A Sediment Budget of an Urban Creek in Toronto

by

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Abstract

Wilket Creek is a second order stream located in Toronto, Ontario. Over the past decade, management efforts have intensified to protect infrastructure including walking paths, bridges, sanitary sewers and private property. As a result, the City of Toronto and the Toronto and Region Conservation Authority have undertaken projects to protect infrastructure by re-aligning the creek and hardening banks. Many of the projects have not been successful over the long term and efforts to protect infrastructure are ongoing.

The goal of this research project has been to understand how sediment moves through Wilket Creek. This was accomplished by conducting a sediment budget which is an account of sediment inputs, outputs and storage in a fluvial or geomorphic system. Initially a morphological approach was employed to estimate volumetric sediment transport. The results contributed to a comprehensive sediment budget which assessed relative sediment input, output and storage components. As part of the study, efforts were undertaken to establish Wilket Creek as a long term field monitoring site for research on urbanization and sediment transport.

Fieldwork was carried out over a two year period to assess input, output and storage terms of the sediment budget and estimate sediment transport. A comprehensive sediment budget identified bank erosion in the middle and lower reaches as the primary sediment inputs. A dam and bank storage in the lower area of the watershed were the main storage terms. Sediment outputs included the confluence with the West Don River, bank storage near the confluence and dredging behind a dam. Sediment transport calculations estimated that sediment output at the confluence was between 680 and 1,300 ton/yr/km^2. Based on field measurements and observations, isolated locations of channel instability were identified in the middle reaches while a more general trend of channel adjustment was observed in the lower reaches upstream of the West Don River.

Further research should concentrate on obtaining reliable discharge measurements, refining estimations of sediment budget terms and conducting additional analysis of historical aerial imagery. Finally, additional study should be undertaken to identify the causes of channel adjustment prior to initiating new restoration efforts.

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1.0 Introduction

As awareness of ecological degradation has increased, desire to rehabilitate ecosystems has resulted in a proliferation of river restoration activities over the past decades (Roni et al 2008). It is estimated that in the United States more than US$1 billion is spent annually on river restoration and that US$14 billion was spent between 1990 and 2005 (Bernhardt et al 2005). There are similar expenditures in Europe with the German state of Nord Rhine-Westphalia, for example, budgeting 80 million Euros every year through 2027 (Lorenz et al 2012).

In urban areas, restoration has been increasingly employed to protect infrastructure and achieve water quality goals (Kenney et al 2012). Compared to other settings, urban stream restoration is more complicated and costly due to factors such as minimal space, land cost and multiple property owners. As a result, most stream restoration costs in the United States are spent on a relatively small number of urban streams (Violin et al 2011). Within North America, the City of Baltimore, Maryland, for example, estimated that stream restoration costs ranged between US$1640/m and US$3937/m (Kenney et al 2012). In comparison, restoration costs for small rangeland streams can be as little as US$165/m (Nagle 2007).

Although a great deal of money has been spent on urban streams, success has proved elusive (Bernhardt and Palmer 2011, Violin et al 2011, Kenney et al 2012, Booth 2005). In many cases, watershed level constraints were not considered (Booth 2005, Roni et al 2008). In others, rehabilitation efforts were carried out in reaches undergoing adjustment making them poor candidates for restoration (Miller and Kochel 2010).

Although often considered long term, academic endeavors, sediment budgets have the potential to provide useful information to watershed managers within typical planning time frames (Reid and Dunne 1996, Reid and Dunne 2002). A sediment budget is an account of sediment inputs, outputs and storage in a fluvial or geomorphic system (Biedenharn et al 2010). As a management tool they can be used to locate areas of erosion, determine the cause, establish management priorities and evaluate potential responses (Reid 1990, Reid and Dunne 2002). Sediment budgets typically do not result in precise, numerical answers for erosion, deposition, storage and sediment yield of a system. Instead, they assess the processes by which sediment moves through a system and provide relative or order of magnitude estimates (Reid 1990). Sediment budgets are considered by some as the single most important tool for management of a fluvial system (Phillips 1991). However, relatively few sediment budgets have been completed for urban systems.

The goal of this research was to understand sediment transport through an urban stream system in Toronto by conducting a sediment budget. The site was selected as it provides a clear example of an urban watershed developed without any plan for mitigating the adverse effects associated with stormwater. The objectives of this study are i) utilize cross sectional surveys to estimate sediment transport and quantify certain inputs and outputs to the system, and ii) conduct a comprehensive sediment budget to asses input, storage and output terms. In conjunction with this project, a study was undertaken to examine the effects of a recent in-stream restoration (completed in 2012) on sediment mobility and transport and assess its stability. Together, these projects contribute to understanding how urbanization affects watershed sediment production and transport and whether stream restoration and stormwater management schemes can be designed to restore the balance between the hydrological and sediment regime.

The two studies mentioned above will include conducting a complete longitudinal survey, establishing monumented cross sections, installing pressure gauges, conducting stream flow measurements and characterizing the bed at selected locations. Therefore, it is anticipated that these projects will result in the establishment of Wilket Creek as a long term monitoring site for research on urbanization and sediment transport. From a research perspective, Wilket Creek is an excellent candidate for a long term study site as it has a varied morphology with an extremely sinuous section as well as locations that have been heavily modified. In addition, there is a range of different slopes and an extremely varied discharge with numerous bankfull events each year. Finally, as an area with high public usage, there is interest from both the City of Toronto and the Toronto and Region Conservation Authority (TRCA) in gathering long term data on Wilket Creek to better inform management efforts.

This study begins with a literature review of urban streams and the sediment budget methodology as these topics were pertinent to the research. The literature review ends with a statement of the thesis objectives. This is followed by a discussion of the methods beginning with a description of the field site and preliminary data collection efforts. Next, analysis of aerial imagery and field methods are described in detail along with a discussion on how data was processed. Results of the aerial imagery analysis and field measurements are then presented. The subsequent section deals with the actual sediment budget and addresses three areas: the contribution of bed and bank material, an estimation of sediment transport rates and sediment yield at the creek's confluence and a comprehensive sediment budget for Wilket Creek. The last section is a discussion of the finding and recommendations for future investigations.

2.0 Literature Review

2.1 Urban Streams

Healthy rivers and streams are conceptualised as existing in a state of dynamic equilibrium in which the river system achieves balance between the hydrologic and sediment regimes over long spans of time. During this period, the bed slope may undergo subtle adjustment to facilitate the transport of sediment (Mackin 1948, Schumm and Lichty 1965). As a result, the river achieves a stable morphology in which deposition and erosion are roughly equal over time scales of a few years to decades. The bed is neither aggrading nor degrading, the channel has relatively stable banks and the planform does not significantly change (Levell and Chang 2008, Chin 2006). The process of urbanization initiates a series of events that disturbs the balance between the sedimentological and hydrological regimes resulting in morphological changes to the stream (Schiff et al 2011, Levell and Chang 2008).

One of the first models describing the effects of urbanization on stream channels was proposed by M.G. Wolman. Prior to development, the stream channel is in a state of dynamic equilibrium. Next, the process of urbanization begins with a phase of active construction. During this period there is an increased sediment supply to rivers and streams (Wolman 1967). As the urban area expands, natural cover is replaced with roads, houses, buildings and other structures increasing the area of impervious surfaces and reducing sediment input (Wolman 1967, Allmendinger et al 2007). Additionally, urban infrastructure such as sanitary and storm sewer systems are greatly expanded (Schiff et al 2011). The combination of increasing impervious surface and stormwater management radically alter the natural hydrologic regime (Konrad et al 2005). The combination of changes in sediment and hydrology ultimately result in significant changes in stream morphology (Figure 1). In addition to morphological changes through modification of hydrology and sediment supply, direct modification of channels frequently occurs during urbanization through straightening, channel relocation or confinement (Schwartz and Herricks 2007). These actions can damage long term stream stability, water quality and habitat (Booth 2005, Rhoads et al 2008).

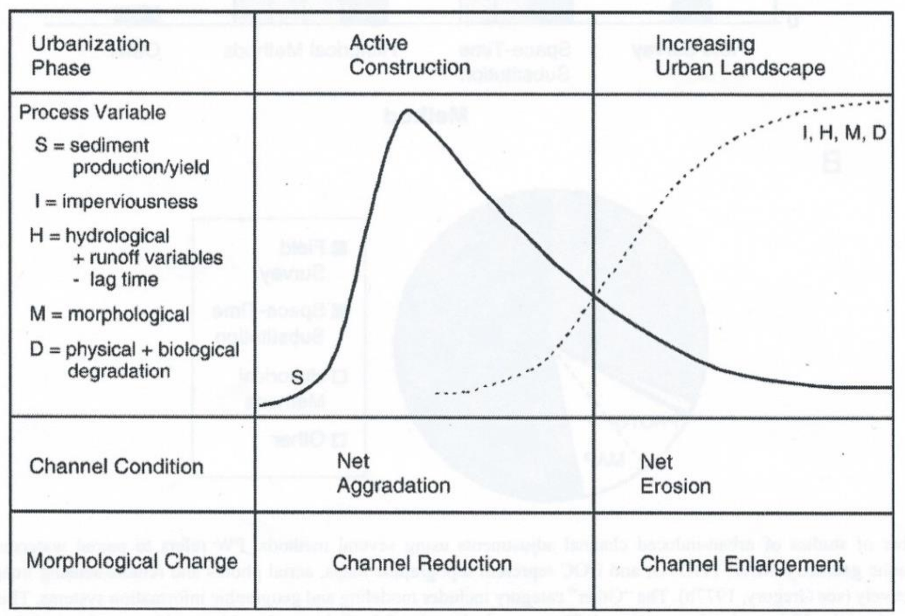

Figure 1. Phases of urbanization illustrating effect on stream channel (Chin 2006 based on Wolman 1967).

2.1.1 Sediment Regime

The conceptual model first suggested by Wolman, has generally been validated by numerous studies throughout the world (Chin 2006). The first natural process disrupted by urbanization is the sediment regime. During the period of initial construction, the amount of sediment delivered to the stream in the form of both washload and bedload greatly increases (Allmendinger et al 2007, Pizzuto et al 2000). Initially, this may result in sediment deposition on the banks or downstream (Jordan et al 2010). Channel capacity may be reduced as the sediment supply exceeds the hydrologic capacity (Leopold 1973). Once build out within the watershed is complete, sediment production drastically decreases as sediment is not actively supplied to the stream by the construction process (Allmendinger et al 2007, Pizzuto et al 2000). Furthermore, impervious cover and residential landscapes contribute much less sediment to the stream system than naturally occurring cover (Jordan et al 2010). Instead of having a surplus sediment load as in the early stages of urbanization, the stream system is now starved for sediment.

The increase in sediment production during the initial construction associated with urbanization has been well documented. Studies have found that construction sites may contribute up to 80% of the sediment yield in a watershed undergoing urbanization (Fusillo et al 1977). The increase of sediment yield above background conditions can also be extremely high, with studies in the United States experiencing increases of 45 times (Guy 1974), 47 times (Fusillo et al 1977) and 300 times (Wolman and Schick 1967) the yield associated with background conditions. Smith et al (2011) reported similar results in their sediment budget of a watershed in the Piedmont region of Maryland, United States. Land cover in the watershed consists of forest, agriculture and suburban areas with the relative percentages remaining fairly constant over last 50 years. The study found that suburban area made up 15% of the watershed and yielded 450 tonnes km^{-2} yr^{-1}. In contrast, the area of the watershed undergoing active construction was 0.2% yet the sediment yield was assessed to be 2102 tonnes km^{-2} yr^{-1} (Smith et al 2011).

Although significant effort has been spent quantifying the contribution of active construction to sediment yield, less attention has been given to the sediment yield of established urban and suburban areas. However, some investigations have compared sediment production among basins that were rural/forested with those that were undergoing active construction and those in which urbanization was mature. A study in Tahiti, for example, found that a basin undergoing active construction had an increase in sediment yield of 12 times that of a rural/forested basin while a basin with mature urban development experienced a 2.4 time increase (Wotling and Bouvier 2002). In the seminal work by Wolman (1967), he noted that basins undergoing active construction and those that were completely developed had respective sediment yields that were 200 and 5 times greater than a rural/forested basin in the same region.

2.1.2 Hydrology

In addition to changes in sediment regime, urbanization results in profound changes to hydrology. An increase in the percentage of impervious land cover within the watershed reduces infiltration and increases surface runoff. As a result, precipitation is delivered to streams quicker and in a greater quantity (Chin et al 2010). This situation is further exacerbated by storm sewer systems which directly rout flows from impervious surfaces to the stream channel (Hammer 1972). These changes to the natural hydrology result in an increased magnitude and frequency of peak flows with shorter durations (Violin et al 2011). Although the magnitude of peak flows increase, base flow is reduced as precipitation that previously infiltrated into the soil is now routed directly to the stream consequently lowering the water table (Walsh et al 2005).

The effect of urbanization on stream hydrology is well documented. For example, Watts Branch is a second order stream located in Maryland, United States with a watershed of approximately 4.0 km^2. Hydrologic modeling concluded that urbanization of the Watts Branch watershed in Maryland resulted in an increase of the two year peak discharge by a factor of 1.3 to 3.0 between 1951 and 2007. Another second order watershed in Maryland was estimated to have experienced a 1.3 to 7.7 factor increase in peak discharge due to an increase in impervious cover resulting from urbanization (Allmendinger et al 2007). In a study of restored streams in Connecticut, United States, discharge was found to increase significantly in a watershed following urbanization. The Norwalk River is a gauged fourth order stream with a 70 km^2 watershed with 24% of the land cover consisting of dense urban land use. In 1977, stream gauge records show that the discharge suddenly increased. What had previously been a 10-year storm event was now a 2-year storm event. This coincided with a period of urban development in the watershed including commercial and residential construction along with an expansion of roads and sewer networks (Schiff et al 2011).

Although urbanization typically increases peak flow rates, storm sewer routing and flow diversions structures may reduce peak flows in some instances. This situation was documented in a study of two urban watersheds in Santa Clara Valley, California (Jordan et al 2010). Berryessa Creek has seen an increase in its effective watershed due to storm water routing from adjacent watersheds while Upper Penitencia Creek has a reduced effective watershed due to stormwater routing out of the system. To investigate these influences on hydrology, the authors simulated three scenarios: i) pre-urbanization, ii) post-urbanization ignoring storm sewers and flow diversions, and iii) post-urbanization with storm sewers and flow diversions. The study found that peak discharges in Berryessa Creek were 18% greater due to urbanization alone and up to 77% greater if storm sewers were considered. Although Upper Penitencia creek experienced a 15% increase as a result of urbanization alone, peak discharge decreased 12% when including storm sewers and flow diversions (Jordan et al 2011). Although, this article shows that storm sewer routing can reduce peak flows in some instances, it is important to keep in mind that stormwater routing out of one basin implies stormwater additions to another basin.

2.1.3 Stream Morphology and Aquatic Habitat

The alteration of hydrology and sediment supply has significant effects on stream channel morphology (Levell and Chang 2008). Urban streams with increased peak flows and reduced sediment supply are subject to channel incision and disconnection from the adjacent flood plain. (Booth 1990, Sudduth et al 2011) Additionally, streams are subject to bank erosion and knickpoint migration (Hammer 1972, Booth 1990, Pizzuto et al 2000). As a consequence of bank erosion and incision, urban channels are often larger than their non-urbanized counterparts (Allmendinger et al 2007). The combined effects of changes to channel morphology ultimately lead to impairment of aquatic habitat. As pools aggrade and riffles erode, channel morphology becomes homogeneous reducing aquatic habitat variation (Schwartz and Herricks 2007, Sudduth et al 2011).

In a study conducted by Allmendinger et al (2007), urbanization was found to contribute to channel widening in a small watershed (4.05 km^2) in Maryland. The Good Hope Tributary is located in a watershed which has seen urban and suburban development in three periods between 1951 and 1996. During this time, impervious cover grew from 1.4% to 7.5%. To examine the effect of urbanization on channel size, a series of cross sections were established in tributaries to the Good Hope Tributary as well as the Good Hope Tributary itself. Regression equations were developed based on drainage area and impervious cover to estimate cross section areas in 1951.

The channel enlargement ratio for the Good Hope Tributary, defined as the area after urbanization divided by the area prior to urbanization, ranged between 1.3 and 2.4 with an average of 1.7. Of the eight tributaries examined, five showed little or no change between the two periods. One of the five had no impervious area in its watershed. The other four had large detention basins in their headwaters. The remaining three tributaries had enlargement rations of 2.1, 2.4 and 2.5 (Allmendinger et al 2007). The results of this investigation illustrate the effect impervious cover in a watershed can have on channel area. Additionally, it also shows that sediment control measures may be effective in preventing channel enlargement in low order streams in urbanizing watersheds.

Pizzuto et al (2000) noted changes to both morphology and habitat in an investigation that compared eight urbanized watersheds in Philadelphia, Pennsylvania with rural counterparts. The urbanized watersheds ranged from six to 4,010 ha and had between 34% and 50% impervious land cover. The paired rural watersheds were of similar size. All of the study reaches were at least 100 m long and had five riffle/pool sequences. The study found that urban streams had bankfull widths and areas that were respectively 26% and 180 % larger than streams in rural watersheds. Aquatic habitat in urban streams had become more homogenous with median sinuosities 7% lower and median pool depths 31% shallower. Due to lower sinuosities and pool depths, Manning's n values were 10% lower in urban streams. Surprisingly, there was no difference in median grain size. It was speculated that upstream hillslope sediment production combined with bed and bank erosion was sufficient to maintain similar bed material size (Pizutto et al 2000).

These findings were echoed in a study conducted by Violin et al (2011). Their investigation compared four restored streams to four urban un-restored and four rural streams in the North Carolina Piedmont. The authors found that non-restored urban streams exhibited a greater degree of incision than the other stream types. Additionally both types of urban streams had smaller median substrate sizes with forested streams having a median substrate size of 35.75 mm while urban restored streams and un-restored streams had median substrate sizes of 8.0 mm and 4.75 mm respectively. Furthermore, urban streams had fewer habitat transitions per 100 m of stream length corresponding to less habitat variation (Violin et al 2011).

Similar results were reported by Schwartz and Herricks (2007). As part of a stream restoration project in Chicago, Illinois, physical habitat surveys were conducted during the pre-design analysis as well as the post-project appraisal. Data collected included a “streambed longitudinal profile, mesohabitat unit delineation and habitat quality attribute identification including bed substrate, large woody debris (LWD) and shade” (Schwartz and Herricks 2007). The initial surveys found that the stream morphology was characterized primarily by glide/riffle sequences. The few pool/riffle sequences that did exist were found to be degraded with a lack of deep pools. Consequently, ecological surveys determined that the creek had little quality habitat and low fish bio-diversity compared with non-urban streams (Schwartz and Herricks, 2007).

A study conducted in the Lake Champlain Basin of Vermont found that changes in hydrology due to urbanization had dramatic effects on channel process, morphology and habitat (Fitzgerald et al 2012). Sixteen watersheds with areas ranging from 0.7 to 41.9 km^2 were selected for analysis. Eleven of the watersheds were urban and the remainder were rural. Reaches were categorized as high gradient (>0.5%) or low gradient (≤0.5%) and total impervious area was calculated. Rapid geomorphic (RGA) and habitat assessments (RHA) were conducted using protocols developed by the Vermont Department of Environmental Quality (Fitzgerald et al 2012). Employing analysis of covariance, the investigation found that impervious cover and drainage area were significant variables in regards to channel width and cross section area with urban streams having greater width and cross section area. This effect was more noticeable in lower order reaches and less noticeable in drainage areas greater than 15 km^2. Slope was not found to be significant. The RGA assessment noted a decline in geomorphic stability with an increase in impervious cover. This was especially true in high gradient reaches where less than 5% impervious cover resulted in some degree of geomorphic instability. However, there was a levelled response in watersheds with impervious cover exceeding 10%. RHA assessment found that urban streams had an average score of 0.55 while rural streams had an average score of 0.75 suggesting the urban stream habitat is impaired in comparison with rural streams (Fitzgerald et al 2012).

2.1.4 Management Implications/Stormwater

Due to changes in sediment regime, hydrology and ultimately morphology, urban streams present a unique series of management challenges. An increase in peak flows along with bank erosion and channel migration result in increased risk of flooding and damage to property and infrastructure. Depending on the location, channel degradation can even threaten municipal water supplies (Buchanan et al 2012, Burns et al 2012, Larson et al 2001, Schwartz and Herricks 2007). Additionally, urbanization results in the homogenization of bed morphology, loss of habitat as well as water quality issues (Sudduth et al 2011, Schwartz and Herricks 2007). These changes have a profound ecological repercussions resulting in the deterioration of algal, micro-invertebrate and fish populations (Chin 2006).

To address these issues, urban river restoration utilizing a natural channel design has become a popular management strategy. The primary purpose of naturalization projects is to restore the natural geomorphological form and function of a channel by balancing the hydrologic and sediment regimes (Rosgen 1996, TRCA et al 2009). Once the physical processes are restored, the assumption is that the aquatic and riparian ecosystems will respond in a positive manner (Ernst et al 2012, TRCA et al 2009). However, there is little evidence that stream restoration can restore geomorphic stability or aquatic richness and diversity (Booth 2005, Violin et al 2011).

One reason for the lack of success is that stream channels may still be adjusting to changes in hydrology and sediment regime imposed by urbanization. Such streams may be neither hydrologically nor geomorphically stable. Thus, any in-channel action taken while the streams are in a state of adjustment is not likely to be successful (Miller and Kochel 2010, Rhoads et al 2008). This then begs the question, how long does it take for a stream to channel to reach a state of equilibrium in response to urban sediment and flow regimes?

Theoretically, once the channel has widened enough to accommodate increased discharges and reduce shear stresses, and the channel is no longer eroding, a new equilibrium stage should be achieved. How long this process may take is not well defined. In a review of relevant studies, Chin (2006) found that channel widening in Philadelphia levelled off after 30 years while in

British Columbia and Washington State, this process took approximately 20 years. However, stream systems in Connecticut were undergoing adjustment after 40 years and in southern California streams were still subject to severe erosion 40 to 50 years after development (Chin 2006).

Achievement of a stable stream with the hydrology and sediment regime in balance is primarily reliant on two conditions. First, the period of active construction must cease and the sediment production must be stable. Secondly, impervious cover must be stabilized and the artificial drainage network must be complete. However, this will not guarantee a stable channel. Substantial incision and climate variation complicate the process. In addition, another important consideration is whether the channel is free to undergo planform migration. Although channel stability is theoretically possible and has been observed in some cases, it is difficult to achieve on a practical level (Chin 2006). This inability to attain some level of equilibrium during decision making time frames severely complicates management efforts.

There is an increasing realization that in-channel efforts at the reach scale have little possibility of mitigating watershed level stressors, particularly hydrology. Consequently, more researchers are advocating restoration of natural processes, particularly a natural flow regime, as the best the best course of action in managing urban streams (Booth 2005, Konrad et al 2005, Walsh et al 2005). The most obvious way to re-establish a near-natural flow regime is through stormwater management (Burns et al 2012, Walsh et al 2005).

Although some authors suggest the restoration of a near natural flow regimes via stormwater management, they recognize the difficulty in such an enterprise. Booth (2005) recognized that re-establishment of near natural flow regimes is not likely and Burns et al (2012) question whether return to a “natural” flow regime in an urban stream is even appropriate. That said, return to a near natural flow regime is a pre-requisite for any restoration or management scheme (Burns et al 2012). Additionally, past practices should not preclude future implementation of new approaches to managing stormwater at the watershed scale and continuing on a path that permanently impairs long term stream improvements. At the very least, knowledge of the limitations of in-channel, reach level efforts should act as a remainder of the futility of spending large amounts of money on goals that can never be reached (Booth 2005).

Urban river management was has typically employed restoration techniques at the reach level while ignoring larger watershed scale issues. Such an approach is not likely to be effective over the long term. Furthermore, most river restoration strategies are based upon the premise of dynamic equilibrium which maintains that river systems achieve balance between the hydrologic and sediment regimes over long spans of time (Rhoads et al 2008). However, dynamic equilibrium may not be achievable during management decision making time frames and the concept itself may create unrealistic expectations (Chin 2006, Rhoads et al 2008). Rhoads et al (2008) suggest that the critical management issue is whether a channel is physically adjusting at a time scale that generates concern. Consequently, they propose that channels be evaluated according to three factors:

1. What is the rate of channel evolution relative to human time scales?
2. Is the rate of channel change relatively steady, or is it accelerating relative to some previous rate?
3. Are changes occurring within a balanced sediment transport regime?

The points above highlight the importance of collecting and analyzing data to develop management plans.

2.2 Sediment Budgets

A sediment budget is an account of sediment moving in and out of a site (Biedenharn et al 2010) or geomorphic system. On a large scale, this could be a mountain range or watershed. At a smaller scale, the geomorphic system could include a hillslope segment or a channel reach (Reid and Dunne 2002). At a very basic level, a sediment budget can be thought of as the balance between sediment input, output and change in storage over time within a watershed (Allmendinger et al 2007). This can be expressed simply in an equation as:

$$\text{Input} + \Delta\text{Storage} = \text{Output} \tag{1}$$

However, when considering many different processes, it may be helpful to create a conceptual model of the sediment budget using a flow chart (Figure 2).

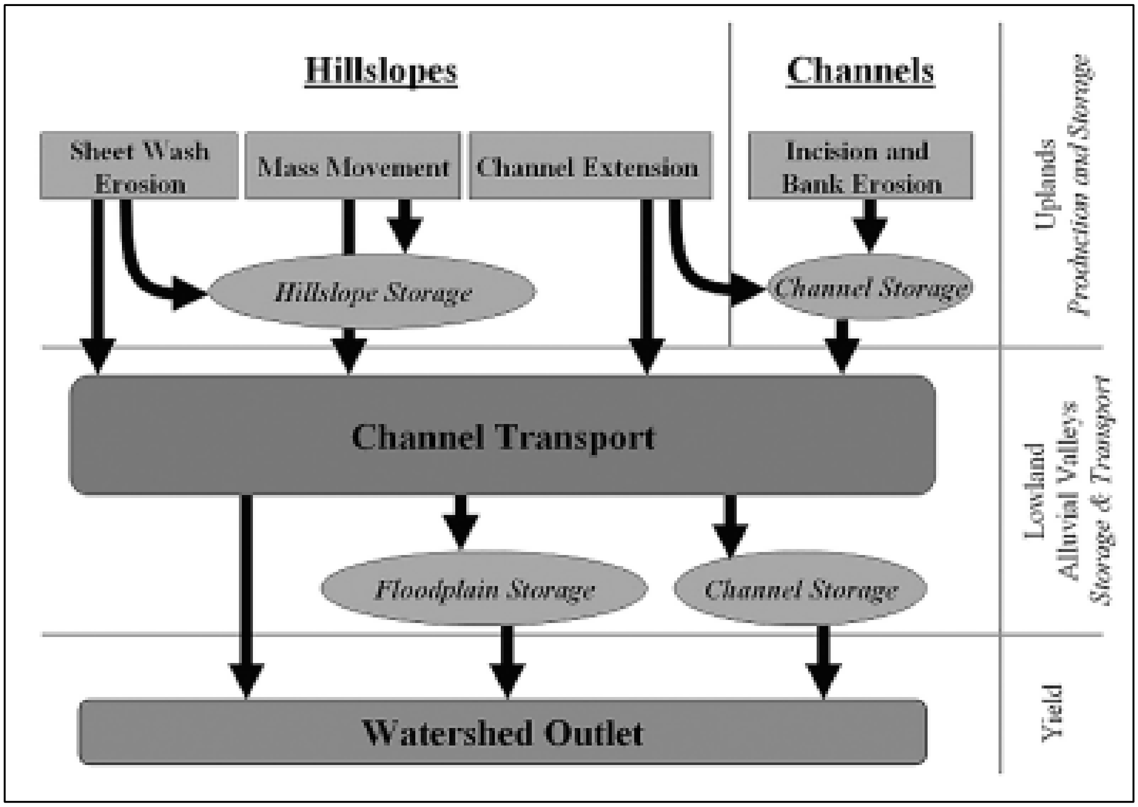

Figure 2. Example of conceptual sediment budget using a flow chart (Smith et al 2011).

In its fullest form a sediment budget considers all sources of input (hillslope processes, bank and channel process), in-channel transport (suspended and bed load) and storage (in-channel and bank or floodplain) (Stream Notes 2004, Reid and Dunne 2002). However, a sediment budget may take many forms. Depending on the objective of the study or site characteristics, it may focus on a particular process, transport mechanism or storage component (Rovira et al 2005). In addition, to taking different forms, it can be carried out with different levels of precision, ranging from a purely qualitative description of sediment transport and storage to a detailed, quantitative estimate of inputs, outputs and storage terms (Reid and Dunne 2002).

An important point to keep in mind is that a sediment budget is not a single technique or tool. Rather, it is a conceptual framework for analyzing sediment transport and storage interactions over time in a geomorphic feature. It should be viewed as a "general approach to geomorphic problem solving" (Reid and Dunne 2002).

Geologists and geomorphologists have conceptualized sediment processes in terms of the balance between sediment supply and transport for quite some time. Measurement of sediment production and transport rates has been conducted since the late 1800s. Early work included measurement of landslides to determine the effect on landscape evolution in 1896 and an analysis of the effects of sediment produced by hydraulic mining in the mountains on navigation in San Francisco Bay in 1917 (Reid and Dunne 2002). However, the concept of a sediment budget as a theoretical framework to study the movement of sediment through a system was first elaborated by Dietrich and Dunne (1978). They applied the conceptual framework of a sediment budget to characterize significant mechanisms influencing the production and transport of sediment on a small watershed in the coastal mountains of Oregon. Since their initial work, sediment budgets have been increasingly used as an analytical tool in numerous academic studies (Rovira et al 2005, Reid and Dunne 2002)

2.2.1 Sediment Budgets as a Management Tool

Sediment budgets are commonly employed in academic and research settings, but have seen less use as a management tool. The main reason is that they are viewed by land managers as long term research projects that are not capable of providing useful input to short term land use planning (Stream Notes 2004). There have also been few detailed studies involving sediment budgets of watersheds in established urban areas. This is unfortunate as sediment budgets have the potential to be a valuable tool for watershed managers. As a consequence, this is a research gap that this study is attempting to address. A main impediment is that sediment budgets often rely on long term observation and measurement whereas land management decisions in urban areas are often made in a relatively short time frame to address issues of immediate concern. As a result, there is not sufficient time to implement long term monitoring. Additionally, there is a lack of historical data as well as in-stream gauges to provide current sediment and discharge data. Finally, most of the models used to estimate upland or hillslope erosion are calibrated for agricultural areas and are not directly applicable to urban areas (Allmendinger et al 2007).

However, given the flexibility of sediment budgets as a theoretical framework, Reid and Dunne (1996) contend that sediment budgets focused on specific objectives can be completed in a short amount of time with as little as two months of fieldwork. Furthermore, there is a growing realization that sediment budgets in some form or level of precision have the ability to provide valuable insight not attainable by other methods. Phillips (1991) states that, "Budgets are the most sensitive indicator of a basin to environmental change and are considered by some to be the single most important piece of information about a fluvial system".

As a management tool, sediment budgets can be used to compare conditions between and within catchments (Reid and Dunne 2002) allowing managers to estimate how changes in land use may be reflected in sedimentation and erosion rates, sediment storage and the transport of sediment through a system. More specifically, they may allow managers to predict where sediment erosion and deposition will occur, where storage may occur and when sediment may be released from storage (Stream Notes 2004). Consequently, data gained from sediment budgets can inform priorities as well as contributing to the design of sediment and erosion control efforts and restoration strategies. After various strategies have been developed, sediment budgets can provide information to evaluate management options, select the most appropriate option and develop a management strategy (Reid and Dunne 2002).

The sediment budget as a conceptual framework can be applied to a variety of problems in wide range of settings. One example is in the area of river restoration. It has been established that excess sedimentation and turbidity have multiple negative effects on stream ecosystems. Correspondingly, stream restoration has come to be viewed as a potential method for reducing the sediment load and turbidity within the stream channel as well as receiving bodies of water (Doyle and Shields 2012). However, to design an effective restoration it is useful to know the rates and location of erosion as well as potential areas of deposition. Land managers and restoration designers are increasingly realizing the utility of sediment budgets to guide design and inform management decisions (Smith et al 2011).

Another area where there is a growing realization of the utility of sediment budgets is in developing nations. Environmental concerns are a global phenomenon. However, in developing countries there is seldom sufficient data or funding to collect data necessary for addressing geomorphological or sediment related issues. In such settings, simplified sediment budgets can be designed and carried out in a relatively short time with little money (Reid 1990). As an example, Reid (1990) conducted a sediment budget to identify constraints on agriculture in Tanzania. Using the sediment budget concept he was able to identify areas of erosion, determine the cause and suggest possible solutions.

Additional examples of the utility of sediment budgets include estimating sediment yield from landslides, developing catchment rehabilitation strategies and estimating the effects of logging on sediment input to streams (Reid and Dunne 2002). These cases as well as the ones above are only brief examples illustrating the applicability of sediment budgets to land management decisions in a range of settings with varying levels of precision.

2.2.2 Conducting a Sediment Budget

One of the biggest difficulties in constructing a sediment budget is that it is not a well-defined technique or mechanistic process. As there is no single method, sediment budgets can take very different forms depending upon the purpose, the focal issue, the spatial scale and the temporal scale (Reid and Dunne 2002). However, there are specific elements in constructing a budget that help lead to meaningful results. These include "(1) recognition and quantification of transport processes, (2) recognition and quantification of storage elements, and (3) identification of linkages among transport processes and storage elements (Dietrich et al 1982)". Although these elements were developed primarily for geological hillslope processes at the watershed scale they can readily be applied to a fluvial environment.

In considering sediment budgets in the context of fluvial geomorphology, Reid and Dunne (2002) identified 11 attributes of a sediment budget. These elements including examples of their respective options are shown in the table below (

Table 1). The selection of one or more alternatives from the listed attributes sets the stage for an individual sediment budget (Reid and Dunne 2002). The various alternatives define the scope of the sediment budget as well as suggest techniques for data collection and the form of the result.

Table 1. Attributes of a sediment budget with possible options for designating the scope of the study (Reid and Dunne 2002).

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1. Purpose of Budget

Explain landform
Explain change or impact
Describe effect of activity
Describe effect of event
Prioritize, plan remediation
Describe system
Compare systems
Predict system response

2. Focal Issue

Land-use activity
Land-use effects
Background
Particular event
Particular impact

3. Form of Result

Absolute amounts
Relative amounts
Description of interactions
Locations
Timing of response

4. Spatial Organization

Distributed by sites
Generalized by strata
Conceptual
Lumped
Hypothetical

5. Temporal Context

Reconstruct past
Describe present
Predict future

6. Duration Considered

Event specific
Specified duration
Long-term average
Land-use activity
Synthetic average

7. Precision

Qualitative
Order-of-magnitude
Precise

8. Part of Sediment Regime

Weathering
Hillslope transport
Hillslope storage
Erosion
Delivery to channel
Channel storage
Channel transport
Sediment attrition
Sediment yield
Morphology

9. Landscape Element

Hillslopes
Catchment
Specific landform
Land-use activity site
Channel reach
Channel system
Particular process
Particular land-use sites
Administrative unit

10. Material

All
Non-dissolved
Suspended sediment
Bedload
Sand
Gravel
Organic material

11. Method

Modeling
Existing evidence
Inference
Analogy
Historical records
Air photos
Remote sensing
Stratigraphic Analysis
Monitoring

Sediment budgets conducted for academic studies are generally more detailed than required for land management purposes. In addition, the time frame, level of detail and scope can be daunting. To overcome these reservations, Reid and Dunne (1996) proposed a methodology consisting of seven steps that can be completed in a time frame and at a level of precision to be of use to land managers. The steps are:

1. Define the problem

    It is important to define the problem as precisely as possible to avoid needless work as many questions do not require a comprehensive sediment budget to provide a useful answer (Reid 1990). Once the problem is defined, it is easier to determine what data is actually required to address the question. In many cases, issues or data initially thought to be important are determined to be irrelevant. A critical part of this step is also deciding on the level of precision. Typically, precise values are not required and an order-of-magnitude result is sufficient for most management applications. Too often this step is little more than a formality but its importance cannot be over-stressed. Proper problem definition will streamline the fieldwork process and contribute to the timely completion of the project (Reid 1990, Reid and Dunne 1996).

2. Acquire background information

    Relevant background information includes maps, aerial imagery and discharge records for streams. Additionally, data should be collected on climate, local erosion rates and geology. If local data is not available for topics such as erosion rates, data from similar climactic regions may be useful. Anecdotal evidence from individuals should not be overlooked as they may be able to provide useful information regarding flood events and areas of erosion (Reid 1990, Reid and Dunne 1996).

3. Subdivide the area

    In many cases, the area of interest may be very large or diverse. Therefore, the area should be sub-divided into manageable units according to natural characteristics like vegetation, geology, soils or topography. Other criteria could be anthropogenic in nature such as land use, administrative boundaries, roads and dams (Reid 1990, Reid and Dunne 1996). Useful tools to sub-divide an area include aerial imagery, GIS (Reid and Dunne 1996) or personal knowledge.

4. Interpret aerial photographs

   Aerial imagery provides a visual history of the field site documenting changes in land use and topography. It also allows for a preliminary assessment of the site which is especially important if it is not possible to visit prior to data collection. Using aerial imagery, locations of landslides, gullies, disturbed river channels and bank erosion may be identified. Based on the quality of the images and the time of the year the photos were taken, measurements can be made for erosion and transport process. Finally, aerial images can help identify potential field sites (Reid 1990, Reid and Dunne 1996).

5. Conduct fieldwork

   Before conducting fieldwork, a preliminary site visit should be made to identify areas of active erosion and locate areas where sediment transport processes are occurring. This is also a good opportunity to verify the location of field sites identified in the previous step. The actual fieldwork should be focused and only data relevant to answering the questions defined in step one should be collected (Reid 1990, Reid and Dunne 1996).

6. Analyze data

   After field data has been collected, the data is analyzed. If several appropriate methods are available to estimate transport rates, they should all be employed and their results compared against each another (Reid and Dunne 1996). In addition, the results of predictive equations should be verified against field measurements. If possible the findings of the sediment budget should be compared with published results for the same region (Reid 1990, Reid and Dunne 1996).

7. Check results

   The final step in the methodology proposed by Reid and Dunne (1996) is to check the results. To some degree this was covered in the previous step. However, the authors reiterate the importance of comparing results to studies from the same area or at least from locations with similar climate, geology, land use, etc.

In some cases there is overlap between the steps. It is also important to note that although Reid and Dunne provide a methodology for conducting a sediment budget as well as examples of its application, there a many different methods or techniques for evaluating sediment transport and storage. As a result, the practitioner will have to evaluate whether a particular technique is suitable by reviewing the literature to verify its assumptions and determine whether it has been independently validated (Reid and Dunne 1996).

2.2.3 Examples/Case Studies

Reid and Dunne (1996) emphasize that their seven step process for conducting a sediment budget is a merely a rough guide. A sediment budget can take many forms based upon the questions posed. This results in a variety of measurement and analytical techniques that are employed to address the question at hand. As a result, it is useful to examine a variety of case studies to get an idea of how sediment budgets are actually conducted.

Case 1 – Soil Erosion in Tanzania (Reid 1990)

Reid (1990) closely followed the seven step process for this study. A development program investigating limitations on agricultural production in the Shinyanga Region of Tanzania had previously identified soil erosion as a major constraint. To determine the extent and severity of soil loss a sediment budget was conducted.

The first step was to clearly define the problem and determine what level of precision was necessary. After consideration, it was determined that there were three questions pertinent to assess the extent and severity of soil loss:

1. Where is major soil erosion occurring?
2. What is the cause of major soil erosion?
3. How severe is erosion/how much soil is lost?

Once the problem is defined, the level of precision required may be determined. The first two questions are qualitative and do not require a level of precision. To answer the third question, a level of magnitude estimate was considered sufficient (Reid 1990).

After the problem was clearly defined, background data such as rainfall and population records and geological maps were gathered. Previous studies in similar regions were reviewed for comparative erosion rates and to ascertain erosional processes that may be active in the area. During this process, it was learned that school teachers in the region collected rainfall data and visits were scheduled to meet with some of them (Reid 1990).

As the Shinyanga region is extremely large (21,000 km^2) it was subdivided into 25 sections. The subdivision was based on vegetation, topography and geology. Administrative borders were also considered in order to facilitate access to agricultural and population records (Reid 1990).

As no modern aerial imagery was available, a light airplane was used to take photographs of the study region. During the flights, observers counted livestock, buildings and noted erosional features such as gullies, widespread sheet erosion and incised channels. The imagery and observational data were analyzed and used to characterize the 25 sub-regions in regards to livestock population, land use and erosion. Additionally, this provided the basis for determining potential study sites (Reid 1990).

Aerial analysis indicated that gullying, sheetwash and wind erosion, and streambank erosion were major sources of sediment loss. Fieldwork was scheduled to asses these processes early in the rainy season while they were likely to be active and ground cover was still extensive. The chronology and cause of gullying was assessed and physical measurements were taken at selected sites to aid in a more comprehensive evaluation using aerial imagery. The contribution of sheetwash and wind erosion to sediment production was estimated with three different models: the Universal Soil Loss Equation, the Soil Loss Estimation Method for Southern Africa and the Wind Erosion Equation. Data for these models was collected from rangelands as well as fallow and active croplands. Fieldwork efforts to quantify bank erosion consisted of physical measurements as well as anecdotal evidence from local residents (Reid 1990).

After fieldwork was completed, the data were analyzed and erosion was calculated for each sub-region. Results from the soil loss equations were compared to field measurements as well as values reported in the literature. Calculations for total soil loss concluded that typical erosion rates in the Northwest sub-regions were on the order of 500 $m^3km^{-2}year^{-1}$. Rates in the Southeast were much higher with a rate of 2640 $m^3km^{-2}year^{-1}$ considered typical (Reid 1990).

The study concluded that erosion was most severe in the southern region of the study area where rainfall is low and monocultural cropping is common. Grazing also accelerated sheet and wind erosion due to reduced vegetative cover. Continued use of these farming and rangeland practices was estimated to exhaust the agricultural capacity of the land within 50 years. However, a return to traditional farming practices was expected to significantly reduce active erosion and expand soil's lifespan (Reid 1990).

Case 2 – An urbanizing watershed in Maryland, U.S.A. (Allmendinger et al 2007)

Allmendinger et al (2007) constructed a comprehensive sediment budget for the Good Hope Tributary, a 2nd order stream in an urbanizing watershed of the Piedmont Geomorphic Province of Maryland. The objective of the sediment budget was threefold: determine if bank erosion was a significant source of sediment yield, assess whether upland sediment production was significant and establish the significance of floodplain storage. For ease of analysis the budget was divided into two parts. One sediment budget was formulated for first order tributaries. Another sediment budget was carried for the rest of the watershed with the output from the first order tributaries as an input (Allmendinger et at 2007).

As they addressed different parts of the watershed, the two components of the sediment budget contained different terms. Excluding output, the only terms in the first order budget were upland sediment production and sediment produced from channel enlargement. A storage term was not included due to a lack of floodplains. The sediment budget for the remaining watershed included three input terms: supply from the first order tributaries, channel enlargement and upland sediment production. The only storage term was floodplain storage (Allmendinger et al 2007).

An important point to note is that in-channel sediment storage was not considered. This term was ignored as it has been statistically proven in the study area that channels have similar width to depth ratios irrespective of the age/level of urbanization. As a result, changes in channel cross section area implicitly include bed as well as bank erosion (Allmendinger et al 2007).

Initially, the authors attempted to use a computer model to calculate upland sediment production in the first order tributary budget. As it was designed for agricultural use, they decided to use regression equations based upon the percentage of land in construction. Sediment production due to channel enlargement was estimated by first measuring 25 cross sections along the first order tributaries. The authors then developed empirical methods to estimate historical channel cross section area using survey data. To calculate sediment production the changes in cross section area were multiplied by the length of the tributary (Allmendinger et al 2007).

For the second part of the sediment budget nine cross sections were measured along the Good Hope Tributary. Regression equations were developed to estimate historical channel cross section area using watershed size and percent impervious cover. The volume of sediment produced by channel enlargement was then estimated by multiplying the change in cross section area by the distance between sampling sites. The bank storage term was estimated by measuring the depth of sediment accumulation above a number of trees' original rooting depth. Core samples were taken of the tree and dendrochronology was used to estimate the age of the tree. In this way the researchers were able to estimate a storage rate (Allmendinger et al 2007).

The study ultimately concluded that upland erosion, channel enlargement and bank storage were all significant factors in the sediment budget. The terms were equal in magnitude with upland sediment production contributing 5700 m^3, channel enlargement contributing 6400 m^3 and bank storage sequestering 4000 m^3 of sediment (Allmendinger et al 2007).

