

DRAFT FOR REVIEW

Erosion Hazard Assessment: Van Gaal Drain, Richmond, ON

Submitted to:	David Schaeffer Engineering Limited
Prepared by:	M.H. Davies, Ph.D., P.Eng.
	Coldwater Consulting Ltd. 5510 Canotek Road, Suite 203 Ottawa, ON, K1J 9J4 (613) 747-2544
Version:	1.2
Date:	15 October 2013

Version History

					r
Version	Date	Status	Comments	Reviewed by	Approved by
0.91	3 October 2013	For discussion	Completed 1 st draft	NJM	MHD
		with DSEL			
1.0	10 Oct 2013	For discussion	Working Draft	MHD	MHD
		with RVCA and			
		City			
1.1	15 Oct 2013	For discussion	Working Draft	MHD	MHD
		with RVCA and			
		City			
1.2	15 Oct 2013	For discussion	Working Draft	MHD	MHD
		with RVCA and			
		City			

For further information please contact:

Michael Davies (mdavies@coldwater-consulting.com) 613 747-2544

Provisos

This report was prepared by Coldwater Consulting Ltd. The recommendations and opinions contained in this report are based upon a limited dataset and a limited scope of work. The material contained herein reflects the judgement of Coldwater Consulting Ltd. in light of the information available to them at the time of preparation. Any use which a Third Party makes of this report, or any reliance on decisions to be made based on it, is the responsibility of such Third Parties. Coldwater Consulting Ltd. accepts no responsibility for damages, if any, suffered by any Third Party as a result of decisions made or actions based on this report.

Submitted 15 October 2013,

H. oreice.

M.H. Davies, Ph.D., P.Eng. Coldwater Consulting Ltd.

Table of Contents

1	Intr	oduction4
	1.1	Background Information4
2	Bac	kground5
	2.1	Previous Work5
	2.2	Review7
3	Fiel	d Investigation7
4	Ero	sion Model9
	4.1	Methodology9
	4.2	Critical Shear Stress10
	4.3	HEC-RAS Model Refinement10
	4.4	Model Operation11
5	Res	ults12
	5.1	Single Event Simulation12
	5.2	Long-term Simulations14
6	Res	toration and Protection Works16
7	Sun	nmary
8	Bib	liography20

1 Introduction

Coldwater Consulting Ltd., (Coldwater) has been engaged to provide the following analysis and design services to David Schaeffer Engineering Ltd (DSEL):

- Review previous studies of the Van Gaal Drain, its present condition and hydraulic conditions as provided by DSEL;
- Conduct site investigations of the drain, its bed composition, morphology and bank characteristics for the reach (VGR1) extending from Perth Street downstream to its confluence with the Jock River; and,
- Develop a preliminary erosion hazard model and present quantitative estimates for any required restoration works.

1.1 Background Information

The following documents were referenced when preparing this design brief:

- Report from JFSA "Floodplain mapping report for the van Gaal and Arbuckle municipal drains in the village of Richmond", provided by DSEL dated November 2009.
- Report by Robinson Consultants (Robinson) for the City of Ottawa on the Arbuckle Municipal Drain dated February 2010
- Report by Parish Geomorphic (Parish) and Kilgour and Associates (Kilgour) for Mattamy Homes on the Mattamy Lands natural environment and assessment on impacts from development dated February 2010
- Report from JTB Environmental Systems Inc. " Van Gaal Drain Erosion Assessment, Richmond, Ontario", provided by DSEL dated October 2012.

- Memorandum from JTB Environmental Systems Inc. "Richmond Village Development: Existing Erosion Remediation Costs", provided by DSEL dated November 2012.
- Report from JTB Environmental Systems Inc. "Van Gaal Drain Restoration Memo, Richmond, Ontario", provided by DSEL dated January 2013.
- HEC-RAS model developed and provided by JFSA, September 2013.
- Continuous time series of discharge for pre- and post-development at 4 junctions (provided by JFSA, September 2013),
- Stormwater Management Planning and Design Manual, (Ontario MoE, March 2003),
- Cross-sectional data (Arbuckle drain cross sections.dwg) surveyed by J.D.Barnes and provided by DSEL.

2 Background

2.1 Previous Work

Six reports dealing with Van Gaal Drain and surrounding area were reviewed in the preparation of the present report. These reports are the first six documents listed in Section 1.1.

