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EFFECTS OF CLIMATE CHANGE ON STREAM EROSION IN A SMALL WATERSHED

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Abstract: The effects of climate change on stream erosion are evaluated in Watts Creek basin, located in Ottawa, Ontario, Canada. The subwatershed has a drainage area of 21 km^2 with land use split between urban development (68%), forest (12%) and agricultural lands (20%). The SWMHYMO platform was used to develop a lumped hydrologic model of the area. The model was calibrated using field data collected between May and August 2015 and May and October 2016. Precipitation time series simulated by the Canadian Regional Climate Model 4 (CanRCM4) regional climate model ran under Representative Concentration Pathway (RCP) 85 for the 2041-2080 period at the MacDonald Cartier International Airport were downscaled using quantile matching and then used as input to the hydrologic model. A cumulative effective work index in response to reach-averaged shear stress was calculated in a reach of Watts Creek for both the historic (1967 – 2007) and projected future (2041-2080) flows. Results suggest an increase of 240% in the work index compared to historic conditions for the average measured bed material critical shear stress for entrainment of 3.7 Pa. The increased work is shown to occur in fewer, relatively more intense events, suggesting a significant change to the flow and erosion regime in Watts Creek.

1 INTRODUCTION

River engineers and geoscientists have engaged in river analysis and restoration design for several decades. These endeavors have focused largely on mitigating or reversing the negative effects of human activity on watercourses due to land-use changes associated with urbanisation and its many related industries (Hammer 1972; FISRWG 1998). An increasing number of studies have identified potential changes in both precipitation frequency and intensity in the future. These changes may lead to further impacts on our watercourses (IPCC 2012). Therefore, there is a need to consider how potential climatic change can be incorporated into river analysis and restoration design by current practitioners.

The purpose of this project is to assess the impacts of future rainfall patterns on the erosion potential within Watts Creek using continuous simulations from a lumped hydrologic model and a shear stress exceedance routine to assess erosion potential. This study builds on previous work assessing the existing state of the Creek resulting from ongoing effects of past land-use changes (agricultural and urban) on channel stability and fish habitat utilisation (Maarschalk-Bliss 2014; Parsapour-moghaddam et al. 2015; Rennie 2014; Salem et al. 2014).

Watts Creek is located in Ottawa, Ontario, Canada, and has a drainage area of approximately 21 km^2 with land use split between urban development (68%), forest (12%) and agricultural lands (20%). The system has been found to support important fish habitat, but is undergoing active erosion that can potentially lead to degraded water quality (Rennie 2014). The Creek also has meander bends adjacent to a rail bed, raising the question of risk to infrastructure due to erosion. This study aims to assess how the erosive regime may change in the future as a result of climate change. Figure 1 shows the Watts Creek subwatershed general location. The river drains in a generally north-easterly direction to the Ottawa River. The studied reaches are on lands owned by the National Capital Commission (NCC) that form part of the Capital Greenbelt.