Case 3 – Gravel bed river (Martin and Church 1995)

As morphology of a river or stream is governed by the transport and nature of bed material, it should be possible to derive information about transport by measuring changes in morphology over time. This methodology is referred to as the morphological approach to sediment transport analysis. To evaluate this hypothesis, Martin and Church (1995) estimated bed material transport for a reach of the Vedder River in British Columbia using a number of cross sections, sediment sample data, and the sediment budget methodology. The authors began by considering the basic equation for a sediment budget:

$$\mathrm{O} = \mathrm{I} - \Delta S \qquad (2)$$

where O is bed material output, I is bed material input and ΔS is the change in storage. By measuring two of these terms, the third can be calculated. If these terms are considered over a finite time, the equation can be expressed as:

$$\mathrm{Q_o} = \mathrm{Q_i} - (1 - \mathrm{p})(\Delta S/\Delta \mathrm{t}) \qquad (3)$$

where Q_o is volumetric sediment transport out of the reach, Q_i is volumetric transport into the reach, p is porosity, Δt is the time between surveys. The term ΔS can be measured by cross sectional surveys. If bed transport is known or can be estimated at one cross section, calculations can be made upstream and downstream as Q_o at one section is Q_i for a downstream section. An important point to remember when using this approach is that any sediment stored and re-mobilized between survey periods is lost (Martin and Church 1995).

The study was carried out between 1981 and 1991 on an 8 km section of the Vedder River. Immediately after the study section, the river has been channelized and is referred to as the Vedder Canal. The first three kilometers of the river has a slope of 0.0046 while the remaining reach has a slope of 0.0035. The river bed is composed primarily of cobble and gravel. However, the bed of Vedder Canal is sandy. The bed of the study reach is periodically dredged with known volumes, dates and locations where the sediment was removed. The sand fraction of the bed was estimated at 14 to 22% and acts primarily as infill of the gravel matrix. As a result, the sediment budget is restricted to the gravel fraction of sediment (Martin and Church 1995).

Data collection for the study included 49 cross sections. Surveys were conducted yearly from 1981 to 1985, 1987, 1989 and 1990. Sediment size distribution was measured by taking bulk sediment samples of 300-500 kg at 19 locations (Martin and Church 1995). Following surveys, cross sectional area was measured and differences were noted. Changes in net volume of sediment were estimated by assuming that "change in area at a cross-section is representative of the distance between it and the half-distance to each adjacent cross-section" (Martin and Church 1995). This can be represented by:

$$\Delta V = \frac{\Delta A_j + \Delta A_{(j+1)}}{2} L_{j,j+1} \tag{4}$$

Where ΔV represents the change in volume between sections, ΔA_j is change in area at cross section j, $\Delta A_{(j+1)}$ is change in area at the cross section immediately upstream and $L_{(j,\ j+1)}$ represents the distance between the two cross sections (Martin and Church 1995).

To construct the sediment budget and calculate a transport rate, the study reach was divided into 10 sub-sections consisting of four to seven cross sections. Porosity was estimated as 0.25 ± 0.05 based upon the findings of other studies. An initial estimate of sediment transport was determined for the most downstream cross section based on channel slope measurements from the 1924 channel construction project and from the slope measurements made as part of the study (Martin and Church 1995).

The results of the study were that over a nine year period, 1050 m^3/yr of gravel were transported out of the study reach. In contrast, the average bulk volume of sediment transported into the reach was estimated to be 36,600 m^3/yr ± 5,600 m^3 (Martin and Church 1995).

Case 4 – River with perennial and ephemeral reaches (Rovira et al 2005)

Another study employing channel cross sections and the morphological approach was carried out by Rovira et al (2005). The interesting point of this study is that a net sediment balance determined by cross sectional surveys was subsequently compared with a sediment budget estimated by bedload and suspended sediment sampling (Rovira et al 2005).

The study was carried out on the Todera River in Spain between 1997 and 1999. The watershed is 894 km^2 and the study reach is 11 km long terminating in the Mediterranean Sea. The study area consists of an upstream and downstream section. Flow in the upper section is perennial and ephemeral in the lower section. Lateral water and sediment inputs from tributaries are small and insignificant (Rovira et al 2005). The components of the budget included sediment input from upstream, output at the mouth and bed storage. Unlike the study by Allmendinger et al (2007) which considered bank storage and neglected in-channel storage, this study considered in-channel storage but did not consider bank storage. In this case, in-channel storage was an important component as flow in the lower section of the river is ephemeral. In some years, flow does not reach the sea. Consequently, sediment is stored in the channel until it is washed out of the river in later flow events (Rovira et al 2005).

Sediment input and output were estimated by measuring both suspended and bedload sediment. Samples were taken at a single location in the upstream and downstream locations. In total, 168 suspended and 113 bedload samples were collected in the upper portion while 53 suspended and 384 bedload samples were collected in the downstream portion. The sediment samples and hydrologic data were used to construct rating curves and calculate sediment transport rates for both suspended and bedload sediment (Rovira et al 2005).

To monitor changes in the channel bed, 19 cross sections were established along the 11 mile study reach. Cross sections were separated by approximately 600 m and surveyed annually. Net change in area was calculated at each cross section. Net volumetric change was calculated by multiplying the change in cross section area by half the distance to the upstream and downstream sites. It was assumed that change at a given cross section was representative of this measured distance. This net balance was used to characterize the river as aggrading or degrading. Additionally, it was compared to the sediment budget determined from measured transport rates (Rovira et al 2005).

In-channel storage and residence time were estimated based upon equations derived from a study by Dietrich and Dunne (1978). In the upper, perennial section of the study reach, storage and residence time were calculated separately for sand and gravel fractions over three levels of discharge: baseflow to 3.3 m^3/s, 3.3 to 24.0 m^3/s and greater than the bankfull discharge of 24 m^3/s (Rovira et al 2005). In the lower, ephemeral reach "volumes of sand and gravel particles in storage were calculated for the single whole range of discharges" (Rovira et al 2005).

From suspended and bedload sediment measurements it was estimated that between 1997 and 1999, 156,700 tonnes of sediment entered the study reach while 107,000 tonnes exited the Todera and entered the Mediterranean Sea. As a result, 49,600 tonnes of sediment were stored in the active channel during this period. Considering an annual net deposit of 14,000 tonnes, an 11 km study reach, a 100 m average channel width, a sediment density of 2.65 $tons/m^3$ and a porosity of 0.36, it was estimated that the annual aggradation rate was 6.8 mm/yr. This estimation was supported by data from the cross sections which indicated a mean weighted net accumulation of 4.1 mm/yr (Rovira et al 2005).

2.3 Identification of Research Gaps

Sediment budgets have the potential to be a valuable management tool as they can document the location and estimate the rate of erosional and depositional processes. However, there are few sediment budgets of urbanized watersheds in the literature. This may be primarily because sediment budgets often do not fit in a management time frame. Additionally, there is often little discharge or sediment data and models predicting upland sediment yield are not calibrated for urban areas (Allmendinger et al 2007). Dietrich et al (1982) note that there is a lack of models able to realistically predict sediment transport rates. Furthermore, there is little field data available to estimate transport rates or inform the development of improved models. Finally, there is little data documenting long term adjustments of urban streams. As a result, it is difficult to determine whether streams can achieve a new equilibrium state to a stabilized urban hydrologic and sediment regime (Chin 2006).

3.0 Methods

3.1 Site Description

Wilket Creek is a second order stream that flows through the city of Toronto. It lies in an urban watershed of 15.4 km^2 and is a tributary of the West Don River (Figure 3). Prior to discharging to an open channel, the creek is confined in a buried culvert. The watershed area corresponding to the buried portion of the creek is 10.1 km^2. After issuing from the culvert, Wilket Creek travels approximately 6 km in a southeasterly direction before entering the West Don River. The stream is laterally confined over much of this length and unable to freely meander across the width of the valley. This is due to the presence of sanitary sewers, bridges, streets, walking paths and other infrastructure. At two locations Wilket Creek passes through relatively narrow culverts. In addition, there are two low head dams located in parks along the channel (Figure 4). This project considers the exposed extent of Wilket Creek from York Mills Road to the confluence with the West Don River.

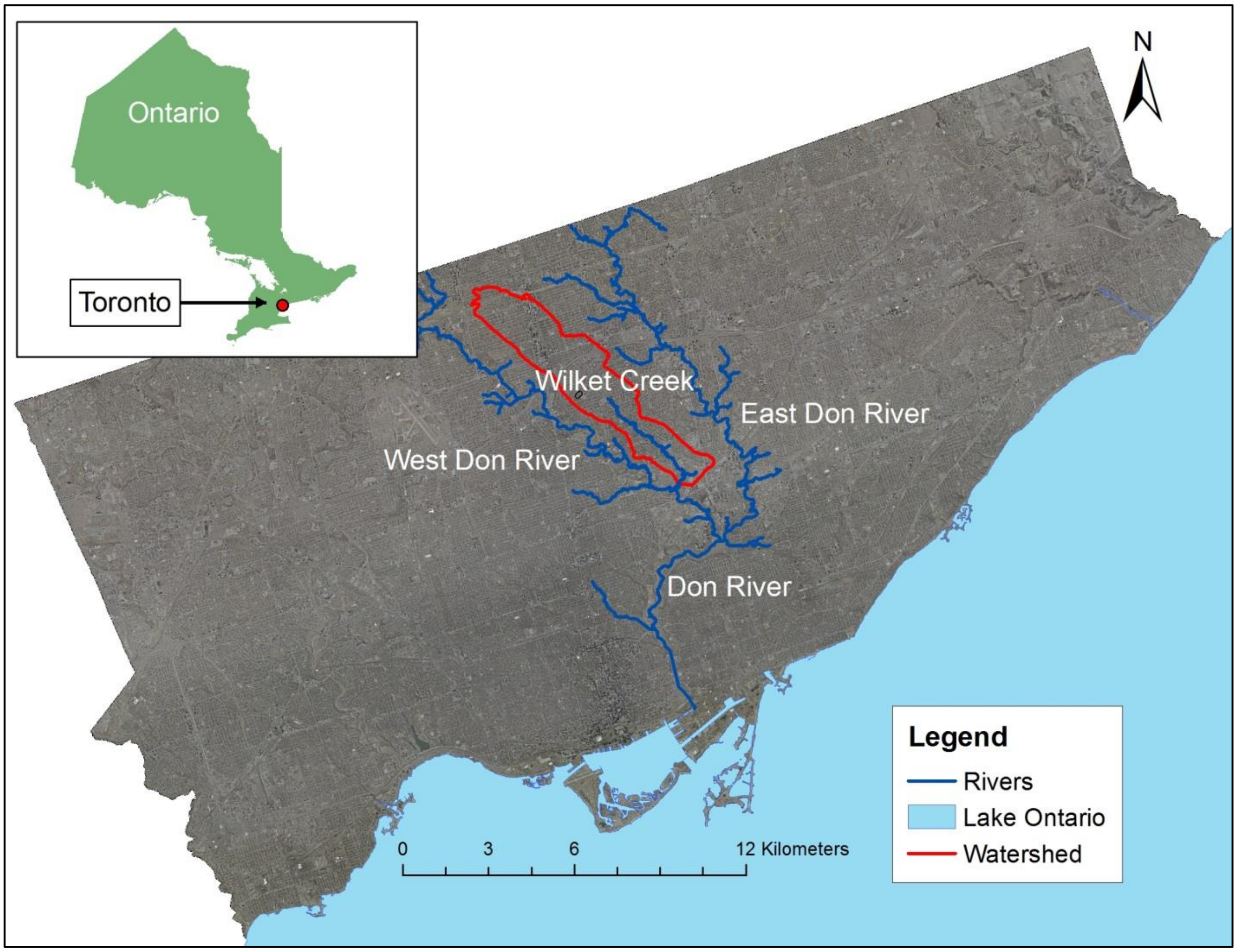


Figure 3. Map of Wilket Creek and watershed in relation to the City of Toronto and the Province of Ontario.

Analysis of aerial imagery and field observations reveal that Wilket Creek has been extensively modified over the past decades. All of the historical tributaries have been buried and now discharge to the creek via culverts. Numerous storm sewers also discharge to the creek without the benefit of stormwater management. Anecdotal evidence from long-time residents suggests that the creek has greatly enlarged over the past 30 to 40 years. Due to incision and channel widening, the City of Toronto and the TRCA have undertaken numerous emergency works to protect sanitary sewers which run along the length of the creek. This has resulted in extensive bank hardening to prevent further erosion. Additionally, foot bridges have been replaced as the channel has enlarged.

Site familiarization at inception of the study revealed that the exposed section of Wilket Creek was discontinuous, with conspicuous differences in channel morphology, streambed composition, level of anthropogenic alteration and topography. Due to these differences, the study area was divided into three sections for the purposes of analysis, (Figure 4). The delineation considered reaches that were similar in morphology and anthropogenic alteration. Of special consideration were the location of dams as it was initially hypothesized that a sediment outflow of zero could be assumed at these locations.

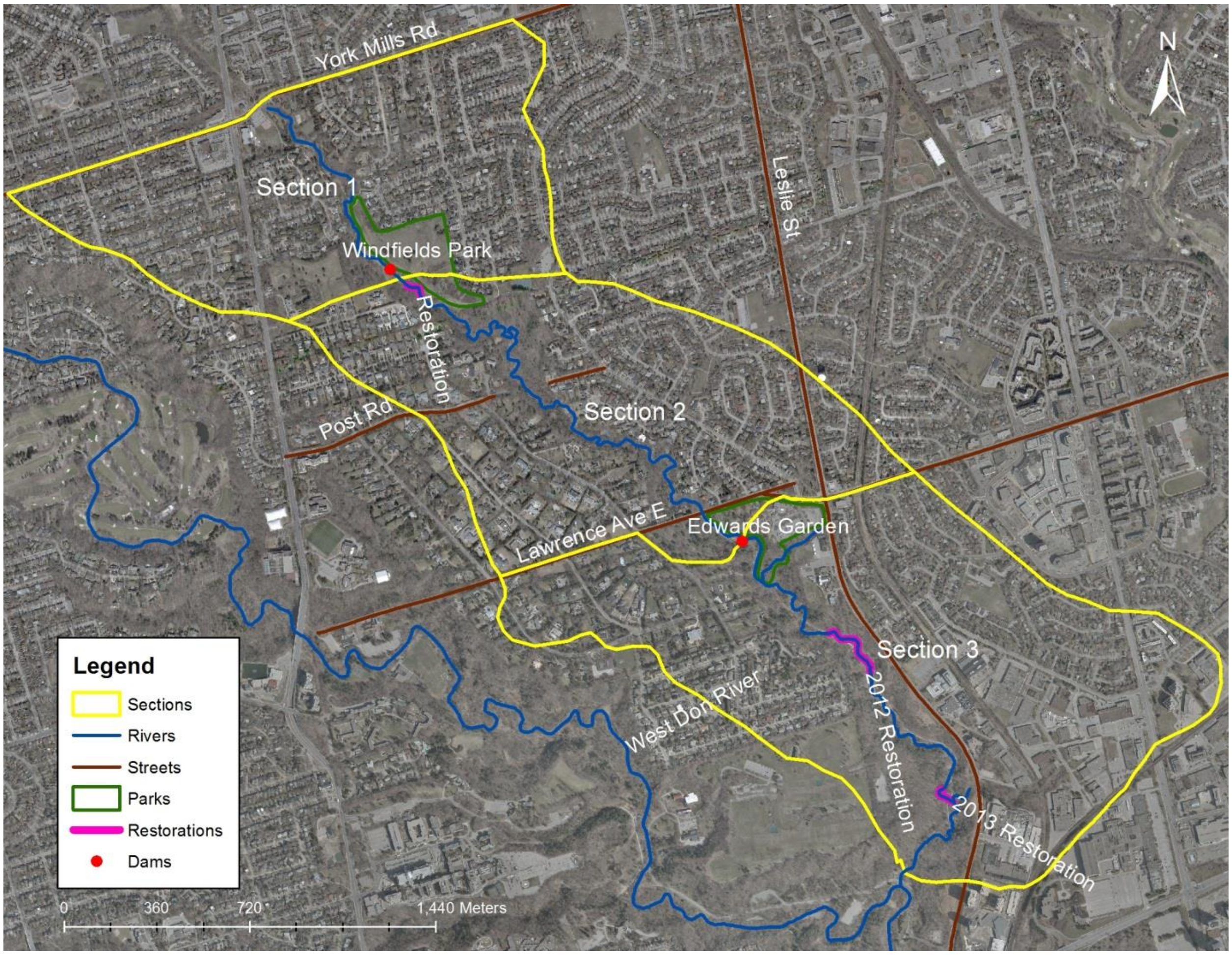


Figure 4. Study boundaries and division of Wilket Creek into sections for purposes of analysis.

Section 1 extends from York Mills Road to Windfields Park and is about 1125 m long (Figure 4). The creek exits from a buried culvert into a channel that has been heavily modified with gabion baskets and rip rap. A dam is located approximately 40 m upstream of the end of the section. It consists of removable flashboards and is operated seasonally. The flashboards are installed in

April or May after the initial spring floods and removed in November for the winter. The downstream end of the section is marked by a bridge culvert that is known to experience overtopping at high flows.

Section 2 begins at the bridge culvert that marks the end of Section 1 and extends about 2195 m to the dam in Edwards Garden (Figure 4). Most of the stream is largely unmodified and there are few hardening structures or storm sewer outlets. The stream channel in the middle portion is quite sinuous relative to the other areas of Wilket Creek and contains a large amount of woody debris. About 60 m downstream from the bridge culvert in Windfields Park, there is an in-stream restoration that is approximately 115 m in length. It was built within the last decade and is the oldest restoration with a riffle-pool design in Wilket Creek. At high discharges, water flows over the right bank and is in the process of cutting a new channel bypassing the meander bend. Near the end of the section, the creek passes through a narrow bridge culvert at Lawrence Avenue and enters a pool in Edwards Gardens. The section terminates at a dam which is located about 200 m downstream of Lawrence Avenue and is operated seasonally. Initially, it was thought that it would be possible to assume a downstream sediment transport rate of zero at this location from May to November. However, after talking with maintenance personnel, it was learned that the sluice gate to the dam is opened in response to high discharge events throughout the year. As a result, it is not possible to assume a sediment transport rate of zero at this location.

The third section begins at the dam located in Edwards Gardens and extends 2465 m to the confluence with the West Don River (Figure 4). This section has been extensively modified with retaining walls, gabion baskets, and rip rap. Two restorations with a riffle-pool design have been recently carried out in the lower portion of this section. The first was completed in the summer of 2012 and is approximately 590 m downstream of the dam in Edwards Garden. The second restoration was finished in the spring of 2013 and is about 1500 m downstream of the dam. Compared to the other sections, the lower portion of Section 3 is characterized by steep valley walls on both the left and right sides of the channel. At four locations, the valley wall is distinguished by large areas of exposed glacial till. Three of these sites are in direct contact with the creek and act as banks. This section also contains two major tributaries which issue from culverts on the east side of Wilket Creek. The first tributary enters into Wilket Creek at the downstream end of Edwards Garden. The second tributary enters Wilket Creek immediately downstream of the 2013 restoration. At the downstream end of Wilket Creek, the channel is highly constrained by armor stones. The outlet is a single, rectangular channel with high walls formed by armor stone.

3.2 Preliminary Data Collection

Preliminary assessment of Wilket Creek began during the summer of 2012. A qualitative survey of Wilket Creek from York Mills Road to the confluence with the West Don River was made. The survey noted both anthropogenic and natural features and recorded their position with a hand held GPS. Man-made features included: culverts, bridges, roads, dams and storm and sanitary sewers. Additionally hardening features such as rip rap, armour stones, gabions, and concrete blocks were noted. Natural features that were recorded included areas of erosion and deposition, pools, ponds, avulsions, tributaries and large woody debris. An important point to note is that all tributaries entering Wilket Creek issue from culverts. This initial survey was an important step in learning about the character of Wilket Creek and identifying areas of concern.

A longitudinal survey of the creek from York Mills Road to the West Don River was carried out between November of 2012 and February of 2013 (Figure 5). The survey was completed according to the guidelines in Harrelson et al (1994) using Sokkia SET530R and Trimble S6 DR3000+ total stations and a Sokkia GRX1/U Real Time Kinematic (RTK) global position system (GPS). A total of 540 points were surveyed in the thalweg. Points were surveyed as needed to capture bedforms including the top and bottom of riffles and the deepest point of pools or every two to three channel widths. No points were surveyed from 252 m to 1132 m upstream of the confluence with the West Don River. However, the results of a 2011 survey were used to provide data from 252 m to 675 m upstream of the confluence.

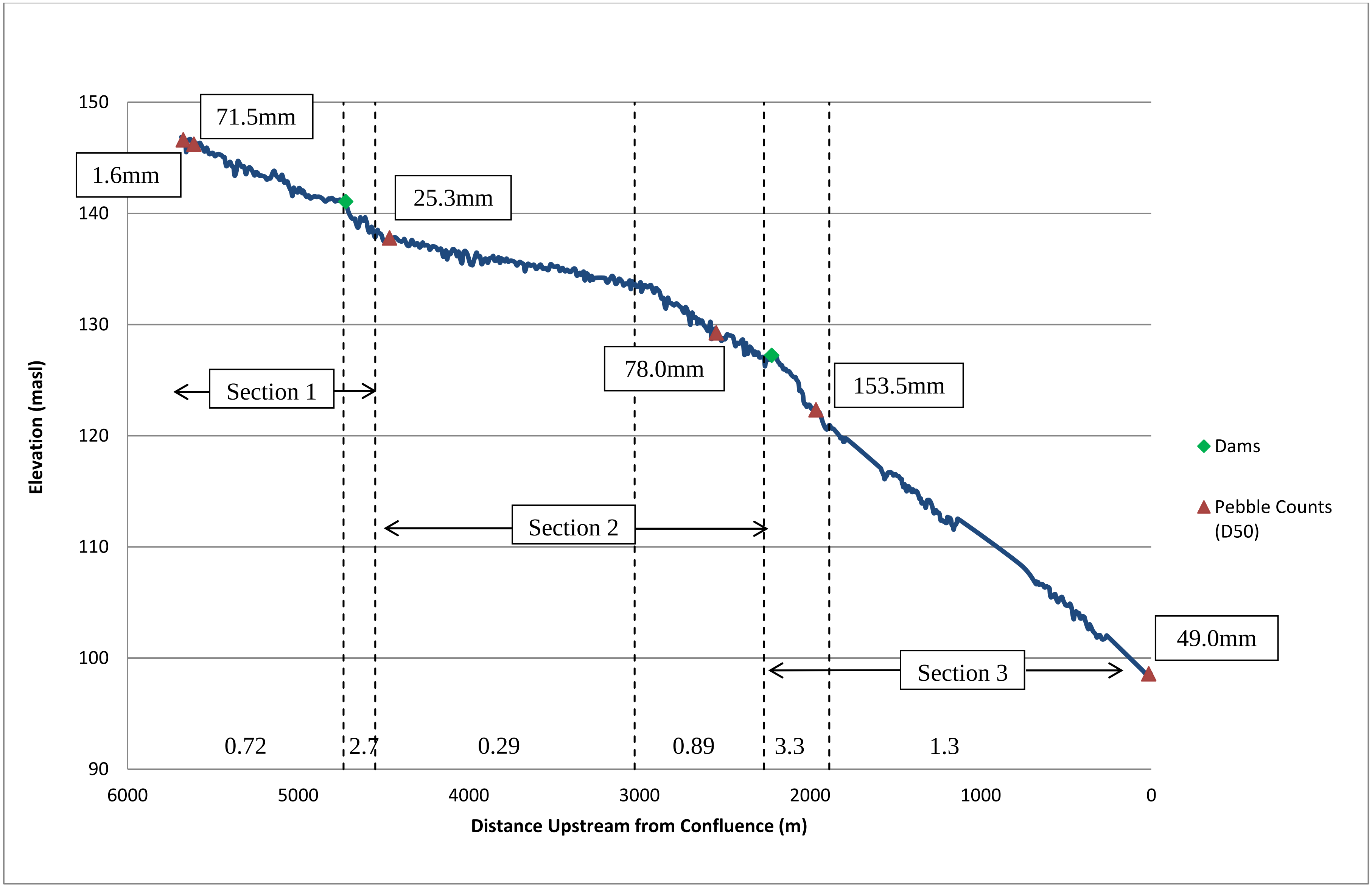


Figure 5. Longitudinal profile of Wilket Creek with location of sections, changes in slope and location of median particle size from pebble counts.

The longitudinal profile was helpful in discerning the character of the creek and illustrating the discontinuous breaks in slope that occur along its length. Based on the breaks in slope, the creek was further divided into subsections. Section 1a extends from the culvert at York Mills Road to the dam in Windfields Park. Section 1b corresponds to a sudden increase in slope from 0.72 % to 2.7 % that occurs between the dam and the bridge culvert in Windfields Park. Section 2a is located in the reach with a 2.7 % slope and runs from the bridge culvert to a distance of 186 m downstream, terminating just prior to the most sinuous portion of Wilket Creek. Beginning at this location, Section 2b extends 1520 m downstream to a point immediately upstream of a slope change from 0.29 % to 0.89 %. Section 2c stretches from this location to the end of Section 2 at the pond in Edwards Garden. Section 3a begins at the dam in Edwards Garden and extends 384 m downstream to a point where the slope transitions from 3.3 % to 1.3 %. From here, Section 3b runs a distance of approximately 600 m downstream terminating just below the 2012 restoration. Section 3b begins at the downstream end of the 2012 restoration and continues for the length of the creek. Although no sudden breaks in slope occur below Section 3b, an additional section was warranted as this stretch of Wilket Creek is characterized by several instances of extensive erosion.

In addition to further sub-dividing the creek into reaches for analysis purposes, the determination of slope was important in assessing the movement of sediment through the creek. Furthermore, it is the most complete longitudinal profile of the entire creek and could serve as a baseline for subsequent surveys.

3.3 Data Collection

Sediment budget terms include input, output and storage (Equation 1). Fieldwork beginning in April of 2013 was focused on gathering data to assess these terms in the different sections of the creek. In general, sediment input terms include: the input from the culvert at York Mills Road, hillslope and valley wall erosion, and channel enlargement due to bank and bed erosion. Storage terms include bank storage and storage in the channel. Sediment outputs typically consisted of a single location at the downstream end of each section. The data collected and the purpose for which it was gathered are shown in Table 2. The locations of data collection sites are shown in Figure 6.

Table 2. Data collected for sediment budget of Wilket Creek.

Data Collected	Purpose
Aerial imagery: planform analysis of width and lateral migration	Qualitatively assess where contribution of bank material is occurring, corroborate channel widening with lateral migration, assess whether Wilket Creek is still adjusting to urbanization
Streambed composition	Calculate sediment transport capacity of reaches
Cross sections	Quantify erosion and deposition at selected cross sections, estimate volumetric sediment contributions at the reach level
Erosion pins	Substantiate results of surveys of selected cross sections, estimate lateral bank erosion in areas lacking monumented cross sections
Windfields Park pond bathymetry	Calculate sediment inflow (Q_{in}) at a known location
Bank deposition pins	Assess storage of sediment on banks and within selected channel locations
Direct reflex survey of valley walls	Estimate contribution of sediment from valley walls in Section 3

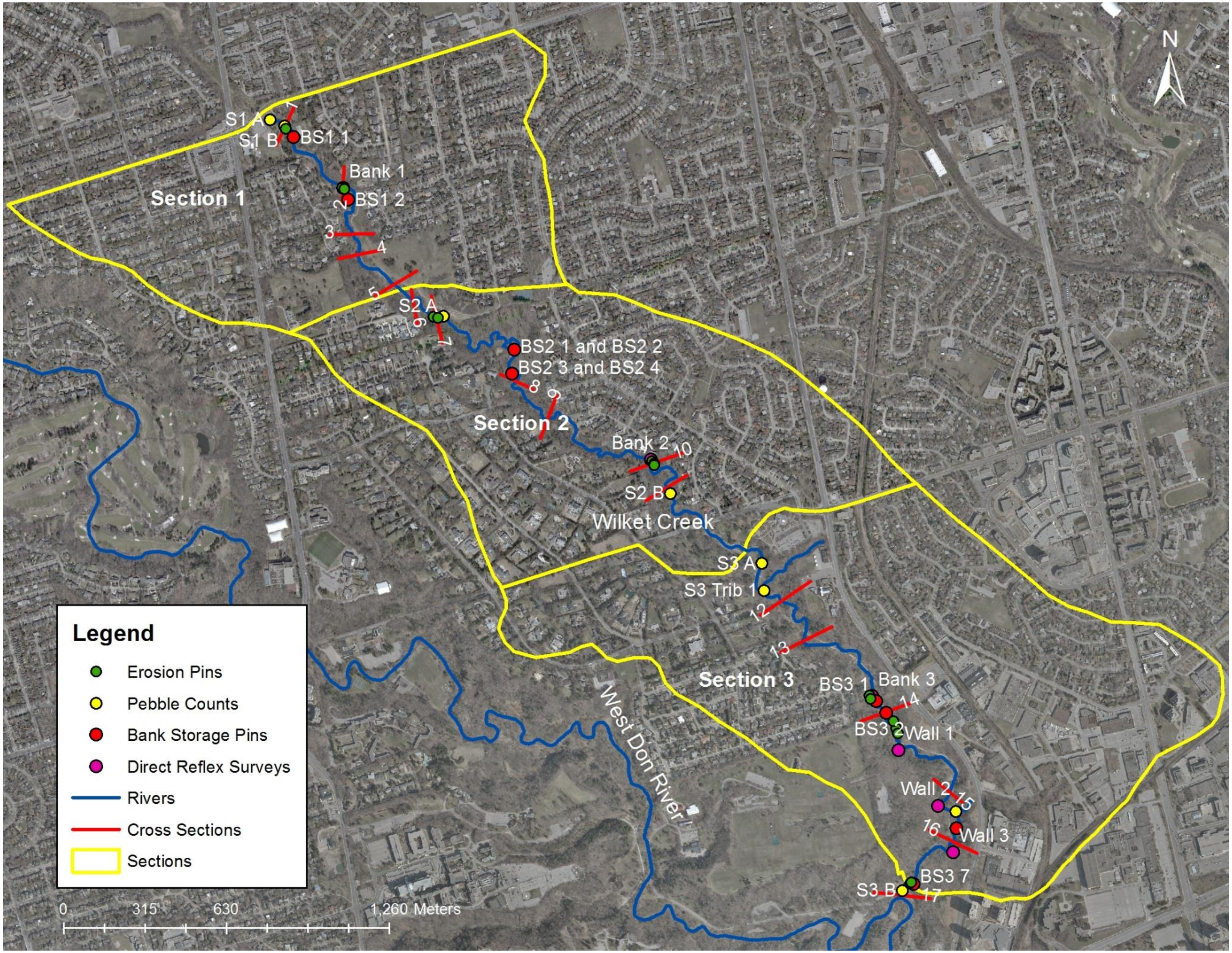


Figure 6. Data collection sites in Wilket Creek.

Baseline measurements such as initial cross section surveys were completed in June of 2013. Shortly after they were completed, a large flood occurred in Wilket Creek. On 8 July 2013, Toronto experienced a large rain event that resulted in flooding throughout the city including Wilket Creek. The high water mark was identified by the location of woody debris on the banks. Using an established cross section in the 2012 restoration and Manning's flow resistance equation, the discharge of the flood was estimated to be 8.3 m^3/s (Chapuis 2013). A flow of this magnitude would be above bankfull throughout most of the creek and exceed the top of the bank in many locations. A week after the flood, data collection resumed to assess the effects of the flood. The methods by which data were collected and processed are described below.

3.3.1 Aerial Imagery: Planform Analysis

The longitudinal survey and aerial imagery between 1999 and 2009 were analyzed using ArcGIS 10.1 to qualitatively assess where contribution of bank material is occurring, corroborate channel widening with lateral migration, and determine whether Wilket Creek is still adjusting to urbanization. In particular, changes in stream width between 1999 and 2009 and changes in planform from 1999 to 2012/2013 were investigated. Data consisted of a longitudinal survey of Wilket Creek completed during the winter of 2012/2013 and aerial imagery from the years 2009, 2003, and 1999. Geo-referenced aerial imagery from 2009 was acquired from the University of Waterloo Geospatial Centre. Raw electronic aerial imagery for the years 2003 and 1999 was acquired from Parish Geomorphic courtesy of John Parish.

Aerial imagery for the years 1999 and 2003 was geo-referenced in ArcGIS 10.1 using procedures developed by the United States Forest Service Remote Sensing Applications Center. During the geo-referencing procedure, ArcGIS calculates the total error for each geo-referenced image. The total error is the root mean square of all the residual errors which are the differences between where a control point ended up compared to where it was actually placed. In every case, the total error for each geo-referenced photo was less than five meters and in most cases less than three. After aerial imagery was geo-referenced, the left and right banks of the active stream channel were delineated. For the purposes of the study the active channel was defined as the portion of the channel with no perennial vegetation. Once the banks were delineated, sections of the respective bank polylines were characterized according to quality: excellent, good, not good and poor. Banks were characterized as “excellent” when the stream and the bank were clearly visible, “good” when the banks and channel were slightly obscured due to vegetation, “not good” when the channel was barely visible due to vegetation or shadows and “poor” when the channel was not visible at all.

After the channels were delineated, an ArcGIS module called the Channel Planform Statistics (CPS) Toolbox was used to measure the channel width at selected intervals and generate polyline shapefiles of the channel centerline for the years 1999, 2003 and 2009 (Lauer 2012). CPS was developed by J. Wesley Lauer for the National Center for Earth Surface Dynamics and uses line shapefiles of the left and right banks to find evenly spaced points between the two banks. The distance between the points is specified by the user. The program connects the points to form a centerline. Channel width is measured during the interpolation process and each channel width measurement is saved in a text file along with the distance of each point from the initial starting point. This module produces a shapefile of the centerline as well as calculating the length of the channel centerline and the width of the channel at specified intervals (Lauer 2012).

For this analysis, width measurements were generated every five meters along the length of the channel. Based upon the characterization of the left and right banks, the width data and channel centerline were characterized as excellent, good, not good and poor. Only width measurements characterized as excellent or good were analyzed. Using Microsoft Excel, width versus distance downstream was plotted for the years 1999, 2003 and 2009. In addition, the average width, maximum width and the sum of width measurements for each year were calculated.

The change in planform over time was evaluated by comparing the movement of the channel centerline. A baseline longitudinal survey carried out during the winter of 2012/2013 provided a starting point for comparison. As described above, channel centerlines were generated for 1999, 2003 and 2009 using CPS. Assuming that left and right bank delineations were equally displaced, the channel centerline should be approximately in the center of the channel. A visual inspection of the CPS generated channel centerlines indicated that they provided an acceptable depiction of the center of the channel for the respective years.

CPS was employed to measure the lateral change of the stream centerlines (Figure 7). Using the nodes interpolated during creation of the channel centerline, the CPS tool compares the lateral and normal distance between the two centerlines. The tool prompts the user for a reference centerline and then for a line to which distances will be measured. If the line to which the distance is measured is to the right of the reference centerline, the lateral displacement is positive. If it is to the left, the lateral displacement is negative (Lauer 2012).

Figure 7. Channel Planform Statistics Tool output showing lateral movement from the blue reference line (2009) to the red line (2012). Lateral measurements to the right of the reference line are positive and negative to the left.

Using the CPS tool, the centerline for each year was compared with the subsequent year. Additionally, the centerline for the latest year (2012/2013) was compared to all other years. Within ArcGIS, yearly migration rate was calculated by dividing the migration distance by the difference in time between the two centerlines. The subsequent migration data were exported from ArcGIS shapefiles to text files which were then exported to Excel for analysis. Lateral migration data was only compared between centerlines that were rated “excellent” or “good” based on their respective channel delineations.

Within Excel average, minimum and maximum migration rates were calculated between subsequent years and between 1999 and 2012/2013 for Sections 1, 2 and 3. Migration rates at individual nodes were also plotted against distance downstream.

3.3.2 Streambed Composition

Steambed composition is an important parameter to quantify as it influences channel form, hydraulics, erosion rates and sediment supply (Harrelson et al 1994). Furthermore, streambed monitoring is critical for assessing the consequences of development in the riparian zone and the watershed as well as the effects of stream rehabilitation efforts (Bunte and Abt 2001). In the case of this study, characterization of streambed composition was necessary to calculate sediment transport capacity.

Streambed composition was characterized at nine locations. Sampling locations were typically near the upstream and downstream ends of each of the three sections. Sampling was also conducted at the downstream ends of two major tributaries in the lower section of Wilket Creek (Figure 6). Two methods were employed based upon the characteristics of the site: volumetric sampling and pebble counts.

A single volumetric sample was collected on 14 August 2013 at York Mills Road. At this location Wilket Creek issues from a large culvert and empties into a trapezoidal basin with a concrete apron and walls (S1 A). A volumetric sample was collected because sediment in the basin consists overwhelmingly of sand and small gravel. The size of the sample was 12.22 kg which is consistent with the recommended sample size for an error of 1% where the largest particle has an a-axis of 62 mm, a b-axis of 42-mm and a c-axis of 34 mm (Bunte and Abt 2001). The volumetric sample was brought back to the University of Waterloo Sediment Laboratory for analysis according to method described by Bunte and Abt (2001).

The remaining samples consisted of pebble counts which were conducted according to recommendations by Bunte and Abt (2001) and Harrelson et al (1994). The spatial extent of pebble counts was typically from the top of one riffle to the top of the subsequent riffle. The aim was to collect a minimum of 200 particles with a b-axis greater than 8.0 mm. This sample size was chosen as it estimates grain size within a 10% error (Rice and Church 1996). All particles with a b-axis of 128.0 mm or less were measured with a gravelometer manufactured by Albert Scientific (http://albertscientific.com). Particles larger than 128.0 mm were measured *in-situ* with a measuring tape. Particles less than 8.0 mm were recorded as a single class size but did not count towards the 200 particle sample size. Sampling proceeded from upstream to downstream. If after a single pass, 200 samples greater than 8.0 mm were not collected, a second pass from downstream to upstream was carried out. Pebble count data were processed in Excel. The D_5, D_{10}, D_{16}, D_{25}, D_{50}, D_{75}, D_{84}, D_{90} and D_{95} particle sizes were calculated along with their cumulative frequency.

The first pebble count was conducted about 35 m downstream from York Mills Road (S1 B) on 14 August 2013. The spatial extent of the pebble count was from the crest of a riffle to the top of the next downstream riffle totaling approximately 90 m in length. The active channel was sampled using a 1 m by 1 m grid. In total, the sample consisted of 224 particles greater than 8.0 mm in diameter.

The next sampling location (S2 A) was selected to characterize the sediment at the transition from Section 1 to Section 2. The site is located approximately 1,230 m downstream of the source and 220 m downstream from the beginning of Section 2. This site was chosen because it is the first more or less natural reach in Section 2. A pebble count was conducted at this site on 14 August, 2013. The spatial extent of the sampling was from the bottom of a riffle to the bottom of the next downstream riffle. The active channel was sampled using a 2 m by 2 m grid with 255 particles greater than 8.0 mm collected.

An additional sample was collected from the lower end of Section 2 approximately 3,145 m downstream from Wilket Creek's source (S2 B). This site consists of a riffle which is 23 m in length with a channel about 2 m wide on the right and a larger bar of about 5 m in width on the left side of the channel. On 20 August 2013, a pebble count was conducted on the riffle and associated bar with a total of 233 particles greater than 8.0 mm gathered.

In Section 3, a pebble count was conducted about 110 m downstream from the dam in Edwards Garden which forms the boundary between Sections 2 and 3. The sample reach is 27 m in length and spans from the top of one riffle to the top of the next downstream riffle. The sample was taken on 20 August 2013 and consisted of 216 particles.

The site of the most downstream pebble count is located at the confluence with the West Don River. The sampling reach is approximately 40 m in length. It starts at the top of the last riffle in Wilket Creek, proceeds through a pool and continues to the confluence where there is an alluvial fan. Sampling occurred on 21 August 2013. In total, 490 particles were sampled.

In addition to the main stream channel, pebble counts were conducted in two tributaries in the lower portion of Wilket Creek. These tributaries were sampled because they are the largest tributaries and because they appeared to contribute gravel and cobble sized particles to Wilket Creek whereas most other tributaries appeared to contribute finer material. The first tributary sampled is located about 240 m downstream of the dam in Edwards Gardens. The source of the tributary is a large culvert that discharges at Lawrence Avenue. At the confluence of the tributary with Wilket Creek, there is an alluvial fan. The pebble count was conducted on 22 August 2013 and particle collection was carried out on a 1 m by 1 m grid. Sampling began at the fan and preceded upstream until 287 particles were collected.

The second tributary sampled is located 500 m upstream from the confluence of Wilket Creek with the West Don River. Like the previous tributary, it issues from a culvert located at Lawrence Avenue. At the confluence with Wilket Creek there is a large alluvial fan. Data collection was carried out on 21 August 2013 using the same procedure as the previous tributary. In total, 254 particles greater than 8.0 mm were collected.

3.3.3 Cross Sections

Monumented cross sections are an important component in river research and have been used extensively to monitor changes in channel geometry due to urbanization (Hammer 1972, Pizzuto et al 2000, Hawley et al 2012). Depending on the nature of the study, cross sections may also play a large role in sediment budgets (Allmendinger et al 2007, Martin and Church 1995 and Rovira et al 2005). Repeated measurements over time can be used to quantify whether the bed is aggrading or eroding at a cross section. A rate of aggradation or degradation may be determined by dividing the change in area by the time period (Jordan et al 2010). At a larger scale, the morphological approach to sediment transport analysis can be used to estimate volumetric change in sediment for a reach by assuming that a given cross section is representative of the channel a certain distance upstream and downstream (Martin and Church 1995, Rovira et al 2005). This change in volume can be used to estimate the storage term of a sediment budget as per Equation 4.

To quantify bed degradation and aggradation as well as lateral bank erosion throughout Wilket Creek, 17 cross sections were established between the 7th and the 17th of June, 2013. The cross sections begin just downstream of the source at York Mills Road and extend to the confluence with the West Don River (Figure 6). The naming convention begins with Transect 1, which is the most upstream location, and proceeds sequentially to Transect 17 which is located at the mouth of Wilket Creek. Cross sections were distributed fairly evenly throughout the creek with five in Section 1, six in Section 2 and six in Section 3. Cross sections were placed so as to capture a variety of bedforms and morphologies (Table 3).

Table 3. Description of monitoring transects.

Transect	Section	Bedform	Located on Bend on Straight Area	Information
1	1a	Pool	Bend	Immediately downstream of source in an area of lateral erosion on right bank
2	1a	Pool	Straight	Area of erosion/deposition after end of gabioned section
3	1a	Pool	Bend	Area of lateral erosion on left bank with a steep right bank slope
4	1a	Pool	Straight	Wide area of fine sediment streambed deposition near a tributary.
5	1b	Riffle	Straight	Located downstream of Windfields Park dam with lateral erosion on left bank
6	2a	Riffle	Straight	Downstream of large culvert in an area with an avulsion on right bank
7	2a	Pool	Straight	Extensive erosion on right bank
8	2b	Pool	Bend	Area of lateral erosion on left bank and major sand deposition on right bank
9	2b	Riffle	Straight	Steep right bank
10	2c	Riffle	Bend	Area of extensive bank widening on private property
11	2c	Riffle-Almost a Step/Pool	Straight	Immediately downstream of grade control structure with a large grave/cobble bar on left bank
12	3b	Pool	Straight	Downstream of bridge
13	3b	Pool	Bend	Located immediately upstream 2012 restoration with erosion on right bank and gravel bar/sand deposition on left bank
14	3c	Riffle	Straight	Immediately downstream of 2012 restoration - extensive erosion and avulsion on right bank and large sand deposition on left bank
15	3c	Riffle	Straight	Immediately upstream of 2013 restoration
16	3c	Pool	Bend	Extensive erosion on left bank and large sand deposit on right bank
17	3c	Riffle	Straight	Mouth of Wilket Creek

Cross sections were established by driving pins into both banks. To measure the cross sections, a tape was stretched from the left bank (0.0 m) to the right bank. Within the channel, measurements were taken every 0.3 m along the tape using a Sokkia SDL50 auto level or a Trimble S6 DR3000+ total station. On the bank, measurements were taken as needed to capture the topography (Figure 8). Other measurements taken during the survey included water depth and bankfull width. After establishing the cross sections and conducting an initial survey, subsequent measurements were made between the 16th and 18th of July and the 20th and 25th of November, 2013.

Figure 8. Auto level configuration for surveying cross sections.

In the study of rivers and the practice of river restoration, the concept of bankfull flow or stage has become prevalent. Bankfull stage is typically defined as "the flow that just fills the channel to the top of its banks and at a point where the water begins to overflow into the floodplain" (Rosgen 1996). Bankfull flow is considered important as it is thought to be the discharge that is most important in channel formation and maintenance (Rosgen 1996). In field conditions, identification of bankfull stage may be more complicated, especially where the floodplain is not well defined. As a result, there are several indicators that may be used (Harrelson et al 1994):

1. Break in slope or topography

2. Sudden change in vegetation
3. Waterline stains on rocks or the bank
4. The elevation of depositional features (for example the top of a point bar)

A typical cross section is shown in Figure 9 with the purple line representing bankfull stage while the blue, red and green lines reflect survey data gathered on 13 June, 17 July and 21 November 2013 respectively.

