Feedmill Creek SWM Criteria Study

Pond 7 Increased Drainage Area - Erosion and In-stream Works Analysis

Submitted to: David Schaeffer Engineering Ltd.

Prepared by: N.J. MacDonald, Ph.D., P.Eng.
Coldwater Consulting Ltd.
5510 Canotek Road, Suite 203
Ottawa, ON, K1J 9J4
(613) 747-2544

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For further information please contact:

Neil MacDonald (nmacdonald@coldwater-consulting.com, 613-747-2544)

Provisos

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Contents

Introduction

Between 2015 and 2017, Coldwater Consulting Ltd. (Coldwater) and J.F. Sabourin and Associates (JFSA) conducted a study of Feedmill Creek for the City of Ottawa. The study involved a multi-day field survey and extensive computer modelling to assess the creek's geomorphologic condition, erosion potential under current (Interim) and future (Ultimate) hydrologic conditions, and requirements for in-stream works. The findings of the study were presented in two reports, (Coldwater, 2017a) and (Coldwater, 2017b). The approach and recommendations employed in that study were based on natural channel design principals and, while their focus was on erosion control, they also aimed to improve the functionality of the creek from both a hydraulic and habitat standpoint.

David Schaeffer Engineering Ltd. (DSEL) and JFSA have been assessing the feasibility of changes to the drainage area going of Pond 7, a stormwater management pond in the Feedmill Creek watershed. These changes may have an impact on the erosion potential of the creek that is different from that which could be expected under the conditions developed during the City of Ottawa study. The aim of the present analysis is to assess changes and to determine whether the new hydrologic conditions would alter requirements for in-stream works.

Design Philosophy[1]

The goal of natural channel design is to restore the hydraulic and ecological functioning of a channel through the re-creation of natural features such as banks, runs, riffles, meanders, and pools. Planting of appropriate natural vegetation is integral to the design for both its ecological value, and to aid in soil retention and erosion protection. In natural river/stream systems there can be multiple, nested flow channels depending upon flow conditions. Base flow can be carried in a low flow meandering central channel, bankfull flow carried within the main banks of the channel, and overland flow carried through the broader floodplain which might be wooded or heavily vegetated. Approaches to natural channel design typically use the geomorphic and hydraulic characteristics of stable, natural river/stream reaches as reference conditions to guide the design. These reference reaches may be taken from the subject watershed or from other watersheds that demonstrate similar geomorphic and hydraulic characteristics.

There are two general approaches to natural channel design/restoration in the literature. The first is the *classification-based procedure* as advocated by Rosgen (1994) and which has become dominant in the field of fluvial geomorphology. In this method, a geomorphically-stable natural river reach is selected as a reference case and used as an analogue to guide the design of restoration works. Classification of stream reaches is essential within this process to ensure the similarity and suitability of the reference reach. The design of the restoration works then relies upon the scaling of the reference reach features based on the relative bankfull riffle

[1]This section appears in the original study report (Coldwater, 2017b); it is reproduced here for reference

width of the reference and subject reaches. This method uses the reference reach as a scale model for the restoration project.

The second approach is a process-based method that is sometimes referred to as a *regime* or *rational* design. In this approach, predictive relationships for sediment mobility, cross-sectional and planform geometry are used to support river observations and to develop a restoration design. The relationships used are based on a combination of analysis of natural rivers and streams, and theoretical and experimental research in the fields of fluid mechanics, sediment transport and fluvial geomorphology. This approach is best applied in conjunction with an appropriate reference reach so that the design relationships can be used to scale the reference reach features for use in the study reach to allow for differences in boundary conditions between the two reaches. These boundary conditions include hydraulics, sediment characteristics and the sediment transport processes. In situations where no appropriate reference reach is readily available, the rational design approach can still be used to define appropriate planform and cross-sectional channel geometry.

The qualitative classification-based procedure approaches provide valuable clues to the likely response of a stream to hydrologic changes but were never intended for engineering design (Simon, et al., 2005). A limitation with this approach is that the determination of required quantities is often based on observations, or to ''*predict a river's behavior from its appearance*" (Rosgen D. L., 1996), and thus implicitly assumes stable conditions. This is especially problematic in eroded streams, such as Feedmill Creek. Here, for example, the discharge associated with local bankfull conditions can vary widely over short distances. (Even the usefulness of the bankfull discharge as a metric is questionable since the Feedmill Creek channel is incised over much of its length.) The reference reach approach would remedy this if nearby examples were not also heavily impacted by changes in land-use, hydrology and construction. Consequently, the methodology adopted in the present work combines aspects of both approaches and includes theoretical, observational, and computational inputs.

A key aspect of natural channel design is that structures, where warranted, are designed in a manner such that they not only fulfill their desired hydraulic impact (flow diversion, scour reduction, level control, etc.) but also give an environmental benefit (flow concentration for pool development, provision of shade and habitat, etc.). The design of these engineered structures, where required, will make extensive use of natural materials.

Background

Feedmill Creek flows in a generally north-eastern direction starting at the outlet of the Eco Woods Pond at Lloydalex Crescent (see Figure 1). Shortly downstream from this, the creek enters a wetland that is divided by Overland Drive. After crossing the Maple Grove footpath, the creek enters agricultural land and, in some sections, has been channelized into a straight drain. After crossing Hwy. 417, the creek enters a wooded area and takes on a meandering form. The creek crosses Palladium Drive and the Hwy. 417 West off-ramp at Palladium Drive via three culverts and then runs northwest to Huntmar Drive. Below Huntmar Drive, the creek first follows a meandering form before entering the Carp River via a straight section, which was constructed sometime between 1976 and 1991. This final section bypasses an old natural channel.

Reaches for Feedmill Creek were defined after the 2015 field survey (Coldwater, 2017a). These were selected to ensure that each reach shared a broadly similar morphology, flow, land use, vegetation, channel gradient, boundary material composition and physiography along its length. The eight reaches in the present study (see Figure 1) differ only slightly from the five reaches used in the Carp River Watershed/Sub-watershed Study (Robinson, 2004):

- downstream of Huntmar Drive, RCN-01 has been divided into two reaches, and;
- upstream of Hwy. 417, RCN-05 has been divided into 3 reaches.

The analysis in this report is presented in terms of these new reaches. Since any hydrologic changes the creek resulting from changes to Pond 7 will only impact that part of the creek downstream of the Hwy. 417 crossing, the present study will only examine Reaches 1 through 5.

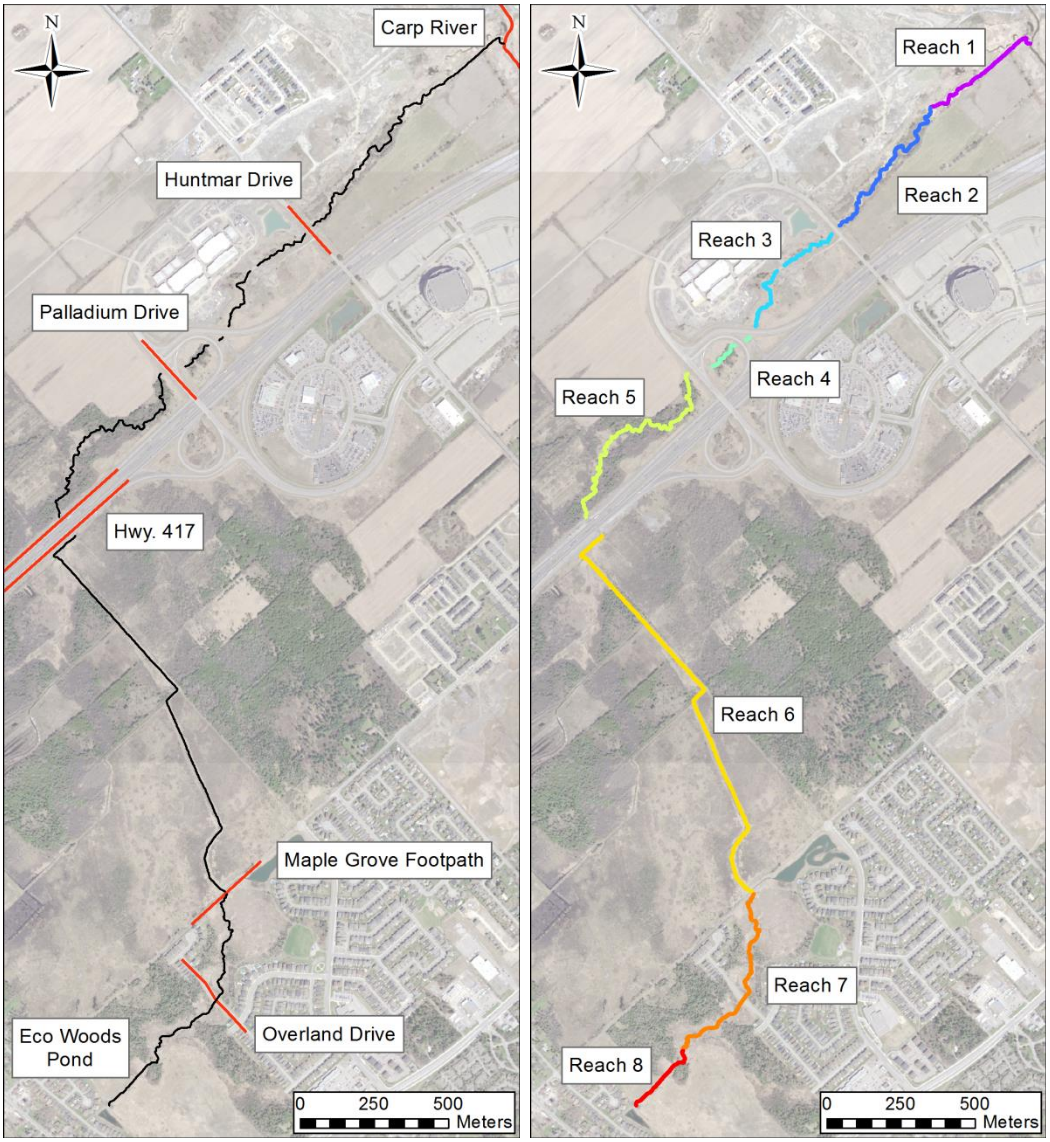

Figure 1 Feedmill Creek: geographic features (left); reaches used in present work (right)

