Analysis of the D'Olive Creek Watershed: Identifying the Local Drivers That Have led to Stream Degradation

by

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Dedicated to the memory of my grandfather, Robert Victor Raab (1942-2017).

Abstract

Anthropogenic activities have influenced the characteristics of streams and tributaries throughout the Southeastern U.S., correlating with varying levels of degradation and prompting major restoration activities. This anthropogenic impact on fluvial environments can cause extensive, systemic alterations—geomorphology, hydrology, and ecology—and lead to environmental stress. To aid local stream restoration activities, this study identified the drivers of stream degradation in the D'Olive Creek Watershed and contextualized them in relation to the adjacent Fly Creek Watershed, both located in Southern Alabama. Methods included, spatial investigation via the utilization of geographic information systems, and a field data driven case study.

Primary findings reveal that the presence and expansion of impervious surfaces has led to changes in local drainage patterns, resulting in an increase in the volume and velocity of stormwater runoff. Urban expansion and resulting environmental stress is currently occurring in both watersheds, but research indicates that streams and tributaries in the D'Olive Creek Watershed are experiencing more degradation and issues related to sediment erosion and deposition. Key differences highlighted during research are two-part: the D'Olive Creek Watershed is experiencing a higher rate and distribution of urban expansion; and its landscape is steeper, compared to the Fly Creek Watershed. This study has implications for both current watershed restoration efforts and future restoration design, ultimately providing stakeholders with valuable information about the primary drivers of local stream degradation.

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1—Introduction

For thousands of years, humans have exerted influence over natural environments across the globe (Chapin, Matson, & Vitousek, 2012). Similarly, anthropogenic activities have affected river process and form for centuries or even millennia (Wohl & Merritts, 2007). For example, impervious surfaces are ubiquitous in urban areas; these anthropogenic surfaces reroute runoff and pollutants, which can ultimately impact the morphology, water quality, vegetation, and floodplain soils of a local watershed. Regardless of the anthropogenic presence throughout environments across the globe, environmental benchmarks can be set—physical, chemical, and biological—regarding what constitutes a healthy, natural environment for a particular region (Hughes, Larsen, & Omernik, 1986). These parameters are important factors in environmental remediation activities and parallel the concept of "reference conditions." Based on a spectrum of watershed conditions, ranging from reference to disturbed, comparisons and analyses can be made to identify local variables regarding watershed health, drivers of degradation, and restoration goals (Hughes et al., 1986).

Fluvial environments around the world are experiencing significant changes as a result of anthropogenic influence (Wohl, Lane, & Wilcox, 2015). This change parallels an increase in river restoration in many industrialized countries (Wohl & Merritts, 2007). Stream restoration and monitoring of restoration activities require an understanding of immutable controls (e.g. climate and geology) and processes (e.g. delivery of sediment and water) that impact watershed and estuarine ecosystems (Fennessy, 2006); hence the effective management of fluvial systems requires an understanding of the complexities that are inherent in natural systems (Fennessy, 2006; James, 2013; Wohl et al., 2015; Wohl & Merritts, 2007). Several studies reveal that the science of pre- and post-restoration assessment is still in its infancy and suggest that addressing the complexities inherent in natural systems along with long-term monitoring will benefit future analyses (Bennett, Nimmo, & Radford, 2014; Bernhardt et al., 2005; Bernhardt & Palmer, 2011; Lave, Doyle, & Robertson, 2010; Palmer, Hondula, & Koch, 2014; Wohl et al., 2015; Wohl & Merritts, 2007). This gap in the current state of knowledge related to analyzing pre- and post-restoration activities, as well as acknowledging the many factors that contribute to the complex nature of fluvial systems, are the basis for this study.

Research Questions

It is well-documented that anthropogenic activities have influenced the local streams and tributaries in the Mobile Bay area, located in southern Alabama (Figure 1), which has led to detrimental effects such as erosion, sedimentation, and pollution from stormwater runoff (Coffee, 2010; M. Cook, 2007; Ellis, Spruce, Swann, Smoot, & Hilbert, 2011; Estes et al., 2015; Stout, Heck Jr., Valentine, Dunn, & Spitzer, 1998). Local restoration and mitigation activities have been implemented to address these issues (Coffee, 2010). In an effort to aid local stream restoration and enhance the current state of knowledge, this study identified the drivers of stream degradation in the D’Olive Creek Watershed, a critical watershed in the Mobile Bay area (Figure 1). The D’Olive Creek Watershed empties into Mobile Bay and greatly contributes to its environmental quality (Coffee, 2010). Since the 1970s, the watershed has quickly urbanized, correlating with an increase in local stream degradation. Key research questions, therefore, are as follows: What are the critical drivers of stream degradation in the D’Olive Creek Watershed?

How do these drivers compare to those of the Fly Creek Watershed, an adjacent watershed that is in the early stages of urbanization?

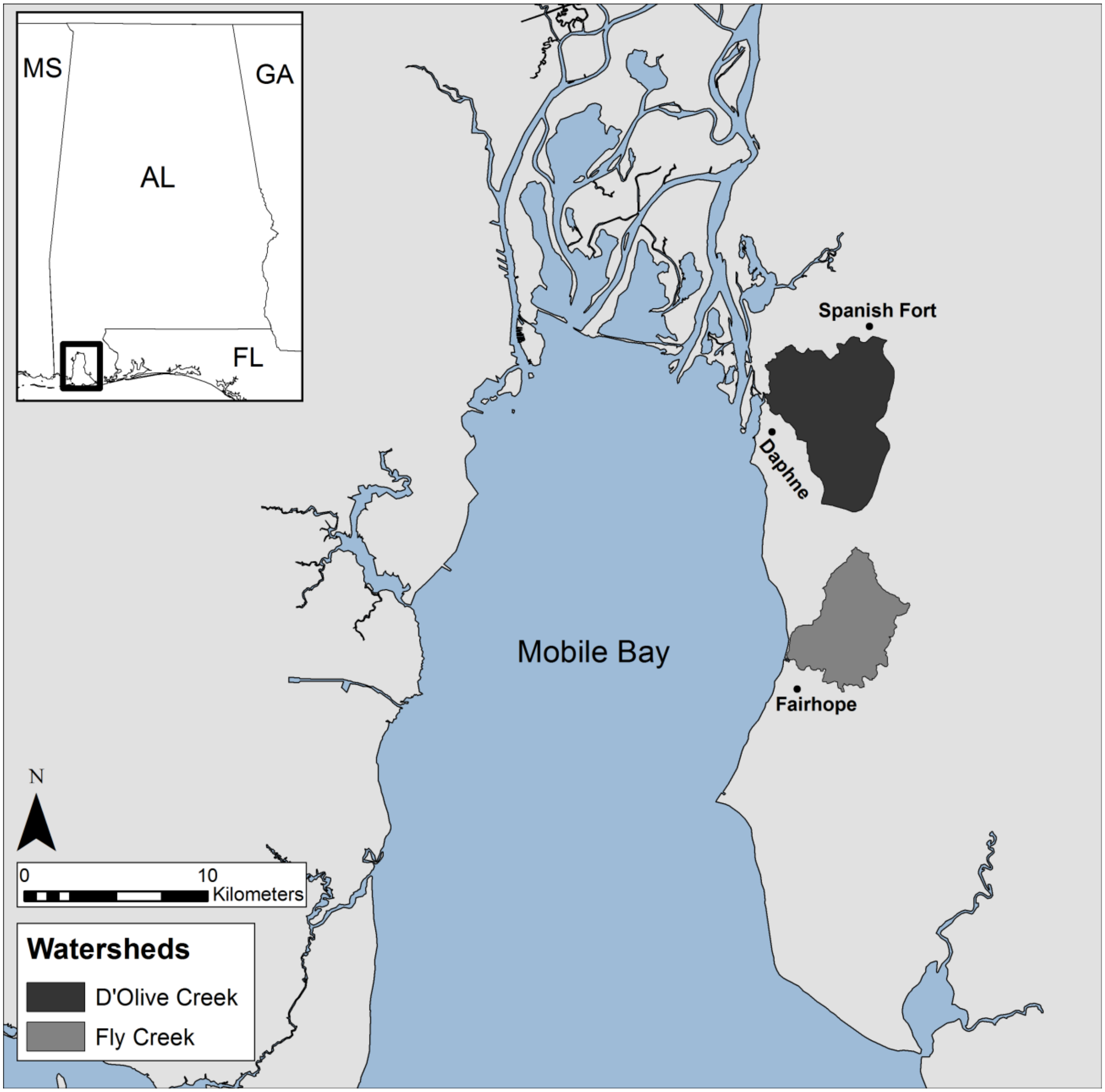


Figure 1: Location of Mobile Bay, D’Olive Creek Watershed, and Fly Creek Watershed.

To address the research questions, I utilized two primary methods: spatial investigation via the application of geographic information systems (GIS) and remote sensing, and a field data driven case study. We hypothesize that impervious surfaces and watershed slope are the critical drivers of stream degradation in the D’Olive Creek Watershed. Assessing local, environmentally detrimental drivers is a crucial step in understanding and mitigating anthropogenic impact on the environment; this is a key research need that has been identified by restoration groups working in the area. This project will provide stakeholders with valuable information regarding the primary drivers of stream degradation in the D'Olive Creek Watershed and will aid in directing relevant mitigation and restoration efforts.

Study Area

Mobile Bay

Mobile Bay is classified as one of the largest and most ecologically significant estuaries in the United States (Stout et al., 1998). Regarding climate and precipitation, the Mobile Bay area is a Humid Subtropical zone (Köppen classification Ca) and the city of Mobile, located directly across the Bay from both watersheds, has an average annual precipitation of approximately 1,680 mm (NWS Mobile/Pensacola). The D'Olive Creek and Fly Creek Watersheds flow into Mobile Bay and are integral parts of the environmental health of the bay. Both watersheds network flow through coastal, non-cohesive soils with no confining bedrock (Coffee, 2010). The network of habitats found in Mobile Bay supports the greatest diversity of species out of all states east of the Mississippi River (Swann & Herder, 2014). Mobile Bay has the fourth largest discharge of all estuaries in the U.S. at 1,800 m^3/s. Mobile Bay has experienced much environmental stress related to anthropogenic activities, specifically urbanization: erosion, sedimentation, and pollution (Coffee, 2010; Ellis et al., 2011; *Fly Creek Watershed Project*, 2013; Stout et al., 1998). This environmental stress has affected many important, natural systems in the area: wetlands, streams, submerged aquatic vegetation (SAV), longleaf pine forests, and maritime forests (Swann & Herder, 2014).

The Mobile Bay National Estuary Program (NEP) was established in 1995 and is a combination of industry, citizen groups, academia, federal, state, and local agencies working together to address local, environmental issues, restoration goals, and related factors (Swann & Herder, 2014). Section 320 of the Clean Water Act (CWA) established the NEP in 1987 to sustain and restore estuaries designated as nationally significant (Swann & Herder, 2014). The NEP encourages local communities to manage waterways in their jurisdiction by initiating collaborative decision-making processes to address and restore the ecological health and water quality of local systems (Swann & Herder, 2014). In the 1990s, Mobile Bay was identified as an estuary of national significance. The estuary has economic importance in recreation, shipping, and fisheries (Ellis et al., 2011).

The Mobile Bay NEP partnered with the National Aeronautics and Space Administration (NASA) in 2008 to analyze land use and land cover (LULC) change around Mobile Bay (Ellis et al., 2011; Swann & Herder, 2014). This study found that, relative to 1974, from 1978 to 2008 urban landscapes consistently increase; there is significant fluctuation in the upland forest and upland herbaceous cover; and woody wetlands slightly increased and non-woody wetlands decreased (Figure 2). This local increase in urban cover correlates with an increase in erosion, sedimentation, and pollution throughout Mobile Bay over the past few decades (Coffee, 2010; Swann & Herder, 2014). It is worth noting that this study also found that from 1974 to 2008, urban coverage increased from 5.59 percent to 8.88 percent along the eastern shore of Mobile Bay, reflecting an overall 59 percent gain in urban cover in this area (Swann & Herder, 2014).

Current research reveals much erosion, sedimentation, and pollution in fluvial environments throughout the Mobile Bay area and correlates it with a local increase in anthropogenic activity (Coffee, 2010; Ellis et al., 2011; *Fly Creek Watershed Project*, 2013;

Stout et al., 1998). Both D'Olive Creek and Fly Creek Watersheds influence the overall environmental quality of Mobile Bay by contributing clean freshwater and organic materials that contribute to the local ecosystem (Coffee, 2010; *Fly Creek Watershed Project*, 2013). The watersheds have also experienced a significant increase in population over the past few decades, which has resulted in related ecological issues (Coffee, 2010; *Fly Creek Watershed Project*, 2013; Stout et al., 1998). Identifying the local drivers of stream degradation will ultimately aid in mitigating anthropogenic impact on the local environment and highlight the most critical factors related to corresponding processes.

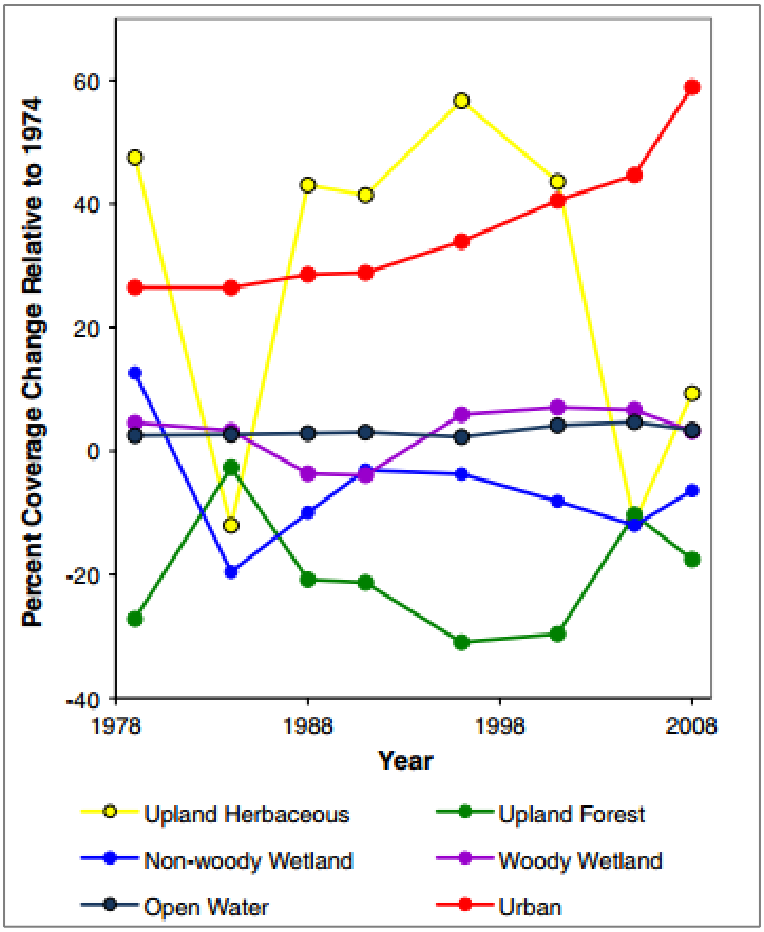


Figure 2: Percent coverage change relative to 1974 for each land use and land cover class for the Mobile Bay Area, from Ellis et al. (2011).

D’Olive Creek Watershed

D’Olive Creek is named after Louis D’Olive, a French settler who first visited the area in the early 1800s. The D’Olive Creek Watershed covers approximately 32 sq. km along the eastern side of Mobile Bay (Figure 3). The watershed was mostly underdeveloped until the late 1960s (Coffee, 2010). Significant amounts of urban development have occurred in this area since the 1970s and have had negative environmental effects: erosion, sedimentation, and pollution (Coffee, 2010). Based on the intense growth that the D’Olive Creek Watershed has experienced, there is a strong possibility that the area could reach a 100% build-out condition by 2020 (Coffee, 2010). Analyzing watershed characteristics will aid in reaching a 100% build-out condition that minimizes environmental impact.

In 2010, a group of public and private participants—city and county governments, private companies, homeowner associations, and government agencies—secured by the Mobile Bay NEP, completed a Watershed Management Plan; this plan is used to aid local restoration efforts (Coffee, 2010). Despite prevailing restoration and mitigation efforts, the watershed still displays much stress from local, urban processes. Streams in parts of the D’Olive Creek Watershed continue to show signs of environmental stress (Coffee, 2010). D’Olive Creek Watershed has experienced a significant amount of urban expansion over the past few decades (Coffee, 2010). Although related issues—erosion, sedimentation, and pollution—are well-known in the literature and restoration activities are being implemented, the area continues to show signs of anthropogenic impact. The inevitable urban expansion calls for identification and detailed analysis of the specific drivers of stream degradation in the watershed. In order for the D’Olive Creek Watershed area to sustainably reach 100% build-out condition with the lowest impact on the local environment, identification of environmentally detrimental factors, thorough monitoring of watershed characteristics, and related restoration activities must be implemented.

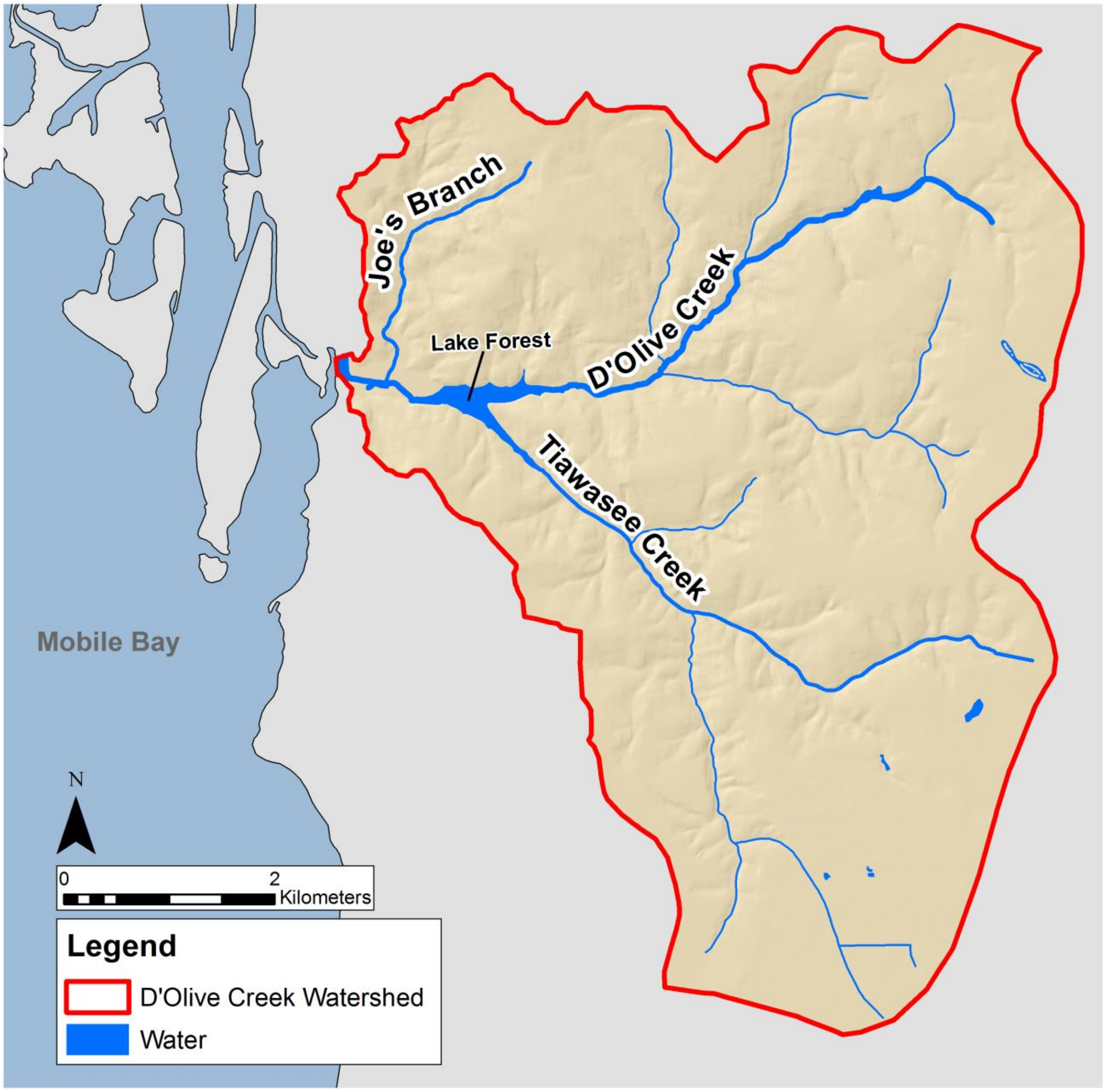


Figure 3: The D’Olive Creek Watershed and its stream network.

Fly Creek Watershed

The Fly Creek Watershed lies along the eastern side of Mobile Bay (Figure 4) and covers approximately 20 sq. km. Similar to the D’Olive Creek Watershed, the Fly Creek Watershed is recognized by the Mobile Bay NEP as being quite ecologically significant. Although the importance of the watershed is well-known, the Mobile Bay NEP currently has no official watershed management plan under development for Fly Creek. Nevertheless, watershed restoration and related activities are occurring in the area and a number of stakeholders are participating: industry, citizen groups, academia, federal, state, and local agencies.

Over the past few decades, an increase in anthropogenic activities parallels a rise in local, environmental stress in the Fly Creek Watershed (*Fly Creek Watershed Project*, 2013). Much urban expansion has also occurred in the area during this timeframe (Stout et al., 1998). The recent expansion of impervious surface in the Fly Creek Watershed, along with the correlating increase in anthropogenic disturbance, parallels local issues in the area—erosion, sedimentation, and pollution—identified in the literature. Based on this, it is apparent that the watershed has experienced (and is still under) environmental stress (Stout et al., 1998). Identifying local stressors is a crucial step in aiding restoration and mitigation efforts, establishing applicable datasets, and addressing factors related to land management.

Figure 4: The Fly Creek Watershed and its stream network.

Urban Expansion, Sediment Load, and Impacted Streams

Urban expansion and resulting environmental stress is occurring in both watersheds, but research indicates that streams and tributaries in the D'Olive Creek Watershed are experiencing more degradation and issues related to sediment erosion and deposition than the Fly Creek Watershed (Coffee, 2010; Cook, 2007; Cook, Moss, Rogers, & Mac, 2014; Cook, 2005, 2017; Swann & Herder, 2014; Vittor, 2010). In the D'Olive Creek Watershed, sediment load problems began to critically affect stream health and become a matter of public concern in the 1970s, after the construction of the Lake Forest subdivision (Swann & Herder, 2014). An erosion study by Crisler for the United States Department of Agriculture (USDA) in 1981 confirmed that the construction of this subdivision is one of the primary sources of excess sediment in the watershed. Similarly, Carlton and Gail reaffirmed this assertion in 1981, supporting that the subdivision is generating much excess sediment due to lack of erosion prevention measures and stormwater. The total amount of eroded sediment that had washed downstream from urban expansion in the watershed increased from approximately 1.03 x 107 kg/yr pre-development to an estimated 6.56 x 107 kg/yr post-development (Isphording et al., 1984). As a result of continued development, over the past decade, areas in the watershed have experienced up to 14 times the expected erosion and deposition rates of a natural watershed. The aforementioned research highlights a trend between urban processes and fluvial environments in the watershed: as construction and urban expansion occur, sediment erosion and deposition increase (Byrnes, Berlinghoff, & Griffee, 2013; Coffee, 2010; Cook, 2007; Cook et al., 2014; Cook, 2005, 2017).

In 2007, Cook assessed how construction and the resulting impervious surfaces influenced sedimentation rates throughout the D'Olive Creek Watershed, including the tributary being used for this study, and concluded that changes in LULC are indeed having a detrimental impact on local streams via amplifying sediment erosion and deposition. Similarly, in 2012, Cook and Moss evaluated sediment loads in the main watershed tributary, D'Olive Creek, and found that the presence and expansion of impervious surfaces has increased total sediment loads 1.4 times beyond the natural geologic erosion rate. Moreover, in 2016, Cook measured sedimentation rates along the tributary being used for this study and found that from 2006 to 2016, bed sediment transport doubled during moderate to high flows and suspended sediment also increased. When paired with the LULC trends, these data support the conclusion that the occurrence of sediment erosion and deposition throughout local streams and tributaries is caused by urbanization. Monitoring of sediment transport and sediment impaired stream reaches is not occurring in the Fly Creek Watershed currently, but local stakeholders have acknowledged that the majority of stream degradation within the watershed relates to erosion and sedimentation resulting from urban expansion (*Fly Creek Watershed Project*, 2013).

Currently, all the streams and tributaries in the D'Olive Creek Watershed are listed as non-supportive of their designated use under section 303(d) of the CWA, with the source of degradation predominantly being land development resulting in siltation. The primary named tributaries, D'Olive Creek, Joe's Branch, and Tiawassee Creek, have all been listed under section 303(d) of the CWA since 2008 with medium priority, overall. In contrast, streams and tributaries in the Fly Creek Watershed are only recently displaying similar signs of degradation (*Fly Creek Watershed Project*, 2013). The primary named tributary, Fly Creek, was just listed in 2018 as non-supportive of its designated use under section 303(d) of the CWA, with the source of degradation being pasture grazing resulting in pathogens and deemed a low priority. It is worth noting that the Fly Creek Watershed is experiencing a lower rate and distribution of urban expansion, compared to the D'Olive Creek Watershed (*Fly Creek Watershed Project*, 2013).