<u>Floodplain Mapping Report for the Van Gaal and Arbuckle Municipal Drains in the Village of</u> <u>Richmond (JFSA, 2009)</u>

The JFSA report details the flood risk mapping that was performed for the Arbuckle and Van Gaal Drains. Hydrologic analyses were performed using the SYMHYMO model and hydraulic analyses using the HEC-RAS model. Based on a review of earlier DSEL models, the drainage area was estimated at 1147 ha. The report notes that access to certain areas could be obtained and so it was necessary to assume cross-sectional profiles based on earlier data at these sections. Channel sections were modelled using a Manning's n value of 0.035 for the channels, and 0.08 for the summer floodplain and 0.05 for the spring floodplain.

Three 100-year spring and summer event discharges were studied and the maximum discharge from the Van Gaal Drain at the Jock River was found to be 16.419 m³/s. The 2-year spring and summer event discharges varied ranged from 5.666 m³/s to 7.883 m³/s. Flood risk elevations were computed at various stations along the river from the maximum of three values (Van Gaal Drain spring flood, Van Gaal Drain summer flood, Jock River flood).

Engineer's Report, Arbuckle Municipal Drain Modifications and Improvements, Goulbourn Ward (Robinson, 2010)

The Robinson report notes that while the Arbuckle Award Drain has existed from the late 1800s, the Van Gaal Municipal Drain was only constructed in 1971. Based on contour mapping, the drainage area was estimated at 1095 ha. SYMHYMO modelling was also

performed and 2-year return period flows at various points in the Van Gaal Drain were within the range determined be JFSA (2009); the 100-year event was not investigated. The report details recommendations for:

- works to improve drainage, including culvert replacement and re-leveling, and land clearing and excavation;
- erosion control, such as buffer strips, rock protection, rootwads and revetment, and;
- flow checks and sediment traps.

The report also contains a discussion of the apportioning of costs for construction and future maintenance. The discussion identifies six principles that should be used to determine assessment and then applies the principles and rules from the Drainage Act to determine project cost sharing.

<u>Mattamy Richmond Lands Natural Environment and Impact Assessment Study</u>, (Parish and Kilgour, 2010)

This report covers a broad range of environmental topics, including an erosion threshold analysis. The erosion threshold analysis was conducted at four sites; however, only one site ("VG-R2") was located on the main branch of the Van Gaal Drain and this site was upstream of Perth St, the limit of the present analysis. The analysis was based on critical shear stress and permissible velocities, and found that the calculated erosion thresholds for the four reaches were discharges well below bankfull. At the VG-R2 site, the critical discharge was calculated to be 0.33 m³/s.

Van Gaal Drain Erosion Assessment, (JTBES, 2012a)

This report describes work that was undertaken to investigate erosion downstream of Perth Street, a reach not specifically investigated in the earlier Mattamy report (Parish and Kilgour, 2010). This study delineated the drain into three reaches: Reach 1 running between the Jock River and the Fowler Culvert; Reach 2 running between the Fowler Culvert and the Fortune Culvert, and; Reach 3 running between the Fortune Culvert and the Perth Culvert. Following on a site visit, 51 erosion assessment sites were investigated and categorized, and, based on this, four sites were chosen for erosion threshold assessment. The threshold was determined as the critical velocity for the bank material, which in this case is coarse clay. The critical velocity for coarse clay was given as 0.225 m/s, which led to critical discharges for the four sections ranging from 0.02 to $0.05 \text{ m}^3/\text{s}$.

Richmond Village Development: Existing Erosion Remediation Costs, (JTBES, 2012b)

The purpose of this memo was to summarize the causes of erosion along the Van Gaal Drain and to estimate costs to remediate the erosion. It was concluded that, under existing conditions, Reach 3 had the most severe erosion and that, although not all sites required remediation, repairs at selected locations could simply shift the problem to a

downstream site. It was deemed preferable to remediate all sites at once. It was also noted that even if the additional stormwater flows were limited to the threshold rate, erosion of the Drain would continue to occur. Consequently, a redesign for the section south of Perth Street was recommended. The cost for all 51 sites identified previously was estimated to be \$1.41 million.

Van Gaal Drain Restoration Memo, (JTBES, 2013)

The purpose of this memo was to detail remediation costs for the erosion problems on the Van Gaal Drain downstream of Perth St. The work expands on the information provided in the earlier memo (JTBES, 2012b) and identifies 32 sites for remediation (4 in Reach 1, 7 in Reach 2 and 21 in Reach 3). Descriptions of works at the sites are presented. No reassessment of the erosion threshold is attempted; however, it is noted that after the proposed remediation works were completed, the threshold discharges for the site could be increased an undefined amount.

