EVALUATION OF URBAN RIPARIAN BUFFERS ON STREAM HEALTH IN THE TOOKANY WATERSHED, PA

A Thesis
Submitted to
the Temple University Graduate Board

In Partial Fulfillment
of the Requirements for the Degree
MASTER OF SCIENCE

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by
Emily G. Arnold
December 2016

Examining Committee Members:

Dr. Laura Toran, Graduate Advisor, Earth and Environmental Science

Dr. Jonathan Nyquist, Committee Member, Earth and Environmental Science

Dr. Steven Chemtob, Committee Member, Earth and Environmental Science

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

ABSTRACT

Stream channels and their corresponding riparian zones are composed of complex spatially and temporally dynamic systems. Changing land-use associated with urbanization has resulted in large shifts in riparian assemblages, stream hydraulics, and sediment dynamics leading to the degradation of the world's waterways. To combat degradation, restoration and management of riparian zones is becoming increasingly common. However, the relationship between flora, especially the influence of invasive species, on sediment dynamics is poorly understood. This relationship must be studied further to ensure the success of management practices.

Three methods were used to monitor erosion and turbidity within the Tookany Creek and its tributary Mill Run in the greater Philadelphia, PA region. To evaluate the influence of the invasive species *Reynoutria japonica* (Japanese knotweed) on erosion, reaches were chosen based on their riparian vegetation and degree of incision. Methods used to estimate sediment erosion included measuring changes in bank pins, repeated total station transects, and monitoring turbidity responses to storm events. While each method has been used in previous studies to monitor sediment flux, the combination of methods in this study allowed their applicability to be compared.

Measurements taken with YSI turbidity loggers showed large fluctuations in turbidity based both on riparian conditions and geomorphic positioning, suggesting that future studies need to be careful with logger placement when using sediment calibration curves to estimate sediment yield within streams. There were pros and cons of using both total station and bank pins to estimate bank erosion. Total station has the potential to produce highly accurate measurements but a greater risk of loss of data if the control points used to establish the grid cannot be re-established from one measurement to the next. Bank pins are more likely to influence bank erosion and be affected by freeze-thaw conditions but provide a simple method of monitoring erosion at frequent intervals.

Volume calculations based on total station transects along the main stem of the Tookany did not show a consistent relationship between riparian type and erosion rates. However, erosion calculations based on bank pins suggest greater erosion in reaches dominated by knotweed with $4.7\text{x}10^{-1}$ m^3/m and $8.3\text{x}10^{-2}$ m^3/m more erosion than those dominated by trees at Chelten Hills and Mill Run respectively. Turbidity responses to storm events were also higher (76.7 v 54.2 NTU) in reaches with knotweed, although this increase was found when the reach dominated by knotweed was also incised. Thus, this study linked knotweed to increased erosion using multiple methods.

ACKNOWLEDGMENTS

This work could not have been completed without the advice and dedication of my advisor, Dr. Laura Toran. From designing the proposal to field procedures and throughout the writing process her input has been invaluable. Additional thanks are owed to my committee members, Dr. Jonathan Nyquist and Dr. Steve Chemtob, for their input and edits, Dr. David Grandstaff for help in statistical analysis, and Dr. Nicholas Davatzes for advise in MATLAB scripting. Lastly, I thank my network of support, my friends, my family, and Chris Witzigman, for all those long days of data collection in the summer heat and fall hurricanes.

This work was supported by a grant from the William Penn Foundation to the Temple Ambler Center for Sustainable Communities under the Delaware River Watershed Initiative.

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INTRODUCTION

1.1 Urban Stream Syndrome

Stream and water resource degradation in response to human activities has a long history. Evidence of eutrophication of coastal waters in response to increased nutrient input dates back to the Roman era (Caldara et al., 2002) while soil erosion in response to agricultural practices post-American colonialism has long been recognized (Merchant, 2007). More recently, the Industrial Revolution and urbanization have resulted in large shifts in both stream hydraulics and sediment dynamics. As of 2000, there were over 130,000 km of impaired streams and rivers in the United States (Paul and Meyer, 2001). Unless development patterns are managed, the degradation of waterways will continue as populations rise. This growth will occur primarily in urban centers, as urban populations surpassed the number of people living in rural areas in 2009 (United Nations, 2009), making the provision of urban drinking water and sanitation two of the greatest challenges of the 21st century (Kaushal and Belt, 2012).