Study Sites

Field research was performed along a stream reach in the D’Olive Creek Watershed at three designated sites: impaired, restored, and reference (Figure 5). All sites are along the same reach, and thus they share many of the same environmental characteristics. The impaired site, farthest downstream, was chosen because of the presence of impervious surfaces located upstream (Figure 6 A-C). The restored site, centermost location, was designed based on a hybrid between the natural channel design method (Rosgen, 1996) and a modified hydraulic design aimed at emulating local, natural hydrology (Figure 7). The reference site, farthest upstream, flows into the eastern boarder of the restored site and is heavily forested upstream (Figure 8). Because of the land use history of Southern Alabama, this is not a pristine reference site, but rather a post-agricultural reforested stream; thus, there may be legacy effects of prior land use on vegetation, sediment, and geomorphology.

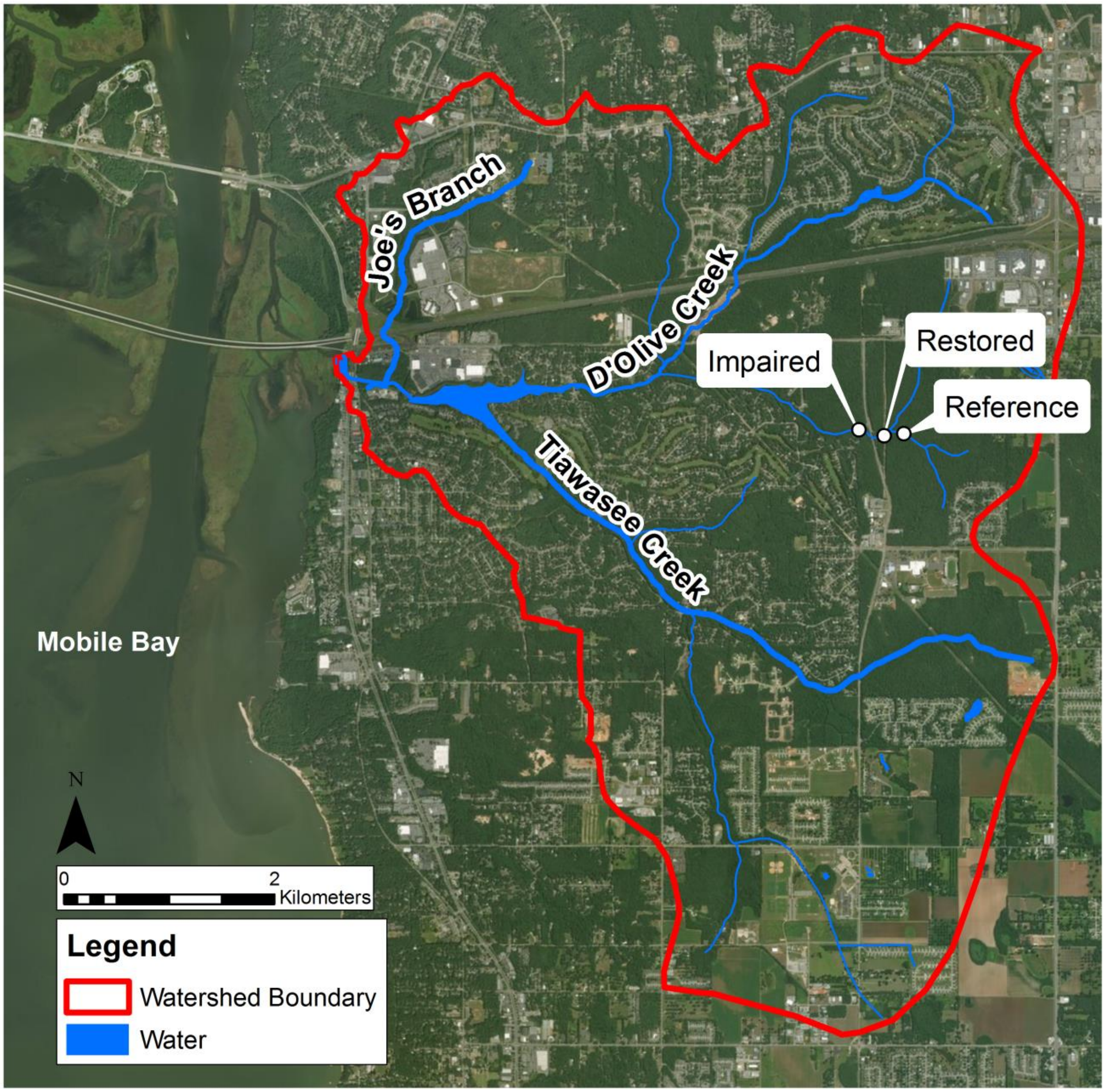


Figure 5: Location of field sites in the D'Olive Creek Watershed: impaired, restored, and reference.

Figure 6 A, B, and C:
Reference images of the impaired location
A) Looking upstream at the impaired tributary;
B) Concrete channel located upstream of site;
C) Culvert located upstream of site.

Figure 7: The use of rock material (e.g. boulders) and riparian vegetation to modify flow dynamics at the restored site, following a hybrid natural channel design and modified hydraulic design method (Rosgen, 1994).

Figure 8: Looking upstream towards forested area at the reference tributary.

2—Background

Urbanization and Watersheds

Local changes in LULC are significant because natural land cover provides ecosystems with vital, environmental components: energy resources; clean air and water; the production of food and fiber; and biodiversity (J. L. Huang & Klemas, 2012; Napton, Auch, Headley, & Taylor, 2010). Anthropogenic activities related to LULC can have negative effects on fluvial systems. Urbanization of watersheds can have detrimental impacts on stream systems—including, increased sediment loads, flow variability, and increased discharge—which relates to the impervious surfaces inherent in urban cover (Chin, 2006; Poff, Bledsoe, & Cuhaciyan, 2006; Wolman, 1967). Impervious surfaces are defined as any surface that is impenetrable to water: sidewalks, roofs, driveways, parking lots, and so forth (Weng, 2012). These surfaces alter natural patterns of runoff and rainwater infiltration, which can amplify problems related to erosion, sedimentation, and pollution (Figure 9). Thus, understanding anthropogenic impact, both the direct and indirect effects, on these systems is crucial for research and management efforts (Caldwell, Sun, McNulty, Cohen, & Moore Myers, 2012; Poff et al., 2006).

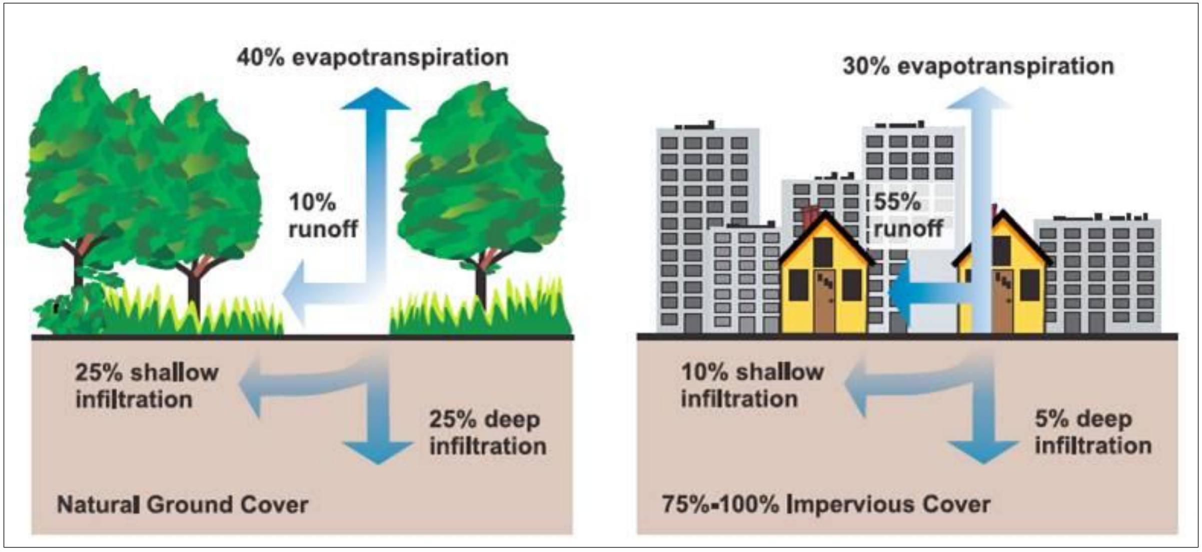


Figure 9: Relationship between impervious surfaces and surface runoff: natural ground cover typically has a 10% rate of surface runoff; in contrast, an area with 75-100% impervious cover has a 55% rate of surface runoff, from U.S. Environmental Protection Agency, (2008).

Impervious surfaces in a watershed can have detrimental impacts on local streams in two primary ways: an increase in the rate and quantity at which runoff is delivered to stream channels; and an increase in the pollutant load that is discharged (Lord, Germanoski, & Allmendinger, 2009). Similarly, changes in channel characteristics and sediment yield accompany changes in land use in a watershed (Figure 10) (Wolman, 1967). According to Wolman (1967), the process of urbanization that is reflected in system characteristics consists of three stages: a landscape that is primarily forested or agricultural and associated with initial stable or equilibrium conditions; a stage where bare land is exposed to erosion, associated with construction; and a new urban landscape dominated by impervious surfaces. As forested or agricultural lands are cleared and erosion increases, the dynamic equilibrium is altered due to an increase in sediment and eventually a new equilibrium or disequilibrium is reached (Chin, 2006; Lord et al., 2009; Wolman, 1967). Urbanization in a watershed generates an initial phase of increased sediment production and deposition within the system, followed by another phase of decline where increased runoff leads to erosion and enlarging channels. These two phases contribute to fluctuations in channel stabilization and system equilibrium and, given their inherent changing nature, can pose problems for management (Chin, 2006).

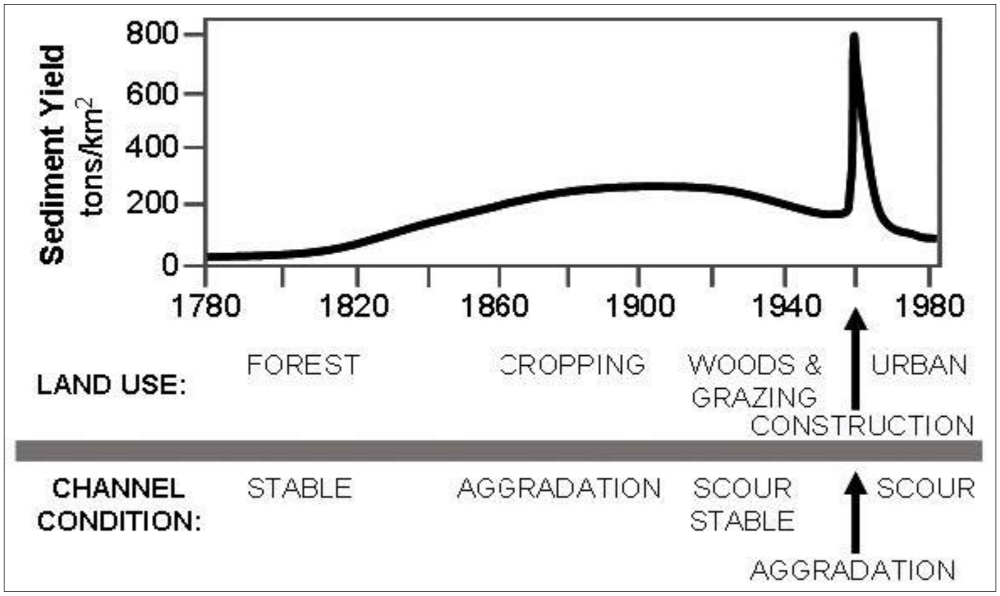


Figure 10: Change in sediment yield through time as land use changes, from Wolman (1967) and modified by Lord et. al (2009).

There is a dynamic, interconnected relationship between land use, hydrology, geomorphology, and ecology of streams (Figure 11). Moreover, in fluvial systems there is a natural upstream to downstream linear relationship. Processes that occur upstream dictate downstream characteristics (Ibisate, Ollero, & Díaz, 2011). Similarly, the impact of urbanization on fluvial systems often extends downstream (Gregory, Davis, & Downs, 1992; Keen-Zebert, 2007). Landscape changes resulting from urbanization ultimately affect the controls on channel morphology: geomorphology, hydrology, and ecology (Keen-Zebert, 2007). Furthermore, streams are not static, and urban streams should be considered a different system if there are not new sediment inputs (Shepherd, Dixon, Davis, & Feinstein, 2010).

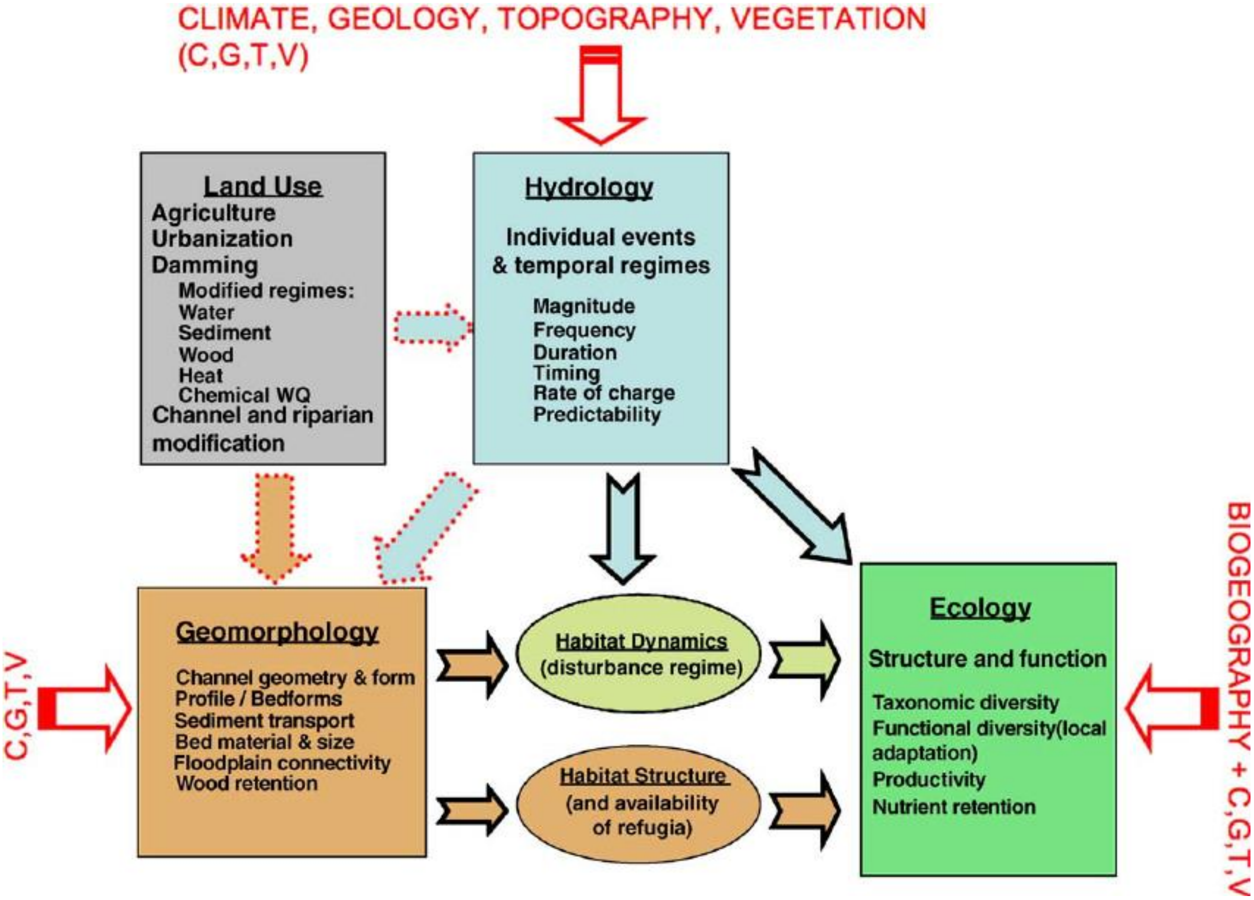


Figure 11: Relationship between land use, hydrology, geomorphology and ecology of fluvial systems. Terms in red indicate extrinsic controlling factors, from Poff et al. (2006).

The relationship between watershed urbanization and alteration of stream morphology is well-documented (Booth, Roy, Smith, & Capps, 2016; Caldwell et al., 2012; King et al., 2005; Ladson, Walsh, Fletcher, Cornish, & Horton, 2004; Leopold, 1968; Wickham, Wade, & Norton, 2014). Characteristics of urban stream syndrome are commonly found in urbanized watersheds worldwide: altered channel geomorphology and stability; a flashier hydrograph; reduced biotic richness; elevated concentrations of nutrients and contaminants, all in response to urban processes (Booth et al., 2016; Halstead, Kliman, Berheide, Chaucer, & Cock-Esteb, 2014; Walsh et al., 2005; Wickham et al., 2014). Different stream types will display variations in degree and type of degradation, depending on mode of sediment of transport (suspended load versus bedload); relative erodibility of banks and bed; entrenchment; scale; spatial configuration of urban land use and its proximity to stream channels; and other related factors (Bledsoe & Watson, 2001; King et al., 2005; Walsh et al., 2005). Nonetheless, as a watershed urbanizes, there are common stream channel phenomena observed: an increase in stream velocity, volume of water, and discharge; channel deepening and widening; disrupted natural flow regime (i.e. stream flashiness); degradation of riparian vegetation; and alterations to channel slope (Hupp & Osterkamp, 1996; Ladson et al., 2004; Leopold, 1968; Roodsari & Chandler, 2017; Vietz, Walsh, & Fletcher, 2015; Walsh et al., 2005; Wickham et al., 2014). As urban cover increases in a watershed, so does the need to understand the principles of urban stream behavior and implement related mitigation and restoration efforts (Wolman, 1967).

River Restoration

In the United States alone, billions of dollars are being spent on river restoration annually (Bernhardt et al., 2005; Bernhardt & Palmer, 2011). Common goals for restoration efforts in the U.S. include, enhancing water quality, managing riparian zones, improving in-stream habitat, stabilization banks, and providing fish passage. Some restoration projects also have goals of modifying flows, reconnecting floodplains, improving aesthetics or recreation, and reconfiguring river and stream channels (Bernhardt et al., 2005; Palmer et al., 2014). Although the overall consensus confirms that river restoration is important, what constitutes a successful restoration is still contested (Bernhardt et al., 2005; Lave, Doyle, & Robertson, 2010; Palmer et al., 2014; Wohl & Merritts, 2007).

How is restoration success measured? Also, what is measured? The process and science of pre- and post-restoration assessment is in its infancy (Bernhardt et al., 2005; Lave et al., 2010; Palmer et al., 2014; Wohl & Merritts, 2007). The dynamic nature of fluvial systems, along with situational factors and goals (e.g. stakeholders, stream location, scale of study, and so forth), contributes to the fuzziness of what constitutes restoration success (Bernhardt et al., 2005; Wohl & Merritts, 2007). Therefore, outlining river restoration science in the U.S. is an essential step for the progression of restoration theory and practice, and thus this study.

The History of River Restoration in the U.S.

Rivers have been manipulated by people for recreational and aesthetic purposes for over a century. However, until the end of the 20th century, river manipulation for recreational and aesthetic purposes endured as the exception to a more universal approach of river management that focused on improving navigation and reducing the risks of loss of life and property (Wohl et al., 2015). This management model led to the modification of rivers throughout North America that typically focused on creating navigable river corridors, which resulted in geomorphically simplified and uniform river channels with less ecological diversity. Historically, increasing recognition of how these past river engineering projects extensively altered rivers, paralleled a growth in river restoration activities (Wohl et al., 2015).

In 1972, the CWA broadened the goals of restoration projects to include improving water quality via reducing inflow of toxic substances and/or organic pollution from point and nonpoint sources (Lave et al., 2010; Wohl et al., 2015). Section 404 of the CWA also makes it hard for relevant stakeholders to culvert or reroute spatially inconvenient streams without significant contribution to restoring a comparable stream (Lave et al., 2010). In the 1980s, restoration theory and practice began to gain momentum in the scientific community, and the number of related research publications rose exponentially from the 1990s into the twenty-first century (Lave et al., 2010; Palmer et al., 2014).

Modern river restoration science has placed an increasing focus on several types of process-based restoration efforts, correlating with calls from researchers to emphasize river function and/or process, instead of only river form (Wohl et al., 2015). Over the past few decades, the scientific nucleus of river restoration has shifted from the public sector (i.e. academia and federal research agencies) to the private sector (Lave et al., 2010). This shift to the private sector has had much impact on the path of restoration science and was primarily influenced by the theories of one individual: Dave Rosgen (Lave et al., 2010; Palmer et al., 2014).

The Rosgen Wars

Dave Rosgen is a Professional Hydrologist, Geomorphologist, and owner of Wildland Hydrology, a restoration-based consulting company that he established in 1985 (Lave et al., 2010). The Rosgen classification system (Rosgen, 1994) and his natural channel design (NCD) methods (Rosgen, 1996) are the most commonly used approaches during restoration projects, yet they are controversial topics within the domain of stream restoration science (Lave et al., 2010; Palmer et al., 2014; Wohl et al., 2015). There is an unfounded assumption within these approaches implying that once the channel can handle prevailing flow and fluxes in sediment, then ecological processes will be restored, known as the “field of dreams hypothesis” (Palmer et al., 2014). This assumption, along with the privatization of river restoration science evolving alongside the creation and growing popularity of Rosgen’s methods, are two of the many factors that have influenced the “Rosgen Wars” within restoration science (Lave et al., 2010; Palmer et al., 2014; Simon et al., 2007).

The NCD approach has three main components: a universally applicable classification system that categorizes channels into nine categories based on evaluations of their form (Figure

12); standardized restoration structures and methods for implementing channel designs; and a set of restoration design guidelines that specify a 40-step design process (Rosgen, 1994). This method is generally excluded from standard engineering continuing education courses (e.g. the American Society of Civil Engineers) and university curricula because of the federal and academic opposition to his work (Bernhardt & Palmer, 2011; Lave et al., 2010; Simon et al., 2007). Thus, to promote his design approach and classification system, Rosgen developed a series of four short courses. These courses are heavily attended by private consultants and agency staff and can cost between $1,500-3,000 per person. After completing the 29-day course, participants become Rosgen-certified, which is a preferred training requirement being emphasized by a growing number of agencies for consultants bidding on projects (Lave et al., 2010).

Since the mid-1990s, Rosgen’s methods have become widely adopted within stream restoration efforts, but an increase in criticism from public sector scientists has paralleled this growing popularity (Lave et al., 2010; Simon et al., 2007). These methods answer the increasing calls for modern scientists to produce applied science that can form the basis for new markets in ecosystem services; be used by agencies to justify decisions; and be taught (and bought) as a standardized package. The acceptance of Rosgen as the scientific expert and the growth of private engineering firms that conduct restoration have contributed to the shift of restoration science out of the public sector (Lave et al., 2010). Nonetheless, addressing the complexities of fluvial systems and moving away from the Rosgen’s methods to expand the scope of river restoration is the current trend identified in the literature (Bernhardt & Palmer, 2011; Lave et al., 2010; Palmer et al., 2014; Simon et al., 2007; Wohl et al., 2015).

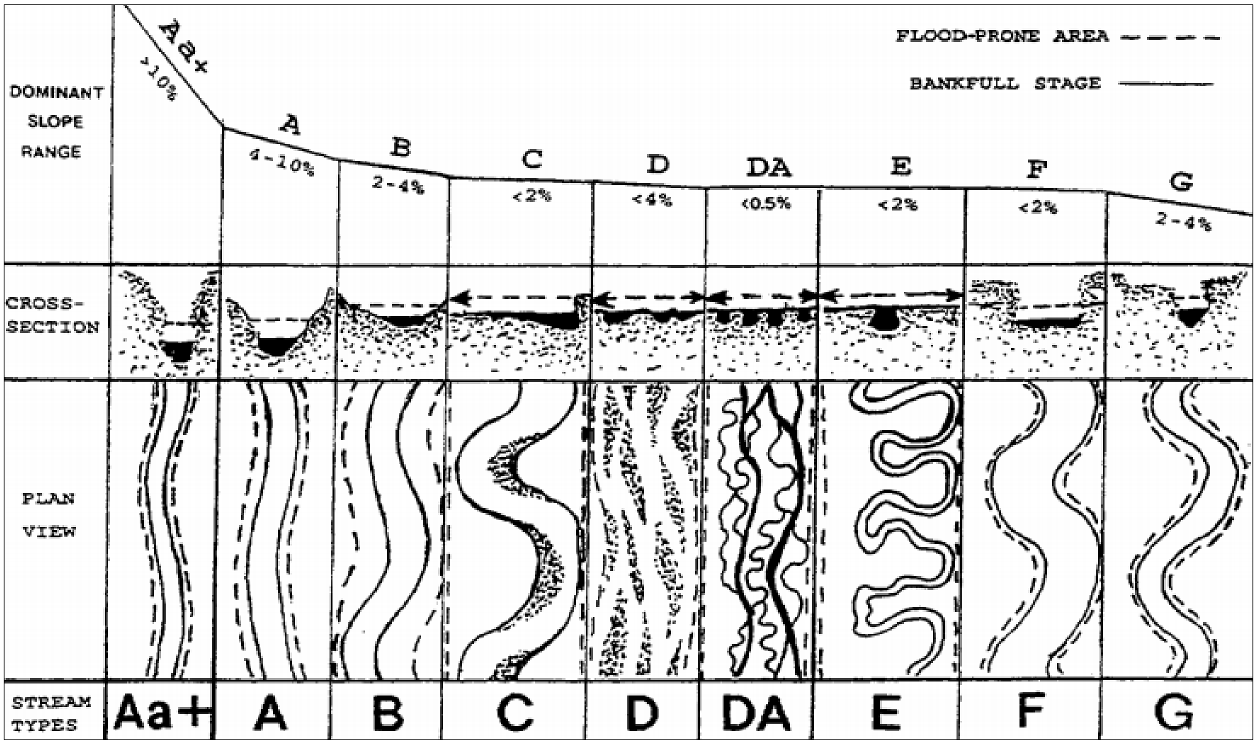


Figure 12: Comparison of longitudinal, cross-sectional, and plan views of Rosgen's nine major stream types. During Rosgen classification, stream type is further categorized into numbered sub-divisions based on entrenchment-ratio, width/depth ration, sinuosity, slope, and channel material, from Rosgen (1994).