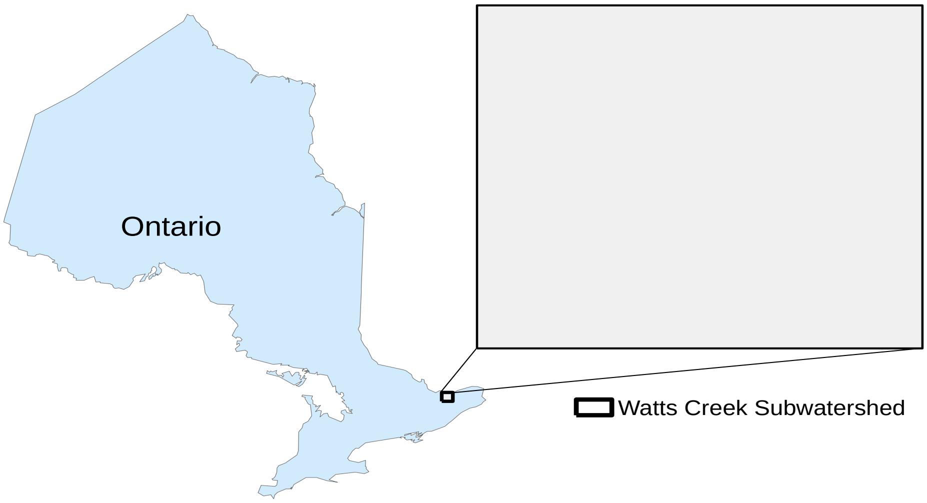

Figure 1: Watts Creek general location and subwatershed

2 METHODS

The study was designed as a joint field monitoring and numerical exercise. Since Watts Creek is an ungauged watershed, continuous flow and precipitation data were collected during the 2015 and 2016 summer seasons to serve for the calibration of the hydrologic model. Given the short length of the observation time series, the model was not validated.

2.1 Field Measurements

Watts Creek, like many small subwatersheds in Ontario, is ungauged and, as such, historic streamflow data or rating curves are unavailable. Water levels were measured at the upstream (-75°52’37.75’’W, 45°20’25.62”N) and downstream (-75°52’34.29”W, 45°20’25.72”N) extents of the study reach (referred to as reach M3 following the convention from previous studies by Maarschalk-Bliss (2014) and Rennie (2014)). Pressure transducers (Onset® Hobo water level loggers) were installed within the Creek at both locations (upstream site named WC3 and downstream site named WC4). The total pressure readings from the underwater transducers were compensated for air pressure based on concurrent readings from a third transducer which was installed nearby above the water line. The underwater loggers were fastened to rebar posts that were hammered into the creek substrate. The compensated water depth readings were converted to water level values based on periodic in-field depth measurements at the rebar posts. The geodetic elevation of the top of rebar was surveyed using a Hemisphere® Real Time Kinematic (RTK) GPS on Sept 18, 2015. It was assumed that the top of rebar elevation did not change throughout the study period.

The pressure transducers were installed from May 31 to Aug 21, 2015 and May 30 to October 23, 2016. The loggers were set to record every five (5) minutes. Subsequently in this paper, when referring to continuous field data or hydrologic model output, the data have a measurement period of five (5) minutes.

Periodic flow measurements were collected at WC4 in 2014 and 2015 as part of a previous study on sediment erodibility in Watts Creek (Parsapour-moghaddam et al. 2015; Rennie 2014). Those five (5) flow measurements [range 40 L/s to 1,368 L/s] were augmented with a summer low flow measurement [12 L/s] on Aug 11, 2016 (using a propeller meter and the velocity-area method) and a mid-range flow measurement [391 L/s] on Oct 23 2016 using a SonTek RiverSurveyor® M9 acoustic Doppler current profiler (aDcp). The previous flow measurements in 2014 and 2015 were also recorded with the SonTek M9 aDcp. Note that some flow measurements were taken within a few hundred metres upstream of WC4, though an assumption of constant discharge between the measurement location(s) and WC4 is reasonable based on field observations.

The continuous water level records at the downstream station (WC4) were converted to flow series for the 2015 and 2016 seasons using a rating curve derived by fitting a power function to the paired depth-flow data described above.