Degradation of urban streams and their receiving waters is common, resulting in a suite of impairments dubbed "Urban Stream Syndrome" (Walsh et al., 2005). Waterways suffering from Urban Stream Syndrome tend to have increased nutrient and contaminant concentrations, modified channel morphology, reduced ecological function, and a hydrograph with steeper ascending and descending limbs. These symptoms are consistently observed in urbanized areas, although the degree to which degradation occurs depends on additional factors such as geological conditions, historical land use, development patterns, and drainage connectivity. Other impacts might include decreases in groundwater baseflow or increased suspended solids, but are not present in all urban areas (Walsh et al., 2005).

As urban development progresses, land cover is first cleared and then replaced with impervious surfaces such as roads, sidewalks, and roofs. This leads to the installation of stormwater drainage systems due to a decrease in infiltration and an increase in surface runoff. Cities have historically been associated with the “sanitary city” model, which aims to drain water rapidly out of urban areas and into adjacent streams through stormwater drainage systems (Kaushal and Belt, 2012). Until recently, this practice was considered the best method of stormwater management, as it was believed to control flooding, erosion, and human exposure to potential pathogens and contaminants (Morris, 2008). However, urban drainage systems are one of the largest contributing factors to Urban Stream Syndrome, as they disconnect urban runoff from natural hydrological processes (Walsh et al., 2005; Wenger et al., 2009; Kaushal and Belt, 2012).

The percent total imperviousness (TI) in a watershed is often used as an indicator of urban intensity and is highly correlated with stream degradation. Relative to forested reaches, runoff increases twofold as a catchment’s TI increases to 10-20% (Figure 1-1) and more than fivefold with 75-100% TI (Paul and Meyer, 2001). Due to variations in stormwater connectivity, Urban Stream Syndrome is observable at different levels of total catchment imperviousness. While a TI of 10-20% is often considered to be a lower threshold for degradation, urban streams have shown measurable impacts with as low as 4% TI (Wegner et al., 2009) depending on catchment specific conditions. Peak discharges have been found to be over 250% greater in urban catchments in New York and Texas than in forested watersheds (Paul and Meyer, 2001). Therefore, while TI can be used as an indicator, Wegner et al. (2009) warn against using TI as a universal measure of urban stream degradation as the relationship between TI and increased runoff is non-linear (Paul and Meyer, 2001).

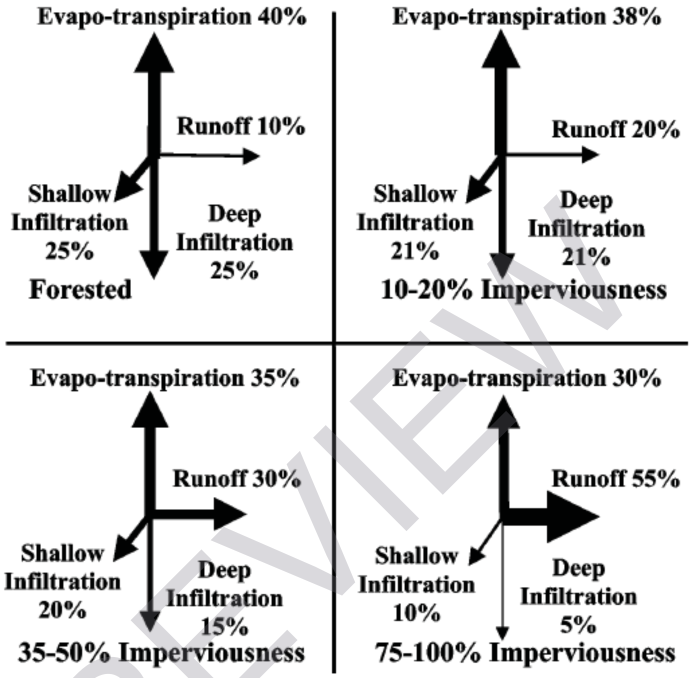

Figure 1-1: Urbanization's Impact on Runoff. Increasing total imperviousness (TI) in a watershed influences natural processes including runoff, infiltration, and evapotranspiration. Taken from Paul and Meyer, 2001.