From Degradation to Restoration

A seminal concept in the realm of physical geography is the assertion that causal variables will differ with changes in spatial and temporal scale (Schumm & Lichty, 1965). What defines degradation and "natural conditions" will vary with the location and scale of a specific study (Hughes, Colston, & Mountford, 2005; Wohl & Merritts, 2007). Furthermore, the assumption that river instability does not exist outside of anthropogenic perturbations is incorrect, as the existence of stability depends on the scale of reference (Hughes et al., 2005; Wohl & Merritts, 2007). Similarly, the function and form of a geomorphic system is the end product of several dynamic processes that interact and operate at many scales (De Boer, 1992;

Schumm & Lichty, 1965). Every geomorphic system is hierarchical and composed of multiple lower-level systems that contribute to the higher-level system; thus, as the scale changes, so does the interpretation of the specific system (De Boer, 1992; Leopold, Wolman, & Miller, 1965; Schumm & Lichty, 1965). Together, these variables and their relationship with scale affect specific research inquiries, such as river restoration theory and practice, as many related factors vary with changes in temporal and spatial scale: drivers of degradation, success of a restoration project, and what are considered natural conditions for the specific system (Bernhardt & Palmer, 2011; Sear, 1994; Wohl & Merritts, 2007).

Humans have been altering river process and form for centuries or even millennia, which has influenced current river characteristics across the globe and affected the understanding of what is perceived as a natural river and how rivers should naturally behave (Wohl & Merritts, 2007). Together, these expectations and ambiguities of what is natural, along with the aforementioned concept of scale, can inaccurately guide the policies of river restoration projects (Wohl & Merritts, 2007). It is important to analyze constructions of “natural” to fully understand situations that involve it. When identifying degradation and establishing restoration goals, addressing scale and understanding the factors that contribute to defining natural conditions is a critical step (Bernhardt & Palmer, 2011; Wohl & Merritts, 2007).

A holistic, systemic view of fluvial systems throughout restoration efforts is the current scientific movement identified in the literature (Jähnig et al., 2011; Palmer et al., 2014; Violin et al., 2011; Wohl et al., 2015). Typically, restoration projects have been performed at the reach scale, yet the sources of degradation are often beyond this scale in the watershed (Palmer et al., 2014). This limits restoration efforts and does not address the dynamic nature of fluvial systems. In contrast, sustainable and successful restoration efforts should focus on addressing the source(s) of degradation, rather than simply modifying river characteristics (Palmer et al., 2014). Restoration theory suggests that, instead of altering river features, mitigating the stressor(s) of a river at a larger scale—such as uncontrolled runoff, non-native vegetation, or pollutant inputs—will allow it to recover on its own (Falk, Palmer, & Zedler, 2006; Wohl et al., 2015). Therefore, understanding the drivers of change in fluvial systems is key to fully addressing their dynamic nature and promoting successful restoration efforts (Palmer et al., 2014; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980).

Even with the growing acknowledgement of addressing the complexities of fluvial systems at multiple scales; properly defining natural conditions; and contextualizing river restoration and process outside of the river corridor, persistent themes have been emphasized by the research community: a high number of projects do not improve river function in the context of biological communities or water quality; there is limited monitoring of projects to objectively and quantitatively measure restoration success; and incorporating the nonscientific community into river restoration efforts is essential (Bernhardt & Palmer, 2011; Violin et al., 2011; Wohl et al., 2015). Thus, key challenges that currently face river restoration theory and practice include: conceptualizing river restoration and how projects are approached; developing restoration projects in relation to the science of restoration itself; and at the interface of science and society (Wohl et al., 2015).

Each restoration project will ultimately have different goals, but broadly conceptualizing river dynamics will inform the identification of restoration goals or objectives, and in turn, address how the success of the restoration process is measured (Palmer et al., 2014; Wohl et al., 2015). Acknowledging the spatial and temporal variability of river dynamics is also an important factor when conceptualizing river restoration. Recognizing this variability addresses related points: the dynamic nature of fluvial systems; the fault in attempting to restore a stream to a previous state; and it fosters an understanding that the diversity and dynamics of rivers are important for sustainable restoration (Leopold et al., 1965; Schumm & Lichty, 1965; Wohl et al., 2015). If a clear conceptualization of river dynamics is developed, river restoration must be considered in reference to its social context because: who has standing to set objectives for the river will vary with each project; and the acceptance of restoration outcomes by those who live in close proximity to a river may affect the initial implementation of the project (Wohl et al., 2015).

Acknowledging the complex relationships inherent to fluvial systems is a critical step for the progression of restoration theory and practice (Bernhardt & Palmer, 2011; Jähnig et al., 2011; Palmer et al., 2014; Wohl et al., 2015). Moreover, it is understood that not every restoration project will have extensive monitoring, but standardized methods regarding pre- and post-assessment could aid in clarifying what constitutes restoration success (Bernhardt et al., 2005). Together, considering scale and natural conditions when defining degradation; acknowledging the complex variability of fluvial systems; conceptualizing river dynamics; and understanding the drivers of change in these environments will improve future decisions related to watershed management and further the progression of restoration theory and practice (Jähnig et al., 2011; Kondolf & Micheli, 1995; Palmer et al., 2014; Wohl & Merritts, 2007).

3—Methods

During this investigation, two primary methods were implemented: spatial investigation via the utilization of GIS and remote sensing, and a field data driven case study. Throughout the preliminary stage of research, stakeholders involved with projects in the watersheds were contacted to obtain literature and data deemed relevant for this study. Together, information obtained from the preliminary stage and GIS data were utilized to identify the critical drivers that influence stream degradation in both watersheds. After this stage, the field data driven case study was performed to assess these results. Field research included stream surveying and vegetation analysis. The combination of these methods should aid identifying gaps in the current state of knowledge, clarifying existing points, and developing new ideas.

Geographic Information Systems

This study employed GIS to tackle two critical factors related to the D'Olive Creek and Fly Creek Watersheds: local LULC change, and morphometric analysis. To create the land cover change maps, 2001 and 2011 land cover data were downloaded from the National Land Cover Database (NLCD) and imported into ArcMap; NLCD rasters were then clipped to each watershed; and land cover percentage change (urban and non-urban) was calculated using raster statistics. DEM data were obtained through the United States Geological Survey (USGS) and America View. For each watershed, slope was calculated in ArcMap by converting the DEM (10 m) to a slope raster using the slope function; and zonal statistics as table function was used to calculate average. The slope for individual streams was also calculated using this method but used only elevation data for the individual stream lines instead of the entire watershed. Sinuosity, stream length, and drainage density were all calculated using the stream toolbox from Dilts (2015), with tool inputs being the streamline shapefiles and study DEM.

Field Data Driven Case Study

Stream Surveying

Reach scale stream surveys were performed at each of the three sites, including a longitudinal profile, one to three cross-sections (Appendix A), and pebble counts according to standard methods (Harrelson, Rawlins, & Potyondy, 1994; Kondolf & Piégay, 2005; Wolman, 1954). Due to stream incision and geomorphic instability, only one cross-section was possible at the impaired site. Longitudinal profile and cross-section data were collected using a Trimble S6 5: Robotic Total Station (Figures 13, 14, and 15). Geographic coordinate and elevation data (x, y, and z) for water level, centerline, thalweg, and bankfull height were collected over a distance of 10 to 20 channel widths (Harrelson et al., 1994).

Pebble counts were performed at each cross-section using the adapted Wolman method (Harrelson et al., 1994; Kondolf & Piégay, 2005; Wolman, 1954). The b-axis (medial axis) of particles greater than 2 mm was measured with a ruler. Particles that were less than 2 mm were measured qualitatively by moving the sediment between the forefinger and thumb. Survey data were input into the Ohio Department of Natural Resources STREAMS Module (Ward, Mecklenburg, D’Ambrosio, & Witter, 2011), a set of Excel spreadsheets that calculates geomorphic metrics: bankfull characteristics, hydraulic radius, shear stress, stream power, and other related data. These data were used to classify each reach according to Rosgen’s methods (Rosgen, 1996; Rosgen, 1994) and make quantitative comparisons between the study sites. Due to the temporal extent of this project, field research was only performed in the D'Olive Creek Watershed.

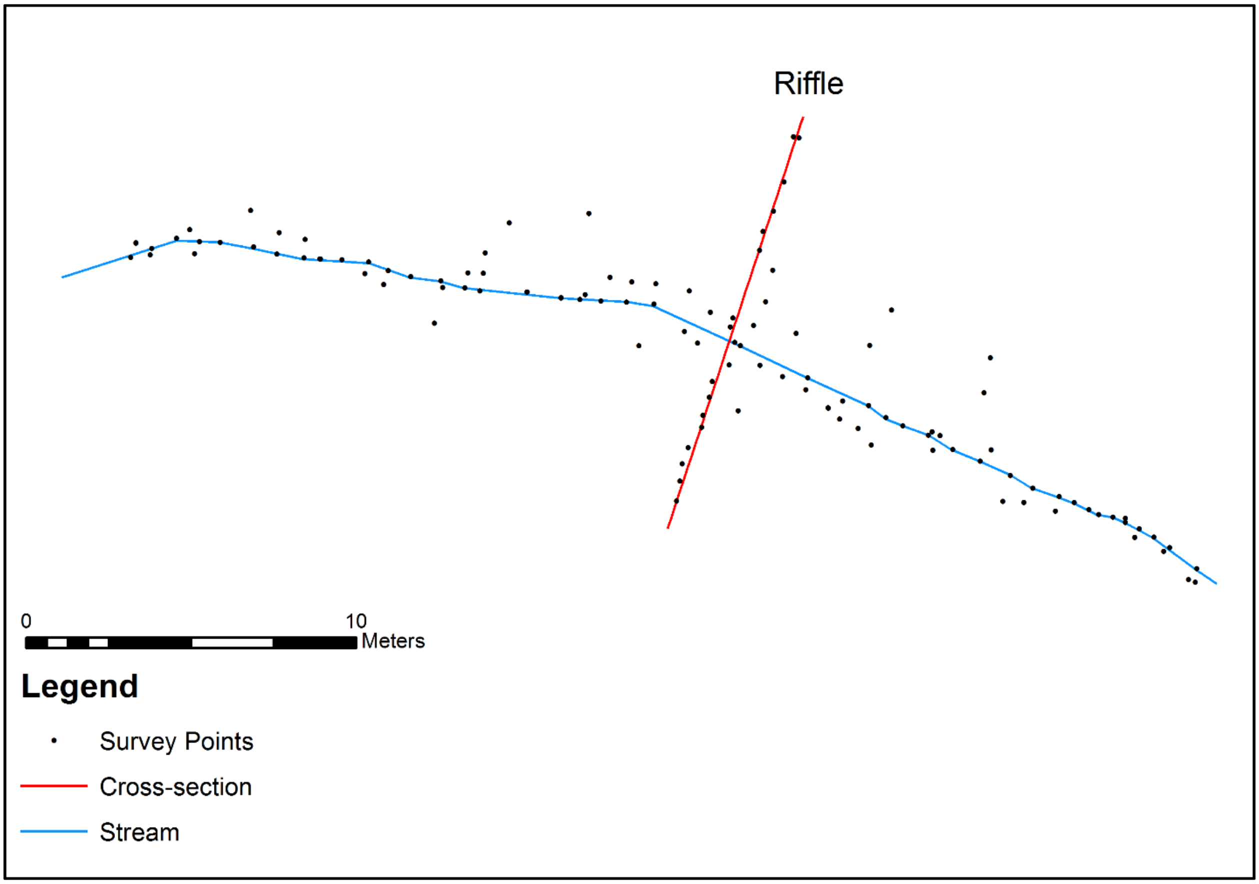


Figure 13: Longitudinal and cross-section survey points of impaired site.

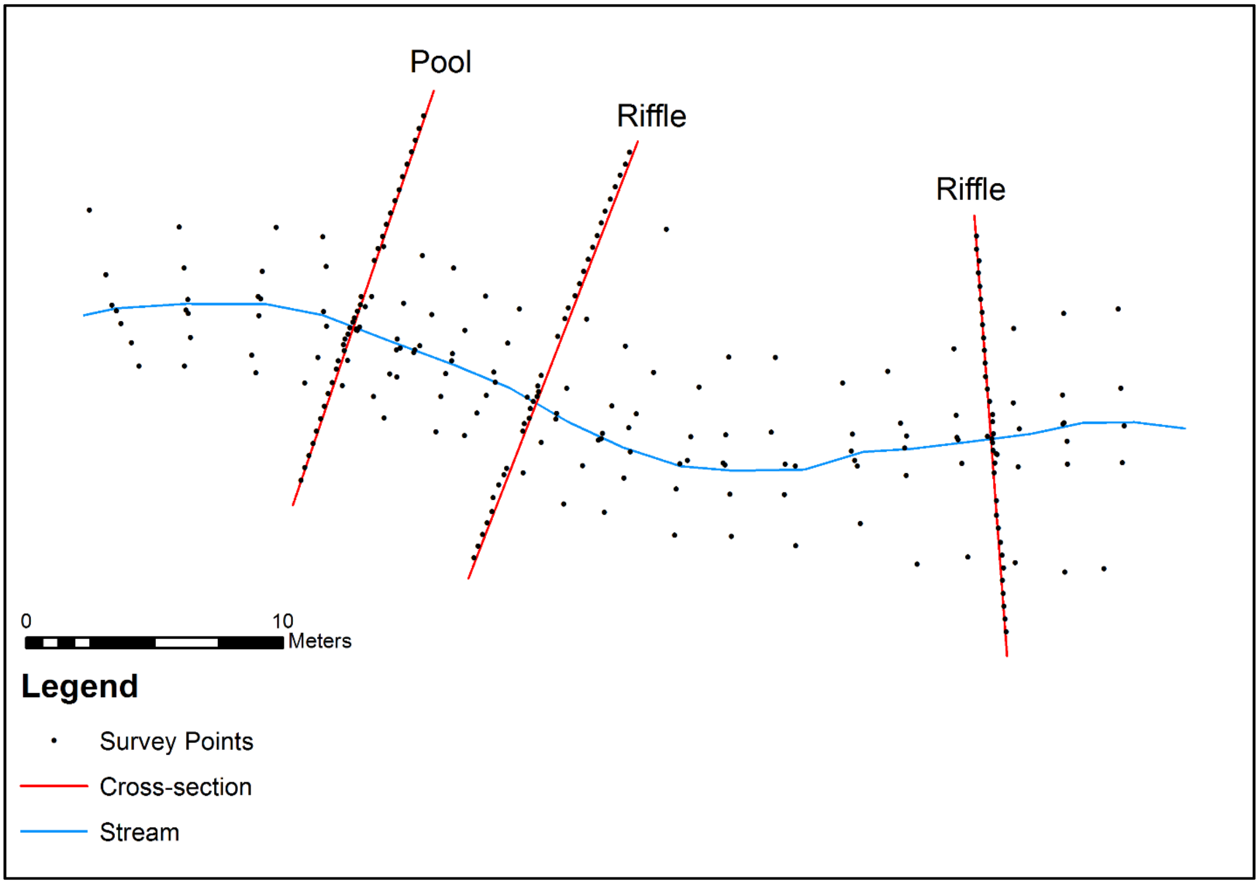


Figure 14: Longitudinal and cross-section survey points of restored site.

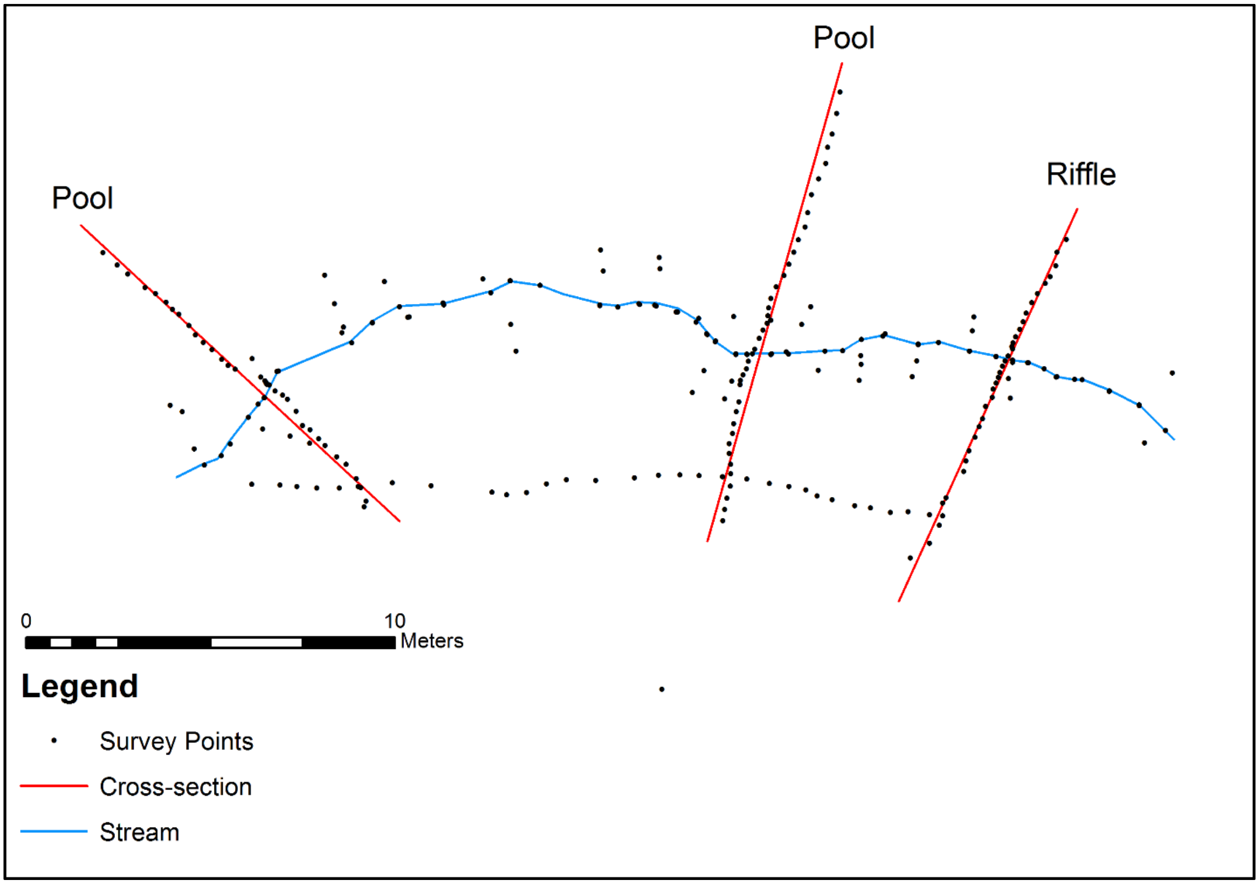


Figure 15: Longitudinal and cross-section survey points of reference site.

Vegetation Analysis

Vegetation analyses were conducted using adapted methods from the North Carolina State University Rapid Stream Assessment Protocol (Appendix B) ("NCSU Stream Restoration Program," n.d.), which documents metrics such as structural complexity and species diversity; planted trees, shrubs, and/or livestakes; invasive exotic species; streambank root mass; floodplain connection; vegetated buffer width; floodplain habitat; floodplain encroachment; percent exposed bare ground; and stormwater outfall quality. Each category is graded on a scale ranging from one to four; this data is used to quantitatively evaluate the characteristics of riparian vegetation at each site and can be used collectively to grade each site from 0 to 100 (where 100 represents perfect conditions). Vegetation surveys were conducted along cross-section transects from the top of stream bank to 10 m of floodplain on both sides of the stream. If the floodplain was not 10 m in length, the vegetation survey was conducted to the edge of valley.

4—Results

Primary findings reveal that the presence and expansion of impervious surfaces has led to changes in local drainage patterns, resulting in an increase in the volume and velocity of stormwater runoff. Key differences highlighted during research are two-part: the D'Olive Creek Watershed is experiencing a higher rate and distribution of urban expansion; and its landscape is steeper, compared to the Fly Creek Watershed. Field research showed that the impaired stream site displays characteristics of hydrogeomorphic and ecological changes related to anthropogenic influence via upstream impervious surfaces.

GIS Investigation

Along the eastern shore of Mobile Bay, the northeastern area displays the highest elevation (Figure 16). Spatial analysis of land cover change from 2001 to 2011 in the D'Olive Creek Watershed revealed non-urban, no change 49% (16 sq. km); non-urban to urban 12% (4 sq. km); and urban, no change 39% (12 sq. km) (Figure 17). The D'Olive Creek Watershed has an average slope of 6.24% and an average stream network slope of 1.64%. The three major tributaries in the watershed—Joe's Branch, D'Olive Creek, and Tiawasee Creek—have slopes of 1.6%, 0.58%, and 0.88%, respectively. The watershed has an average sinuosity of 1.04; a stream network length of 34.56 km; a major tributary sinuosity of 1.20; and a drainage density of 1.08 km/km2 (Figure 18). Spatial analysis of land cover change from 2001 to 2011 in the Fly Creek Watershed revealed non-urban, no change 84% (17 sq. km); non-urban to urban 6% (1 sq. km); and urban, no change 10% (2 sq. km) (Figure 19). The Fly Creek Watershed has an average slope of 4.44% and an average stream network slope of 1.08%. Fly Creek has a slope of 0.46%. The watershed has an average sinuosity of 1.06; a stream network length of 24.6 km; a major tributary sinuosity of 1.75; and a drainage density of 1.23 km/km2 (Figure 20).

From 2001 to 2011 the D’Olive Creek Watershed experienced approximately twice the amount of urban expansion, compared to the Fly Creek Watershed (12% and 6% non-urban to urban land cover change, respectively). The D’Olive Creek Watershed has a steeper average watershed slope (6.24% and 4.44%, respectively); a steeper average stream network slope (1.64% and 1.08%, respectively); a lower average sinuosity (1.04 and 1.06, respectively); a lower major tributary sinuosity (1.20 and 1.75, respectively); and a lower drainage density (1.08 and 1.23 km/km2), compared to the Fly Creek Watershed. The D’Olive Creek Watershed also has a higher maximum elevation (62 m and 46 m, respectively), and its boundary encompasses some of the highest elevations along the eastern shore of Mobile Bay. Table 1 displays a summary of the characteristics for each watershed calculated during the GIS investigation.

