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MORPHODYNAMIC RESPONSE OF LOWER SPENCER CREEK TO LARGE PRECIPITATION EVENTS AND CHANNEL MODIFICATIONS

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Abstract: Severe weather events are occurring more frequently with significant repercussions as our climate changes. Between 2004 and 2012 the city of Hamilton, Ontario experienced 17 storm events that caused flooding. Of these 17 events, five were classified as either 50- or 100-year storm events, with one classified as a storm with a return period greater than 100 years. Events of this magnitude can lead to rapid morphological adjustments in rivers, including instability of river banks, bank collapse, and alterations in stream channel alignment. It is important to understand the hydraulic and geomorphic response of rivers and streams to future storm events to predict long term morphological change, protect hydraulic structures, and manage aquatic ecosystems. The goal of this research is to examine the influence of extreme precipitation events on the morphodynamic response of Lower Spencer Creek under current channel morphological conditions and simulated modifications. Two events are simulated using the one-dimensional computational model, HEC-RAS: an averaged base flow event and a 100-year return period event. Additionally, channel modification simulations were made to four cross sections at the downstream end of Lower Spencer Creek. The first modification widened the channel at these sections, while the second modification lengthened the channel at these sections to be representative of increased meandering of the stream. Based on the flow events, the first modification to the channel showed the largest reduction in velocity, sediment concentration, and shear stress at all cross sections. The results from this study will contribute to building a framework for analyzing the morphodynamic response of urban streams to storm events of varying return periods and durations, and will assist river engineers and hydrologists in managing and restoring urban creeks to mitigate flooding while balancing erosion and ecological processes.

1 INTRODUCTION

Due to numerous natural and anthropogenic effects, urban rivers and streams are often challenged to satisfy hydraulic, geomorphic, and ecological functions. The risk of flooding in urban rivers and streams is increased as a result of climate change and land use changes, such as urbanization and river channel modifications (Khattak et al., 2016; Ashmore and Church, 2001). Heavy rainfall and flooding affect the channel morphology, sediment characteristics, soil erosion, and aquatic habitat (Rae, 1987; Blom and Voesenek, 1996; Ashmore and Church, 2001).

Channelization is used as an approach in river engineering to control floods, stabilize banks, and modify navigation routes. Historically, channelization was utilized to manage rivers in urban environments. However, such modifications to channels often have an unfavourable impact on sedimentologic, hydrologic, and biologic channel properties (Kroes and Hupp, 2010; Bukaceckas, 2007; Soar and Thorne, 2001). Impacts include, but are not limited to, loss of aquatic habitat, increase in water temperature and sediment concentration, and changes in water levels and flow conditions (Shields and Palermo, 1982).

Mathematical models are often used as cost-effective tools for understanding river channel dynamics, such as channel morphology, flow, and sediment transport. Mathematical modeling tools can be used to evaluate stream restoration options to help determine an optimal stream morphological design to balance hydraulic, geomorphic, and ecological functions. Additionally, mathematical modeling tools can be used in the investigation of stream hydraulic and geomorphic response to changes in flow regime. These tools have been widely used in theoretical and practical applications of flood prediction and floodwave routing in urban rivers and streams (Horrit and Bates, 2002).

The Hydraulic Engineering Centre River Analysis System (HEC-RAS), created by the U.S. Department of Defense, Army Corps of Engineers, is widely used by river engineers in stream flow and floodplain analyses. This model is capable of simulating steady flow, unsteady flow, and sediment transport with one-dimensional and two-dimensional approximations. HEC-RAS has been used in a variety of applications relating to flooding in channels. For example, Hicks and Peacock (2005) used this program to evaluate flood routing and water level forecasting, Sholtes and Doyle (2011) applied the program to model synthetic and field-based stream reaches for impaired and restored reaches, and Khattak et al. (2016) combined this program with ArcGIS to develop floodplain maps for the Kubal River.

The city of Hamilton in Southwestern Ontario, Canada, is susceptible to flooding due to rainfall events and snowmelt, with 17 storm events resulting in flooding between 2004 and 2012 (Citizens of City Hall, 2012). A well-known example of flooding in Southwestern Ontario is Hurricane Hazel, which occurred on October 15 and 16, 1954. This event was found to have a 100-year return period, with 200 mm of rain in 24 hours and wind speeds as high as 124 km/h. Events of this magnitude have since occurred in in Southwestern Ontario and are likely to occur in the future. Therefore, it is important to understand and evaluate the effects of large precipitation events on the morphology and ecology in urban streams (Marsh, 2012).