Changes to urban hydrology influence catchment and stream morphology. Natural channel density decreases as small streams are filled in or replaced with pipes while artificial drainage increases through the construction of drainage networks such as stormwater pipes and road culverts (Paul and Meyer, 2001; Kaushal and Belt, 2012). These artificial passages often increase the drainage density of the overall catchment where they act as 1st and 2nd order tributaries that drain into 2nd or 3rd order surface streams (Figure 1-2). These drainage networks limit the area of the catchment that is hydrologically connected to geomorphological features such as floodplains, limiting natural processes such as biological processes, nutrient and contaminant uptake, water retention, and sediment deposition (Kaushal and Belt, 2012).

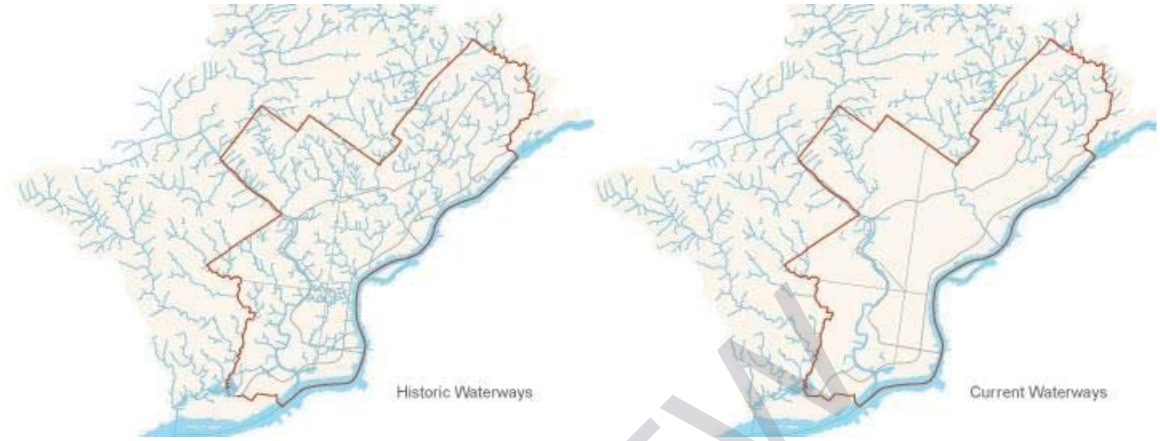

Figure 1-2: Burial of Urban Streams. The burial of headwater streams and construction of artificial stormwater drainage pathways in the City of Philadelphia has decreased the length of stream reaches that are connected to floodplain systems by 73% while greatly increasing the catchment drainage density overall. This pattern holds true in most urbanized centers. Taken from phillywatersheds.org.

1.2 Sediment Flux

The streambed is a dynamic system that can change geomorphic form during storm events. Stream sediment provides habit for aquatic organisms and is the location of many biogeochemical processes. Changes in the streambed occur at variable spatial and temporal scales and contribute to the overall health of fluvial ecosystems. Sediment fluxes change in urban systems because of the increased flow rates, and erosion and deposition are one of the main stressors in urban streams.

There is no defined amount of suspended sediment associated with degraded streams as the turbidity in natural hydraulic systems can vary significantly based on the density of the drainage basin, local geology, and the size of the stream or river. Turbidity is a measurement of the influence of suspended solids on an aqueous solution's ability to transmit light. Sensors measure the degree a beam of light is either absorbed or scattered by suspended sediment and other un-dissolved materials, such as organic matter, when passing through the water sample (Minella et al., 2008). However, a positive sediment flux within the watershed is indicative of a system with erosion rates that are out of equilibrium with deposition. There are multiple concerns associated with turbidity, including, but not limited to, decrease in light penetration, degradation of aquatic resources such as fish habitat, sedimentation of receiving waters such as lakes and estuaries, and transport of other contaminants.

Non-point source pollutants such as heavy metals and nutrients can form complexes with clay minerals and other fine-grained sediments which can be remobilized. Eroding cut-banks in the mid-Atlantic region often consist of fine-grained legacy sediment (or sediment that was deposited in mill ponds during the Colonial and Industrial eras) which may be contaminated (Walter and Merritts, 2008; Taylor and Owens, 2009; Pizzuto et al., 2014). The remobilization of these sediments can increase nutrient loading leading to eutrophication of lakes and high toxicity in aquatic organisms that live or feed in the benthic zone (Nelson and Booth, 2002). Sediment deposition in lakes, estuaries, and harbors can impact economics through decreased quality of recreational activities as well as disrupting commercial navigation (USACE, 2013).