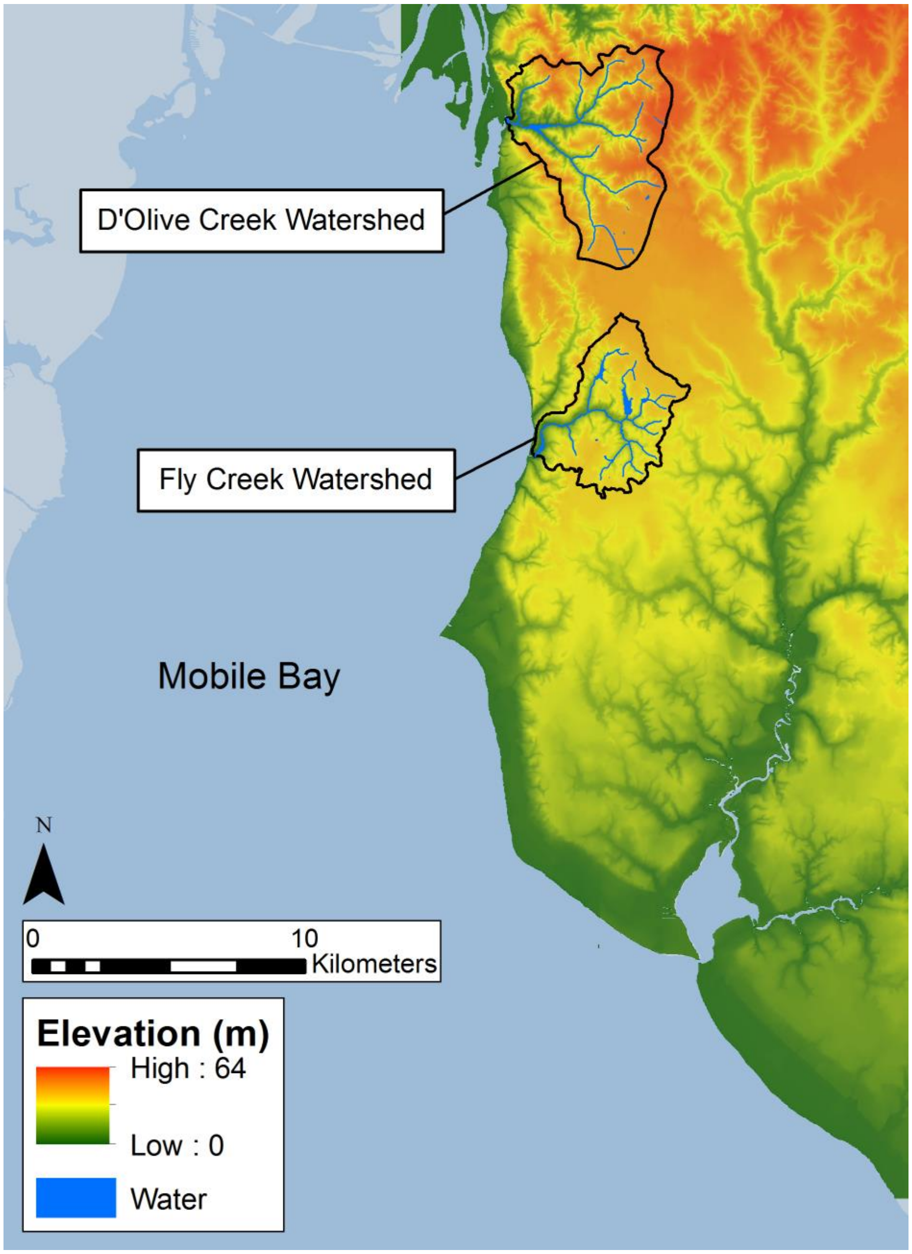


Figure 16: Elevation analysis of the eastern shore of Mobile Bay. Note: the northeastern portion of the map and a section of the D'Olive Creek Watershed display the highest elevations.

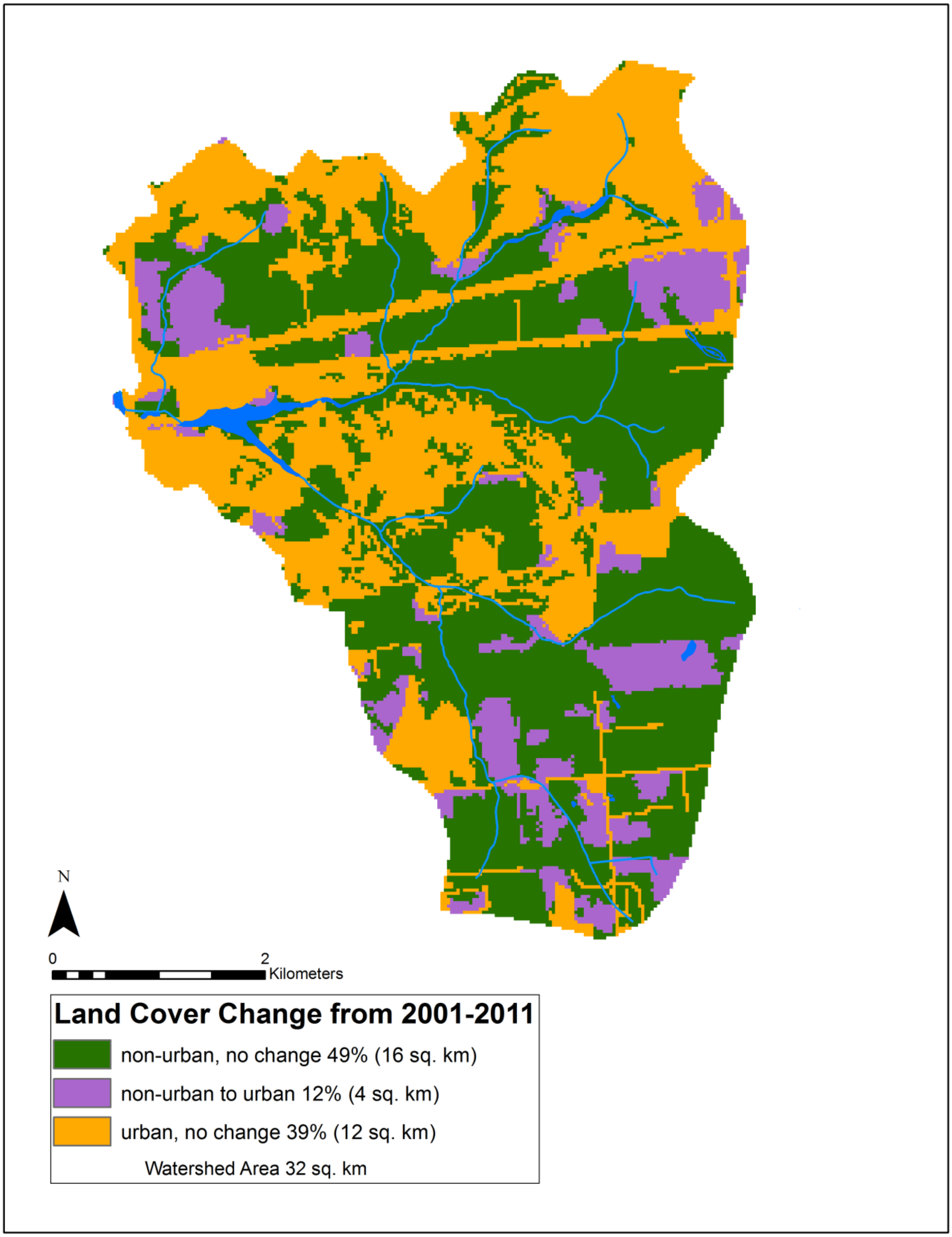


Figure 17: D’Olive Creek Watershed land cover change and percentages (2001-2011).
Land cover designations are non-urban, no change; non-urban to urban; and urban, no change.

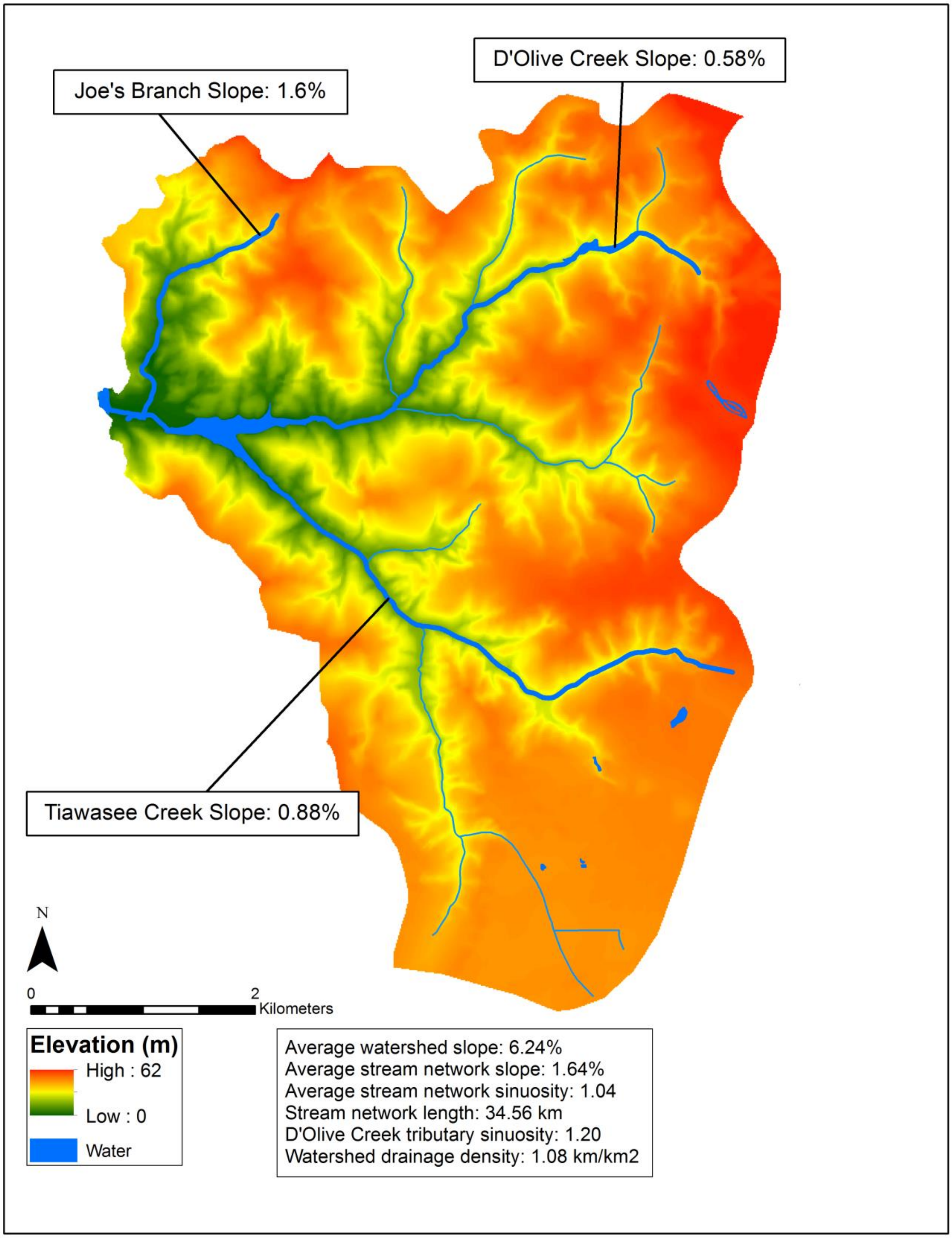


Figure 18: D’Olive Creek Watershed morphometric analysis.

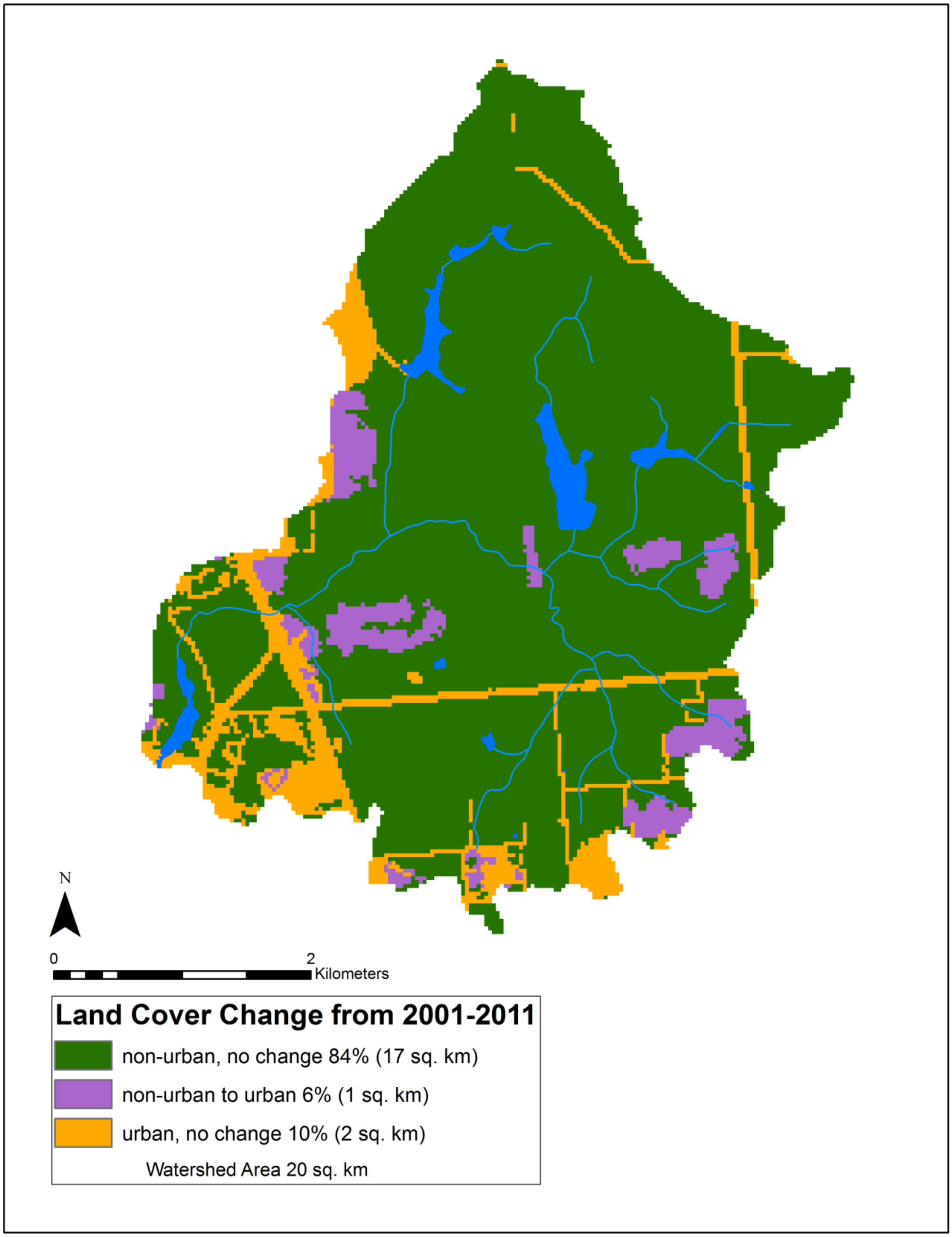
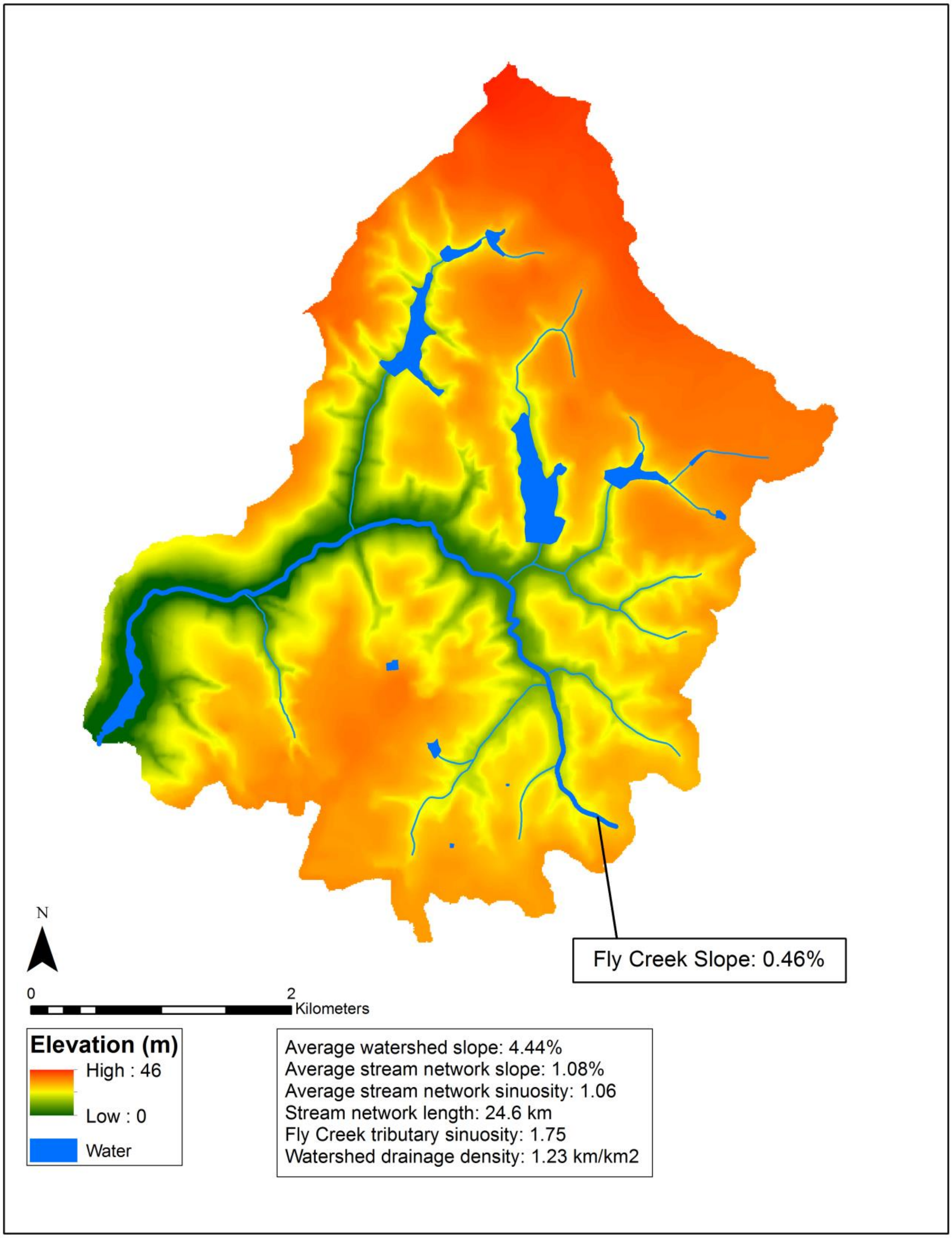


Figure 19: Fly Creek Watershed land cover change and percentages (2001-2011).
Land cover designations are non-urban, no change; non-urban to urban; and urban, no change.



Fly Creek Slope: 0.46%

Average watershed slope: 4.44%
Average stream network slope: 1.08%
Average stream network sinuosity: 1.06
Stream network length: 24.6 km
Fly Creek tributary sinuosity: 1.75
Watershed drainage density: 1.23 km/km2

Figure 20: Fly Creek Watershed morphometric analysis.

	D'Olive Creek Watershed	Fly Creek Watershed
LULC		
Open water	0.35%	0.73%
Urban	51%	16%
Forest	28%	22%
Pasture	4%	14%
Crops	4%	26%
Wetland	6%	10%
Grass/shrub	6%	10%
Other	0.65%	1.27%
Basin Morphometry		
Drainage area	32 sq. km	20 sq. km
Avg. watershed slope	6.24%	4.44%
Avg. stream network slope	1.64%	1.08%
Avg. stream network sinuosity	1.04	1.06
Stream network length	34.56 km	24.6
Drainage density	1.08 km/km2	1.23 km/km2

Table 1: Summary of watershed characteristics. Note: LULC calculations are based on NLCD 2011 data.

Field Data Driven Case Study

Stream Surveying

Of the three sites, the restored site has the highest width to depth ratio (WDR), followed by the reference and impaired sites (28.2, 13.2, and 3.9, respectively) (Table 1). Bankfull discharge refers to the discharge when a stream will overlap its banks and floodplain (Riley, 1972; Williams, 1978). Of the three sites, the impaired site has the highest bankfull discharge value, followed by the reference and restored sites (147.1, 7.1, and 1.1 m^3/s, respectively). Due to incision, the impaired stream is not able to connect with its floodplain. Bankfull cross-sectional area is also highest at the impaired site, compared to the restored and reference sites (12.1, 2.5, and 2.3 m^2, respectively). The impaired site also has the highest shear stress capacity, followed by the restored and reference sites (337.12, 130.7, and 24.8 N/sq. m, respectively) (Table 2). The restored site has the highest channel slope, followed by the impaired and reference sites (4.6%, 2.7%, and 0.75%, respectively) (Figures 21, 22, and 23). Regarding long profile bed morphology, the impaired site lacks a distinct riffle-pool sequence, compared to the other sites. In contrast, the restored site displays a uniform, engineered riffle-pool sequence. Moreover, the refence site shows a non-uniform riffle-pool sequence.

Site	Bankfull Width (m)	Bankfull Mean Depth (m)	Bankfull Cross-sectional Area (m^2)	Width to Depth Ratio	Hydraulic Radius (m)	Bankfull Discharge (m^3/s)
Impaired	6.9	1.77	12.1	3.9	1.3	147.1
Restored	8.4	0.30	2.5	28.2	0.3	1.1
Reference	5.5	0.42	2.3	13.2	0.3	7.1

Table 2: Geomorphic characteristics of all field sites calculated from Ohio Department of Natural Resources STREAMS Module. Note: bankfull discharge is calculated from the surveyed height of the channel banks.

Site	Shear Stress (N/sq. m)	Stream Power (N/s)
Impaired	337.12	38,974.4
Restored	130.7	500.5
Reference	24.8	520.8

Table 3: Shear stress and stream power values of all field sites.

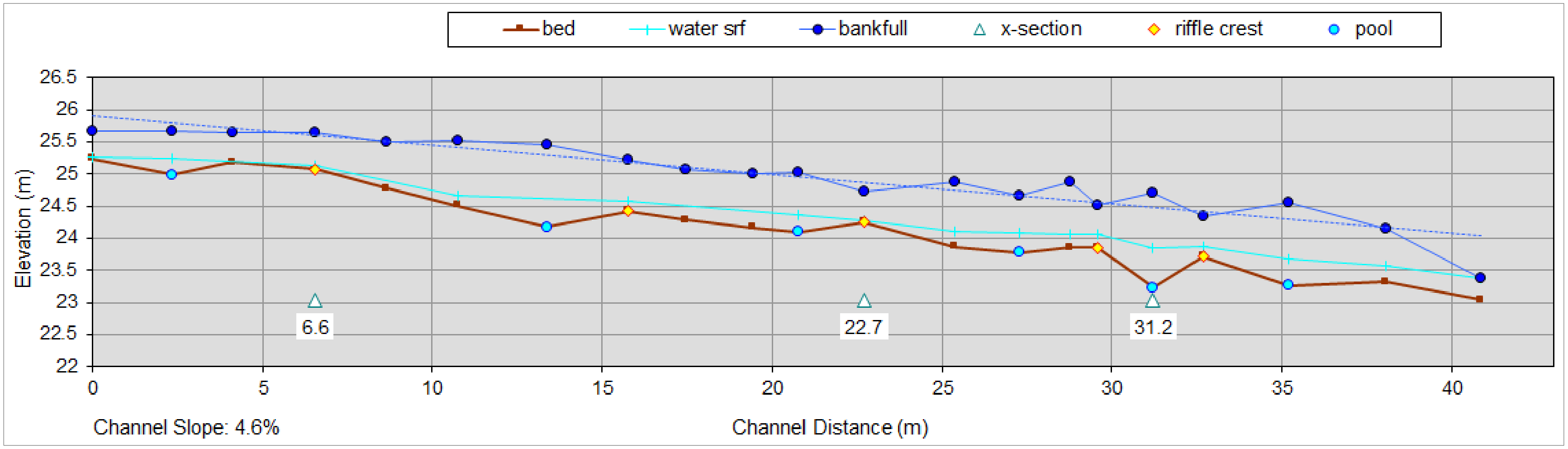


Figure 21: Longitudinal profile of the reference site.

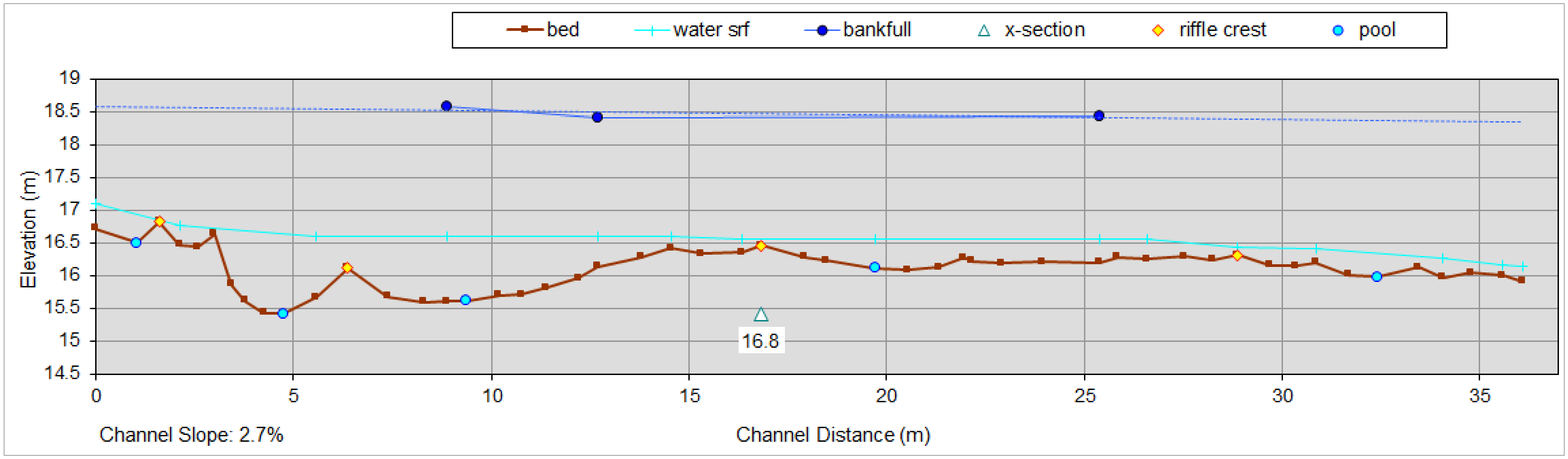


Figure 22: Longitudinal profile of the impaired site.