2.2 Review

The report and memos cited in the previous section provide valuable information about the previous work performed on the Van Gaal Drain. Of paramount importance here are the four last documents, which address erosion threshold analyses and provide a basis for the design of the stormwater management system and the required treatment of the existing drain.

A problem with the approaches taken by both Parish and JTBES is that even when using reasonable critical shear stress values, calculations performed in narrow channels will predict erosive conditions for almost all flows. However, erosion is a natural process and the erosion threshold in the channel should be exceeded to maintain a healthy system. It is not the aim of the development works to eliminate erosion, but to ensure that post-development conditions do result in a substantial increase in erosion. Clearly, a more sophisticated approach that integrates the impact of all events is required. The present work will examine not just the frequency with which the erosion threshold is exceeded but also the total amount of erosion that occurs both pre- and post-project.

In common with both the Parish and JTBES approaches, the present work will require an erosion threshold for the Van Gaal Drain. The first erosion threshold analysis (Parish and Kilgour, 2010) utilized a permissible tractive force technique to establish a critical discharge. Although the resulting discharge may appear to be low, this is a valid geomorphic approach and an approach based on similar principles will be employed in the present work. Loose, clayey soils are competent below unit tractive forces, or shear stresses, ranging between 0.5 Pa and 2 Pa (Chow, 1959). This range of critical shear stresses will be used for the modelling work presented herein.

3 Field Investigation

A site visit to Van Gaal Drain was conducted on 26 August 2013 to review and characterize the site. The day was sunny with some cloudy periods with daytime high of 24°C. The last recorded

precipitation was 22 August 2013. Photos and notes regarding the channel geometry were taken at numerous locations at this time. A rapid geomorphic assessment and a rapid stream assessment were also taken during the site visit.

The field investigation found several sites with significant erosion on the Van Gaal Drain. This agrees with previous studies. For most of the reach between Perth St. and Jock River, the channel is too narrow for the current hydrologic conditions. The existing drain will continue to erode and widen until it reaches equilibrium - even without the proposed storm management plan. Figure 1 through Figure 4 show examples of erosion in the Van Gaal Drain. Figure 5 shows the location of each photo.



Figure 1 Typical undercutting banks between Perth St. and Fortune St.



Figure 2 Eroding bank downstream of Fortune St.



Figure 3 Bank widening upstream of Fowler St.



Figure 4 Eroding banks downstream of Fowler St.



Figure 5 Locations of photographs

4 Erosion Model

Flow conditions in the Van Gaal drain were evaluated under existing conditions (pre-project) as well as under fully developed conditions (post-project) which includes the proposed storm water management pond. As noted in previous studies (JTB 2012, DSEL 2009), the erosion thresholds for this reach are very low and hence are exceeded frequently. In such situations, it is often beneficial to examine not just the frequency with which the erosion threshold is exceeded but also the total amount of erosion that occurs both pre- and post-project. By computing the amount by which the erosion threshold is exceeded, its duration, and the area of stream-bed affected, the erosional effort of 'effective work' can be computed (MOE, 2003). This measure, in comparison to frequency of exceedance analysis, provides a more complete picture of the erosional consequences of a project.

4.1 Methodology

An erosion hazard model was developed to estimate the erosion potential for pre- and postdevelopment on the Van Gaal Drain. A cumulative effective work approach was developed In addition to analysis of the frequency of exceedance of erosion thresholds. This model computes an erosion index (EI) based on the cumulative effective work, W_i The cumulative effective work is calculated as :

$$W_i = \sum (\tau - \tau_c) V \Delta t \tag{Eq. 1}$$

where τ is the shear stress generated by the flow, τ_c is critical shear stress for either the bed or the bank, V is the mean channel velocity and Δt is the time step. For the present analysis, EI is multiplied by the wetted perimeter, P, to express the results as the total erosional energy across the channel width (Joules/m):

$$EI = \sum (\tau - \tau_c) V P \Delta t$$
 (Eq. 2)

Calculating EI requires a continuous time series of discharge and a table relating discharge to shear stress, velocity and wetted perimeter. The continuous time series of discharge for preand post-development was provided by JFSA from their hydrologic model (JFSA, 2009). The dataset spans 36 years (April to October) between 1967 and 2003 with a time step of 15minutes.

