arrival at each site, 80-meter reaches were measured and taped off at the lower and upper ends of the stream restoration project limits (Figure 18). The 80-meter reach was selected based on the 75-meter reach methods stated in the Maryland Biological Stream Survey (Stranko et al. 2017). This study design was selected as most of the sites did not have an accessible upstream or downstream unrestored reach. After the reaches were measured in Mid-April, the habitubes were placed in the middle of the channel at the lower end of the upper and lower reaches. When sampling occurred, starting in Mid-May, the habitubes from the lower reach were collected, after being in the stream 5 to 6 weeks, percent small organic matter retention cover was measured, traditional macroinvertebrate sampling occurred, the number of large woody debris counted, and cross section measurement completed. This process was then completed again for the upper 80-meter reach. The same methods were conducted for each of the ten sites.

![Experimental design diagram](image-url)

*Figure 18: Experimental design diagram that was used for all evaluated reaches.*
Field Methods

*GPS Coordinates:* GPS coordinates were recorded with maps on iPhone using WGS84 datum (Table 0-1A). GPS coordinates were recorded at the top of the stream restoration site (top of upper 80-meter reach), at the bottom of the upper 80-meter reach, as well as for the location of the habitubes in the upper 80-meter reach. The same measurements were completed for the lower 80-meter reach (top, bottom, and habitube locations). This was completed for all ten sites and the information was placed into Geographic Information Systems (GIS) for further analysis of physiographic provinces.

*Cross – Section:* Cross sections showing the stream profile were completed at each site and within each reach, upper and lower. The location for the cross section was the middle of the 80-meter reach. The pins were located at the top of bank so a field tape could be stretched across the stream and not touch the water surface. The auto level was located on the bank in a location that had unblocked access across the entire stream. Several points were recorded across the stream width including some required points: top left bank, water’s edge – left, middle / thalweg, water’s edge – right, and top right bank. If the stream depth was drastically different throughout the channel, additional measurements were recorded to make sure an accurate representation was reported. After completion of the field measurements, the data were added to Excel and a cross section graph was created and the hydraulic radius of the stream channel calculated. The hydraulic radius was calculated using a spreadsheet from Biohabitats, Inc. (Table 0-1B).

*Organic Retention - Objective 1:* Small coarse particulate organic matter (CPOM) retention was measured at every site within the upper and lower reaches of the restored stream. CPOM, for this study, was defined as any small allochthonous material
(< 10 cm diameter but still observable) originating from outside of the stream that washed, or fell, into the water. Based on this definition CPOM included leaves, branches, seed cones, and twigs. Transects were completed every ten meters to evaluate wetted width measurements for organic retention throughout the standard 80-meter stream reach. This resulted in nine wetted width and organic retention measurements for each reach, upper and lower. Organic retention was measured by conducting point counts every ten centimeters along the wetted width transect. This allowed for an estimated percent cover to be calculated for each reach. Any wood that was present in the stream channel that had a diameter > 10 cm was called large woody debris and counted separately from the organic retention point counts. All measurements were recorded on a data sheet and then evaluated in the lab at a later time in order to calculate estimated percent cover of small organic retention in each reach. The wetted width measurements were averaged to find the average wetted width of the upper and lower reach of the stream.

**Macroinvertebrates**

*Traditional Sampling - Objective 2:* Traditional macroinvertebrate sampling methods were conducted with twenty dip net jabs in different but representative habitat types within the upper and lower stream reaches for each site using a D-frame kick net. This allowed 1.9 m² (20 ft²) of the stream to be sampled in a variety of habitats, such as overhanging vegetation, riffles, and woody debris, resulting in a representative sample of the reach (MBSS protocol). The collected macroinvertebrates were compiled into five-gallon buckets between each jab collection until the total collection was completed. After collection completion, the macroinvertebrates were sorted in the field using a sieve and tweezers. This allowed for removal of all plant matter and other debris before the
macroinvertebrates were placed into sample bottles with ethanol, where upon they were taken back to the lab.

**Habitube Sampling - Secondary Objective:** The placement location for the habitubes was in the middle of the channel on the downstream end of the upper and lower reaches of the restored stream. The habitubes, 20 by 25 centimeters, were placed and secured using curved top rebar so they would not be transported during high flow events. For the purpose of this study the habitubes were not filled with leaves as the coconut fiber mat within acted as an artificial substrate. Two habitubes were placed in each 80-meter reach, upper and lower, but only one was collected. This allowed an extra habitube to be present in case one was removed or destroyed by a storm event or humans. The two habitubes were not placed directly next to each other to help increase the chances that the habitubes would be present upon collection. The habitubes were deployed at all ten sites in Mid / End – April, allowing them to be in the streams for five or six weeks before collection. If both of the habitubes were present in the stream come collection, a random number generator was used to select which one was collected and evaluated. A net was placed below the habitubes when they were lifted for collection, in order to collect displaced organisms. If habitubes were too hard to collect by hand due to the rebar, a crowbar was used to remove the rebar. Once removed from the stream, the habitube was placed in a container, the macroinvertebrates present were removed and placed in a sample bottle with ethanol. The water from the placement of habitube was poured through a sieve to collect any other macroinvertebrates, before placing them in the container with ethanol. The samples were then taken back to the lab for identification.
Lab Methods

**Drainage Area and Percent Impervious**: Drainage areas and percent impervious surfaces of the watershed, used for analyses, were collected from the design reports, when design reports were available. Design reports were preferred as they use high resolution data, making the small urban drainage basins more accurate, and are created by experts in the field. If design reports were not available, Streamstats was used as it is focused on water systems and used by engineers for stream design. Streamstats is a web-based Geographic Information Systems (GIS) application that provides tools for water-resources planning and management, such as drainage area and percent impervious of the watershed (USGS).

**Macroinvertebrates**: All of the macroinvertebrates that were collected in the field, from traditional sampling and habitube sampling methods, were identified to the family level (Lenat and Resh 2001). This was completed using dissecting microscopes and multiple field guides to identify the organisms. Each site had a running list of families identified for both sampling methods and within the upper and lower reaches of the restored channels. Macroinvertebrates identified were used to calculate the percent EPT (the number of *Ephemeroptera* (mayflies), *Plecoptera* (stoneflies), and *Trichoptera* (caddisflies)), diversity (Simpson’s and Shannon metrics), functional feeding groups, family richness, and abundance.

A spreadsheet from Biohabitats, Inc. was used to calculated the 5 – metric BIBI, percent EPT, and classify the macroinvertebrates into functional feeding groups (Table 0-3C & Table 0-3C). Macroinvertebrates were classified as scrapers, collectors, predators, shredders, or filterers based on the family level identification identified in the
spreadsheet. This eliminated the possibility of a family having multiple functional feeding groups listed in a field guide. The importance of the functional feeding groups was initiated from the River Continuum Concept (Vannote et al. 1987).

Stream health was measured using a 5 - metric BIBI at the family level (Biohbitats, Inc. Spreadsheet, Table 0-2C & Table 0-3C). This index consists of metrics that characterize the richness, composition, pollution tolerance, trophic status, and habitat (physiographic province) of the sampled benthic community. BIBI’s range from 1 to 5 and are further divided into classes. The classes are excellent (5), good (4-5), fair (3-4), poor (2-3), and very poor (1-2). BIBI scores provide an easy way to explore the relationship between biological conditions and land cover (Booth et al. 2004). The family level BIBI was completed for traditional sampling (upper and lower reaches combined) and habitatube samples (upper and lower reaches combined) for all ten sites. This allowed an evaluation of the two sampling methods for each site.

**Statistical Analysis**

All statistical analyses were performed in RStudio (v.1.1.414). A significance level of 0.05 was used to analyze the data; however; due to the small sample size, if the p-value was larger than 0.05, a significance level of 0.1 was used to see if a trend was present.

**Organic Retention Data Analysis**

Depending on the normality of the data, two sample t - tests or Wilcoxon rank sum tests were used to compare the means or medians of the percent cover of small CPOM retention between the upper and lower reaches of each site. This was completed
to see if the differences between the upper and lower reaches were significant or due to random chance.

ANOVA’s were used to evaluate organic retention to analyze the differences among group means of the two different restoration practices as well as in the upper and lower reaches. Tukey HSD tests were run to determine which means amongst a set of means, from ANOVA, differ from the rest.

Simple linear regressions were used to analyze the relationship between the drainage area of watershed and median organic retention present in each stream. Simple linear regressions were also used to analyze the relationship between the hydraulic radius of the channel and organic retention medians for each sampled reach.

**Macroinvertebrates Data Analysis**

Depending on the normality, two sample t-tests or Wilcoxon rank sum tests were used to compare the two restoration practices within the upper and lower reaches for both sampling techniques as well as to evaluate conveyance channels to material processing channels for both sampling methods in terms of macroinvertebrate richness and abundance. These tests were used to see if the average difference between the two restoration practices, differ between the upper and lower reaches and differ between the sampling techniques, and if so to see whether they were significant or due to random chance. They allowed an evaluation of how the habitubes and traditional methods sampled the two restoration practices and if there was any difference as the stream progressed through the restored reach (upper to lower).