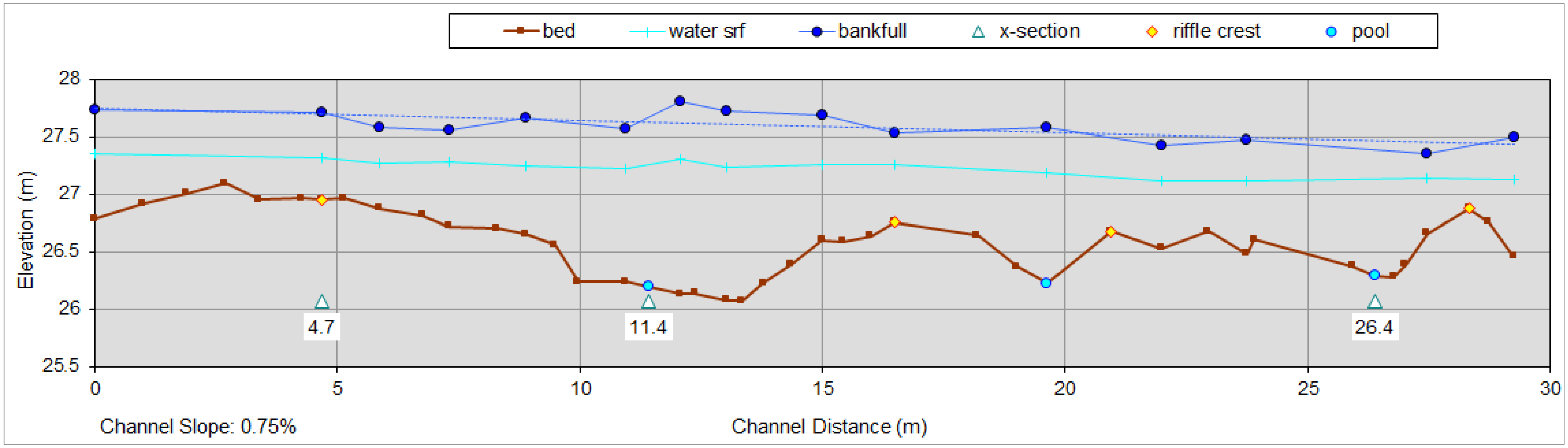
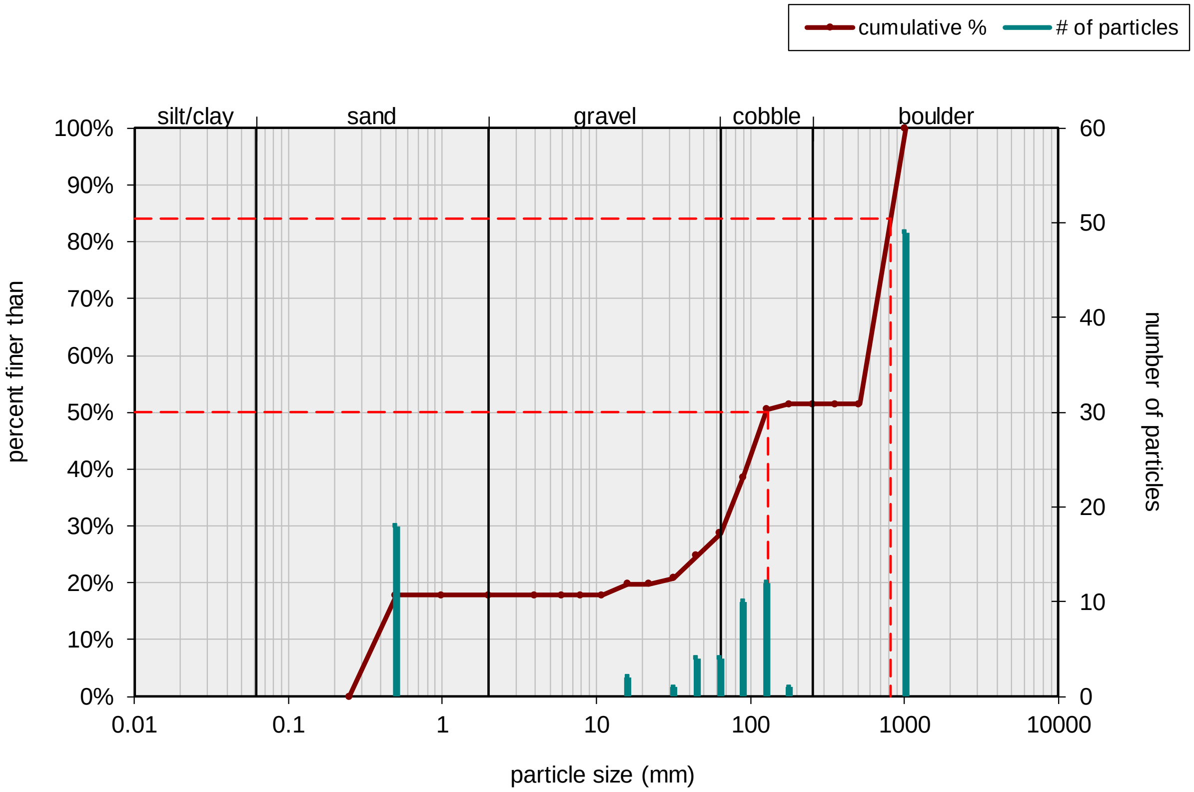


Figure 23: Longitudinal profile of the reference site.

Bed D50 and D95 is the 50% and 95% cumulative percentile of particle size in a sediment sample (Komar & Carling, 1991). The impaired site has the smallest bed D50, and the restored site has the largest (0.26 and 130 mm, respectively) (Table 3). Similarly, regarding bed D95 size, the impaired site has the smallest, and the restored site has the largest (2 and 950 mm, respectively). Based on a modified Wentworth (1922) scale, the common bed substrate type is largest at the restored site (boulder 49%) (Figure 24). Bed substrate type at the impaired and reference sites is predominantly sand-sized (50% and 98%, respectively) (Figures 25 and 26). Pebble counts were individually calculated for each cross-section (Appendix C).

Site	**Bed D50 (mm)**	**Bed D95 (mm)**
Impaired	0.26	2
Restored	130	950
Reference	0.65	0.96

Table 4: D50 and D95 (mm) particle diameter sizes for all sites.

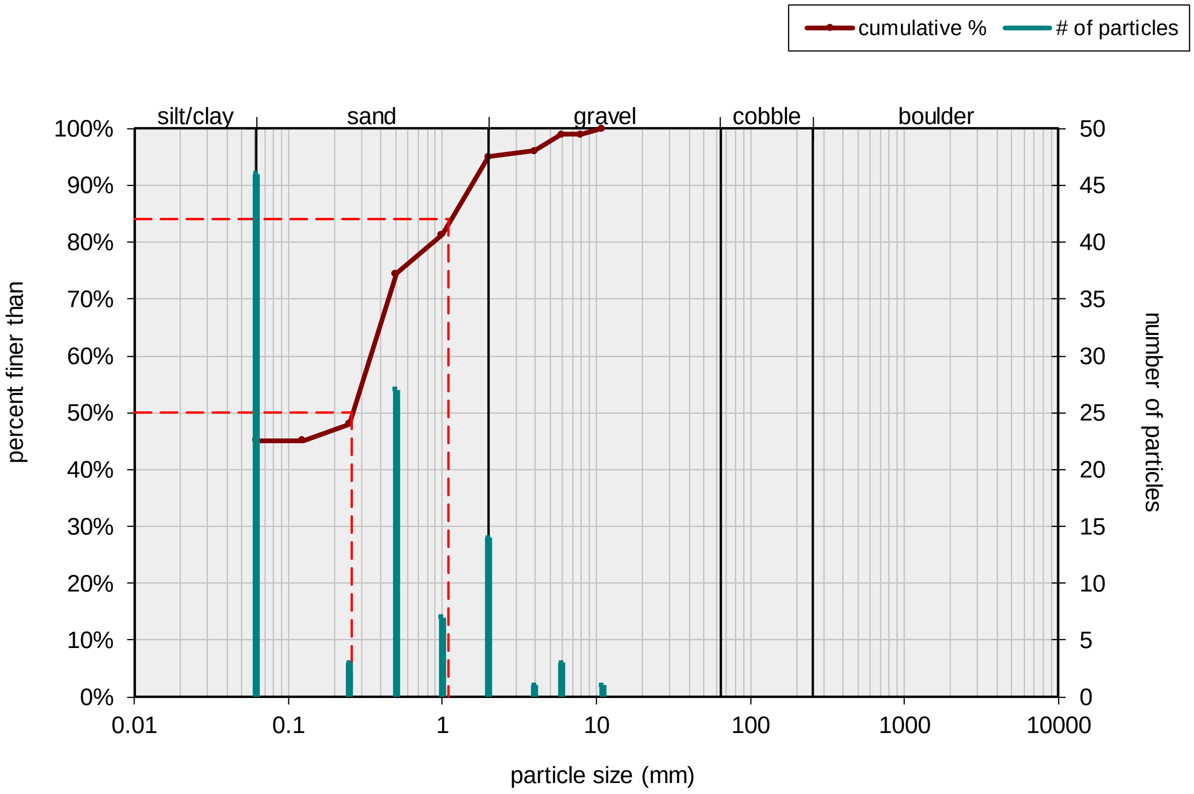


Size (mm)	
D16	0.47
D35	79
D50	130
D65	620
D84	810
D95	950

Size Distribution	
mean	19.5
dispersion	141.4
skewness	-0.46

Type	
silt/clay	0%
sand	18%
gravel	11%
cobble	23%
boulder	49%

Figure 24: Riffle surface pebble count grain size distribution for the restored site.

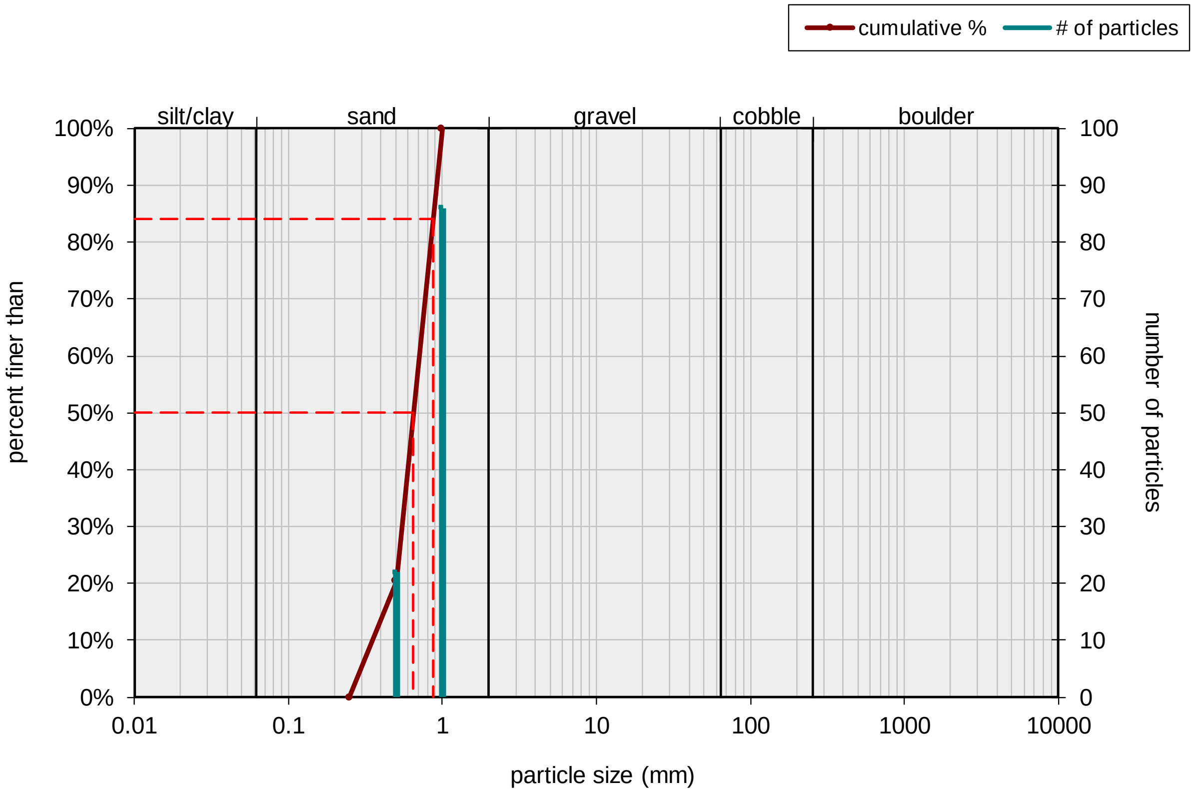


Size (mm)	
D16	0.062
D35	0.062
D50	0.26
D65	0.39
D84	1.1
D95	2

Size Distribution	
mean	0.3
dispersion	4.2
skewness	0.00

Type	
silt/clay	45%
sand	50%
gravel	5%
cobble	0%
boulder	0%

Figure 25: Riffle surface pebble count grain size distribution for the impaired site.



Size (mm)	
D16	0.43
D35	0.57
D50	0.65
D65	0.74
D84	0.87
D95	0.96

Size Distribution	
mean	0.6
dispersion	1.4
skewness	-0.05

Type			
silt/clay	0%		
sand	98%		
gravel	0%	wood/det	2%
cobble	0%		
boulder	0%		

Figure 26: Riffle surface pebble count grain size distribution for the reference site.

Rosgen Classification

Table 4 shows the metrics used for Rosgen stream classification during this study. Note that some input values were adjusted during classification based on the continuum of river morphological variables, stating that the dynamic nature of fluvial systems permits an allowable margin of variation when calculating related metrics (Rosgen, 1996). The impaired site is classified as a G5 stream type (Table 5), which are commonly narrow, entrenched, and deep, with a low to moderate sinuosity. G5 streams are extremely sensitive to disturbance; have very poor recovery potential; very high sediment supply; very high streambank erosion potential; and high vegetation controlling influence (Rosgen, 1994; Rosgen, 1996).

The restored site is classified as a B2a stream type, which exist on moderately steep to gently sloped terrain, are moderately entrenched, have a bed D50 of approximately boulder-size, with a low sinuosity. B2a streams have a very low sensitivity to disturbance; excellent recovery potential; very low sediment supply and streambank erosion potential; and a negligible vegetation controlling influence (Rosgen, 1994; Rosgen, 1996).

The reference site is classified as a C5 stream type, which have a channel slope of 2% or less, a well-developed floodplain (slightly entrenched), and are relatively sinuous. C5 streams are very sensitive to disturbance; have a fair recovery potential; very high sediment supply; very high streambank erosion potential; and very high vegetation controlling influence (Rosgen, 1994; Rosgen, 1996). It is worth noting that an ephemeral stream channel, connected to the perennial reach, was identified at the reference site, but for a stream to be classified as multi-channel during Rosgen classification, it must have three or more channels (Rosgen, 1996).

Site	Entrenchment Ratio	Width to Depth Ratio	Sinuosity	Slope (%)	Channel Material (D50)	Single Thread	Multiple Thread
Impaired	< 1.4	3.9	1.10	2.7	Sand	yes	no
Restored	>2.2	28.2	1.03	4.6	Boulders	yes	no
Reference	>2.2	13.2	1.11	0.75	Sand	yes	no

Table 5: Site data used for Rosgen Classification calculated from Ohio Department of Natural Resources STREAMS Module. Note: during Rosgen Classification, input values can vary based on the continuum of river morphological variables (Rosgen, 1994; Rosgen, 1996). Entrenchment ratios were calculated using both quantitative survey values and qualitative field observations.

Site	Stream Type	Sensitivity to Disturbance[a]	Recovery Potential[b]	Sediment Supply[c]	Streambank Erosion Potential	Vegetation Controlling Influence[d]
Impaired	G5	extreme	very poor	very high	very high	high
Restored	B2a	very low	excellent	very low	very low	negligible
Reference	C5	very high	fair	very high	very high	very high

Table 6: Management interpretations of all sites, modified from Rosgen (1994) and (1996).

[a] Includes increases in streamflow magnitude and timing and/or sediment increases.

[b] Assumes natural recovery once cause of instability is corrected.

[c] Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.

[d] Vegetation that influences width/depth ratio-stability.

Vegetation

The impaired cross-section (Figure 27) had at least four classes of vegetation >20%; 5-20% of total cover represented by invasive exotic vegetation (*Cinnamomum camphora*); <30% of streambank had evidence of a deep, binding root mass; high flows (> 2X bankfull) not able to enter floodplain (deeply entrenched); <10% of cross-section had exposed soil surface. Collective quantitative analysis of vegetation data for the impaired site equaled 50/100.

Figure 27: Cross-section at the impaired site along which the vegetation analysis was performed.

All three cross-sections at the restored site displayed >80% of *Urochloa ramosa* (L.) *Nguyen* (Figure 28); very few invasive species (*Albizia julibrissin* was identified at one cross-section); <30% of streambanks had evidence of a deep, binding root mass; high flows (> bankfull) able to enter the floodplain; vegetated buffer width >15.24 m; clear mix of wetland and non-wetland habitats (evidence of pooling water); <10% of cross-sections had exposed soil surface. Collective quantitative analysis of vegetation data for the restored site equaled 80/100.

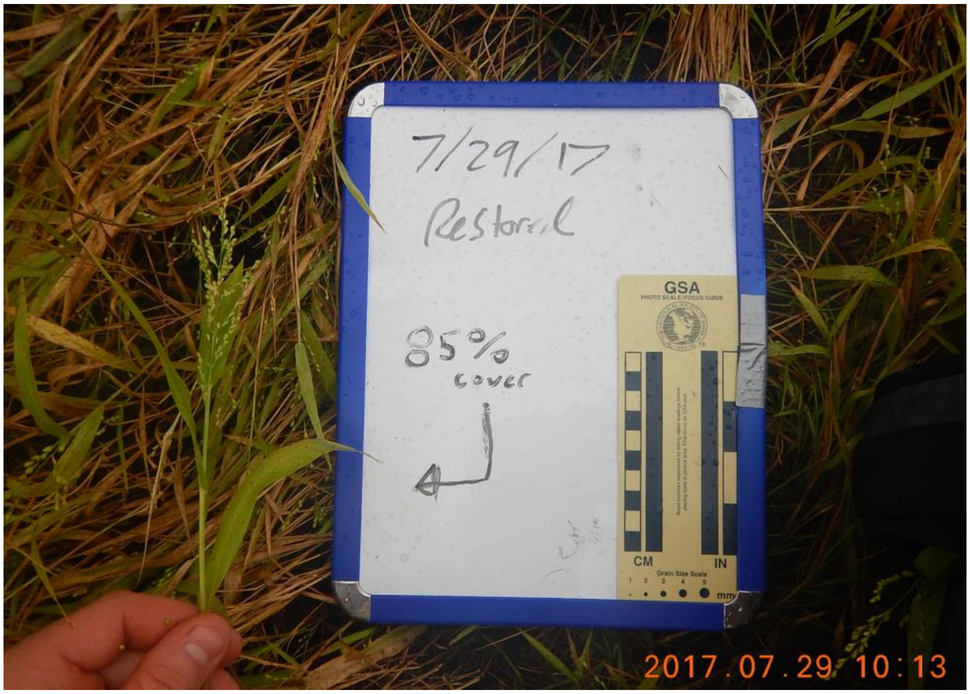


Figure 28: *Urochloa ramosa* (L.) *Nguyen* at the restored site.

All three cross-sections at the reference site had at least four classes of vegetation >20%; 5-20% of total cover represented by invasive exotic vegetation; 30-60% of streambank had evidence of a deep, binding root mass (Figure 29); high flows (> bankfull) able to enter the floodplain; vegetated buffer width >15.24 m; clear mix of wetland and non-wetland habitats (evidence of pooling water). Exposed soil surface varied at each cross-section from 5 to 25%. Collective quantitative analysis of vegetation data for the reference site equaled 86/100.

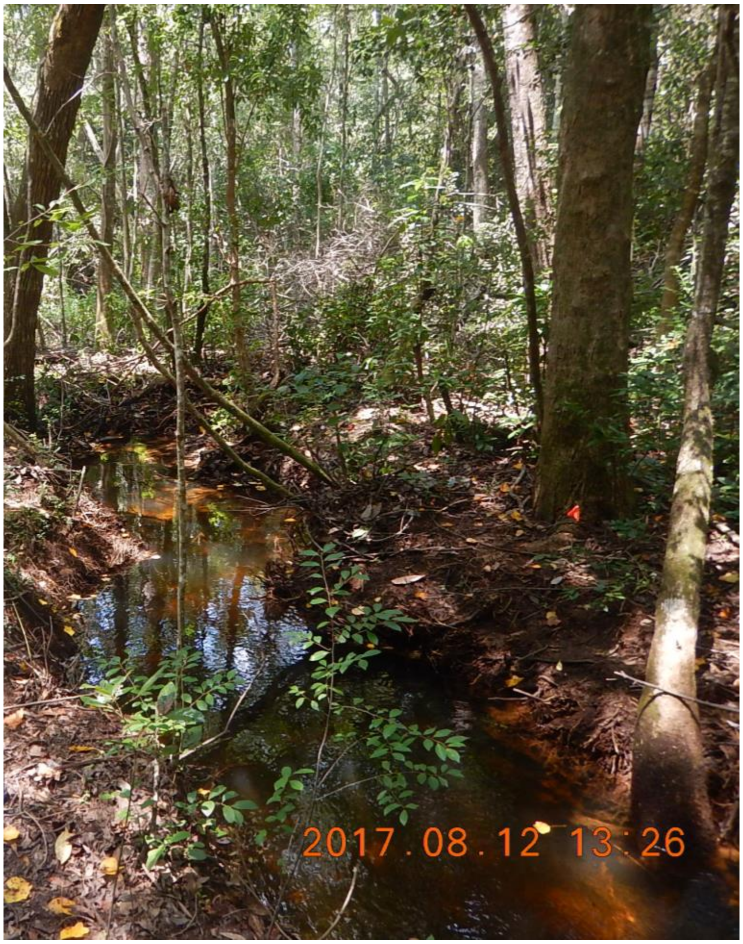


Figure 29: Vegetation diversity along the streambank resulting in root masses along the reference tributary.

5—Discussion

I found that there is a strong relationship between impervious surfaces, slope, and stream degradation. The presence and expansion of impervious surfaces has amplified runoff volume and velocity in both watersheds, correlating with the occurrence of stream degradation related to sediment erosion and deposition as outlined by Cook (2007 and 2016), and Cook and Moss (2012). The relationship between impervious surfaces and fluvial systems has been well-studied (Booth, Roy, Smith, & Capps, 2016; Caldwell, Sun, McNulty, Cohen, & Moore Myers, 2012; Ladson, Walsh, Fletcher, Cornish, & Horton, 2004; Wickham, Wade, & Norton, 2014). The results support key points outlined in Wolman (1967), Chin (2006) and Lord (2009): watershed urbanization generates an initial phase of increased sediment production and deposition within the system, followed by another phase of decline where increased runoff leads to erosion and enlarging channels. Furthermore, as slope increases, assuming that surface cover is impervious, runoff volume and velocity increase; and flooding, erosion, and sediment transport intensifies (Gibbons, 1998; He, Cai, & Liu, 2012; Huang & Bradford, 1993; Huang, Zhao, & Wu, 2013; Leopold et al., 1965).

The impaired site consistently displayed more degraded systemic characteristics and also symptoms of urban stream syndrome as described in Walsh et al. (2005) and Booth et al. (2016): an increase in stream velocity, volume of water, and discharge; channel deepening and widening; disrupted natural flow regime (i.e. stream flashiness); degradation of riparian vegetation; and alterations to channel slope. Although both watersheds are urbanizing, the D’Olive Creek

Watershed is experiencing more stream degradation (Coffee, 2010; *Fly Creek Watershed Project*, 2013; Swann & Herder, 2014; Vittor, 2010). As outlined in detail below, key differences include, the D'Olive Creek Watershed is experiencing a higher rate and distribution of urban expansion and its terrain has an above average slope for a watershed in the coastal plain.

GIS Investigation

The GIS investigation confirmed that the D'Olive Creek and Fly Creek Watersheds are experiencing urban expansion, as described by the Mobile Bay NEP, Ellis et al. (2011), and Swann & Herder (2014), contending that the presence and expansion of impervious surfaces is leading to local stream degradation. Furthermore, these results support the relationship between impervious surfaces and surface runoff proposed by the U.S. Environmental Protection Agency (2008), asserting that, an increase in surface runoff parallels the expansion of impervious surfaces, which can ultimately degrade local, fluvial systems.

D'Olive Creek and its stream network flow through coastal, non-cohesive soils with no confining bedrock (Coffee, 2010). Although the watershed is only approximately 32 sq. km in size, elevations range from 62 m, some of the highest area along the eastern shore of Mobile Bay, to near sea level. Fly Creek and its stream network also flow through coastal non-cohesive soils with no confining bedrock (*Fly Creek Watershed Project*, 2013). Elevations in the Fly Creek Watershed range from 46 m to near sea level. The above average relief of the D'Olive Creek Watershed has led to an unusually steep terrain for a fluvial system in the coastal plain, with an average watershed slope of 6.24%. This slope, along with the presence and expansion of impervious surface, allows the landscape of the watershed to convey more runoff than it would naturally. Therefore, as a combined result of these factors, the terrain of the D'Olive Creek Watershed imparts much power to runoff, which has contributed to issues in local, fluvial systems, and is one of the main reasons the streams have been able to transport enhanced sediment loads. These factors could also contribute to the lower average stream network and main tributary sinuosity in the D'Olive Creek Watershed, compared to the Fly Creek Watershed.