Erosion Assessment Methodology[2]

Flow conditions in the Feedmill Creek were evaluated under existing conditions (Interim) and under fully developed conditions (Ultimate), which includes proposed stormwater management features. As with most streams, there are several different erosion thresholds that can be applied, each appropriate for the material being transported. These vary from very low values for the fine sediment deposited in many areas, to higher values appropriate for the lag material and the underlying clay substrate. In these situations, it is often beneficial to examine not just the frequency with which various erosion thresholds are exceeded, but also the total amount of erosion that occurs both pre- and post-project. By computing the amount

[2] This section appears in the original study report (Coldwater, 2017b); it is reproduced here for reference.

by which the erosion threshold is exceeded and its duration, the erosion effort or effective work can be computed (TRCA, 2012). This measure, in comparison to frequency of exceedance analysis, provides a more complete picture of the erosion consequences of a project.

Effective Work[3]

An erosion assessment model used to estimate the erosion potential for pre- and post-development is based upon a cumulative effective work approach. Work done (or erosive power) calculations have a sound theoretical basis in energetic-based sediment transport relationships (Bagnold, 1956, p. 270) and have been are widely accepted in both engineering (Yalin, 1977, p. 118) and fluvial geomorphology (Leopold, Wolman, & Miller, 1964, 1992, p. 178) literature. Computation of an erosion index based on velocity over threshold is identified in MOE Stormwater Management Manual (MOE, 2003, pp. H-9) as an accepted means of evaluating erosion potential. This approach has been extended in the TRCA Stormwater Management Criteria (TRCA, 2012, pp. Appendix B, Section 4.5) to an effective work index:

$$W_i = \sum (\tau - \tau_c) V \Delta t \quad \text{for } \tau > \tau_c \qquad \text{Equation 1}$$

where W_i is the cumulative effective work (J/m^2), τ is the shear stress (Pa), τ_c is the critical shear stress (Pa), V is the stream velocity (m/s) and Δt is the model time step. Note that W_i can be expressed in units of kW·h/m^2 if multiplied by 2.778×10^{-7} kW·h/J. In several recent projects, Coldwater has modified Equation 1 by including the hydraulic perimeter, which allows differentiation of work across sections of different sizes; however, for consistency with other studies, the standard form given by Equation 1 is used in this study.

Shear Stress*

It was originally intended to obtain W_i values directly from PCSWMM model output; however, it was determined by JFSA through correspondence with the model's developers that certain aspects of the model's predictions of the shear stress, τ, could lead to issues in the present case. The shear stress can be computed as:

$$\tau = \gamma S \mathbb{R} \qquad \text{Equation 2}$$

where γ is the specific weight of water (N/m^3), $\mathbb{R}$ is the hydraulic radius (m), and S is the slope. PCSWMM determines the shear stress using:

$$\tau = 0.97 \gamma S_o h \qquad \text{Equation 3}$$

where h is the water depth in the section (m) and S_o is the bed slope (m/m). Although the use of bed slope is a suitable approximation in uniform flow situations, several sections of the Feedmill Creek model have an adverse bed slope, which can lead to erroneous shear predictions. To overcome this limitation, Coldwater estimated the shear stress using a velocity-based methodology. The shear stress can be calculated as:

[3] This section appears in the original study report (Coldwater, 2017b); it is reproduced here for reference.

$$\tau = \rho {u_*}^2 \quad \text{Equation 4}$$

where ρ is the density of water (kg/m^3) and u_* is the shear velocity (m/s) given by:

$$u_* = {}^{V}/_{C} \quad \text{Equation 5}$$

Here C is the Chézy friction coefficient which can be related to the Manning friction, n, which is used in PCSWMM by:

$$C = \frac{\mathbb{R}^{1/6}}{n\sqrt{g}} \quad \text{Equation 6}$$

where g is gravitational acceleration (m/s^2). A value of n = 0.05 was adopted for the present work since this was the central channel value used in the PCSWMM simulations and, thus, corresponds to the predicted velocities. The hydraulic radius, $\mathbb{R}$, is often approximated by the water depth, h; however, this is only valid for very wide channels and is not representative of the small, gully-like channels found in Feedmill Creek. Using field survey measurements, a better approximation was found to be:

$$\mathbb{R} = 0.75h \quad \text{Equation 7}$$

Note that the term $0.97h$ is Equation 3 is a similar approximation. The resulting equation for shear stress is thus:

$$\tau = \frac{\gamma n^2 V^2}{(0.75h)^{1/3}} \quad \text{Equation 8}$$

The effective work is computed for each time step of the model using Equation 1 with τ specified using Equation 8. The cumulative results for the entire simulation are then reduced to annual average values for analysis.

Selection of Critical Shear Stress[4]

The effective work equation (Equation 1) is dependent upon the value of the critical shear, τ_c. This represents the flow conditions at which movement of bed sediments commences, and hence, the flow condition at which erosion initiates. Critical shear stress is dependent on a range of variables, including sediment size and type, density, weathering, vegetation, biological activity, etc. It can vary spatially and temporally, depending upon weather conditions, freeze-thaw activities and exposure. Since the sediments that make up the bed and banks of Feedmill Creek vary in composition and competency, so too do the critical or threshold erosion values. In many places, the bed is composed of firm, erosion-resistant marine clay, while the banks are composed of weathered clays and tills that are relatively easier to erode. Surficial silts and organics are even easier to erode.

[4] This section appears in the original study report (Coldwater, 2017b); it is present here for reference.

The use of a single value for critical shear stress in a natural waterway is problematic. A very low threshold could be set that identifies the onset of sediment transport of the finest materials present in the existing system (silts, organics). Analysis of the system using a very low critical shear stress value may be useful in assessing siltation, but higher values are generally more appropriate for channel morphology studies. If the critical threshold is set too low, then any analysis and interpretation will tend to be biased toward eliminating all sediment transport processes. This would result in a stagnant and heavily vegetated waterway rather than one in a state of dynamic equilibrium where erosion and deposition processes are balanced. A more suitable threshold can be established by consideration of changes to channel morphology (channel widening, meandering, stream bed downcutting, etc.). In this case, an erosion threshold is selected for the materials that control overall channel morphology. This approach generally provides threshold shear stresses that are consistent with channel-forming flow conditions.

Reach-averaged shear stress during the July 2015 field survey was calculated using Equation 2 and is presented in Table 1 (Coldwater, 2017a). These reach-average shear values may be higher than would be expected, but this is believed to be due to the pool-riffle nature of the creek; the average surface slope is, on a local scale, composed of steeper riffle sections and flatter pool sections. Type E streams in Ontario have been found to have riffle to pool slope ratios between 2 and 4 (see Appendix G.2-31, Table 10 (MNR, 2002)); in Feedmill Creek, ratios up to 10 were observed. These riffles are generally armoured with coarser material than the banks.

Table 1 Measured channel characteristics including reach-averaged shear during July 2015 field survey

Reach	Length (m)	Surface Slope, S	Hydraulic Radius, $\mathbb{R}$ (m)	Shear stress, τ (Pa)
1	465	0.0012	0.35	4.1
2	645	0.0043	0.15	6.3
3	515	0.0039	0.25	9.6
4	140	0.0050	0.15	7.4
5	905	0.0061	0.20	12.0
6	1500	0.0020	0.25	4.9
7	685	0.0060	0.15	8.8
8	280	0.0070	0.10	6.9

The underlying clay material is similarly more resistant. *In situ* measurements by Coldwater using a jet erosion meter (JEM) were used to estimate τ_c = 43 Pa for the firm, unexposed clay(Coldwater, 2017a). The clayey till soil that comprises the creek banks material is less compact, with a voids ratio around 0.7. A critical shear for this material would be 10 Pa, consistent with compact, sandy clay (Chow, 1959, p. 174). As this material weakens and becomes loser, the critical shear stress lowers to 1 Pa and 2 Pa.