Bankfull metrics were calculated in AutoCAD. Cross section data were imported from Excel and the bankfull water elevation was drawn by connecting end points noted in the field survey. Using the "Trim" function, the region between bankfull water elevation and the bed elevation was delineated for all three surveys at a given cross section. The area between bankfull elevation and the bed elevations was subsequently measured. Bankfull depth was determined for each cross section survey by dividing bankfull area by bankfull width. The depth of scour or deposition between surveys was calculated by first determining the differences in areas between the June and July surveys, the July and November surveys and between the initial June survey and the final one in November. The difference in area between two surveys was divided by the bankfull width of the last survey which resulted in a scour or deposition depth between given surveys.

As bankfull width can be problematic to identify in the field, metrics for the top of bank were calculated in a similar manner to the methods described above. In the case where the tops of the left and right banks were of markedly different elevations, the lower bank was used to identify the "top of bank" (Figure 9).

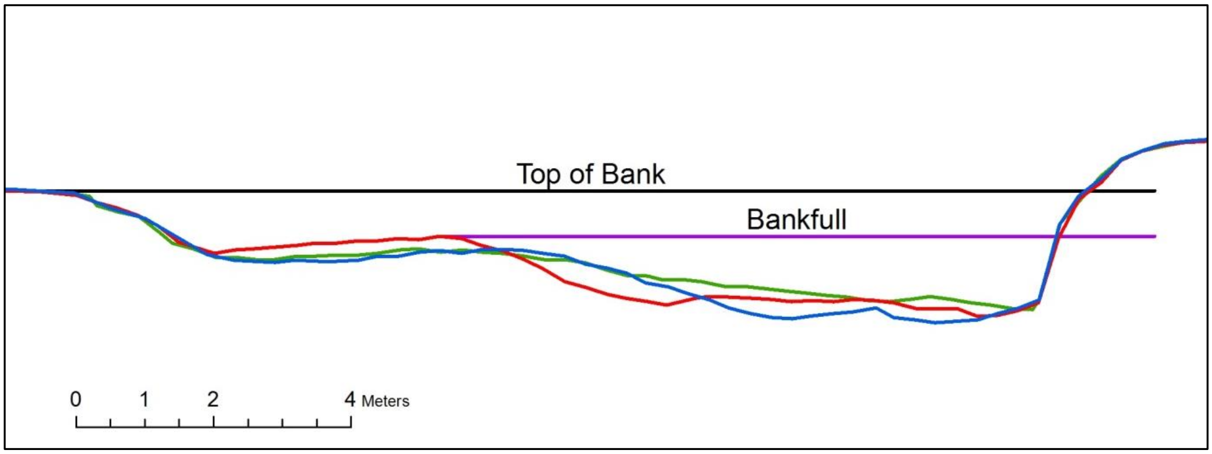


Figure 9. Cross section of Transect 13 showing bankfull and top of bank delineations.

Although erosion and deposition at a single cross section could have been calculated using AutoCAD, ArcGIS 10.1 was used as it allows more precise evaluation of individual locations of erosion and deposition. In particular, it more fully captures bank erosion, especially in the case where the top of bank on one side is much lower than the other. Additionally, the visualization is superior and the areas of erosion and deposition at a cross section can easily be exported into Excel for further processing. Survey data from Excel were imported into ArcGIS 10.1 as an event layer. To display the data in a cross section as opposed to the typical ArcGIS planform view, the distance along the cross section was used for the x coordinate and the elevation served as the y coordinate. Due to this, it was not possible to convert the cross section event layer into a permanent shapefile. Instead, polyline shapefiles with a spatial reference of NAD 1983 Zone 17 N were created for each cross sectional survey by tracing the measured points (Figure 10).

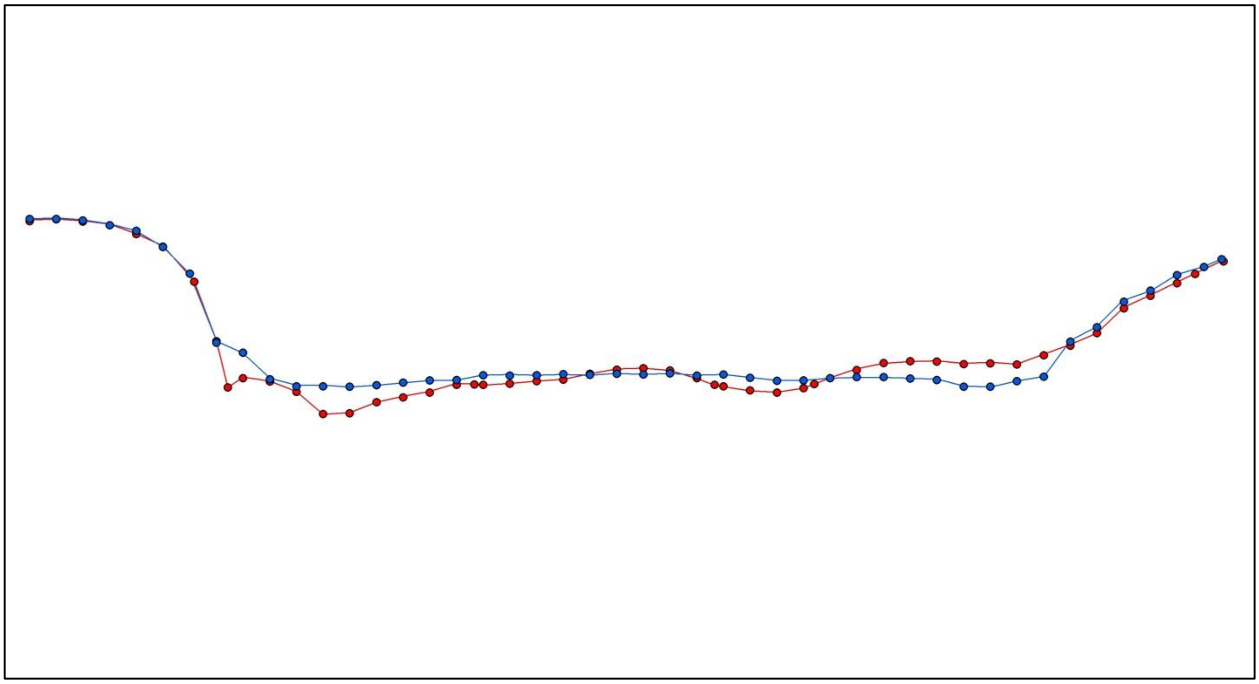


Figure 10. Transect 9 survey points and ArcGIS 10.1 shapefile polylines from 11 June 2013 (Blue) and 21 November 2013 (Red).

The next step was to determine net areas of erosion and deposition. This was done by converting the polylines to polygons whose area can be automatically calculated using the “Calculate Geometry” tool. Afterwards, individual polygons within the shapefile were denoted as areas of erosion or deposition (Figure 11).

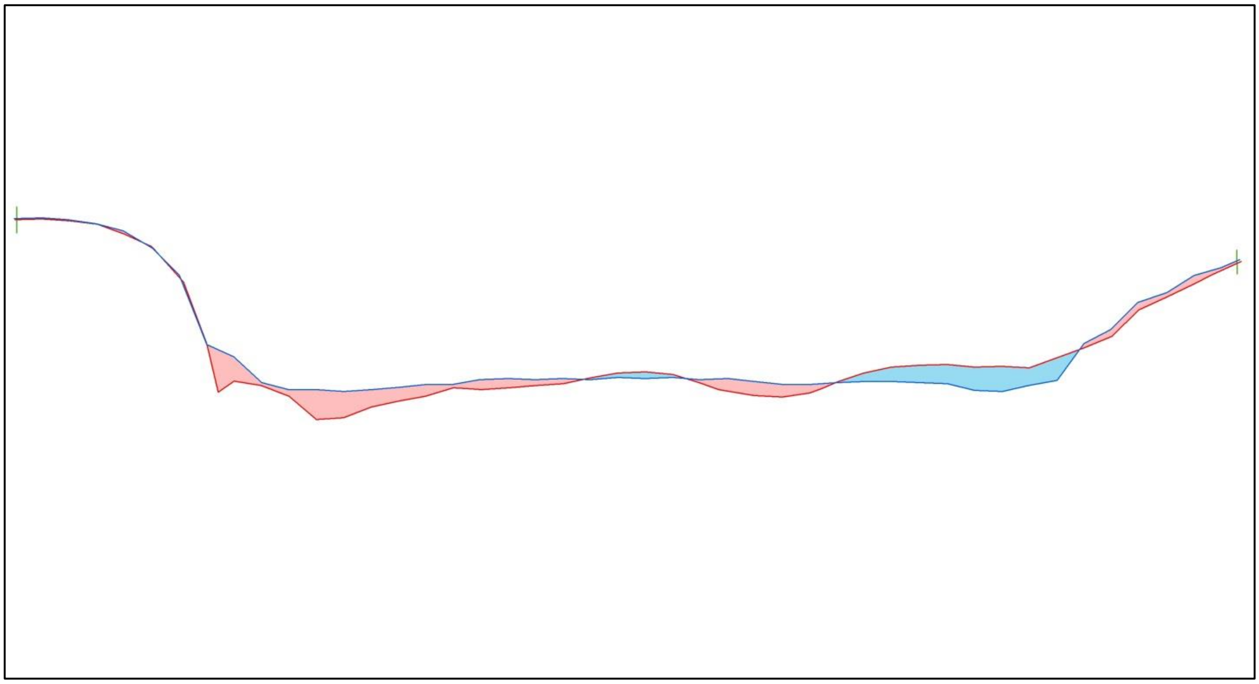


Figure 11. Polygons showing areas of deposition (Blue) and erosion (Red) at Transect 9.

Using this procedure, the net areas of erosion and deposition were calculated between June and July, July and November and June and November for each of the 17 cross sections. The data tables for the polygon shapefiles were exported as text files and then subsequently imported into Excel for processing.

3.3.4 Erosion Pins

Erosion pins were used to estimate lateral streambank migration. Erosion pins are metal rods, typically between 1.0 and 1.5 meters in length, which are driven horizontally into stream banks. Pins are driven flush into the bank or with a small, measured section exposed. Periodically or following high flow events, the length of exposed pin is measured and the exposed pin is driven back into the bank. In the case where an entire pin is lost, the erosion is assumed to be at least the length of the pin. If available, another pin is driven into the location (Harrelson et al 1994, Rosgen 1996).

Erosion pins were employed to act as a check on cross section surveys and provide a gross estimate of erosion in selected locations lacking cross sections. A total of 15 were installed in

Wilket Creek between 27 June and 2 July 2013 (Figure 4). The pins were constructed from rebar and cut to 0.8 m in length. Pins were typically employed to provide a crude estimate of lateral bank retreat in locations where erosion was evident or expected. The table below details the date of installation, distance to the closest transect and the bank it was installed in (Table 4).

Table 4. Location of erosion pins in Wilket Creek.

Pin	Date of Installation	Closest Transect	Distance to Transect (m)	Bank (Left or Right)
EP1 1A	27-Jun-13	Transect 1	1.2 Upstream	Right
EP1 1B	27-Jun-13	Transect1	2.9 Downstream	Right
EP1 2A	27-Jun-13	Transect 2	4.3 Upstream	Right
EP1 2B	27-Jun-13	Transect 2	5.2 Downstream	Right
EP2 1A	27-Jun-13	Transect 7	10.4 Upstream	Right
EP2 1B	27-Jun-13	Transect 7	6.5 Downstream	Right
EP2 2A	27-Jun-13	Transect 10	12.2 Upstream	Left
EP2 2B	27-Jun-13	Transect 10	3.1 Downstream	Left
EP2 2C	27-Jun-13	Transect 10	12.7 Downstream	Left
EP3 1A	27-Jun-13	Transect 14	93.4 Upstream	Right
EP3 1B	27-Jun-13	Transect 14	93.4 Upstream	Right
EP3 1C	27-Jun-13	Transect 14	81.7 Upstream	Right
EP3 2A	27-Jun-13	Transect 14	85.5 Downstream	Left
EP3 2B	27-Jun-13	Transect 14	105.7 Downstream	Left
EP3 2C	27-Jun-13	Transect 14	105.7 Downstream	Left
EP3 3A	02-Jul-13	Transect 17	70.8 Upstream	Left
EP3 3B	02-Jul-13	Transect 17	70.8 Upstream	Left

The erosion pins were re-measured between 23 July and 8 August 2013. The pins were occasionally inspected during the remainder of the field season but showed no evidence of significant erosion.

3.3.5 Windfields Park Pond Bathymetry

Sediment transport out of Section 1 was estimated by measuring the change in the volume of sediment behind the dam in Windfields Park between April and September of 2013 (Figure 12). The dam consists of a concrete base, wing walls and apron with wooden flashboards. It is operated seasonally with the flashboards installed in spring and removed for the winter.

Following installation of the flashboards in spring, it was thought that the dam might trap a significant portion of sediment generated upstream. The sediment would be held behind the barrier until the flashboards were removed in winter, at which time the sediment would be transported downstream to Section 2. To estimate sediment transported from York Mills Road to the end of Section 1, bathymetric surveys of the pond were conducted prior to installation of the flashboards and following a high flow event. The initial bathymetric survey was conducted on 20 April 2013, days prior to installation of the flashboards. The survey was conducted using a Sokkia SET530R Total Station and Sokkia GRX1/U Real Time RTK. The pool was surveyed a second time on 10 September 2013 utilizing the total station. Data from the April and September surveys were imported into ArcGIS 10.1 to determine the change in volume of sediment.

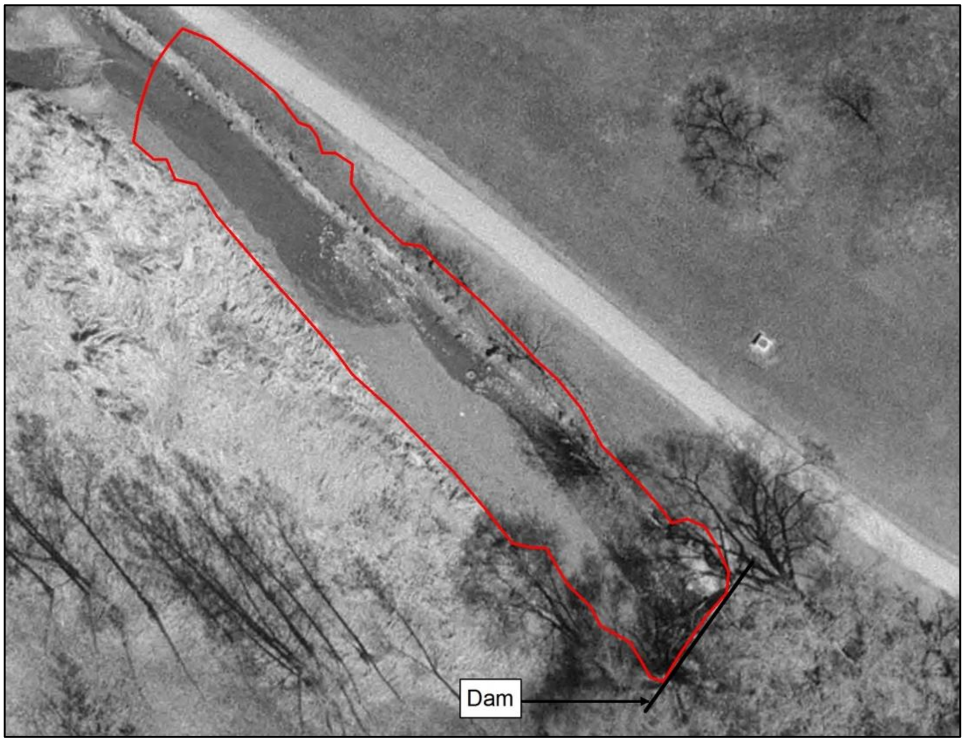


Figure 12. Area of bathymetric survey outlined in red from 2003 aerial photos (Source: Parish Geomorphic).

The change in sediment was calculated using three different methods to ensure the results were of the same order of magnitude. The first method involved creating rasters of the surveys and then using the raster calculator and the "Zonal Statistics as Table" tool. To begin, a "mask" was created for the channel as this was the area of interest and the survey extended beyond this area. The next step was to create an interpolated surface for both the April and the September data. Using the “Interpolation” tool and the “mask” created for the channel, interpolated surfaces were created using a variety of methods including inverse distance weighting (IDW), kriging, natural neighbor and spline. In all cases, the default settings were used except cell size which was set at 0.2 m by 0.2 m. The reason for using multiple interpolation methods was to determine what effect interpolation method might have on results. Of the methods tested, natural neighbor and spline created very artificial looking surfaces. As a result, only the IDW and kriging interpolations were used.

Once surfaces were created for the April and September data using both IDW and kriging, the ArcGIS raster calculator was used to subtract the April raster from the respective September raster. As each cell in the raster contains an interpolated elevation based on the survey data, subtracting one raster from another will result in a sediment height which may be either positive or negative. The “Zonal Statistics as Table” tool was then used to determine the sum of the values of the cells in the rasters. The sum of height values was subsequently multiplied by the cell size of 0.2 m by 0.2 m to estimate the change in sediment volume.

The next method used to measure change in sediment in the pond for both IDW and kriging interpolations was the “Cut Fill” tool, which calculates the volume change between two raster surfaces. Inputs for the tool include the raster surface from April (before) and the raster surface in September (after). The output is a raster showing areas of net gain, net loss and unchanged. The table associated with the output raster includes the volume and surface area of each separate area of net gain and net loss in addition to the surface area of those locations where no change occurred. All of the volumes in the raster were summed in Excel to determine the net change in volume.

The final method used to estimate accumulated sediment was the “Surface Volume” tool in ArcGIS 10.1. The “Surface Volume” tool calculates the area and volume projected above or below a given reference plane. The input for this tool was the surface created by subtracting the September raster from the April raster (See Figure 45 for the input). In addition to the raster, the other input variable is a reference plane. The surface area and volume of the input raster can be calculated either above or below this reference (Figure 13). After the areas and volumes above and below a reference plane are calculated, they may be summed to get the total area or volume under a surface.

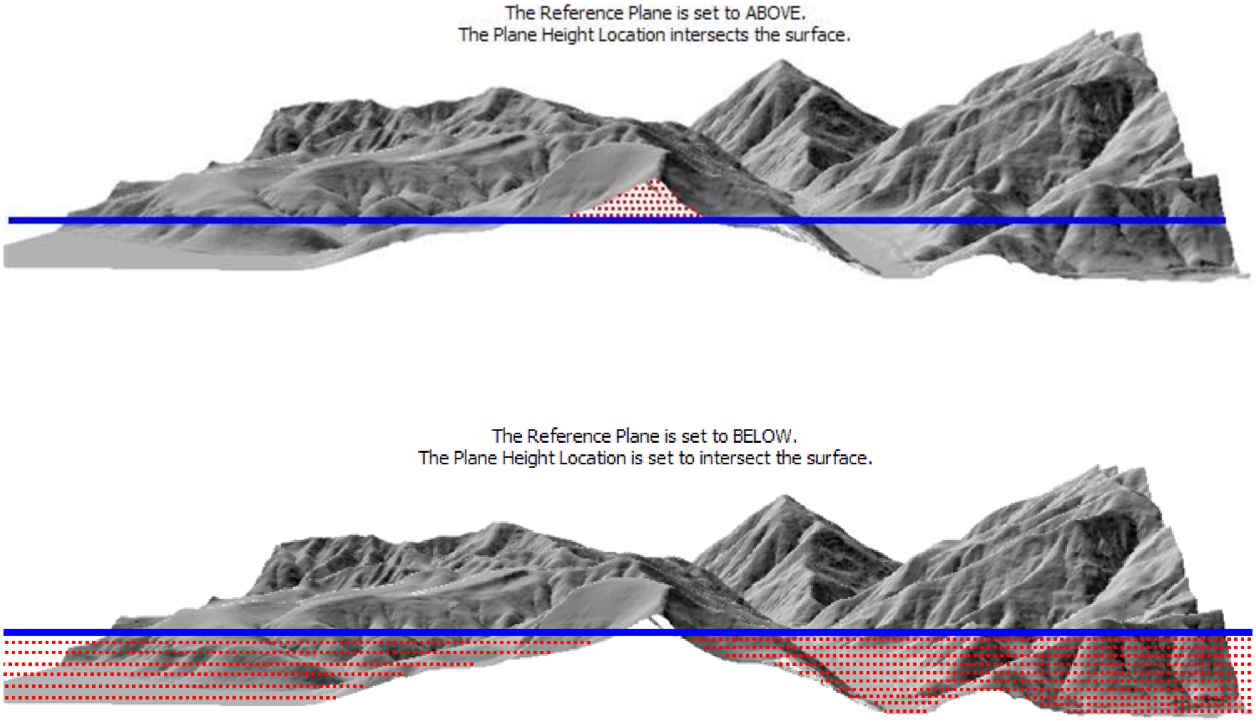


Figure 13. Illustration of volume calculated above a reference height and below a reference height (ESRI: ArcGIS 10.1 Desktop Help).

For both the IDW and the kriged surfaces, reference heights of 0.07 m and -0.07 m were chosen. The volume was then calculated above a height of 0.07 m and below -0.07 m. The reason for selecting these reference heights is that a measurement error of around 0.1 m was estimated for the surveys. The output of the “Surface Volume” tool is a text file that includes area and volume. Using Excel, the volumes above and below the reference height were summed to get the total volume of the surface created by subtracting the April from the September bed surface interpolation.

An important consideration in calculating sediment volume is porosity. As no measurements were made during the study, values in the literature must be relied upon. In their sediment budget for a gravel bed river in British Columbia, Martin and Church (1995) used a value of 0.25 ± 0.05. Assuming a particle density of 2.65 g/cm for quartz and feldspar gravels, Bunte and Abt (2001) cite a range of porosity values for different sediment classes (Table 5). Based on these studies, a porosity of 0.25 was assumed for sediments in Wilket Creek. As a result, all volume calculations were multiplied by 0.75 to account for porosity.

Table 5. Range of porosity values for sediment particles.

Particle Type	Porosity
Course Sand	0.15 - 0.35
Range in Gravel Bed Rivers	0.02 - 0.36
Mean in Gravel Bed Rivers	0.21

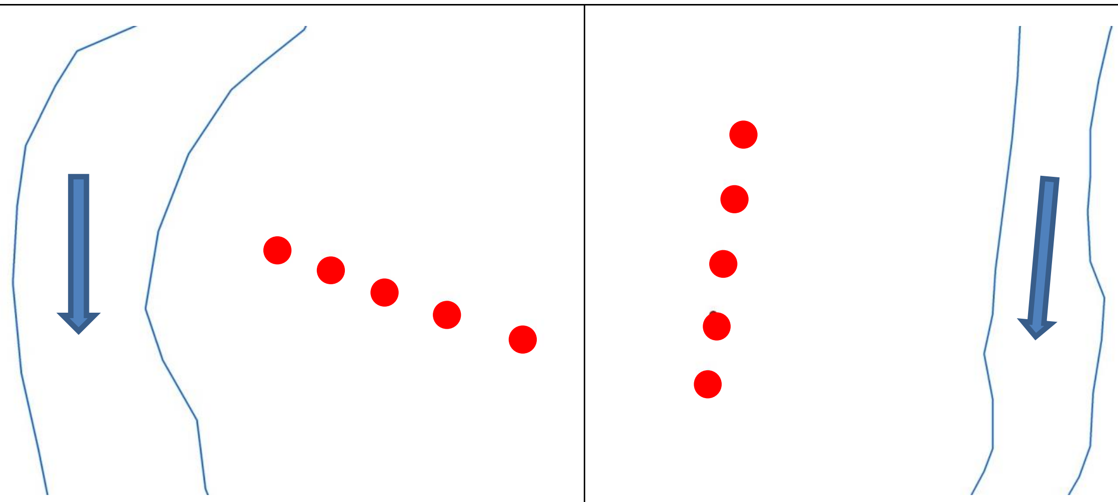
3.3.6 Bank Storage Pins

Initial surveys of Wilket Creek indicated that, in some areas, there was a significant deposition of sand on banks. In other cases, erosion on the surface of the bank was evident. Bank storage pins were used to generate a rough estimate of erosion and deposition on the surface of banks in order to qualitatively assess sediment storage for the sediment budget. The locations were selected based on observations of where deposition or erosion appeared to be actively occurring.

Bank storage pins were made of metal rods which were 0.64 cm in diameter and cut to lengths of 0.3 m. Typically pins were driven vertically into the top of banks where erosion and/or deposition were occurring. At two locations, pins were driven into the active channel where extensive sand bars occurred. Additionally, two transects of pins were located in a relic channel in Section 3 where sediment was accumulating. In total, seven transects or arrays of pins were established throughout Wilket Creek (Figure 6).

In Section 1, two bank pin transects were established. The first transect (BS1 1) is located about 130 m downstream of the source and consists of five pins. It is oriented more or less perpendicular to the stream. The first pin is located approximately 5 meters from the left bank.

Subsequent pins are located 2.5, 5, 7, and 11 m inland from the initial pin. The uneven spacing was due to obstructions in the ground surface such as rocks, concrete blocks and tree roots (Figure 14). The second transect (BS1 2) is located 390 m downstream of the initial transect and consists of five pins located parallel to the channel with a spacing of 2 m between pins (Figure 14).

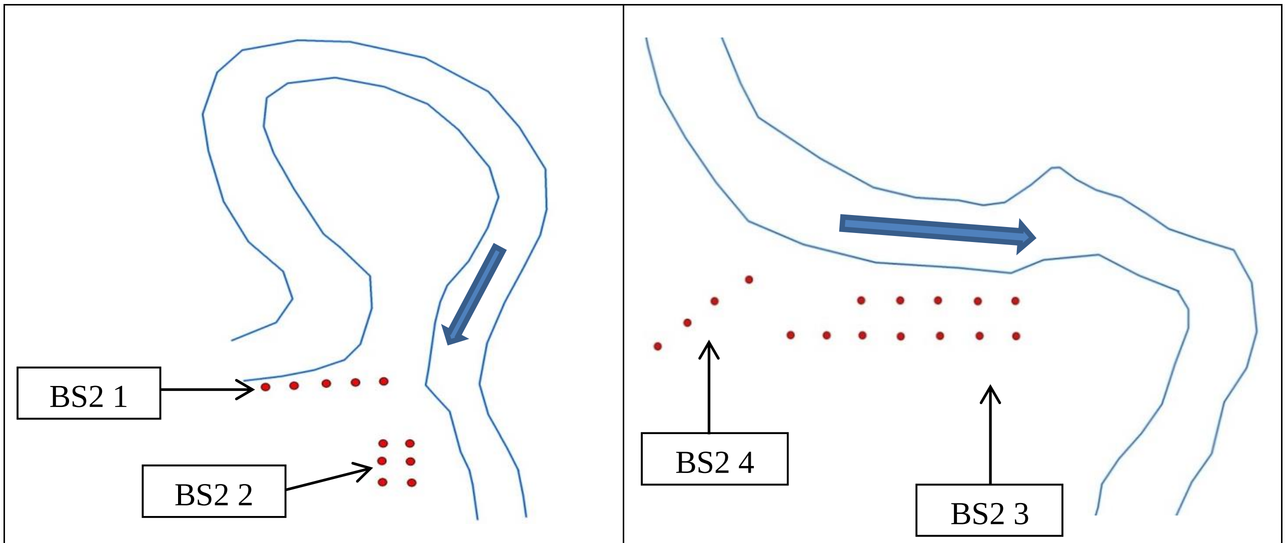


Transect BS1 1 located near the source of Wilket Creek.

Transect BS1 2 located upstream of Windfields Park.

Figure 14. Bank storage pins in Section 1 of Wilket Creek.

Section 2 contains two pin complexes each containing two banks of pins. Both of the bank pin complexes are located in an extremely sinuous section of the creek. The first complex is located 1750 m downstream of the source and consists of a transect of five pins and an array of six pins. The transect (BS2 1) is located roughly parallel with the channel. There is a spacing of 1 m between the first 4 pins and a spacing of 3 m between the fifth and sixth pins. The array of six pins (BS2 2) is made of two transects of three pins. The transects are a meter apart and the spacing of the pins on each transect is also 1m (Figure 15). The second complex is approximately 100 m downstream and is also made up of one transect and one array. The array (BS2 3) is made up of two transects, the first having five pins and the second having seven. In each transect, there is a spacing of 1 m between pins. Likewise, the space between the transects is 1 m. The transect (BS2 4) consists of four pins with a 1 m spacing (Figure 15).

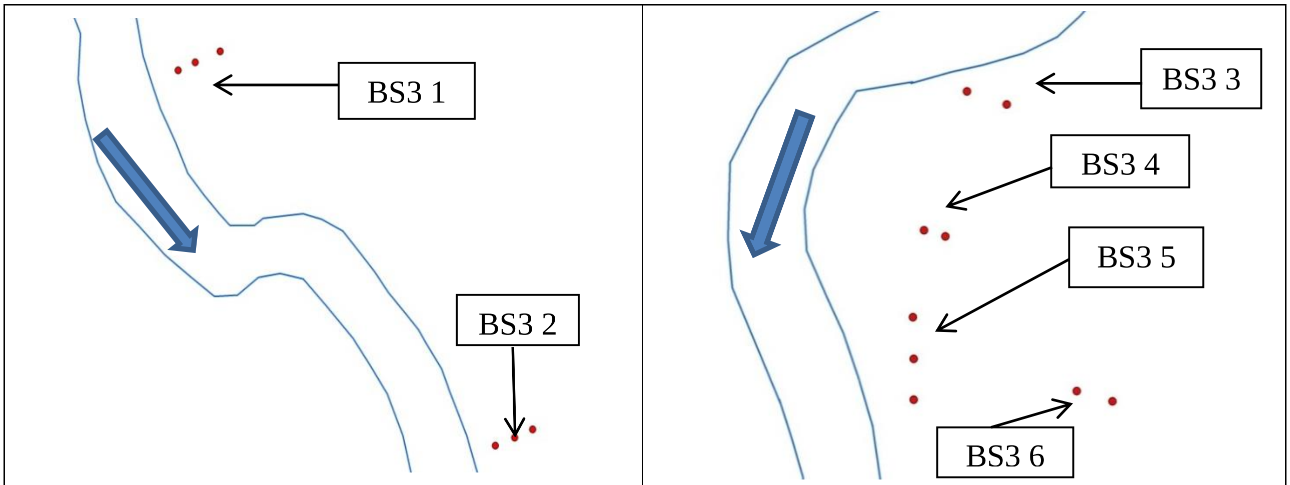


Complex of bank erosion pins consisting of a transect (BS2 1) and an array (BS2 2)

Complex of bank erosion pins consisting of an array (BS2 3) and a transect (BS2 4)

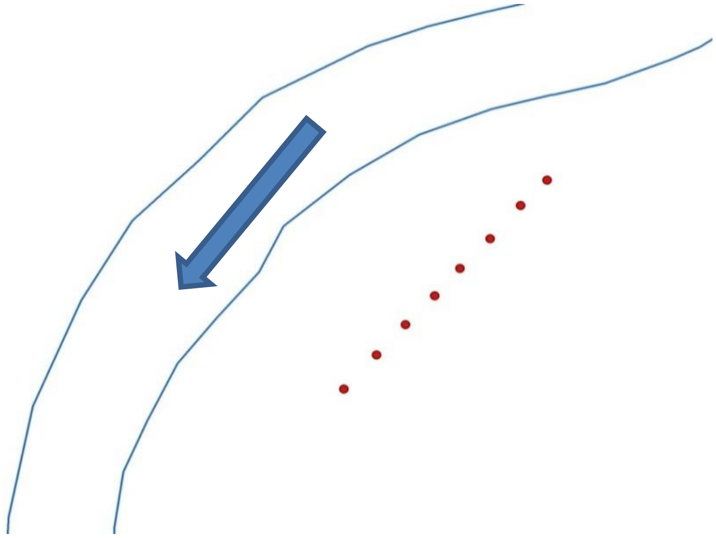
Figure 15. Bank erosion pins located in Section 2 of Wilket Creek.

Section 3 has two transects, a complex of four transects and a final transect near the confluence with the West Don River. The first two transects (BS3 1 and BS3 2) are located just downstream of the 2012 restoration. This is an area of extensive bank erosion and deposition within the active channel. Both transects consist of three pins (Figure 16) and are located within the active channel as this is where deposition is occurring. At the location of Transect BS3 1, vegetation is starting to become established and this area may start to act as a bank or terrace in the future. The complex of bank erosion pins is located approximately 5430 m downstream of the source of Wilket Creek. The complex is made of four transects (BS3 3 through BS3 6). Beginning upstream, there are two transects of two pins each (BS3 3 and BS3 4). The two pins in transect BS3 3 are separated by two meters while the two pins in transect BS3 4 are separated by a meter. Transects BS3 5 and BS3 6 occur in a relic channel where extensive deposition occurs at high flows. Transect BS3 5 contains three pins each separated by two meters. The final transect (BS3 6) is made up of two pins with a spacing of two and a half meters (Figure 16). The final transect (BS3 7) is located about 80 m upstream of the confluence with the West Don River. The transect is oriented roughly parallel with the creek and consists of eight pins with a one meter spacing between pins (Figure 16).



Bank erosion pin Transects BS3 1 and BS3 2.

Complex of bank erosion pins consisting of Transects BS3 3, BS3 4 and BS3 5, and BS3 6.



Bank erosion pin Transect BS3 7 located immediately upstream of confluence with the West Don River.

Figure 16. Bank erosion pins in Section 3 of Wilket Creek.

All bank storage pins were established on 2 July 2013. A major flood that topped the banks throughout Wilket Creek occurred on 8 July 2013. Consequently, the height of the pins above or below the surface was re-measured between 24 July and 8 August 2013. Although large discharges have topped the banks in isolated areas, a discharge large enough to exceed the banks throughout the entire creek has not occurred since the July 8 flood.

3.3.7 Direct Reflex Surveys of Valley Walls and Banks

In Section 3 there are several very large walls formed of glacial till that act as banks and whose sediment contribution to Wilket Creek is unknown. To better assess erosion on exposed valley walls, a number of these features were surveyed with a Trimble S6 DR3000+ total station using direct reflex technology. Direct reflex or reflectorless technology allows surveying instruments to accurately measure remote points without using a prism.

Direct reflex measurements are generally achieved using one of two technologies: Time of Flight or Phase Shift. The Trimble S6 uses Time of Flight technology to carry out direct reflex measurements. In the Time of Flight method, the instrument generates many short laser pulses which are transmitted to the target through a telescope. The pulses reflect off the target and return to the machine where the round trip time for each pulse is determined. The travel time is used to compute the distance between the instrument and the target (Hoglund and Large 2005). According to a paper by Hoglund and Large (2005), the Time of Flight method employed by the Trimble S6 provides a longer range when measuring to wet surfaces as well as the likelihood of a successful measurement to wet and oblique surfaces compared to instruments using the Phase Shift method. This feature is important as many of the walls are wet due to groundwater seepage. In regards to accuracy, operating in Direct Reflex mode is comparable to Prism Mode (Hogland and Large 2005). When measuring surfaces using the direct reflex technology, the Trimble S6 can be employed to automatically take measurements using scanning mode. Using this mode, the total station takes measurements at defined vertical and horizontal distances between pre-set points (Trimble 2005).

In total, three large walls were scanned using reflectorless technology. A qualitative survey of Wilket Creek revealed that there were four very large walls in the downstream area of Section 3. Three of these walls were selected for scanning. Two of the walls are located directly on the creek, forming the bank on the outside of a bend. One of the walls is located on the terrace of an outside bend and is not connected directly to the stream. As a result, it would only be exposed to the stream under flood conditions. It was selected for scanning to serve as a comparison with the other sites which are constantly exposed to streamflow (Figure 6). During the scanning procedure, the total station was programmed to take measurements every 0.5 m on the horizontal and vertical planes (Table 6).

In addition to the valley walls, three stream banks located in separate sections of Wilket Creek were chosen for scanning. The purpose was to test whether they would provide a more accurate assessment of bank erosion (Table 6).

Table 6. Valley walls and banks surveyed using reflectorless technology.

Feature Scanned	Location	Date of Scan	Horizontal Point Distance (m)	Vertical Point Distance (m)
Wall 1	Section 3	29 September 2013	0.5	0.5
Wall 2	Section 3	27 September 2013	0.5	0.5
Wall 3	Section 3	30 September 2013	0.5	0.5
Bank 1	Section 1	22 October 2013	0.3	0.3
Bank 2	Section 2	26 September 2013	0.5	0.3
Bank3	Section 3	27 September 2013	0.3	0.3

The scanning of valley walls and banks occurred late in the fieldwork season with no major flooding prior to widespread freezing of the creek in December. Consequently, it was not possible to conduct a subsequent survey. However, these surveys may act as a baseline for other research efforts.

3.4 Sediment Budget

The sediment budget for Wilket Creek was conducted based on the six step methodology proposed by Reid and Dunne (1996) and had two objectives. The first was to assess the sediment contribution of the streambank and bed to Wilket Creek and estimate volumetric sediment transport using the morphological approach outlined by Martin and Church (1995). This step was necessary towards achieving the second objective of developing a comprehensive sediment budget for Wilket Creek.

3.4.1 Morphological Approach - Reach Contribution and Sediment Transport

The assessment of the bank and bed contribution to sediment production was based on repeated surveys of monumented cross sections. As described above, 17 cross sections were surveyed over the course of a year to measure erosion and deposition. Using Equation 4, previous researchers (Martin and Church 1995, Rovira et al 2005) calculated volumetric changes at the reach level by assuming that change at a cross section was representative of half the distance to the upstream and downstream cross sections. In this case, the character of the stream is well known. Therefore, reaches were characterized based on their upstream and downstream similarity to given cross sections (Figure 17). The criteria used to determine similarity of the channel to a given cross section were morphology (width, erosion/deposition, banks, sinuosity) and level of anthropogenic alteration (gabions, rip rap, restorations).

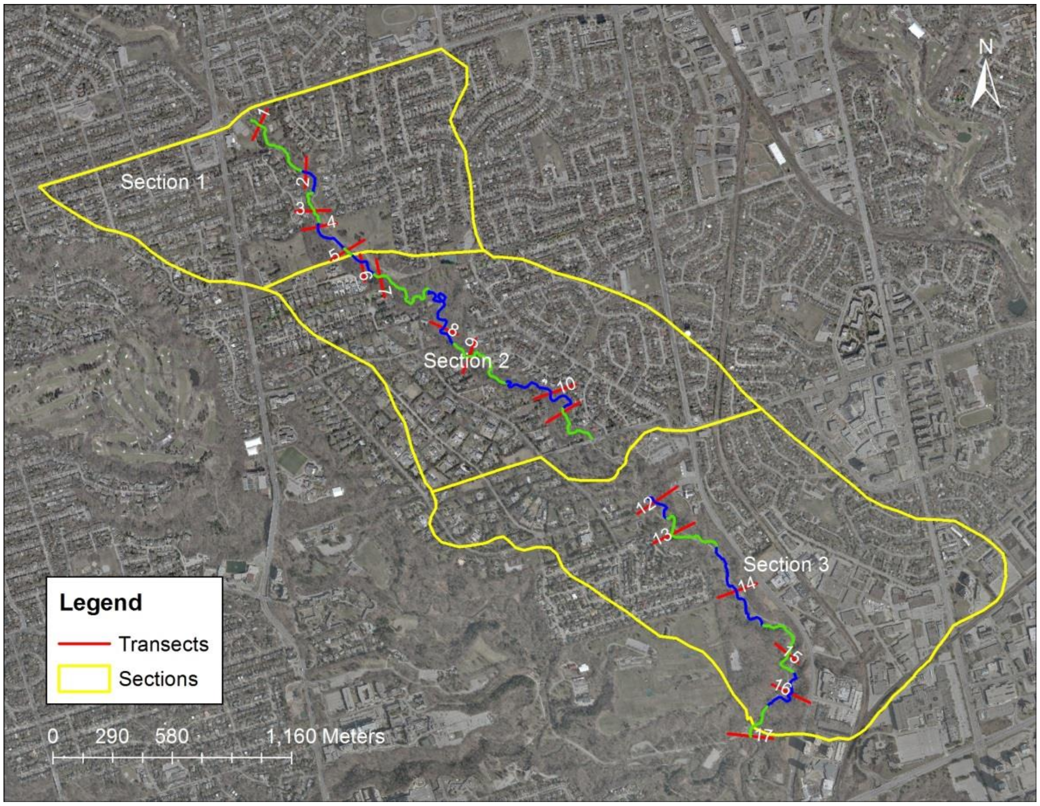


Figure 17. Zones of influence representative of given transects denoted by blue and green lines.

The lengths of the reaches representative of a given cross section were measured in ArcGIS and identified by the number of their respective cross section. The measured lengths were multiplied by changes in cross section area for the given periods of measurement and porosity to estimate volumetric change in sediment for each reach.

Volumetric sediment transport through Wilket Creek was estimated using Equation 3 per Martin and Church (1995). For explanation purposes the equation is given again below:

$$Q_o = Q_i - (1 - p)(\Delta S/\Delta t)$$

where Q_o is volumetric transport out of the reach, Q_i is volumetric transport into the reach, p is porosity, and Δt is the time between surveys. The term ΔS denotes volumetric change and can be determined through cross section surveys. If either Q_o or Q_i is known, the remaining term can be calculated. Once all of the terms are known at a particular reach, calculations can progress downstream or upstream with Q_o representing Q_i at the subsequent downstream reach and Q_i representing Q_o for the reach immediately upstream (Martin and Church 1995).

For the period between June and July, the dam in Windfields Park was closed and sediment transport out of Reach 4 was assumed to be zero. However, from July to November and June to November 2013, the dam at Windfields Park was not closed for the entire period. Consequently, there was no reach where a sediment transport rate of zero could be assumed. Therefore, two methods were used to determine a sediment transport rate that could serve as a starting point for calculations: i) sediment transport capacity and, ii) the results of the bathymetric survey.

The first method employed the Meyer-Peter Müller equation to assess sediment transport capacity throughout Wilket Creek. The purpose was to determine where it would be acceptable to assume sediment transport was zero. The Meyer-Peter Müller equation is a shear stress based approach to transport capacity and is most applicable to sediment sizes between 0.40 mm and 30 mm (Mays 2005). The equation can be formulated as (Gyr and Hoyer 2006, Julien 1995):

$$q_s = 8\sqrt{(G - 1)gD_s^3}\,(\tau_* - \tau_{*c})^{\frac{3}{2}} \tag{5}$$

where G equals 2.65 and is the specific gravity of quartz which is the predominant material in sand and gravel. Other terms include g which is the gravitational constant, D_s which is the particle size of interest, τ_* which is the Shields parameter and τ_{*c} which is the Critical Shields parameter. The Critical Shields parameter can be determined from the relevant literature while the Shields parameter is defined as:

$$\tau_* = \frac{\tau_o}{(G-1)\gamma_m D_s} \tag{6}$$

where τ_o is the bed shear stress which is defined as the specific weight of water (γ_m) multiplied by the hydraulic radius (R) and the slope (S). Employing this method, sediment transport at the top of bank discharge was estimated for the periods of July to November and June to November 2013 for all of the transects and two other selected locations.

The second method used the results of the bathymetric survey to calculate a sediment transport rate into Reach 4. With this term and the results of the cross section survey, calculations for volumetric sediment transport could proceed upstream and downstream.

3.4.2 Comprehensive Sediment Budget by Section

The comprehensive sediment budget assesses sediment inputs, outputs and storage terms for the three study sections of Wilket Creek. It was developed based on field observations over nearly two years and data collection between June and November 2013 (Table 2). Consequently, it relies on the results of the field study and estimation of volumetric sediment transport developed using the morphological approach.

Input terms were similar for all sections and included: i) output from the previous section (including the culvert at York Mills Road), ii) storm sewers/tributaries, iii) hillslope/valley wall erosion, and iv) bank erosion. Input from the culvert at York Mills Road was estimated using Equation 3 per the method previously described.

Contributions from storm sewers/tributaries were based on the output from the culvert at York Mills Road. The rate of sediment delivered from the culvert was divided by the area of the watershed resulting in rate per area (m^3/day/km^2). The areas of Sections 1, 2 and 3 were multiplied by this term to estimate a rate of sediment delivery (m^3/day) for all of the culverts in a section.

Hillslope/valley wall contributions were estimated from topographic maps and sediment yields given in the literature. Topographic maps and field observations of the study area were used to define areas in where the hillslope or valley wall was in direct contact with the creek. The sediment contributions were estimated by multiplying these areas by values of urban hillslope sediment production found in the literature (Table 7). As all of the estimates of hillslope production were many orders of magnitude smaller than other input terms, the largest estimate was used.