ANOVAs / Kruskal – Wallis tests were used to analyze the differences among group means of the two different restoration practices as well as in the upper and lower
reaches, depending on the normality of the data set. ANOVAs / Kruskal – Wallis tests were completed for a variety of metrics including: richness, abundance, Shannon diversity, Simpsons diversity, and BIBI scores (habitube and traditional for upper and lower reaches for both restoration practices). Tukey HSD tests were run to determine which means amongst a set of means differ from the rest.

Simple linear regressions were used to analyze the relationship between the amount of organic retention present in the channel and traditional macroinvertebrate abundance and as well as for the percent shredders collected for each of the sampling techniques in both of the restoration practices.

**Results**

The Mid-Atlantic region received record levels of precipitation in 2018 (National Oceanic and Atmospheric Administration and National Weather Service 2019), resulting in a record flood events and record rainfall amounts in many locations, including Baltimore, Maryland (~182 centimeters) and Washington, D.C (~168 centimeters). The average rainfall per year in these locations is normally around 102 centimeters. As a result, the sites were heavily impacted before, during, and after evaluation.

**Organic Retention**

Organic retention, measured as estimated percent cover, varied between material processing channels (average 40%) and conveyance channels (average 18%), with material processing channels having greater variation, ranging from 3% cover to 78% cover across all five sites (Table 3). In comparison, the percent cover of organic retention ranged from 7% to 37% in the conveyance channels, resulting in a smaller variation
Since the number of large woody debris present could impact organic retention, material processing channels had an average of 10 pieces per site and conveyance channels had an average of 1 piece of large woody debris per site, most appeared to be placed during construction.

Material processing channel means differed from the conveyance channel means by about 22% (ANOVA p = 0.009), with material processing channels having higher organic matter retention rates (Tukey HSD). Two-sample t – tests / Wilcoxon rank sum tests confirmed that three sites had significant differences in organic retention between upper and lower reaches, based on the 0.05 significance alpha level. The three sites were: Davis Branch (p = 0.004) being higher in the upper reach, Spa Creek (p = 0.002) being higher in the lower reach, and Alger Park (p = 0.015) being higher in the lower reach, all material processing channels. However, Muddy Creek BGE, a conveyance channel, had significant differences between the upper and lower reaches under the 0.1 significance alpha level, the upper reach having a higher percent cover (p = 0.059) (Figure 19).
Figure 19: Estimated percent cover of small organic retention present in each reach for each site for both restoration practices (* = significant difference between upper and lower reaches).

Even though drainage areas varied across all the sites (0.13 km$^2$ to 59 km$^2$), drainage areas did not impact the organic matter retention as much as expected ($p = 0.291$, $R^2 = 0.157$). The 59 km$^2$ drainage area was excluded, so it would not skew the data, as it was almost 25 times larger than the second largest drainage area (Figure 20).
Figure 20: Linear regression of the drainage area with percent organic retention for all sites.

A larger hydraulic radius should result in increased organic matter retention due to the increased channel size and thus friction, creating roughness for organic matter to be retained. Even though hydraulic radius measurements and organic retention measurements varied across all reaches, the hydraulic radius did not impact organic matter retention as much as expected (material processing (black circles) $p = 0.177$, $R^2 = 0.215$, conveyance channels (green circles) $p = 0.993$, $R^2 = 1.01 \times 10^{-5}$) (Figure 21). However, material processing channels had a larger average hydraulic radius (0.27 m) and higher retention rates. Conveyance channels had a smaller average hydraulic radius (0.19 m) and lower retention rates.
Macroinvertebrates

Macroinvertebrate Richness

Material Processing Channels and Conveyance Channels

Macroinvertebrate richness varied across the two restoration practices and sampling methods (Table 0-1C). Material processing channels had an average of 3 families, with a range of 1 to 9 families across all reaches, collected from habitube samples and 7 families, with a range of 1 to 14 families across all reaches, collected from traditional samples. Conveyance channels had an average of 8 families, with a range of 4 to 12 families across all reaches, collected from habitube samples and 6 families, with a range of 2 to 10 families across all reaches, collected from traditional samples (Figure 22 and Figure 23).
Traditional Sampling and Habitube Sampling Methods

Traditional sampling methods collected higher richness in material processing channels (habitubes average 3 families and traditional average 7 families); however, habitube sampling collected higher richness in conveyance channels (habitubes average 8 families and traditional average 6 families). Traditional sampling methods collected even richness across material processing channels (1 to 14 families) and conveyance channels (2 to 10 families). In contrast, habitube richness differed between the restoration methods with conveyance channels having a higher richness (average 8 families) when sampled with habitubes (ANOVA, p = 0.0004). Looking at the differences between upper and lower reaches for both restoration practices, in terms of habitube collections, allowed for a further evaluation of the differences between richness collections. Material processing upper habitube richness and conveyance upper habitube richness as well as material processing lower habitube richness and conveyance lower habitube richness showed that conveyance channels collected higher richness over material processing channels (Wilcoxon rank sum test p = 0.025 & t-test p = 0.004, respectively). Habitube collections appear to be more similar to other habitube collections than they are to traditional sampling collections (Figure 23). Traditional sampling methods appear to have more variation between upper and lower reaches, than between restoration practices (Figure 23).
Figure 22: Macroinvertebrate richness collected for each site, with each sampling technique for both restoration practices. The boxes around the name indicate that the sampling for these sites occurred after a large rain event.

Figure 23: Macroinvertebrate richness, each site is combined by sampling location and sampling method for each restoration practice (Material = material processing channels, convey = conveyance channels, T = traditional sampling methods, and H = habitube sampling methods).
Macroinvertebrate Abundance

Material Processing Channels and Conveyance Channels

Macroinvertebrate abundances varied across the two restoration practices and sampling methods (Table 0-1C). Material processing channels had an average of 53 individuals, with a range of 2 to 229 individuals across all reaches, collected from habitube samples; and an average of 57 individuals, with a range of 1 to 123 individuals across all reaches, collected from traditional samples. Conveyance channels had an average of 76 individuals, with a range of 35 to 130 individuals across all reaches, collected from habitube samples; and an average of 20 individuals, with a range of 4 to 50 individuals across all reaches, collected from traditional samples (Figure 24 and Figure 25).

Traditional Sampling and Habitube Sampling Methods

Traditional sampling collected slightly higher abundances in material processing channels (traditional average 57 individuals, habitube average 53 individuals). Meanwhile, conveyance channels had higher abundances from habitube sampling (traditional average 20 individuals and habitube average 76 individuals) (Figure 24). Narrowing in and looking at the lower reaches of conveyance channels, traditional sampling collected an average abundance of 19 individuals and habitube samples collected an average abundance of 87 individuals (t-test, p = 0.005). Moving to focus on the two stream restoration practices, in terms of macroinvertebrate abundance from habitubes, material processing habitube abundances had an average of 29 individuals, while conveyance habitube abundances had an average of 70 individuals (t-test, p =
0.008). Habitubes and traditional sampling methods appear to sample more similar in upper and lower reaches than they do to traditional sampling methods (Figure 25).

Figure 24: Macroinvertebrate abundances collected for each site, with each sampling technique for both restoration practices. The box around the site name indicates that a large sampling event occurred prior to sampling.

Figure 25: Macroinvertebrate abundance of individuals, each site combined by sampling location and sampling method for each restoration practice (Material = material processing channels, convey = conveyance channels, T = traditional sampling methods, and H = habitube sampling methods).
Macroinvertebrate Diversity

The five-metric family level BIBI works to assess the quality of waters based on the macroinvertebrates and the diversity collected within each stream channel. The physiographic province could impact the results, as coastal plains do not support macroinvertebrates as well as the piedmont province. Most of the conveyance sites were in piedmont and most of the material processing sites were in the coastal plain. All of the sites and reaches for both sampling methods showed very poor to fair (1 – 3) BIBI scores (Table 2). The average family BIBI for material processing channels was 1.24 and the average for conveyance channels was 1.93. EPT individuals and diversity impact the BIBI scores. The average of EPT individuals in material processing channels was 1.24% and 12.8% of EPT individuals in conveyance channels. Diversity was measured with Shannon diversity index and Simpsons diversity index for all sites. The average Shannon diversity in material processing channels was 1.02 and for conveyance channels the average was 1.49. The average Simpsons diversity for material processing channels 0.50 and for conveyance channels it was 0.69 (Table 2).
Macroinvertebrates and Organic Retention

Traditional sampling is often focused on organic habitats that are present within the stream channel (e.g., woody debris, organic matter, etc.), along with the streambed material. That being said, organic retention significantly impacted the abundance of macroinvertebrates collected via traditional sampling methods (p = 0.04, R² = 0.22) (Figure 26). Since the amount of organic matter present in the stream channel positively influenced the abundance of macroinvertebrates, organic retention was evaluated to see if it influenced the percentage of shredders that were collected via traditional and habitube sampling for both restoration practices (Figure 0-1C). For conveyance channels, organic retention did impact (using the 0.1 alpha level for significance) the number of shredders

Table 2: Macroinvertebrate diversity for both restoration practices and both sampling methods.