This research provides part of a framework to evaluate hydraulic, geomorphic, and ecological performance of rivers under varying conditions. With the use of HEC-RAS, two channel modifications are made to the downstream cross sections of Lower Spencer Creek. These channel modifications aim to reduce velocity and sediment transport within the channel, thereby reducing the erosion and adverse ecological impact. Due to the expected increase in frequency of heavy storm events, simulations are conducted for each channel modification of large flow events to determine which modification could be a sustainable solution for Lower Spencer Creek.

2 STUDY AREA

Spencer Creek, located in the Lower Spencer subwatershed in Hamilton, Ontario, Canada, is presently under investigation by the Hamilton Conservation Authority (HCA) to return the channel to a more natural channel pattern. The plan proposes a relocation of the existing Spencer Creek Trail near Cootes Drive, replacement of dead ash trees, and removal of invasive grasses. These transformations will attempt to balance sediment transport, flood prevention, and ecology. By creating nesting areas, the plan has potential to protect the existing turtle population in the Spencer Creek area. Lower Spencer Creek, shown in Figure 1, is 7 km in length; however, the present research only examines the lower 4.25 km of the creek between King Street (i.e., XS 2) and Cootes Drive (i.e., XS 18). The widths of cross sections within this reach range from 4 m to 15 m. The initial phase of alterations performed by the HCA will focus on 300 m of Lower Spencer Creek closest to Cootes Drive, with future restoration moving upstream towards Thorpe Street (Leitner, 2014).

3 METHODS

The present research utilizes the one-dimensional computational model, HEC-RAS 4.1, to investigate the morphological performance of Lower Spencer Creek to large simulated precipitation events and multiple channel modifications. A complete description of the methodology followed in this work is provided in Martin (2017).

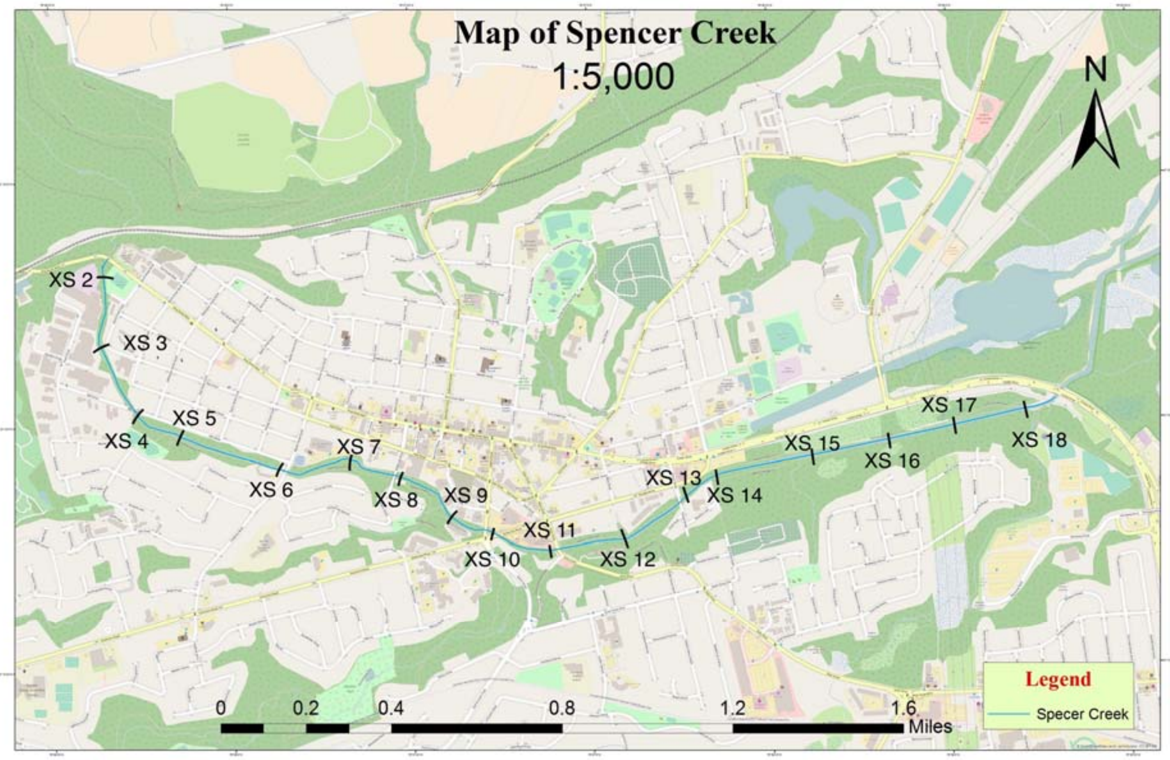

Figure 1: Map of Lower Spencer Subwatershed and Cross Sections in Lower Spencer Creek