Table 7. Values of urban hillslope sediment production.

Authors	**tons/h/yr**	**kg/m^2/yr**	**m^3/m^2/yr**	**m^3/m^2/day**
Phillips 1991	0.49	0.049	0.000018	0.0000000507
Phillips 1991	1.14	0.114	0.000043	0.0000001179
Phillips 1991	0.88	0.088	0.000033	0.0000000910
Maniquiz et al 2009	1.52	0.152	0.000057	0.0000001571

The contribution of bank erosion was identical to the method of calculating volumetric change at the reach level. However, in this case, only the direct contribution of sediment from the bank areas was considered. Losses at the bed were not included as they represent pulses of sediment moving along the creek and not an actual input of sediment resulting from erosion at the bed.

Storage terms of the sediment budget include bank storage and storage behind the dam in Windfields Park and Edwards Garden. Temporary and permanent bank storage was calculated from bank storage pin measurements. Bank storage locations were identified in ArcGIS. The area of these locations was multiplied by the average burial depth of bank erosion pins and the time between pin measurements to determine a storage rate.

Storage in the dam at Windfields Park was calculated from the bathymetric survey. Estimating storage behind the dam in Edwards Gardens was more complicated because the sluice gate is routinely opened in response to anticipated rainfall events. However, the pond was dredged in March of 2014 with a total of 617 tons removed (City of Toronto Parks, Forestry and Recreation Personal Communication, 2014). Parks personnel also mentioned that the pond was previously dredged in 2007. Assuming a particle density of 2650 kg/m^3, a storage rate of 0.09 m^3/day was calculated.

4.0 Results

4.1 Aerial Imagery: Planform Analysis

Using aerial imagery from 1999, 2003 and 2009, the left and right banks were delineated in ArcGIS 10.1 and channel width calculated every five meters with the CPS tool. Channel width was plotted against distance downstream for the individual years to explore downstream trends in morphology (Figure 18 to Figure 20). In addition, all years were plotted in a single graph (Figure 21).

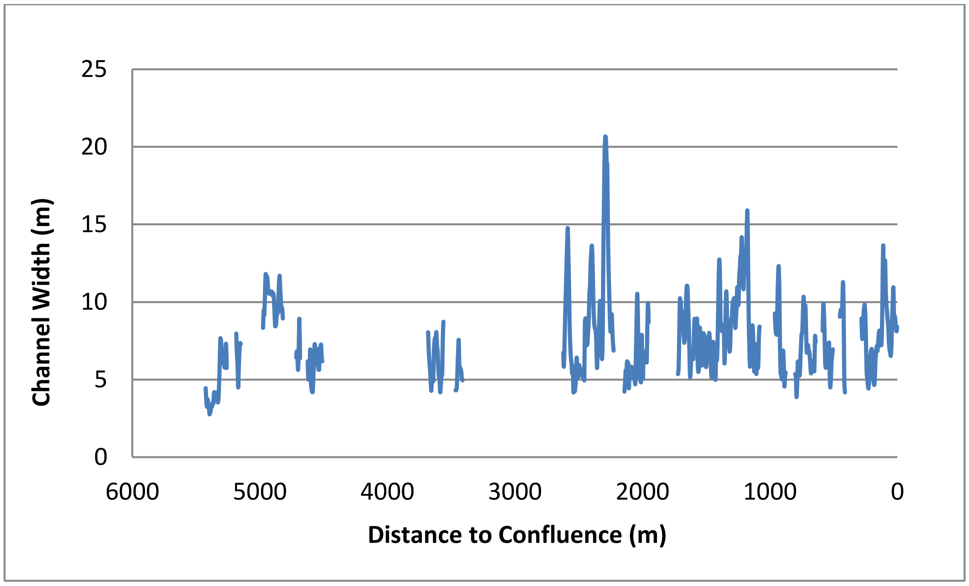


Figure 18. Channel width versus distance to confluence for 1999.

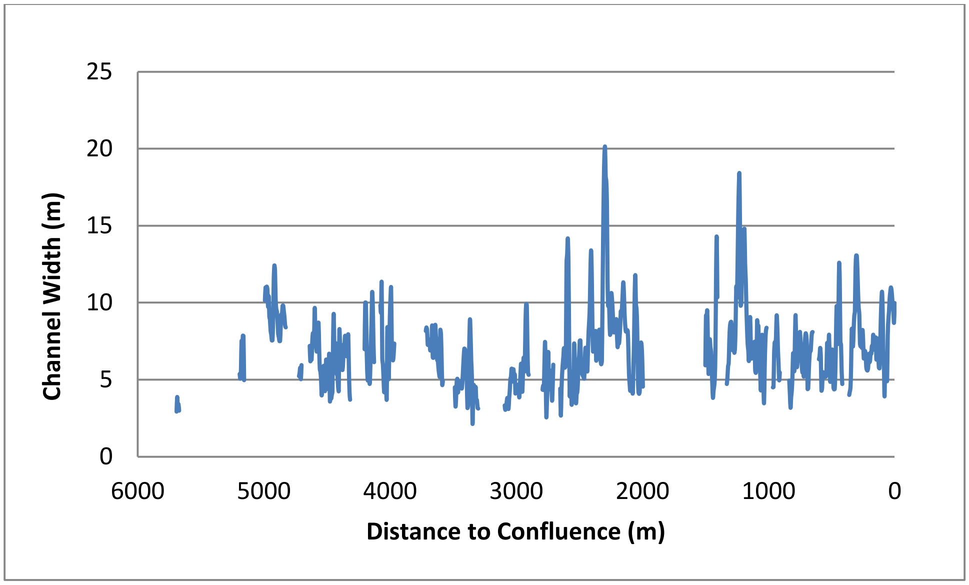


Figure 19. Channel width versus distance to confluence for 2003.

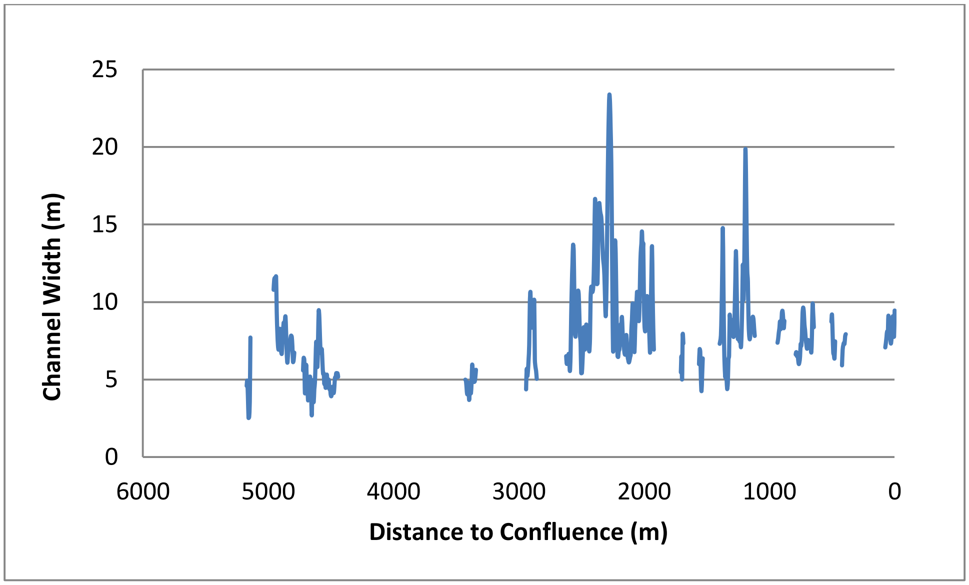


Figure 20. Channel width versus distance to confluence for 2009.

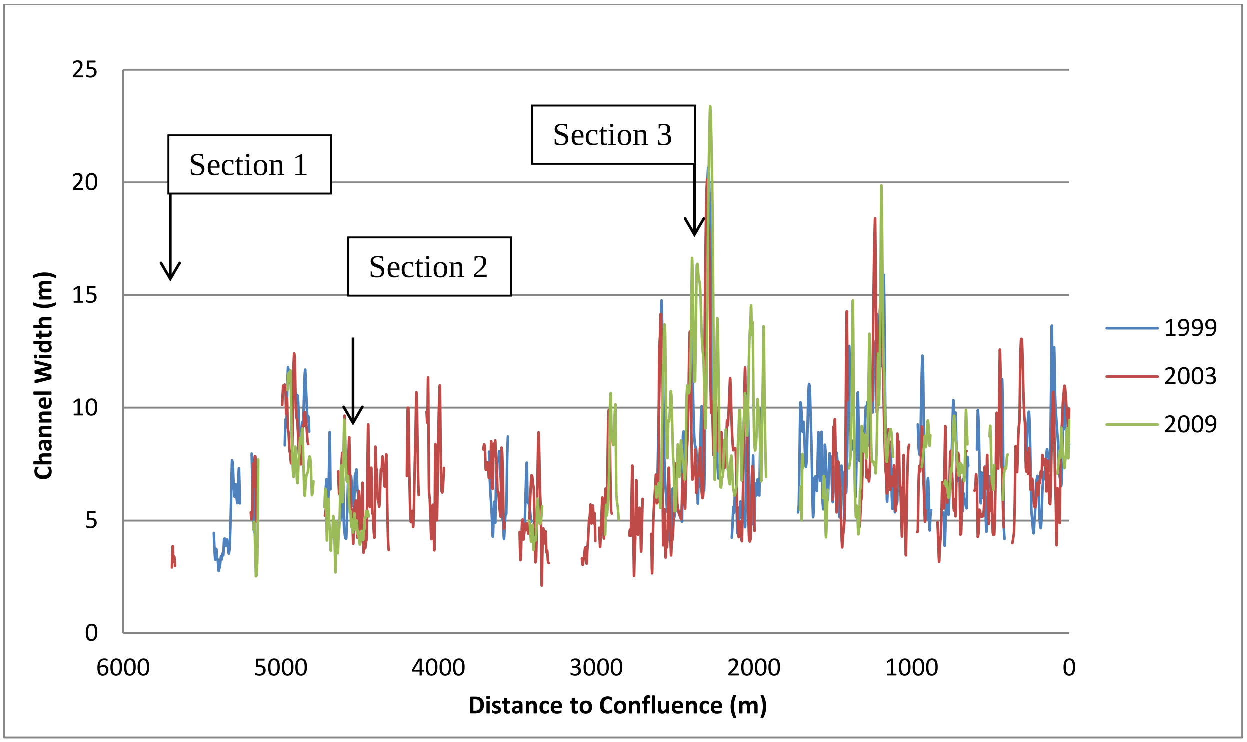


Figure 21. Channel width versus distance to confluence for 1999, 2003 and 2009.

A general observation from the figures above (Figure 18 to Figure 21) is that channel width is between 5 and 10 m throughout the length of Wilket Creek. Although, there are isolated instances of channel widening, particularly in Section 3, there is no strong trend towards downstream widening.

During the period from 1999 to 2009, two locations were consistently wider than other locations in the same section (Figure 21). The first of these is the area behind the dam in Windfields Park which roughly occurs between 4,850 m and 4,950 m upstream of the confluence. The second location is in the vicinity of Edwards Gardens where there is extensive channel alteration including a pond at an approximate distance of 2,260 m to 2,400 m above the confluence.

Areas of considerable widening between 1999 and 2003 occurred at approximately 1,415 m and 1,235 m above the confluence. At about 1,415 m, the creek passes under a bridge and makes a sharp bend. Channel erosion on the right bank is matched by a large gravel and cobble point bar on the left bank. A little further downstream 1,235 m, there has been extensive erosion on the right bank which is composed of sandy non-cohesive material. On the opposite side of the bank, gravel and cobble have been deposited near the channel. A little further inland from the channel, large amounts of sand have been deposited. As of 2013, this area was still experiencing significant erosion on the right bank and deposition on the left.

Between 2003 and 2009, slight widening continued to occur at the same locations; 1,415 and 1,235 m above the confluence. Additionally, a spike in channel width occurred approximately at 2026 m. This location is immediately upstream of a tributary where the channel has been artificially hardened.

Using banks characterized as "excellent" or "good" the average channel width for the entire length of Wilket Creek as well as for the individual sections was calculated (Table 8).

Table 8. Channel width for excellent and good bank characterization for the entire length of Wilket Creek and individual sections.

Section	**1999 Average Width (m)**	**2003 Average Width (m)**	**2009 Average Width (m)**
Entire	7.63	7.09	8.20
Section 1	7.24	8.21	7.41
Section 2	6.37	6.04	6.34
Section 3	8.08	7.74	9.35

The table shows that the along its entire length, Wilket Creek has experienced some widening between 1999 and 2009. Surprisingly, except for Section 1, the 2003 channel widths are narrower than 1999. However, it is important to note that this may be due to errors in delineating aerial imagery rather than a real physical difference. In both 1999 and 2009, the most downstream section (Section 3) is the widest. The most striking observation is that Section 2 is the narrowest in all years. This may be due to extensive alterations to the channel in Sections 1 and 3 while Section 2 is relatively unmodified.

As a check on the ArcGIS delineation process and widths generated by the CPS tool, active channel widths from the cross section surveys were compared to the channel widths from bank delineation. As Table 9 indicates, the ArcGIS channel delineation tended to overestimate channel width by an average of 50%. As a result, channel widths determined from ArcGIS analysis cannot be considered an accurate approximation of actual channel widths. However, it may be possible to compare channel widths between aerial imagery from different years to get a rough idea how channel width changes over time in response to urbanization.

Table 9. Comparison of ArcGIS channel widths to surveyed cross section widths.

Cross Section	June, 2013 Survey (m)	2009 Arc GIS 10.1 (m)	Percent Difference (%)
1	8.0	3.9	51
2	13.1	5.8	56
3	10.4	7.4	29
4	13.5	10.3	23
5	14.1	5.3	62
6	14.8	5.5	63
7	15.9	4.7	70
8	23.7	12.9	45
9	11.4	5.0	56
10	13.4	6.8	49
11	13.5	7.3	46
12	11.3	6.8	40
13	15.4	6.5	58
14	21.3	9.6	55
15	12.5	4.9	61
16	24.1	8.2	66
17	9.1	7.6	17
Average Percent Difference (%)			50

In contrast to the channel widths, the channel centerlines created by the CPS tool appear to be good approximations of the actual centerlines. This was confirmed by a visual inspection of CPS generated centerlines in ArcGIS. Using these centerlines, lateral movement was assessed with the CPS tool for the following time periods: 1999 – 2003, 2003 – 2009, 2009 – 2012 and 1999 – 2012. Only centerlines that were derived from banks classified as “excellent” or “good” were used in the assessment. Plots were made of lateral migration rate versus distance to the confluence (Figure 22 to Figure 25). No figures are given for lateral migration versus distance to the confluence as the patterns are identical. Note that values above zero indicate channel movement to the right of the original channel position and values below zero represent channel movement to the left.

A visual inspection of the CPS generated channel centerlines indicated that they provided an acceptable depiction of the center of the channel for the respective years. Therefore, unlike the channel width estimates determined using ArcGIS, the channel centerlines appear reasonable.

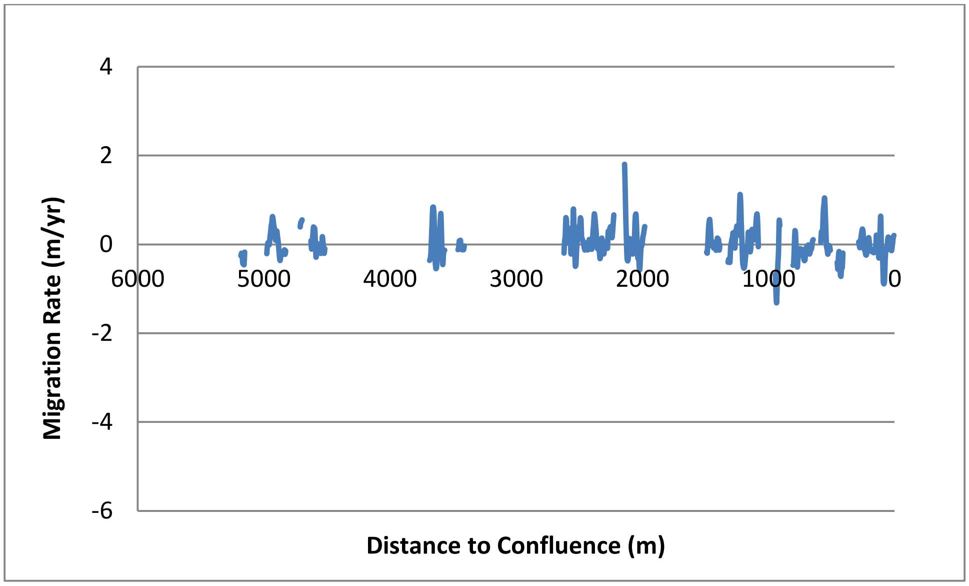


Figure 22. Channel lateral migration rate versus distance to confluence for the years 1999-2003.

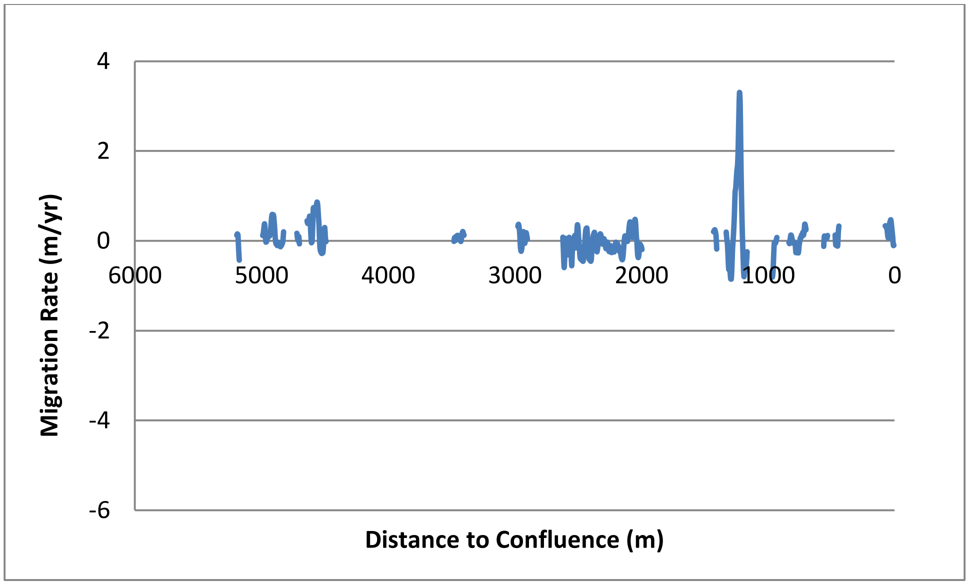


Figure 23. Channel lateral migration rate versus distance to confluence for the years 2003-2009.

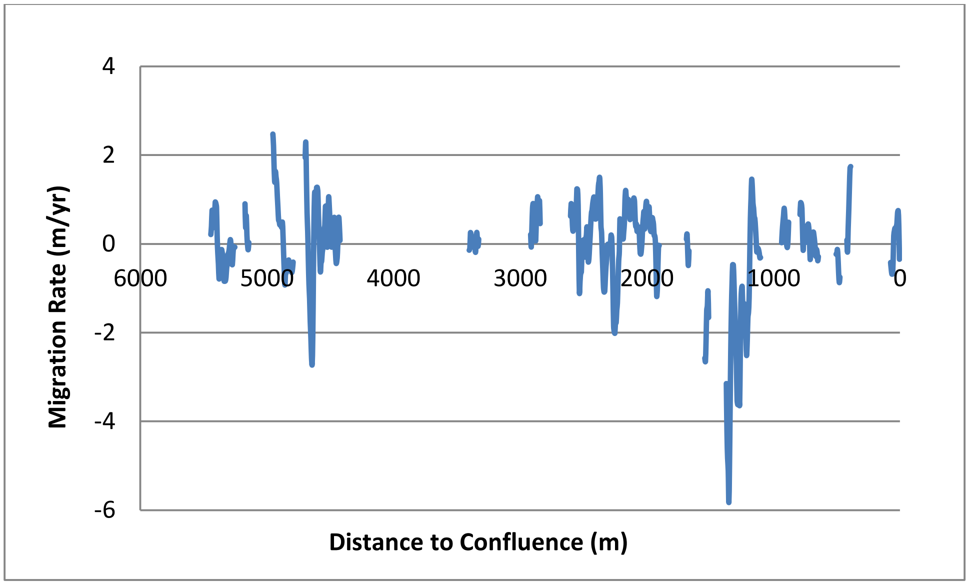


Figure 24. Channel lateral migration rate versus distance to confluence for the years 2009-2012.

In general, the period between 1999 and 2003 (Figure 22) shows greater fluctuations than the period from 2003 to 2009 (Figure 23) which is distinguished by a large spike at about 1,225 m above the confluence. More interesting is Figure 24, which indicates that 2009 to 2012 was the most active period in Wilket Creek.

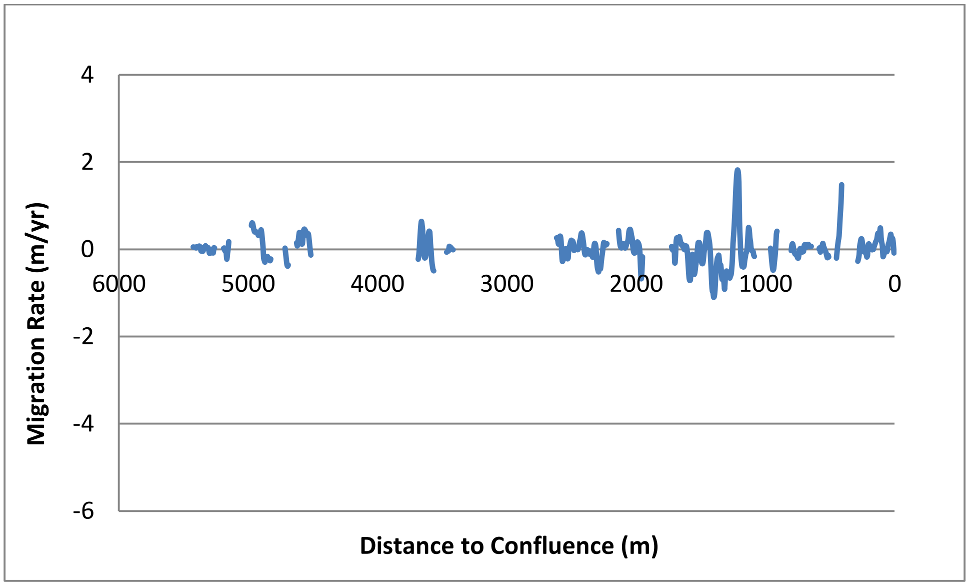


Figure 25. Channel lateral migration rate versus distance to confluence for the years 1999-2012.

The rates of lateral migration between 1999 and 2012 (Figure 25) are relatively subdued compared to the period from 2009 to 2012 (Figure 24). This may be because positive and negative fluctuations about the original centerline position "average out" over longer periods of time.

Average, maximum and minimum migration distances (Table 10) and rates (Table 11) were estimated for the entire creek and individual sections. Migration distances and rates contain both positive and negative values. Negative values indicate that lateral displacement was to the left of the baseline (earliest) year. Positive values indicate displacement to the right. Therefore, maximum lateral migration represents movement of the channel to the right and minimum lateral migration represents movement to the left.

Table 10. Lateral migration distances between 1999 and 2012.

Time Period		**Section 1**	**Section 2**	**Section 3**	**Entire**
1999 - 2003	Mean (m)	-0.056	0.300	-0.003	0.09
	Minimum (m)	-1.842	-2.191	-5.255	-5.255
	Maximum (m)	2.498	3.359	7.218	7.218
2003 - 2009	Mean (m)	0.642	0.208	0.572	0.43
	Minimum (m)	-2.568	-3.565	-5.092	-5.092
	Maximum (m)	3.541	5.184	19.819	19.819
2009 - 2012	Mean (m)	0.277	0.299	-0.848	-0.23
	Minimum (m)	-2.784	-8.148	-17.496	-17.496
	Maximum (m)	7.426	6.857	5.229	7.426
1999 - 2012	Mean (m)	0.869	0.457	-0.048	0.221
	Minimum (m)	-3.841	-6.729	-14.289	-14.289
	Maximum (m)	7.854	8.302	23.607	23.607

As shown in Table 10, the most active time period in regards to single instances of lateral migration is 2003 and 2009. An interesting point to note is that over all time periods Section 3 has typically experienced the largest instances of lateral movement. Table 11 which depict rates of migration shows essentially the same patterns as Table 10.

Table 11. Lateral migration rates between 1999 and 2012.

Time Period		Section 1	Section 2	Section 3	Entire
1999 -2003	Mean (m/yr)	-0.014	0.075	-0.001	0.023
	Minimum (m/yr)	-0.461	-0.548	-1.314	-1.314
	Maximum (m/yr)	0.625	0.840	1.805	1.805
2003 - 2009	Mean (m/yr)	0.107	0.035	0.095	0.071
	Minimum (m/yr)	-0.428	-0.594	-0.849	-0.849
	Maximum (m/yr)	0.590	0.864	3.303	3.303
2009 - 2012	Mean (m/yr)	0.092	0.100	-0.283	-0.076
	Minimum (m/yr)	-0.928	-2.716	-5.832	-5.832
	Maximum (m/yr)	2.475	2.286	1.743	2.475
1999 - 2012	Mean (m/yr)	0.067	0.035	-0.004	0.017
	Minimum (m/yr)	-0.295	-0.518	-1.099	-1.099
	Maximum (m/yr)	0.604	0.639	1.816	1.816

Table 11 shows that Wilket Creek underwent the most adjustment between 2009 and 2012 and that Section 3 was the most active. Over the period 1999 to 2012 the largest mean rate of lateral migration took place from 2009 to 2012. Furthermore, over every time period the largest absolute rates of lateral migration occurred in Section 3. These findings are corroborated by field observations, erosion pins and transect surveys.

4.2 Streambed Composition

To begin the analysis of streambed composition, the cumulative frequency of sediment particle sizes was plotted for each location. As the sediment at York Mills Road (S1 A) consisted predominantly of fine gravel and sand, a volumetric sample was obtained. All other samples consisted of pebble counts. Figure 26 illustrates the grain size distribution for the main channel of Wilket Creek.

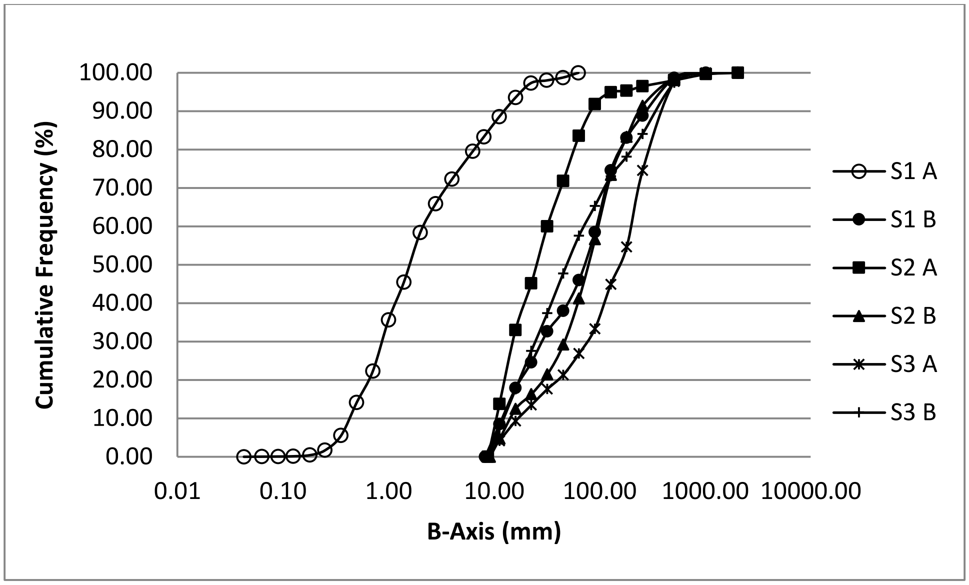


Figure 26. Cumulative frequency of grain sizes at five sites in the main channel of Wilket Creek.

The sediment entering Wilket Creek at York Mills Road is much finer than the other locations sample (Figure 26). Additionally, the most downstream site is finer than a number of sites located upstream. To more clearly illustrate the differences, one graph was made for the main channel in Sections 1 and 2 (Figure 27). Another graph was made for Section 3 which includes samples from the main channel as well as two tributaries (Figure 30).

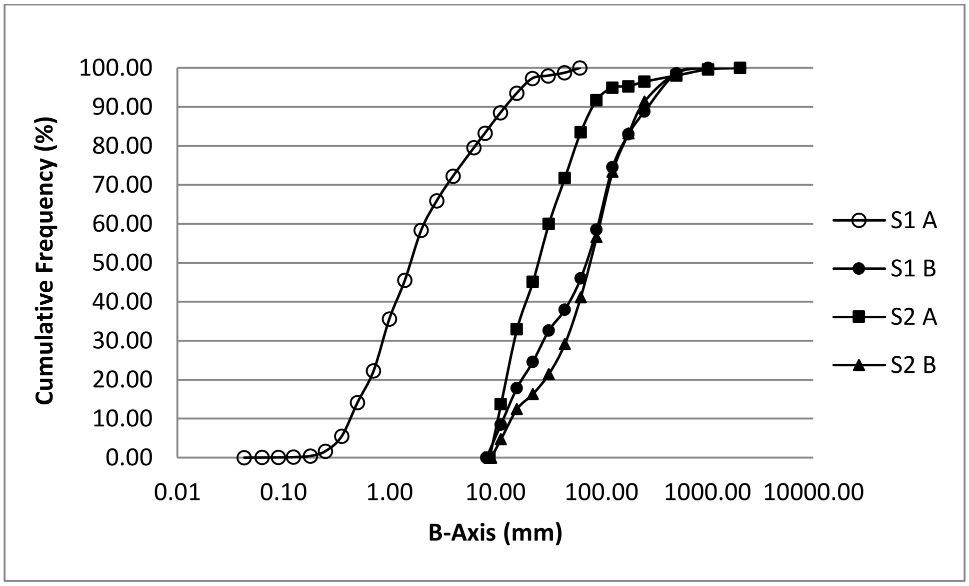


Figure 27. Cumulative frequency of grain sizes at three sites in Sections 1 and 2 of the main channel of Wilket Creek.

Although sites S1 B and S2 B have bed material that is very similar, the origin is very different. The channel at the upstream location of S1 B is modified with rip rap, some of which has fallen into the channel contributing to the bed composition (Figure 28) while the banks and bed at location S2 B are composed primarily of natural material. Regarding the relatively fine bed material at S2 A, this site is located downstream of a dam that is operated seasonally and traps sediment for about six months of the year. Additionally, the right bank at this site (which is located at Transect 7) is composed of fine material with overhanging banks which occasionally slump into the channel (Figure 29).

Figure 28. Site conditions at S1 A illustrating rip rap on the left bank which has migrated into the channel.

Figure 29. Right bank in area of S2 A composed of fine sediment that is actively eroding into the channel.

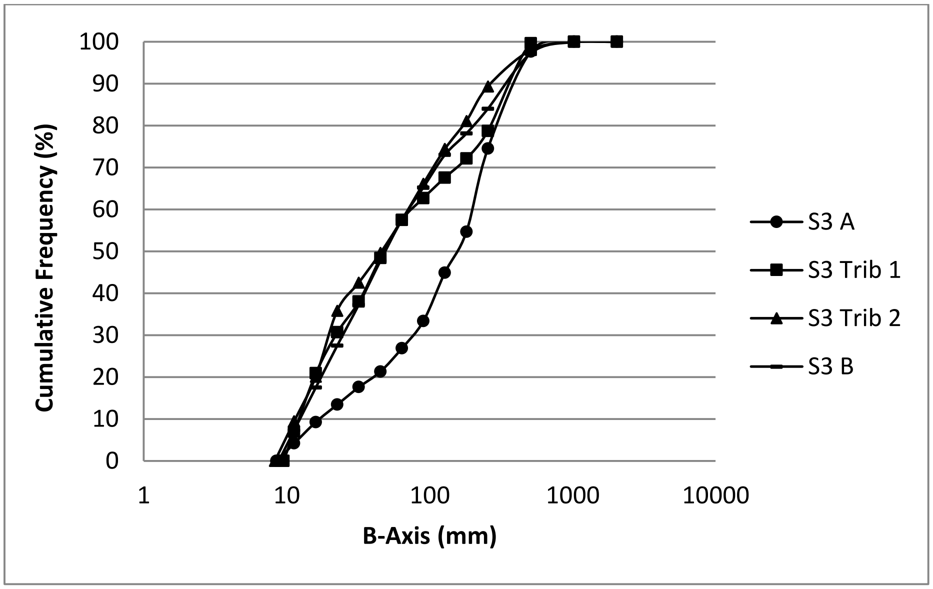


Figure 30. Cumulative frequency of grain sizes in Section 3 of Wilket Creek.

Urban streams may often experience downstream coarsening of the bed (Chin 2006, Hawley et al 2013). However, as shown in Figure 30, the coarsest site in Section 3 (S3 A) was furthest upstream. This site is located just downstream of the dam in Edwards Garden and the bed and banks have been re-enforced with boulder sized sediment added as part of a restoration in 2005

(Figure 31). Downstream, two tributaries (S3 Trib 1 and S3 Trib 2) issue from culverts and contribute material to Wilket Creek very similar to that found near the confluence (S3 B).

Figure 31. Wilket Creek near pebble count Site S3 A showing engineered banks with large particles sizes.

The b-axes of the various particle size percentiles ($D_{\#}$) were compared by site (Table 12). Representative particle sizes were then plotted against distance downstream to picture how particle size changes with longitudinal location (Figure 32). Particle size was found to be smaller in low gradient areas while larger particle size corresponded to steeper slopes and locations where the bank or bed has been engineered.

Table 12. B-axis measurement for sediment size classes in the main channel of Wilket Creek.

Sediment Class	S1 A	S1 B	S2 A	S2 B	S3 A	S3 B
D5	0.3	9.9	9.6	11.4	12.0	10.4
D10	0.4	12.0	10.6	14.3	17.0	12.4
D16	0.5	14.9	11.8	22.0	28.0	15.2
D25	0.8	23.0	13.9	37.5	57.0	20.7
D50	1.6	71.5	25.3	78.0	153.5	49.0
D75	4.7	130.4	49.8	135.4	259.6	146.0
D84	8.4	191.7	65.3	186.8	339.9	254.8
D90	12.4	277.9	84.0	241.0	406.8	348.8
D95	18.2	395.4	139.6	359.8	472.4	452.9

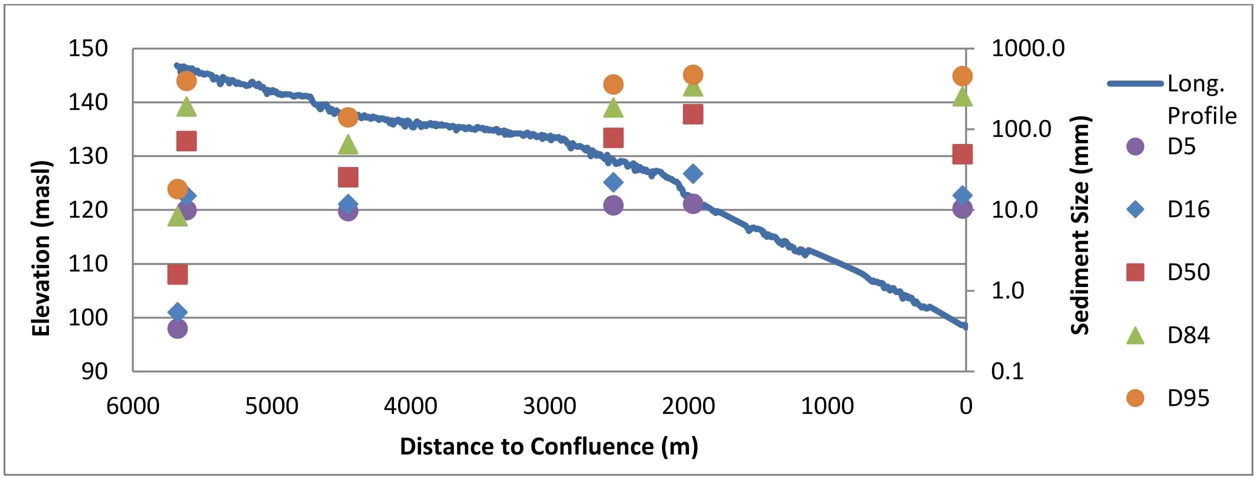


Figure 32. Size of D_5, D_{16}, D_{50}, D_{84} and D_{95} particle size classes with distance along stream.

4.3 Cross Sections

Surveyed data from the cross sections were plotted on graphs to illustrate the change in cross section area and width over time (Figure 33 to Figure 40).

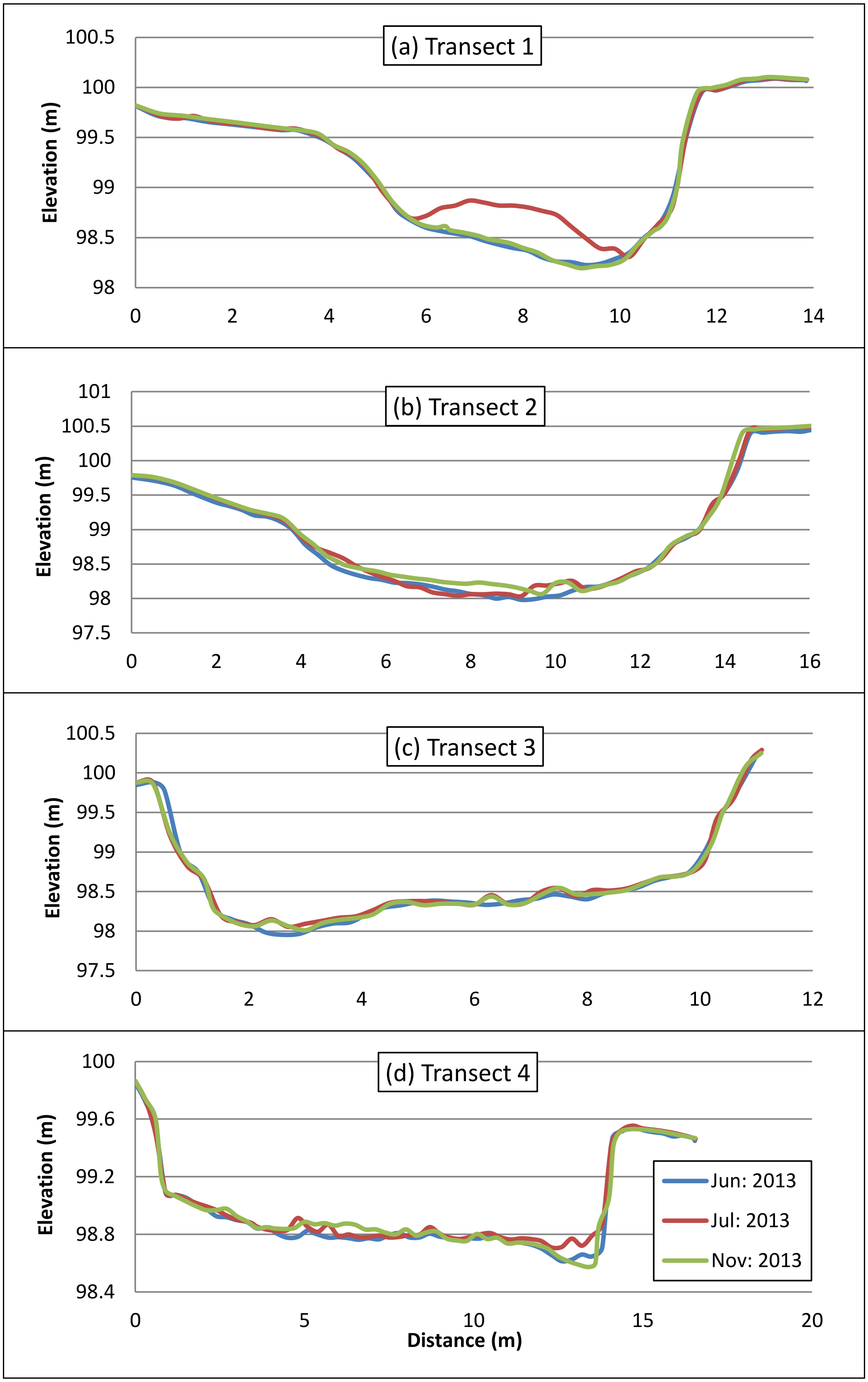


Figure 33. Cross sectional surveys of transects located in Section 1a between June and November 2013.

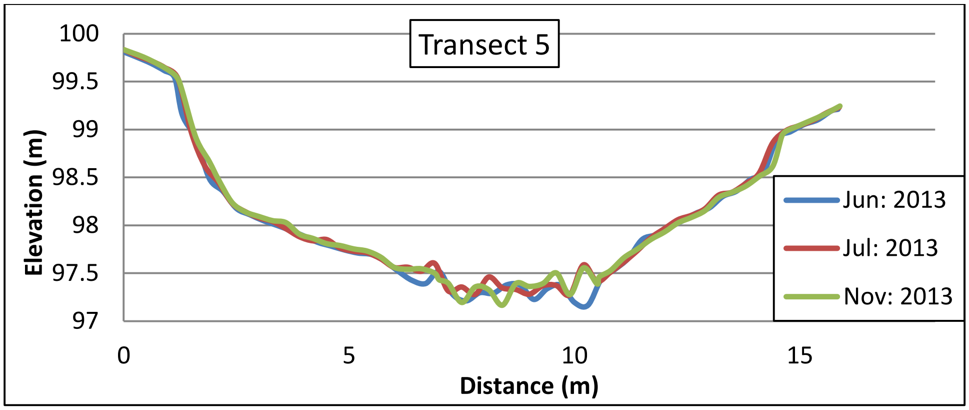


Figure 34. Cross sectional surveys of Transect 5 in Sub-Section 1b conducted between June and November 2013.

The transects from Section 1 show little change with the exception of Transect 1 located in Sub-Section 1a (Figure 33). At this transect, sediment was deposited on the bed between the June and July surveys. By November, this sediment had been washed downstream. A visual inspection of the channels in this section indicates that extensive widening occurred in the past. During the study, some channel erosion was evident, primarily on the left bank in some reaches in Windfields Park. However, little or no bank erosion occurred at established transects. Overall, Section 1 exhibits less bank erosion along its length compared to the other sections.

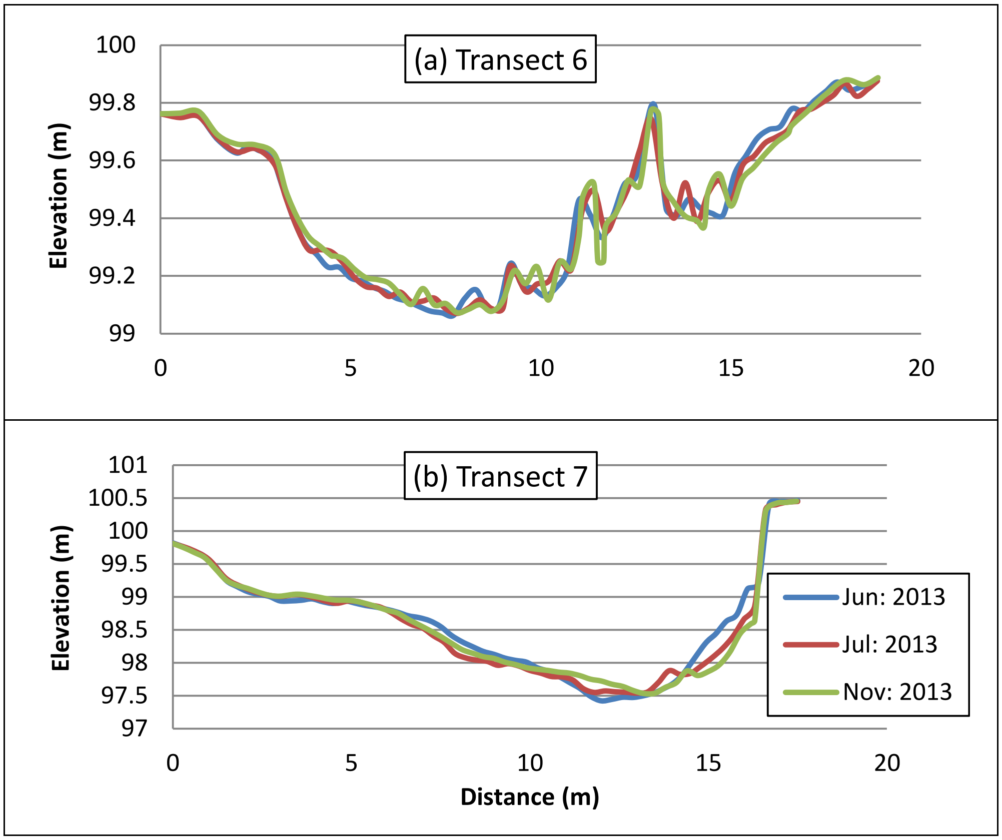


Figure 35. Cross sectional surveys of transects located in Section 2a between June and November 2013.