Together, the pace of LULC change, distribution of LULC, and landscape slope in each watershed correlates with the occurrence of stream degradation and identified impacted stream sections. From 2001 to 2011, the D'Olive Creek Watershed experienced twice the amount of urban expansion; had a LULC distribution of 50% urban total, compared to 15% in the Fly Creek Watershed; its landscape is steeper (6.24% and 4.44%, respectively); and its stream network is steeper (1.64% and 1.08%, respectively). During this timeframe, the primary named tributaries, D'Olive Creek, Joe's Branch, and Tiawassee Creek, were all listed under section 303(d) of the CWA as non-supportive of their designated use, with the source of degradation predominantly being land development resulting in siltation. In contrast, Fly Creek, was listed in 2018 as non-supportive of its designated use under section 303(d) of the CWA, with the source of degradation being pasture grazing resulting in pathogens and deemed a low priority. Moreover, the near-channel land cover of D'Olive Creek is predominantly urban, and its slope is 0.56%, whereas Fly Creek is primarily non-urban, and its slope is 0.46%. The above parallels key points outlined in the Fly Creek Watershed Project (2013), arguing that the Fly Creek Watershed is still primarily non-urban, and the D'Olive Creek Watershed is experiencing more issues with sediment erosion and deposition because of the higher expansion rate and overall distribution of impervious surfaces. Similarly, Coffee (2010) found that the relationship between watershed urbanization and slope is significantly contributing to the degradation of local streams and tributaries throughout the D'Olive Creek Watershed.

Field Data Driven Case Study

It is well-documented that urban sprawl and related processes negatively affect stream health (Chin, 2006; Gregory et al., 1992; Keen-Zebert, 2007; Poff et al., 2006; Shepherd et al., 2010; Wolman, 1967). The expansion of impervious surfaces parallels an increase in a stream's ability to carry more sediment and non-point source pollutants; thus, its erosive ability is amplified and environmental degradation is intensified (Center for Watershed Protection, 2003; Walsh et al., 2005; Weng, 2012; J. Wickham, Neale, Mehaffey, Jarnagin, & Norton, 2016). Metrics such as WDR are commonly used during geomorphic evaluation to conceptualize the distribution of energy and erosive ability within a stream channel (Rosgen, 1994; Rosgen, 1996). Of the three sites, WDR is highest at the restored location and lowest at the impaired site (28.2 and 3.9, respectively). Increasing WDR was one of the restoration goals; thus, the higher WDR at the restored site is a result from the restoration process. A lower WDR at the impaired site is a symptom of incision due to downcutting and highlights the influence of the impervious surfaces centrally located between the upstream restored site and downstream impaired site. This inference is based on the calculated bankfull discharge value for the impaired site, which is the highest of all three study sites.

At the impaired site, the changes in geomorphology in response to upstream impervious surfaces has caused a significant increase in bankfull discharge, shear stress, and stream power. Higher values associated with these metrics can escalate bank erosion and habitat degradation, as the capacity to erode and carry more sediments during stormflow is increased. Factors such as geomorphological adjustments to upstream impervious surfaces (i.e. channel incision), and the resulting high values for bankfull discharge, shear stress, and stream power have led to erosion and related processes at the impaired site. In contrast, land cover upstream of the restored and reference sites is primarily forested. This aligns with phenomena discussed in Schumm, Sunada, Mcwhorter, & Chester (1984), stating that stream channels respond to urban-induced hydromodification: incision, widening, alterations in equilibrium, and so forth.

Significantly, if all other factors are held at a constant, an increase in stream gradient will amplify stream power and shear stress (Bagnold, 1966; Gartner, 2016) which could influence environmental degradation. Longitudinal slope is steepest at the restored site, yet stream power and shear stress values are rather low in the context of this study, when compared to the other sites. This is because the location was once severely degraded, and restoration efforts focused on using streambank vegetation, boulders, ephemeral wetland areas, and an appropriate riffle-pool sequence to regulate fluvial processes without mitigating landscape slope. Also, it is expected that gradient decreases as you travel downstream. In contrast to this concept, longitudinal slope at the downstream impaired site is steeper than the reference location, which reflects geomorphological adjustments to the upstream impervious surfaces. It is worth noting that channel steps, resulting from high percentage of consolidated silt/clay in the bed-material, affected slope at this site. These steps primarily occurred upstream of the site and at the beginning of the survey. Downstream slope of the survey decreased due to lack of these features. Thus, the survey was performed at a central location, deemed as a site average.

Bed-material particle size varies and downstream fining occurs at several scales along a stream reach, as it takes more energy to move larger material downstream (Bunte & Abt, 2001; L. B. Leopold et al., 1965). Because the restored site was engineered, and it is centrally located between the other sites, there is a lack of linear, downstream bed-material fining occurring in the context of the entire study reach. Furthermore, the relationship between impervious surfaces and suspended sediment load is well-studied: an increase in impervious surfaces parallels higher suspended sediment loads (Brown & Chanson, 2012; Fankhauser et al., 2013; Pappas, Smith, Huang, Shuster, & Bonta, 2008; Selbig, Bannerman, & Corsi, 2013). Based on this relationship, the impervious surfaces upstream of the impaired site could potentially contribute to higher suspended sediment loads during stormflow, as described by Cook (2007 and 2016), and Cook and Moss (2012).

The impaired site displays characteristics of urban stream syndrome and related hydrologic flashiness as outlined in Walsh et al. (2005), Booth et al. (2016), and Roodsari & Chandler (2017). I argue that this phenomenon is occurring at the impaired site based on geomorphological and ecological conditions (Figure 30) and related field data, compared to the other sites: higher stream power, shear stress, and WDR values; channel deepening and widening; alterations to channel slope; and degradation of riparian vegetation. Also, previous studies of the D'Olive Creek Watershed found that local tributaries are indeed experiencing symptoms of urban stream syndrome and hydrologic flashiness as urban processes increase (Coffee, 2010; M. Cook et al., 2014; Swann & Herder, 2014).

The importance of riparian vegetation to overall stream health is well-established in the scholarly literature (Bennett et al., 2014; Dosskey et al., 2010; Hupp & Osterkamp, 1996; Merritt, Scott, Leroy Poff, Auble, & Lytle, 2010; Tabacchi et al., 2000). Typically, riparian vegetation patterns are indicative of ambient hydrogeomorphic conditions. Therefore, riparian vegetation characteristics are an important factor when assessing stream health (Hupp & Osterkamp, 1996). The degradation of riparian vegetation at the impaired site is the result of modified flow regimes from the upstream impervious surfaces. This contention is based on the observed riparian vegetation conditions of the site and the related NCSU Rapid Stream Assessment Protocol results. Of the three sites, the impaired site displayed the lowest collective quantitative analysis mark (50/100), reflecting low grades in all the respective categories used for analysis. Moreover, previous vegetation studies claim that hydrologic flashiness occurring outside of the natural temporal and volumetric spectrum due to urban processes parallels a decrease in local riparian vegetation patterns throughout the Mobile Bay area (Coffee, 2010; Estes et al., 2015; *Fly Creek Watershed Project*, 2013; Swann & Herder, 2014). Furthermore, other related investigations in the scientific literature further confirm that hydrologic flashiness due to urban processes correlates with a decline in riparian vegetation in fluvial environments (Dosskey et al., 2010; Hupp & Osterkamp, 1996; Merritt et al., 2010; Osterkamp, Hupp, & Stoffel, 2012; Tabacchi et al., 2000).

Figure 30: Example of bank incision at the impaired site. This type of incision is common in urban areas and is associated with hydrologic changes related to impervious surfaces (i.e. stream flashiness).

Management interpretations and other stream characteristics as described in Rosgen (1994) and (1996) support claims made above. For example, management interpretations and characteristics of G5 stream types aligned well with field research results for the impaired site: narrow, entrenched, and deep channel; extremely sensitive to disturbance; very high sediment supply; high vegetation controlling influence; and very high streambank erosion potential. Moreover, B2a stream management interpretations and characteristics were evident in the field research results for the restored site: a very low sensitivity to disturbance; excellent recovery potential; very low sediment supply and streambank erosion potential. Furthermore, two distinct C5 stream type attributes were observed in field research results for the reference site: a very high vegetation controlling influence, and a fair recovery potential.

Field data results show that upstream impervious surfaces at the impaired site are increasing the volume and velocity of stormwater runoff, ultimately altering channel characteristics; thus, modifying the natural hydrologic regime and leading to erosion, sedimentation, and pollution from runoff. Although I did not perform field research and verification in the Fly Creek Watershed, the findings from this study suggest that impervious surfaces are having negative effects on its streams and tributaries, as well. Further supporting this argument, local investigations (Ellis et al., 2011; Estes et al., 2015; *Fly Creek Watershed Project*, 2013; Stout et al., 1998; Swann & Herder, 2014) and other related analyses in the literature (Center for Watershed Protection, 2003; Ladson et al., 2004; Pappas et al., 2008; Roodsari & Chandler, 2017; Violin et al., 2011; Walsh et al., 2005), support the relationship between impervious surfaces and stream health presented in this study and its significance.

Stream adjustment to LULC change can be significant both geomorphically and ecologically and result in environmental degradation unless properly addressed. Furthermore, this study supports the wide-ranging conceptual model described in Poff et al. (2006), asserting that there is an interconnected relationship between land use, hydrology, geomorphology and ecology of fluvial systems. It is worth noting that these components can function as a feedback loop, either positive and/or negative depending on the specific factors and scale. Building on this model, I claim that the factors affecting stream health in urban environments can be broadly separated into three categories: extrinsic natural, extrinsic anthropogenic, and intrinsic fluvial (Figure 31). Similarly, this study calls for future comprehensive, multidisciplinary research and approaches in watershed science to further illuminate the systemic understanding of fluvial systems.

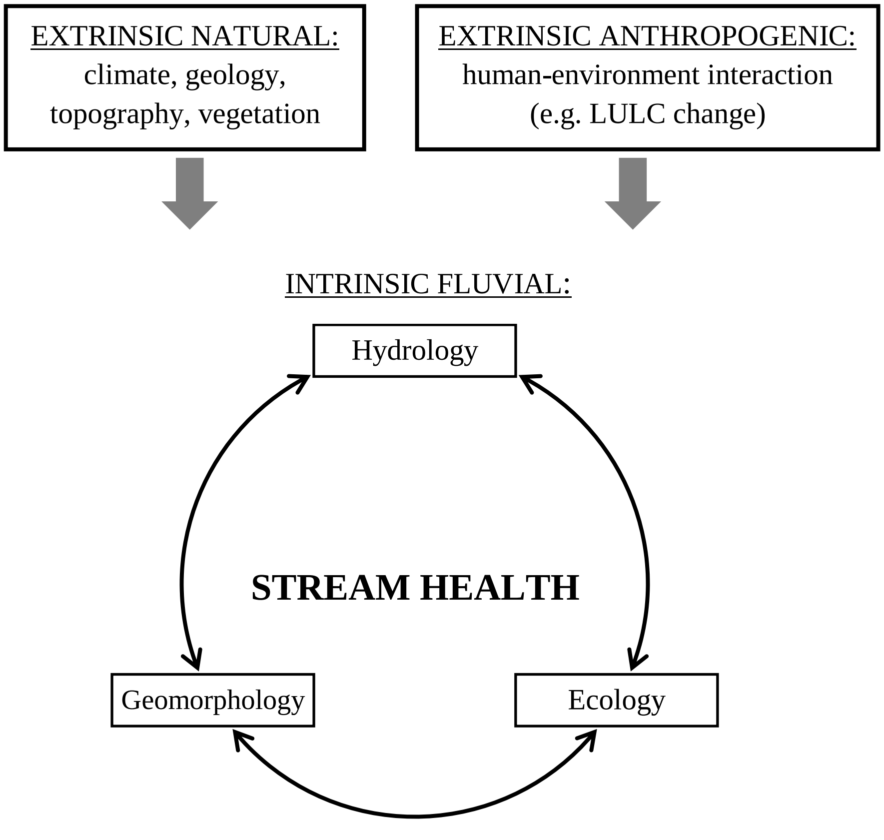


Figure 31: Three major categories that affect stream health in urban environments: extrinsic natural, extrinsic anthropogenic, and intrinsic fluvial.

Conclusions and Recommendations

This study reaffirmed that impervious surfaces have influenced stream degradation in both the D’Olive Creek and Fly Creek Watersheds, as discussed in the literature (Coffee, 2010; Ellis et al., 2011; Estes et al., 2015; *Fly Creek Watershed Project*, 2013). Loss of natural ground cover and the expansion and/or presence of urban, impervious surfaces has intensified erosion, sedimentation, and pollution from stormwater runoff in both watersheds. The higher rate and distribution of urban expansion, along with an unusually steep terrain for a coastal plain drainage, have significantly contributed to stream degradation in the D’Olive Creek Watershed. Overall, land cover type influences fluvial systems and watershed health at numerous scales based on dynamic factors related to local surface hydrology. Similarly, watershed slope can affect the movement of surface runoff as it travels across the landscape. The relationship between land cover type and landscape slope has serious implications on the characteristics of fluvial systems.

In regards to the real-world application of this research, I suggest that stakeholders implement three praxes: identify and monitor goals pre- and post-restoration extensively; utilize Best Management Practices (BMP) outside of local river corridors to mitigate runoff and related issues (Figure 32); and map and predict the rate and spatial extent of urban expansion that needs to occur in order for the watershed to experience 100% build-out condition and implement related BMP accordingly. Ultimately, 100% build-out condition should be avoided and addressed carefully, but the above is assuming worst-case scenario. This creates three related opportunities for future research: summarizing and monitoring restoration goals in the D’Olive Creek Watershed; identifying and implementing appropriate, local BMP to mitigate stream degradation; and mapping and classifying LULC change to spatially analyze and predict 100% build-out condition.

Figure 32 A, B, and C:
BMP examples at the Donald E. Davis Arboretum, Auburn University
A) Pervious concrete sidewalk;
B) Pervious concrete inserted into an impervious concrete sidewalk;
C) BMP apparatus installed across the landscape to mitigate runoff before it enters a downhill stream.

Significance

River restoration is a billion dollar enterprise annually across the U.S. (Bernhardt et al., 2007). Projects are often designed to only address a specific management issue. Building on this point, post-restoration assessment is typically restricted to the short-term monitoring of a limited number of parameters (Bernhardt et al., 2005; Palmer et al., 2014). This approach restricts research efforts and does not view the functionality of a river as a dynamic system. Identifying specific drivers of stream degradation in a watershed acknowledges the complexities associated with natural systems and can aid pre- and post-restoration assessment; because they are ultimately the result of several characteristics inherent to the system, these drivers can also help to explain antecedent conditions that will impact the watershed in the future. Identifying the primary drivers of stream degradation in the D'Olive Creek Watershed will ultimately contribute to local restoration efforts via focusing and directing related activities. This study also established a broad range of relevant parameters, along with a database of relevant sources (Appendix D), that can be used during future projects.

References

2018 Alabama Draft 303 (d) List 2018. (2018).

Bagnold, R. A. (1966). An Approach to the Sediment Transport Problem from General Physics. *U.S. Geological Survey Professional Paper*, *422–I*, I1–I37. https://doi.org/10.1017/S0016756800049074

Bennett, A. F., Nimmo, D. G., & Radford, J. Q. (2014). Riparian vegetation has disproportionate benefits for landscape-scale conservation of woodland birds in highly modified environments. *Journal of Applied Ecology*, *51*(2), 514–523. https://doi.org/10.1111/1365-2664.12200

Bernhardt, E. S., & Palmer, M. A. (2011). River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecological Applications*. https://doi.org/10.1890/10-1574.1

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., … Sudduth, O. (2005). Synthesizing U.S. river restoration efforts. *Science*. https://doi.org/10.1126/science.1109769

Bernhardt, E. S., Sudduth, E. B., Palmer, M. A., Allan, J. D., Meyer, J. L., Alexander, G., … Pagano, L. (2007). Restoring rivers one reach at a time: Results from a survey of U.S. river restoration practitioners. *Restoration Ecology*, *15*(3), 482–493. https://doi.org/10.1111/j.1526-100X.2007.00244.x

Bledsoe, B. P., & Watson, C. C. (2001). EFFECTS OF URBANIZATION ON CHANNEL INSTABILITY. *Journal of the American Water Resources Association*, *37*(2), 255–270. https://doi.org/10.1111/j.1752-1688.2001.tb00966.x

Booth, D. B., Roy, A. H., Smith, B., & Capps, K. (2016). Global perspectives on the urban stream syndrome. *Journal of Freshwater Science*, *35*(1), 412–420. https://doi.org/10.1086/684940.

Brown, R., & Chanson, H. (2012). Suspended sediment properties and suspended sediment flux estimates in an inundated urban environment during a major flood event. *Water Resources Research*, *48*(11). https://doi.org/10.1029/2012WR012381

Bunte, K., & Abt, S. R. (2001). Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport , Hydraulics , and Streambed Monitoring. *0*, 450. https://doi.org/10.1017/CBO9781107415324.004

Byrnes, M. R., Berlinghoff, J. L., & Griffee, S. F. (2013). Sediment Dynamics in Mobile Bay, Alabama: Development of an Operational Sediment Budget, (March). Retrieved from http://www.mobilebaynep.com/images/uploads/library/mobile_bay_sediment_budget_final_report_plus_appendices_032013.pdf

Caldwell, P. V., Sun, G., McNulty, S. G., Cohen, E. C., & Moore Myers, J. A. (2012). Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrology and Earth System Sciences*, *16*(8), 2839–2857. https://doi.org/10.5194/hess-16-2839-2012

Center for Watershed Protection. (2003). Impacts of Impervious Cover on Aquatic Systems. *Watershed Protection Research Monograph*, (1), 1–142.

Chin, A. (2006). Urban transformation of river landscapes in a global context. *Geomorphology*, *79*(3–4), 460–487. https://doi.org/10.1016/j.geomorph.2006.06.033

Coffee, G. L. (2010). *Watershed Management Plan for the D'Olive Creek, Tiawasee Creek, and Joe's Branch Watersheds Daphne, Spanish Fort, and Baldwin County, Alabama*.

Cook, M. (2007). *Analysis of Sediment Loading Rates and Impacts of Land-Use Change on the D ' Olive and Tiawasee Creek Watersheds , Baldwin County , Alabama , 2007*.

Cook, M., Moss, N., Rogers, A., & Mac, M. (2014). *PHASE II POST-RESTORATION ANALYSIS OF DISCHARGE , SEDIMENT TRANSPORT RATES , AND WATER QUALITY IN TRIBUTARIES OF JOES BRANCH IN SPANISH FORT , BALDWIN COUNTY , ALABAMA.*

Cook, M. R. (2005). *Assessment of Lake Forest Lake Sediment Trapping Efficiency and Capacity* (Vol. 10).

Cook, M. R. (2017). *DISCHARGE RATING , CONFIRMATION AND UPDATES OF SEDIMENT TRANSPORT REGRESSION CURVES , AND WATER QUALITY FOR SELECTED SITES IN THE D ' OLIVE CREEK WATERS HED ,.*

de Boer, D. H. (1992). Hierarchies and spatial scale in process geomorphology: a review. *Geomorphology*, *4*(5), 303–318. https://doi.org/10.1016/0169-555X(92)90026-K

Dilts, T. (2015). Stream Gradient and Sinuosity Toolbox for ArcGIS 10.1. Retrieved from http://www.arcgis.com/home/item.html?id=c8eb4ce1384e45258ccba1b33cd4e3cb

Dosskey, M. G., Vidon, P., Gurwick, N. P., Allan, C. J., Duval, T. P., & Lowrance, R. (2010). The role of riparian vegetation in protecting and improving water qulity in streams. *Journal Of The American Water Resources Association*, *46*(2), 1–18. https://doi.org/10.1111/j.1752-1688.2010.00419.x

Ellis, J. T., Spruce, J. P., Swann, R. A., Smoot, J. C., & Hilbert, K. W. (2011). An assessment of coastal land-use and land-cover change from 1974-2008 in the vicinity of Mobile Bay, Alabama. *Journal of Coastal Conservation*, *15*(1), 139–149. https://doi.org/10.1007/s11852-010-0127-y

Estes, M. G., Al-Hamdan, M. Z., Ellis, J. T., Judd, C., Woodruff, D., Thom, R. M., … Herder, T.

(2015). A modeling system to assess land cover land use change effects on SAV habitat in the Mobile Bay Estuary. *Journal of the American Water Resources Association*, *51*(2), 513–536. https://doi.org/10.1111/jawr.12263

Falk, D. A., Palmer, M. A., & Zedler, J. B. (2006). *Foundations of Restoration Ecology*. *Inquiry* (Vol. 39). https://doi.org/10.1080/00201749608602417

Fankhauser, R., Margot, J., Curdy, R., Rossi, L., Che, N., Babut, M., … Barry, D. A. (2013). Sediment contamination assessment in urban areas based on total suspended solids. *Water Research*, *47*(1), 339–350. https://doi.org/10.1016/j.watres.2012.10.011

Fennessy, S. (2006). Monitoring Stream and Watershed Restoration. *Ecology*, *87*(2), 530–531. https://doi.org/10.1890/0012-9658(2006)87[530:MSAWR]2.0.CO;2

Fly Creek Watershed Project. (2013). Fairhope, Alabama.

Gartner, J. (2016). Stream Power: Origins, Geomorphic Applications, and GIS Procedures. *Water Publications*, 35. Retrieved from http://scholarworks.umass.edu/water_publications/1

Gibbons, J. (1998). *Addressing Imperviousness In Plans , Site Design and Land Use Regulations*.

Gregory, K. J., Davis, R. J., & Downs, P. W. (1992). Identification of river channel change to due to urbanization. *Applied Geography*, *12*(4), 299–318. https://doi.org/10.1016/0143-6228(92)90011-B

Halstead, J. A., Kliman, S., Berheide, C. W., Chaucer, A., & Cock-Esteb, A. (2014). Urban stream syndrome in a small, lightly developed watershed: A statistical analysis of water chemistry parameters, land use patterns, and natural sources. *Environmental Monitoring and Assessment*, *186*(6), 3391–3414. https://doi.org/10.1007/s10661-014-3625-9

Harrelson, C., Rawlins, C. L., & Potyondy, J. (1994). *Stream channel reference sites: an illustrated guide to field technique*. *General Technical Report RM-245*. https://doi.org/Gen. Tech. Rep. RM-245.

He, J. J., Cai, Q. G., & Liu, S. B. (2012). Effects of slope gradient on slope runoff and sediment yield under different single rainfall conditions. *Ying Yong Sheng Tai Xue Bao*, *23*(5), 1263–1268. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/22919836

Huang, C. H., & Bradford, J. M. (1993). Analyses of Slope and Runoff Factors Based on the Wepp Erosion Model. *Soil Science Society of America Journal*, *57*(5), 1176–1183.

Huang, J. L., & Klemas, V. (2012). Using Remote Sensing of Land Cover Change in Coastal Watersheds to Predict Downstream Water Quality. *Journal Of Coastal Research*, *28*(4), 930–944. https://doi.org/10.2112/JCOASTRES-D-11-00176.1

Huang, J., Zhao, X., & Wu, P. (2013). Surface runoff volumes from vegetated slopes during simulated rainfall events. *Journal of Soil and Water Conservation*, *68*(4), 283–295.

https://doi.org/10.2489/jswc.68.4.283

Hughes, F. M. R., Colston, A., & Mountford, J. O. (2005). Restoring riparian ecosystems: The challenge of accommodating variability and designing restoration trajectories. *Ecology and Society*. https://doi.org/12\nArtn 12

Hughes, R. M., Larsen, D. P., & Omernik, J. M. (1986). Regional reference sites: a method for assessing stream potentials. *Environmental Management*, *10*(5), 629–635. https://doi.org/10.1007/BF01866767

Hupp, C. R., & Osterkamp, W. R. (1996). Riparian vegetation and fluvial geomorphic processes. *Geomorphology*, *14*(4 SPEC. ISS.), 277–295. https://doi.org/10.1016/0169-555X(95)00042-4

Ibisate, A., Ollero, A., & Díaz, E. (2011). Influence of catchment processes on fluvial morphology and river habitats. *Limnetica*, *30*(2), 169–182.