<table>
<thead>
<tr>
<th>Site</th>
<th>Method</th>
<th>Simpson Diversity</th>
<th>Shannon Diversity</th>
<th>Family IBI</th>
<th>% EPT</th>
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<tbody>
<tr>
<td>Linnean Park</td>
<td>Traditional</td>
<td>0.61</td>
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present in traditional samples, but did not influence the number of shredders collected with habitube samples ($p = 0.08 & 0.53$, $R^2 = 0.69 & 0.15$, respectively) (Figure 27). In the habitube samples for conveyance channels, it appears that more shredders were present when low levels of organic retention were collected (Figure 27, orange circles). For material processing channels, the organic retention did impact (using the 0.1 alpha level for significance) the number of shredders present in both traditional and habitube samples ($p = 0.1 & 0.08$, $R^2 = 0.66 & 0.68$, respectively) (Figure 28). Material processing channels had an overall positive trend with the percent of shredders collected and organic matter retention across both sampling techniques (Figure 28).

![Figure 26: Linear regression of percent organic matter retention and impact on abundance of individuals collected with traditional sampling methods for all sampled reaches.](image)

Figure 27: Linear regression of the percent of shredders found in conveyance channels with both traditional sampling and habitube sampling and organic retention.

Figure 28: Linear regression of the percent of shredders found in material processing channels with both traditional sampling and habitube sampling and organic retention.
Results by Site

Due to the differences in site characteristics (e.g., drainage area, percent impervious, physiographic province) and precipitation amounts, most of the sites differ too much for a direct comparison, so a site by site evaluation was deemed more appropriate.

1. Linnean Park

Traditional sampling for upper and lower reaches collected the same dominant family, *Chironomidae* (midges). Habitatube sampling for upper and lower reaches collected the same dominant family, *Physidae* (snail) (Table 4). The upper reach was dominated by the collector functional feeding group, and the lower reach was dominated by scrapers. The average wetted channel width was 3.4 m in the lower reach and 3.6 m in the upper reach (Table 3). The channel shape was similar in both reaches, the lower reach had a hydraulic radius of 0.34 m and 0.40 m in the upper reach (Figure 29). There were 45 pieces of large woody debris within the reaches evaluated. These reaches had an average 53% cover of organic retention (Table 3).

![Graph of Linnean Park - Lower Reach Cross Section](image)

**Figure 29:** The upper reach has a distance of 0.32 meters from top of bank to water. The lower reach has a distance of 0.74 meters from top of bank to water.
2. **Davis Branch**

Traditional sampling collected different dominant families in the upper and lower reaches. The upper reach was dominated by *Physidae* (snail) and the lower reach was dominated by *Chironomidae* (midges). Habitube sampling collected a different dominant family in the upper and lower reaches. The upper reach was dominated by *Hirudinea* (leeches) and the lower reach was dominated by *Coenagrionidae* (dragonfly) (Table 4). Traditional samples in the upper reach were dominated by the collector functional feeding group and the lower reach was dominated by scrapers. Habitube samples were dominated by the predator functional feeding group in upper and lower reaches. The average wetted channel width was 3.0 m in the lower reach and 1.9 m in the upper reach (Table 3). The channel shape differed in upper and lower reaches, the hydraulic radius was 0.24 m in the lower reach and 0.12 m in the upper reach (Figure 30). There were 7 pieces of large woody debris within in the reaches of evaluation. These reaches had an average 33% cover of organic retention (Table 3).

![Davis Branch - Lower Reach Cross Section](image1)

![Davis Branch - Upper Reach Cross Section](image2)

**Figure 30:** The upper reach has a distance of 0.09 meters from top of bank to water. The lower reach has a distance of 0.38 meters from top of bank to water.
3. **Hawkins Cove**

Traditional sampling for upper and lower reaches collected the same dominant family, *Culicidae* (mosquito). Habitube sampling collected a different dominant family in the upper and lower reaches. The upper reach was dominated by *Chironomidae* (midge) and the lower reach was dominated by *Oligochaeta* (worm) (Table 4). Sampling techniques for upper and lower reaches collected filtering collectors as the dominant functional feeding group. The average wetted channel width was 2.9 m in the lower reach and 3.7 m in the upper reach (Table 3). The channel shapes were relatively similar, the hydraulic radius was 0.21 m in the lower reach and 0.34 m in the upper reach (Figure 31). There were 24 pieces of large woody debris within in the reaches of evaluation. These reaches had an average 40% cover of organic retention (Table 3).

![Figure 31: The upper reach has a distance of 0.39 meters from top of bank to water. The lower reach has a distance of 0.32 meters from top of bank to water.](image)
4. **Spa Creek**

No families were collected via traditional sampling in the upper reach but the lower reach was dominated by *Dystisidae* (diving beetle). Habitube sampling collected different dominant families in the upper and lower reaches. The upper reach was dominated by *Dixidae* (dixid midges) and the lower reach was dominated by *Aselidae* (isopod) (Table 4). Traditional sampling in the lower reach was dominated by the predator functional feeding group. Habitube samples were dominated by filtering collectors in the upper reach and shredders in the lower reach. The average wetted channel width was 4.8 m in the lower reach and 3.6 m in the upper reach (Table 3). The channel shapes were different in upper and lower reaches, the lower reach had a hydraulic radius of 0.43 m and 0.27 m for the upper reach (Figure 32). There were 16 pieces of large woody debris within the reaches of evaluation. These reaches had an average 11% cover of organic retention (Table 3).

![Spa Creek - Lower Reach Cross Section](image1)
![Spa Creek - Upper Reach Cross Section](image2)

*Figure 32: The upper reach has a distance of 0.38 meters from top of bank to water. The lower reach has a distance of 0.2 meters from top of bank to water.*
5. Alger Park

Traditional and habitube sampling for upper and lower reaches collected the same dominant family, *Dixidae* (dixid midges) (Table 4). Both sampling techniques for upper and lower reaches were dominated by the filtering collector functional feeding group. The average wetted channel width was 3.2 m in the lower reach and 5.1 m in the upper reach (Table 3). The channel shape differed between upper and lower reaches, the lower reach had a hydraulic radius of 0.12 m and 0.21 m for the upper reach (Figure 33). There were 10 pieces of large woody debris within in the reaches of evaluation. These reaches had an average 62% cover of organic retention (Table 3).
6. **Jones Falls**

Traditional sampling collected different dominant family in the upper and lower reaches. The upper reach was dominated by *Veliidae* (waterstriders) and the lower reach was dominated by *Elmidae* (beetles). Habitube sampling collected different dominant families in the upper and lower reaches. The upper reach was dominated by *Hydropsychidae* (caddisfly) and the lower reach was dominated by *Palaemonidae* (shrimp) (Table 4). Traditional sampling in the upper reach had predators as the dominant functional feeding group and the lower reach was dominated by collectors. Habitube sampling in the upper reach collected filterers as the dominant functional feeding group and the lower reach was dominated by collectors. The average wetted channel width was 8.5 m in the lower reach and 7.6 m in the upper reach (Table 3). The channel shapes were similar in the upper and lower reaches, they both had the same hydraulic radius, 0.34 m (Figure 34). There were 4 pieces of large woody debris within in the reaches of evaluation. These reaches had an average 8% cover of organic retention (Table 3).
7. **Muddy Creek BGE**

Traditional and habitube sampling for upper and lower reaches collected the same dominant family, *Amphipoda* (scuds) (Table 4). Both sampling techniques for upper and lower reaches collected filterers as the functional feeding group. The average wetted channel width was 0.70 m in the lower reach and 0.70 m in the upper reach (Table 3). The channel shape was similar in upper and lower reaches, the lower reach had a hydraulic radius of 0.15 m and 0.21 m for the upper reach (Figure 35).

There was no large woody debris present in the reaches of evaluation. These reaches had an average 31% cover of organic retention (Table 3).

![Muddy Creek BGE - Lower Reach Cross Section](image)

![Muddy Creek BGE - Upper Reach Cross Section](image)

Figure 35: The upper reach has a distance of 0.38 meters from top of bank to water. The lower reach has a distance of 0.2 meters from top of bank to water.
8. Brampton Hills

No families were collected via traditional sampling in the lower reach so there is no dominant family or functional feeding group. Traditional sampling in the upper reach collected Physidae (snail) as the dominant family. The habitube sampling method collected different dominant families in the upper and lower reaches. The upper reach was dominated by Chironomidae (midge) and the lower reach was dominated by Hydropsychidae (caddisfly) (Table 4). The dominant functional feeding group for the traditional sampling upper reach was scraper. The dominant functional feeding group for the habitube upper reach was collector and the lower reach was dominated by filterers.

The average wetted channel width was 1.3 m in the lower reach and 1.2 m in the upper reach (Table 3). This stream had a very low water level within the channel resulting in a very low hydraulic radius of 0.09 m for the lower reach and 0.03 m for the upper reach (Figure 36). There were 2 pieces of large woody debris within in the reaches of evaluation. These reaches had an average 16% cover of organic retention (Table 3).
9. **Moore’s Branch**

Traditional sampling collected different dominant families in the upper and lower reaches. The upper reach was dominated by *Simuliidae* (blackfly) and the lower reach was dominated by *Dystisidae* (diving beetle). Habitube sampling collected *Simuliidae* (blackfly) as the dominant family in the upper and lower reaches (Table 4). Traditional sampling in the upper reach collected filterers as the dominant functional feeding group and the lower reach was dominated by predators. Habitube sampling in the upper and lower reach had filterers as the dominant functional feeding group. The average wetted channel width was 3.2 m in the lower reach and 3.1 m in the upper reach (Table 3). The channel shape differed in the upper and lower reaches, the lower reach had a hydraulic radius of 0.15 m and 0.27 m in the upper reach (Figure 37). There was no large woody debris present within in the reaches of evaluation. These reaches had an average 11% cover of organic retention (Table 3).