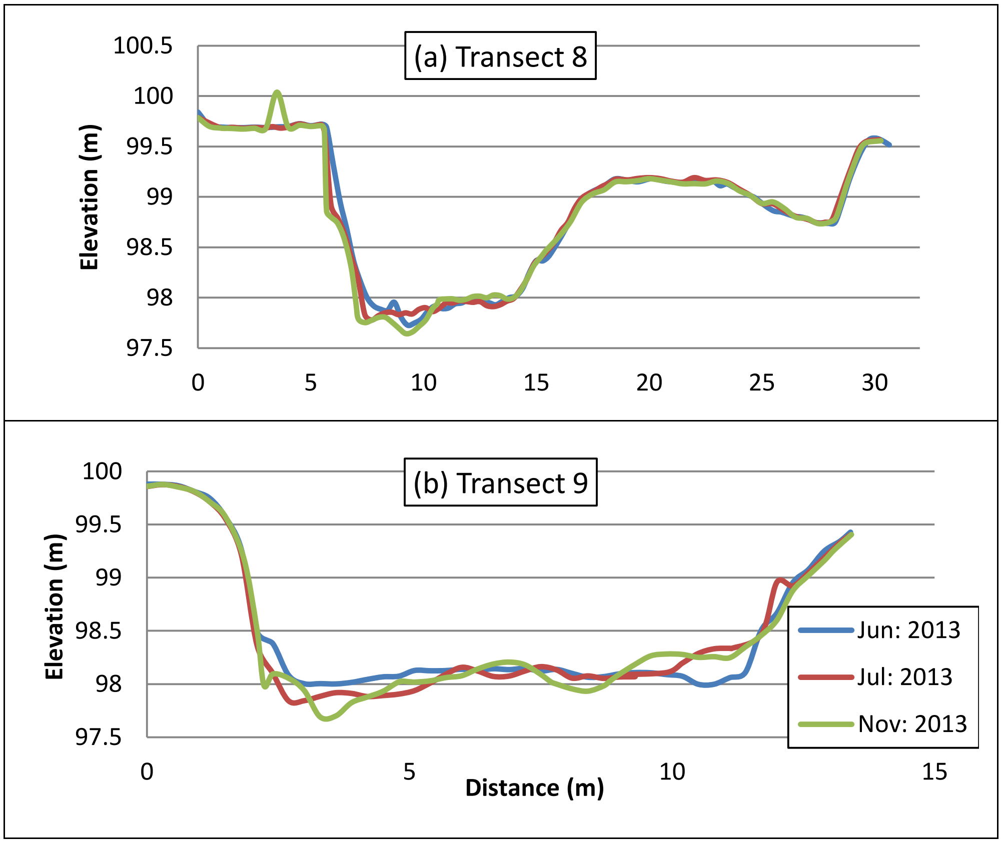


Figure 36. Cross sectional surveys of transects located in Section 2b between June and November 2013.

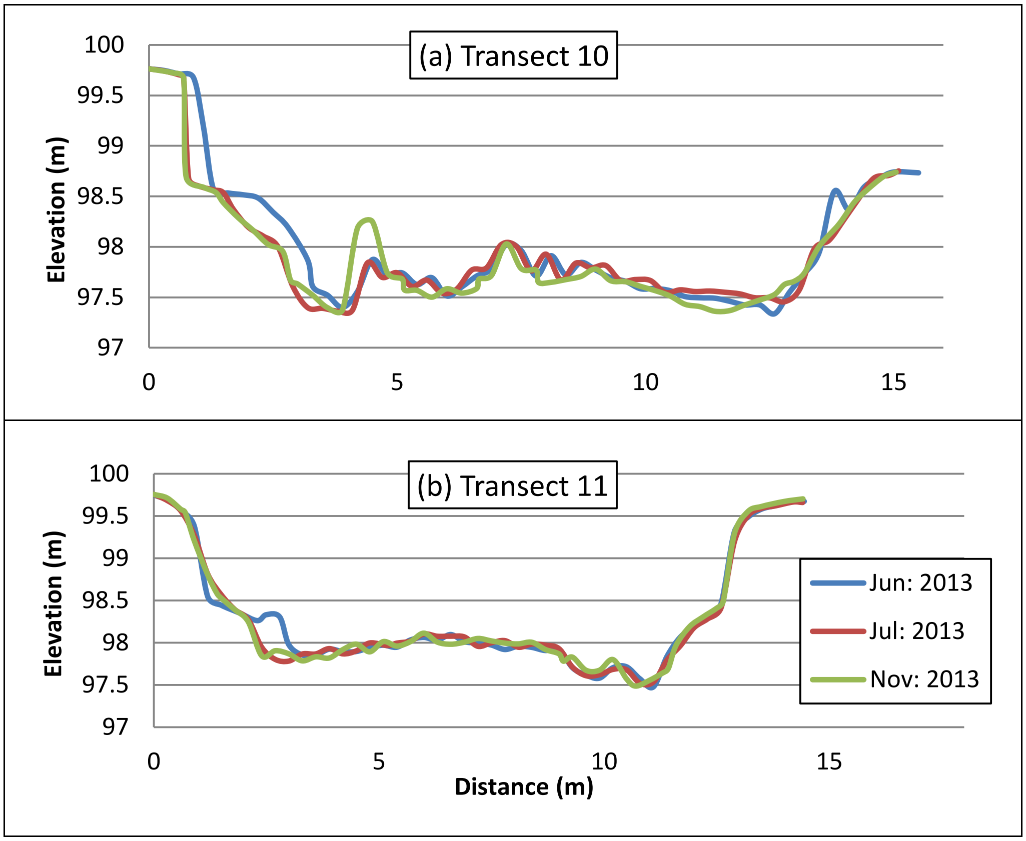


Figure 37. Cross sectional surveys of transects located in Section 2c between June and November 2013.

Transects in Section 2 exhibit some bank erosion, particularly on the outside of pools. Within the sinuous reach (Section 2b), erosion on the outer bank is often matched by deposition on the inner bank (Figure 36). However, in the regions of Transects 7 and 10, excessive erosion is occurring on one bank with little or no deposition on the opposite bank. Both of these transects occur in sub-sections where there is an increase in slope. Transect 7 is located at the end of Sub-Section 2a, where the slope is 2.7 % (Figure 35). Although it is located in the same sub-section, Transect 6 experienced little bank erosion as it is located in the riffle-pool restoration and its banks are hardened and very shallow. Transect 10 is located immediately downstream of the break in slope corresponding to Sub-Section 2c and has experienced ongoing erosion on the right bank (Figure 37). Although field measurements occurred between June and November of 2013, field observations and conversations with the property owner suggest that erosion has been ongoing at this location over several years (Figure 38). A field visit on 7 May 2014 revealed that extensive erosion occurred at these locations since the previous November.

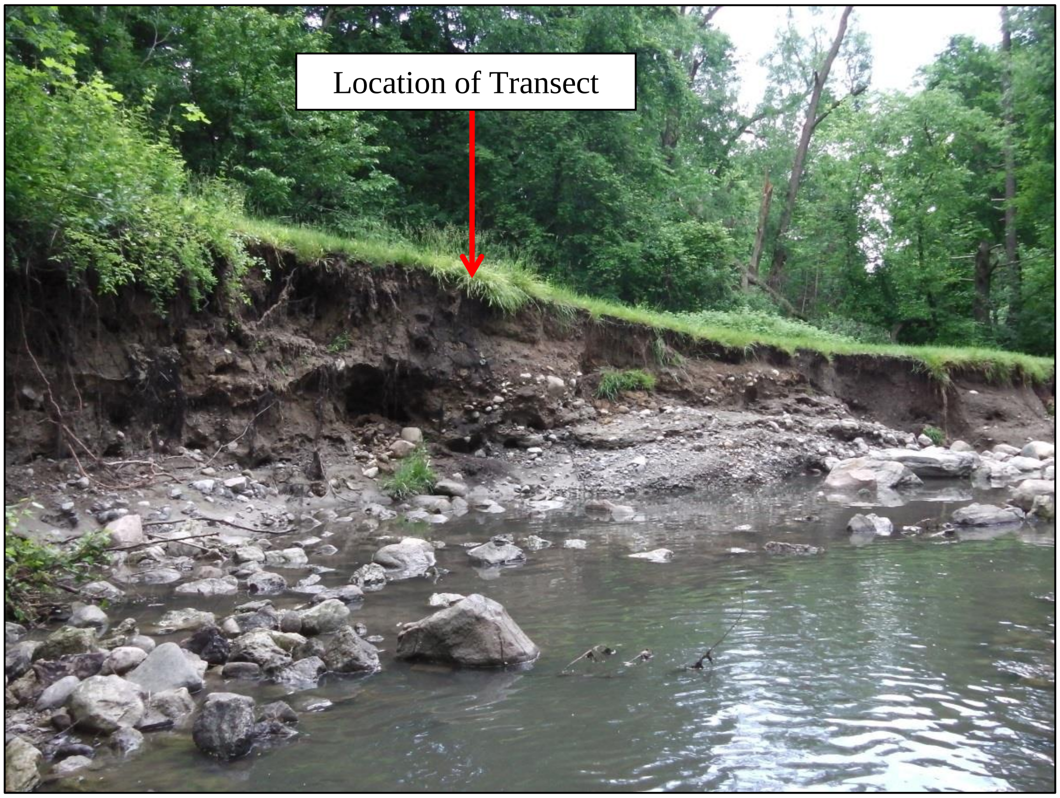


Figure 38. Erosion on the left bank of Transect 10.

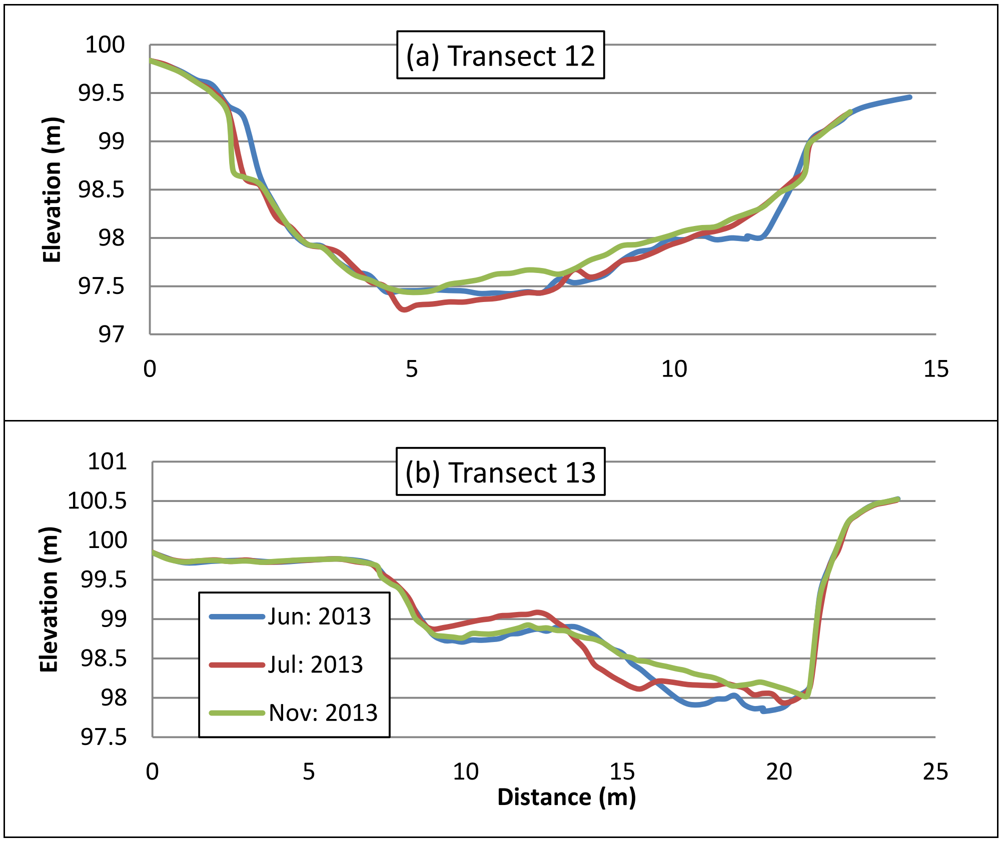


Figure 39. Cross sectional surveys of transects located in Section 3b between June and November 2013.

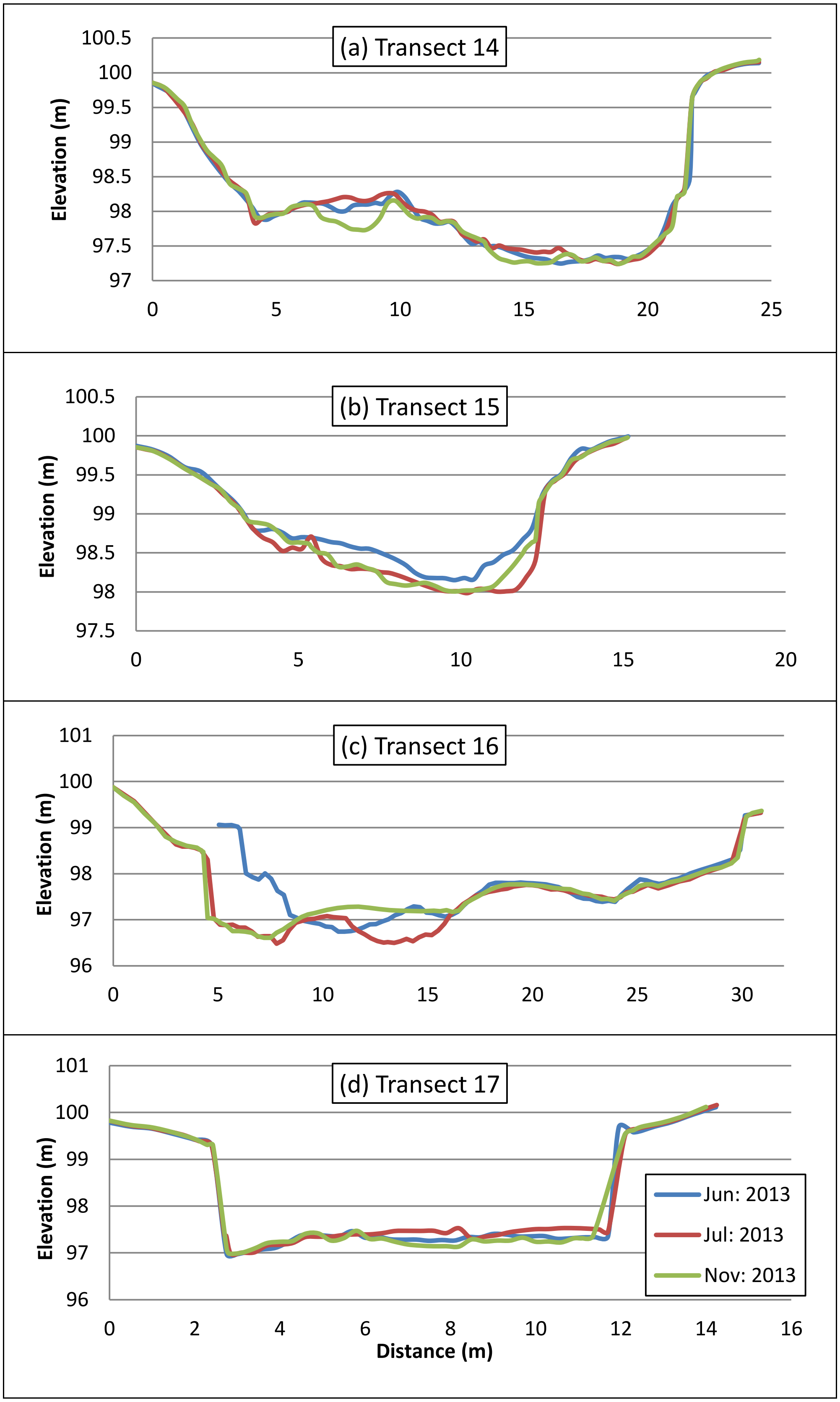


Figure 40. Cross sectional surveys of transects located in Section 3c between June and November 2013.

Throughout Section 3, transects are characterized by periodic deposition of sediment in the channel that is subsequently washed downstream. This is particularly evident at Transects 12, 13, 15 and 16 (Figure 39 and Figure 40). In the case of Transect 12, much of the sediment washed into this area likely comes from the dam in Edwards Garden as the channel between these two sections is very steep and the banks have been hardened and show very little signs of erosion.

Much of the sediment in Section 3c appears to come from bank erosion, which is extensive in the region (Figure 40). Unfortunately, the bank erosion that occurs in this section is only captured by Transect 16, which experienced nearly four meters of bank erosion between June and November. Between, June 2013 and May 2014, bank erosion similar to Transect 16 was observed between the 2012 restoration and Transect 14 and approximately 65 m upstream of the confluence.

Bankfull and top of bank metrics were calculated for June, July and November for each transect (Table 13 and Table 14). Table 13 indicates that there was a general decrease in bankfull area in Section 1 of Wilket Creek between June and November. In contrast, the trend in Sections 2 and 3 is towards an increase in bankfull area during the same period. A definite trend regarding change in width by section between June and November is not especially notable. The main exception is Transect 16 which increased its width by 3.8 m between the June and November surveys. Throughout most of Wilket Creek, a significant (> 5cm) increase in bankfull depth was not observed. Greater changes in depth occurred in Section 3 but an inclination towards erosion and deposition was not observed as two sites had a decrease in depth (Transects 12 and 13), two sites had an increase (Transects 14 and 15), and two sites (Transects 16 and 17) did not experience a change greater than 5.0 cm. As with bankfull depth, scour/deposition depth did not exhibit major changes between June and November. The table shows that there is only a single example of scour/deposition depth greater than 5 cm in both Sections 1 and 2 (Transects 2 and 10). Section 3 appears to be more active with two transects in the upper region (Transects 12 and 13) experiencing deposition and three transects in the lower region (Transects 14, 15 and 16) experiencing scour. Measurements for top bank metrics (Table 14) show a pattern very similar to bankfull metrics.

Table 13. Bankfull (BF) areas, widths, depths and, scour/deposition depth from June, July and November 2013 Surveys.

Transect	**Sub-Section**	**BF Area 2013 (m^2)**			**BF Width 2013 (m)**			**BF Depth 2013 (m)**			**Scour/Deposition Depth (m)**		
		Jun	**Jul**	**Nov**	**Jun**	**Jul**	**Nov**	**Jun**	**Jul**	**Nov**	**Jun-Jul**	**Jul-Nov**	**Jun-Nov**
1	1a	2.39	1.08	2.37	5.76	5.83	5.79	0.42	0.19	0.41	0.22	-0.22	0
2	1a	8.45	8.02	7.67	10.29	10.09	10.05	0.82	0.79	0.76	0.04	0.04	0.08
3	1a	8.2	7.93	8.06	9.53	9.65	9.67	0.86	0.82	0.83	0.03	-0.01	0.01
4	1a	8.01	7.51	7.4	13.4	13.41	13.45	0.6	0.56	0.55	0.04	0.01	0.05
5	1b	6.4	6.01	6.03	10.74	10.65	10.67	0.6	0.56	0.56	0.04	0	0.03
6	2a	5.29	5.23	5.22	14.81	15.22	15.19	0.36	0.34	0.34	0	0	0
7	2a	9.08	9.83	9.72	11.97	12.14	11.76	0.76	0.81	0.83	-0.06	0.01	-0.05
8	2b	6.71	6.81	7.11	9.87	10.05	10.25	0.68	0.68	0.69	-0.01	-0.03	-0.04
9	2b	3.86	4.09	4.11	9.6	9.68	9.7	0.4	0.42	0.42	-0.02	0	-0.03
10	2c	9.63	10.2	10.44	12.73	12.88	13.06	0.76	0.79	0.8	-0.04	-0.02	-0.06
11	2c	6.98	7.18	7.2	11.46	11.19	11.28	0.61	0.64	0.64	-0.02	0	-0.02
12	3b	9.59	9.61	8.66	10.3	10.73	10.91	0.93	0.9	0.79	0	0.09	0.09
13	3b	7.31	6.61	5.85	12.65	12.78	12.83	0.58	0.52	0.46	0.05	0.06	0.11
14	3c	9.11	8.64	10.19	17.75	17.55	17.52	0.51	0.49	0.58	0.03	-0.09	-0.06
15	3c	7.36	9.49	8.88	10.02	10.11	10.06	0.73	0.94	0.88	-0.21	0.06	-0.15
16	3c	5.12	9.46	6.48	16.27	19.76	20.07	0.31	0.48	0.32	-0.22	0.15	-0.07
17	3c	4.25	3.49	4.47	9.11	9.11	9.11	0.47	0.38	0.49	0.08	-0.11	-0.02

Table 14. Top of bank (TOB) areas, widths, depths and, scour/deposition depth from June, July and November 2013 Surveys.

Transect	**Sub-Section**	**TOB Area 2013 (m^2)**			**TOB Width 2013 (m)**			**TOB Depth 2013 (m)**			**Scour/Deposition Depth (m)**		
		Jun	**Jul**	**Nov**	**Jun**	**Jul**	**Nov**	**Jun**	**Jul**	**Nov**	**Jun-Jul**	**Jul-Nov**	**Jun-Nov**
1	1a	7.00	5.75	7.00	7.97	7.86	7.79	0.88	0.73	0.90	0.16	-0.16	0.00
2	1a	14.11	13.55	13.19	13.10	12.90	12.78	1.08	1.05	1.03	0.04	0.03	0.07
3	1a	14.31	14.12	14.24	10.35	10.40	10.35	1.38	1.36	1.38	0.02	-0.01	0.01
4	1a	8.82	8.38	8.55	13.45	13.55	13.58	0.66	0.62	0.63	0.03	-0.01	0.02
5	1b	17.40	16.95	16.98	14.10	13.98	13.89	1.23	1.21	1.22	0.03	0.00	0.03
6	2a	5.29	5.23	5.23	14.81	15.22	15.19	0.36	0.34	0.34	0.00	0.00	0.00
7	2a	20.16	20.83	20.74	15.93	15.89	15.98	1.27	1.31	1.30	-0.04	0.01	-0.04
8	2b	20.67	20.74	21.41	23.66	23.71	23.84	0.87	0.87	0.90	0.00	-0.03	-0.03
9	2b	12.34	12.56	12.68	11.38	11.47	11.50	1.09	1.09	1.10	-0.02	-0.01	-0.03
10	2c	11.52	12.13	12.37	13.44	13.80	13.97	0.86	0.88	0.89	-0.04	-0.02	-0.06
11	2c	19.63	19.82	19.80	13.51	13.58	13.28	1.45	1.46	1.49	-0.01	0.00	-0.01
12	3b	14.97	15.16	14.26	11.31	11.54	11.60	1.32	1.31	1.23	-0.02	0.08	0.06
13	3b	15.76	15.01	14.36	14.38	14.42	14.38	1.10	1.04	1.00	0.05	0.05	0.10
14	3c	38.16	37.50	38.99	21.34	21.31	21.22	1.79	1.76	1.84	0.03	-0.07	-0.04
15	3c	12.20	14.44	13.81	12.45	12.86	12.93	0.98	1.12	1.07	-0.17	0.05	-0.12
16	3c	35.92	44.83	41.79	24.10	27.86	27.98	1.49	1.61	1.49	-0.32	0.11	-0.21
17	3c	4.25	3.49	4.47	9.11	9.11	9.11	0.47	0.38	0.49	0.08	-0.11	-0.02

In a subsequent analysis, ArcGIS was used to assess erosion and deposition at each transect in greater detail for the periods from June to July, July to November and June to November (Table 15). The results of this analysis were similar to the AutoCAD findings (Table 13 and Table 14). From June to July, the trend in Section 1 was towards deposition while Section 2 was uniformly experiencing erosion. In Section 3, there were areas of both deposition and erosion with an extremely large erosion event occurring at Transect 16. Between July and November, there is not a clear pattern as erosion and deposition occurs in each Section. However, there are two interesting points to note. At Transect 1, almost all of the sediment that was deposited on the bed between June and July had been washed downstream. Transect 16, which previously experienced extensive of erosion on its left bank, had a large amount of sediment deposited on the right side of the channel. Over the longer term (June to November), the trends were similar to the period between June and July with the responses being somewhat muted.

Table 15. Erosion/deposition calculated from ArcGIS analysis.

		Net Erosion/Deposition (m^2)		
Transect	**Sub-Section**	**Jun-Jul**	**Jul-Nov**	**Jun-Nov**
1	1a	1.404	-1.202	0.203
2	1a	0.709	0.458	1.168
3	1a	0.183	-0.040	0.106
4	1a	0.457	-0.170	0.286
5	1b	0.483	-0.037	0.445
6	2a	-0.041	0.093	0.051
7	2a	-0.653	0.096	-0.557
8	2b	-0.255	-0.734	-0.987
9	2b	-0.244	-0.108	-0.352
10	2c	-0.979	-0.257	-1.236
11	2c	-0.237	0.068	-0.168
12	3b	-0.233	0.870	0.637
13	3b	0.656	0.621	1.276
14	3c	0.699	-1.470	-0.771
15	3c	-2.288	0.650	-1.638
16	3c	-9.124	3.072	-6.051
17	3c	0.680	-0.612	0.067
Total		-8.781	1.298	-7.520
Mean		-0.517	0.076	-0.442

To illustrate how net erosion or deposition varied with slope and distance downstream in Wilket Creek, net erosion/deposition was plotted along with the longitudianal profile. The time periods plotted were June to July, 2013 (Figure 41), July to November, 2013 (Figure 42) and June to November 2013 (Figure 43).

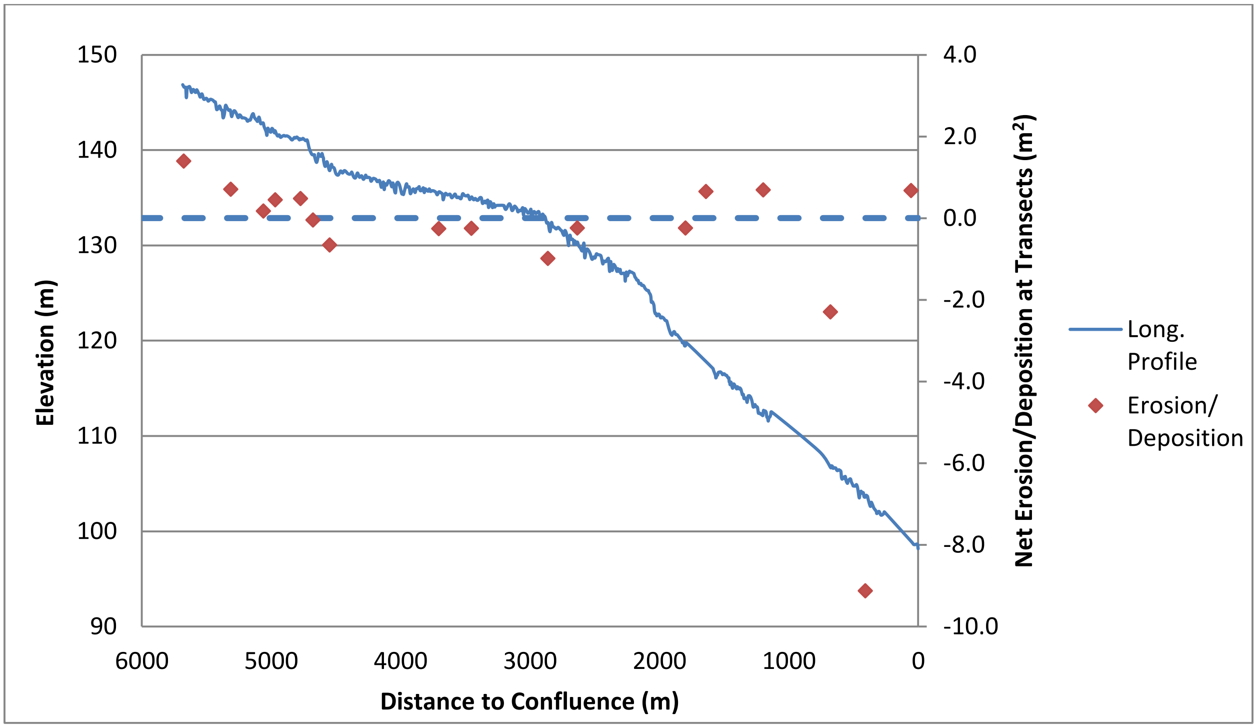


Figure 41. Net erosion/deposition and longitudinal profile of Wilket Creek between June and July 2013.

Figure 41 illustrates the results of the survey after the large flood in July 2013. It indicates that the upstream transects experienced deposition. In contrast, the middle of section of Wilket Creek was erosional. In the downstream areas of Wilket Creek there were an even number of sites experiencing both erosion and deposition. However, the Transects 15 and 16 experienced an extreme amount of erosion which overwhelmed depositional gains at the other transects.

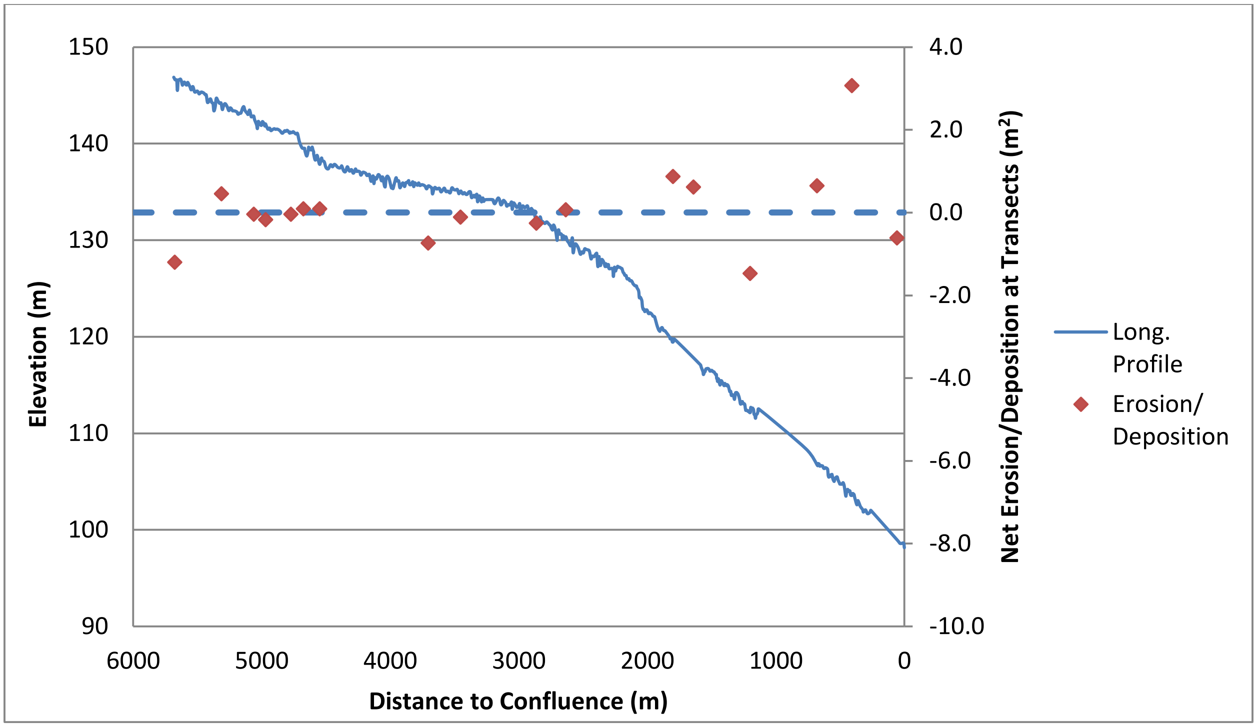


Figure 42. Net erosion/deposition and longitudinal profile of Wilket Creek between July and November 2013.

Between July and November the net amount of erosion and deposition was less than between June and July. In this period, both Sections 1 and 2 tended towards a small amount of erosion. Section 3 was more depositional character with the greatest gain in deposition occurring at the location where there had been the greatest loss in the previous period (Transect 16).

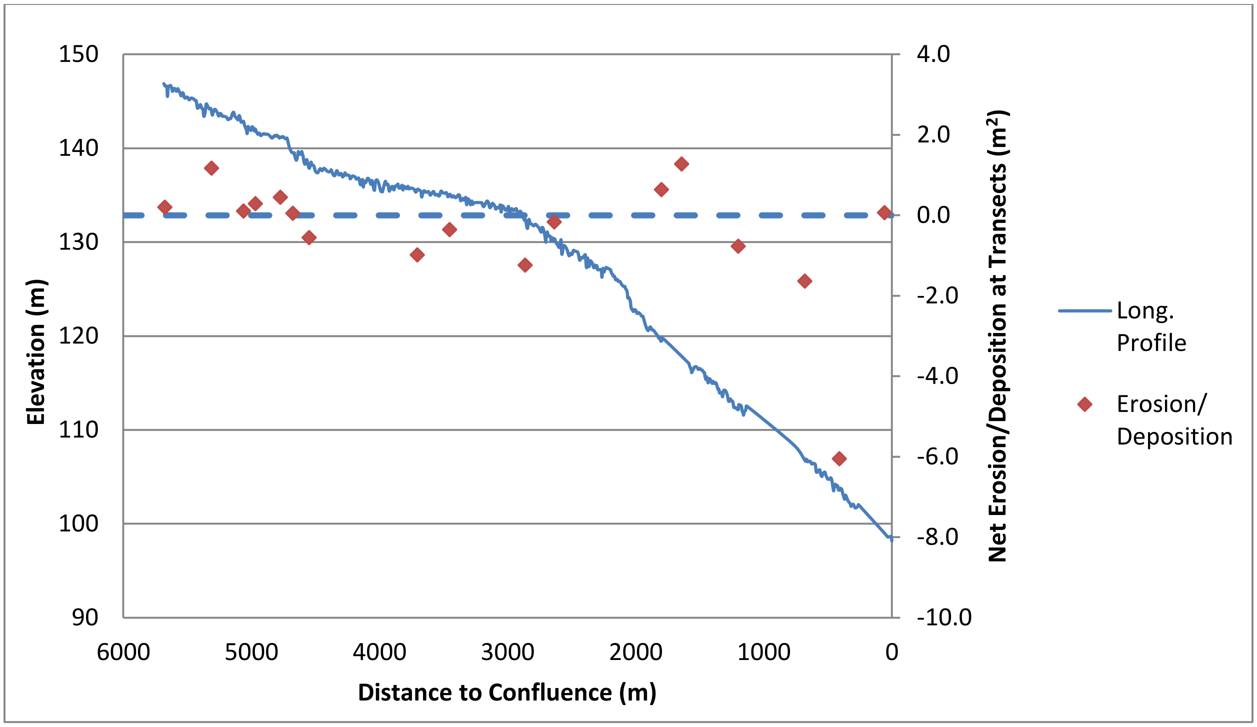


Figure 43. Net erosion/deposition and longitudinal profile of Wilket Creek between June and November 2013.

Figure 43 illustrates net erosion during the total survey period. This figure is close to Figure 41and indicates the changes in the channel as a result of the July flood were typically more significant in terms of erosion and deposition than later events.

4.4 Erosion Pins

An inspection of the erosion pins was made between July 23 and July 25 2013 (Table 16). At this time the length of the pin extending from the bank was measured. The presence or absence of pins was noted and a determination was made in regards to whether they had been washed away or buried by sediment from the upper portion of the banks.

Table 16. Erosion pin measurements for Wilket Creek.

Pin	Estimated Erosion (cm)	Recovered
EP1 1A	0.0	Yes
EP1 1B	1.9	Yes
EP1 2A	4.4	Yes
EP1 2B	3.0	Yes
EP2 1A	1.0	Yes
EP2 1B	3.6	Yes
EP2 2A	40.0	Yes
EP2 2B	58.4	Yes
EP2 2C	≥ 80.0	No
EP3 1A	buried	No
EP3 1B	buried	No
EP3 1C	buried	No
EP3 2A	36.5	Yes
EP3 2B	0.0	Yes
EP3 2C	buried	No
EP3 3A	5.4	Yes
EP3 3B	≥ 80.0	No

In total, 11 out of 17 pins were recovered. In Sections 1 all four pins were found while in Section 2, four out of five pins were recovered. Section 3 had the worst recovery rate with only 3 out of eight pins located.

Erosion pins in Section 1 confirmed that bank erosion was minimal. Pins were installed at Transects 1 and 2 and in all cases, only a short portion of the pin was exposed. This finding is corroborated by the cross section surveys of Transects 1 and 2 which also show very little lateral bank erosion.

Although the results were not always consistent with cross section surveys and field observations, erosion pins in Section 2 ultimately indicated that lateral bank erosion was occurring. At Transect 7, pins EP2 1A and EP2 1B showed little sign of erosion. This is inconsistent with field observations as well as the survey of Transect 7, which shows nearly a meter of erosion on the lower portion of the right bank. The pins experienced little erosion as they were placed higher up on the bank where only minor erosion occurred. However, on a quick field visit conducted on 7 May 2014, extensive erosion was noted on the left bank of Transect 7. Pin EP2 1A was located and found to extend 20 cm from the bank. In the region of Transect 10, erosion pins reveal that lateral erosion on the right bank is pervasive over a length of approximately 40 m. At the location of the most downstream pin (EP2 2C) bank erosion was extensive and the pin was not located. Therefore, erosion at this location was estimated to be at least 80 cm which was the length of the pin. Erosion at this location was verified by the results of the Transect 10 survey. Additionally, a field visit on 7 May 2014 found that pin EP2 2A extended 50 cm from the bank.

Poor pin recovery in Section 3 reveals that this area is quite active with significant bank erosion occurring throughout its length. Pins EP3 1A, EP3 1B and EP3 1C were not recovered and assumed to be buried. An examination of the bank at this location (Bank 3) indicated that upper parts of the bank had sloughed off resulting in significant deposition on the lower face of the banks where the pins were located (Figure 44). Pin EP3 2A was found to extend 36.5 cm from the bank while pin EP3 3B, which was located near the confluence was not found at all and erosion is assumed to be in excess of 80 cm.

Figure 44. Conditions at Bank 3 located immediately downstream of the 2012 restoration in Section 3.

In general, erosion pins provided a gross confirmation of transect measurements. However, pins in the lower portion of Section 3 were instrumental in confirming erosion and channel widening in this area.

4.5 Windfields Park Pond Bathymetry

The volume of sediment deposited behind the Windfields Park Dam was estimated using three different methods (Raster Calculator, Cut Fill and Surface Volume) with two interpolation schemes (IDW and kriging) for the rasters generated from the survey data. Both the Raster Calculator and the Cut Fill tool have a visual output while the Surface Volume tool only provides a table of values.

The Raster Calculator results for the IDW interpolation are shown below (Figure 45). The final raster is the result of subtracting the interpolations of the September and April surveys. The results show that erosion actually occurred in the area near the dam (green and yellow areas). Deposition primarily occurred in the upper three quarters of the survey area and was especially pronounced towards the left bank (brown and white areas). The results of the kriging interpolation are very similar.

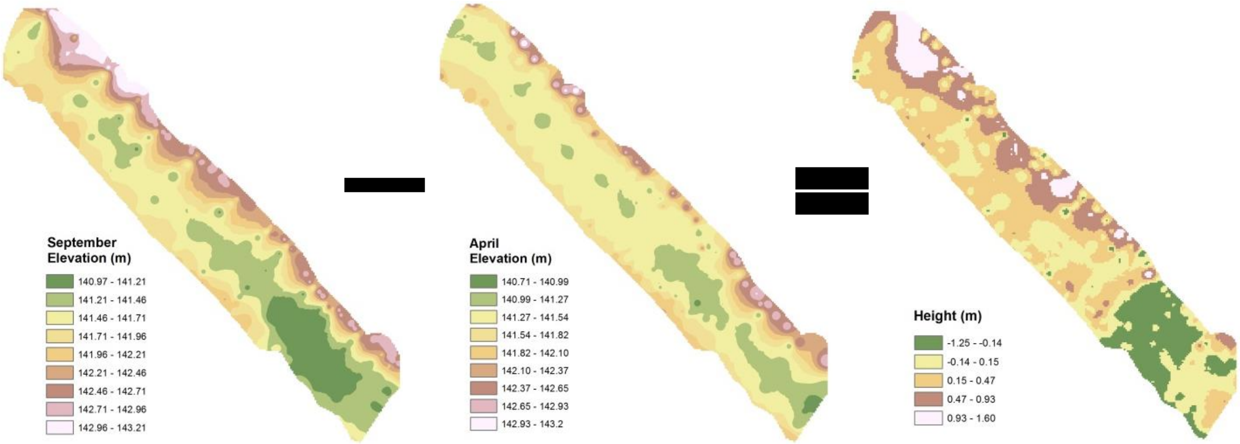


Figure 45. April IDW bed interpolation subtracted from September IDW bed interpolation to estimate change in streambed depth.

An example of the raster output of the “Cut Fill” tool for the IDW interpolated surfaces is illustrated in the figure below (Figure 46). The image generated by this tool shows only net losses, net gains and areas where there is no change. The areas of net gain and net loss correspond closely to the results for the raster calculator, with a net loss occurring near the dam and net gain elsewhere. There were no areas in which remained the same between surveys. As with the Raster Calculator, the results of the kriging interpolation are similar.

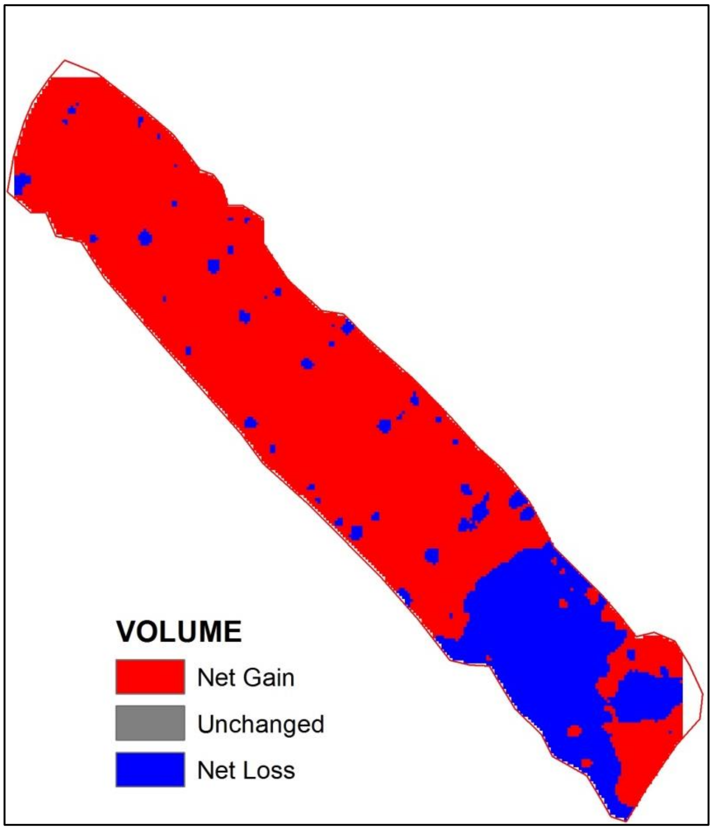


Figure 46. Raster output of the "Cut Fill" Tool showing areas of net sediment gain and loss.

Calculations for the volume of sediment deposited behind the dam are shown in Table 17. Additionally, the rate of sediment accumulation was estimated by dividing the volume by the time between measurements which was 138 days. The results show that the volume and rate of sediment accumulation were similar for all methods and both the IDW and kriging interpolation schemes.

Table 17. Volume and rate of sediment accumulation in Windfields Park pond between 25 April and 10 September 2013 (138 Days).

Method	**Volume (m^3)**		**Rate (m^3/day)**	
	IDW	**Kriging**	**IDW**	**Kriging**
Raster Calculator/Zonal Statistics as Table	124	142	0.90	1.03
Cut Fill	124	142	0.90	1.03
Surface Volume	137	157	0.99	1.14

4.6 Bank Storage Pins

Bank storage pins were initially installed on 2 July 2013 and re-measured between 24 July and 8 August 2013 following a large flood that topped the banks throughout much of Wilket Creek on 8 July 2013.

The bank storage pins in Section 1 indicate that both erosion and deposition of fine sediments occur depending on location. At the most upstream location, where the transect is perpendicular to the channel, measurements indicated that a small amount of erosion (< 1.0 cm) occurred (Figure 47). Note that erosion is greatest near the stream and decreases with distance from the stream.

Further downstream near Windfields Park, the right bank is characterized by deposition of sand. In this area, the bank is frequently topped and extensive sand deposition on the right bank was observed during the 2013 field season This observation was born out by the Transect BS1 2, which is oriented parallel to the creek. Althought sediment was lost at one pin location, Figure 47 illustrates that the general trend was depositional. As the transect is located about 20 m from the stream, it indicates the deposition occurs at quite some distance from the channel.