4.2 Critical Shear Stress

It is difficult to accurately determine the *in situ* critical shear stress for small streams. Typically, there is no single specific value that captures the range of erosion and transport processes that occur. Critical shear stress is dependent on a range of variables, include sediment size and type, weathering, vegetation, biological activity, etc. It can vary spatially for even small streams and can also be dependent upon weather conditions, freeze-thaw activities and exposure. The present modelling exercise was performed using several critical shear stress values that spanned the range of expected values. Based on the characteristics of the stream bed and banks, critical shear thresholds are estimated to be between 0.5 and 2.0 Pa.

Sensitivity tests were performed which showed that, while the magnitudes of the predicted erosion varied, the relative performance of the two scenarios tested (pre- and post-development) were unaffected by the value of critical shear stress selected.

4.3 HEC-RAS Model Refinement

The original HEC-RAS model (JFSA, 2009) covers a very large domain and was found not to have sufficient resolution in the reach downstream of Fortune St. New cross-sectional survey data was provided by DSEL and were incorporated into the HEC-RAS model by Coldwater. Figure 6 shows the original model (with only one cross-section below Fowler St.) and Figure 7 shows the refined model (with 7 cross-sections below Fowler St.).



Figure 6 Original HEC-RAS model provided by JFSA with limited number of cross-sections d/s of Fortune St.



Figure 7 HEC-RAS model provided by JFSA with supplemental cross-sections added.

4.4 Model Operation

The erosion model requires two types of input; the predicted discharge for the scenario being studied and station-specific values for shear stress, velocity and wetted perimeter as a function of discharge. These station-specific values were calculated using the refined HEC-RAS model. At each station, 22 discharges scenarios ranging between 0 m^3 /s and 16.42 m^3 /s were modelled to obtain these relationships (16.42m^3 /s being the 1:100 year flow level). In total 726 (= 22 scenarios x 33 stations) sets of discharge, shear stress, velocity and wetted perimeter data were created to model the Van Gaal Drain between Perth St. and Jock River.

The erosion model was applied sequentially to each station. For each year, the erosion model stepped through the 15-minute time series of discharges from the JFSA hydrologic model. At each time step, the model interpolated the shear stress, velocity and wetted perimeter from the input discharge. These values were used to compute EI. The cumulative value of EI was also stored, as was the total time where the shear stress at the station was above critical.

Simulations were performed for both pre-development and post-development hydrographs. At noted in Section 4.2 above, the erosion model was run for a range of critical shear stresses. The results presented below are from the simulations with τ_c = 0.5 Pa.

5 Results

5.1 Single Event Simulation

This section shows comparisons of erosion potential for pre- and post-development on the Van Gaal Drain for a selected rainfall event, 9 April 1980 to 12 April 1980, at Station 592, using a critical shear threshold of 0.5 Pa.

Figure 8 shows the hydrograph for the event. The peak discharge decreases by 0.5 m³/s from pre- to post-development. Pre-development discharge remains higher than post-development condition until it hits the 19.25 hour mark. The shear stress, shown in Figure 9, mimics the pattern. The shear stress is lower up until after the peak of the event. Shear stress is above critical until 31.75 hr for pre-development condition and until 40.5 hr for post-development case. Figure 10 shows the erosion index (EI) results; post-development EI remains lower than pre-development conditions until 19.25 hr. In total, there's 30.75 hours of erosion for the pre-development condition and 39.5 hours of erosion for the post-development condition. The cumulative erosion index for the event, a measure the impact of the event on the stream, is shown in Figure 11. Although the total duration of erosion for the pre-development case is 66.1 MJ and 50.8 MJ for the post-development case. This pattern was found to be repeated for the majority of the events at stations downstream of the retention pond (Stations 746 and lower). Stations upstream of this point showed lesser variation in the results of the two scenarios.



Figure 8 Continuous time series of discharge for pre- and post-development cases for the April 1980 event



Figure 9 Continuous time series of shear stress for pre- and post-development cases for the April 1980 event



Figure 10 Continuous time series of erosion index for pre- and post-development cases for the April 1980 event



Figure 11 Cumulative erosion index for pre- and post-development cases for the April 1980 event

5.2 Long-term Simulations

The results in this section are for the model application at all stations for a 36-year simulation.