3.1 Description of data

Field measurements were conducted to collect cross sectional geometry and substrate data required for modeling. Field measurements, including bankfull widths, cross-sectional depths, and sediment samples were collected at cross sections 15, 16, 17, and 18 of Lower Spencer Creek. A bank-to-bank width was measured at each section, and depth measurements were taken at five locations across each section. Sediment samples at each location of depth measurement were collected to characterize the substrate conditions in the reach. Five (5) samples were collected at each cross section for use in analysis.

Hydrometer tests were performed according to ASTM D422 on the collected sediment samples to determine the grain size distribution for the sediment passing through a No. 200 sieve. This data was used to provide more accurate sediment data at cross sections 15, 16, 17, and 18.

3.2 Channel Modifications

With the use of the channel modification extension in HEC-RAS, simulated modifications were made to the cross sections between Thorpe Street and Cootes Drive, namely, cross sections 15, 16, 17, and 18. The goal of the modifications was to evaluate the degree of improvement in flood control, sediment transport, and channel stability in these sections. These sections were selected for proposed modifications due to the high risk of flooding and stream instability in this reach.

Modification 1 examines widening downstream sections in Lower Spencer Creek (cross sections 15, 16, 17 and 18) by 15%, in efforts to reduce velocity and sediment transport in the channel. Modification 2, which lengthened the distance between cross sections 15, 16, 17, and 18 by 10%, thereby reducing the slope and simulating the creation of a more sinuous channel, aimed to return Lower Spencer Creek a more natural, pre-channelization condition. These modifications both aimed to reduce velocity within the creek, thereby decreasing its sediment transport capacity; this will result in less erosion and channel instability

(Watson et al., 1999). Sediment conditions for the modified simulations remained consistent with the existing channel simulations.

3.3 Precipitation Events

Rainfall events with long durations and high intensities are a common cause of flooding. A well-known example of this is Hurricane Hazel, which was classified as a 100-year event (Marsh, 2012). Storm events of this magnitude are expected to occur more frequently in the future (Takemura and Fukoma, 2014). For this reason, simulations with a 100-year return period were performed on Lower Spencer Creek.

Hydrographs were created for two events using the Soil Conservation Service (SCS) method (see Figure 2). The first event, henceforth referred to as Event 1, had a constant discharge of 1.25 m^3/s over a 24-hour period; this flow was calculated by assessing the average of the peak flows over a 5-year period between 2011 and 2015 in this reach of Lower Spencer Creek. The second event, henceforth referred to as Event 2, was a 100-year event over 24-hours with a peak flow of 12.23 m^3/s. This event was chosen to simulate the Hurricane Hazel event.