![Figure 37](image-url): The upper reach has a distance of 2.6 meters from top of bank to water. The lower reach has a distance of 1.6 meters from top of bank to water.
10. Plumtree Run

Traditional sampling collected a different dominant family in the upper and lower reaches. The upper reach was dominated by *Gammaridae* (scuds) and the lower reach was dominated by *Physidae* (snail). Habitube sampling collected a different dominant family in the upper and lower reaches. The upper reach was dominated by *Tipulidae* (cranefly) and the lower reach was dominated by *Dixidae* (dixid midges) (Table 4). Traditional sampling in the upper reach collected shredders as the dominant functional feeding group and the lower reach was dominated by scrapers. Habitube sampling in the upper reach had shredders as the dominant functional feeding group and the lower reach was dominated by filtering collectors.

The average wetted channel width was 3.2 m in the lower reach and 2.7 m in the upper reach (Table 3). The channel shape differed between reaches, but the channels had the same hydraulic radius, 0.18 m, in lower and upper reaches (Figure 38). There were 27 pieces of large woody debris within in the reaches of evaluation. These reaches had an average 22% cover of organic retention (Table 3).
11. Extra: EJC Arboretum

This site was only sampled with habitubes in the upper reach as the lower reach was dry during the spring season when habitubes were placed. The dominant family was Physidae (snail), within the scraper functional feeding group. This site had a Shannon diversity of 1.54 and a Simpsons diversity of 0.76. Seven families were collected resulting in an abundance of 24 individuals.

Table 3: Data that was collected for each sampled reach for all project objectives.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Restoration Type</th>
<th>Wetted Channel Width (m)</th>
<th>Organic Retention (%)</th>
<th>Number Large Woody Debris</th>
<th>Hydraulic Radius (m)</th>
<th>Trad - Macro Abundance</th>
<th>Hab - Macro Abundance</th>
<th>Trad - Macro Richness</th>
<th>Hab - Macro Richness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linnean Park</td>
<td>Upper Material</td>
<td>3.60</td>
<td>49.70</td>
<td>27</td>
<td>0.40</td>
<td>55</td>
<td>142</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Davis Branch</td>
<td>Upper Material</td>
<td>1.90</td>
<td>48.20</td>
<td>3</td>
<td>0.12</td>
<td>81</td>
<td>88</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Lower Material</td>
<td>3.02</td>
<td>17.00</td>
<td>4</td>
<td>0.24</td>
<td>91</td>
<td>23</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>Hawkins Cove</td>
<td>Upper Material</td>
<td>3.70</td>
<td>45.50</td>
<td>9</td>
<td>0.34</td>
<td>123</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Lower Material</td>
<td>2.90</td>
<td>34.80</td>
<td>15</td>
<td>0.21</td>
<td>14</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Spa Creek</td>
<td>Upper Material</td>
<td>3.60</td>
<td>3.20</td>
<td>1</td>
<td>0.27</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Lower Material</td>
<td>4.80</td>
<td>18.50</td>
<td>15</td>
<td>0.43</td>
<td>11</td>
<td>229</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Alge Park</td>
<td>Upper Material</td>
<td>5.12</td>
<td>46.30</td>
<td>6</td>
<td>0.21</td>
<td>75</td>
<td>7</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Lower Material</td>
<td>3.16</td>
<td>77.70</td>
<td>4</td>
<td>0.12</td>
<td>57</td>
<td>2</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Moore's Branch</td>
<td>Upper Conveyance</td>
<td>1.19</td>
<td>14.70</td>
<td>1</td>
<td>0.03</td>
<td>5</td>
<td>35</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Lower Conveyance</td>
<td>1.32</td>
<td>19.10</td>
<td>1</td>
<td>0.09</td>
<td>6</td>
<td>78</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Plumtree Run</td>
<td>Upper Conveyance</td>
<td>3.10</td>
<td>11.80</td>
<td>0</td>
<td>0.27</td>
<td>36</td>
<td>79</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Lower Conveyance</td>
<td>3.23</td>
<td>10.60</td>
<td>0</td>
<td>0.15</td>
<td>11</td>
<td>63</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>
Table 4: Dominant macroinvertebrates collected for each sampled reach and the percent at which they dominated the sample (based on number of individuals collected).

<table>
<thead>
<tr>
<th>Sampling Technique</th>
<th>Reach</th>
<th>Dominant Family</th>
<th>Dominance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Linnean Park</strong></td>
<td>HabitubeUpper</td>
<td>Chironomidae</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Chironomidae</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Physidae</td>
<td>51%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Physidae</td>
<td>54%</td>
</tr>
<tr>
<td><strong>Davis Branch</strong></td>
<td>HabitubeUpper</td>
<td>Chironomidae</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Coenagrionidae</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Physidae</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Chironomidae</td>
<td>48%</td>
</tr>
<tr>
<td><strong>Hawkins Cove</strong></td>
<td>HabitubeUpper</td>
<td>Chironomidae</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Oligochaeta</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Culicidae</td>
<td>72%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Culicidae</td>
<td>72%</td>
</tr>
<tr>
<td><strong>Spa Creek</strong></td>
<td>HabitubeUpper</td>
<td>Dixoideae</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Asellidae</td>
<td>88%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Dystisidae</td>
<td>46%</td>
</tr>
<tr>
<td><strong>Alger Park</strong></td>
<td>HabitubeUpper</td>
<td>Dixoideae</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Dixoideae</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Dixoideae</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Dixoideae</td>
<td>35%</td>
</tr>
<tr>
<td><strong>Jones Falls</strong></td>
<td>HabitubeUpper</td>
<td>Hydropsychidae</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Palaemonidae</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Veliidae</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Elmidae</td>
<td>33%</td>
</tr>
<tr>
<td><strong>Muddy Creek</strong></td>
<td>HabitubeUpper</td>
<td>Amphipoda</td>
<td>59%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Amphipoda</td>
<td>89%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Amphipoda</td>
<td>78%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Amphipoda</td>
<td>78%</td>
</tr>
<tr>
<td><strong>Brampton Hills</strong></td>
<td>HabitubeUpper</td>
<td>Chironomidae</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Hydropsychidae</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Moore's Branch</strong></td>
<td>HabitubeUpper</td>
<td>Simuliidae</td>
<td>62%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Simuliidae</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Simuliidae</td>
<td>61%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Dystisidae</td>
<td>38%</td>
</tr>
<tr>
<td><strong>Plumtree Run</strong></td>
<td>HabitubeUpper</td>
<td>Tipulidae</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Dixidae</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td>TraditionalUpper</td>
<td>Gammaridae</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Physidae</td>
<td>43%</td>
</tr>
</tbody>
</table>
Discussion

It is hypothesized that streams that are restored for conveyance work to transport the water through the channel without any damage to surrounding infrastructure, and as a result would retain less organic matter. On the other hand, it is hypothesized that streams restored to process materials in-stream would have higher organic matter retention due to increased in-stream structures. It was further expected that streams with increased organic matter retention would have higher macroinvertebrate richness, abundance, and diversity. This is due to the streams having more habitat and food source potential. This study found only some of that to be supported.

The Mid-Atlantic region received record levels of precipitation in 2018 (National Oceanic and Atmospheric Administration and National Weather Service 2019), resulting in a record flood events and record rainfall amounts in many locations, including Baltimore, Maryland (~182 centimeters) and Washington, D.C (~168 centimeters). The average rainfall per year in these locations is normally around 102 centimeters. As a result, the sites were heavily impacted before, during, and after evaluation.

Due to the differences in site characteristics (e.g., drainage area, percent impervious, physiographic province) and precipitation amounts, most of the sites differ too much for a direct comparison, so a site by site evaluation was deemed more appropriate. Some of the metrics were compared across all of the material processing sites to all of the conveyance sites, to see if a trend was seen and worth being evaluated in future studies.
Organic Retention

Conveyance channels are designed to have the smallest cross-sectional area while transporting the largest volume of water. This means a smaller surface area to largest volume, decreasing the potential of organic matter and nutrient retention within the stream channel. On the other hand, material processing channels are restored to create a large cross-sectional area while transporting a large volume of water. These channels are created to have a larger surface area so more water can touch the landscape, increasing the amount of organic and nutrient retention and slowing the flow of water.

Material processing channels had a higher and a larger variation of organic matter retention rates than conveyance channels (Figure 19). This is could be due to more woody debris being present in each of the channels working to trap the organic matter and keep it from flushing out of the system to downstream reaches, even though there was no significant correlation of woody debris and organic retention. Material processing channels had an average of 10 pieces of large woody debris per site and conveyance channels had an average of 1 piece per site. Most appeared to be placed during construction, especially since most streams were recently restored. Urban streams that come from pipes have the potential to have increased organic matter as all of the organic matter that is present on the streets is washed through the storm water drain network into the stream channel. Four of the five material processing sites evaluated in this study came from a pipe or spent time in a pipe prior to entering the restored reach, potentially impacting the results.