Laboratory and *in situ* tests by the University of Ottawa (Salem, Lambert, & Rennie, 2016) found critical shear values for bed sediments ranging from 3 Pa to 5 Pa for the re-worked, dark coloured material with high clay and organic content, to 7 Pa to 12 Pa for the light grey, homogeneous clay. Higher values (> 30 Pa) were estimated for the undisturbed, firm clay, which is consistent with the value determined by JEM testing. It is believed that this underlying, firm clay material is virtually non-erodible by the hydraulic forces of the stream. This is consistent with observations at locations where this material is exposed. Only after weathering of this material, either by organic activity, frost action or exposure to the atmosphere, can the stream undergo a process of incision. The process involves an initial fracturing followed by removal of pebble-sized pieces which are then capable of transport and further reduction in size primarily through abrasion.

Therefore, the present analysis examines model results at three critical shear stress values: τ_c = 1 Pa, representing the surficial deposits, and τ_c = 5 Pa and τ_c = 10 Pa representing the range of material type and condition expected to be most affected by stream flows and thus impact channel morphology and migration. These values can also be applied for assessment of reaches where the bed has been armoured by lag deposits, since widening and lateral movement is initiated via bank undercutting. Use of the three critical shear stresses will also permit an assessment of sensitivity to the selected thresholds.

Model Application

During the City of Ottawa study, the PCSWMM model was run by JFSA to simulate present-day (Interim) and future (Ultimate) conditions. The Interim scenario describes conditions in the existing creek as of 2015. Several post-development scenarios were studied and from these tests Ultimate B was identified as the preferred option (Coldwater, 2017b).

JFSA has generated two new simulations which will be examined in the present work: Interim' represents the earlier present-day conditions, but with modified Pond 7 drainage and potential future watershed development, and; Ultimate B', which represents the preferred approach from the original study and modifications due to an enhanced Pond 7, which will result in larger Pond 7 drainage area and increased runoff volume being contributed across the culvert below Highway 417 than the Ultimate B scenario. Descriptions of these scenarios are provided in Table 2.

Table 2 Descriptions of the hydrologic modelling scenarios

Scenario	Description	
Interim	2015 conditions	Describes the existing (2015) conditions within the Feedmill Creek subwatershed.
Interim'	Present-day conditions	Describes the existing (2015) conditions within the Feedmill Creek subwatershed, modified Pond 7 drainage and potential future watershed development.
Ultimate B	Ultimate – Detention + moderate retention	Future full build-out with SWM control scenario B, which is detention facilities and a moderate level of LID controls (retention) within future developments.
Ultimate B'	Ultimate – Detention + moderate retention + Pond 7 changes	Future full build-out with SWM control scenario B, which is detention facilities and a moderate level of LID controls (retention) within future developments) plus a larger drainage area for pond 7 and more runoff to the creek from the culvert below Highway 417.

The four simulations were each 41 years in length, spanning the period 1967 to 2007; however, because of a lack of hydrologic input for two of the years, results from 2001 and 2005 were ignored.

Thirteen model sections (referred to as *conduits* in PCSWMM) were selected for analysis. This is a sub-set of the original 16 conduits studied, since hydrologic changes the creek resulting from changes to Pond 7 will only impact that part of the creek downstream of the Hwy. 417 crossing. These sections are shown in Figure 2 through Figure 4. Detailed information about these sections is presented in Table 10, which is given in Appendix A – Descriptions of PCSWMM Model Sections

In some cases, results from adjacent sections were analysed to ensure that the analysis was spatially consistent. There are no changes in any of the cross-sections between simulations.

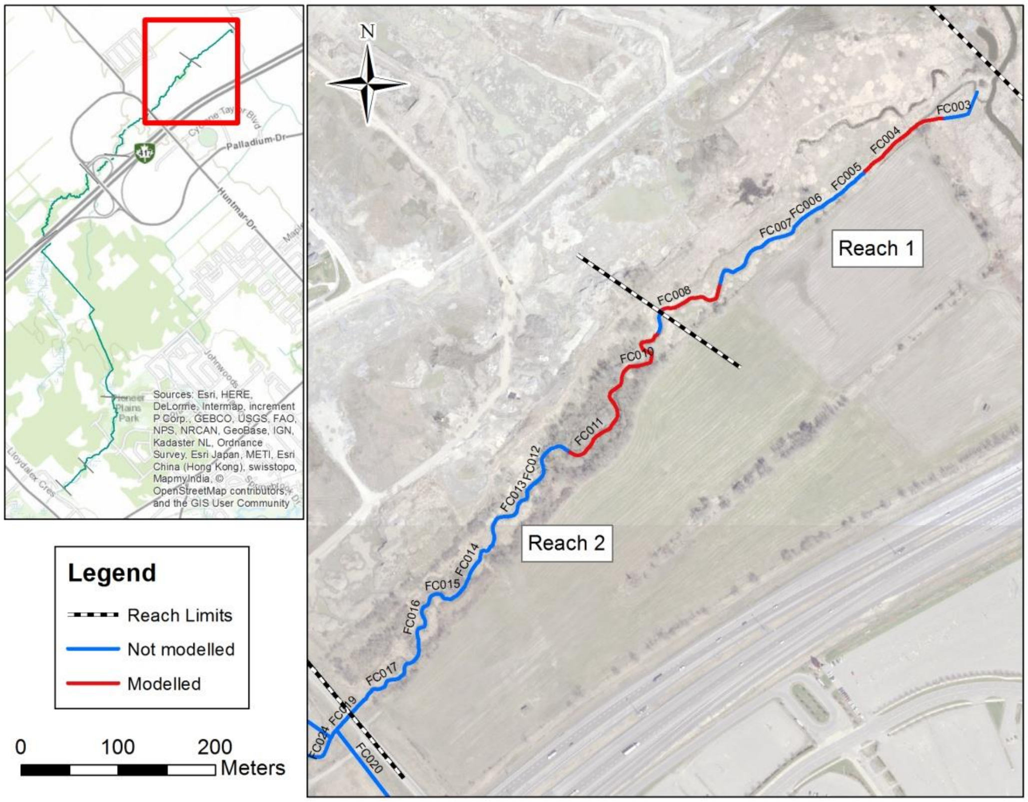

Figure 2 PCSWMM model conduits - effective work analysis performed at red sections (1/3)

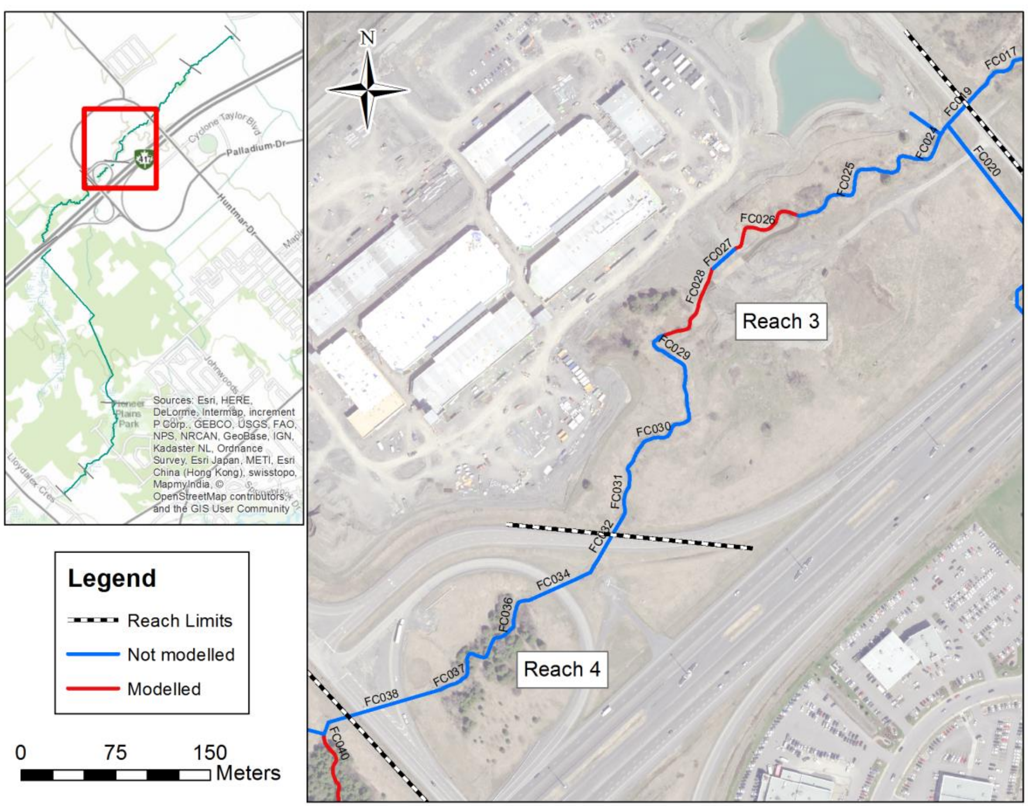

Figure 3 PCSWMM model conduits - effective work analysis performed at red sections (2/3)