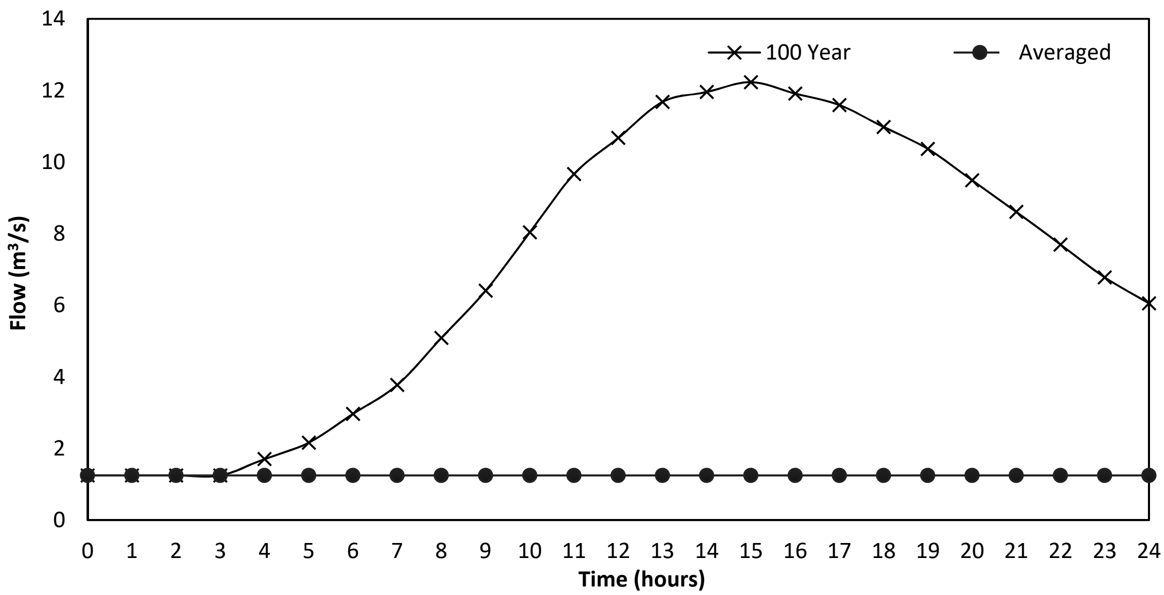

Figure 2: Storm Hydrographs

4 RESULTS AND DISCUSSION

4.1 Results

Channel modifications were performed on the existing channel with the intention of decreasing velocity and sediment concentration within the channel. Applying Modification 1 to the channel confirmed a decrease in velocity at cross section 15, 16, 17, and 18 for Event 1 compared to the existing channel configuration; the largest decrease occurred at cross section 15, with a decrease in velocity by 51% as shown in Figure 3. Similarly, applying Modification 1 to Event 2 produced a decrease in velocity at all cross sections, with the largest change occurring at cross section 18 (40%) as shown in Figure 4. Modification 2 resulted in a minor change in velocity at cross section 15 for Event 1, and no change at subsequent cross sections. Applying Modification 2 to Event 2 resulted minor changes at cross sections 16, 17, and 18, and resulted in an increase in velocity at cross section 15 by 4%.

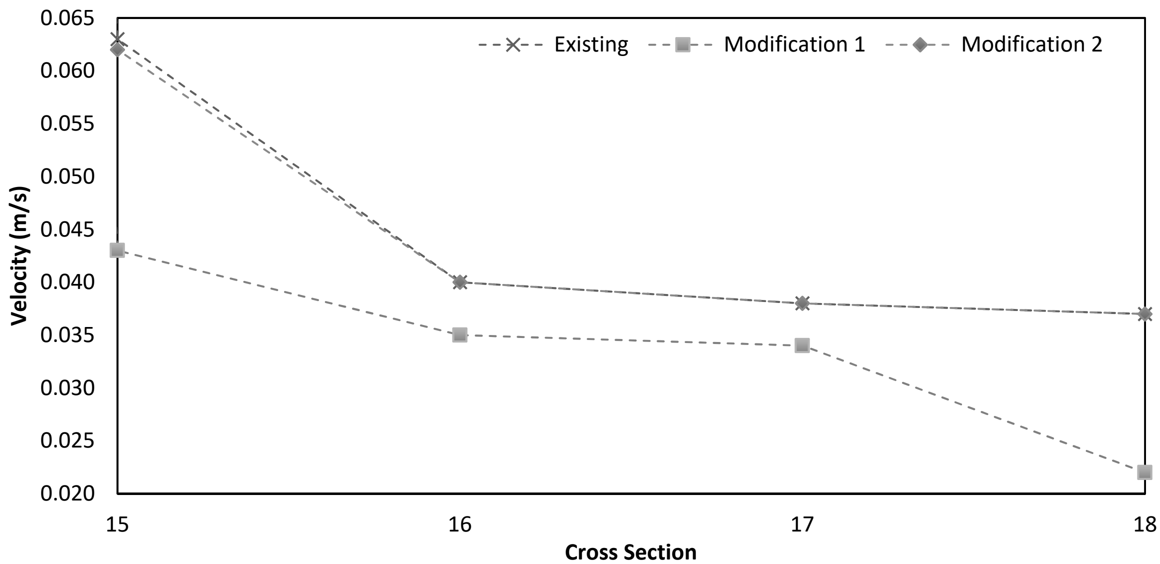

Figure 3: Comparison of Maximum Velocity at XS 15-18 for All Channel Configurations for Event 1