A larger hydraulic radius should provide more opportunity for organic retention due to increased friction of the water on the stream channel surface. It would be expected
that material processing channels would have a higher hydraulic radius as they are designed to process materials instream and connect to the floodplain, more so than conveyance channels. The average hydraulic radius for the 10 material processing reaches, upper and lower for all 5 sites, was 0.27 m and the average for the 10 conveyance reaches was 0.19 m. However, the hydraulic radius of the stream channels for both material processing and conveyance channels, did not significantly impact the amount of organic retention. The hydraulic radius explained about 22% of the variance in the organic retention rates for material processing channels (Figure 21, black circles), but explained less than 1% of the variance for conveyance channels (Figure 21, green circles). This fits the expected results, as most of the material processing channels had a larger hydraulic radius and more woody debris present thus retaining higher levels of organic matter. The conveyance channels had a smaller average hydraulic radius, less woody debris present within the channels, and a smaller organic matter retention average. A lot of variation existed between sites, so a site by site evaluation is highly relevant as well.

It was expected that the drainage areas of the sites would impact the amount of organic matter that was retained, either positively or negatively. A larger drainage area means more water being drained into the stream, which could wash out any organic matter retention in a channel that has very little in-stream complexity. On the other hand, a large drainage area could increase the amount of organic matter that is being washed into the stream from surrounding locations. However, it was seen that drainage area did not significantly impact organic retention, although about 23% of variance were explained when largest drainage area was removed. This is most likely due to small
sample size and large site variability (Figure 20). Sites with the largest drainage areas were conveyance channels, thus had smaller organic retention rates. Increased water flow and lack of in-stream structures impacted the amount of small organic matter retained, especially during high flow events, which most of the sites were sampled after.

Similar to drainage area, percent imperviousness of the watershed could impact organic retention potential positively or negatively. After evaluating the percent of impervious surfaces of the watershed, it was seen that they did not significantly impact the amount of organic retention. Increased impervious surfaces results in more overland flow, increasing the amount of water entering the stream potentially bringing higher small organic matter into the stream channel. The lack of trend could be the result of the increased precipitation and the variation in watershed and percent impervious surfaces between the sites. Flooding prior to sampling could have washed out all organic matter that was present, impacting the results that were collected.

Four sites had noticeable differences in organic retention between upper and lower reaches, three of which were material processing channels. Davis Branch had significantly higher organic retention rates in the upper reach, due to the beaver dams present working to retain organic matter. Spa Creek had significantly higher retention rates in the lower reach, this is most likely due to the extreme flooding that occurred coupled with a beaver impoundment just upstream of the lower reach. The upper reach comes from a pipe and it was stripped clean of organic matter after flooding, pushing organic matter that was present into the beaver dam analog reach. Alger Park had significantly higher organic retention in the lower reaches. The upper reach comes from a pipe and during high flow events washes all organic matter downstream to the lower
gradient reach. Muddy Creek BGE, a conveyance channel, had significantly higher retention, under the 0.1 significance level, in the upper reach. This makes sense as the upper reach was located closest to the present trees near the site, forest edge, as the power lines above the stream prevented trees along the restored channel.

**Macr**o**invertebrates**

**Macroinvertebrate Richness**

**Material Processing Channels and Conveyance Channels**

Considering the increased organic matter in material processing channels, it would be expected that material processing channels would have increased macroinvertebrate richness, this did not appear to be the case when all the sites were combined for evaluation. There are many reasons (e.g., physiographic province, sampling date, upstream reach) that could have impacted the results seen.

In contrast to our original expectations, conveyance channels had an average macroinvertebrate richness that was higher than that of material processing channels (Figure 22 & Figure 23). Conveyance channels had an average richness of 8 for habitube samples and 6 for traditional samples, where material processing channels had an average richness of 3 for habitube samples and 7 for traditional samples. This could be because all but one of the conveyance channels were located within the piedmont physiographic province, and only two of the material processing channels are in the piedmont province. It is documented that the different physiographic provinces could support different aquatic macroinvertebrate populations, especially when impacted by urbanization (Utz
The conveyance channels also had more time to recover since restoration, as the sites tended to be older.

**Traditional Sampling and Habitube Sampling Methods**

There was no significant difference between macroinvertebrate richness using traditional sampling for the two different restoration practices. There was however a significant difference between macroinvertebrate richness in habitube sampling for the two different restoration practices. Habitube richness was significantly higher in conveyance channels (p = 0.0004). Habitubes collected an average richness of 8 families, for both upper and lower reaches, for conveyance channels; while material processing channels collected an average richness of 4 and 3 families, upper and lower reaches respectively. The same trend was seen when the upper and lower reaches for both sampling methods and for both restoration practices were separated. Conveyance channels would not normally have any surface like the artificial substrate that habitubes provide in the stream channel, potentially working to attract macroinvertebrates (Letovsky et al. 2012). This results in families that normally would not be caught with traditional sampling being collected in habitube samples. Whereas material processing channels have a lot of substrate available within the channel (e.g., woody debris, organic matter, etc.) that works to provide habitat that is then sampled with traditional sampling, resulting in no significant difference between habitube and traditional sampling methods.

Focusing on just the sampling techniques and not the restoration practices, habitubes collected similar average richness’s as traditional samples (7 families). There was a lot of variation across all sites due to rain and sampling dates as well as variation in
site characteristics. This means that habitubes have the potential to be a sampling technique, if the trends are further evaluated and persist.

The richness boxplot appears to show that habitubes are more similar to each other than they are to traditional sampling, when looking at the two different restoration practices. This means habitubes appear to collect a consistent number of families throughout (Figure 23). Traditional sampling had more variation between upper and lower reaches, this could be due to the differences in the channel structure, sampling effort, or error.

**Macroinvertebrate Abundance**

**Material Processing Channels and Conveyance Channels**

Macroinvertebrate abundances varied across the two restoration practices but a significant difference between material processing and conveyance channels was seen. Material processing channels collected an average macroinvertebrate abundance that was slightly higher than that of conveyance channels, potentially because they retained higher levels of organic matter than conveyance channels (Figure 19 & Figure 25). Material processing channels had an average of 53 individuals collected from habitube samples and 57 individuals collected from traditional samples. This makes sense considering material processing channels have more sampling location potential within the stream reach. This could have been a large factor this summer with rainfall increasing flow rates and potentially washing macroinvertebrates downstream. Conveyance channels had an average of 76 individuals collected from habitube samples and 20 individuals collected from traditional samples (Figure 24 and Figure 25). Conveyance channels collected smaller abundances with traditional sampling as there was less habitat complexity. In
contrast, when looking at the habitube collection they could have provided an artificial substrate for refuge in high flow events.

**Traditional Sampling and Habitube Sampling Methods**

Material processing habitube samples and conveyance habitube samples collected significantly different abundances of individuals ($p = 0.008$) (material processing 57 and conveyance 76), indicating that there is a difference in the habitube collections between restoration practices. When using habitubes for comparison, there was a greater abundance collected in conveyance channels. When using traditional samples for comparison, there was a greater abundance collected in material processing channels. The material processing channels had increased presence of large woody debris and organic matter retention to provide habitat and ample sampling locations with a D-frame kick net. Conveyance channels had less large woody debris and organic matter retention present, impacting the D-frame kick net samples, but the habitubes worked as an artificial substrate attracting families and more individuals that would not normally be collected.

Focusing on just the sampling techniques and not the restoration practices, abundance varied greatly across all sites. Although, habitubes collected a higher average abundance then traditional sampling, most likely due to the habitat that they provide in the stream channel that would not otherwise be present. The variation across all sites is not surprising due to all of the rain that occurred and the variation in sampling dates across all sites. This means that habitubes have the potential to be a sampling technique, if the trends are further evaluated and persist.

The abundance boxplot appears to show that habitubes and traditional sampling methods are closer within upper and lower reaches of each sampling technique, than they
are to each other (habitube versus traditional sampling). The sampling methods appear to be consistent across sites, but there are differences between the two sampling methods when looking at the two restoration practices (Figure 25). Although slight differences exist, there are no significant differences between habitube and traditional sampling methods.

**Macroinvertebrate Diversity**

There was no significant difference in habitube and traditional sampling methods in terms of Shannon or Simpsons diversity, as expected. This means that the sampling methods collected similarly enough to each other and one did not out preform the other. According to both of the indices, the average across material processing channels were a little lower, thus less diverse, than the conveyance channels (Table 3). This was opposite of the expected results, as material processing channels had more organic habitat and food source potential, but it could be due to the habitubes collecting higher richness in conveyance channels or due to the location of the conveyance channels within the piedmont physiographic province. Most of the conveyance channels also had an upstream reach that could have allowed faster colonization after restoration and the two oldest sites sampled were conveyance channels allowing more time for colonization.

Since all of the evaluated streams were in urban locations and were all restored within the last 10 years, it was expected that the percent of EPT and BIBI scores would be relatively low, as recently restored streams take time to recover to full potential (Violin et al. 2011). All sites, for both sampling methods and reaches, showed a low level of EPT families present. About 13% of the individuals collected in conveyance channels were EPT, while only 1.2% of the individuals collected in material processing channels
were EPT, corresponding to the results seen from the diversity indices. Most of the conveyance channels were in the piedmont province whereas the material processing channels were mostly in the coastal plain province, this could have impacted the results seen between the two sampling techniques. There was an average of about 3 EPT families present at the piedmont sites and an average of about 1 EPT family present at the coastal plain sites, ignoring all other metrics. The five metric BIBI, which uses EPT, showed that all of the sampled reaches were very poor to fair (1 – 3). The average BIBI for material processing was 1.24, and the average BIBI for conveyance channels was 1.93. One consideration of the BIBI calculation was the physiographic province, piedmont or coastal plain, so they could equally be compared. The numbers collected for percent EPT and family level BIBI were as expected, considering these were urban streams with high impervious surfaces within the watershed and were recently restored (Rubin et al. 2017). Only 29% of streams in Maryland were rated as good using the benthic macroinvertebrate IBI through Maryland Biological Stream Survey in 2007 – 2009 (MBSS Report). Road runoff, especially in urban areas, results in increased nutrients, sediment, and pollutants entering the stream. Many of the material processing channels were designed to slow the flow of water to help settle out the increased nutrients, sediment, and pollutants, but increased precipitation prevents the water from settling out quickly, as it keeps being disrupted.