Figure 12 and Figure 13 show the average annual time above critical shear and the change in this measure computed as post-development minus pre-development. Upstream of Station 746 there is little change. Downstream of this point, the post-development case tends to spend more time in an erosional state. However, as was illustrated by the example in Section 5.1, this is not truly representative of the impact of the changes to the system on potential erosion of the stream. Figure 14 and Figure 15 show the annual average erosion index and change in this measure. These plots illustrate that the impact on the stream of the changes to the system lead to a reduction in erosion potential along the entire reach. This is illustrated in plan view in Figure 16.



Figure 12 Average annual time above critical shear for a 36-year simulation



Figure 13 Change in annual time above critical shear for a 36-year simulation (post - pre)







Figure 15 Change in erosion index for a 36-year simulation (post - pre)



Figure 16 Annual average pre-development erosion index and change in erosion index over the 36-year simulation

6 Restoration and Protection Works

As described in JTB (2012), opportunities exist to implement restoration works in critical reaches in order to reduce erosion and to restore natural channel processes. Most notably these are required in the waters immediately upstream and downstream of the Fortune St. crossing as well as downstream of Fowler St.

As shown in Figure 17, conceptual restoration works have been developed for five specific sites. Bank restoration works are proposed both upstream of Fortune St. and downstream of Fowler St. This involves re-grading of the slopes, riprap bank protection and live stake plantings to re-establish vegetative cover.

The existing meander immediately downstream of Fortune St. is creating an erosional hotspot. Here, a channel re-alignment is recommended (Item C in the Figure 17) that will shift the channel away from the eroding bank. Cross-vanes will be used to develop riffle-pool structures that will stabilize the channel in its new location while also providing natural in-stream features.

The upstream wingwall for the Fowler St. crossing is presently being undercut, as identified in Item B in Figure 17, wingwall restoration works are proposed to remedy this situation.

Downstream of Fowler St., bank re-grading and revetment is required to protect the adjacent property on the west side of the stream. A small timber weir exists beneath the pedestrian bridge just upstream of this site and the remnants of a somewhat larger timber weir exist further downstream. It is quite possible that the loss of this downstream weir has significantly increased erosion upstream. We are proposing several cross-vane weir structures composed of quarrystone to replace and improve the function of these weirs. These structures will reduce channel slope in the area and help to stabilize the banks.

Preliminary cost estimates for these works are presented in Figure 18.