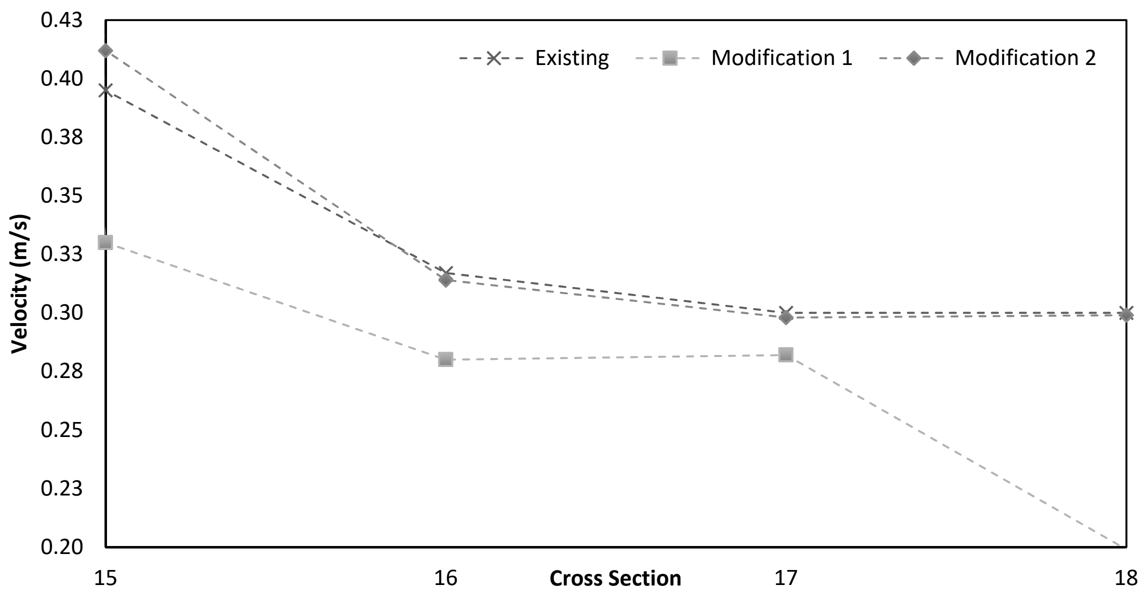

Figure 4: Comparison of Maximum Velocity at XS 15-18 for All Channel Configurations for Event 2

In addition to decreasing the velocity within the channel, channel modifications also reduced sediment concentration within the channel. Modification 1 and Modification 2 resulted in a decrease in sediment concentration at cross sections 15, 16, 17, and 18 for Event 1, with the largest change occurring at cross section 15 for both modifications. For Event 2, however, the sediment concentration was reduced at cross section 15 for both events, and only minor changes (i.e. sediment concentration changes of less that 1%) were observed at cross sections 16, 17, and 18.

All channel configurations resulted in aggradation within the channel at cross sections 15, 16, 17, and 18. As predicted, Modification 1 increased the amount of aggradation occurring at these cross sections; this was predicted due to the decrease in velocity. Modification 2 produced minimal change in aggradation patterns. The resulting aggradation implies these sections may be at risk of harming the fish habitat in the channel, the vegetation on the bed and banks of the channel, and have an adverse impact on stream stability, increasing the potential for erosion.

Erosion in a channel can occur due to numerous factors, such as stream velocity, sediment characteristics, climate, and vegetation. Riverbank erosion is likely to occur in Lower Spencer Creek during rainfall events with a long duration and high intensity. Due to the range of sediment sizes present on the stream bed and banks, hydraulic erosion is likely to occur within the channel. Lower Spencer Creek is largely composed of gravel, sand, silt, and clay. Cross sections 15 and 16 are composed of gravel (76%), sand (17%), and silt and clay (7%). Due to the silt-clay content at these sections, erosion occurring will likely be due to hydraulic processes. Cross section 17 is made up of sand (68%), silt (31%), and clay (1%), while cross section 18 is made up of sand (76%), silt (23%), and clay (1%). These sections have higher silt-clay contents, meaning occurrence of erosion will likely be caused by hydraulic and subaerial processes (Julian and Torres, 2006).

Erosion rates were calculated at cross sections 15, 16,17, and 18 using Equation 1, below, where E is the lateral erosion rate (m/yr), k is the erodibility coefficient, τ is the shear stress by flow (N/m^2), and τ_0 is the critical shear stress (N/m^2) (Julian and Torres, 2006). Negative values resulting from this equation indicate deposition is occurring within the channel, while a positive value indicates erosion is occurring in the channel.

$$[1]\ E = k(\tau - \tau_C)$$

In the existing channel, Event 1 resulted in negative erosion rates, indicating deposition occurring at cross section 15, 16, 17, and 18. Event 2, however, resulted in high erosion rates, indicating there may be instability in the channel during high flow events. Applying Modification 1 resulted in a decrease in erosion rates for cross section 15, 17, and 18 for Event 1 and Event 2. Conversely, an increased erosion rate during Event 1 and Event 2 was observed at cross section 16. Modification 2 produced in a decrease in erosion rates at all cross sections for Event 2, and no change in erosion rates in the channel during Event 1. A comparison of the velocity in the channel and the erosion rates is shown in Figure 5. As anticipated, these results demonstrate an increase in erosion rate as the velocity increases. Conversely, a reduction in velocity in the channel suggests greater potential for deposition in the channel.