2.2 Hydrologic Modelling

The SWMHYMO platform (JFSA 2000) was used to develop a hydrologic model of the Watts Creek watershed to simulate historic and future flow series at the study reach (M3). SWMHYMO is a lumped hydrologic model with routines for simulating runoff from watersheds with mixed land use (urban, agricultural and natural), and has the ability to perform multi-year simulations with low computational cost. The model uses the unit hydrograph method to convolute runoff volume into a runoff hydrograph at the sub-catchment level. Sub-catchment runoff hydrographs can be routed through: reservoirs to simulate stormwater detention facilities; pipes to simulate travel through storm sewer systems and culverts; and channel sections to simulate watercourses. Conceptually, the model consists of a series of hydrographs (flow-time series) that can be added to one another and routed along the various hydraulic features within the subwatershed. At all nodes for hydrograph generation, addition and routing, the model returns the total drainage area, runoff volume, maximum peak flow and time to peak flow. At hydrograph generation nodes the runoff coefficient (ratio of runoff volume to rainfall volume) is also returned. The user has the option to save the hydrograph time series at any or all nodes. The natural catchment hydrograph routines include a baseflow subroutine, which stores infiltrated volume in a groundwater reservoir. This groundwater reservoir can be depleted by baseflow discharge to the watercourse (volume returned to runoff hydrograph) or recharge to the deep aquifer (volume not returned as runoff). The groundwater reservoir behavior is user-defined for each catchment. The platform reads in rainfall data files and can accept design storm or continuous data. The continuous option has been used for this work. SWMHYMO also has an erosion routine to calculate erosion potential, which was modified as part of the present research program to be based on a shear stress exceedance method, see section 2.2.2 below for a description of the modifications.

Input data for the hydrologic model were collected from a variety of sources. Detailed information on storm sewer catchment delineation, underground and surface storage (detention) facilities, drainage direction and catchment imperviousness for the urban areas were based on a stormwater management (SWM) report prepared for the City of Ottawa (AECOM 2015). The hydrologic model prepared in that 2015 study was provided for use in this analysis by the City of Ottawa. Drainage boundaries for the agricultural and natural catchments were delineated based on LiDAR information provided by the NCC, which was converted into a digital elevation model (DEM) using ArcGIS©. The SCS runoff method option, see Eq. 1, has been used to calculate runoff excess (and infiltration) in response to precipitation in the model.

$$[1] \qquad Q = \frac{(P-I_a)^2}{P-I_a+S}$$

In Eq. 1 above, Q is the runoff volume, P is the total precipitation, I_a is the initial abstraction and S is soil storage; all values have units of volume, expressed in mm (depth over the catchment area). Soil storage is defined as a function of the non-dimensional curve number (CN), see Eq. 2.

$$[2] \qquad CN = \frac{25\,400}{254+S}$$

In Eq. 2 above, CN is a non-dimensional value that can range from 1 to 99 and all values on the right-hand-side have units of mm.

Initial abstraction is defined as a fixed depth by the user to represent interception and depression storage losses. This is a modified form of the original SCS method, in which I_a was defined as 20% of S. The modification allowed the method to be expanded to simulate runoff volumes from frequent (small volume) storms as well as infrequent flood events, as expressed in various USDA, Natural Resources Conservation Service (NRCS) documents (USDA 1986; Woodward et al. n.d.). With the modification of I_a from the original method, a modification of CN and or S is also required to maintain the runoff volume response for a given precipitation volume. Hawkins et al. (2001) propose a straightforward equation to modify (reduce) literature CN values for this purpose; equation 9 from their paper is reproduced below as Eq. 3.

$$[3] \qquad CN_{0.05} = \frac{100}{1.879\left[\frac{100}{CN_{0.20}}-1\right]^{1.15}+1}$$

In Eq. 3 above, $CN_{0.05}$ is the modified CN value to account for a reduced I_a and $CN_{0.20}$ is the typical CN that one would extract from literature tables prepared for the SCS method.

The CN values for the non-urban catchments were selected from literature tables included in the product's user's manual (JFSA 2000) based on an area weighting of hydrologic soil group (HSG) from the Soil Survey Complex map data (OMAFRA 2015) and land-use based on Provincial Landcover map data (OMAFRA 1999) for each catchment. The corresponding modified CN value was calculated using Eq. 3 and input to the model. Topographical characteristics like catchment length and slope were extracted from the DEM and used to calculate the time to peak (t_p) response for each catchment using several time of concentration (t_c) methods and the 85/10 method suggested by the Ministry of Transportation Ontario (MTO 1997, Ch 8). Time to peak is equal to 2/3 the time of concentration value. The model response to various t_c methods was assessed as a calibration exercise, and the method that resulted in the closest timing match with the measured data, Bransby-Williams, was selected (Eq. 4).

$$[4] \qquad t_c = \frac{0.605 * L}{A^{0.2} S^{0.1}}$$

The time of concentration (t_c) is in minutes, catchment length (L) is in km, drainage area (A) is in km^2 and average catchment slope (S) is in percent.