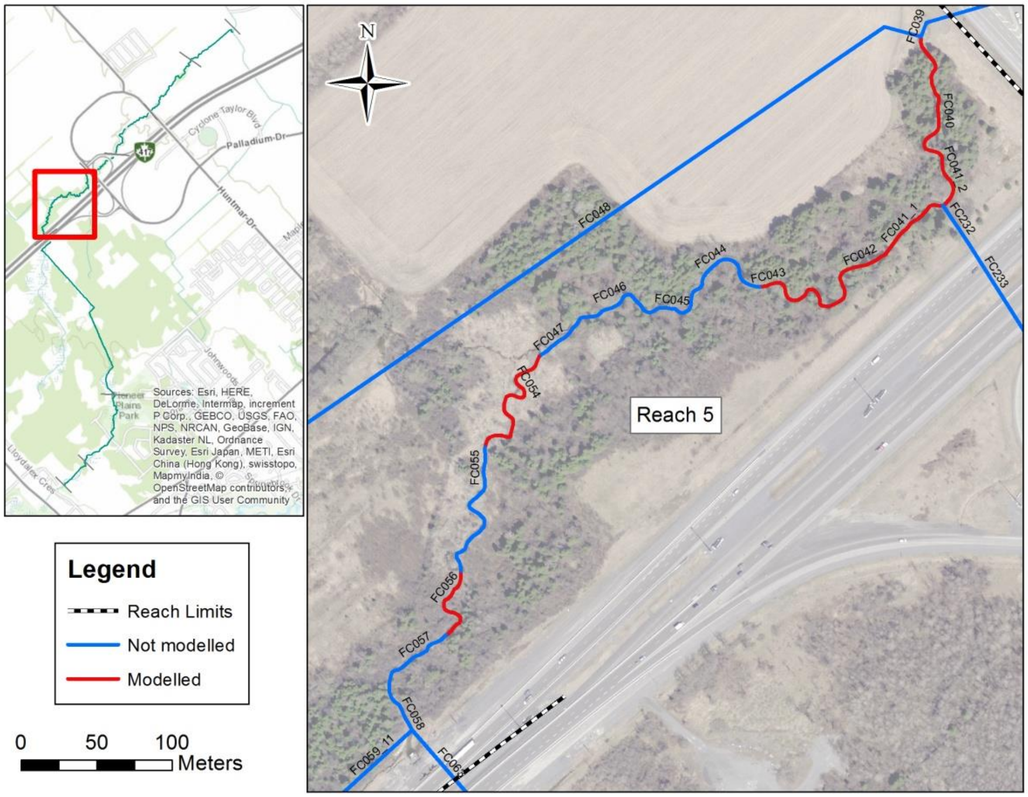

Figure 4 PCSWMM model conduits - effective work analysis performed at red sections (3/3)

It is important to note that flows in the creek will increase under both the Interim' and both Ultimate scenarios (see Figure 5). Discharge at the mouth (FC004) will increase by 14% under Interim' conditions, 31% under Ultimate B conditions and 38% under Ultimate B' conditions. The greatest increases will be in Reach 5 (FC040 through FC056); increases in discharge here are approximately 50% over Interim and 40% over Interim' (see Figure 6 and Figure 7). These increases will be reflected in the effective work results presented in the next section.

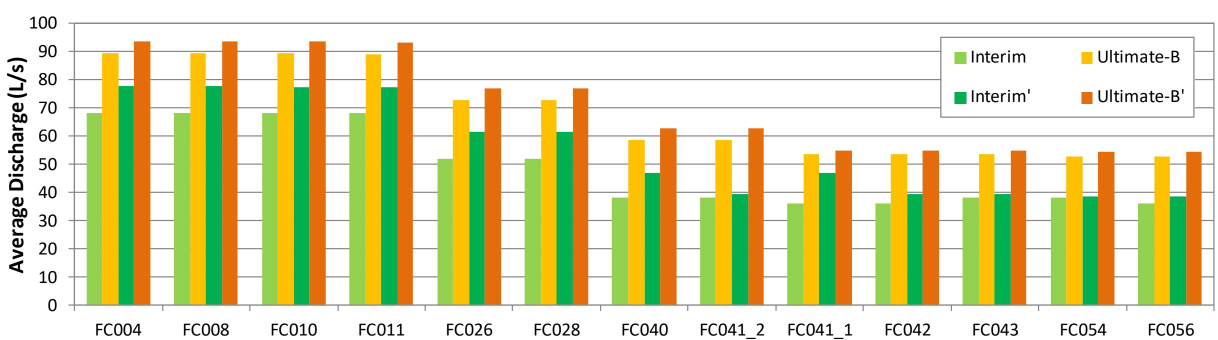

Figure 5 Average annual discharge at selected atations for the scenarios studied

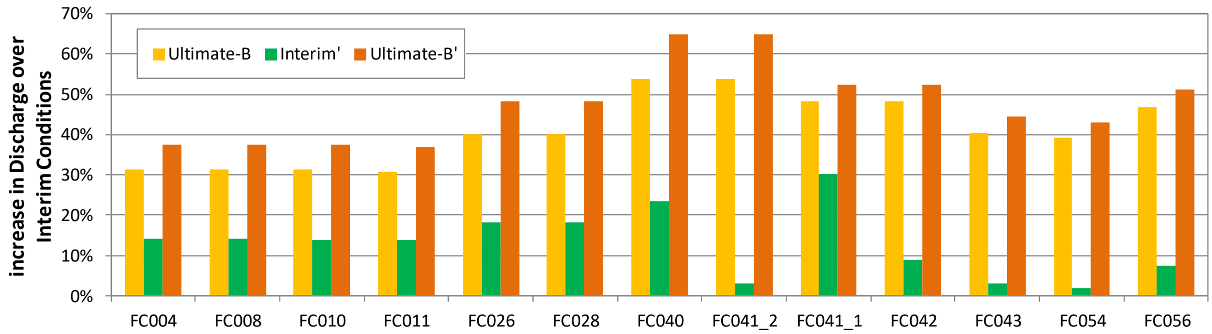

Figure 6 Increase in discharge from Interim conditions under the Interim' and two Ultimate scenarios studied

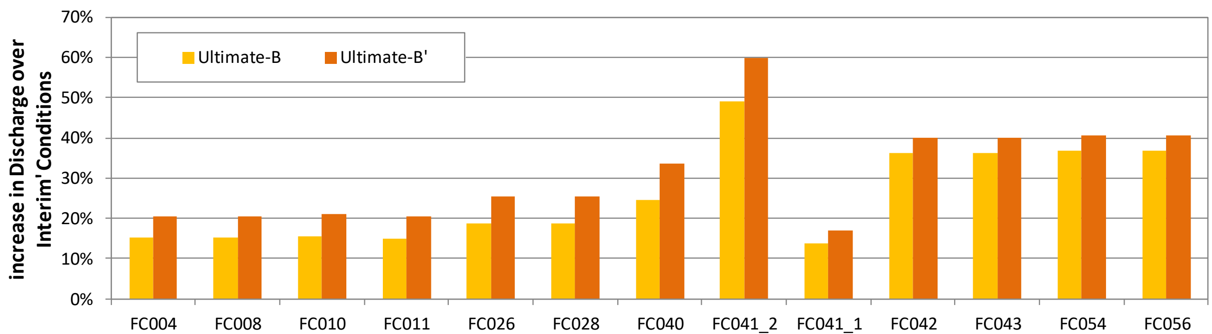

Figure 7 Increase in discharge from Interim' conditions under the two Ultimate scenarios studied

Model Results

The section by section computed values of average annual effective work index for critical shear stresses of τ_c = 1 Pa, 5 Pa and 10 Pa are presented in tables provided in *Appendix B – PCSWMM Model Results*. In this section, the τ_c = 5 Pa results from the sections have been combined to produce reach–based estimates of average annual effective work index. In reaches where more than one section was modelled, the results were weighted according to each section's length. Estimates have not been produced for Reach 4 (the short section within the Hwy. 417 interchange); the results here are expected to be similar to those of Reach 3 and 5. The results are tabulated in Table 3 and shown graphically in Figure 8 through Figure 11. Note that in each reach Interim' is less than Ultimate B and Ultimate B' is larger than Ultimate B.

Table 3 Length-weighted average annual effective work index, W_i (kW·h/m²), by reach and overall

Reach	Interim	Interim'	Ultimate B	Ultimate B'
1	0.706	0.215*	1.029	1.076
2	0.195	0.254	0.305	0.324
3	1.614	1.392	1.620	1.693
5	1.804	2.020	2.825	2.855
Average	1.154	1.110	1.607	1.646

* *the PCSWMM model boundary conditions differ in this case near this area*

In Reach 1 (see Figure 8), the new Interim' has a very low erosive potential, much lower than any of the other options. This is believed to be due to the PCSWMM model boundary conditions in this case, which differ from those of the Interim model near this area. Increased erosion potential for both Ultimate cases suggest channel re-shaping and migration is likely. In-stream works are required in this area.