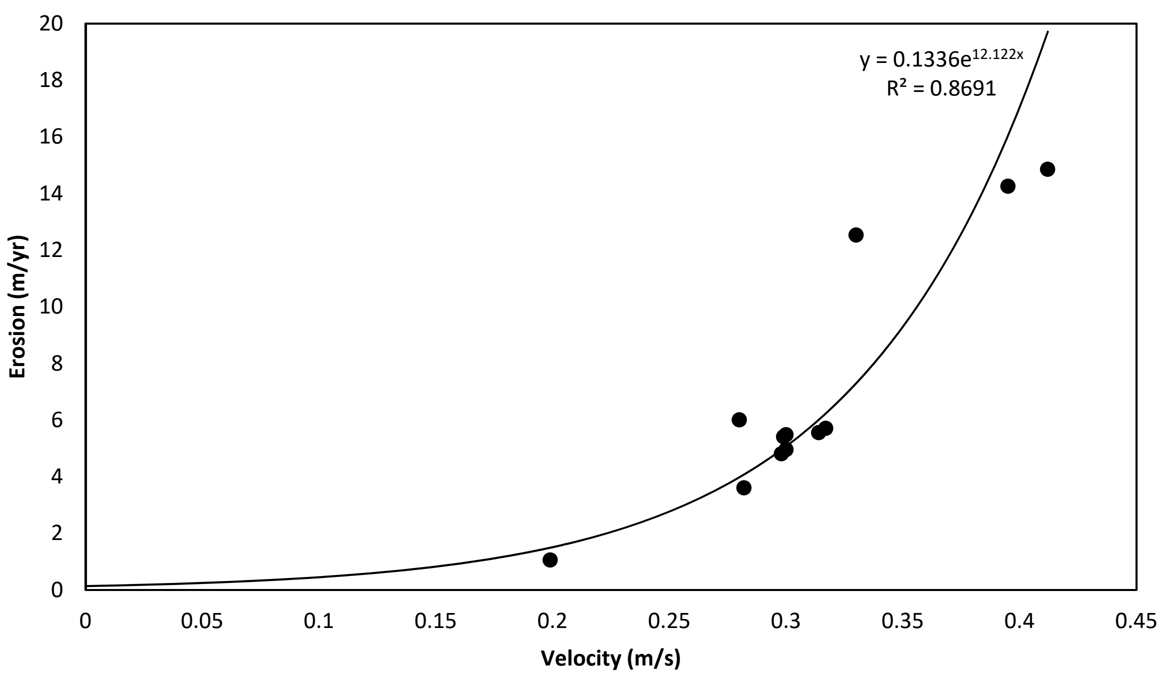

Figure 5: Velocity vs Erosion Rate for Lower Spencer Creek

Erosion rates and sediment concentrations are plotted in Figure 6. Lower erosion rates resulted in lower sediment concentrations. However, when erosion rates are negative and deposition was occurring in the channel, the sediment concentrations began to rise. The lowest sediment concentration of 420.6 mg/L occurred when the erosion rate was 1.05 m/yr. As the erosion rate began to rise, indicating increased erosion was occurring, the sediment concentration began to rise as well. The highest sediment concentration of 516 mg/L occurred at 14.25 m/yr.