The Watts Creek hydrologic model has 50 catchments for the urban area, 32 of which (1197.5 ha) have significant impervious cover (residential, commercial or industrial land use) with an average total imperviousness of 39%. The remaining 18 urban catchments (234.9 ha) contain mostly pervious areas (golf courses, parks, etc.) with an average CN of 62. Some of the urban catchments drain to SWM facilities that provide some runoff control, as such, there are 17 reservoir commands in the model. The balance of the watershed is comprised of agricultural and forested areas (678.9 ha), which are simulated with 9 sub-catchment routines and have an average CN of 63.

2.2.1 Model calibration

Model calibration was conducted to improve the match with the 2015 and 2016 field flow data. Total runoff volume was assessed first, as the model was initially overestimating volume for both years. The directly connected impervious areas (originally 87% of total impervious areas) were reduced to 64%. This reduction was applied for areas with relatively deep lots and large yards (rooftops assumed to be non-directly connected (NDC) areas) where the roads had no curb or sidewalk (some driveways considered NDC areas). This configuration applies to at least 60% of the urban area.

The model timing was adjusted by selection of a t_c method as described above and by increasing the Manning's n values for the impervious surfaces in catchments where ditches or creeks comprised part of the drainage network. The catchment length parameter (*LGI*) was also increased for some large urban catchments to consider the length of the drainage network. Watts Creek, and its largest tributary the Kizell Drain, were simulated using channel routing commands. The cross-section shape, channel lengths and roughness values were originally based on the model prepared previously by others. The channel lengths were investigated in detail and modified where appropriate based on aerial imagery. The channel and overbank roughness (*n*) values were increased in some areas (from 0.04 to 0.085) to reflect the field conditions observed in 2016 (overall range of *n* 0.03 to 0.085). Those routing modifications slowed the runoff response, which improved the match to the field flows. Table 1 summarises the calibration results for the 2015 and 2016 data. The Nash-Sutcliffe efficiency for 2015 is 54% while 2016 is 46%. The calibration was stopped since the model was providing a slight underestimate for the June and July 2015 data but an overestimate for August 2015 and all months in 2016.

Table 1: Hydrologic Model Flow and Runoff Volume Results Compared to Field Values

a) 2015

		FIELD FLOW			MODEL FLOW		
MONTH	Rainfall Volume (mm)	Runoff Volume (mm)	Average Flow (L/s)	Maximum Peak Flow (m^3/s)	Runoff Volume (mm)	Average Flow (L/s)	Maximum Peak Flow (m^3/s)
JUNE	88.6	16.9	137.4	5.2	11.4	92.8	1.7
JULY	65.0	10.4	81.9	2.3	8.2	64.6	2.5
AUG	71.4	3.3	39.9	3.2	8.9	108.9	3.6
TOTAL	225.0	30.5	92.1	5.2	28.5	86.0	3.6

b) 2016

		FIELD FLOW			MODEL FLOW		
MONTH	Rainfall Volume (mm)	Runoff Volume (mm)	Average Flow (L/s)	Maximum Peak Flow (m^3/s)	Runoff Volume (mm)	Average Flow (L/s)	Maximum Peak Flow (m^3/s)
JUNE	63.0	4.4	35.9	5.2	13.9	112.9	7.6
JULY	91.2	4.9	38.6	3.3	16.8	132.3	4.4
AUG	119.1	21.4	260.9	17.4	35.4	432.1	22.0
TOTAL	273.3	30.7	92.5	17.4	66.0	199.1	22.0

The less than 1% increase in calculated field flow volume from 2015 to 2016 shown in Tables 1a and 1b is less than expected based on the measured rainfall. Work to improve this calculation is ongoing, the issue seems to be based in part on the differing hydraulic conditions during 2015 and 2016. Figure 2a and 2b show the measured rainfall, field and model flows for July of 2015 and 2016 respectively.