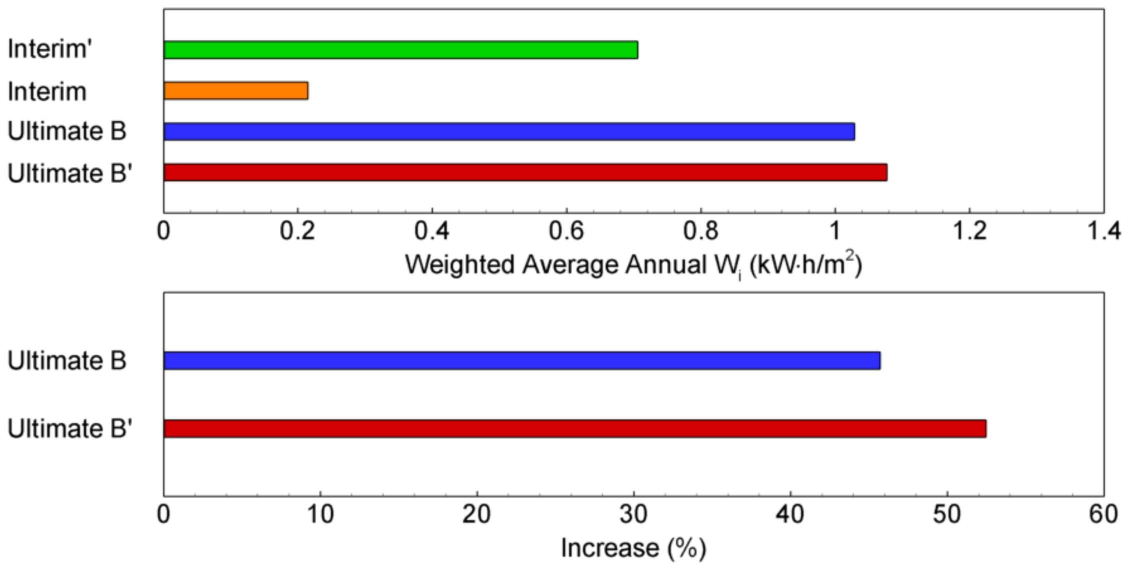

Figure 8 Average annual effective work index for Reach 1 (top); increase over Interim values (bottom).

The average values are lower in Reach 2 (see Figure 9), but the patterns are similar; both Ultimate options exceed Interim conditions. The increases in W_i at the 5 Pa threshold suggest that there is significant potential for channel reshaping and in-stream works will be required in this area.

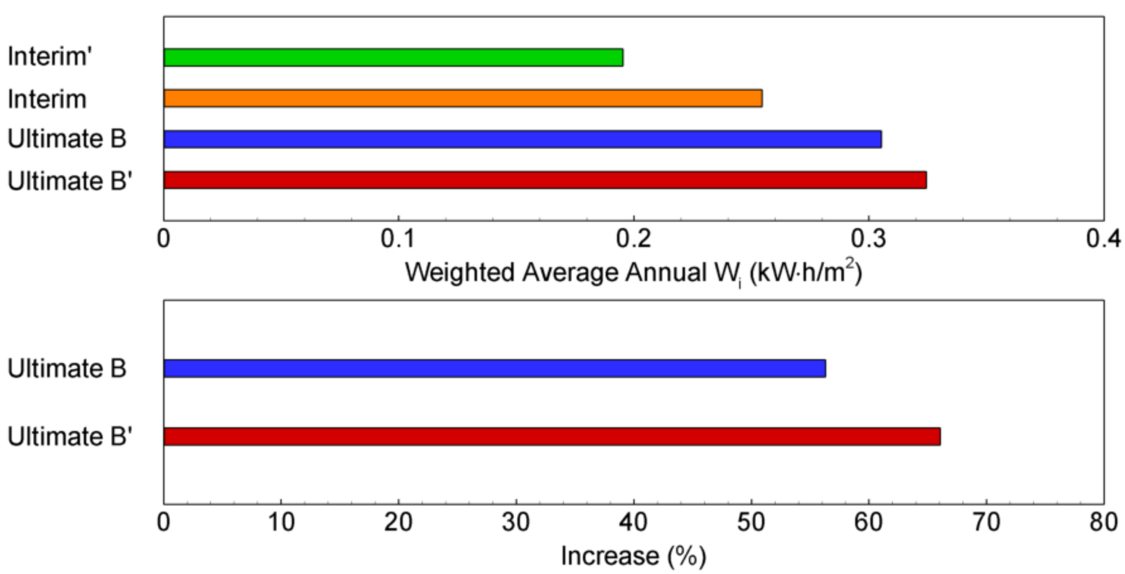

Figure 9 Average annual effective work index for Reach 2 (top); increase over Interim values (bottom).

In Reach 3 (see Figure 10), both Ultimate options only slightly exceed the Interim value, so some channel reshaping would be expected in these areas. There is a bed of hard, firm clay exposed in a section of this reach and this likely has a higher threshold than 10 Pa which will control downcutting rate and slope readjustment of the section. There are large eroding bends with this reach and these areas will likely see some increased development under these new flow conditions. In-stream works will be required in part of this reach.

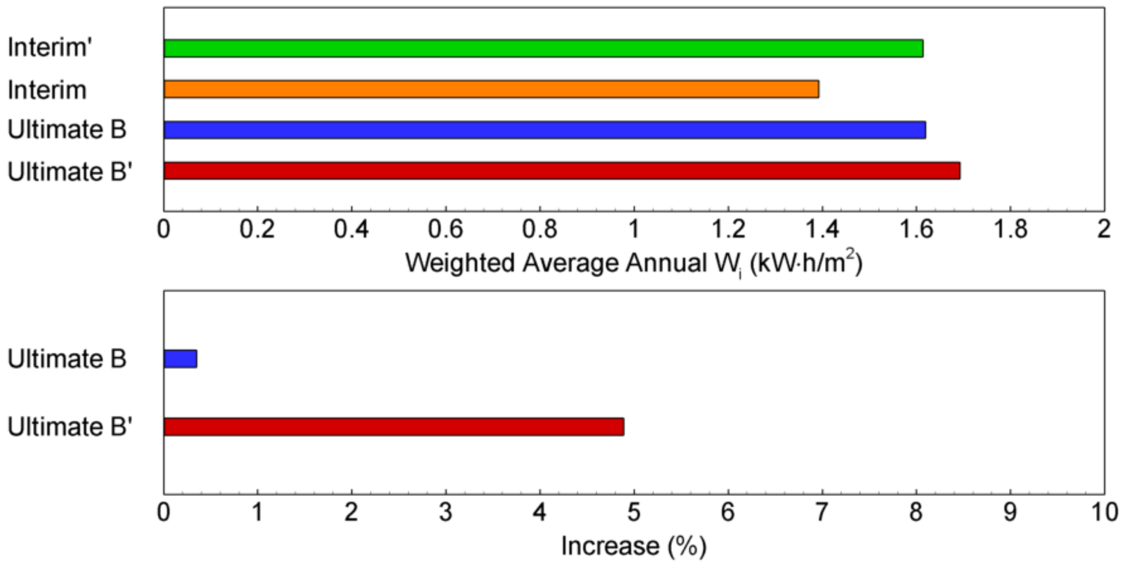

Figure 10 Average annual effective work index for Reach 3 (top); increase over Interim values (bottom).

The pattern for Reach 5 is like that of Reach 2 (see Figure 11); both Ultimate options are similar and will exceed Interim conditions by a considerable amount. Many parts of this reach are relatively steep and thus experience the high shears and there is evidence of on-going stream realignment in this reach. This area is also expected to see the greatest relative increase in discharge (see Figure 6). Basal scour, bank and tree root undercutting are of concern, since the creek is likely to show greater lateral migration rather than vertical adjustment. The results under either Ultimate condition suggest that significantly increased erosion will occur in along this reach. In-stream works will be required in this area.