Jähnig, S. C., Lorenz, A. W., Hering, D., Antons, C., Sundermann, A., Jedicke, E., & Haase, P. (2011). River restoration success: A question of perception. *Ecological Applications*, *21*(6), 2007–2015. https://doi.org/10.1890/10-0618.1

James, L. A. (2013). Legacy sediment: Definitions and processes of episodically produced anthropogenic sediment. *Anthropocene*, *2*, 16–26. https://doi.org/10.1016/j.ancene.2013.04.001

Keen-Zebert, A. (2007). Channel Responses to Urbanization: Scull and Mud Creeks in Fayetteville, Arkansas. *Physical Geography*, *28*(3), 249–260. https://doi.org/10.2747/0272-3646.28.3.249

King, R. S., Baker, M. E., Whigham, D. F., Weller, D. E., Jordan, T. E., Kazyak, P. F., & Hurd, M. K. (2005). Spatial considerations for linking watershed land cover to ecological indicators in streams. *Ecological Applications*, *15*(1), 137–153. https://doi.org/10.1890/04-0481

Komar, P. D., & Carling, P. A. (1991). Grain sorting in gravel-bed streams and the choice of particle sizes for flow-competence evaluations. *Sedimentology*, *38*(3), 489–502. https://doi.org/10.1111/j.1365-3091.1991.tb00363.x

Kondolf, G. M., & Micheli, E. R. (1995). Evaluating stream restoration projects. *Environmental Management*, *19*(1), 1–15. https://doi.org/10.1007/BF02471999

Kondolf, G. M., & Piégay, H. (2005). *Tools in fluvial geomorphology*. *Tools in Fluvial Geomorphology*. https://doi.org/10.1002/0470868333

Ladson, A. R., Walsh, C. J., Fletcher, T. D., Cornish, S., & Horton, P. (2004). Improving stream health by reducing the connection between impervious surfaces and waterways. In *International Conference on Water Sensitive Urban Design* (pp. 1–12).

Lave, R., Doyle, M., & Robertson, M. (2010). Privatizing stream restoration in the US. *Social Studies of Science*, *40*(5), 677–703. https://doi.org/10.1177/0306312710379671

Leopold, L. (1968). Hydrology for Urban Land Planning - A Guidebook on the Hydrologic Effects of Urban Land Use. *Geological Survey Circular*, *554*, 1–21. https://doi.org/10.1017/CBO9781107415324.004

Leopold, L. B., Wolman, M. G., & Miller, J. P. (1965). Fluvial processes in geomorphology. *Journal of Hydrology*. https://doi.org/10.1016/0022-1694(65)90101-0

Lord, M. L., Germanoski, D., & Allmendinger, N. E. (2009). Fluvial geomorphology: Monitoring stream systems in response to a changing environment. In *Geological monitoring* (pp. 69–103). https://doi.org/10.1130/2009.monitoring(04).

Merritt, D. M., Scott, M. L., Leroy Poff, N., Auble, G. T., & Lytle, D. A. (2010). Theory, methods and tools for determining environmental flows for riparian vegetation: Riparian vegetation-flow response guilds. *Freshwater Biology*, *55*(1), 206–225. https://doi.org/10.1111/j.1365-2427.2009.02206.x

Napton, D. E., Auch, R. F., Headley, R., & Taylor, J. L. (2010). Land changes and their driving forces in the Southeastern United States. *Regional Environmental Change*, *10*(1), 37–53. https://doi.org/10.1007/s10113-009-0084-x

NCSU Stream Restoration Program. (n.d.). Retrieved from https://www.bae.ncsu.edu/extension/srp/

Osterkamp, W. R., Hupp, C. R., & Stoffel, M. (2012). The interactions between vegetation and erosion: New directions for research at the interface of ecology and geomorphology. *Earth Surface Processes and Landforms*. https://doi.org/10.1002/esp.2173

Palmer, M. A., Hondula, K. L., & Koch, B. J. (2014). Ecological Restoration of Streams and Rivers: Shifting Strategies and Shifting Goals. *Annual Review of Ecology, Evolution, and Systematics*, *45*(1), 247–269. https://doi.org/10.1146/annurev-ecolsys-120213-091935

Pappas, E. A., Smith, D. R., Huang, C., Shuster, W. D., & Bonta, J. V. (2008). Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation. *Catena*, *72*(1), 146–152. https://doi.org/10.1016/j.catena.2007.05.001

Poff, N. L. R., Bledsoe, B. P., & Cuhaciyan, C. O. (2006). Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. *Geomorphology*, *79*(3–4), 264–285. https://doi.org/10.1016/j.geomorph.2006.06.032

Riley, S. J. (1972). A comparison of morphometric measures of bankfull. *Journal of Hydrology*, *17*(1–2), 23–31. https://doi.org/10.1016/0022-1694(72)90064-9

Roodsari, B. K., & Chandler, D. G. (2017). Distribution of surface imperviousness in small urban catchments predicts runoff peak flows and stream flashiness. *Hydrological Processes*, *31*(17), 2990–3002. https://doi.org/10.1002/hyp.11230

Rosgen, D. (1996). *Applied River Morphology*. Wildland Hydrology.

Rosgen, D. L. (1994). A classification of natural rivers. *Catena*, *22*(3), 169–199. https://doi.org/10.1016/0341-8162(94)90001-9

Schumm, S. A., & Lichty, R. W. (1965). Time, space, and causality in geomorphology. *American Journal of Science*, *263*(2), 110–119. https://doi.org/10.2475/ajs.263.2.110

Schumm, S. A., Sunada, D., Mcwhorter, D., & Chester, C. (1984). *Incised Channels: Morphology, Dynamics, and Control*. Water Resources Publications, LLC.

Sear, D. A. (1994). River restoration and geomorphology. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *4*(2), 169–177. https://doi.org/10.1002/aqc.3270040207

Selbig, W. R., Bannerman, R., & Corsi, S. R. (2013). From streets to streams: Assessing the toxicity potential of urban sediment by particle size. *Science of the Total Environment*, *444*, 381–391. https://doi.org/10.1016/j.scitotenv.2012.11.094

Shepherd, S. L., Dixon, J. C., Davis, R. K., & Feinstein, R. (2010). The effect of land use on channel geometry and sediment distribution in gravel mantled bedrock streams, Illinois River watershed, Arkansas. *River Research and Applications*, *27*(7), 857–866. https://doi.org/10.1002/rra.1401

Simon, A., Doyle, M., Kondolf, M., Shields, F. D., Rhoads, B., & McPhillips, M. (2007). Critical evaluation of how the Rosgen classification and associated “natural channel design” methods fail to integrate and quantify fluvial processes and channel response. *Journal of the American Water Resources Association*. https://doi.org/10.1111/j.1752-1688.2007.00091.x

Stout, J. P., Heck Jr., K., Valentine, J. F., Dunn, S. J., & Spitzer, P. M. (1998). *PRELIMINARY CHARACTERIZATION OF HABITAT LOSS: MOBILE BAY NATIONAL ESTUARY PROGRAM*. Dauphin Island, Alabama.

Stuart Chapin, F., Matson, P. A., & Vitousek, P. M. (2012). *Principles of terrestrial ecosystem ecology*. *Principles of Terrestrial Ecosystem Ecology*. https://doi.org/10.1007/978-1-4419-9504-9

Swann, R., & Herder, T. (2014). *The Mobile Bay Estuary and Coastal Population Growth: The Challenge of Keeping What We’ve Got*.

Tabacchi, E., Lambs, L., Guilloy, H., Planty-Tabacchi, A. M., Muller, E., & Décamps, H. (2000). Impacts of riparian vegetation on hydrological processes. *Hydrological Processes*, *14*(16–17), 2959–2976. https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2959::AID-HYP129>3.0.CO;2-B

U. S. Environmental Protection Agency. (2008). Protecting water quality from urban runoff. Retrieved April 1, 2017, from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20004PP1.txt

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*(1), 130–137. https://doi.org/10.1139/f80-017

Vietz, G. J., Walsh, C. J., & Fletcher, T. D. (2015). Urban hydrogeomorphology and the urban stream syndrome: Treating the symptoms and causes of geomorphic change. *Progress in Physical Geography*, *40*(3), 480–492. https://doi.org/10.1177/0309133315605048

Violin, C. R., Cada, P., Sudduth, E. B., Hassett, B. A., Penrose, D. L., & Bernhardt, E. S. (2011). Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. *Ecological Applications*, *21*(6), 1932–1949. https://doi.org/10.1890/10-1551.1

Vittor, B. A. (2010). WETLAND CONDITION EVALUATION: BRANCH WATERSHEDS.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3), 706–723. https://doi.org/10.1899/04-028.1

Ward, A., Mecklenburg, D. E., D'Ambrosio, J., & Witter, J. (2011). Spreadsheet Tools for River Evaluation, Assessment, and Monitoring (STREAM). In *World Environmental and Water Resources Congress 2011* (pp. 2552–2561). https://doi.org/10.1061/41173(414)265

Weng, Q. (2012). Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. *Remote Sensing of Environment*, *117*, 34–49. https://doi.org/10.1016/j.rse.2011.02.030

Wentworth, C. K. (1922). A Scale of Grade and Class Terms for Clastic Sediments. *The Journal of Geology*, *30*(5), 377–392. https://doi.org/10.1086/622910

Wickham, J. D., Wade, T. G., & Norton, D. J. (2014). Spatial patterns of watershed impervious cover relative to stream location. *Ecological Indicators*, *40*, 109–116. https://doi.org/10.1016/j.ecolind.2014.01.013

Wickham, J., Neale, A., Mehaffey, M., Jarnagin, T., & Norton, D. (2016). Temporal Trends in the Spatial Distribution of Impervious Cover Relative to Stream Location. *Journal of the American Water Resources Association*, *52*(2), 409–419. https://doi.org/10.1111/1752-1688.12393

Williams, G. P. (1978). Bank-full discharge of rivers. *Water Resources Research*, *14*(6), 1141–1154. https://doi.org/10.1029/WR014i006p01141

Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, *51*(8), 5974–5997. https://doi.org/10.1002/2014WR016874

Wohl, E., & Merritts, D. J. (2007). What Is a Natural River? *Geography Compass*, *1*(4), 871–900. https://doi.org/doi:10.1111/j.1749-8198.2007.00049.x

Wolman, M. G. (1954). A method of sampling coarse river bed material. *Eos, Transactions American Geophysical Union*, *35*(6), 951–956. https://doi.org/10.1029/TR035i006p00951

Wolman, M. G. (1967). A Cycle of Sedimentation and Erosion in Urban River Channels. *Geografiska Annaler. Series A, Physical Geography*, *49*(2/4), 385–395. https://doi.org/10.2307/520904

Appendix A

Cross-section Results

Bankfull Dimensions	
12.1	x-section area (m.sq.)
6.9	width (m)
1.8	mean depth (m)
2.1	max depth (m)
9.5	wetted parimeter (m)
1.3	hyd radi (m)
3.9	width-depth ratio

Flood Dimensions	
---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials	
0.26	D50 Riffle (mm)
1.1	D84 Riffle (mm)
347	threshold grain size (mm):

Bankfull Flow	
12.1	velocity (m/s)
147.1	discharge rate (cms)
3.43	Froude number

Flow Resistance	
0.016	Manning's roughness
0.02	D'Arcy-Weisbach fric.
20.9	resistance factor u/u*
1608.2	relative roughness

Forces & Power	
2.7	channel slope (%)
337.12	shear stress (N/sq.m.)
0.58	shear velocity (m/s)
5687	unit strm power (watts/sq.m.)

Bankfull Dimensions

3.1	x-section area (m.sq.)
5.3	width (m)
0.6	mean depth (m)
1.2	max depth (m)
6.0	wetted parimeter (m)
0.5	hyd radi (m)
9.2	width-depth ratio

Flood Dimensions

---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials

130	D50 Riffle (mm)
810	D84 Riffle (mm)
238	threshold grain size (mm):

Bankfull Flow

1.2	velocity (m/s)
3.6	discharge rate (cms)
0.52	Froude number

Flow Resistance

0.118	Manning's roughness
0.92	D'Arcy-Weisbach fric.
2.4	resistance factor u/u*
0.7	relative roughness

Forces & Power

4.6	channel slope (%)
231.48	shear stress (N/sq.m.)
0.48	shear velocity (m/s)
306	unit strm power (watts/sq.m.)

Bankfull Dimensions	
3.2	x-section area (m.sq.)
8.3	width (m)
0.4	mean depth (m)
0.9	max depth (m)
8.7	wetted parimeter (m)
0.4	hyd radi (m)
21.7	width-depth ratio

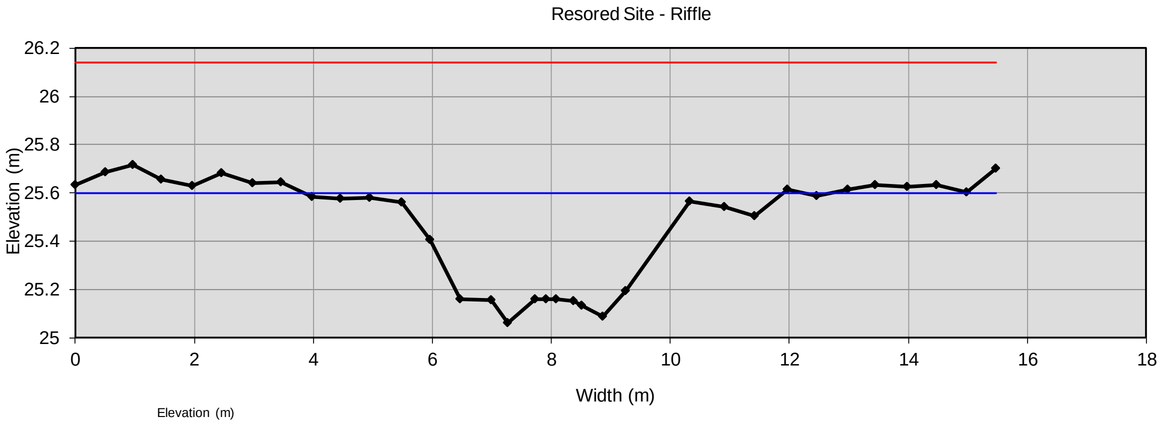
Flood Dimensions	
---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials	
130	D50 Riffle (mm)
810	D84 Riffle (mm)
170	threshold grain size (mm):

Bankfull Flow	
0.6	velocity (m/s)
2.1	discharge rate (cms)
0.34	Froude number

Flow Resistance	
0.169	Manning's roughness
2.18	D'Arcy-Weisbach fric.
1.6	resistance factor u/u*
0.5	relative roughness

Forces & Power	
4.6	channel slope (%)
165.14	shear stress (N/sq.m.)
0.41	shear velocity (m/s)
112	unit strm power (watts/sq.m.)



Bankfull Dimensions

1.9	x-section area (m.sq.)
8.6	width (m)
0.2	mean depth (m)
0.5	max depth (m)
8.8	wetted parimeter (m)
0.2	hyd radi (m)
39.2	width-depth ratio

Flood Dimensions

---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials

130	D50 Riffle (mm)
810	D84 Riffle (mm)
99	threshold grain size (mm):

Bankfull Flow

0.1	velocity (m/s)
0.2	discharge rate (cms)
0.06	Froude number

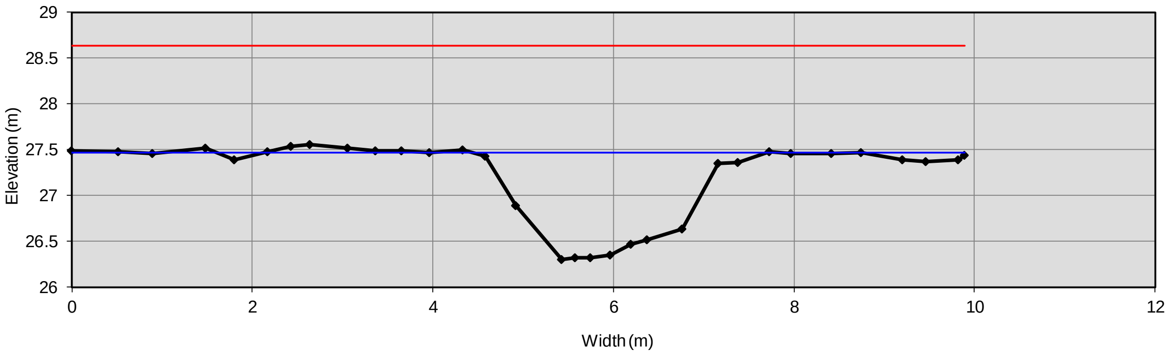
Flow Resistance

0.888	Manning's roughness
4.82	D'Arcy-Weisbach fric.
0.3	resistance factor u/u*
0.3	relative roughness

Forces & Power

4.6	channel slope (%)
96.25	shear stress (N/sq.m.)
0.31	shear velocity (m/s)
8.5	unit strm power (watts/sq.m.)

Reference Site - Pool



Bankfull Dimensions	
2.3	x-section area (m.sq.)
6.1	width (m)
0.4	mean depth (m)
1.2	max depth (m)
7.2	wetted parimeter (m)
0.3	hyd radi (m)
16.3	width-depth ratio

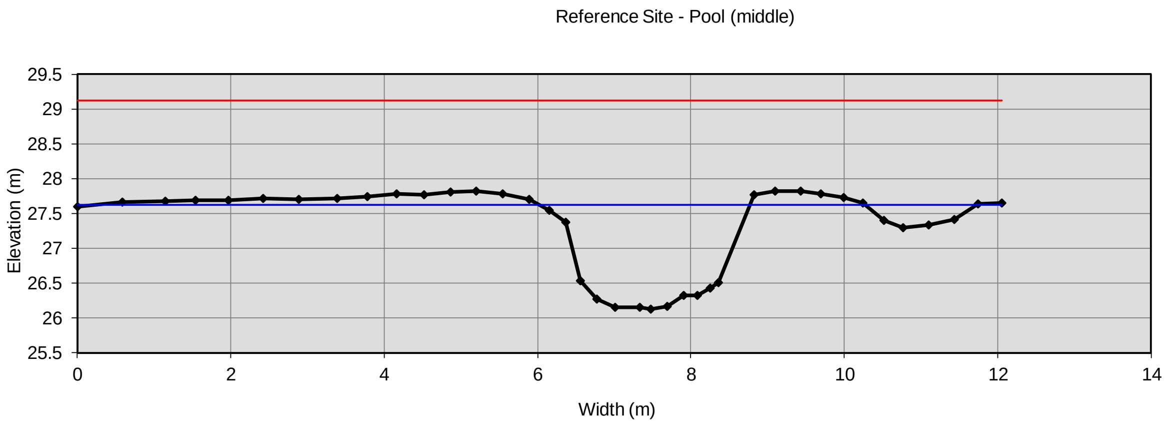
Flood Dimensions	
---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials	
0.65	D50 Riffle (mm)
0.87	D84 Riffle (mm)
24	threshold grain size (mm):

Bankfull Flow	
2.8	velocity (m/s)
6.4	discharge rate (cms)
1.61	Froude number

Flow Resistance	
0.014	Manning's roughness
0.02	D'Arcy-Weisbach fric.
18.6	resistance factor u/u*
429.2	relative roughness

Forces & Power	
0.75	channel slope (%)
23.20	shear stress (N/sq.m.)
0.15	shear velocity (m/s)
78	unit strm power (watts/sq.m.)



Bankfull Dimensions	
3.2	x-section area (m.sq.)
4.4	width (m)
0.7	mean depth (m)
1.5	max depth (m)
6.4	wetted parimeter (m)
0.5	hyd radi (m)
6.1	width-depth ratio

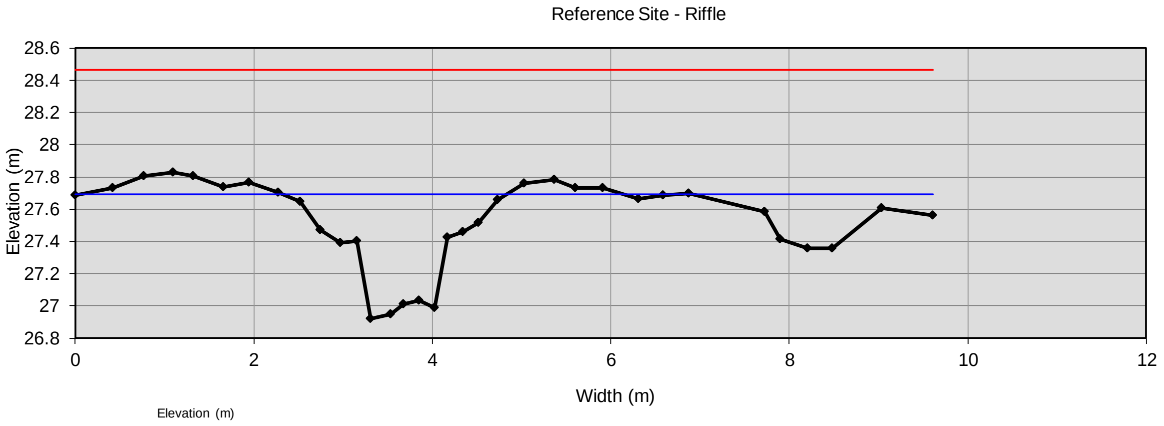
Flood Dimensions	
---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials	
0.65	D50 Riffle (mm)
0.87	D84 Riffle (mm)
38	threshold grain size (mm):

Bankfull Flow	
3.8	velocity (m/s)
11.9	discharge rate (cms)
1.70	Froude number

Flow Resistance	
0.014	Manning's roughness
0.02	D'Arcy-Weisbach fric.
19.6	resistance factor u/u*
828.2	relative roughness

Forces & Power	
0.75	channel slope (%)
36.59	shear stress (N/sq.m.)
0.19	shear velocity (m/s)
199	unit strm power (watts/sq.m.)



Bankfull Dimensions	
1.4	x-section area (m.sq.)
5.9	width (m)
0.2	mean depth (m)
0.8	max depth (m)
6.9	wetted parimeter (m)
0.2	hyd radi (m)
25.6	width-depth ratio

Flood Dimensions	
---	W flood prone area (m)
---	entrenchment ratio
---	low bank height (m)
---	low bank height ratio

Materials	
0.65	D50 Riffle (mm)
0.87	D84 Riffle (mm)
15	threshold grain size (mm):

Bankfull Flow	
2.1	velocity (m/s)
2.9	discharge rate (cms)
1.52	Froude number

Flow Resistance	
0.014	Manning's roughness
0.03	D'Arcy-Weisbach fric.
17.5	resistance factor u/u*
265.3	relative roughness

Forces & Power	
0.75	channel slope (%)
14.56	shear stress (N/sq.m.)
0.12	shear velocity (m/s)
36	unit strm power (watts/sq.m.)

Appendix B

NCSU Rapid Stream Assessment Protocol

Riparian Vegetation Assessment

1. Structural Complexity & Species Diversity	
4	At least 3 classes of vegetation >30% OR 5 classes of vegetation >20%.
3	At least one woody class and one herbaceous class >30% OR at least 4 classes of vegetation >20%.
2	At least one woody and one herbaceous class >10%.
1	No woody class >10%.
2. Planted Trees, Shrubs, and/or Livestakes	
4	Green, robust leaves, new growth, clean undamaged bark, upright (no j-rooting). Low mortality.
3	Patchy survival. Yellowish leaves, stunted leaves with no new growth, unhealthy bark.
2	Browse marks, root sprouts, choking out by invasive plants.
1	Complete mortality.
3. Natural Tree & Shrub Regeneration	
4	> 20% of total cover of woody vegetation represented.
3	10 - 20% of total cover of woody vegetation represented.
2	1 - 10% of total cover of woody vegetation is represented.
1	No naturally regenerating woody vegetation is present.

Riparian Vegetation Assessment Continued

4. Invasive Exotic Species

4	< 5% of total cover represented by invasive exotic vegetation.
3	5 - 20% of total cover represented by invasive exotic vegetation.
2	20 - 50% of total cover represented by invasive exotic vegetation.
1	> 50% of total cover represented by invasive exotic vegetation.

5. Streambank Root Mass

4	> 85% of streambank has evidence of a deep, binding root mass.
3	60 - 85% of streambank has evidence of a deep, binding root mass OR > 85% with root mass, but > 5% highly erosive.
2	30 - 60% of streambank has evidence of a deep, binding root mass.
1	< 30% of streambank has evidence of a deep, binding root mass.

Floodplain Assessment

6. Floodplain Connection

4	High flows (> bankfull) able to enter floodplain. Stream not deeply incised.
3	High flows (> bankfull) able to enter floodplain. Some incision occurring.
2	High flows (> bankfull but < 2X bankfull) not able to enter floodplain. Stream deeply entrenched.
1	High flows (> 2X bankfull) not able to enter floodplain. Stream deeply entrenched.

7. Vegetated Buffer Width

4	Width of buffer zone > 50 ft; human activities (i.e. parking lots, roads, clear cuts, lawns, crops) have not impacted zone.
3	Width of buffer zone 25-50 ft; human activities have minimally impacted zone.
2	Width of buffer zone 10-15 ft; human activities have significantly impacted zone.
1	Width of buffer zone < 10 ft; little or no riparian vegetation due to human activities.

Floodplain Assessment Continued

8. Floodplain Habitat

4	Mix of wetland and non-wetland habitats, evidence of standing/pooling water.
3	Mix of wetland and non-wetland habitats, no evidence of standing/pooling water.
2	Either all wetland or all non-wetland habitat, evidence of standing/pooling water.
1	Either all wetland or all non-wetland habitat, no evidence of standing/pooling water.

9. Floodplain Encroachment

4	No evidence of floodplain encroachment in the form of fill material, land development, or manmade structures.
3	Minor floodplain encroachment in the form of fill material, land development, or manmade structures, but not affecting floodplain function.
2	Moderate floodplain encroachment in the form of filling, land development, or manmade structures, some effect on floodplain function.
1	Significant floodplain encroachment (i.e. fill material, land development, or manmade structures), significant effect of floodplain function.