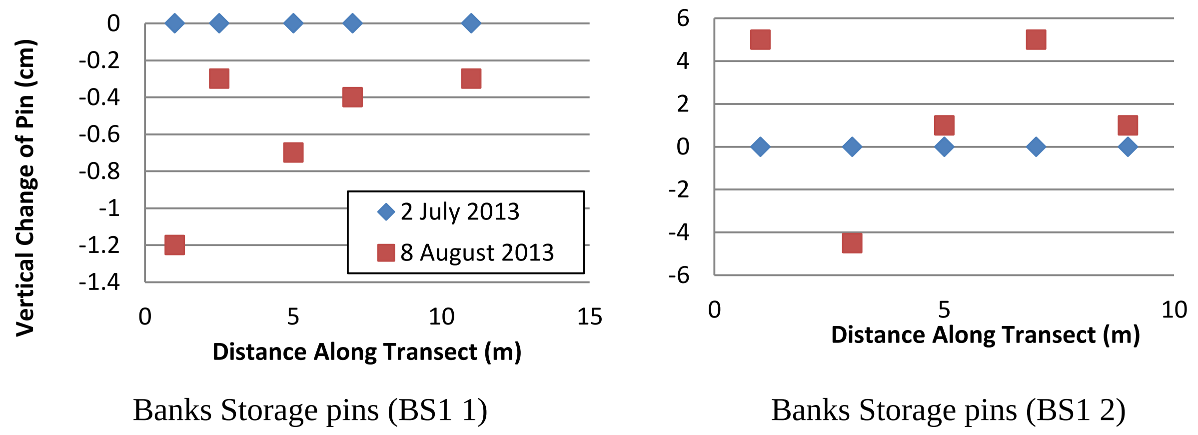
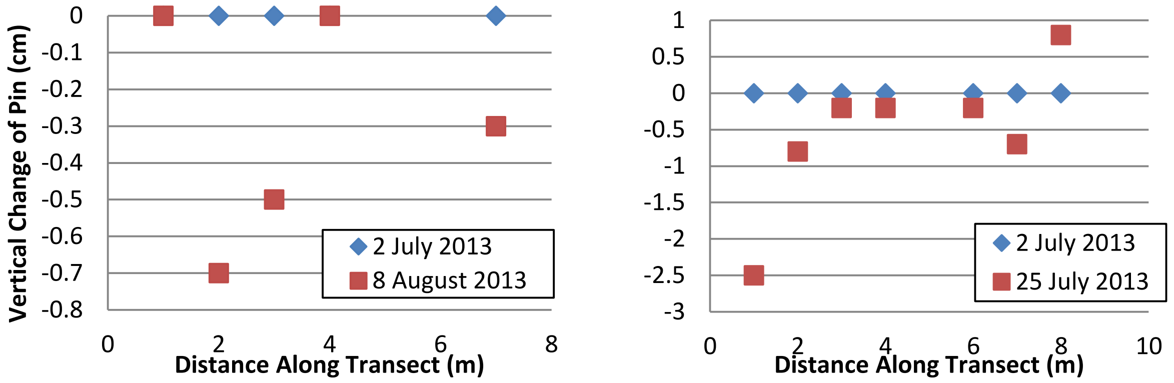


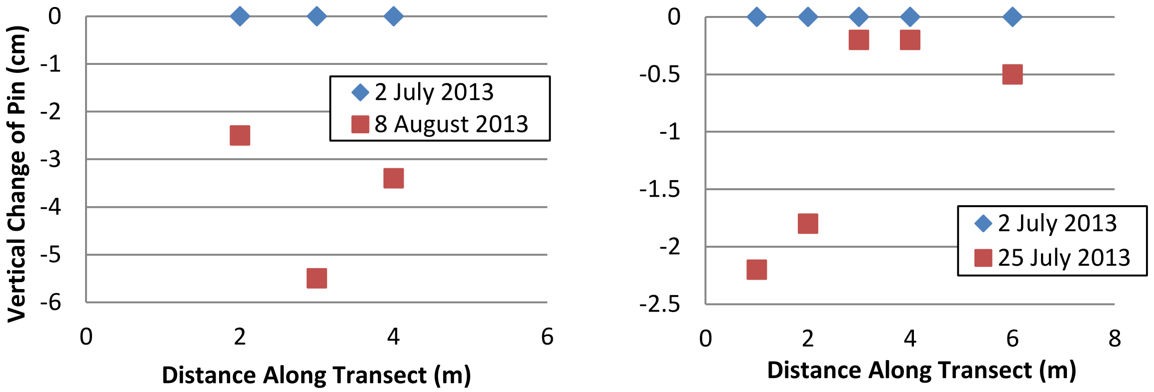
Figure 47. Bank storage pins indicating erosion at one location and both erosion and deposition at a downstream site.

Section 2 is the most “natural” area in Wilket Creek. The stream is extremely sinous and when overtopping of the banks occurs, water can move inland quite some distance on the left bank. During the period when fieldwork occured, the character of this section was overwhelmingly erosional. This is illustrated in the upstream complex of pins (BS2 1 and BS2 2) consisting of Transects 1, 2a and 2b. The downstream complex of pins in Section 2 (BS2 3 and BS2 4) consisting of Transects 3a, 3b and 4 also indicated that some erosion was occurring on the top of the banks (Figure 48).



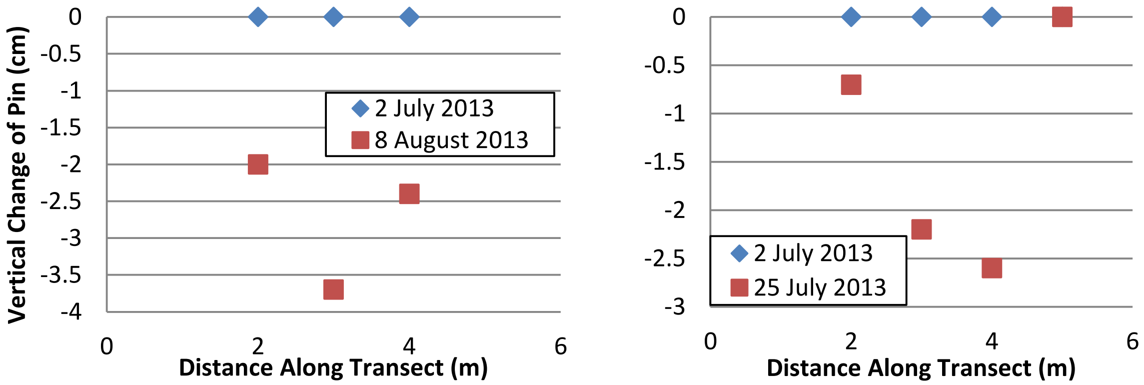
Banks Storage Pins (BS2 1)

Banks Storage Pins (BS2 3a)



Banks Storage Pins (BS2 2a)

Banks Storage Pins (BS2 3b)

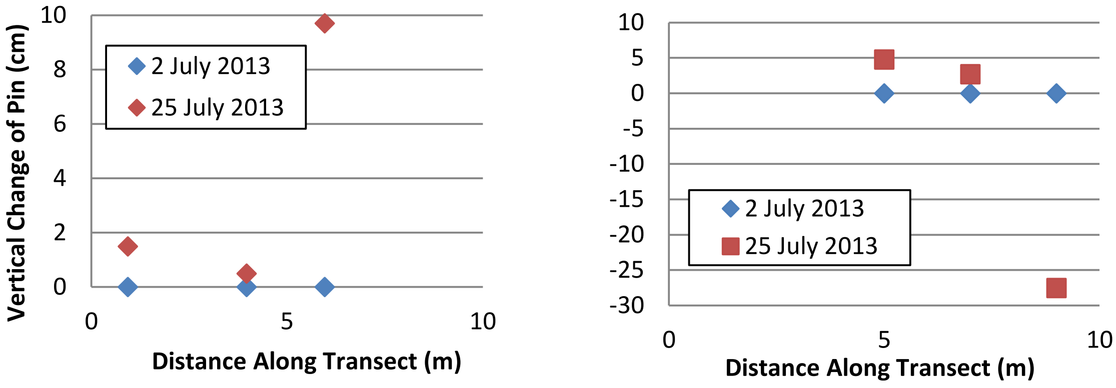


Banks Storage Pins (BS2 2b)

Banks Storage Pins (BS2 4)

Figure 48. Bank storage pins for Section 2 illustrating that no storage occurred at these locations over the study period.

The pins in Section 3 were located in the active channel and in a relic channel as well as on the banks. Bank storage transects BS3 1 and BS3 2 were both located to the left of the stream in the active channel perpendicular to the creek (Figure 49). BS3 1 is located higher up on the bank and is not inundated unless a bankfull event occurs. BS3 2 is located within a few meters of the stream and is inundated much more frequently.



Banks Storage Pins (BS3 1)

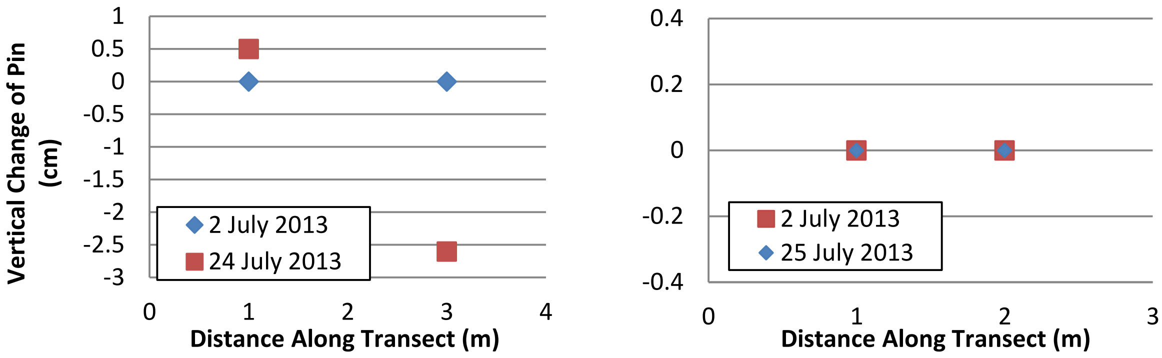
Banks Storage Pins (BS3 2)

Figure 49. Bank storage pins in Section 2 located within the channel.

Transects BS3 3 through BS3 6 form a complex of pins with two transects located on the bank and two in a relic channel (Figure 50). Transects BS3 3 and BS3 4 are located on the left bank and are inundated at high flows. During high discharge events, water flows over the transects and runs into the relic channel containing Transects BS3 5 and BS3 6.

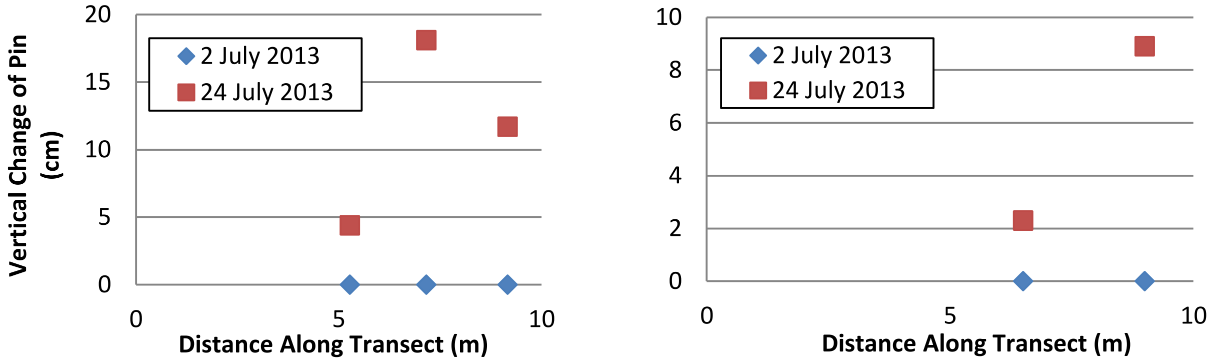
Transects BS3 5 and BS3 6 are both located in a relic channel. At discharges that exceed bankfull, the stream flows over Transects BS3 3 and BS3 4 and into the relic channel. At lesser discharge events, water flows from the creek into the channel. As shown in Figure 50, the relic channel receives a large input of sand and small gravels.

The last transect of bank storage pins is located on the left bank near the confluence. Based on fieldwork observations, this area has experienced extensive deposits of sand in the recent past. These observations are reflected in Figure 50 which illustrates an area characterized more by deposition than erosion.



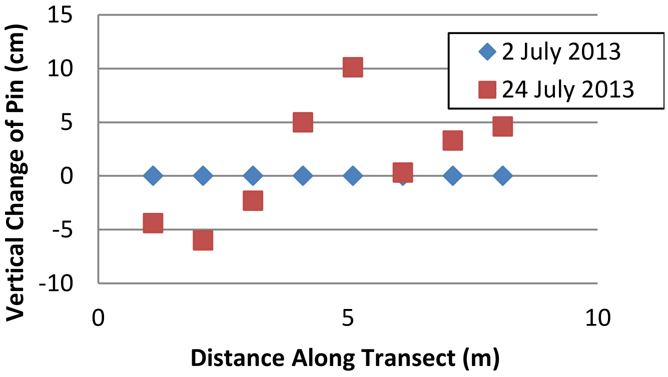
Banks Storage Pins (BS3 3)

Banks Storage Pins (BS3 4)



Banks Storage Pins (BS3 5)

Banks Storage Pins (BS3 6)



Banks Storage Pins (BS3 7)

Figure 50. Bank storage pins located in lower end of Section 3.

4.7 Direct Reflex Survey of Valley Walls and Banks

Scans were made of banks in each section of Wilket Creek as well as three of the valley walls in Section 3. The data was then imported for display in ArcScene 10.1 as it allows for 3D rotation of data. After initial input of the data as a shapefile, extraneous points that were outside the area of the bank or valley wall were removed. Individual data points were then categorized according to their unique elevation values for visual display. Next, a triangulated irregular network (TIN) was created. Examples of one bank (Figure 51 and Figure 52) and one valley wall (Figure 53 and Figure 54) in both shapefile and TIN formats are provided below.

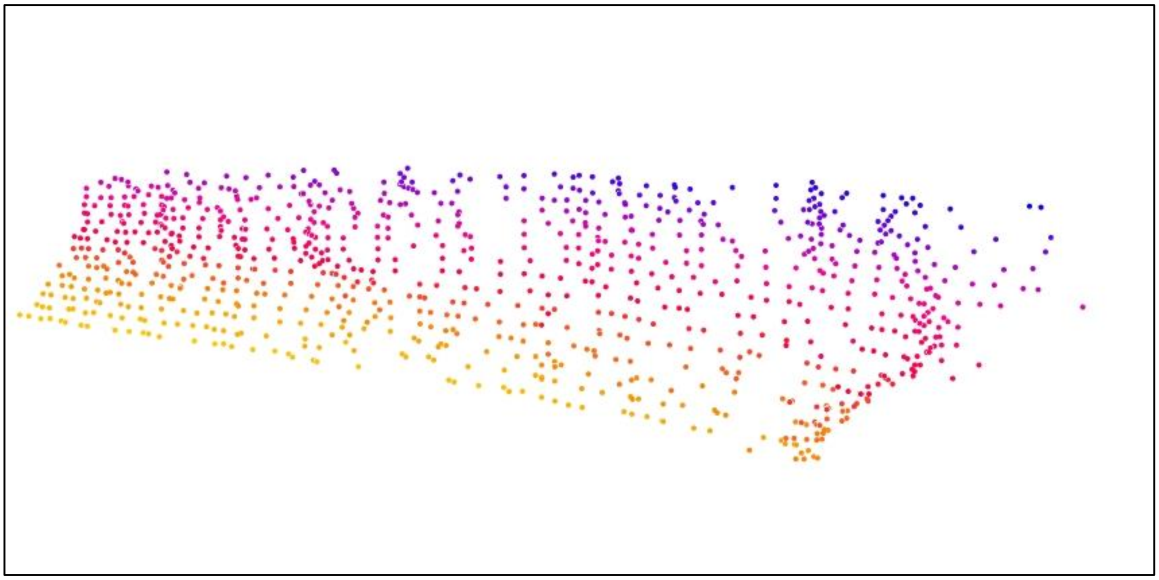


Figure 51. Shapefile for the Bank 3 survey utilizing the Trimble S6 DR3000+ with lighter colors representing lower elevation and darker colors representing higher elevations.

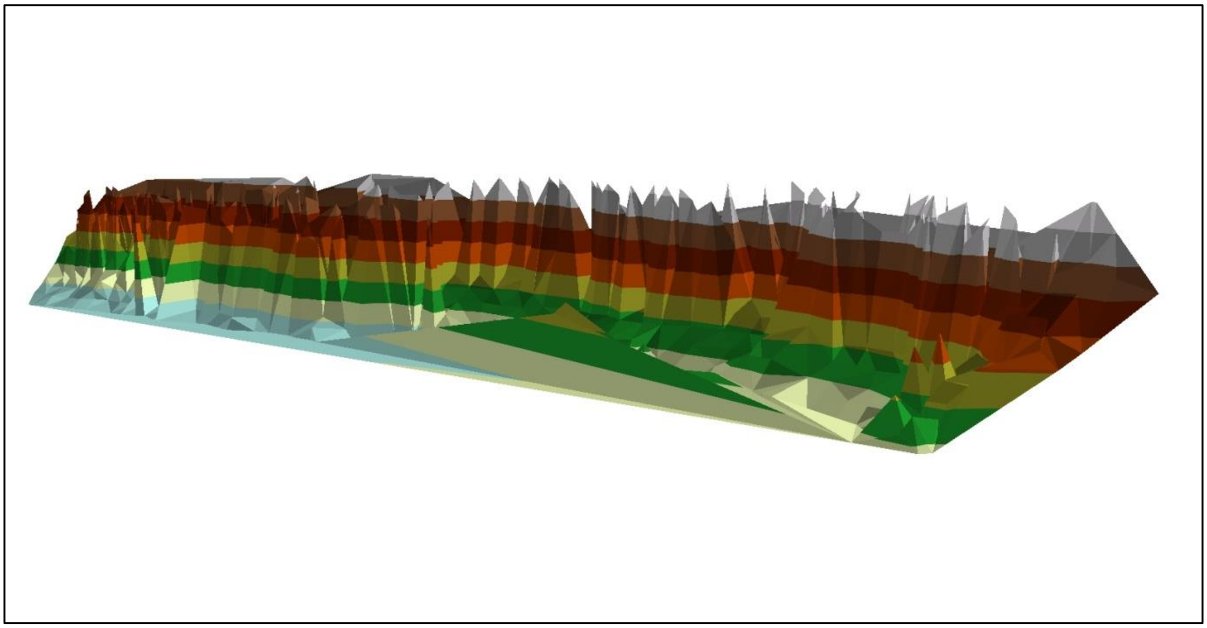


Figure 52. Shapefile of the Bank 3 survey in TIN Format with blue representing the lowest elevation and grey representing the highest elevation.

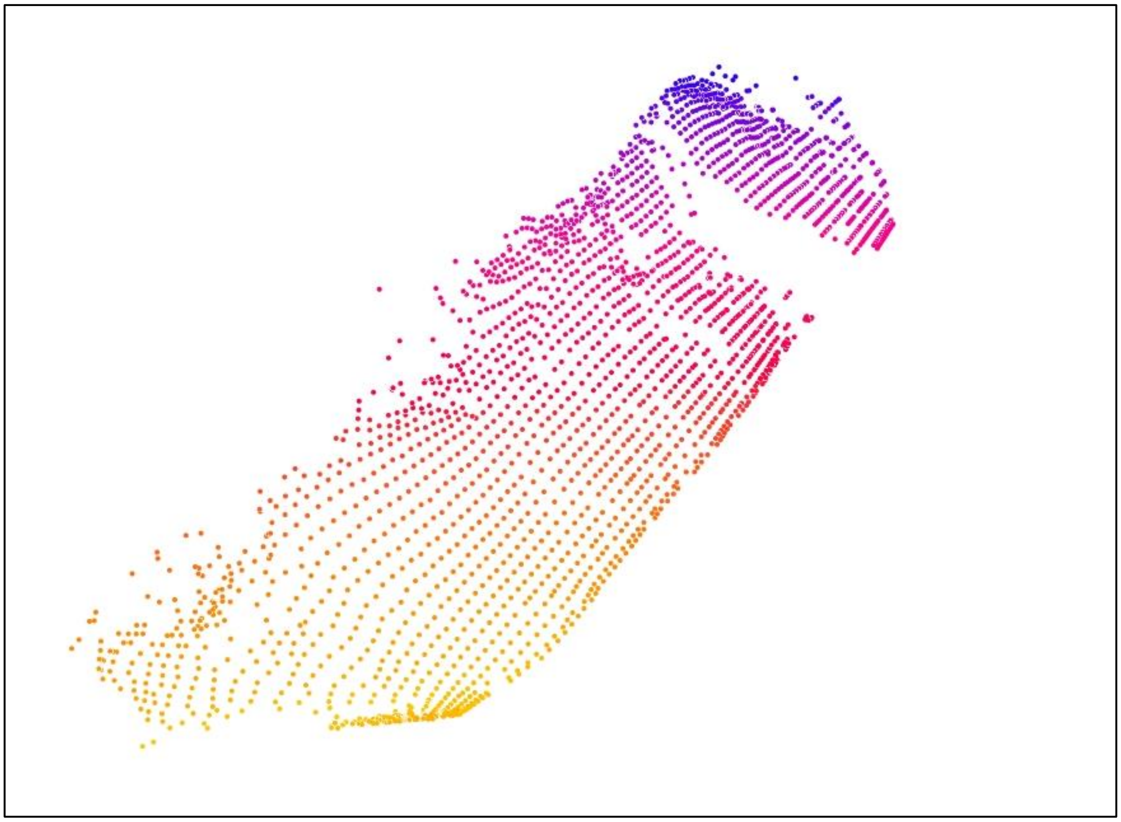


Figure 53. Shapefile of the Valley Wall 1 survey utilizing the Trimble S6 DR3000+ with lighter colors representing lower elevation and darker colors representing higher elevations.

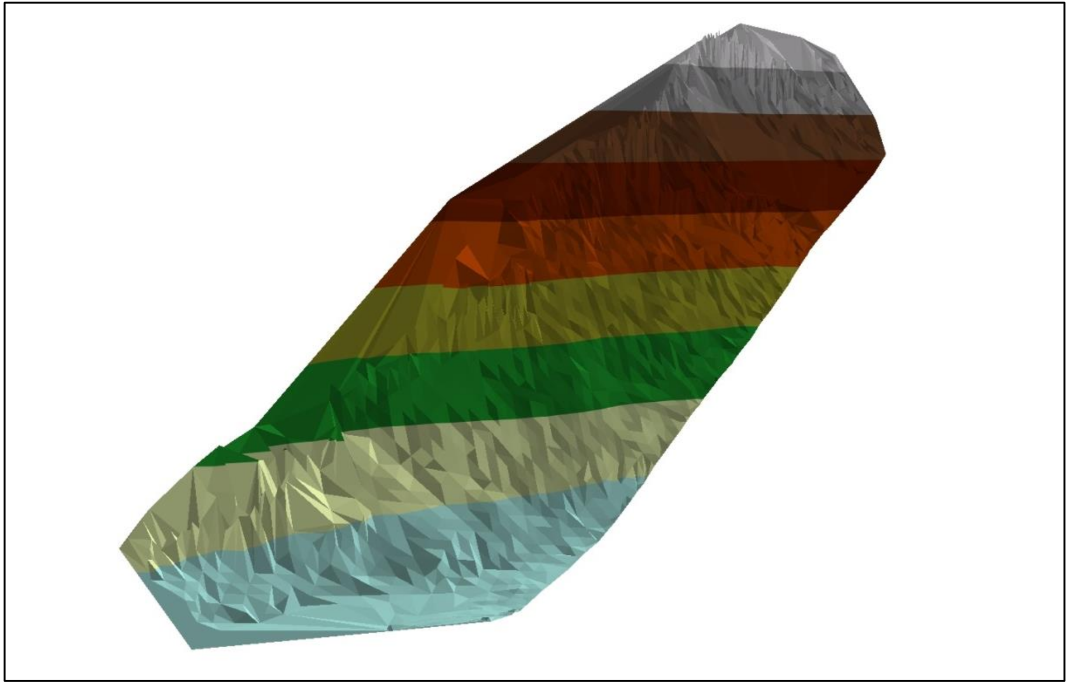


Figure 54. Shapefile of Valley Wall 1 in TIN format with blue representing the lowest elevation and grey representing the highest elevation.

As mentioned in the Methods section, these surveys were completed late in the fieldwork season and there was not an opportunity to conduct a subsequent survey. It is hoped that these surveys can serve as a baseline for future measurements.

4.8 Summary of Results

A summary table of the most pertinent results is given below (Table 18). The table includes: i) sub-section, ii) slope, iii) distance from confluence, iv) D_{50} by site, v) transect, vii) channel migration between 1999 and 2013, viii) November bankfull width, ix) November top of bank width, x) bankfull scour depth between June and November 2013, xi) top of bank scour depth between June and November 2013, xii) erosion/deposition between June and November 2013 and xiii) erosion pin data.

Table 18. Summary of selected data for length of Wilket Creek.

Sub-Section	Slope (%)	Distance from Confluence (m)	D_{50} (mm)/Site	Transect	1999-2013 Channel Migration	Nov BF Width (m)	Nov TOB Width (m)	Jun-Nov BF Scour Depth (m)	Jun-Nov TOB Scour Depth (m)	Jun-Nov Erosion/Deposition (m^2)	Erosion Pins Erosion (cm)/Pin #
1a	0.72	5677	1.6/S1 A	-	-	-	-	-	-	-	-
		5611	71.5/S1 B	1	-0.213	5.79	7.79	0.00	0.00	0.203	0.0/EP1 1A
											1.96/EP1 1B
		5243	-	2	0.493	10.05	12.78	0.08	0.07	1.168	4.4/EP1 2A
											3.0/EP1 2B
		4995	-	3	1.29	9.67	10.35	0.01	0.01	0.106	-
		1903	-	4	5.81	13.45	13.58	0.05	0.02	0.286	-
1b	2.7	4708	-	5	-1.333	10.67	13.89	0.03	0.03	0.445	-
2a		4611	-	6	-4.556	15.19	15.19	0.00	0.00	0.051	-
		4476	13.9/S2 A	7	5.62	11.76	15.98	-0.05	-0.04	-0.557	1.0/EP2 1A
											3.6/EP2 1B
2b	0.29	3638	-	8	-12.502	10.25	23.84	-0.04	-0.03	-0.987	-
		3395	-	9	4.314	9.70	11.50	-0.03	-0.03	-0.352	-
2c	0.89	2796	-	10	1.628	13.06	13.97	-0.06	-0.06	-1.236	40.0/EP2 2A
											58.4/EP2 2B
											≥80.0/EP2 2C
		2566	78.0/S2 B	11	1.569	11.28	13.28	-0.02	-0.01	-0.168	-
3a	3.3	1965	153.5/S3 A	-		-	-	-		-	-
3b	1.3	1832	-	12	0.985	10.91	11.60	0.09	0.06	0.637	-
		1575	-	13	3.376	12.83	14.38	0.11	0.10	1.276	-
		1132	-	-	-	-	-	-	-	-	buried/EP3 1A
											buried/EP3 1B
		1122	-	-	-	-	-	-	-	-	buried/EP3 1C
3c		1040	-	14	-4.987	17.52	21.22	-0.06	-0.04	-0.771	-
		981	-	-	-	-	-	-	-	-	36.5/ EP3 2A
		935	-	-	-	-	-	-	-	-	0.0/EP3 2B
											buried/EP3 2C
		613	-	15	0.816	10.06	12.93	-0.15	-0.12	-1.638	-
		343	-	16	8.889	20.07	27.98	-0.07	-0.21	-6.051	-
		73	-	-	-	-	-	-	-	-	5.4/ EP3 3A
		96	-	-	-	-	-	-	-	-	≥80.0/EP3 3B
		0	49.0/S3 A	17	-1.04	9.11	9.11	-0.02	-0.02	0.067	-

5.0 Sediment Budget

5.1 Introduction

Two methodologies were used in conducting a sediment budget for Wilket Creek. The first is called the morphological approach and only considers changes in cross sectional area at established transects. This approach is valid if bank erosion is the major source of sediment supply to the creek, a conjecture supported by previous research (Booth 1990, Wolman 1967). A requirement of this approach is that the sediment transport rate at one reach must be known in order to continue calculations upstream and downstream. The second method is a comprehensive sediment budget and considers all potential input, output and storage terms.

5.2 Morphological Approach

The morphological approach is based on the premise that sediment contributions to a stream system come primarily from channel erosion while other sources are negligible. In an urban setting where the upper watershed is primarily composed of impervious cover, Booth (1990) hypothesized that most of the sediment delivered to a stream would occur through mass wasting of streambanks. Additionally, Wolman (1967) thought that upland sediment production in urban areas would be minimal due to increase in impervious cover.

Two cases were considered in applying the morphological approach. The first case is applicable between June and July and assumes that sediment transport out of Reach 4 is zero due to the dam in Windfields Park. Although some bed material will move out of the reach at flows exceeding the height of the dam, most of the sediment generated upstream will remain behind the dam. The second case addresses the periods between June and November and July and November. As the dam in Windfields Park was open during this period, it is necessary to determine a sediment transport rate at one of the reaches in Wilket Creek. This was done in two ways: i) assuming no net transport of bed material at Reach 8 based on sediment transport capacity calculations and, ii) using the bathymetric survey to estimate a sediment transport rate into Reach 4.

An assumption of both cases is that sediment transported out of Reach 11 will pass through the dam in Edwards Gardens, which is operated intermittently, into Reach 12 with minimal contribution from streambanks. The justification for this is that immediately below the dam the slope jumps to 0.033 resulting in an increase in transport capacity which should move sediment downstream to Reach 12 where the gradient drops to 0.013. Furthermore, the bank and bed should contribute very little sediment as they have been extensively hardened throughout Edwards Garden.

The starting point of the morphological approach for both cases is the cross sectional surveys estimating erosion and deposition. Reaches were defined based on their upstream and downstream similarity to given transects (Figure 17). The reach distance, change in area and change in volume for the measurement periods are given in Table 19.

Table 19. Changes in cross sectional area and estimated volumetric change in reaches.

Transect	Reach Distance (m)	June - July		July - November		June - November	
		Area Change (m^2)	Volumetric Change (m^3)	Area Change (m^2)	Volumetric Change (m^3)	Area Change (m^2)	Volumetric Change (m^3)
1	397.90	1.40	419	-1.20	-359	0.20	61
2	144.56	0.71	77	0.46	50	1.17	127
3	189.30	0.18	26	-0.04	-6	0.11	15
4	196.22	0.46	67	-0.17	-25	0.29	42
5	56.02	0.48	20	-0.04	-2	0.45	19
6	150.93	-0.04	-5	0.09	11	0.05	6
7	434.88	-0.65	-213	0.10	31	-0.56	-182
8	520.45	-0.26	-100	-0.73	-287	-0.99	-385
9	407.78	-0.24	-74	-0.11	-33	-0.35	-108
10	493.24	-0.98	-362	-0.26	-95	-1.24	-457
11	264.29	-0.24	-47	0.07	13	-0.17	-33
12	175.28	-0.23	-31	0.87	114	0.64	84
13	386.55	0.66	190	0.62	180	1.28	370
14	518.64	0.70	272	-1.47	-572	-0.77	-300
15	391.46	-2.29	-672	0.65	191	-1.64	-481
16	306.99	-9.12	-2101	3.07	707	-6.05	-1393
17	182.29	0.68	93	-0.61	-84	0.07	9
Total		-8.78	-2439	1.30	-163	-7.52	-2607
Mean		-0.52	-143	0.08	-10	-0.44	-153

5.2.1 Case 1: June to July 2013

Employing Equation 3, sediment transport out of the 17 reaches (Q_o) was calculated for the period between June and July of 2013 (Table 20). Initial calculations began at Reach 4 using a porosity of 0.25. Assuming sediment transport out of the reach (Q_o) was zero and considering the change in volume for Reach 4, sediment transport into the reach was calculated (Q_i). Calculations then proceeded upstream and downstream. In some cases, transport out of a reach had a negative value denoting sediment accumulation within the reach. In this case, Q_o was set to a value of zero for the subsequent calculation downstream.

Table 20. Sediment transport rates out of reaches using a porosity of 0.25 between June and July of 2013.

Reach	Volumetric Change (m^3)	Time (days)	Q_{out} (m^3/day)
Culvert	-	-	15.24
1	419	29	4.40
2	77	29	2.41
3	26	29	1.74
4	67	29	0.00
5	20	29	-0.52
6	-5	29	0.12
7	-213	35	4.68
8	-100	36	6.76
9	-74	36	8.31
10	-362	33	16.53
11	-47	33	17.60
12	-31	34	18.28
13	190	34	14.08
14	272	36	8.42
15	-672	36	22.41
16	-2101	35	67.42
17	93	37	65.54

Calculations were continued upstream of Transect 1 to determine the sediment contribution from the culvert at York Mills Road which was estimated as 15.24 m^3/day. It is important to note that these transport rates were calculated over a rather short (~ 30 day) period of time that coincided with a large flood which delivered a relatively large pulse of sediment into the system.

5.2.2 Case 2: July to November 2013 and June to November 2013

In this case, volumetric sediment transport was considered for the periods from July to November and June to November 2013. As the dam at Windfields Park was opened in October, it was necessary to determine a rate of sediment transport at one reach to begin calculations. This was accomplished using two methods.

In the first instance, the Meyer-Peter Müller sediment transport capacity equation (Equation 5) was used to determine if there is a location where a sediment transport of zero could be assumed. The equation was applied to the 17 transects, pebble count site S3 A and a transect in the 2012 restoration (Table 21). Sediment transport capacity considered the top of bank discharge and was initially calculated for a particle size of 1.6 mm, which is the D_{50} of sediment delivered from the culvert at York Mills Road (Pebble Count Site S1 A). Based on observation of sediment movement through Wilket Creek over a two year period, it also roughly corresponds to the size of sediment that is most commonly transported throughout the creek. Next, transport capacities for the D_{16}, D_{25}, and D_{50} sizes were calculated. In this case, the particle size in question was associated with a sediment sampling site located in the vicinity of a particular cross section. For example, the D_{50} from site S1 B was associated with Transects 1 through 6, the D_{50} from Site S2 A was associated with Transects 7 through 9 and so on (Refer to Figure 5 and Figure 6). The sediment transport capacities were also plotted versus distance from the confluence along with the longitudinal profile (Figure 55 and Figure 56). At Transects 1 and 4, there was no sediment transport capacity for the D_{50} as the Critical Shields parameter (τ_{*c}) was larger than the Shields parameter (τ_{*}). This essentially means that the shear force required to move a particle of a given size is greater than the shear force acting on the particle (see Equation 6).

Table 21. Results of the sediment transport capacity calculations using the Meyer-Peter Müller Equation.

Transect	**Q_s (m^3/s)**	**Particle Size of Closest Pebble Count Location**		
		Qs (m^3/s)		
	D_{50} of Site S1 A	**D_{16}**	**D_{25}**	**D_{50}**
1	4,354	3,196	2,509	No Transport
2	9,596	7,479	6,199	399
3	10,516	8,604	7,430	1,562
4	4,837	3,134	2,163	No Transport
5	94,313	89,378	86,205	67,141
6	42,942	38,812	36,275	21,695
7	4,063	2,711	2,436	1,107
8	3,579	1,937	1,621	266
9	2,159	1,293	1,122	338
10	10,201	6,701	4,203	23
11	20,967	16,543	13,161	5,548
S3A	43,544	38,279	32,316	14,663
12	26,345	20,589	14,443	367
13	23,969	19,062	15,949	1,814
Parish 13	15,889	12,191	9,872	241
14	87,285	77,328	70,798	35,632
15	24,624	21,673	20,754	16,754
16	88,292	80,692	78,302	67,771
17	29,174	26,687	25,904	22,456

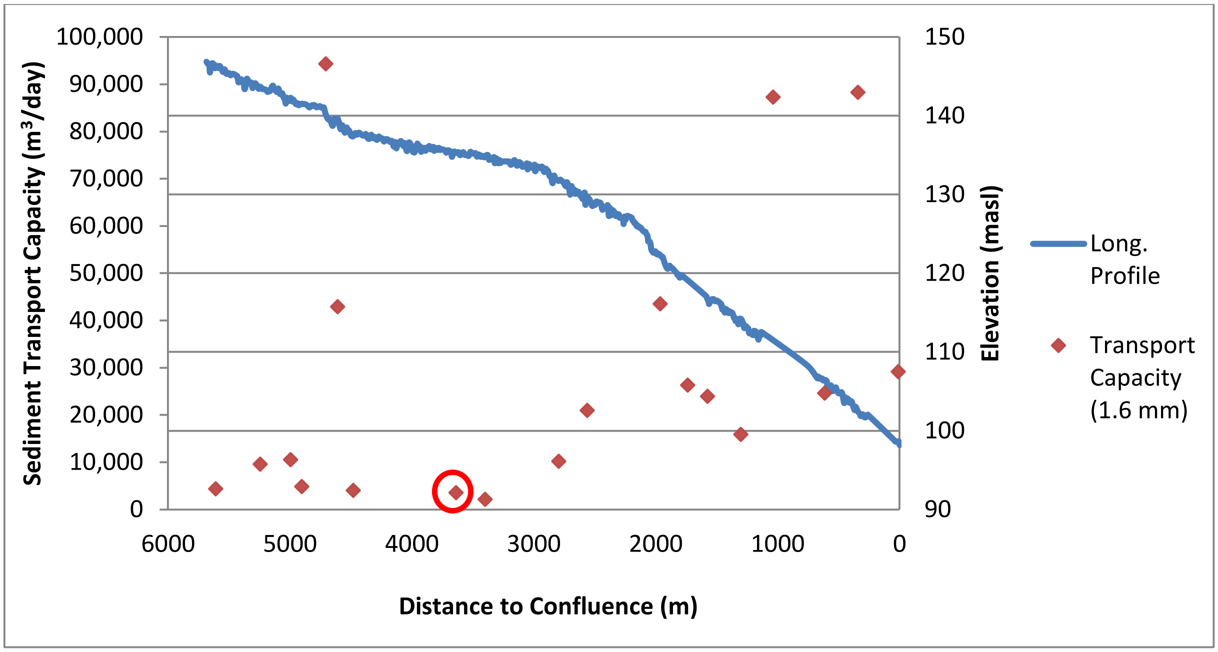


Figure 55. Transport capacity of 1.6 mm particles throughout Wilket Creek at top of bank discharge with Transect 8 circled in red.

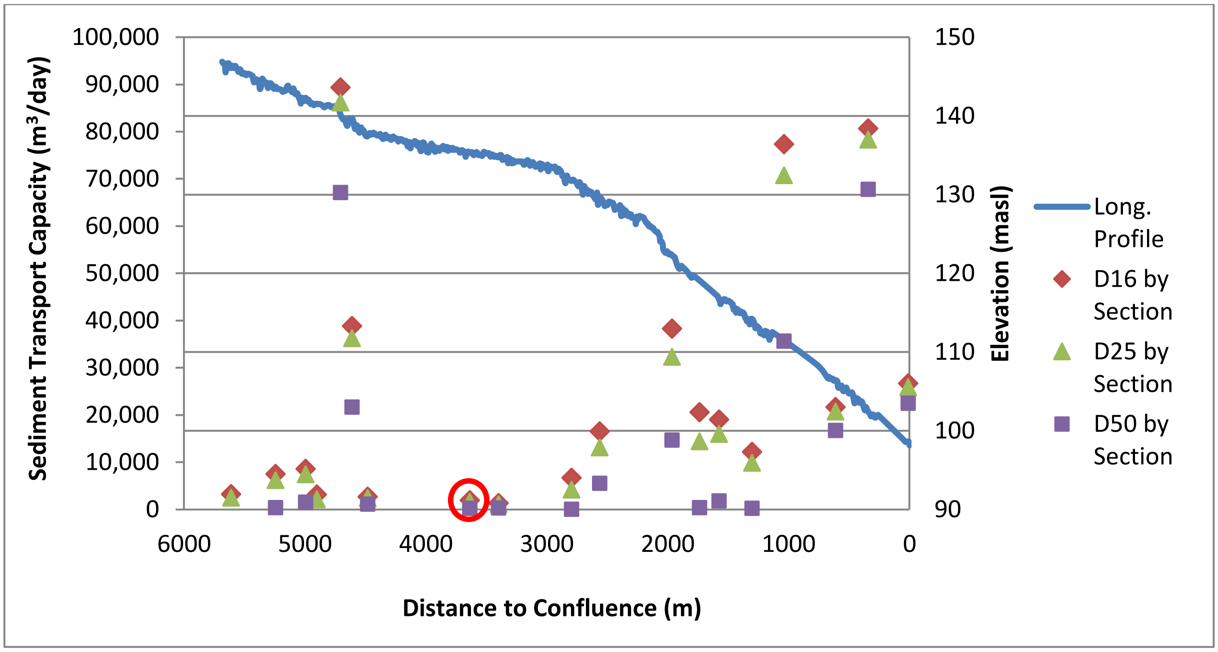


Figure 56. Transport capacity of D_{16}, D_{25} and D_{50} particle sizes throughout Wilket Creek at top of bank discharge with Transect 8 circled in red.

Transect 8 was selected as the point at which a transport capacity of zero would be assumed for the periods of July to November 2013 and June to November 2013. Calculated transport capacity at Transect 9 was slightly lower. However, this was due in part to Transect 9 having a much shorter cross section length than Transect 8. Additionally, based on the physical characteristics of the sites, it is likely that transport capacities are lower at Transect 8 as it is located in a low gradient area immediately upstream of a tight bend with an accumulation of large woody debris. Furthermore, a vast amount of sediment has been deposited on the right bank indicating a low sediment transport capacity at this location (Figure 57).

Figure 57. Transect 8 in Section 2 of Wilket Creek with large sand bar on right bank.

Assuming a transport rate of zero out of Reach 8 ($Q_o = 0$ m^3/day), Equation 3 was used to estimate sediment transport out of the 17 reaches for the periods of July to November and June to November (Table 22).

The second method of estimating a sediment transport rate used the results of the bathymetric survey of the dam in Windfields Park to calculate sediment transport (Q_{in}) into Reach 4. The boundaries of the reach associated with Transect 4 are shown by yellow dots in Figure 58. The area of the bathymetric survey is located in the lower section of the reach. It covers a little less than half the length of the reach. Due to this, the sediment transport into this reach may be an underestimate of the true sediment input. On the other hand, the period of measurement between April and September includes the high sediment input that occurred as a result of the major flood that occurred on July 8, 2013. In this case, it is possible that the bathymetric survey overestimates sediment input into the reach between July and November 2013. Keeping these considerations in mind, it was decided to use the low estimate of 0.9 m^3/day (see Table 17) to begin sediment transport calculations upstream and downstream (Table 22).

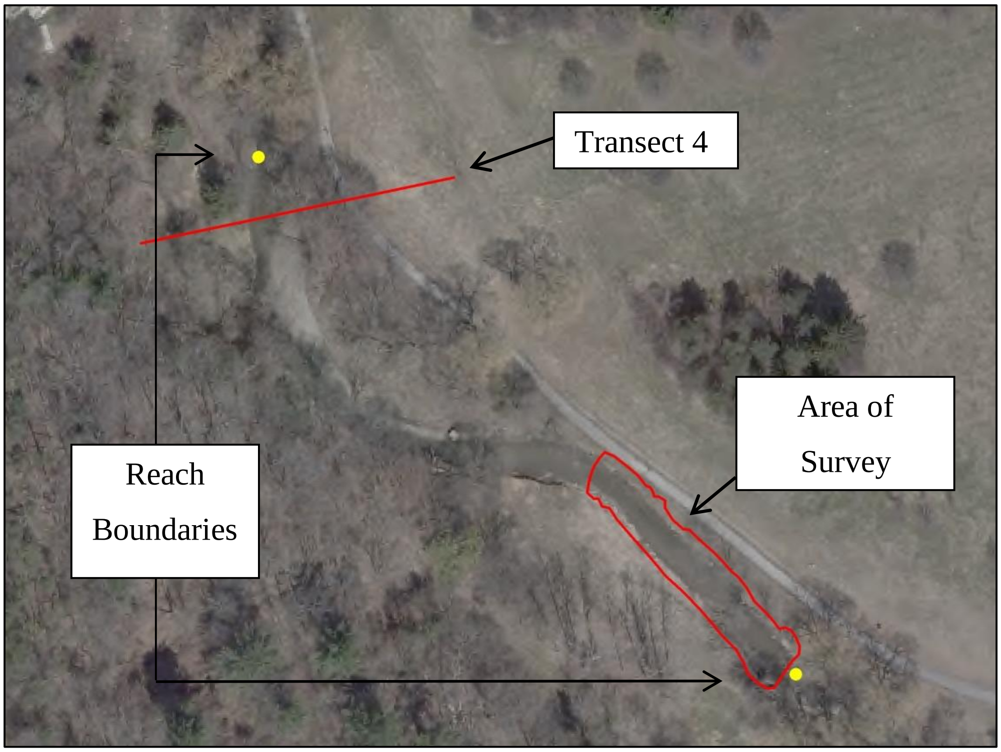


Figure 58. Reach 4 of Wilket Creek and area of bathymetric survey.