Figure 17 Restoration Conceptual Designs

Preliminary Cost Estimate - (Class D - Indicative estimate) Proiect: Van Gaal Drain							
		Prepared by:			J. Cousineau		
Rank Restoration		Спеска	ea v	y:	M.L	Javies	
Items	Quantity	Unite		Unit Price		Price	
II/S of Fortune St	Quantity	Onus		<u>Omi Irice</u>		<u>1700</u>	
Mobilization/Demobilization	1	LS	\$	5.000.00	\$	5.000	
Rinran	110	m^2	\$	125.00	\$	13 750	
Non Woven Contextile	110	m ²	¢	5.00	¢	550	
	110	m ³	ф ф	5.00	ф ¢	550	
Backfill	10	m 2	\$	45.00	\$	/9/	
Final grading of the proposed bank	110	m ⁻	\$	10.00	\$	1,100	
Plantings	110	mĩ	\$	25.00	\$	2,750	
Silt Fence	54	m	\$	25.00	\$	1,350	
Sediment trap	1	LS	\$ E	1,000.00	\$	1,000	
D/C of Freedow C/		Cost at	FO	tune St. :	\$	20,297	
<u>D/S 0J FOWler St.</u> Mobilization/Damobilization	1	15	¢	5 000 00	¢	5 000	
Mobilization/Demobilization	1	LS 2	ф ¢	3,000.00	ф ф	5,000	
Кіргар	110	<i>m</i>	\$	125.00	\$	14,500	
Non-Woven Geotextile	110	<i>m²</i> ,	\$	5.00	\$	580	
Backfill	19	m°	\$	45.00	\$	837	
Final grading of the proposed bank	116	m^2	\$	10.00	\$	1,160	
Plantings	116	m^2	\$	25.00	\$	2,900	
Silt Fence	136	т	\$	25.00	\$	3,400	
Sediment trap	1	LS	\$	1,000.00	\$	1,000	
		Cost a	t Fo	wler St. :	\$	29,377	
	-						
	Bai	nk Rest	orat	tion Cost:	\$	55,674	
Channel Realignment d/s of Fortune St.	0 "	T T 1 /				р ·	
<u>Items</u> Mahiliandan (Damahiliandan	Quantity	Units	¢	<u>Unit Price</u>	¢	<u>Price</u> 5.000	
	1	LS 3	ф ¢	3,000.00	ф ф	5,000	
Stockpile salvage riprap material	48	m 3	\$	25.00	\$	1,200	
Excavation of the proposed channel	180	<i>m</i> 2	\$	10.00	\$	1,800	
Final grading of the proposed channel	200	m	\$	10.00	\$	2,000	
Cross-vane	2	EA	\$	3,500.00	\$	7,000	
Place salvage riprap material	48	m	\$	25.00	\$	1,200	
Hydric soil	350	m^2	\$	5.00	\$	1,750	
Filling excavated material in the existing channel	212	m^3	\$	10.00	\$	2,120	
Final grading of the old channel	150	m^2	\$	10.00	\$	1,500	
Pumping of construction area	1	LS	\$	750.00	\$	750	
Silt Fence	170	т	\$	25.00	\$	4,250	
Sediment trap	1	LS	\$	1,000.00	\$	1,000	
	Channe	l Realig	<i>gnm</i>	ent Cost:	\$	29,570	
Cross-vane downstream of Fowler St.	- ·						
<u>Items</u>	Quantity	<u>Units</u>	¢	Unit Price	¢	<u>Price</u>	
Mobilization/Demobilization	1		\$	3,000.00	\$ ¢	5,000	
Cross-vane	1	EA	\$	3,500.00	Ф	3,500	
		Cros	c - V	ano Cost.	\$	8 500	
		Cros	s- v (une Cosi.	φ	8,500	
	Total Construction Cost.				¢	03 744	
	10	ui Con	suu	cuon cosi.	φ	95,744	
Additional Itams							
Contingency				150%	¢	11 062	
Engineering Design				20%	ф \$	18 740	
Construction Monitoring				15%	φ \$	14.062	
Sub-total				1370	φ .\$	121 868	
HST				13%	\$	15 843	
Total				10/0	\$	137 711	

Figure 18 Planning level cost estimate - PRELIMINARY

7 Summary

The Van Gaal Drain is presently experiencing high levels of erosion. This erosion is expected to continue to erode until it reaches a new equilibrium, even without the proposed storm management plan.

From the erosion hazard model, the proposed storm water management plan is predicted to reduce erosion by an average of 15% - the drain will, however, continue to experience erosion.

Conceptual designs have been developed for protection and restoration measures that will protect critical areas – notably in the immediate vicinity of Fortune St. and downstream of Fowler St. Erosion sites upstream of the proposed SWM outfall could be left to naturally erode or could be improved – in large part, by excavating the drain to form a wider cross-section. Eroding sections in undeveloped reaches such as those between Fortune St. and Fowler St. are best left to re-shape naturally without the introduction of restoration works.

8 **Bibliography**

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

- Copeland, R., McComas, D., Thorne, C., Soar, P. J., & Fripp, J. (2001). *Hydraulic Design of Stream Restoration Projects*. Vicksburg, MS: U.S. Army Corps of Engineers.
- JFSA. (2009). Floodplain Mapping Report for the Van Gaal and Arbuckle Municipal Drains in the Village of Richmond. Ottawa, ON: J.F. Sabourin and Associates Inc.
- JFSA. (2009). Floodplain Mapping Report for the van Gaal and Arbuckle Municipal Drains in the Village of Richmond . Ottawa.
- JTBES. (2012a). Van Gaal Drain Erosion Assessment. Cambridge, ON: JTB Environmental Systems Inc.
- JTBES. (2012b). *Richmond Village Development: Existing Erosion Remediation Costs.* Cambridge, ON: JTB Environmental Systems Inc.
- JTBES. (2013). Van Gaal Drain Restoration Memo. Cambridge, ON: JTB Environmental Systems Inc.

MOE. (2003). Stormwater Management Planning and Design Manual.

- Parish and Kilgour. (2010). *Mattamy Richmond Lands Natural Environment and Impact Assessment Study*. Ottawa, ON: Parish Geomorphic Ltd. and Kilgour and Associates Ltd.
- Robinson. (2010). *Engineer's Report, Arbuckle Municipal Drain Modifications and Improvements, Goulbourn Ward*. Ottawa, ON: Robnison Consultants Inc.

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