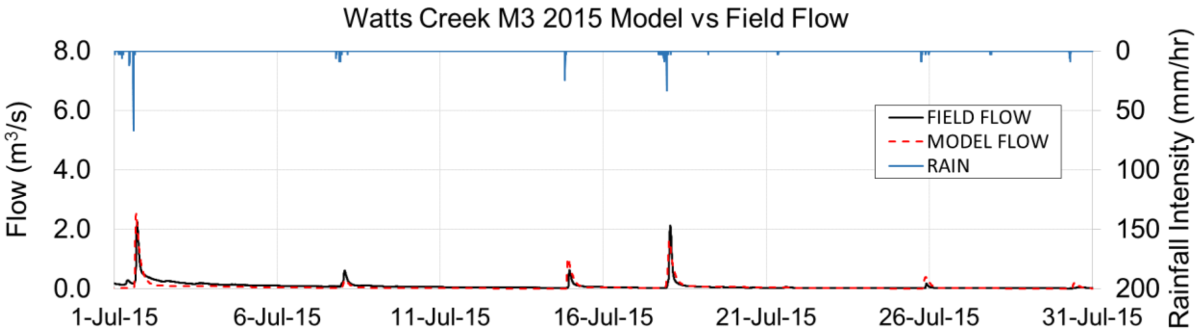

Figure 2a: Hydrologic model calibration results field flow versus model flow at reach M3 2015

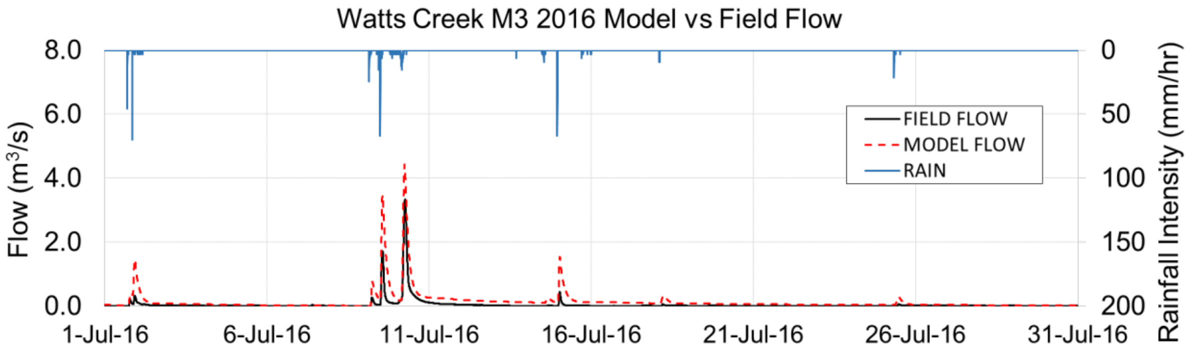

Figure 2b: Hydrologic model calibration results field flow versus model flow at reach M3 2016

The model was used to generate continuous hydrographs at the study reach for the periods when historic hourly rainfall data are available, 1968 to 2007 inclusive (excluding 2001 and 2005 due to missing data). The input rain data used for the historic runs were the hourly rainfall data (HLY03, element 123) collected by Environment Canada at the Ottawa International Airport Gauge. The data do not include frozen precipitation, so the model runs were constrained from April 1 to Oct 31 for each year.

The same model was also used to generate future hydrographs for 2041 to 2080. Derivation of the future hourly rainfall dataset is discussed in section 2.3.

2.2.2 Modified Erosion Index Routine

To assess the effects of climate change on erosion at the study site, both the historic and future hydrographs were analysed with the erosion index routine.