Table 22. Transport out of reaches for the periods of July to November 2013 and June to November 2013 for a porosity of 0.25.

	July to November			June to November		
		Q_{out} (m^3/days)			Q_{out} (m^3/days)	
Reach	Volumetric Change (m^3)	(Transect 8: Q_{out} =0)	Bathymetric Survey	Volumetric Change (m^3)	(Transect 8: Q_{out} =0)	Bathymetric Survey
Culvert	-	-1.77	-0.96	-	1.29	1.87
1	-359	0.35	1.16	61	1.00	1.58
2	50	0.06	0.87	127	0.39	0.97
3	-6	0.09	0.90	15	0.32	0.90
4	-25	0.24	1.05	42	0.12	0.70
5	-2	0.25	1.06	19	0.03	0.61
6	11	0.19	1.00	6	-0.85	0.58
7	31	-1.69	0.81	-182	-1.77	1.43
8	-287	0.00	2.50	-385	0.00	3.20
9	-33	0.20	2.70	-108	0.50	3.69
10	-95	0.76	3.26	-457	2.64	5.84
11	13	0.68	3.18	-33	2.79	5.99
12	114	0.00	2.50	84	2.40	5.60
13	180	-1.06	1.44	370	0.68	3.88
14	-572	3.40	4.84	-300	2.07	5.27
15	191	2.27	3.71	-481	4.30	7.49
16	707	-1.94	-0.50	-1393	10.79	13.98
17	-84	0.48	0.48	9	10.74	13.94

As shown in Table 22, calculations continued upstream of Transect 1 to estimate the sediment input delivered by the culvert at York Mills Road. For the period from July to November, the contribution from the culvert had a negative value, indicating that no sediment was transported out of the culvert. While this is not the case, it can be assumed that sediment transport out of the culvert was much lower than the period between June and July of 2013. Another point to note is that sediment transport out of Reach 17 between July and November is the same for both conditions. This is due to sediment deposition in the upstream reach. As Reach 16 experienced deposition during this period, the term denoting transport out of the reach (Q_o in Equation 3) was set to zero for the downstream calculation. Subsequently, sediment transport out of Reach 17 was based solely on change in storage at that location resulting in the same answer for both calculations.

The yearly sediment output of Wilket Creek was calculated based on the results given in Table 20 and Table 22. Output is calculated according to volume per year, mass per year and mass per year per watershed area. Volume per year was calculated by multiplying the sediment outflow (Q_o) in Table 20 and Table 22 by 365. Mass per year is calculated by multiplying the output of Table 20 and Table 22 by 2,650 kg/m^3, 1 ton/1000 kg and 365. Mass per year per area was calculated by dividing the mass per year by the watershed area of 15.4 km^2 (Table 23).

Table 23. Estimated yearly sediment output based on cross sectional surveys conducted between June and November 2013.

Measure of Sediment Output	**June to July Q_{out}**	**July to November**		**June to November**	
		(Transect 8: Q_{out} =0) Q_{out}	**Bathymetric Survey Q_{out}**	**(Transect 8: Q_{out} =0) Q_{out}**	**Bathymetric Survey Q_{out}**
Volume per Year (m^3/yr)	23,922	176	176	3,922	5,089
Mass per Year (ton/yr)	63,393	467	467	10,392	13,486
Sediment Yield (ton/yr/km^2)	4,116	30	30	675	876

5.3 Comprehensive Sediment Budget by Section

The comprehensive sediment budget is based on the results of the field study and the volumetric sediment transport calculations from the morphological approach. Separate budgets were completed for each section as they are very different in terms of morphology, sediment transport capacity, topographic relief and level of anthropogenic alteration. Basic characteristics of each section including area, length of creek, slope and D_{50} are given below (Table 24). In comparison with the study sections, the area of the Wilket Creek watershed above York Mills Road is much larger at 10.1 km^2. The combined total of the study sections and the upper watershed is 15.4 km^2.

Table 24. Basic characteristics of Wilket Creek sections.

Section		Watershed Area (km^2)	Length of Creek (m)	Slope	D_{50}
1	1a	1.42	999	0.7	1.6 (S1 A)*
	1b			2.7	71.5 (S1 B)
2	2a	1.62	2501	2.7	25.3 (S2 A)
	2b			0.3	78.0 (S2 B)
3	3a	2.27	2247	3.3	153.5 (S3 A)
	3b			1.3	49.0 (S3 B)
	3c			1.3	

(* - Streambed Composition Sampling Site)

5.3.1 Section 1

Sediment input terms for Section 1 include the culvert at York Mills Road, bank erosion, storm sewers/tributaries and hillslopes. Bank erosion was minimal in Section 1 with only slight losses at Transects 3 and 4. Aside from the culvert at York Mills Road, there are only four locations where storm sewers/tributaries discharge to the creek (Figure 59). Hillslopes were in close contact with the stream channel at four points and were all under 1000 m^2 in area. Sediment storage terms include, the channel, banks and behind the dam. Although channel storage is included in the comprehensive budget, it was not calculated as it is thought to move downstream in pulses that are shorter than the period between surveys. Between approximately May and November, sediment generated upstream is trapped behind the dam in Windfields Park. Bathymetric surveys of the area behind the dam indicate that between 124 and 157 m^3 of sediment was stored between 25 April and 10 September 2013. Field observations and bank storage pin measurements also indicate that storage occurs on the right bank in a couple of localized areas (Figure 59). Output from Section 1 occurs through the culvert about 35 m downstream of the dam in Windfields Park. Figure 59 provides a visual display of the sediment budget while estimations for each term are given in Figure 60.

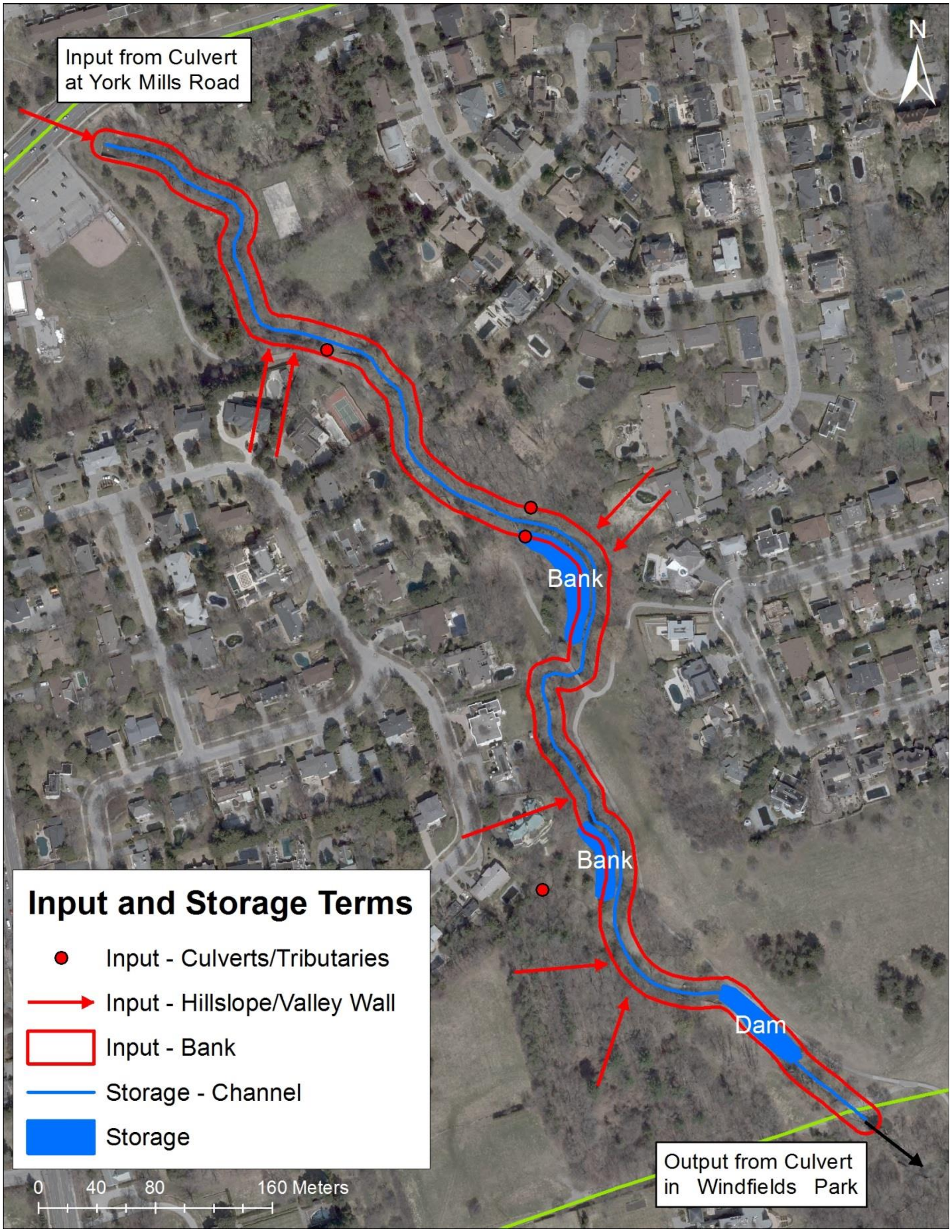
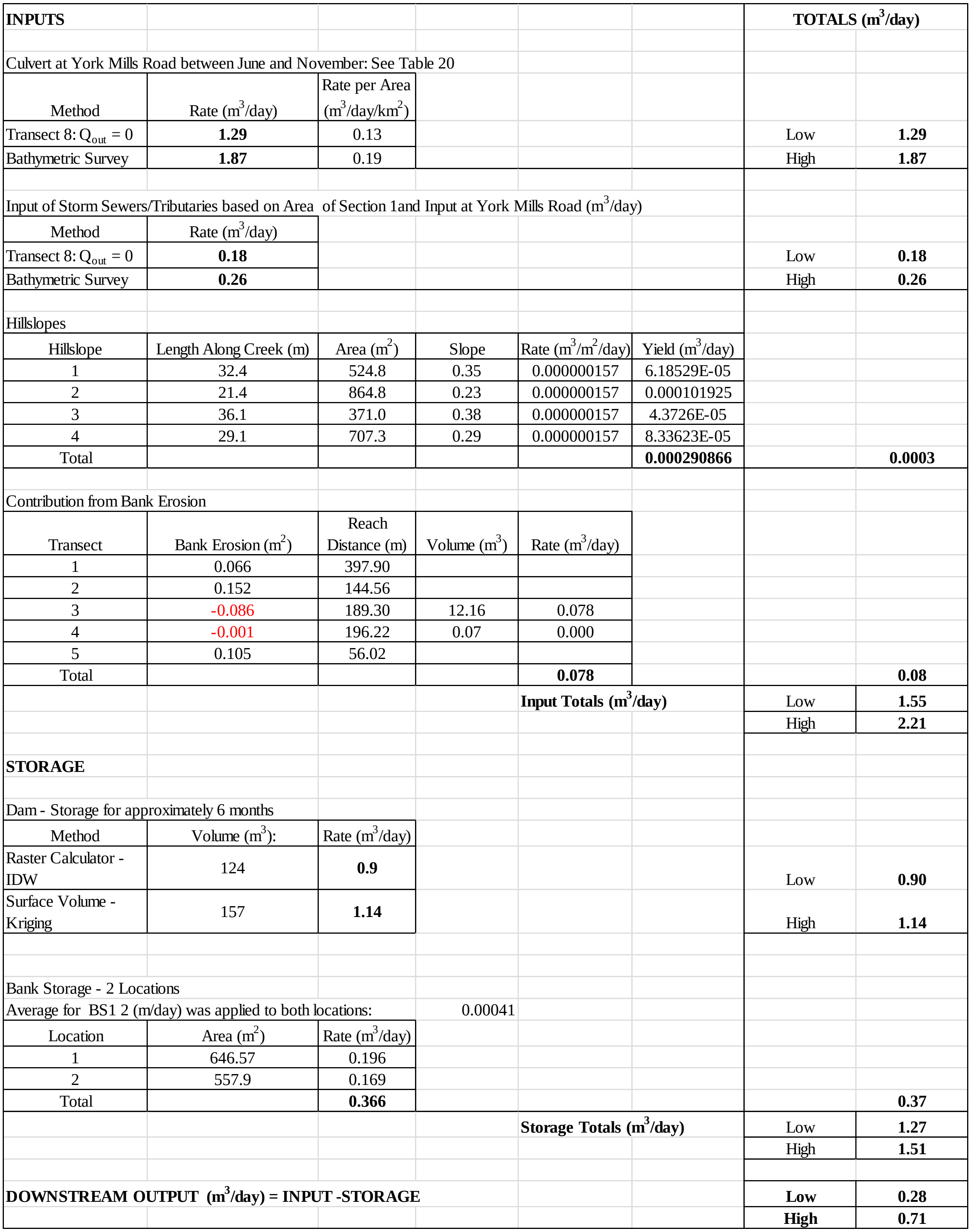


Figure 59. Terms of the comprehensive sediment budget for Section 1 of Wilket Creek with red, Blue and black representing sediment input, storage and output respectively.



INPUTS						**TOTALS (m^3/day)**	
Culvert at York Mills Road between June and November: See Table 20							
Method	Rate (m^3/day)	Rate per Area (m^3/day/km^2)					
Transect 8: $Q_{out} = 0$	**1.29**	0.13				Low	**1.29**
Bathymetric Survey	**1.87**	0.19				High	**1.87**
Input of Storm Sewers/Tributaries based on Area of Section 1and Input at York Mills Road (m^3/day)							
Method	Rate (m^3/day)						
Transect 8: $Q_{out} = 0$	**0.18**					Low	**0.18**
Bathymetric Survey	**0.26**					High	**0.26**
Hillslopes							
Hillslope	Length Along Creek (m)	Area (m^2)	Slope	Rate (m^3/m^2/day)	Yield (m^3/day)		
1	32.4	524.8	0.35	0.000000157	6.18529E-05		
2	21.4	864.8	0.23	0.000000157	0.000101925		
3	36.1	371.0	0.38	0.000000157	4.3726E-05		
4	29.1	707.3	0.29	0.000000157	8.33623E-05		
Total					**0.000290866**		**0.0003**
Contribution from Bank Erosion							
Transect	Bank Erosion (m^2)	Reach Distance (m)	Volume (m^3)	Rate (m^3/day)			
1	0.066	397.90					
2	0.152	144.56					
3	-0.086	189.30	12.16	0.078			
4	-0.001	196.22	0.07	0.000			
5	0.105	56.02					
Total				**0.078**			**0.08**
				Input Totals (m^3/day)		Low	**1.55**
						High	**2.21**
STORAGE							
Dam - Storage for approximately 6 months							
Method	Volume (m^3):	Rate (m^3/day)					
Raster Calculator - IDW	124	**0.9**				Low	**0.90**
Surface Volume - Kriging	157	**1.14**				High	**1.14**
Bank Storage - 2 Locations							
Average for BS1 2 (m/day) was applied to both locations:			0.00041				
Location	Area (m^2)	Rate (m^3/day)					
1	646.57	0.196					
2	557.9	0.169					
Total		**0.366**					**0.37**
				Storage Totals (m^3/day)		Low	**1.27**
						High	**1.51**
DOWNSTREAM OUTPUT (m^3/day) = INPUT -STORAGE						**Low**	**0.28**
						High	**0.71**

Figure 60. Sediment budget worksheet for Section 1.

5.3.2 Section 2

The terms of the sediment budget for Section 2 are similar to the previous section. The sediment contribution from Section 1 should be minimal between spring and fall when the dam in Windfields Park is operational. Once the dam is removed, an initial pulse of sediment should move rapidly into Section 2 as the slope transitions from 0.72% to 2.7%. This section contains eight contributions from storm sewers/tributaries and four from hillslopes (Figure 61). Hillslope area is larger than the previous section and ranges from 624.5 m^2 to 2760.1 m^2. Bank erosion is much greater with large losses occurring at Transects 7 and 10. Sediment storage terms were limited to channel and bank storage. There were no direct measurements of channel storage and bank storage pins only indicated a slight amount of erosion (Figure 48). Estimates of sediment output at the pond in Edwards Gardens were made based on recent dredging carried out by the City of Toronto Parks Department. A map and estimates of the sediment budget terms and are given in Figure 61 and Figure 62 respectively.

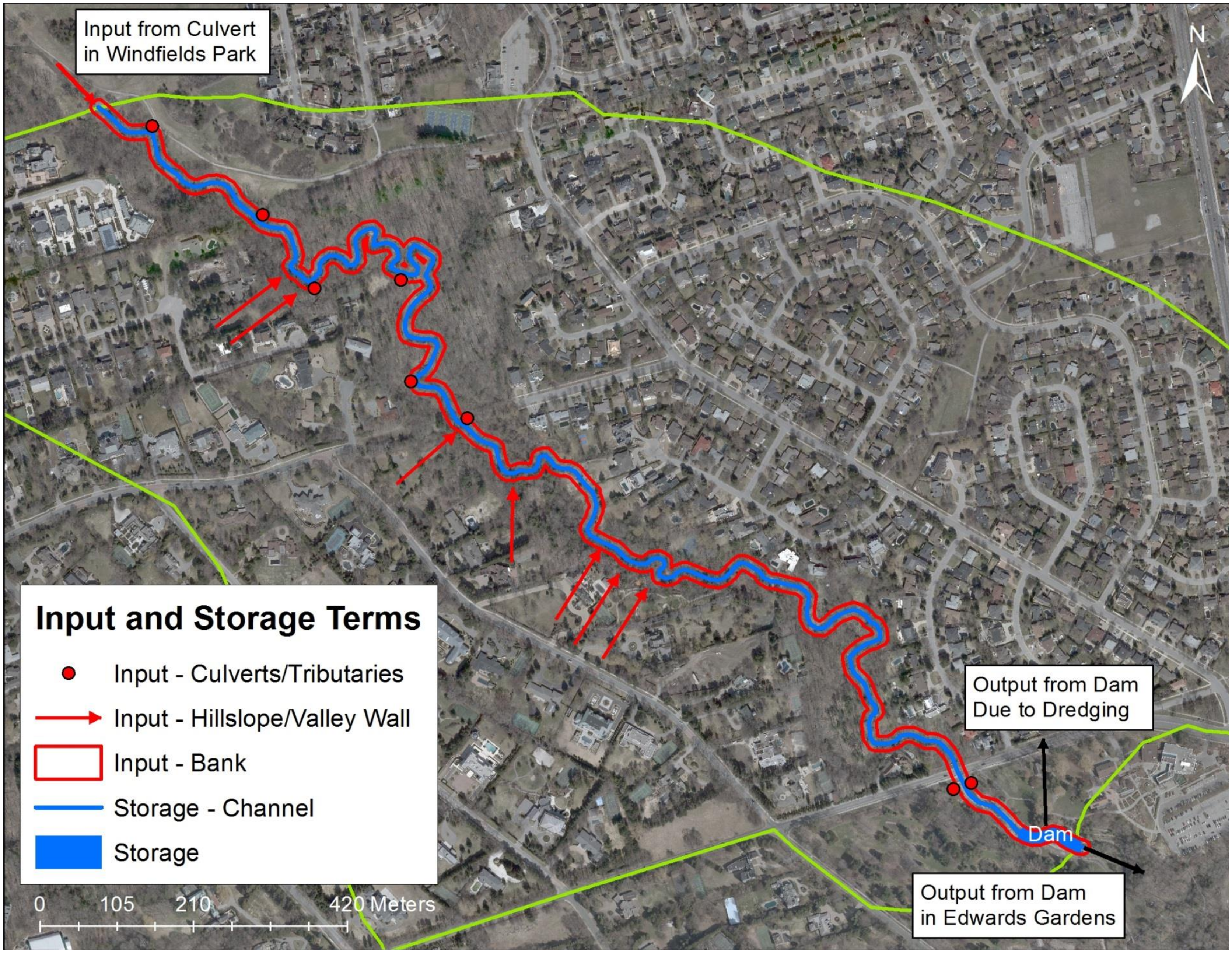


Figure 61. Terms of the comprehensive sediment budget for Section 2 of Wilket Creek with red, blue and black representing sediment input, storage and output respectively.

INPUTS						**TOTALS (m^3/day)**	
Output from Previous Section (m^3/day)						Low	**0.28**
						High	**0.71**
Input of Storm Sewers/Tributaries based on Area of Section 1and Input at York Mills Road (m^3/day)							
Method	Rate (m^3/day)						
Transect 8: Q_{out} = 0	**0.21**					Low	**0.21**
Bathymetric Survey	**0.30**					High	**0.30**
Hillslopes							
Hillslope	Length Along Creek (m)	Area (m^2)	Slope	Rate (m^3/m^2/day)	Yield (m^3/day)		
1	36.1	1984.2	0.22	0.00000012	0.000178578		
2	32.4	695.1	0.36	0.00000012	0.000062559		
3	17.6	624.5	0.57	0.00000012	0.000056205		
4	147.6	2760.1	0.35	0.00000012	0.000248409		
Total					0.000545751		**0.000545751**
Contribution from Bank Erosion							
Transect	Bank Erosion (m^2)	Reach	Volume (m^3)	Rate (m^3/day)			
6	-	150.93					
7	-0.818	434.88	266.73	1.66			
8	-0.763	520.45	297.71	1.83			
9	-0.251	407.78	76.88	0.47			
10	-1.044	493.24	386.04	2.41			
11	0.120	264.29					
Total				6.37			**6.37**
				Input Totals (m^3/day)		Low	**6.86**
						High	**7.37**
STORAGE							
Bank Storage - 2 Locations							
Bank storage pins on indicated very slight erosion at locations in Section 2 - No storage occurred							
Location	Area (m^2)	Rate (m^3/day)					
1							
2						Low	**0.00**
Total						High	**0.00**
				Storage Totals (m^3/day)		Low	**0.00**
						High	**0.00**
OUTPUT							
Dam - Dredged March 2014 and 2007							
Volume (m^3):	Rate (m^3/day)						
233	**0.09**						**0.09**
DOWNSTREAM OUTPUT (m^3/day) = INPUT -STORAGE - OUTPUT AT DAM						**Low**	**6.77**
						High	**7.28**

Figure 62. Sediment budget worksheet for Section 2.

5.3.3 Section 3

The first term to consider regarding sediment input is the dam in Edwards Garden. Between approximately November and April, the sluice gate is open and sediment can pass downstream. The rest of the year the dam is operated intermittently and sediment typically passes downstream when the sluice gate is open for anticipated high discharge events. There are 15 storm sewers/tributaries that discharge to the creek in Section 3 (Figure 63). Of particular interest are two very large culverts that discharge near Leslie Avenue and flow through large ravines into Wilket Creek. These undoubtedly provide the largest inputs of sediment of all the storm sewers/tributaries that flow into Wilket Creek. This section is also distinguished by hillslopes and valley walls that are in close contact with the creek. Overall, 14 locations were considered and their average area was 1812.3 m^2. Bank erosion contributed sediment at three transects with an extremely large input at Transect 16.

Bank storage was noted at two locations in Section 3. The first is a relic channel located upstream of Transect 16. Accumulation of sediment in the relic channel was documented by bank storage pin transects BS3 5 and BS3 6. The second area of storage is on the left bank near the confluence. Storage here was recorded by bank storage pin transect BS3 7. Given the orientation of this site, it is unlikely that the sediment will be re-mobilized and enter the creek. Therefore, the sediment at this location is considered an output. Additional output of sediment occurs at the confluence with the West Don River. A map of the terms (Figure 63) as well as estimates (Figure 64) are given below.

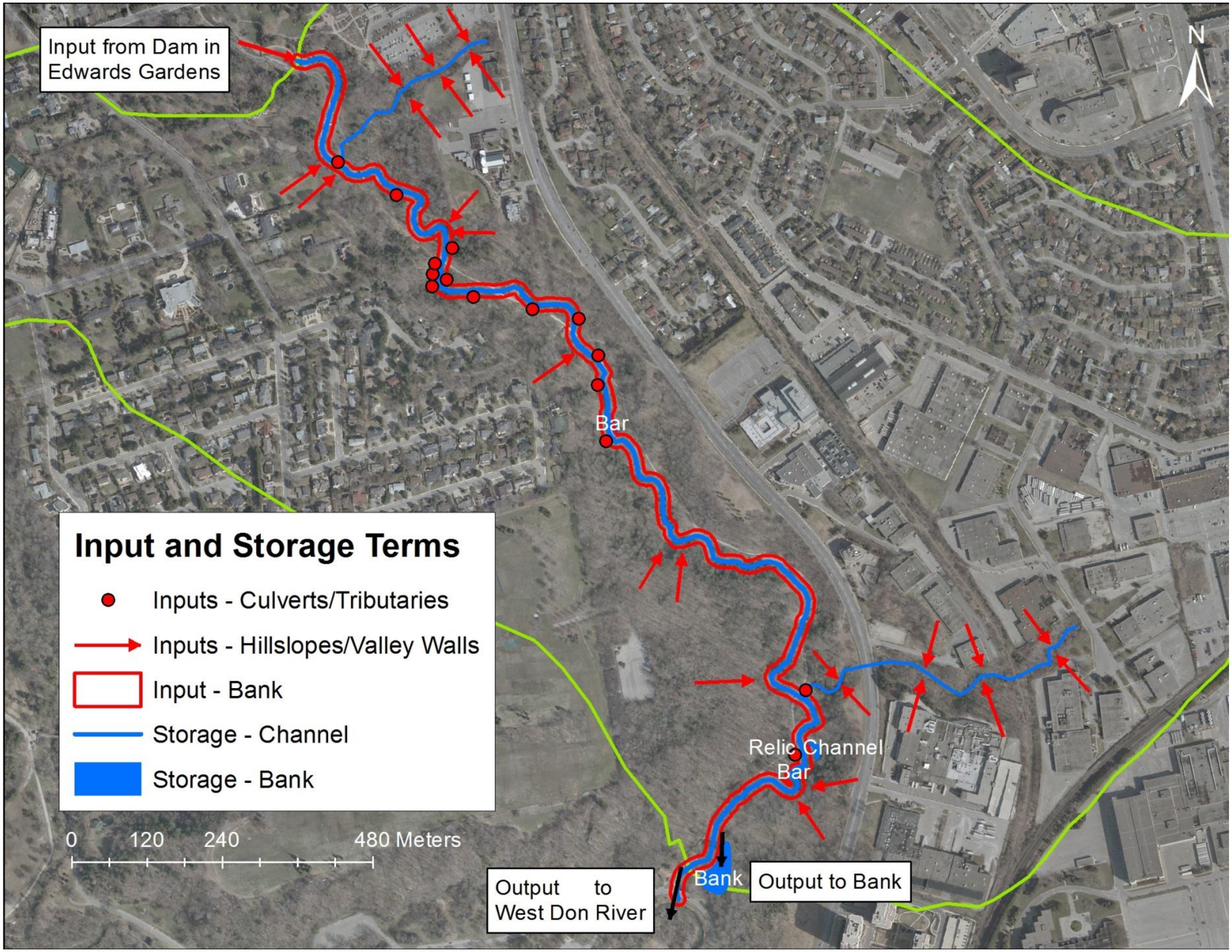


Figure 63. Terms of the comprehensive sediment budget for Section 3 of Wilket Creek with red, blue and black representing sediment input, storage and output respectively.

INPUTS						**TOTALS (m^3/day)**	
Output from Previous Section (m^3/day)						Low	**6.77**
						High	**7.28**
Input of Storm Sewers/Tributaries based on Area of Section 1and Input at York Mills Road (m^3/day)							
Method	Rate (m^3/day)						
Transect 8: Q_{out} = 0	**0.29**					Low	**0.29**
Bathymetric Survey	**0.42**					High	**0.42**
Hillslopes							
Hillslope	Length Along Creek (m)	Area (m^2)	Slope	Rate (m^3/m^2/day)	Yield (m^3/day)		
1	41.8	1233.6	0.61	0.00000012	0.000111024		
2	23.6	1007.4	0.55	0.00000012	0.000090666		
3	25.5	602.0	0.73	0.00000012	0.00005418		
4	25.3	2376.5	0.32	0.00000012	0.000213885		
5	24.2	582.3	0.84	0.00000012	0.000052407		
6	27.7	1020.5	0.64	0.00000012	0.000091845		
7	178.1	3387.0	0.27	0.00000012	0.00030483		
8	178.1	3053.7	0.44	0.00000012	0.000274833		
9	87.9	1263.8	0.26	0.00000012	0.000113742		
0	87.9	1536.8	0.29	0.00000012	0.000138312		
11	196.7	4986.0	0.75	0.00000012	0.00044874		
12	187.8	3403.5	0.45	0.00000012	0.000306315		
13	38.7	553.3	0.45	0.00000012	0.000049797		
14	35.1	365.7	0.21	0.00000012	0.000032913		
Total					0.002283489		**0.002283489**
Contribution from Bank Erosion							
Transect	Bank Erosion (m^2)	Reach Distance (m)	Volume (m^3)	Rate (m^3/day)			
12	-0.372	175.28	48.88	0.30			
13	-0.100	386.55	38.47	0.24			
14	0.178	518.64		0.00			
15	-0.110	391.46	42.95	0.27			
16	-7.204	306.99	2211.43	13.74			
17	-	182.29					
Total				**14.54**			**14.54**
				Input Totals (m^3/day)		Low	**21.61**
						High	**22.25**
STORAGE							
Bank Storage - Locations							
Average for BS3 5 and 6 (m/day) was used:		0.00414					
Location	Area (m^2)	Rate (m^3/day)					
Avulsion	290.1	**0.900**					**0.900**
				Storage Totals (m^3/day)			**0.900**
OUTPUT							
Permenant Storage at Confluence							
Average of BS3 7 (m/day) was used:		0.000591					
Location	Area (m^2)	Rate (m^3/day)					
Confluence	1802.7	**0.799**					**0.799**
TOTAL OUTPUT (m^3/day) = INPUT - STORAGE - PERMANENT STORAGE AT CONFLUENCE						Low	**19.91**
						High	**20.55**

Figure 64. Sediment budget worksheet for Section 3.

The totals of the input, storage and output terms for each section are given in Table 25. Included are both low and high estimates. The downstream output is the difference of the input, temporary storage and permanent storage terms. The total output is the sum of permanent storage and downstream output.

Table 25. Input, storage and output totals for the comprehensive sediment budgets of the study sections.

Section		Inputs (m^3/day)	Temp. Storage (m^3/day)	Outputs		
				Perm. Storage (m^3/day)	**Downstream Output (m^3/day)**	**Total Output (m^3/day)**
1	Low	1.6	1.3	-	0.3	0.3
	High	2.2	1.5	-	0.7	0.7
2	Low	6.9	-	0.1	6.8	6.9
	High	7.4	-	0.1	7.3	7.4
3	Low	21.6	0.9	0.8	19.9	20.7
	High	22.3	0.9	0.8	20.6	21.4

The comprehensive sediment budget was initially presented in sections. However, the sections can be linked together in a flow chart to provide a comprehensive sediment budget for the entire study area (Figure 65). In the figure below the red, blue and black arrows represent input, storage and output terms respectively. In addition, the relative thickness of the arrow corresponds to the magnitude of the term. Table 25 and Figure 65 illustrate the sediment output increases with downstream direction. As indicated by the sediment budget worksheets, this increase in sediment output is primarily due to bank erosion in Sections 2 and 3 which is significantly larger than the other sediment input terms. The recognition of bank erosion as the largest contributor of sediment is probably the most important piece of information to be gleaned from the comprehensive sediment budget.

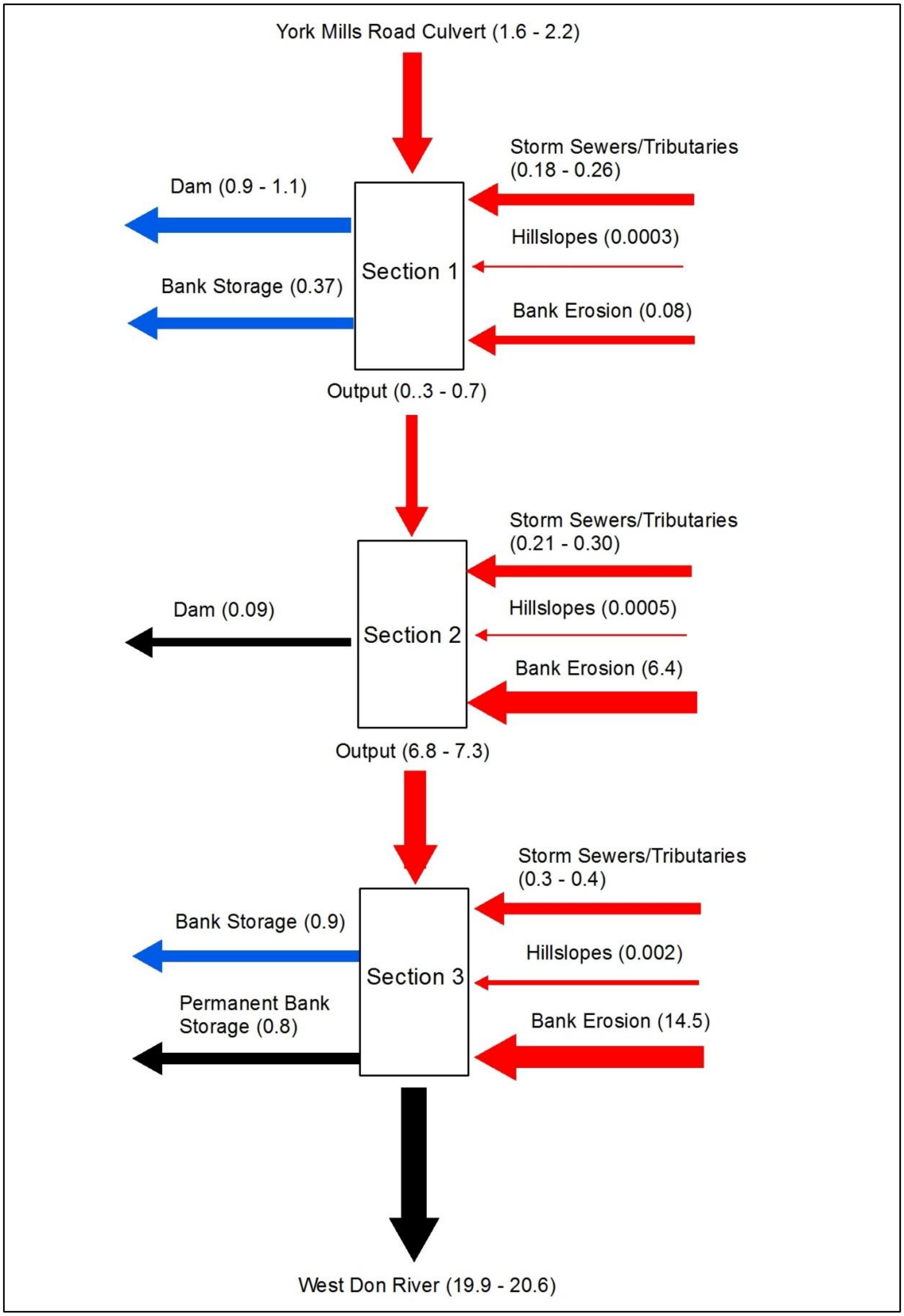


Figure 65. Flow chart of the comprehensive sediment budget for the entire exposed section of Wilket Creek with red, blue and black representing input, storage and output terms respectively. Values given in parenthesis are m^3/day.

6.0 Discussion

A main goal of this study has been to assess conditions in Wilket Creek to assist the City of Toronto and the TRCA in their development of a comprehensive management plan for the creek. Therefore, this section will begin by discussing the character of Wilket Creek based on the analysis of the field results. Conditions in the creek are important in considering the next topic which is the sediment budget. The last issue discussed is recommendations for future research in Wilket Creek.

6.1 Field Results - Character of Wilket Creek

Wilket Creek is a discontinuous stream system. Qualitative surveys revealed differences in morphology, topographic relief, degree of encroachment on the channel and anthropogenic alteration of the channel itself. Online dams and culverts also break up system continuity.

These qualitative findings were confirmed by quantitative measurements including sudden changes in slope, particle size, sediment transport capacities and channel enlargement. For instance, the longitudinal survey identified five changes in slope (Figure 5) along the course of the creek. The two steepest areas occur immediately downstream of dams. As shown in Table 17, transport capacity is among the highest in Wilket Creek at these locations. As a result, smaller sediment sizes are quickly routed downstream once they are able to pass the dams.

Cross sectional surveys, erosion pins and ArcGIS analysis revealed distinct differences in bank erosion and channel enlargement between the study sections of Wilket Creek. Surveys of transects (Figure 33 to Figure 34) and bank erosion pins (Table 9) indicated that very little bank erosion was occurring in Section 1. Erosion was more pronounced in Section 2, particularly at Transects 7 and 10 (Figure 35 and Figure 37) which are located downstream of sudden breaks in slope. Section 3 has undergone the most extensive widening in Wilket Creek with a general pattern of channel enlargement occurring downstream of the 2012 restoration. Excessive erosion is occurring on Bank 3, which is located immediately downstream of the restoration (Figure 44) while the single largest bank loss during the study occurred at Transect 16 (Figure 40).

Additional erosion is occurring upstream of hardening structures near the confluence. In summary, little or no significant channel widening is occurring in Section 1. Isolated widening was recorded in Section 2 while Section 3 shows a tendency towards lateral erosion in its lower half.

To determine whether observed differences in channel width were statistically significant, an Analysis of Variance (ANOVA) was conducted for the top of bank measurements using a 95 percent confidence level. This analysis compared top of bank measurements for the June, July and November surveys. An additional analysis was done comparing the three sections to one another for each survey period (June, July and November). The ANOVA for the June, July and November surveys yielded a null F value of 0.02 and a critical F value of 3.2. As the null F value was less than the critical F value, the difference between the top of bank widths over the study period is not statistically significant. The ANOVA analysis of top of width between sections yielded similar results (Table 26). Although individual cross sections experienced large changes in top of bank width, the ANOVA analysis indicates that there were no significant differences of top of bank of widths between survey periods and sections.

Table 26. ANOVA analysis of top of bank widths by section for June, July and November Surveys.

Sections	**June**			**July**			**November**		
	F-Null	**F-Crit**	**Significant**	**F-Null**	**F-Crit**	**Significant**	**F-Null**	**F-Crit**	**Significant**
All Sections	1.12	3.74	No	1.19	3.74	No	1.22	3.74	No
1 and 2	2.77	5.11	No	3.16	5.12	No	3.20	5.12	No
2 and 3	2.66 E-06	4.96	No	0.03	4.99	No	0.03	4.96	No
1 and 3	1.61	5.12	No	1.77	5.12	No	1.82	5.12	No

Analysis of streambed particles was complicated as there was not a clear pattern regarding particle size and distance along the channel. It was initially thought that coarsening might increase with distance downstream. Such a pattern was not particularly clear from Figure 26. To better understand the data, a box and whisker plot was made (Figure 66). The “box” consisted of the D_{50}, D_{25} and the D_{75}. The “whisker” was made up of the D_5 and D_{95}. In addition, the standard error was calculated for the sample collected at each site. An interesting point of this analysis was that only sites S1 B and S2 A had overlap between their means when standard error was taken into account (Table 27). This overlap appears to be due to be an anomalous occurance as the bed at S1 B is made up, in large part, of rip rap and cobbles from gabion baskets that migrated into the stream (Figure 28). In contrast, the bed particles at site S2 A appear to be of natural origin.

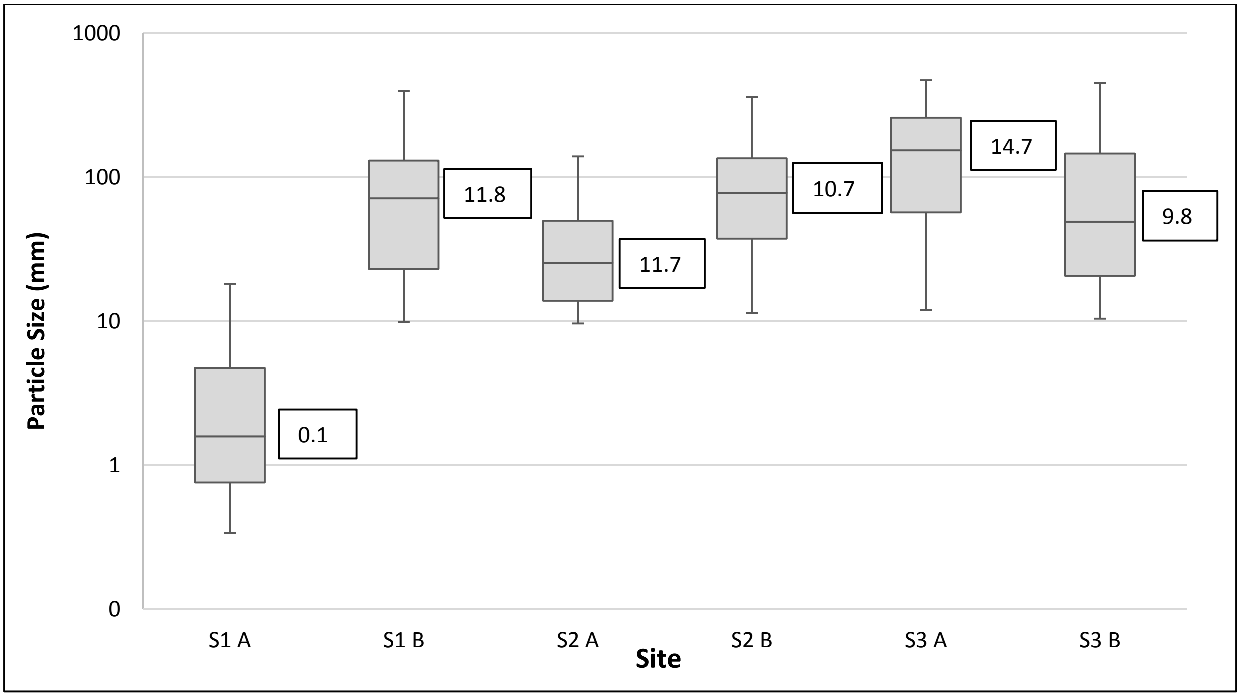


Figure 66. Box and whisker plot showing $D_5$and D_{95} (whiskers) and D_{25}, D_{50} and D_{75} (box) with the standard error displayed next to the appropriate figure.

Table 27. D_{50} and Standard Error of Sediment Sampling Sites.

Site	Standard Error	D_{50} Minus Standard Error	D_{50}	D_{50} Plus Standard Error
S1 A	0.1	1.5	1.6	1.7
S1 B	11.8	59.7	71.5	83.3
S2 A	11.7	13.6	25.3	37.0
S2 B	10.7	67.3	78.0	88.7
S3 A	14.7	138.8	153.5	168.2
S3 B	9.8	39.2	49.0	58.8

Based on pebble count data and qualitative surveys, differences in particle sizes are not simply the result of natural processes. Anthropogenic alteration of the banks at certain locations has resulted in coarser bed material than would naturally occur. This is due to rip rap and cobbles from gabion baskets migrating into the stream channel (Figure 28 and Figure 31). Similar discontinuities in particle sizes were found in a study of an urban stream network in Knoxville Tennessee (Grable and Harden 2006).

Channel migration rate data is an important component in assessing the nature of Wilket Creek. During the periods 1999-2003, 2003-2009 and 2009-2012, Figure 22 through Figure 24 illustrate that the channel migration rate was highest in the latter period. This was particularly true in the lower reaches of Section 3 and the most upstream area of Section 2 where an avulsion is occurring downstream of the culvert in Windfields Park. These locations of greatest lateral migration coincide with recent observations.

To test for statistical significance, an ANOVA was performed on lateral channel migration rate using a 95% confidence level (Table 28). The initial ANOVA for all periods (1999-2003, 2003-2009 and 2009-2012) indicated that there was a statistical difference between lateral channel migration rates. Further analysis determined that lateral channel migration rate was statistically significant only between the periods 2003-2009 and 2009-2012.

Table 28. ANOVA analysis of lateral channel migration rates.