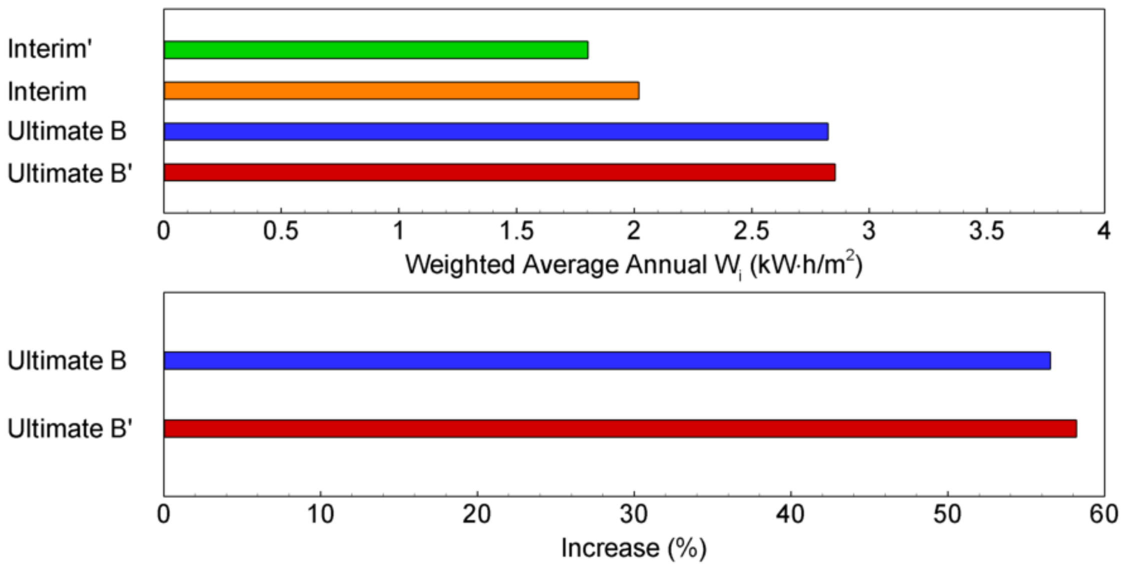

Figure 11 Average annual effective work index for Reach 5 (top); increase over Interim values (bottom).

Overall results for Feedmill Creek were generated by combining the length-weighted values for each scenario in a similar manner as above (see Figure 12). These results show that overall, Interim’ has lower erosive potential than Interim, although this is likely due to the downstream boundary conditions used in the model. The average annual effective work index, which is indicative of erosive potential, generated by Ultimate B’ exceeds that generated by both Interim’ and Ultimate B.

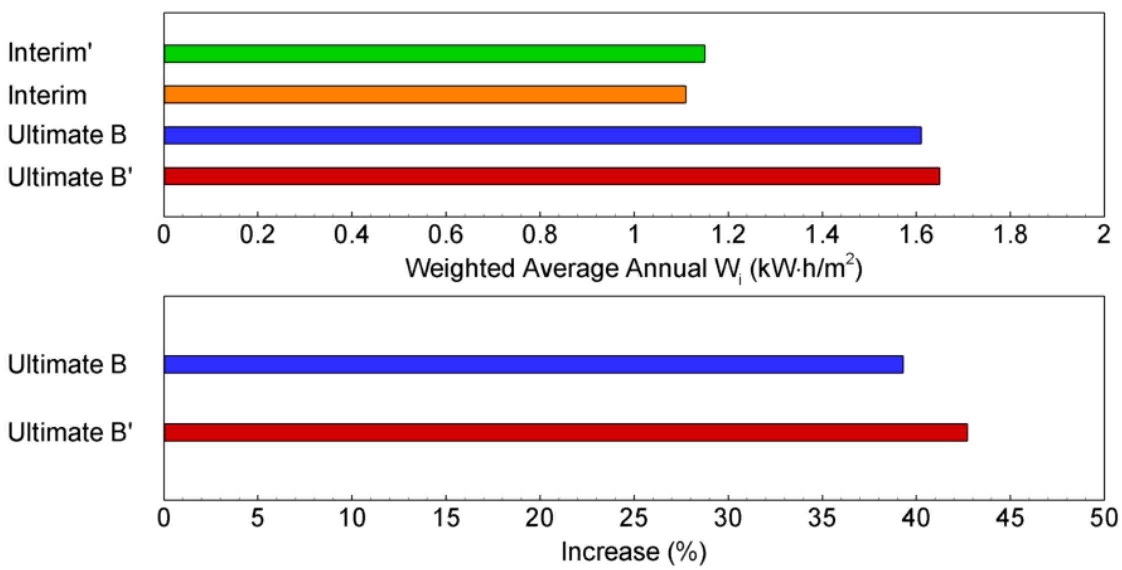

Figure 12 Average annual effective work for all reaches

Table 4 gives the change from Interim conditions in length-weighted average annual effective work index for Reaches 1 to 5 and the whole creek.

Table 4 Change in length-weighted average annual effective work index, W_i (kW·h/m²),

Reach	Interim'	Ultimate B	Ultimate B'
1	-70%	46%	52%
2	30%	56%	66%
3	-14%	0%	5%
5	12%	57%	58%
Average	-4%	39%	43%

The field investigations indicated that some in-stream measures were required to redress existing issues in Feedmill Creek and to help restore it to equilibrium with its environment. The preceding model results suggest that regardless of the approach adopted to handle the hydrologic impacts of future development of the subwatershed, additional in-stream measures will be required to enable the creek to undergo the proposed hydrologic changes without detrimental effects to its function or form. These are also necessary to eliminate morphological changes that could jeopardize adjacent properties or infrastructure.

During the City of Ottawa study, Ultimate B was selected as the preferred option and was used for estimates of in-stream measures in that report (Coldwater, 2017b). The above results suggest that the additional measures would be required if the proposed Ultimate B' scenario was adopted.

Estimation of Dissipation Requirements

The results of the effective work index can be analysed to estimate the amount of additional dissipation that will be required under Ultimate B conditions as opposed to Interim conditions. This estimation is obtained by determining an equivalent head loss equal to the additional effective work. This was done for each reach using bankfull conditions. The bankfull depth, h_{BF}, was determined from the field investigation and PCSWMM model cross-sections. The bankfull flow speed, V_{BF}, was taken as the average of the predicted flow speed at the bankfull depth.

Equation 1 can be approximated as:

$$W_i = \sum (\tau - \tau_c) V \Delta t \cong (\tau_{BF} - \tau_c) V_{BF} \Delta t_{BF} \qquad \text{Equation 9}$$

where τ_{BF} is the shear at bankfull conditions and Δt_{BF} is the duration at bankfull that yields an equivalent amount of effective work in the reach as that calculated using the PCSWMM simulations. Equation 9 can be rearranged to provide an equation for Δt_{BF} as:

$$\Delta t_{BF} = \frac{W_i}{(\tau_{BF} - \tau_c) V_{BF}} \qquad \text{Equation 10}$$

The shear at bankfull conditions, τ_{BF}, can be determined using Equation 2 and Equation 7 and assuming uniform flow:

$$\tau_{BF} = \gamma S_{BF} \mathbb{R}_{BF} \cong \gamma S_o (0.75 h_{BF}) \qquad \text{Equation 11}$$

Substituting Equation 11 into Equation 10 yields:

$$\Delta t_{BF} = \frac{W_i}{[0.75\gamma S_o h_{BF} - \tau_c] V_{BF}} \qquad \text{Equation 12}$$

Solving Equation 12 using the computed values of effective work index from the Ultimate B simulations, $W_{i_{UB}}$, and the reach-average bed slope, S_o, from the field survey allows the estimation of Δt_{BF}, which represents the duration of bankfull-equivalent effective work experienced by each reach. Repeating the process using Interim effect work, W_{i_I}, and letting:

$$S_o = \frac{\Delta z_1}{L} \qquad \text{Equation 13}$$

where Δz_1 is the elevation change over the reach that would yield Interim condition effective work under Ultimate B hydrologic conditions. The difference between the existing elevation change ($\Delta z_o = S_o \cdot L$) and this new value provides a measure of the dissipation required, $\Delta z'$:

$$\Delta z' = \Delta z_o - \Delta z_1 \qquad \text{Equation 14}$$

Calculations using the above method were conducted for Reach 1 though 6. As will be discussed in Recommendations, these are the reaches within which in-stream measures are recommended. The input values and resulting estimates of required dissipation are presented in Table 5. As expected, the pattern of estimated dissipation requirements correlates with the expected change in effective work in each Reach. No additional measures required for Reach 3, while Reaches 2 and 5 will both require significant in-stream works to achieve these reductions.

Table 5 Values used for the estimation of additional dissipation requirements for Reach 1 to 5

Quantity	Reach				
	1	2	3	4	5
S_o (%)	0.15	0.41	0.44	0.54	0.55
L (m)	465	645	515	140	905
τ_c (Pa)	5	5	5	5	5
h_{BF} (m)	1.0	1.0	1.0	1.0	1.0
V_{BF} (m/s)	0.583	0.313	0.904	0.639	0.374
W_i (kW·h/m^2) for I	0.215	0.254	1.392	1.706	2.020
Δt_{BF} (d)	8.37	1.03	2.72	3.21	5.67
Δz_o (m)	0.70	2.64	2.27	0.76	4.98
Ultimate B					
W_i (kW·h/m^2) for UB	1.029	0.305	1.620	2.223	2.825
Δz_1 (m)	0.87	3.89	2.27	0.95	7.45
$\Delta z'$ (m)	0.17	1.24	0.01	0.20	2.47
Ultimate B’					
W_i (kW·h/m^2) for UB’	1.076	0.324	1.693	2.274	2.855
Δz_1 (m)	0.90	4.11	2.36	0.97	7.52
$\Delta z'$ (m)	0.20	1.46	0.09	0.22	2.54
Increase of UB’ over UB					
$\Delta z'$ (m)	0.03	0.22	0.09	0.02	0.07
$\Delta z'$ (%)	18%	18%	800%	10%	3%

Since slopes and conditions vary along each reach, the values generated by the above approach will serve as guidelines, rather than as hard targets in the determination of in-stream works. In addition, impacts to the creek can be mitigated in several ways, including hardening, re-alignment and reshaping of the profile. Actual recommendation will be based the findings of the field investigation described in the first part of the City of Ottawa study (Coldwater, 2017a), the results of the present modelling exercise, and experience.