**Macroinvertebrates and Organic Retention**

Traditional macroinvertebrate sampling is focused on the organic habitat and streambed material present within the channel, so it would be expected that high levels of organic retention would result in larger macroinvertebrate collections. Organic retention
significantly impacted macroinvertebrate abundance collected from traditional sampling and explains about 22% of the variance (Figure 26). This means that the amount of organic matter present impacted the abundance of macroinvertebrates collected with traditional sampling, but not in terms of richness or habitube abundance. This makes sense as habitubes work to create an artificial substrate and potential food source for macroinvertebrates so they do not need to heavily rely on the organic matter present in the stream channel. Less organic matter was present in conveyance channels in comparison to material processing channels so it would make sense that the amount of organic matter can only be seen in material processing channels.

In traditional macroinvertebrate collections in conveyance channels, organic matter retention explained about 69% of the variance of percent shredders collected, while only explaining about 14.6% of the variance from habitube samples (Figure 27). It appears as though conveyance channels with low levels of organic matter retention had a higher percent of shredders collected by habitubes. This is interesting as it appears that the habitubes provide an artificial habitat and potential food source to macroinvertebrates in conveyance channels. As a result, it shows a trend opposite of what was expected. This could suggest that conveyance channels are a poor design as they have increased velocity within the stream channel that conveys organic matter downstream and thus needs an artificial substrate to provide a habitat and food source to in-stream biota.

In traditional macroinvertebrate collections in material processing channels, organic matter retention explained about 54% of the variance of percent shredders, and explained about 58% of the variance collected with habitube samples (Figure 28). It was hypothesized that percent of shredders found in the stream would be associated to the
amount of organic retention in the stream as that is their primary food source. Based on the regression, most of the stream’s organic matter retention explains over 50% of the variance for the percent shredders in material processing restored channels. As previously mentioned, shredders are one of the functional groups that takes longer to establish, so the low numbers seen at these recently restored streams could increase as the streams age and become more established (Westveer et al. 2018).

**Macroinvertebrate Conclusions**

Insufficient time for recovery between restoration and macroinvertebrate sampling could have also impacted the macroinvertebrate data. All of the sites were between one and seven years old, eight were three years old or less and two were greater than six years old, potentially too recent for the stream to recover and provide the best habitat for instream biota (Violin et al. 2011).

**Discussions by Site**

Due to the differences in site characteristics (e.g., drainage area, percent impervious, physiographic province) and precipitation amounts, most of the sites differ too much for a direct comparison, so a site by site evaluation was deemed more appropriate.

1. **Linnean Park**

This coastal plain site had the second highest organic retention rate out of all the sampled sites. The lower reach had higher retention than the upper reach, as the upper reach had a steeper slope washing organic matter downstream. The upper reach had a larger hydraulic radius, compared to the lower reach. There were areas within this site that floodplain reconnection could occur, especially in the middle and lower reaches. This
stream is a headwater stream that comes from a pipe so there was no stable macroinvertebrate population established upstream to easily colonize the stream after restoration. In the upper reach, the habitube samples collected a higher abundance. Whereas in the lower reach, where there is more organic matter, traditional sampling collected a higher abundance. However, traditional sampling collected higher richness than habitube samples in both reaches. A low BIBI (~1) and low diversity was seen in both locations and with both sampling techniques, however habitubes had a lower diversity than traditional samples. Very low EPT families were seen as well (habitubes 0% and traditional 1.8%).

2. **Davis Branch**

Beavers were present in this piedmont stream prior to restoration and were being removed due to backing up water into the pipes and resulting in flow over the bridge. After restoration, the beavers moved back and worked to make the upper reach of the stream more of a ponded stream / wetland, reconnecting the floodplain, and providing in-stream biota with habitat and food as they worked to increase organic retention. As a result, the upper reach had higher organic retention within the channel than the lower reach as there was more woody debris present within the stream channel. This is interesting as

![Figure 39: Upper reach cross section before and after the Ellicott City flooding.](image-url)
the lower reach had a larger hydraulic radius, but it shows how beavers can alter water systems and provide benefits that would not normally be present. After the Ellicott City, Maryland flooding the beaver dams in this site were washed out, changing the channel shape in the upper reach (Figure 39). Even though the channel shape changed after the flood, the hydraulic radius only changed slightly 0.12 m to 0.09 m.

The lower reach had less potential for floodplain reconnection as there were more defined stream banks as the stream started to flow into a heavily wooded area. In the upper reach, habitubes and traditional sampling collected the same richness and abundance. In the lower reach, traditional sampling collected a higher richness and abundance, most likely due to the increased channel complexity. Moderate diversity was present for habitube and traditional samples, but there were low BIBI scores. Only 6.4% EPT families were collected from habitubes and 1.2% EPT families collected from traditional sampling.

3. **Hawkins Cove**

This coastal plain site was recently restored, completed in early 2018, resulting in little time to develop and provide the best habitat for instream biota. Sampling for this site occurred right after a large storm event, which impacted the water quality due to the increased road runoff (high in sediment and oil). Prior to restoration this site was sampled for macroinvertebrates and received an BIBI score of 1. Using the same BIBI calculations traditional sampling for the upper and lower reaches was 1.29, indicating a possible increase since restoration. The habitube still collected an BIBI score of 1. Traditional sampling collected higher macroinvertebrate richness and abundance compared to habitube samples at this site. However, diversity scores were low as most of the samples
were dominated by mosquito larvae and there were low levels of EPT families present. This stream has areas where during high flow events the water could flow out of the channel and into the floodplain. Many of these areas were heavily saturated when this site was sampled due to the previous storm event. There was a high organic retention rate at this site, highest in the upper reach, which makes sense as the upper reach had a larger hydraulic radius and the presence of large woody debris within the stream channel. There were a large number of mature trees on either side of the restored stream reach as well. The ability of this stream to retain organic matter through large storm events is helpful as it prevents the organic matter from being washed directly into the Chesapeake Bay at the downstream end of this restoration project.

4. **Spa Creek**

This coastal plain restoration project was very unique compared to the others as the middle reach had beaver dam analogs, man-made beaver dams that work to encourage beavers to establish their own dams. These beaver dams work to trap the sediment and organic matter, provide good habitat and food sources for in-stream biota, and create floodplain reconnection that was not possible in upstream and downstream reaches due to surrounding infrastructure. For the purposes of this study, it seems that the beaver dam analogs could be impacting the macroinvertebrates in the downstream reach. Few macroinvertebrates were collected from the upper reach with both sampling techniques, as it was sampled after a large storm event. However, the lower habitube sample collected the largest abundance out of all samples collected. The macroinvertebrate richness in the lower reach was still low but it appears that the beaver dam analogs could have worked to slow the flow of water and was a source of macroinvertebrate habitat and
food, allowing populations to grow. This stream is very recently restored and according to the collected samples no EPT families were present and the BIBI and diversity indices show poor water quality.

Since restoration has been completed the beavers have come in and made the center part of this stream more of a wetland environment, providing prime habitat for an urban stream system, especially during high flow events (Figure 40).

![Figure 40: The beaver hut and beaver that are present within the middle reach, where the beaver dam analogs were implemented.](image)

There was relatively low percent organic retention due to the flooding that occurred. This site had the highest impervious watershed out of all the sampled sites, which could have resulted in a worse flooding event for the stream, especially since the upper reach comes from a pipe. The upper reach was washed out after the flood and most of the organic matter was trapped in the middle reach of the stream with the beaver dam analogs. Due to the flood event before sampling, the lower reach of the project had deeper than normal muddy water making it hard to measure the organic retention in the middle of the channel. If flooding had not occurred before sampling this site, the lower reach still probably would have had more organic retention present, compared to the upper reach due to the larger hydraulic radius and the presence of trees. Knowing that the
beaver dams work to trap organic matter during high flow events is good, as it keeps the organic matter from directly entering the Chesapeake Bay at the end of the restored reach. This site is a prime location to do a long-term study to see how the beaver dams change the downstream reach over time, in terms of organic retention and macroinvertebrate richness, abundance, and diversity, as the flooding severely impacted the results collected for this study.