10. Soil Characteristics & Rooting Medium

4	> 85% of the site has sufficient soil to hold water and act as a rooting medium.
3	65 - 85% of the site has sufficient soil to hold water and act as a rooting medium.
2	35 - 64% of the site has sufficient soil to hold water and act as a rooting medium.
1	< 35% of the site has sufficient soil to hold water and act as a rooting medium.

11. Percent Exposed or Bare Ground

4	< 10% of the site with exposed soil surface.
3	10 - 19% of the site has exposed soil surface.
2	20 - 50% of the site has exposed soil surface.
1	> 50% of the site has exposed soil surface.

Floodplain Assessment Continued

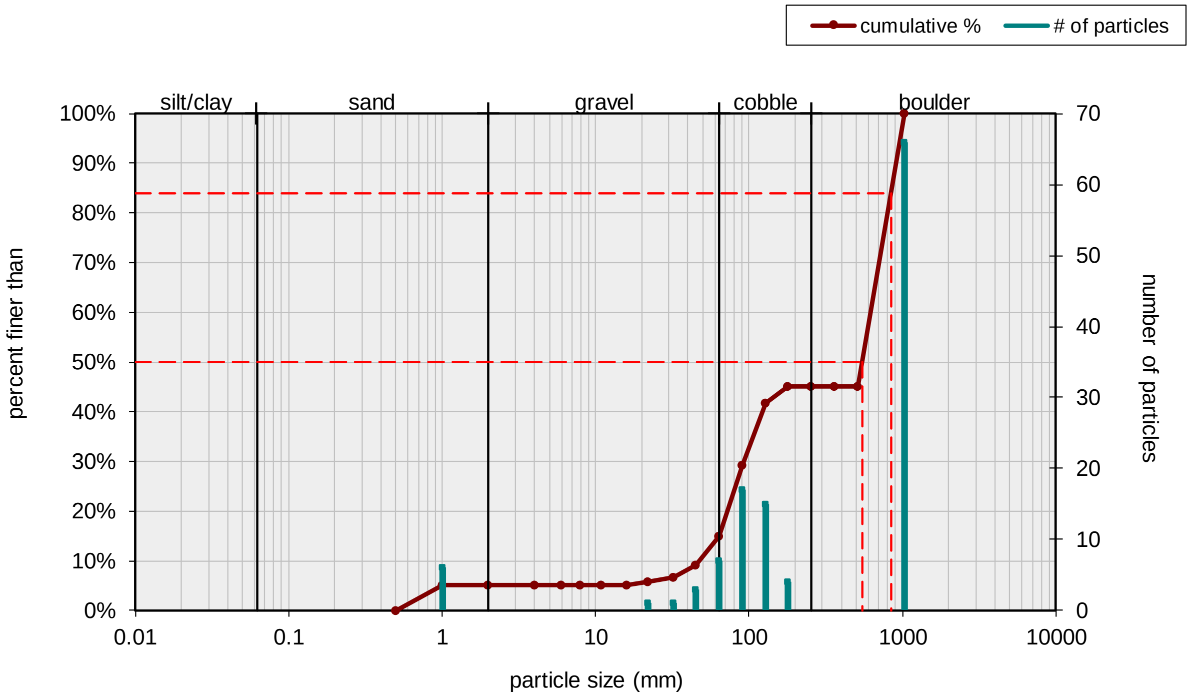
12. Stormwater Outfall Quality (Urban Streams Only)

4	Outfalls appear stable. Little evidence of erosion or degradation. Energy dissipation and treatment is evident.
3	Outfalls have very few problems and are generally stable. Attention has been paid to the design, and some treatment and energy dissipation is expected.
2	Design appears to consider outfalls. However, exhibits limited ability to either dissipate energy or treat runoff.
1	Little to no attention was paid to storm outfalls. Outfalls are failing or are a source of stream floodplain erosion. Either energy dissipation or treatment.
NS	Rural Stream

Appendix C

Pebble Counts for all Cross-sections

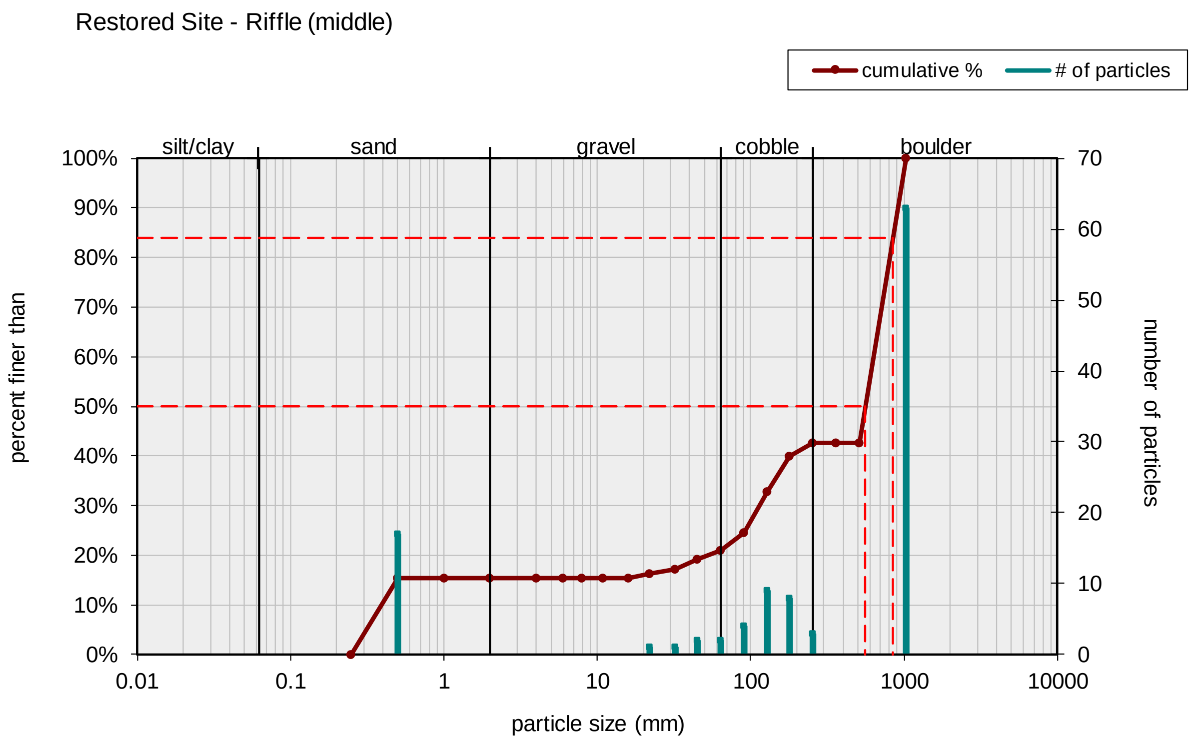
Restored Site - Pool



Size (mm)	
D16	66
D35	110
D50	550
D65	660
D84	840
D95	960

Size Distribution	
mean	235.5
dispersion	4.9
skewness	-0.35

Type	
silt/clay	0%
sand	5%
gravel	10%
cobble	30%
boulder	55%

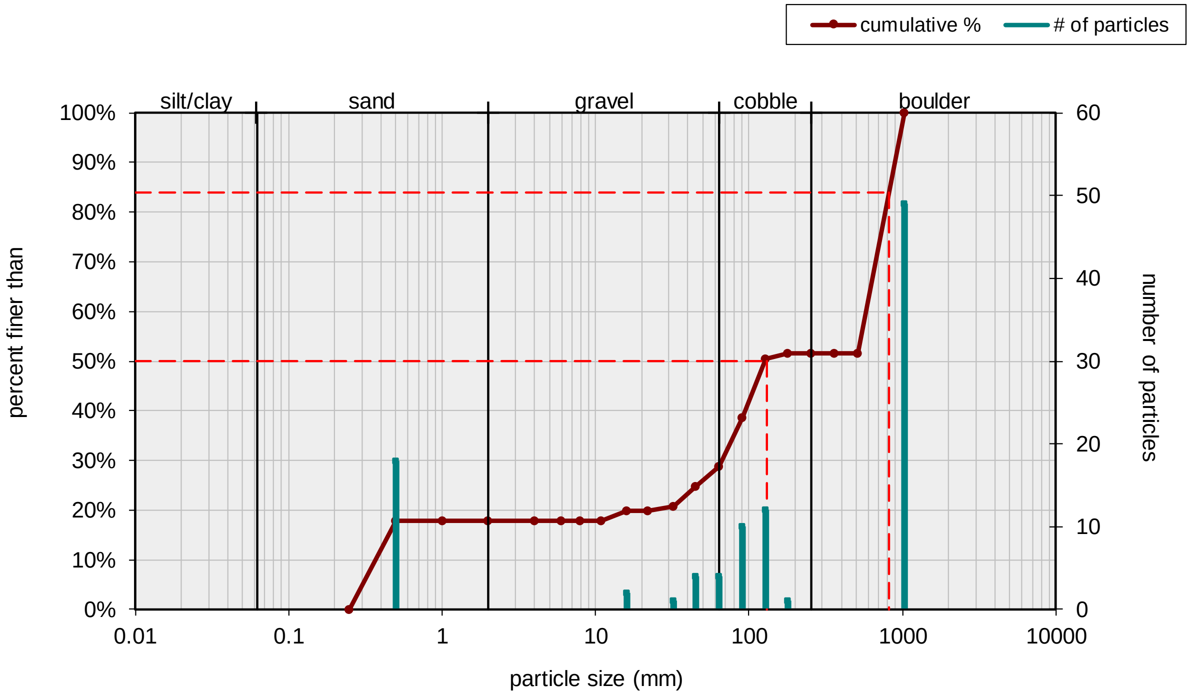


Size (mm)	
D16	19
D35	140
D50	560
D65	670
D84	840
D95	960

Size Distribution	
mean	126.3
dispersion	15.5
skewness	-0.50

Type	
silt/clay	0%
sand	15%
gravel	5%
cobble	22%
boulder	57%

Restored Site - Riffle

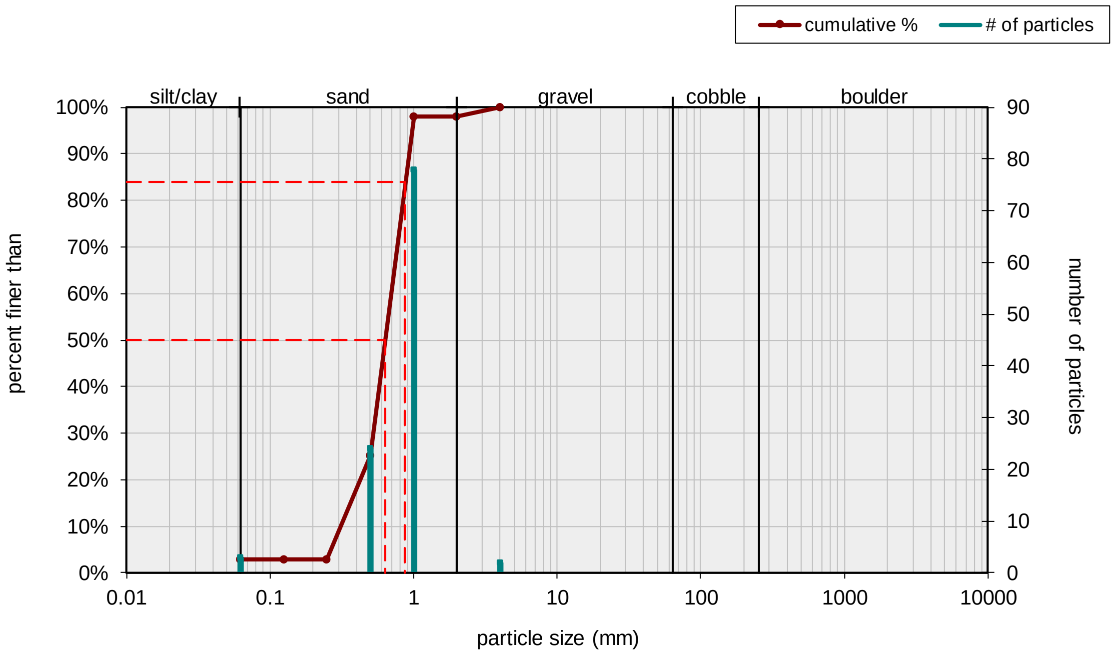


Size (mm)	
D16	0.47
D35	79
D50	130
D65	620
D84	810
D95	950

Size Distribution	
mean	19.5
dispersion	141.4
skewness	-0.46

Type	
silt/clay	0%
sand	18%
gravel	11%
cobble	23%
boulder	49%

Reference Site - Pool

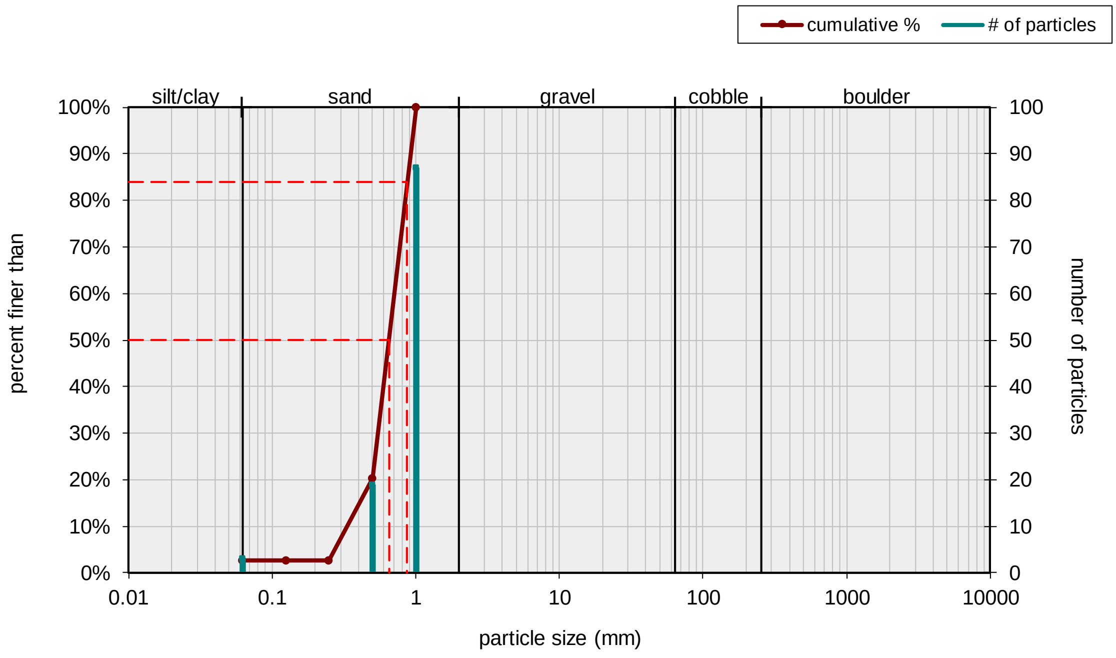


Size (mm)	
D16	0.38
D35	0.55
D50	0.63
D65	0.73
D84	0.87
D95	0.97

Size Distribution	
mean	0.6
dispersion	1.5
skewness	-0.07

Type	
silt/clay	3%
sand	95%
gravel	2%
cobble	0%
boulder	0%

Reference Site - Pool (middle)

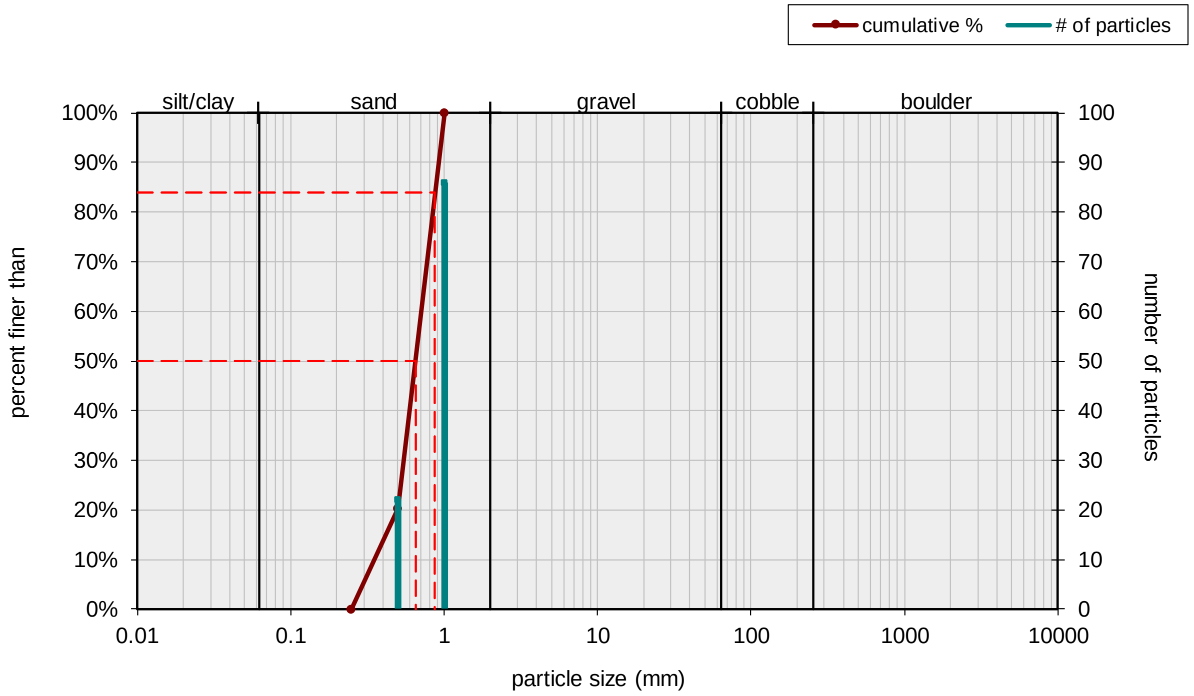


Size (mm)	
D16	0.42
D35	0.57
D50	0.65
D65	0.74
D84	0.87
D95	0.96

Size Distribution	
mean	0.6
dispersion	1.4
skewness	-0.06

Type	
silt/clay	3%
sand	97%
gravel	0%
cobble	0%
boulder	0%

Reference Site - Riffle



Size (mm)	
D16	0.43
D35	0.57
D50	0.65
D65	0.74
D84	0.87
D95	0.96

Size Distribution	
mean	0.6
dispersion	1.4
skewness	-0.05

Type	
silt/clay	0%
sand	100%
gravel	0%
cobble	0%
boulder	0%

Appendix D

Database Created During this Study

Title	Author(s)	Year	Watershed	Stream or Specific Study Area	Public	Description
Watershed Management plan for the D’Olive Creek, Tiawasee Creek, and Joe’s Branch Watersheds Daphne, Spanish Fort, and Baldwin County, AL	Coffee, G	2010	D'Olive	D’Olive Creek, Tiawasee Creek, and Joe’s Branch	Yes	D’Olive Creek Watershed: outlines a holistic approach to reduce sediment sources; repair degraded stream channels; and restore the Watershed’s hydrology to the maximum extent technically feasible.
Analysis of Sediment Loading Rates and Impacts of Land-use Change on the D’Olive and Tiawasee Creek Watersheds	Cook, M	2007	D'Olive	D’Olive and Tiawasee Creeks	Yes	Assess the impacts of land-use change by determining sedimentation rates in streams that receive sediment from construction sites in the watershed
Assessment of Lake Forest Lake Sediment Trapping Efficiency and Capacity	Cook, M	2008	D'Olive	Lake Forest Lake	Yes	Sedimentation and Lake Forest Lake
Analysis of Sediment Rates for the D’Olive Creek Watershed Upstream from the Interstate 10 Crossing	Cook, M, Moss, N	2012	D'Olive	I-10 Project Watershed Area	Yes	Discusses runoff and sediment loads resulting from current impacts of land-use upstream from Interstate 10
Phase II Post-restoration analysis of Discharge, Sediment Transport Rates, and Water Quality in Tributaries of Joes Branch in Spanish Fort	Cook, M, et al	2014	D'Olive	Joes Branch	Yes	Post-restoration analysis: water quality and sediment transport data and documentation of the effectiveness of stream restoration

Title	Author(s)	Year	Watershed	Stream or Specific Study Area	Public	Description
DISCHARGE RATING, CONFIRMATION AND UPDATES OF SEDIMENT TRANSPORT REGRESSION CURVES, AND WATER QUALITY FOR SELECTED SITES IN THE D'OLIVE CREEK WATERSHED, BALDWIN COUNTY, ALABAMA	Cook, M	2017	D'Olive	Watershed	Yes	Post-restoration analysis: water quality and conditions impacting water quality
An assessment of coastal land-use and land-cover change from 1974–2008 in the vicinity of Mobile Bay, Alabama	Ellis, J, et al	2010		Mobile Bay Area	Yes	Geospatial land-use and land-cover (LULC) changes in the coastal counties of Mobile and Baldwin, Alabama using nine Landsat images from 1974–2008
A Modeling System to Assess Land Cover Land use Change Effects on SAV Habitat in the Mobile Bay Estuary	Estes, M, et al	2015		Mobile Bay Area	Yes	Examines the effect of LULC changes on discharge rate, water properties, and submerged aquatic vegetation, including freshwater macrophytes and seagrasses, throughout the estuary.
D'Olive Creek Restoration Project Segments D4-D6 (preliminary plans)	Goodwyn, Mills, and Cawood Inc.	2015	D'Olive	D'Olive Creek	No	Preliminary plans of restoration project: D'Olive Creek Segments D4-D6
Age and Origin of the Citronelle Formation in Alabama	Isphording, W, Lamb, G	1970		Mobile County	Yes	Analysis of Citronelle Formation--located in Mobile County, AL

Title	Author(s)	Year	Watershed	Stream or Specific Study Area	Public	Description
Identification of Short-Term Changes in Sediment Depositional Rates: Importance in Environmental Analysis and Impact Investigations	Isphording, W, et al	1984		D'Olive Bay	Yes	Elaborates on anthropogenic impact on D'Olive Bay (related to sediment): sediment size parameters, heavy mineral and clay mineral ratios, sulphur content and zinc, copper and vanadium percentages.
D'Olive Watershed: Path Toward Restoration (Case Statement)	Mobile Bay NEP	NA	D'Olive	D'Olive Creek	Yes	D'Olive Creek Watershed: discusses local issues (sedimentation, erosions, urban development, and so forth), watershed characteristics, watershed management goals and objectives, watershed measures, community outreach.
Response of Mobile Bay and eastern Mississippi Sound, Alabama, to changes in sediment accommodation and accumulation	Rodriguez, A, et al	2008		Mobile Bay Area	Yes	Using a map of antecedent topography, a sea-level curve, and measured and modeled sedimentation rates, the authors quantify the creation of sediment accommodation and the rate of sediment accumulation for Mobile Bay.
Sediment accommodation control on estuarine evolution: An example from Weeks Bay, AL	Rodriguez, A, et al	2008		Weeks Bay (south of Fly Creek)	Yes	The authors calculate sediment accommodation for Weeks Bay and compare this with calculated sediment accommodation over the late Quaternary evolution of the bay derived from seismic and lithologic data.
Geomorphology of the Mobile Delta: Geological Survey of Alabama	Smith, W	1988		Mobile Bay Area	Yes	Utilizes high altitude color infrared photography and topographic maps to identify and describe primary geomorphic features and geologic and hydrodynamic processes of the Mobile delta

Title	Author(s)	Year	Watershed	Stream or Specific Study Area	Public	Description
An example from Weeks Bay, Al	Stout, J	1998		Mobile Bay Area	Yes	Overview of NEP goals and investigation of local habitat loss
The Mobile Bay Estuary and Coastal Population Growth: The Challenge of Keeping What We've Got	Swann, R, Herder, T	2014		Mobile Bay Area	Yes	Overview of the Mobile Bay Area and local, anthropogenic impact
Appendix-A-E: Erosion Activity Assessment of the D'Olive Creek Watershed	Tetra Tech	2010	D'Olive	D'Olive Creek Watershed	Yes	D'Olive Creek Watershed Investigation: erosion activity assessment, determining the causes of erosion, proposing locations to implement potential sediment and stormwater Best Management Practices (BMPs) to help reduce future erosion and sediment loading to the streams, Lake Forest Lake, and D'Olive Bay.

Title	Author(s)	Year	Watershed	Stream or Specific Study Area	Public	Description
The Ecological Consequences of Channel Dredging in D’Olive Bay, AL	Vittor, B	1972	D'Olive	D'Olive Bay	Yes	Elaborates on how local dredging impacted D'Olive Bay
Wetland Condition Evaluation: D’Olive Creek, Tiawasee Creek, and Joe’s Branch Watersheds	Vittor, B	2010	D'Olive	D’Olive Creek, Tiawasee Creek, and Joe’s Branch	Yes	Characteristics of, and impacts to, wetlands found within the D’Olive Creek, Tiawasee Creek, and Joe’s Branch watersheds: canopy species and closure, midstory and understory species and density, degree of apparent sedimentation, exotic species present, impacts to the surrounding upland buffer, and potential methods that could be used to enhance or restore the wetlands.
Fly Creek Watershed Restoration Project	Thomson Engineering and the City of Fairhope	2013	Fly Creek	Fly Creek	Yes	Provides an overview of the Fly Creek Watershed (note: not USGS HUC 12)