The erosion index routine has been modified to include a shear stress exceedance subroutine. The routine requires a 1-dimensional cross-section definition: station-elevation points, Manning's *n* roughness values for the segments of interest, bed slope and floodplain slope, an inflow hydrograph and the critical shear stress value for bed material entrainment.

The depth-flow relationship is derived from the Manning's equation, Eq. 5:

[5] $$Q = \frac{1}{n}\mathrm{R}_{\mathrm{h}}^{\frac{2}{3}}\mathrm{S}^{\frac{1}{2}}\mathrm{A}$$

In Eq. 5 above, Q is flow (m^3/s), n is the Manning's roughness parameter, R_h is hydraulic radius (m), S is the channel slope (m/m) and A is the flow area (m^2). Shear stress is based on the 1-dimensional reach-averaged shear stress equation, Eq. 6:

[6] $$\tau = \gamma\mathrm{R}_{\mathrm{h}}\mathrm{S}$$

In Eq. 6 above, τ is the bed shear stress (Pa) and γ is the specific weight of water (N/m^3). The cumulative effective work index method, Eq. 7, was presented by the Toronto and Regional Conservation Authority (TRCA) in their SWM Criteria document (TRCA 2012) as a suggested method to estimate erosion potential using a stream power approach.

[7] $$W_i = \sum(\tau - \tau_c)v\Delta t$$

W_i is the cumulative effective work index, τ_c is the user-entered critical shear stress (Pa), τ is the bed shear stress (Pa), v is the main channel mean velocity (m/s) and Δt is the model time step. The erosion index routine returns the work index, the total hours and total flow volume when shear stress exceeds the critical, and the number of events that cross the threshold. These erosion indicators have been used to quantify potential changes to erosion in Watts Creek under climate change induced future rainfall patterns.

2.3 Statistical Downscaling (Quantile Quantile)

The future rainfall data were generated by downscaling precipitation time series simulated by the Canadian Regional Climate Model (CanRCM4) under the RCP85 radiative forcing. RCP85 refers to a scenario where the radiative forcing on the earth surface reaches or exceeds 8.5 W/m^2 by 2100, and continues to rise. The simulation was conducted by the Canadian Centre for Climate Modelling and Analysis (CCCma) in the CORDEX (Coordinated Downscaling Experiment:(Scinocca et al. 2015)); the experiment output data were accessed from their website (Environment and Climate Change Canada 2014).

The quantile-quantile (QQ) downscaling method (or quantile matching) was selected in this study because of its ability to correct the whole distribution of each relevant hydrologic variable (Maraun et al. 2010). It adjusts the regional model results to match the local distribution for the historical period (1961 – 2011) and applies that same bias correction to the predicted future results (2012-2100). The numerical code to perform the downscaling was previously developed in Shirkani et al. (2015) and Seidou et al. (2011) and modified for this study to read in the CanRCM4 RCP format precipitation output. The downscaling approach calculated a QQ transform to fit the model output to the station data for half of the historic period (even years). The odd years in that period were used as a validation dataset. The QQ downscaling was applied to the CanRCM4 outputs at the Ottawa International Airport station to generate precipitation time series that represents the climate in the Watts Creek subwatershed for the 2041-2080 period.

The effect of the bias correction on precipitation occurrence for the historic and future period is shown in Figure 3.