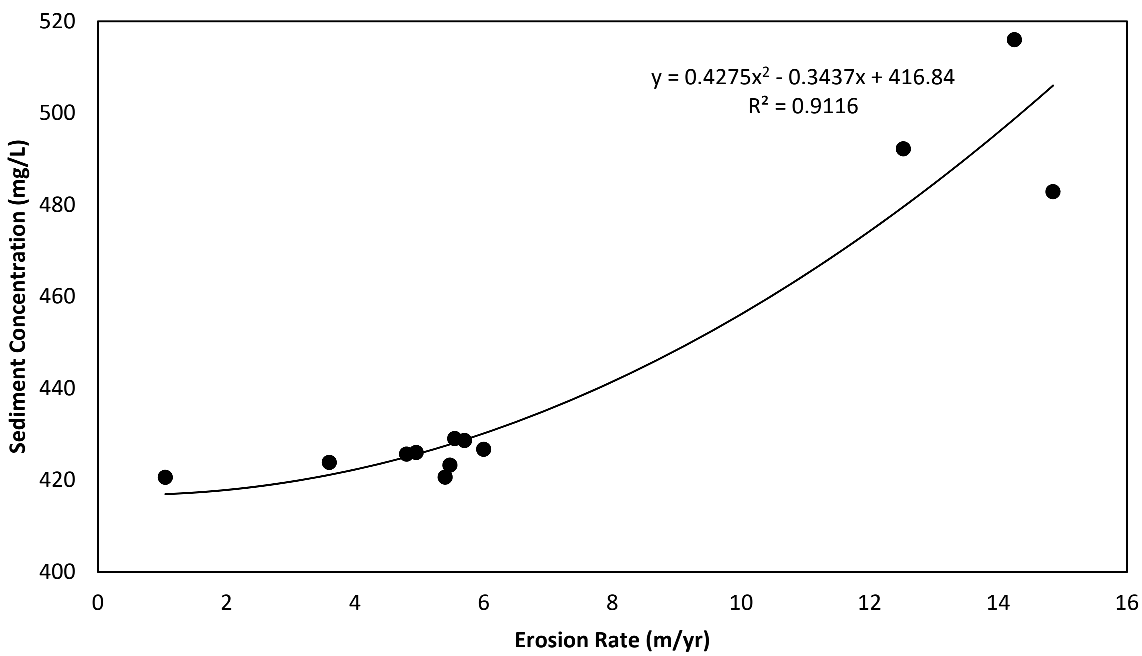

Figure 6: Erosion Rate vs Sediment Concentration for Lower Spencer Creek

4.2 Discussion

The effects of sediment deposition and sediment transport concentrations, both ecological and physical, have become more serious as a result of human activities in close proximity to river channels. The impact of sedimentation processes in a channel can completely alter the morphology and/or ecology of the channel, if extended over several months or years. Excess sediment transport and deposition in a channel is a main cause of habitat degradation and can result in algal blooms, alluvial fans, and deltas. Deposition of fine sediment can reduce light reaching the bed, affecting the food supply in the channel, which will have a lasting effect on fish, benthic organisms, and faunal diversity. Alternatively, limited sediment transport and deposition within a channel can result in bank erosion leading to land loss and/or destruction of nearshore habitat. In addition, excess deposition can diminish vegetation growth, leading to a lack of nutrients in floodplains and marshes (Wood and Armitage, 1997; Fondreist Environmental Inc., 2014; Reiser and White, 1990).

Event 2 showed a large amount of degradation occurring within the channel for all channel configurations. Therefore, when exposed to an event of this magnitude, the ecological habitat within Spencer Creek is at risk of becoming damaged. The Canadian Environmental Quality Guidelines (1999) suggest that a short-term increase in sediment concentration of 25 mg/L could have an adverse impact on aquatic ecosystems. Based on these guidelines, the aquatic ecosystem in Lower Spencer Creek may be adversely impacted in an event of this magnitude.

Based on these results, widening the channel (Modification 1) would be an ideal option for reducing velocity and sediment concentration within the channel. However, due to the resulting decrease in erosion rates with Modification 2, a combination of both options could prove beneficial within the channel. A combination of these modifications could decrease velocity, sediment concentration, and bank erosion within the downstream cross sections.

Although Figures 5 and 6 are based on conditions specific to Lower Spencer Creek, these figures may be used to assist in determining the mean velocity and sediment concentration in a channel based on the permitted amount of erosion. Moreover, these figures could be used to help guide the design of rivers and streams in order to satisfy an erosion limit.

5 CONCLUSION

Models predicting how small, urban streams respond to various rainfall durations and intensities can be useful for future land use planning and river management. When considering alterations to a channel, it is important to consider how the sediment in the channel will be affected, how the flow is altered, and how it will affect erosion of the bed and banks. It is important to understand how the floodplain is affected by rainfall durations and intensities when considering any future construction. Simulations of a 100-year event showed relatively high flow velocities and sediment concentrations in all tested channel configurations. Events of large magnitudes, such as this event, are predicted to occur more frequently in the future. Therefore, it is important to understand the stream hydraulic and morphological response to these events to accurately plan for the future (Takemura and Fukoma, 2014).