5. Alger Park

The upper reach of this piedmont site had no room to connect to the floodplain due to presence of infrastructure on both sides of the stream and the steep topography. The lower reach had a lower channel slope, slowing the water flow, and better allowing it to connect to the floodplain. This site had the highest organic matter retention rates out of all of the sites that were sampled, especially in the lower reach. Large woody debris was present helping to slow the water and provide floodplain reconnection of the lower reach while working to trap organic matter from surrounding locations. The lower reach had a very shallow channel that had areas that were above or equal to water level, as a result the lower reach had a smaller hydraulic radius, but it makes sense as to why there was increased organic matter retention present. This stream also had a lot of trees along the banks and most likely had organic matter input from the surrounding streets that was washed into the stream channel during flood events. The habitubes only collected one family in each reach, resulting in a very low diversity measurement. Traditional sampling collected a greater macroinvertebrate richness and abundance, completely opposite of the conveyance channels. This site was the only site that had traditional sampling conducted by someone different, possibly resulting in sampling technique differences or effort. As a
result, the traditional sampling resulted in a moderate diversity score, which would be expected due to the increased habitat and food sources present in the lower reach.

6. Jones Falls

This piedmont stream was the widest and had tall steep stream banks, reducing the frequency for floodplain connection (Figure 34). This site also had the largest drainage area, 59 km², potentially impacting the results. The wider channel resulted in faster flowing water decreasing the amount of organic retention that was present in the stream channel, even though there was a small amount of large woody debris present along one of the stream banks. This stream had the same hydraulic radius for upper and lower reach, which makes sense for a conveyance channel. This restoration project was on a section of a large stream so there was an established stream reach above the restoration allowing the macroinvertebrates to reestablish quicker and have a more stable population. An even macroinvertebrate richness was collected with the habitube and traditional samples, but the habitubes collected greater abundances compared to traditional samples. Both habitubes and traditional samples collected a large number of EPT families, 30% and 27% respectively. As a result, this site had one of the highest diversity and BIBI (~ 2) measurements out of all of the sampled streams. The healthy macroinvertebrate population present was a good sign as this stream was restored for fish habitat and the macroinvertebrates would be the food source needed in order for the fish to survive.

7. Muddy Creek BGE

This coastal plain stream has a very narrow meandering channel, lined with rocks around the meander bends to prevent erosion, that flows under the power right of way,
resulting in a lack of trees along the stream. The lack of trees present could have impacted the amount of organic matter found in the stream channel, since the only trees near the site are located above the upstream reach at the forest edge. This stream had the smallest width out of all of the sites and relatively low hydraulic radius’s as well. An upstream unrestored reach was present allowing macroinvertebrates to colonize the stream quickly after restoration. As a result, good water quality indicators, EPT families, were collected in habitube and traditional samples. The habitubes and traditional sampling methods collected similar macroinvertebrate richness at this site for both reaches, but habitubes collected larger macroinvertebrate abundances. This is most likely due to the habitubes providing a refuge habitat during high flow events. Due to the location of this site, on the edge of the city and under the power right-of-way, it had the lowest percent impervious watershed out of all of my sites. During large flood events this site had the potential to overflow into the surrounding landscape, as there was a low bank. A pocket wetland existed in the upper reach of the restoration project to trap and filter water during high flow events.

8. **Brampton Hills**

This piedmont stream was the second oldest site, sampled at six years old, allowing a longer time for the stream to establish after restoration. Habitubes collected the highest number of EPT families out of all the sites, 31%, traditional sampling only collected 10% EPT families. The Simpson’s diversity, Shannon diversity, and BIBI were close between the traditional and habitube samples. Traditional sampling collected smaller macroinvertebrate richness and abundance compared to habitube sampling, most likely due to the refuge that habitubes provided during high flow events. This site was
sampled after the Ellicott City, Maryland flood and as a result evidence of the extreme flooding was present on site. Sod placed after restoration and other planting events were lifted and moved from the fast-flowing water and the grass along the banks was flattened along the entire restored reach. This stream had the smallest hydraulic radius measurements out of all of the sampled sites. This site lacked large woody debris within the stream channel and had low organic retention rates as a result. The flooding could have greatly impacted these results as there is an abundance of large trees along the restored reach, and larger rocks within the stream channel that should work to trap organic matter. Reaches of this stream had the ability to enter the floodplain, during high flow events. One of the design features for this stream was a bank full bench for the water to leave the channel during high flow events. On the other hand, there were reaches that were more confined due to the nearby housing development.

9. **Moore’s Branch**

This piedmont stream was the oldest site, sampled at seven years old, allowing the longest time for the stream to establish after restoration. A goal of restoration for this project was fish habitat as the stream used to have a healthy fish population. As previously mentioned this stream is fed from an upstream quarry pond, resulting in cooler water temperatures that are needed for many fish species. This stream had some potential for floodplain reconnection if there was a major storm event, but since the stream comes from the quarry the water flow is pretty well regulated. The banks of this stream were tall in some locations and there was a berm located at the top of the bank preventing water from ever entering the forested area on the other side. The forested area on both sides of this stream increased the organic retention potential, but no large woody debris was
present in the evaluated stream reach, which resulted in relatively low organic retention rates. This stream had hydraulic radius measurements that were similar to some of the material processing sites, but they did not appear to help in the retention of organic matter. This did not seem to impact the macroinvertebrates collected as this site had the highest BIBI scores, traditional was 2.67 and habitube was 3, out of all sampled sites. The diversity metrics from Simpson’s and Shannon diversity were similar between habitube and traditional samples, showing consistency between the samples. This site did not have a large number of EPT families present. None were collected with traditional samples and only about 6% of the habitube samples were EPT families. Since this site was the oldest sampled, it makes sense that the highest BIBI score was seen, as the site had the most time to establish after restoration.

10. Plumtree Run

After previously being daylighted this stream was eroding during large flood events, impacting the surrounding landscape and increasing sediment and nutrient loads that were being transported to the Chesapeake Bay. This restoration project worked to grade the banks back, giving the water some ability to connect to the floodplain and pocket wetlands were created to catch water during high flow events. Large woody debris was incorporated into this restoration project along bends in the channel to slow the flow of water and decrease bank erosion. Sampling occurred after a large flood event, decreasing the amount of organic matter that was present within the channel. However, the large woody debris present within the stream worked well by collecting organic matter and providing habitat during high flow events. This site had the same hydraulic radius in the upper and lower reach, which is typical of a conveyance channel, but had a
smaller hydraulic radius compared to other streams, which could have impacted the organic retention potential. Habitube sampling collected higher family richness and abundance compared to traditional sampling, most likely due to the refuge that the habitubes provided during the high flow event prior to sampling. Traditional sampling collected a fairly high diversity, according to Simpsons diversity, compared to the habitube samples, showing that they collected a more even sample. The traditional samples collected no EPT families, but the habitube collections were 19% EPT families.

11. EXTRA: Edith J. Carrier Arboretum

Prior to restoration no macroinvertebrates were present in this site due to parts of the stream going dry throughout the summer months. A double goal of this restoration project was to create water flow all year so macroinvertebrates could sustain populations. This goal was not completely met as the stream had several dry runs in April and May. Heavy precipitation later in the summer resulted in the stream channel flooding and eroding the banks without established vegetation, transporting heavy sediment loads downstream. As a result, this site was only sampled with the habitubes in the upper reach, to see if there were macroinvertebrates present after restoration. Habitube samples collected macroinvertebrates that indicated poor water quality, a result of recent restoration (within the last year) and supply of water from a highly urbanized watershed. As the restoration project ages, the stream should become more established decreasing the sediment in the stream channel and potentially increasing the macroinvertebrates present. Due to the proximity to James Madison University, this project could benefit from student monitoring to see how it evolves over time.
Conclusions

Based on the data that were collected, there does appear to be differences between conveyance channels and material processing channels. Small organic matter retention rates were higher in material processing channels than conveyance channels (~40% versus ~18%). Previous studies, that focused on the transport of organic matter before retention, noted that woody debris, channel form, and velocity impact the travel distance before retention, indicating that a larger channel size, woody debris presence, and slower water flow result in a shorter travel distance before retention (Brookshire et al. 2003, Quinn et al. 2007, Speaker et al. 1984). This was not evaluated directly within this study; however, sites that had large woody debris present and a larger hydraulic radius had slower water flow and higher retention rates. The increased organic matter retention and woody debris presence in the material processing channels, as well as the larger hydraulic radiiuses, works to provide a lot of habitat potential.

Habitubes collected higher macroinvertebrate richness in conveyance channels, most likely due to the new substrate being available that would not normally be present. These systems also had faster flowing water, making one-time traditional sampling more difficult. That being said, habitubes have the potential to be a sampling technique, when focusing on just the macroinvertebrate sampling methods, traditional collected similar richness averages as habitubes (7 families). Habitubes need to be studied more across different sites and seasons to see if the trends persist. Previous studies have indicated that flooding could impact collection results from artificial substrate samples, so the habitube collections could have been impacted by the record rainfall levels of 2018 (Roby et al. 1978).
The location within physiographic provinces could have impacted the results seen as well. Most of the conveyance channels were located in the piedmont physiographic province, and they appeared to have higher macroinvertebrate richness, compared to the coastal plain sites, mostly material processing channels. Previous studies have shown that urbanization and physiographic provinces could impact the macroinvertebrate potential in restored streams (Utz 2010) and studies have shown that urban streams have lower levels of shredders and tolerant taxa, which corresponds to what was seen with many of these sites (Walsh et al. 2005). Due to the uneven numbers of each restoration type in the two physiographic provinces it was hard to evaluate any trends due to a small sample size. If more sites were in each province a comparison across all of the sites and restoration practice could have been completed to see if the location within the piedmont region was the difference for larger richness collections or if it was more connected to the artificial substrate that the habitubes provided within conveyance channels.