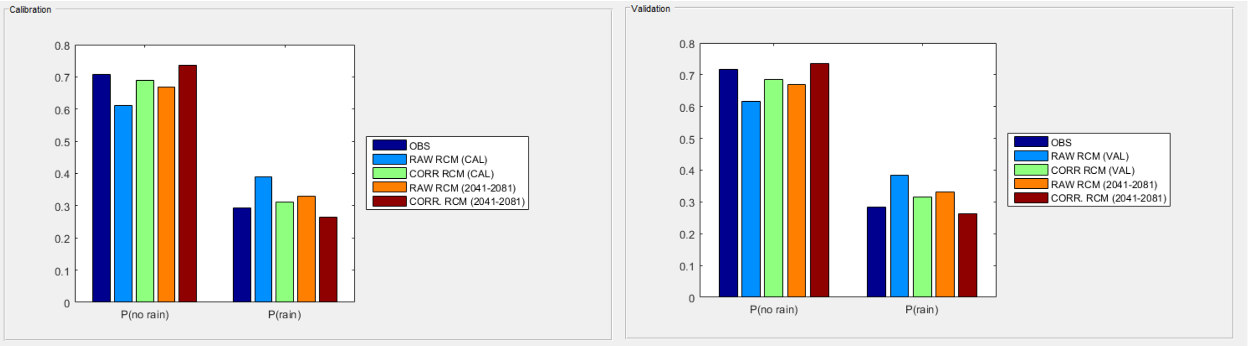

Figure 3: Precipitation occurrence in July, observed and modelled (raw and downscaled) during historical period for calibration (odd years) and validation (even years), and modelled (raw and downscaled) during future period. P(rain) indicates likelihood of precipitation in the daily data set.

Since the subwatershed is approximately 20 km^2, daily data are too infrequent to capture peak flows if used in a hydrologic model. To overcome this obstacle, the daily volume for each wet future day was compared to the historic rainfall data from the airport station. When a historic match was found, the recorded hourly distribution was returned to define the future distribution. The comparison was conducted monthly. This process resulted in a set of hourly future rainfall data in response to the climate change impacts predicted by CanRCM4 RCP 85. A forty year future window from 2041 to 2080 was selected for the erosion analysis.

Precipitation indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) provide consistent metrics for assessing the potential impact of future increase in extreme weather events across climate studies (Zhang et al. 2011). The future results have average increases in both total annual precipitation (PRCPTOT) and number of days with rainfall exceeding 20 mm (R20). The cumulative dry days (CDD) are expected to increase slightly while the consecutive wet days (CWD) decrease very slightly, see Table 2.

Table 2: Average Precipitation Indices for Historic Data and Future Predictions

PERIOD	PRCPTOT (mm)	CDD (days)	CWD (days)	R20 (days)
HISTORIC (1968-2007)	664.1	16.6	4.4	7.8
FUTURE (2041-2080)	805.7	17.8	4.3	11.5
PERCENT DIFFERENCE	21%	7%	-2%	47%

3 RESULTS

The continuous hydrographs at reach M3 for the historic (1968-2007) and future (2041-2080) periods were analyzed with the erosion index method to quantify the expected changes in erosion potential due to the climate change induced future rainfall patterns. Previously measured critical shear stress values for Watts Creek bed material samples ranged from 0.9 Pa to 5.1 Pa (Rennie 2014; Salem et al. 2014) showing significant spatial variability. The average of the two measurements at reach M3 was 3.7 Pa. Table 3 below compares the erosion potential at reach M3 compared to a critical shear stress value of 3.7 Pa.

Table 3 Comparison of Future and Historic Erosion Potential at Reach M3, Critical Shear Stress of 3.7 Pa

PERIOD*	Average Flow (L/s)	Runoff Duration (hours)	Erosion Hours (hours)	Exceedance Percent	No. of erosion events	Total Exceedance Volume (10^3 m^3)	Cumulative Work Index (kPa.m or kJ/m^2)
1968 to 1977	119	5436	63	1%	12	327	292
1978 to 1987	147	5554	84	2%	16	503	442
1988 to 1997	117	5522	65	1%	12	363	322
1998 to 2007**	139	5497	82	1%	15	532	452
All historic	130	5503	73	1%	14	426	373
2041 to 2050	183	5743	110	2%	18	742	682
2051 to 2060	246	5768	143	2%	21	1,290	1,205
2061 to 2070	207	5757	123	2%	21	883	816
2071 to 2080	198	5723	120	2%	17	920	862
All Future	208	5748	124	2%	19	959	891
Percent Difference	60%	4%	70%	63%	36%	125%	139%

*The rainfall input to the hydrologic model is from April 1 to Oct 31 inclusive.
**The historic record is missing data for 2001 and 2005.