Culvert Scour Assessment

Proposed changes to the hydrology of Feedmill Creek may impact the stability of culverts on Feedmill creek. This section presents an assessment of the scour protection requirements of the culverts under these new flows.

There are four Ontario Ministry of Transportation (MTO) and two City of Ottawa culverts on Feedmill Creek. The locations of these culverts are shown in Figure 13 and their physical descriptions are given in Table 6.

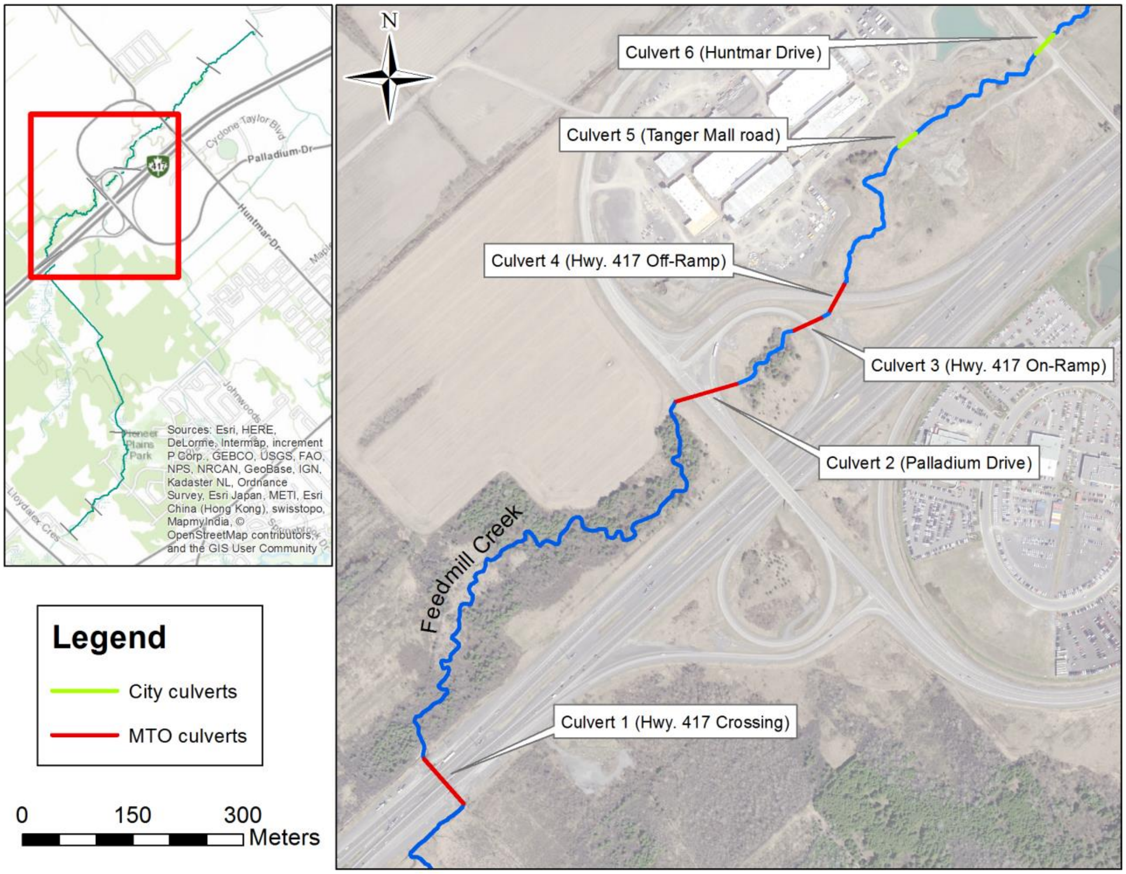

Figure 13 Locations of the MTO and City of Ottawa culverts on Feedmill Creek

Table 6 Characteristic of the MTO and City of Ottawa culverts on Feedmill Creek

Culvert	Type	Owner	Width (m)	Height (m)	Length (m)	Invert Elev. (m)	
						Inlet	Outlet
1	Concrete box	MTO	2.4	1.35	78.21	104.27	103.61
2	Concrete box	MTO	2.4	2.0	91.93	98.65	98.23
3	Concrete box	MTO	2.4	2.0	39.14	97.32	97.11
4	Concrete box	MTO	2.4	2.0	45.11	97.08	96.91
5	Concrete box	City of Ottawa	4.2	2.2	29.2	96.40	96.35
6	Arch C.S.P.	City of Ottawa	3.7	1.8	38.3	95.79	95.38

Design Guidelines

Design guidelines for the MTO culverts are presented in MTO Drainage Design Standards (MTO, 2008).

- Flows for culverts are defined by Design Standard WC-1. All four MTO culverts fall under the Standard Road classification. Section 1.1.1 states that because these culverts are less than 6 m in span, the Design Flow is to be taken as the 50-year flow.
- Section 3.1.1 of Design Standard WC-3 states that scour does not need to be assessed because these culverts all have concrete inverts, and the inlets and outlets of these culverts are armoured to prevent scour.
- Section 3.2.1 of MTO Design Standard WC-3 states that the riprap design for the protective apron should be based on a velocity of 1.5 times the average velocity of the Design Flow and that the apron thickness shall not be less than 1.5 times the median stone size.

Consequently, this section focuses on the scour protection requirements for the four MTO culverts. The same approach is adopted for the City of Ottawa culverts; however, the scour protection for these culverts has been assessed using the 50-year flow velocity for design, rather than 150% of these values.

Design Flows

The design flow conditions for the culverts were provided by JFSA; these are given in Table 7.

Table 7 Design flow at the four MTO and two City of Ottawa culverts on Feedmill Creek

Culvert	Water Surface Elev. (m)		Design Flow (m^3/s)	Velocity (m/s)	1.5 × Velocity (m/s)
	Inlet	Outlet			
1	105.90	105.63	4.463	1.38	2.07
2	100.85	100.21	11.116	2.38	3.57
3	100.13	99.73	10.827	2.26	3.39
4	99.71	99.28	10.826	2.26	3.39
5	98.23	98.11	10.984	1.46	2.19
6	97.80	97.32	12.814	2.44	3.66

Armour Protection

Riprap apron protection for the four MTO culverts can be specified using the methodology specified in Section 10.2 and Appendix D of the HEC-14 report (FHWA, 2006). There are several equations accepted for the determination of riprap stone size and these are summarized in HEC-14 (FHWA, 2006). Several of these equations are based on a design discharge; however, MTO Drainage Design Standards state that the riprap design for the protective apron should be based on a design velocity equal to 1.5 times the 50-year storm velocity. Consequently, a velocity-based formulation is used in the present application. The median riprap size, D_{50}, is given by:

$$D_{50} = \frac{0.692}{S-1}\left(\frac{V^2}{2g}\right) \quad \text{Equation 15}$$

where V is the design velocity, S is the specific gravity of the stone and g is gravitational acceleration. The application of Equation 15 at the culvert locations using S=2.65 is summarized in Table 8, which also gives the required riprap stone gradation.

Table 8 Design riprap apron specifications at the four MTO culverts on Feedmill Creek

Culvert	D_{50} (m)	Riprap	Apron Length (m)	Side Bank Elev. (m)
1	0.092	R-10	8	105.93
2	0.272	R-100	12	100.51
3	0.246	R-100	12	100.03
4	0.246	R-100	12	99.58
5	0.046	R-10	13	98.41
6	0.127	R-10	11	97.62

In confined channels, such as those found in Feedmill Creek, the standard apron 1:3 width expansion is ignored, and riprap is placed up the side banks to an elevation 0.3 m above the 50-year water level. The length of the riprap apron and the elevation to which riprap should be placed on the side banks are given in Table 8. If the banks are below the given elevation, then riprap should be placed up to the top of the bank.

The specifications for the riprap stone gradation are given in Table 9. The R-10 riprap is taken from the provincial standards (OPSE.PROV 1004, 2012) and has an approximate median diameter of D_{50}=0.14 m; the R-100 is based on the R-10 distribution and has an approximate median diameter of D_{50}=0.30 m.

Table 9 Riprap gradations

% Finer by Mass		Mass (kg)	
Lower Bound	Upper Bound	R-10	R-100
-	100	15	150
70	90	10	100
40	55	5	50
0	15	0.5	5

Based on the above analysis, the armour protection requirements for the 6 culverts under Ultimate B' conditions would change only slightly from those under Ultimate B; the protection specified in (Coldwater, 2017b) is still applicable and does not need to be modified.