The results of this study examined the sediment transport and morphological performance of the Lower Spencer Creek in response to a 100-year precipitation event using the mathematical hydraulic model HEC-RAS. The results from this study are specific to Lower Spencer Creek and should not be used beyond the boundaries of this study. Modification 1 widened the channel by 15%. As expected, this modification decreased the velocity and sediment concentration at cross sections for the averaged base flow event and the 100-year storm event. Modification 2 increased the length between each cross section by 10%, thereby decreasing the slope. There was a decrease in sediment concentration at all cross sections during the averaged base flow event and 100-year event for this modification.

The results of the two modification options suggest that Modification 1, widening the channel, would be overall more successful in reducing the velocity and sediment transport within the channel, which can further benefit the ecology of the channel, and reduce the risk of flooding. However, a combination of the two modifications may better reduce the sediment concentration in the channel. Further analysis, however, is recommended as this study only looked at one large event.

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References

Ashmore, Peter, and Michael Anthony Church. *The impact of climate change on rivers and river processes in Canada*. Vol. 555. Geological Survey of Canada, 2001.

Blom, C. W. P. M., and L. A. C. J. Voesenek. "Flooding: the survival strategies of plants." *Trends in Ecology & Evolution*11, no. 7 (1996): 290-295.

Bukaveckas, Paul A. "*Effects of channel restoration on water velocity, transient storage, and nutrient uptake in a channelized stream*." Environmental science & technology 41, no. 5 (2007): 1570-1576.

Canadian Council of Ministres of the Environment (CCME). Canadian environmental quality guidelines, vol. 2, CCME ed. Winnipeg, Man. 1999.
Citizens of City Hall. *The Floods of Hamilton*. Retrieved from http://www.hamiltoncatch.org/view_article.php?id=1072. 2012
Fondreist Environmental, Inc. *Sediment Transprot and Deposition." Fundamentals of Environmental Measurements.* Retrieved from http://www.fondreist.com/environmental-measurements/parameters/hydrology/sediment-transport-deposition/. 2014.
Hicks, F. E., and T. Peacock. "Suitability of HEC-RAS for flood forecasting." *Canadian Water Resources Journal* 30, no. 2 (2005): 159-174.
Horritt, M. S., and P. D. Bates. "Evaluation of 1D and 2D numerical models for predicting river flood inundation." *Journal of Hydrology* 268, no. 1-4 (2002): 87-99.
Julian, Jason P., and Raymond Torres. "Hydraulic erosion of cohesive riverbanks." *Geomorphology* 76, no. 1-2 (2006): 193-206.
Khattak, Muhammad Shahzad, Faizan Anwar, Tariq Usman Saeed, Mohammed Sharif, Khurram Sheraz, and Anwaar Ahmed. "Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River." *Arabian Journal for Science and Engineering* 41, no. 4 (2016): 1375-1390.
Kroes, Daniel E., and Cliff R. Hupp. "The effect of channelization on floodplain sediment deposition and subsidence along the Pocomoke River, Maryland." *JAWRA Journal of the American Water Resources Association* 46, no. 4 (2010): 686-699.
Marsh, J.H. Hurricane Hazel. Retrieved from http://www.thecanadianencyclopedia.ca/en/article/hurricane-hazel. 2012.
Martin, E.M. Morphodynamic Response of Spencer Creek to Heavy Precipitation Events and Channel Modifications: A Case Study. M.E.Sc. thesis, University of Western Ontario, London, Canada (2017).
Rae, J.G. Chapter 2: Effects of Flooding on Soils. In T.T. Kozlowski (Ed.), Flooding and Plant Growth (pp. 10-44). Orlando, FL: Academics Press. 1987.
Shields Jr, F. Douglas, and Michael R. Palermo. *Assessment of Environmental Considerations in the Design and Construction of Waterway Projects*. No. WES/TR/E-82-8. ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIRONMENTAL LAB, 1982.
Sholtes, Joel S., and Martin W. Doyle. "Effect of channel restoration on flood wave attenuation." *Journal of Hydraulic Engineering* 137, no. 2 (2010): 196-208.
Soar, Philip J., and Colin R. Thorne. *Channel restoration design for meandering rivers*. No. ERDC/CHL-CR-01-1. ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS COASTAL AND HYDRAULICSLAB, 2001.
Takemura, Y., and S. Fukuoka. "Effects of channel shape on propagation characteristics of flood flows through a valley." *Journal of Flood Risk Management* 7, no. 2 (2014): 152-158.
Wood, Paul J., and Patrick D. Armitage. "Biological effects of fine sediment in the lotic environment." *Environmental Management* 21, no. 2 (1997): 203-217.