The sites were only evaluated once during the summer season in a year with the highest rainfall on record. This could result in discrepancies in measurements and collections (Webster et al. 1994). There were also many elements that could have impacted the results across the ten sites, they include: drainage area, percent impervious surface of watershed, physiographic province, etc. This study or a similar study should be completed with larger sample sizes in both physiographic regions, through multiple seasons (especially autumn for organic retention and macroinvertebrates), over multiple years to see if the trends persist. This would allow sites to be monitored under a range of environmental conditions, which is highly valuable during this time of climate change. A study conducted over several years would also evaluate how the site develops as it ages,
since most of the sites were recently constructed. Previous studies have shown that sites take several years after restoration to develop, especially in terms of macroinvertebrate community development (Violin et al. 2011 & McDonald et al. 1991).

If the trends seen persist, then the method of stream restoration plays a major role in what material leaves the stream channel and enters downstream reaches. The Mid-Atlantic region should consider implementing more material processing and floodplain reconnection projects to meet the Total Maximum Daily Load goals, increase habitat potential, and ultimately help the health of the Chesapeake Bay, especially during this time of increased urbanization and climate change (Kaushal et al. 2012 & Palmer 2008).
### Appendix A – Supplemental Site and Sampling Information

Table 0-1A: GPS points for the limits of each reach and the location of habitube placement taken (WGS84 datum).

<table>
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<th>Sites</th>
<th>Top of Reach</th>
<th>Bottom of Reach</th>
<th>Habitube Placement</th>
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<td>Linnean Park (Upper)</td>
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Table0-2A: Dates for habitube placement and sampling and whether large rain events occurred before sampling.

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<td>4/28/18</td>
<td>6/8/18</td>
<td>Yes</td>
</tr>
<tr>
<td>Jones Falls</td>
<td>4/14/18</td>
<td>5/24/18</td>
<td>No</td>
</tr>
<tr>
<td>Muddy Creek BGE</td>
<td>4/28/18</td>
<td>5/29/18</td>
<td>Yes</td>
</tr>
<tr>
<td>Brampton Hills</td>
<td>4/28/18</td>
<td>6/4/18</td>
<td>Yes</td>
</tr>
<tr>
<td>Moore’s Branch</td>
<td>4/28/18</td>
<td>6/12/18</td>
<td>Yes</td>
</tr>
<tr>
<td>Plumtree Run</td>
<td>4/28/18</td>
<td>6/12/18</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Appendix B – Supplemental Information for Objective 1

Table 0-1B: Spreadsheet from Biohabitat, Inc. that was used to calculate the hydraulic radius for each sampled reach.
Appendix C – Supplemental Information for Objective 2

Figure 0-1C: Percent of each functional feeding group that was collected across all of the sites.
| Order          | Davis(H) | Hawkins(H) | Spa(T) | Spa(H) | Cor(H) | Cor(T) | Gae(H) | Gae(T) | Hae(H) | Hae(T) | Hyae(H) | Hyae(T) | Linn(H) | Linn(T) | Mc(H) | Mc(T) | Mes(H) | Mes(T) | Philip(H) | Philip(T) | Plato(H) | Plato(T) | Pop(H) | Pop(T) | Pul(H) | Pul(T) | Pul(H) | Pul(T) | Siph(H) | Siph(T) | Tip(H) | Tip(T) | Turc(H) | Turc(T) | Ueni(H) | Ueni(T) | Veli(H) | Veli(T) |
|----------------|----------|------------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|--------|--------|--------|--------|---------|---------|---------|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| **Table 6.1C**: Macroinvertebrate families collected across all 10 sites with both sampling methods (upper and lower reaches combined) (H = family was collected within the site) |
Table 0.2C: Spreadsheet from Biohabitats, Inc. that was used to calculate BIBI scores, percent EPT, and identify functional feeding groups for all of the sites.

<table>
<thead>
<tr>
<th>Location</th>
<th>Site</th>
<th>Score</th>
<th>1% EPT</th>
<th>10% EPT</th>
<th>50% EPT</th>
<th>90% EPT</th>
<th>95% EPT</th>
<th>99% EPT</th>
<th>99.5% EPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biohabitats</td>
<td>A</td>
<td>21</td>
<td>15</td>
<td>59</td>
<td>21</td>
<td>59</td>
<td>21</td>
<td>59</td>
<td>21</td>
</tr>
<tr>
<td>Biohabitats</td>
<td>B</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
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<td>12</td>
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</tbody>
</table>

Spreadsheet

Benthic Macroinvertebrate IBL

<table>
<thead>
<tr>
<th>Location</th>
<th>Site</th>
<th>Score</th>
<th>1% EPT</th>
<th>10% EPT</th>
<th>50% EPT</th>
<th>90% EPT</th>
<th>95% EPT</th>
<th>99% EPT</th>
<th>99.5% EPT</th>
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<tr>
<td>Biohabitats</td>
<td>D</td>
<td>12</td>
<td>12</td>
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<td>12</td>
<td>12</td>
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</tbody>
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Table 0-3C: The benthic macroinvertebrate BIBI metrics by strata and threshold values. Corresponds to Table 0-2C.

<table>
<thead>
<tr>
<th>Benthic IBIs (metrics)</th>
<th>Thresholds</th>
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<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Coastal Plain</strong></td>
<td></td>
</tr>
<tr>
<td>Number of Taxa</td>
<td>≥ 22</td>
</tr>
<tr>
<td></td>
<td>14 – 21</td>
</tr>
<tr>
<td></td>
<td>&lt; 14</td>
</tr>
<tr>
<td>Number of EPT</td>
<td>≥ 5</td>
</tr>
<tr>
<td></td>
<td>2 – 4</td>
</tr>
<tr>
<td></td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Number of Ephemeroptera</td>
<td>≥ 2</td>
</tr>
<tr>
<td></td>
<td>1 – 1</td>
</tr>
<tr>
<td></td>
<td>&lt; 1</td>
</tr>
<tr>
<td>% Intolerant Urban</td>
<td>≥ 28</td>
</tr>
<tr>
<td></td>
<td>10 – 27</td>
</tr>
<tr>
<td></td>
<td>&lt; 10</td>
</tr>
<tr>
<td>% Ephemeroptera</td>
<td>≥ 11</td>
</tr>
<tr>
<td></td>
<td>0.8 – 10.9</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>Number of Scrapers</td>
<td>≥ 2</td>
</tr>
<tr>
<td></td>
<td>1 – 1</td>
</tr>
<tr>
<td></td>
<td>&lt; 1</td>
</tr>
<tr>
<td>% Climbers</td>
<td>≥ 8</td>
</tr>
<tr>
<td></td>
<td>0.9 – 7.9</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.9</td>
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<tr>
<td><strong>Piedmont</strong></td>
<td></td>
</tr>
<tr>
<td>Number of Taxa</td>
<td>≥ 25</td>
</tr>
<tr>
<td></td>
<td>15 – 24</td>
</tr>
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<td></td>
<td>&lt; 15</td>
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<tr>
<td>Number of EPT</td>
<td>≥ 11</td>
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<tr>
<td></td>
<td>5 – 10</td>
</tr>
<tr>
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<td>&lt; 5</td>
</tr>
<tr>
<td>Number of Ephemeroptera</td>
<td>≥ 4</td>
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<tr>
<td></td>
<td>2 – 3</td>
</tr>
<tr>
<td></td>
<td>&lt; 2</td>
</tr>
<tr>
<td>% Intolerant Urban</td>
<td>≥ 51</td>
</tr>
<tr>
<td></td>
<td>12 – 50</td>
</tr>
<tr>
<td></td>
<td>&lt; 12</td>
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<tr>
<td>% Chironomidae</td>
<td>≤ 4.6</td>
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<tr>
<td></td>
<td>4.7 – 63</td>
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<td>&gt; 63</td>
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<tr>
<td>% Clingers</td>
<td>≥ 74</td>
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<tr>
<td></td>
<td>31 – 73</td>
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<td>&lt; 31</td>
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<tr>
<td><strong>Combined Highlands</strong></td>
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<td>Number of Taxa</td>
<td>≥ 24</td>
</tr>
<tr>
<td></td>
<td>15 – 23</td>
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<td>&lt; 15</td>
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<tr>
<td>Number of EPT</td>
<td>≥ 14</td>
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<td>8 – 13</td>
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<td>&lt; 8</td>
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<tr>
<td>Number of Ephemeroptera</td>
<td>≥ 5</td>
</tr>
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<td>3 – 4</td>
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<td></td>
<td>&lt; 3</td>
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<tr>
<td>% Intolerant Urban</td>
<td>≥ 80</td>
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<tr>
<td></td>
<td>38 – 79</td>
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<td>&lt; 38</td>
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<tr>
<td>% Tanytarsini</td>
<td>≥ 4</td>
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<td>0.1 – 3.9</td>
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<td>&lt; 0.1</td>
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<tr>
<td>% Scrapers</td>
<td>≥ 13</td>
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<td></td>
<td>3 – 12</td>
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<tr>
<td>% Swimmers</td>
<td>≥ 18</td>
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<tr>
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<td>3 – 17</td>
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<tr>
<td>% Diptera</td>
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<tr>
<td></td>
<td>27-49</td>
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<tr>
<td></td>
<td>&gt; 50</td>
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