Comparison Periods	F-Null	F-Crit	Significant
All	3.70	2.61	Yes
1999-2003 to 2003-2009	2.65	3.85	No
2003-2009 to 2009-2012	5.47	3.85	Yes
1999-2003 to 2009-2012	3.11	3.85	No

The discontinuous nature of Wilket Creek is expressed morphologically as headcuts, lateral migration, excessive sediment deposition in some areas and extreme bank erosion in others. For the most part, Section 1 appears relatively stable with little evidence channel adjustment. Section 2 is very active in isolated areas. The first area is located in the restoration which is approximately 60 m downstream of the culvert that forms the upper boundary for Section 2 and is centered on Transect 6. At high flows, the stream tops the right bank of the restoration (Figure 67). It is in the process of creating an avulsion and bypassing the meander bend. In Figure 67, the creek is just at bankfull flow and discharge is starting to top the bank and enter the avulsion. Figure 68 is a planform view of the avulsion. A headcut is located at the downstream end and is propagating upstream. It is anticipated that sometime in the near future, a new channel will be formed bypassing the restoration. Extensive and rapid channel widening is also occurring at Transect 10 (Figure 38). As it is located immediately downstream of a sudden increase in slope, all expectations are that this area will also continue to adjust in the near future. Section 3 is relatively stable in the upper regions. This is especially true in the vicinity of Edwards Gardens where the channel has been altered and is quite robust. However, the portion of Section 3 below the 2012 restoration is extremely active. This is particularly evident at Bank 3 (Figure 44), Transect 16 and in the area just upstream of the confluence where bank erosion pin EP3 3B was located. A representative from the City of Toronto recently asked if the creek was still adjusting. Based on this research, the answer is that while some areas could be considered "stable", other areas are very active.

Figure 67. Failing restoration in upper reach of Section 2.

Figure 68. Active avulsion located near Transect 6 in Section 2 with headcut propagating upstream.

The discontinuities observed in Wilket Creek are not unique and have been documented in other urban stream systems. Gregory et al (1992) reported that channel adjustments did not take place uniformly along an urban stream in England with instances of channel widening distributed unevenly along the length of the channel. Additionally, bed aggradation occurred in some areas while deposition was found in the region of bridges and other structures (Gregory et al 1992). In another study, alteration of a stream with a drop structure and other modifications lead to abrupt changes in channel morphology and an imbalance in the sediment regime within the creek (Arnold et al 1982). Discontinuities in particle size, trends towards erosion or deposition and cross-sectional geometry were observed by Grable and Harden (2006) in an urban stream in Tennessee. The authors suggest that due to the complex and dynamic nature of urban streams and discontinuities introduced by anthropogenic alteration, prediction of channel adjustments are uncertain (Grable and Harden 2006).

Based on this research, discontinuities in slope, flow and sediment transport are most pronounced at the interfaces between Sections 1 and 2 and Sections 2 and 3. In the first instance, the dam in Windfields Park is followed by an undersized culvert which is subject to pressurized flow at high discharges with instability occurring immediately downstream in the reaches associated with Transects 6 and 7. In the region between Sections 2 and 3, an undersized culvert at Lawrence Avenue is followed by a dam in Edwards Garden which interrupts downstream sediment continuity. The sudden changes in slope at these locations result in the greatest transport capacities per unit width that occur in Wilket Creek. Resolution of discontinuities at these locations would help move the system towards achieving sediment transport continuity throughout Wilket Creek.

6.2 Sediment Budget

Discussion of the sediment begins with an error estimation of the sediment volume contributions for the morphological approach. This is an important consideration as the results of sediment budgets are typically order of magnitude estimates rather than precise quantities (Reid and Dunne 2002). Additionally, these volumes played a key role in the comprehensive sediment budget. This is followed by a discussion of the sediment budget and a comparison with other studies.

6.2.1 Error Estimate of Volume Contribution

Error analysis in regards to selection of cross section location and surveying was performed following a procedure developed and reported in Martin and Church (1995) and Ashmore and Church (1998). In this method, volume estimates of reaches are compared by dividing them into two groups. One group is composed of odd numbered reaches and the other is composed of even reaches. The difference between the sums of the volumes provides an estimate of error range. In this study, the differences between sums of volumes were large between the June and July surveys and relatively small for the July and November surveys. Therefore the differences between the total study period were selected for error analysis (Table 29).

Table 29. Differences between sediment volumes of odd and even reaches.

Odd Reaches	**June-November Volumetric Change (m^3)**	**Even Reaches**	**June-November Volumetric Change (m^3)**
1	80.75	2	168.82
3	20.08	4	56.18
5	24.93	6	7.70
7	-242.13	8	-513.71
9	-143.47	10	-609.52
11	-44.53	12	111.70
13	493.39	14	-399.76
15	-641.30	16	-1857.64
17	12.28	-	-
Sum	-439		-3036
Difference	±2596		

The period between June and November surveys is approximately 160 days. If this value is applied over the period of a year, the error is ± 5926 m^3/yr. This is close to the values reported by Martin and Church (1995) and Rovira et al (2005) which were ± 6250 m^3/yr and ± 7335 m^3/yr respectively. However, it important to keep in mind differences between this study and the others. First of all, the other studies were carried out in much larger watersheds. Second, both studies selected their reaches based upon the assumption that “change in area at a cross-section is representative of the distance between it and the half-distance to each adjacent cross-section” (Martin and Church 1995). In contrast, the delineation of reach length in this study was based upon knowledge of how the channel upstream and downstream was reflective of a given cross section. As a result, one would expect greater difference in the sums of volumes between reaches.

6.2.2 Sediment Budget

The study found that sediment production in Section 1 occurs primarily through the culvert at York Mills Road with some contributions from bank erosion. Although this sediment is temporarily stored at some locations on the bank, the bed and behind the dam, most of the sediment appears to move into Section 2. Based on cross sectional surveys (Table 8 and Figure

43) as well as sediment transport rates estimating sediment input from the culvert at York Mills Road (Tables 16 and 18), this section contributes the least sediment to Wilket Creek.

As Tables 8 and 15 indicate, Section 2 is erosional in nature and its relative sediment contribution to Wilket Creek is much greater. The banks in the sinuous, middle region consist of un-consolidated easily erodible material. Although, two years of field observations revealed that lateral channel movement in this area is ongoing, erosion on the outer bank is typically matched by deposition on the inside bank. Extensive bank erosion continues to occur at Transects 7 and 10 while in the region of Transect 6, a headcut in an avulsion is moving upstream (Figure 68). Although this region stores large amount of sediment in the channel, downstream transport is unhindered until it reaches the pond behind the dam in Edwards Garden.

The dam in Edwards Garden is open during the winter months and periodically during the rest of the year in response to storm events. However, the dam still highly constrains the movement of sediment downstream as the sluice gate is located on the left hand side of the dam and is approximately 1.5 m in depth and 1.0 m in width. As a result, large amounts of sediment continue to accumulate behind the dam, especially on the right side (Figure 69) and must periodically be removed by dredging. Between 2007 and 2014 this amounted to 617 tons which was removed from the system and did not pass into Section 3. This sediment was not accounted for in the morphological approach but was considered in the comprehensive sediment budget.

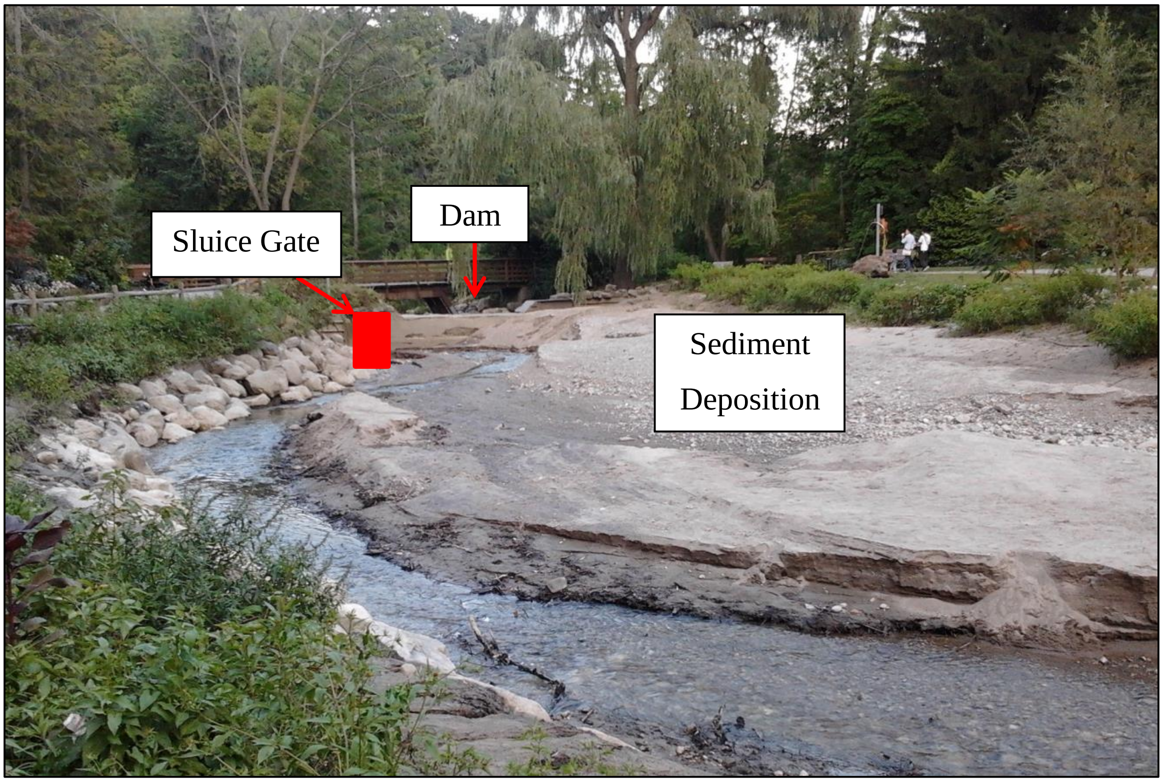


Figure 69. Pond behind the dam in Edwards Garden showing sediment deposition on right side of channel.

Any sediment that does pass through the sluice gate rapidly moves through Edwards Garden into Section 3. As cross section surveys indicate, relatively little sediment is contributed by bank erosion in the upper region of Section 3. Surveys, erosion pins and observations indicate that the area below the 2012 restoration, particularly in the region of Bank 3 and Transect 16, contributes the bulk of sediment produced within Section 3. This is stored on the banks in some locations but most exits at the confluence as well as being permanently stored on the left bank near the confluence.

In summary, Section 1 contributes relatively little sediment to Wilket Creek. In contrast, Section 2 produces a large amount of sediment with significant storage in the pond in Edwards Garden. Sediment that exits Wilket Creek at the confluence and on the banks near the confluence comes primarily from two sources; bank erosion in the lower portion and from behind the dam in Edwards Garden.

The conclusion of this study; that the primary sediment source in Wilket Creek comes from bank erosion, has been suggested by other authors. Streambank instability was cited by Hawley et al (2013) as the largest source of sediment to stream channels. Booth (1990) also found that mass wasting of banks formed the largest sediment input, especially in instances where the upper watershed had been paved. This is consistent with the findings of this study where mass wasting at Transects 7 and 10 in Section 2 and at Bank 3 and Transect 16 were found to be the largest contributors of sediment to Wilket Creek.

6.2.3 Comparison with Other Studies

Comparison of the sediment budget with other studies was difficult as there appear to be few recent studies in the literature involving urban watersheds of similar size in a nearby geographic region. The estimated sediment yields for Wilket Creek along with the findings of other studies are given in Table 30.

Table 30. Comparison of Wilket Creek sediment yield to other studies.

Stream and Location	Drainage Area (km^2)	Sediment Discharge (ton/yr)	Sediment Yield (ton/yr/km^2)
Little Falls Branch, Bethesda, MD*	10.62	8,627	812
Lake Barcroft, Fairfax, VA*	24.6	280,036	11,384
NW Branch Anacostia River, Hyattsville, MD*	127.95	82,891	648
Rock Creek, Washington D.C.*	161.1	90,264	560
NE Branch Anacostia, Riverdale, MD*	188.55	181,276	961
Good Hope Tributary, Colesville, MD**	4	1,400	135
Wilket Creek Morphological Sediment Budget, (June - November: Transect 8 Qout = 0)	15.4	10,000	680
Wilket Creek Morphological Sediment Budget (June - November: Bathymetric Survey)	15.4	13,000	880
Wilket Creek Comprehensive Sediment Budget (Windfields Park Dam Closed): June - November 2013	15.4	19,000	1,300
Wilket Creek Comprehensive Sediment Budget (Windfields Park Dam Open): June - November 2013	15.4	20,000	1,300

* (Wolman and Schick 1967)

** (Allmendinger et al 2007)

In the table above, there is a noticeable difference between the morphological approach and the comprehensive sediment budget. The primary reason for the difference between the two is that the morphological approach implicitly considers channel storage as the entire cross section was used. In contrast, the comprehensive sediment budget only considered the contribution of sediment from the banks and ignored the bed of the channel as losses on the bed represented pulses of sediment moving downstream and not actual bed erosion.

Although both sediment approaches yield slightly different results, it is important to keep in mind the purpose of each. The morphological approach estimates the contribution of bed and bank material to Wilket Creek and provides a method to calculate volumetric sediment transport within the channel. In contrast, the advantage of the comprehensive sediment budget is that it provides a relative estimate of the various input, storage and output terms.

Although the estimates from Wilket Creek are in the range of the other studies cited they may be slightly on the high side. The loss of sediment at Transect 16 between June and July had an effect on sediment yield at the confluence that exceeds its actual contribution. This transect, which is close to the confluence, lost 9 m^2 largely as the result of a single event. The actual distance along the channel for which a similar amount of erosion actually occurred was less than 100 m. However, the given reach length by which volume was calculated was over 300 m, drastically increasing the sediment yield at this reach (See Table 19). If the length of stream representative of Transect 16 is reduced from 307 m to 100 m, the resulting sediment yield for the morphological approach ranges between 400 and 600 $ton/yr/km^2$ while the yield for the comprehensive sediment budget ranges from 670 to 700 $ton/yr/km^2$.

6.2.4 Recommendations for Future Research

There was not sufficient time to rigorously measure all input, output and storage terms for a sediment budget. One key piece of information lacking is reliable long term flow measurements in Wilket Creek. Although a program to monitor discharge was implemented in the summer of 2013, it has not been sufficiently developed to aid in this project. Once established, it could be employed in conjunction with a sediment monitoring scheme at York Mills Road and the confluence with the West Don River. Such a program could provide more reliable information about the input of sediment at York Mills and the delivery of sediment to the West Don.

In regards to storage terms, monitoring storage behind the dam in Edwards Gardens would be useful in order to understand sediment delivery between Section 2 and Section 3. However, given the operation of the dam, this would be very labor intensive. As the largest amount of bank storage appears to occur in the lower region of Section 3, this may also be worth quantifying.

The lower section of Wilket Creek contains large valley walls, some of which are in direct contact with the creek. As a result, it would be worthwhile to assess their sediment contribution.

As initial surveys have been made at three locations, it is hoped that surveys will be made in the near future.

Unfortunately, there is little historical data regarding discharge and sediment in Wilket Creek. The one piece of historical data available is aerial imagery dating back to the 1950's. In depth analysis of this imagery may be able provide estimates of the contribution of channel enlargement to the sediment regime.

Although Wilket Creek is stable in some areas it appears to be undergoing adjustment at certain locations. In Section 2, this is seen at the avulsion near Transect 6 and in the region of Transect 10. As both of these locations occur downstream from sudden breaks in slope, further investigation should be undertaken to determine the cause. Additionally, large instances of bank erosion are occurring in Section 3, particularly downstream of the 2012 restoration and at Transect 16. Further investigation is warranted here prior to undertaking aggressive management actions.

7.0 Conclusions

Although sediment budgets are typically thought of as long term, academic studies, they can be completed within time frames suitable for watershed managers (Reid and Dunne 1996). In developing a long range management plan, the utility of a watershed level sediment budget cannot be underestimated as watershed level conditions may be identified that limit reach level restoration.

7.1 Key Findings

This sediment budget quantified relative sediment contributions, storage and output terms for Wilket Creek. Volumetric contributions at the reach level were calculated based on repeated cross section surveys leading to estimations of sediment transport and yield. Field observations and analysis of data for the sediment budget resulted in the identification of areas of channel instability such as lateral erosion and headcuts. Finally, a review of the findings brought to light gaps in the knowledge which warrant further investigation. Key findings of the study include:

1. Majority of sediment supplied to Wilket Creek comes from mass wasting of banks in Sections 2 and 3.
2. Sediment output at the confluence with the West Don River ranges between 680 to 1300 ton/yr/km^2.
3. Lateral channel migration is still occurring with the period between 2009 and 2012 exhibiting greater rates of migration than the periods between 1999 – 2003 and 2003 – 2009.
4. Wilket Creek exhibits discontinuities in slope, particle size, sediment transport capacity, level of anthropogenic alteration and channel morphology.
5. Large bank losses due to mass wasting in Sections 2 and 3 typically occur at discontinuities such as a break in slope and abrupt, anthropogenically induced changes to the channel (dams, culverts, stream restorations).
6. The channel is still undergoing adjustment in select areas.

As the stream is undergoing adjustment in some areas, further study is required before undertaking extensive restoration efforts as channels undergoing adjustment are poor candidates for restoration (Kochel and Miller 2010). Additionally, Booth (1990) notes that rehabilitation in channels undergoing widening or incision is often taken before conditions for success are optimal.

7.2 Management Recommendations

Anthropogenic alterations of Wilket Creek and its watershed including dams, culverts and stormwater discharges have contributed to discontinuities in the hydrologic and sediment regimes. Accordingly, the long term management strategy should focus on activities that promote the restoration of sedimentological and hydrological continuity throughout Wilket Creek.

The first recommendation would be to implement stormwater management practices in order to reduce large and sudden increases in discharge that occur as the result of storm events. Ideally, these should be implemented throughout the Wilket Creek watershed. However, given the large area involved, this may not be feasible. In this case, stormwater management actions should be focused on the Wilket Creek watershed upstream of York Mills Road. This portion of the watershed makes up two thirds of the total area and will provide the greatest return for effort. Additionally, the watershed above York Mills Road also contains parks and green space that could be used for stormwater infrastructure.

Subsequent management should focus on promoting continuity of the sediment and hydrologic regimes by removing restrictions to the flow of water and sediment, particularly dams and culverts. This effort should be concentrated at the interfaces between Sections 1 and 2 (Windfields Park) and Sections 2 and 3 (Edwards Garden). Management activities in Windfields Park should include permanent removal of the dam and replacement of the culvert immediately downstream with a structure that is properly sized. Once this has been accomplished, it will be necessary to address the avulsion that is in the process of by-passing the in-channel restoration.

To stabilize the grade between Transect 7 and the dam, an in-channel step/pool structure is recommended.

At the interface between Sections 2 and 3, it may not be feasible to address the culvert at Lawrence Avenue nor remove the dam in Edwards Garden. However, the sluice gate of the dam should be modified to allow more sediment to pass downstream. Following modification, the bed slope immediately downstream should be monitored to determine how the channel is adjusting and whether in-channel restoration is warranted.

It is hoped that this document will be a useful management tool for the City of Toronto and the Toronto and Region Conservation Authority. In completing this body of research as well as the concurrent study examining the effects of a stream restoration on sediment transport and mobility, baseline measurements were made that can be compared against future monitoring efforts. Additionally, monumented cross sections were established, pressure gauges installed and initial streamflow measurements were made for a rating curve. As intensive management efforts are ongoing in Wilket Creek, it is hoped that this body of research will serve as a starting point for further studies and have a positive influence on future restoration efforts.

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Appendix A – Cross Section Analysis

Bankfull and Top of Bank Metric Calculations

Calculation of bankfull metrics began with calculating bankfull area. At a few cross sections, one part of the bed was at a higher elevation than bankfull elevations. This resulted in two separate areas that were below the bankfull elevation. These two areas were then summed to get the total area below the bankfull water elevation. The results of the bankfull area calculations were then used in calculations of bankfull depth and scour depth.

Table 31. Calculations for bankfull area at cross sections and differences in area between surveys.

Transect	Area Below BF 1 June 2013 (m^2)	Area Below BF 2 June 2013 (m^2)	Area Above BF June 2013 (m^2)	Total Area Below BF June 2013 (m^2)	Area Below BF 1 July 2013 (m^2)	Area Below BF 2 July 2013 (m^2)	Area Above BF July 2013 (m^2)	Total Area Below BF July 2013 (m^2)	Area Below BF 1 November 2013 (m^2)	BF 2 November 2013 (m^2)	Area Above BF November 2013 (m^2)	Total Area Below BF November 2013 (m^2)	Difference June & July (m^2)	Difference July & November (m^2)	Difference June & November (m^2)
1	2.39			2.39	0.14	0.94	0.00	1.08	2.37			2.37	1.31	-1.29	0.02
2	8.45			8.45	8.02			8.02	7.67			7.67	0.43	0.35	0.78
3	8.20			8.20	7.93			7.93	8.06			8.06	0.27	-0.13	0.14
4	8.01			8.01	7.51			7.51	7.40			7.40	0.51	0.11	0.62
5	6.40			6.40	6.01			6.01	6.03			6.03	0.39	-0.01	0.37
6	4.71	0.58	0.01	5.29	4.64	0.58	0.00	5.23	4.58	0.64	0.01	5.22	0.06	0.01	0.07
7	9.08			9.08	9.83			9.83	9.72			9.72	-0.76	0.12	-0.64
8	6.71			6.71	6.81			6.81	7.11			7.11	-0.09	-0.31	-0.40
9	3.86			3.86	4.09			4.09	4.11			4.11	-0.23	-0.02	-0.25
10	9.59	0.04	0.00	9.63	10.20			10.20	10.44			10.44	-0.57	-0.23	-0.80
11	6.98			6.98	7.18			7.18	7.20			7.20	-0.20	-0.02	-0.22
12	9.59			9.59	9.61			9.61	8.66			8.66	-0.02	0.95	0.93
13	7.31			7.31	6.44	0.17	0.08	6.61	5.85			5.85	0.70	0.76	1.46
14	1.14	7.97	0.01	9.11	0.88	7.76	0.00	8.64	10.19			10.19	0.48	-1.56	-1.08
15	7.36			7.36	9.49			9.49	8.88			8.88	-2.13	0.61	-1.52
16	4.83	0.30	0.80	5.12	9.31	0.15	0.47	9.46	6.32	0.16	0.65	6.48	-4.33	2.97	-1.36
17	4.25			4.25	3.49			3.49	4.47			4.47	0.76	-0.98	-0.22

Table 32. Bankfull depth calculations for June, July and November 2013 surveys.

Transect	BF Area June 2013 (m2)	BF Area July 2013 (m2)	BF Area November 2013 (m2)	BF Width June 2013 (m)	BF Width July 2013 (m)	BF Width November 2013 (m)	BF Depth June 2013 (m)	BF Depth July 2013 (m)	BF Depth November 2013 (m)
1	2.39	1.08	2.37	5.76	5.83	5.79	0.42	0.19	0.41
2	8.45	8.02	7.67	10.29	10.09	10.05	0.82	0.79	0.76
3	8.20	7.93	8.06	9.53	9.65	9.67	0.86	0.82	0.83
4	8.01	7.51	7.40	13.40	13.41	13.45	0.60	0.56	0.55
5	6.40	6.01	6.03	10.74	10.65	10.67	0.60	0.56	0.56
6	5.29	5.23	5.22	14.81	15.22	15.19	0.36	0.34	0.34
7	9.08	9.83	9.72	11.97	12.14	11.76	0.76	0.81	0.83
8	6.71	6.81	7.11	9.87	10.05	10.25	0.68	0.68	0.69
9	3.86	4.09	4.11	9.60	9.68	9.70	0.40	0.42	0.42
10	9.63	10.20	10.44	12.73	12.88	13.06	0.76	0.79	0.80
11	6.98	7.18	7.20	11.46	11.19	11.28	0.61	0.64	0.64
12	9.59	9.61	8.66	10.30	10.73	10.91	0.93	0.90	0.79
13	7.31	6.61	5.85	12.65	12.78	12.83	0.58	0.52	0.46
14	9.11	8.64	10.19	17.75	17.55	17.52	0.51	0.49	0.58
15	7.36	9.49	8.88	10.02	10.11	10.06	0.73	0.94	0.88
16	5.12	9.46	6.48	16.27	19.76	20.07	0.31	0.48	0.32
17	4.25	3.49	4.47	9.11	9.11	9.11	0.47	0.38	0.49

Table 33. Bankfull scour depth calculations for June to July, July to November and June to November 2013.

Transect	Area Difference June & July (m2)	Area Difference July & November (m2)	Area Difference June & November (m2)	Bankfull Width July (m)	Bankfull Width November (m)	Scour/Deposition Depth June-July (m)	Scour/Deposition Depth July-November (m)	Scour/Deposition Depth June-November (m)
1	1.31	-1.29	0.02	5.83	5.79	0.22	-0.22	0.00
2	0.43	0.35	0.78	10.09	10.05	0.04	0.04	0.08
3	0.27	-0.13	0.14	9.65	9.67	0.03	-0.01	0.01
4	0.51	0.11	0.62	13.41	13.45	0.04	0.01	0.05
5	0.39	-0.01	0.37	10.65	10.67	0.04	0.00	0.03
6	0.06	0.01	0.07	15.22	15.19	0.00	0.00	0.00
7	-0.76	0.12	-0.64	12.14	11.76	-0.06	0.01	-0.05
8	-0.09	-0.31	-0.40	10.05	10.25	-0.01	-0.03	-0.04
9	-0.23	-0.02	-0.25	9.68	9.70	-0.02	0.00	-0.03
10	-0.57	-0.23	-0.80	12.88	13.06	-0.04	-0.02	-0.06
11	-0.20	-0.02	-0.22	11.19	11.28	-0.02	0.00	-0.02
12	-0.02	0.95	0.93	10.73	10.91	0.00	0.09	0.09
13	0.70	0.76	1.46	12.78	12.83	0.05	0.06	0.11
14	0.48	-1.56	-1.08	17.55	17.52	0.03	-0.09	-0.06
15	-2.13	0.61	-1.52	10.11	10.06	-0.21	0.06	-0.15
16	-4.33	2.97	-1.36	19.76	20.07	-0.22	0.15	-0.07
17	0.76	-0.98	-0.22	9.11	9.11	0.08	-0.11	-0.02

Table 34. Calculations of top of bank metrics for June, July and November 2013 surveys.

Transect	Top of Bank Area: June 2013 (m^2)	Top of Bank Area: July (m^2)	Top of Bank Area: November 2013 (m^2)	Top of Bank Width: June (m)	Top of Bank Width: July (m)	Top of Bank Width: November (m)	Depth June (m)	Depth July (m)	Depth Nov (m)	Difference June & July (m^2)	Difference July & November (m^2)	Difference June & November (m^2)	Scour/Deposition Depth June-July (m)	Scour/Deposition Depth July-November (m)	Scour/Deposition Depth June-November (m)
1	7.00	5.75	7.00	7.97	7.86	7.79	0.88	0.73	0.90	1.2515	-1.2515	0	0.16	-0.16	0.00
2	14.11	13.55	13.19	13.10	12.90	12.78	1.08	1.05	1.03	0.5561	0.3594	0.9155	0.04	0.03	0.07
3	14.31	14.12	14.24	10.35	10.40	10.35	1.38	1.36	1.38	0.1937	-0.1234	0.0703	0.02	-0.01	0.01
4	8.82	8.38	8.55	13.45	13.55	13.58	0.66	0.62	0.63	0.4316	-0.1629	0.2687	0.03	-0.01	0.02
5	17.40	16.95	16.98	14.10	13.98	13.89	1.23	1.21	1.22	0.46	-0.0357	0.4213	0.03	0.00	0.03
6	5.29	5.23	5.23	14.81	15.22	15.19	0.36	0.34	0.34	0.06	-0.0022	0.0577	0.00	0.00	0.00
7	20.16	20.83	20.74	15.93	15.89	15.98	1.27	1.31	1.30	-0.6718	0.0856	-0.5862	-0.04	0.01	-0.04
8	20.67	20.74	21.41	23.66	23.71	23.84	0.87	0.87	0.90	-0.0742	-0.6673	-0.7415	0.00	-0.03	-0.03
9	12.34	12.56	12.68	11.38	11.47	11.50	1.09	1.09	1.10	-0.2118	-0.1252	-0.337	-0.02	-0.01	-0.03
10	11.52	12.13	12.37	13.44	13.80	13.97	0.86	0.88	0.89	-0.61	-0.2455	-0.8555	-0.04	-0.02	-0.06
11	19.63	19.82	19.80	13.51	13.58	13.28	1.45	1.46	1.49	-0.1913	0.0177	-0.1736	-0.01	0.00	-0.01
12	14.97	15.16	14.26	11.31	11.54	11.60	1.32	1.31	1.23	-0.1869	0.8986	0.7117	-0.02	0.08	0.06
13	15.76	15.01	14.36	14.38	14.42	14.38	1.10	1.04	1.00	0.7473	0.6559	1.4032	0.05	0.05	0.10
14	38.16	37.50	38.99	21.34	21.31	21.22	1.79	1.76	1.84	0.6534	-1.4882	-0.8348	0.03	-0.07	-0.04
15	12.20	14.44	13.81	12.45	12.86	12.93	0.98	1.12	1.07	-2.2391	0.6303	-1.6088	-0.17	0.05	-0.12
16	35.92	44.83	41.79	24.10	27.86	27.98	1.49	1.61	1.49	-8.905	3.0365	-5.8685	-0.32	0.11	-0.21
17	4.25	3.49	4.47	9.11	9.11	9.11	0.47	0.38	0.49	0.7577	-0.9756	-0.2179	0.08	-0.11	-0.02

Deposition and Erosion at Individual Cross Sections

Table 35. ArcGIS analysis of erosion and deposition at individual transects for the June, July and November 2013 surveys.

Transect	June - July Deposition (m^2)	June - July Erosion (m^2)	Budget (m^2)	July - November Deposition (m^2)	July - November Erosion (m^2)	Budget (m^2)	June - November Deposition (m^2)	June - November Erosion (m^2)	Budget (m^2)
1	1.451	0.046	1.404	0.131	1.333	-1.202	0.289	0.086	0.203
2	0.840	0.131	0.709	0.626	0.167	0.458	1.239	0.071	1.168
3	0.369	0.186	0.183	0.107	0.146	-0.040	0.296	0.190	0.106
4	0.475	0.019	0.457	0.201	0.371	-0.170	0.400	0.114	0.286
5	0.575	0.092	0.483	0.259	0.296	-0.037	0.611	0.166	0.445
6	0.222	0.263	-0.041	0.283	0.190	0.093	0.330	0.279	0.051
7	0.533	1.185	-0.653	0.605	0.509	0.096	0.683	1.240	-0.557
8	0.440	0.695	-0.255	0.236	0.970	-0.734	0.316	1.303	-0.987
9	0.494	0.738	-0.244	0.469	0.577	-0.108	0.536	0.888	-0.352
10	0.359	1.338	-0.979	0.531	0.788	-0.257	0.442	1.678	-1.236
11	0.270	0.507	-0.237	0.371	0.303	0.068	0.408	0.577	-0.168
12	0.409	0.641	-0.233	1.028	0.158	0.870	1.039	0.401	0.637
13	1.588	0.932	0.656	1.410	0.789	0.621	1.582	0.305	1.276
14	1.021	0.322	0.699	0.309	1.779	-1.470	0.581	1.352	-0.771
15	0.000	2.288	-2.288	0.807	0.157	0.650	0.055	1.693	-1.638
16	0.737	9.860	-9.124	3.730	0.657	3.072	1.875	7.926	-6.051
17	0.947	0.267	0.680	0.577	1.190	-0.612	0.623	0.555	0.067
Total	10.730	19.511	-8.781	11.680	10.382	1.298	11.304	18.824	-7.520
Mean	0.631	1.148	-0.517	0.687	0.611	0.076	0.665	1.107	-0.442

Appendix B - Sediment Transport Capacities

Table 36. Sediment transport capacity for D_{50} from Site S1 A.

Transect	Channel Area (m2)	Channel Perimeter (m)	Channel Hydraulic Radius (m)	D_{50} (m)	τ_{*c}	τ_{*}	Slope	τ_c (N/m^2)	τ_o (N/m^2)	$\tau_c > \tau$	$\tau_{*c} > \tau_{*}$	q_s (m^2/s)	Channel Top Width: Nov (m)	Q_s (m^3/day)
1	6.9967	8.7529	0.80	0.0016	0.0350	2.1801	0.0072	0.905	56.339	No	No	0.0065	7.79	4354
2	13.1924	13.5967	0.97	0.0016	0.0350	2.6462	0.0072	0.905	68.385	No	No	0.0087	12.78	9596
3	14.24	12.0274	1.18	0.0016	0.0350	3.2290	0.0072	0.905	83.447	No	No	0.0118	10.35	10516
4	8.5471	14.3608	0.60	0.0016	0.0350	1.6232	0.0072	0.905	41.948	No	No	0.0041	13.58	4837
5	16.9811	15.2754	1.11	0.0016	0.0350	11.3693	0.0270	0.905	293.816	No	No	0.0786	13.89	94313
6	5.2188	8.4003	0.62	0.0016	0.0350	6.3538	0.0270	0.905	164.202	No	No	0.0327	15.19	42942
7	20.7425	17.4846	1.19	0.0016	0.0350	1.3032	0.0029	0.905	33.678	No	No	0.0029	15.98	4063
8	21.4118	25.3512	0.84	0.0016	0.0350	0.9278	0.0029	0.905	23.977	No	No	0.0017	23.84	3579
9	12.6814	13.0068	0.97	0.0016	0.0350	1.0710	0.0029	0.905	27.678	No	No	0.0022	11.50	2159
10	12.3717	16.0512	0.77	0.0016	0.0350	2.5984	0.0089	0.905	67.151	No	No	0.0085	13.97	10201
11	19.7988	15.4472	1.28	0.0016	0.0350	4.3209	0.0089	0.905	111.665	No	No	0.0183	13.28	20967
S3A	6.9967	8.7529	0.80	0.0016	0.0350	9.9920	0.0330	0.905	258.222	No	No	0.0647	7.79	43544
12	14.2618	12.7758	1.12	0.0016	0.0350	5.4970	0.0130	0.905	142.059	No	No	0.0263	11.60	26345
13	14.3565	15.7855	0.91	0.0016	0.0350	4.4785	0.0130	0.905	115.737	No	No	0.0193	14.38	23969
Parish 13	10.0442	12.6111	0.80	0.0016	0.0350	3.9219	0.0130	0.905	101.355	No	No	0.0158	11.65	15889
14	38.992	23.5645	1.65	0.0016	0.0350	8.1481	0.0130	0.905	210.571	No	No	0.0476	21.22	87285
15	13.8055	13.9005	0.99	0.0016	0.0350	4.8906	0.0130	0.905	126.387	No	No	0.0220	12.93	24624
16	41.7921	30.1092	1.39	0.0016	0.0350	6.8349	0.0130	0.905	176.635	No	No	0.0365	27.98	88292
17	18.4952	13.1961	1.40	0.0016	0.0350	6.9016	0.0130	0.905	178.359	No	No	0.0371	9.11	29174

Note: γ (N/m^3) = 9789, ν (m^2/s) = 1.01E-06, G = 2.65, ρ (kg/m^3) = 998.2

Table 37. Sediment transport capacity for D_{16} of nearest sediment sampling site.

Transect	Channel Area (m2)	Channel Perimeter (m)	Channel Hydraulic Radius (m)	D_{50} (m)	τ_{*c}	τ_{*}	Slope	τ_c (N/m^2)	τ_o (N/m^2)	$\tau_c > \tau$	$\tau_{*c} > \tau_{*}$	q_s (m^2/s)	Channel Top Width: Nov (m)	Q_s (m^3/day)
1	6.9967	8.7529	0.80	0.0149	0.0466	0.2341	0.0072	11.215	56.339	No	No	0.0048	7.79	3196
2	13.1924	13.5967	0.97	0.0149	0.0466	0.2842	0.0072	11.215	68.385	No	No	0.0068	12.78	7479
3	14.24	12.0274	1.18	0.0149	0.0466	0.3467	0.0072	11.215	83.447	No	No	0.0096	10.35	8604
4	8.5471	14.3608	0.60	0.0149	0.0466	0.1743	0.0072	11.215	41.948	No	No	0.0027	13.58	3134
5	16.9811	15.2754	1.11	0.0149	0.0466	1.2209	0.0270	11.215	293.816	No	No	0.0745	13.89	89378
6	5.2188	8.4003	0.62	0.0149	0.0466	0.6809	0.0270	11.215	163.868	No	No	0.0296	15.19	38812
7	20.7425	17.4846	1.19	0.0118	0.0454	0.1767	0.0029	8.653	33.678	No	No	0.0020	15.98	2711
8	21.4118	25.3512	0.84	0.0118	0.0454	0.1258	0.0029	8.653	23.977	No	No	0.0009	23.84	1937
9	12.6814	13.0068	0.97	0.0118	0.0454	0.1452	0.0029	8.653	27.678	No	No	0.0013	11.50	1293
10	12.3717	16.0512	0.77	0.0220	0.0481	0.1890	0.0089	17.092	67.151	No	No	0.0056	13.97	6701
11	19.7988	15.4472	1.28	0.0220	0.0481	0.3142	0.0089	17.092	111.665	No	No	0.0144	13.28	16543
S3A	6.9967	8.7529	0.80	0.0280	0.0493	0.5714	0.0330	22.296	258.430	No	No	0.0569	7.79	38279
12	14.2618	12.7758	1.12	0.0280	0.0493	0.3141	0.0130	22.296	142.059	No	No	0.0206	11.60	20589
13	14.3565	15.7855	0.91	0.0221	0.0481	0.3242	0.0130	17.170	115.737	No	No	0.0153	14.38	19062
Parish 13	10.0442	12.6111	0.80	0.0221	0.0481	0.2839	0.0130	17.170	101.355	No	No	0.0121	11.65	12191
14	38.992	23.5645	1.65	0.0221	0.0481	0.5899	0.0130	17.170	210.571	No	No	0.0422	21.22	77328
15	13.8055	13.9005	0.99	0.0148	0.0466	0.5287	0.0130	11.140	126.387	No	No	0.0194	12.93	21673
16	41.7921	30.1092	1.39	0.0148	0.0466	0.7389	0.0130	11.140	176.635	No	No	0.0334	27.98	80692
17	18.4952	13.1961	1.40	0.0148	0.0466	0.7461	0.0130	11.140	178.359	No	No	0.0339	9.11	26687

Note: γ (N/m^3) = 9789, ν (m^2/s) = 1.01E-06, G = 2.65, ρ (kg/m^3) = 998.2

Table 38. Sediment transport capacity of D_{25} for nearest sediment sampling site.

Transect	Channel Area (m2)	Channel Perimeter (m)	Channel Hydraulic Radius (m)	D_{50} (m)	τ_{*c}	τ_*	Slope	τ_c (N/m^2)	τ_o (N/m^2)	$\tau_c > \tau$	$\tau_{*c} > \tau_*$	q_s (m^2/s)	Channel Top Width: Nov (m)	Q_s (m^3/day)
1	6.9967	8.7529	0.80	0.0230	0.0483	0.1517	0.0072	17.943	56.339	No	No	0.0037	7.79	2509
2	13.1924	13.5967	0.97	0.0230	0.0483	0.1841	0.0072	17.943	68.385	No	No	0.0056	12.78	6199
3	14.24	12.0274	1.18	0.0230	0.0483	0.2246	0.0072	17.943	83.447	No	No	0.0083	10.35	7430
4	8.5471	14.3608	0.60	0.0230	0.0483	0.1129	0.0072	17.943	41.948	No	No	0.0018	13.58	2163
5	16.9811	15.2754	1.11	0.0230	0.0483	0.7909	0.0270	17.943	293.816	No	No	0.0718	13.89	86205
6	5.2188	8.4003	0.62	0.0230	0.0483	0.4411	0.0270	17.943	163.868	No	No	0.0276	15.19	36275
7	20.7425	17.4846	1.19	0.0139	0.0462	0.1500	0.0029	10.372	33.678	No	No	0.0018	15.98	2436
8	21.4118	25.3512	0.84	0.0139	0.0462	0.1068	0.0029	10.372	23.977	No	No	0.0008	23.84	1621
9	12.6814	13.0068	0.97	0.0139	0.0462	0.1233	0.0029	10.372	27.678	No	No	0.0011	11.50	1122
10	12.3717	16.0512	0.77	0.0375	0.0503	0.1109	0.0089	30.466	67.151	No	No	0.0035	13.97	4203
11	19.7988	15.4472	1.28	0.0375	0.0503	0.1844	0.0089	30.466	111.665	No	No	0.0115	13.28	13161
S3A	6.9967	8.7529	0.80	0.0570	0.0516	0.2807	0.0330	47.506	258.430	No	No	0.0480	7.79	32316
12	14.2618	12.7758	1.12	0.0570	0.0516	0.1543	0.0130	47.506	142.059	No	No	0.0144	11.60	14443
13	14.3565	15.7855	0.91	0.0348	0.0502	0.2059	0.0130	28.217	115.737	No	No	0.0128	14.38	15949
Parish 13	10.0442	12.6111	0.80	0.0348	0.0502	0.1803	0.0130	28.217	101.355	No	No	0.0098	11.65	9872
14	38.992	23.5645	1.65	0.0348	0.0502	0.3746	0.0130	28.217	210.571	No	No	0.0386	21.22	70798
15	13.8055	13.9005	0.99	0.0188	0.0475	0.4162	0.0130	14.424	126.387	No	No	0.0186	12.93	20754
16	41.7921	30.1092	1.39	0.0188	0.0475	0.5817	0.0130	14.424	176.635	No	No	0.0324	27.98	78302
17	18.4952	13.1961	1.40	0.0188	0.0475	0.5874	0.0130	14.424	178.359	No	No	0.0329	9.11	25904

Note: γ (N/m^3) = 9789, ν (m^2/s) = 1.01E-06, G = 2.65, ρ (kg/m^3) = 998.2

Table 39. Sediment transport capacity for D_{50} of nearest sediment samplings site.

Transect	Channel Area (m2)	Channel Perimeter (m)	Channel Hydraulic Radius (m)	D_{50} (m)	τ_{*c}	τ_{*}	Slope	τ_c (N/m^2)	τ_o (N/m^2)	$\tau_c > \tau$	$\tau_{*c} > \tau_{*}$	q_s (m^2/s)	Channel Top Width: Nov (m)	Q_s (m^3/day)
1	6.9967	8.7529	0.80	0.0715	0.0522	0.0488	0.0072	60.284	56.339	Yes	Yes	#NUM!	7.79	#NUM!
2	13.1924	13.5967	0.97	0.0715	0.0522	0.0592	0.0072	60.284	68.385	No	No	0.0004	12.78	399
3	14.24	12.0274	1.18	0.0715	0.0522	0.0723	0.0072	60.284	83.447	No	No	0.0017	10.35	1562
4	8.5471	14.3608	0.60	0.0715	0.0522	0.0363	0.0072	60.284	41.948	Yes	Yes	#NUM!	13.58	#NUM!
5	16.9811	15.2754	1.11	0.0715	0.0522	0.2544	0.0270	60.284	293.816	No	No	0.0560	13.89	67141
6	5.2188	8.4003	0.62	0.0715	0.0522	0.1419	0.0270	60.284	163.868	No	No	0.0165	15.19	21695
7	20.7425	17.4846	1.19	0.0253	0.0487	0.0824	0.0029	19.901	33.678	No	No	0.0008	15.98	1107
8	21.4118	25.3512	0.84	0.0253	0.0487	0.0587	0.0029	19.901	23.977	No	No	0.0001	23.84	266
9	12.6814	13.0068	0.97	0.0253	0.0487	0.0677	0.0029	19.901	27.678	No	No	0.0003	11.50	338
10	12.3717	16.0512	0.77	0.0780	0.0524	0.0533	0.0089	66.016	67.151	No	No	0.000019	13.97	23
11	19.7988	15.4472	1.28	0.0780	0.0524	0.0886	0.0089	66.016	111.665	No	No	0.0048	13.28	5548
S3A	6.9967	8.7529	0.80	0.1535	0.0540	0.1042	0.0330	133.883	258.430	No	No	0.0218	7.79	14663
12	14.2618	12.7758	1.12	0.1535	0.0540	0.0573	0.0130	133.883	142.059	No	No	0.0004	11.60	367
13	14.3565	15.7855	0.91	0.1112	0.0530	0.0644	0.0130	95.193	115.737	No	No	0.0015	14.38	1814
Parish 13	10.0442	12.6111	0.80	0.1112	0.0530	0.0564	0.0130	95.193	101.355	No	No	0.0002	11.65	241
14	38.992	23.5645	1.65	0.1112	0.0530	0.1172	0.0130	95.193	210.571	No	No	0.0194	21.22	35632
15	13.8055	13.9005	0.99	0.0363	0.0500	0.2156	0.0130	29.316	126.387	No	No	0.0150	12.93	16754
16	41.7921	30.1092	1.39	0.0363	0.0500	0.3013	0.0130	29.316	176.635	No	No	0.0280	27.98	67771
17	18.4952	13.1961	1.40	0.0363	0.0500	0.3042	0.0130	29.316	178.359	No	No	0.0285	9.11	22456

Note: γ (N/m^3) = 9789, ν (m^2/s) = 1.01E-06, G = 2.65, ρ (kg/m^3) = 998.2e