Recommendations

The field survey and the results of the effective work analysis both suggest that in-stream erosion control works will be required. Some of these are necessary to redress existing issues and return the creek to equilibrium with its hydrologic environment and some are required to enable the creek to undergo the proposed hydrologic changes without detrimental effects to its function or form, or to experience morphological changes that would jeopardize adjacent properties or infrastructure. The modelling analysis undertaken suggests that adoption of Ultimate B' in place of Ultimate B would require additional in-stream protection measures.

Bibliography

Bagnold, R. (1956). The flow of cohesionless grains in fluids. *Phil. Trans Roy. Soc. London, Art. 246, Vol. 964 (Dec)* .

Chow, V. T. (1959). *Open-Channel Hydraulics.* New York, NY: McGraw-Hill.

Coldwater. (2017a). *Feedmill Creek SWM Criteria Study; Part 1 of 2 - Fluvial Geomorphic Assessment.* Ottawa, ON: Coldwater Consulting Ltd.

Coldwater. (2017b). *Feedmill Creek SWM Criteria Study; Part 2 of 2 - Erosion and In-stream Works Analysis.* Ottawa, ON: Coldwater Consulting Ltd.

FHWA. (2006). *HEC-14; Hydraulic Design of Energy Dissipators for Culverts and Channels.* Arlington, VA: Federal Highway Administration, U.S. Department of Transportation.

JFSA. (2017). *Feedmill Creek Stormwater Management Criteria Study.* Ottawa, ON: J.F. Sabourin and Associates Ltd.

Leopold, L., Wolman, G., & Miller, J. (1964, 1992). *Fluvial Processes in Geomorphology.* New York: Dover.

MNR. (2002). *Technical Guide. River & STream Systems: Erosion Hazard Limit.* Toronto, ON: Ontario Ministry of Natural Resources, Water Resouces Section.

MOE. (2003). *Stormwater Management Planning and Design Manual.* Toronto: Queen's Printer for Ontario.

MTO. (2008). *Highway Drainage Design Standards.* Toronto, ON: Ontario Ministry of Transportation.

OPSE.PROV 1004. (2012). *Ontario Provincial Standard Specification; Mineral Specifications for Aggregates - Miscellaneous.* Toronto, ON: Ontario Provincial Standard Specification.

Robinson. (2004). *Carp River Watershed/Subwatershed Study, Final Report.*

Rosgen, D. (1994). A classification of natural rivers. *Catena, 22* , 169-199.

Rosgen, D. L. (1996). *Applied River Morphology.* Pagosa Springs, Colorado: Wildland Hydrology.

Rosgen, D. L. (2006). River restoration using a geomorphic approach for natural channel design. *Proceeding of the 8th Federal Interagency Sedimentation Conference.*

Salem, H., Lambert, B., & Rennie, C. (2016). *Critical Shear Testing; Feedmill Creek, Ottawa, ON.* Ottawa, ON: Dept. of Civil Engineering, University of Ottawa.

Simon, A., Doyle, M., Kondolf, G., Shields, F., Rhoads, B., Grant, G., et al. (2005). How Well Do the Rosgen Classification and Associated ''Natural Channel Design'' Methods Integrate and Quantify Fluvial Processes and Channel Response? *J. Env. Wat. Res. Inst., ASCE* .

TRCA. (2012). *Toronto Region Conservation Authority Stormwater Management Criteria, Appendix B Erosion and Geomorphology.* Toronto: Sustainable Technologies.

TSH. (2007). *Carp River, Poole Creek and Feedmill Creek Restoration.* Kitchener, ON: Totten Sims Hubicki.

Yalin, M. (1977). *Mechanics of Sediment Transport (2nd Edition).* London: Permagon Press.

Appendix A – Descriptions of PCSWMM Model Sections

Table 10 PCSWMM sections used in the geomorphic analysis

Section	Length	Reach	Description
FC004	100.2	1	Channelized section just upstream from entrance to Carp River. Narrow, incised channel with silt deposits and basal scour.
FC008	77.7	1	Quasi-natural section between upstream natural channel in woodland and downstream channelized section. Sinuous planform. Less undercutting than section downstream.
FC010	100.1	2	Natural section within woodland. Subject to damming by deadfalls. Cobbles and small boulders present. Ford near downstream end.
FC011	99.9	2	Natural section within woodland. Subject to damming by deadfalls. Eroding banks at bends. Some cobbles and small boulders.
FC026	70.7	3	Rock weir at downstream limit. Constructed channel wider than downstream. Planted vegetation. Upstream limit is culvert at internal mall road.
FC028	71.0	3	Downstream limit is culvert at internal mall road. Lower portion is wide, constructed. Narrow, timber flume section with exposed hard clay bed in middle.
FC040	92.7	5	Upstream of Palladium Dr. Natural section away from culvert. Meandering planform. Cobble and boulder bars. Eroding bends. Undercut banks.
FC041_2	40.4	5	Natural section. Meandering planform. Undercut banks. Cobble and boulder armouring bars and bed. Steep section with shallow flow.
FC041_1	52.2	5	Natural section. Meandering planform. Cobble and boulder bars and bed. Eroding bends. Undercut banks. Small culvert in middle.
FC042	62.1	5	Armoured like section below. Eroding banks at bends. Runs through heavy woodland. Shallow, fast flow in steeper areas.
FC043	62.0	5	Runs through heavy woodland. Armoured as below. Undercut banks at bends. Tree roots exposed. Shallow, fast flow in steeper areas.
FC054	100.1	5	Meadow section. Incised channel. Numerous deadfalls. Some eroding banks, other areas have undercut banks hidden by vegetation.
FC056	57.9	5	Incised channel in woodland. Numerous deadfalls. Some eroding banks, other areas have undercut banks hidden by vegetation.

Appendix B – PCSWMM Model Results

Table 11 Average annual effective work, W_i (kW·h/m²), from PCSWMM model with τ_c = 1 Pa

Section	Interim	Interim'	Ultimate B	Ultimate B'
FC004	2.837	1.407	3.866	4.053
FC008	0.498	0.586	0.726	0.759
FC010	1.571	1.874	2.159	2.268
FC011	0.690	0.833	0.953	1.007
FC026	6.003	5.892	6.493	6.883
FC028	0.551	0.756	1.015	1.034
FC040	0.989	1.449	1.883	2.045
FC041_2	6.922	9.111	10.721	11.603
FC041_1	10.951	10.173	14.909	14.542
FC042	4.599	5.106	6.872	7.081
FC043	3.118	3.469	4.653	4.802
FC054	0.255	0.305	0.428	0.442
FC056	1.882	1.978	2.512	2.614

Table 12 Average annual effective work, W_i (kW·h/m²), from PCSWMM model with τ_c = 5 Pa

Section	Interim	Interim'	Ultimate B	Ultimate B'
FC004	1.201	0.331	1.758	1.839
FC008	0.067	0.064	0.088	0.092
FC010	0.324	0.430	0.524	0.553
FC011	0.066	0.079	0.086	0.095
FC026	2.975	2.494	2.833	2.989
FC028	0.259	0.295	0.412	0.402
FC040	0.314	0.500	0.685	0.777
FC041_2	4.074	5.522	6.713	7.274
FC041_1	7.543	7.170	10.788	10.357
FC042	2.483	2.896	4.056	4.099
FC043	1.391	1.654	2.332	2.361
FC054	0.041	0.050	0.071	0.074
FC056	0.191	0.220	0.318	0.328

Table 13 Average annual effective work, W_i (kW·h/m²), from PCSWMM model with τ_c = 10 Pa

Section	Interim	Interim'	Ultimate B	Ultimate B'
FC004	0.444	0.073	0.607	0.639
FC008	0.000	0.000	0.000	0.000
FC010	0.000	0.000	0.000	0.000
FC011	0.000	0.000	0.000	0.000
FC026	1.202	0.441	0.434	0.455
FC028	0.121	0.110	0.165	0.149
FC040	0.021	0.055	0.094	0.121
FC041_2	1.967	2.860	3.567	3.822
FC041_1	4.735	4.651	7.315	6.866
FC042	1.173	1.379	1.996	2.054
FC043	0.502	0.572	0.836	0.871
FC054	0.000	0.000	0.000	0.000
FC056	0.002	0.002	0.003	0.004

Table 14 Average annual effective work, W_i (kW·h/m²), from PCSWMM model – individual reaches and average

Reach	Interim	Interim'	Ultimate B	Ultimate B'
1	0.706	0.215*	1.029	1.076
2	0.195	0.254	0.305	0.324
3	1.614	1.392	1.620	1.693
5	1.804	2.020	2.825	2.855
Average	1.154	1.110	1.607	1.646

* *the PCSWMM model boundary conditions differ for this case near this area*

Table 15 Change in Average annual effective work, W_i (kW·h/m²), from Interim conditions - individual reaches and average

Reach	Interim	Interim'	Ultimate B	Ultimate B'
1	n/a	-70%*	46%	52%
2	n/a	30%	56%	66%
3	n/a	-14%	0%	5%
5	n/a	12%	57%	58%
Average	n/a	-4%	39%	43%

* *the PCSWMM model boundary conditions differ for this case near this area*