Other concerns related to turbidity include health hazards such as water-borne illnesses in drinking water sources (Morris, 2008). This is because disease-causing microbes can be transported with particulate matter. In 1997, New York City issued the Filtration Avoidance Determination, the goal of which is to decrease sediment levels in the surface waters of the Catskill and Delaware public water systems to the point that an expensive filtration system is unnecessary (USEPA, 1997).

The nature of channel-floodplain sediment exchange within hydrologic systems strongly controls the transport distance and fate of particle-bound contaminants, with fine-grained sediments having the potential to be transported substantial distances (Nelson and Booth, 2002; Underwood et al., 2015). Due to the amount of stored sediments, and by extension sediment-bound pollutants, the movement and retention of sediments is likely to remain a concern for the foreseeable future (Hupp et al., 2013).

1.2.1 Potential Sediment Erosion and Deposition

Fluvial systems establish equilibrium by adjusting their channel morphology in response to discharge and sediment load. Variable features include channel width, depth, roughness, and slope (Ritter, et al., 2002; Paul and Meyer, 2001). The influence of urbanization on sediment dynamics has been recognized since the 1960s (Wolman, 1967). According to Paul and Meyer (2001) aggradation and erosion are the two main phases of stream morphology adjustment following urbanization. During construction, hill slope erosion increases, resulting in an increase in sediment load and aggradation of sediment along the streambed and banks.

An erosional phase also occurs in the stream channel following aggradation and can result in both incision and stream widening. Incision is defined as "rapid channel deepening disproportional to the increase in water discharge" (Booth, 1990). Stream width increases in approximate proportion to increased discharge associated with increases in TI (Paul and Meyer, 2001; Ritter, et al., 2002; Walsh et al., 2005; Wegner et al., 2009). In general, incision is more notable than stream widening in urban environments and will occur when the transport capacity of the water exceeds the influx of sediment. Erosion can have major impacts on stream health by decreasing channel complexity, disconnecting urban streams from their riparian zones, and increasing stream turbidity. In addition, serious damage to structures such as roads and bridges can result from erosion and cause changes in catchment hydrology and infrastructure, especially during storm events (Carvalho et al., 2009).

Increased erosion due to urbanization is well documented with sediment sources varying depending on basin characteristics such as stream morphology, location within the watershed, nature of the runoff response, and maturity of the watershed. In Difficult Run, a watershed in the Piedmont Providence in the Chesapeake watershed, urbanization in the upper catchment resulted in double the amount of upstream erosion as compared to downstream storage (Schenk et al., 2013). This erosion has likely resulted in higher than normal bank heights due to incision into fine-grained legacy sediment which decreases connectivity of the stream with the floodplain system (Schenk et al., 2013). In southern California, San Diego Creek saw 10^5 megagrams per year, or 2/3 of the total sediment yield, as the result of stream channel erosion (Trimble, 1997). The combination of decrease of connectivity and increased capacity for sediment transport during storm events in urban streams reduces the potential for overbanking and deposition of sediment on the floodplain.

Multiple studies dating back to the 1980s have found that the majority of the sediment eroded from the watershed is re-deposited within the basin with only 10-20% of the sediment eroded being removed from the basin entirely. The majority of deposition occurs on terraces and floodplains with 20-30% of deposited sediment being temporarily stored within the stream channel (USACE, 2013). Areas of deposition within the channel include both living and fallen vegetation including large woody debris. The nature of deposition is not consistent, with the same areas serving as both sinks and sources of sediment during similarly sized flood events, potentially even changing from a sink to a source during a single flood event (Underwood et al., 2015).

Deposition has also been examined in watersheds of variable sizes and locations with recent studies supporting previous results. Underwood et al (2015) demonstrated that during small to medium sized storms there was a net transfer of sediment from the channel to the stream margins adjacent to the active channel in an undeveloped catchment in New England. Using fallout radionuclides ^{7}Be and ^{210}Pb and the stable isotopes of hydrogen in water, they showed approximately 90% of the sediment mobilized from the streambed being deposited onto the stream margins. Only 10% of the mobilized sediment was transported downstream during storm events as suspended load. Due to the increased capacity for sediment transport in urban streams, the percentage of mobilized sediment that is flushed from the system to the receiving water body might be higher. However, studies quantifying sediment flux in urban catchments are lacking.