As expected, given the increase in average annual precipitation volume and particularly in number of days with greater than 20 mm for the future period shown in Table 2, the future rainfall results in increased erosion potential at reach M3 in Watts Creek.

It is worth noting that the results presented in Table 3 depend upon the estimate of critical shear stress for Watts Creek bed material. In addition to the assessment at a critical shear stress of 3.7 Pa, responses for τ_c ranging from 1 Pa to 10 Pa were assessed. This sensitivity test was conducted due to the difficulties in calculating a precise critical shear stress for clay channels, and the high spatial variability in bed material strength along Watts Creek. Still, the average measured value of $\underline{\tau_c}$ = 3.7 Pa is reasonable.

Results from the sensitivity analysis show that the percent increase for future conditions rise to a maximum at 7 and 8 Pa before falling. This indicates that the highest relative increase in work occurs at flows corresponding to critical shear stress values that are approximately double the measured bed strength at reach M3 of Watts Creek.

Bankfull depth has been estimated as 1.2 m at reach M3 based on the fairly abrupt change in vegetative cover and transverse slope on both banks. The highest discharge measured (1,368 L/s) by Parsapour-moghaddam et al. (2015) corresponded to a depth of approximately 1.1 m at reach M3. Therefore, the bankfull discharge is approximately 1,400 L/s. The erosion index routine returns the critical flow value corresponding to the specified critical shear stress. For the 3.7 Pa estimate of bed strength, the model calculates a flow of 1,230 L/s. This result corresponds quite well with the visual estimate of bankfull discharge, suggesting that 3.7 Pa is likely a good estimate for the strength of the controlling bed layer in this reach and that the model produces a reasonable relationship between flow and potential erosion.

4 DISCUSSION AND CONCLUSION

A lumped hydrologic model developed for the 21 km^2 mixed-use Watts Creek subwatershed was calibrated based on field data collected in 2015 and 2016. While the calibration was reasonably successful, work is ongoing to improve the field flow estimate for 2016. The hydrologic model was setup to perform continuous simulations and has been used to produce flow hydrographs at the study reach for a 40-year historic period (1968 to 2007) and a 40-year future period (2041 to 2080). The future and historic hydrographs were assessed with the model's modified erosion routine, which calculates the cumulative effective work index (CWI) above a defined critical shear stress threshold.

Future rainfall time series were generated at the Ottawa Airport Station by downscaling the output of the regional CanRCM4 model simulated under the RCP85 representative concentration pathway. This produced an hourly future rainfall dataset. The model was used to simulate flow and erosion in the historical period and for a 40-year future period spanning from 2041 to 2080.

Potential changes to the erosion regime at the study reach were assessed for long-term annual average results, accounting for changes to wet and dry periods as well as volume, with low computational cost. This annual average approach has the benefit of overcoming, smoothing out, some of the uncertainties inherent in predicting future stream flows and provides a broader assessment than using a single representative (bankfull) flow approach.

The erosion routine results show an expected increase in the average CWI by approximately 240% with a critical bed shear stress of 3.7 Pa. The total flow volume in exceedance is 225% higher than the historic results while the number of above-critical events per year is only expected to increase by 136%. This suggests that not only will the net erosion more than double, the erosive work will be done by fewer relatively more intense events.

This predicted increase in erosive potential could change the classification of reach M3 from relatively stable to unstable. This, in turn, could have negative consequences for fish habitat and potentially increase risk to nearby infrastructure. These results suggest the need for further study to understand in more detail what the potential effects could be and how to either mitigate them or adapt. Particularly, future work is being considered to incorporate continuous flow hydrograph results for current and future conditions into a 3-D morphodynamic and habitat suitability model.

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