1.2.2 Sediment Residence Times

The travel-times associated with the transport of sediment through watersheds remain highly debated among scientists. Garcia (2006) posits rapid movement of fine-grained sediment from tributaries though the watershed to the receiving waters. Continuous transport of sediment is assumed in many sediment flux models, including those used for environmental management such as in Chesapeake Watershed (Meade, 2007; Pizzuto, 2014; Pizzuto et al., 2014). What models often do not recognize is the importance of long-term storage of sediment with only episodic entrainment. Sediment storage occurs mainly within the floodplain where sediment can remain for years and even millennia.

Channelized transport of sediment during storm events is apparent by both visual observation and continuous turbidity data collection (Skarbovik and Roseth, 2014). However, sediment is more likely, by factors of thousands or more, to be at rest than being transported the majority of the time (Pizzuto, 2014). While mobilization of sediment is a consequence of storm events, the overall timing of the downstream sediment delivery is much more complex and depends on numerous conditions including watershed size, morphology, and biota. Due to storage of sediment in the floodplain, multiple sediment flux studies analyzing sediment age, erosion, and delivery to coastal waters suggest the average residence time of released fine-grained sediment at decades to millennia (Hupp et al., 2013; Meade, 2007; Pizzuto, 2014; Pizzuto et al., 2014; Underwood et al., 2015).

1.2.3 Measuring Fluvial Sediment Budgets

One way to examine sediment within a watershed is to create a sediment budget to categorize all of the sources, sinks, pathways, and processes associated with sediment flux. There are many monitoring techniques to evaluate sediment flux, including direct measurement of erosion and deposition and the use of turbidity as a proxy for sediment levels. Monitoring sediment flux is often considered superior to measuring erosion or deposition alone as it can represent both a positive gain and a negative loss of sediment within the system (Hupp et al., 2013).

Precise measurements for bank erosion, sediment transport, and channel and floodplain deposition to develop stream-scale sediment budgets are difficult to obtain. The creation of a comprehensive sediment budget requires multiple site studies over a minimum of a several year period. The extended time-frame is necessary to account for changes in erosional and depositional patterns due to variable annual precipitation and storm events. In addition, our understanding of sediment yield is complicated by historic and current human land-use. This instability is especially pronounced in urban environments with a long history of alterations in the surrounding watershed, direct management of the stream channel, and both intentional and unintentional introduction of exotic flora and fauna. However, areas that either contribute sediment into the stream or act as sediment traps greatly impact the downstream water quality. Understanding the balance of sediment inputs to outputs within a watershed is essential to determining the best management practices for stream restoration (Hupp et al., 2013; Schenk et al., 2013).

Sediment has been identified as one of the most significant pollutants entering the Chesapeake Bay and legislation has been introduced to implement total maximum daily loads (TMDLs) to control the amount of suspended sediment entering the estuary (Schenk et al., 2013). The Piedmont has been identified as the single greatest sediment source into the Chesapeake Bay despite low relief and low, long-term erosion rates (Schenk et al., 2013; Hupp et al., 2013; USACE, 2013). To meet TMDL requirements it is necessary understand sediment dynamics in tributaries to the Chesapeake Bay. As a preliminary step extensive work to create sediment budgets in tributaries in the Piedmont region is underway. The tributaries included have varying land-use and include Difficult

Run, Little Conestoga Creek, and Linganore Creek which represented urban, urbanizing, and agricultural watersheds respectively. These studies used bank pins to measure cut-bank erosion and clay pads, or artificial horizons, installed to monitor floodplain deposition (Schenk et al., 2013). Measurements in these catchments showed that the net site sediment budget was best predicted by the ratio of the channel to floodplain width. Sediment budgets in the tributaries of other major watersheds along the Atlantic are lacking as TMDLs have not yet been implemented.

Sediment flux can also be monitored by continuous data loggers monitoring turbidity. Sediment levels are often associated with high flow events in response to precipitation. As such, regular sampling intervals used in other water quality studies can miss elevated sediment concentrations during storm events resulting in an underestimate of sediment load (Gao, 2008). Skarbovik and Roseth (2014) showed that turbidity loggers were particularly successful at detecting peak concentration of sediment during storm events. A site-specific calibration curve can be created to relate suspended sediment concentration to the turbidity data. This allows turbidity to be used as a proxy for total suspended sediment within the water column (Gao, 2008; Minella et al., 2008). Turbidity loggers are not typically used on a reach scale, instead focusing on catchment level changes in sediment load. Watershed scale monitoring is especially useful in areas where increases in sediment are associated with non-point sources, an issue that has been recognized for a number of pollutants since the early 1980s (Nelson and Booth, 2002).