APPENDIX C

Geomorphology Technical Memo (Palmer 2020)

Palmer™

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Memorandum

Date: January 15, 2020
Project #: 1903601

To: Fuad Curi, P.Eng. & Bruno Pierre Arpin, P.Eng.
From: Dan McParland, M.Sc., P.Geo. & Robin McKillop, M.Sc., P.Geo.
cc: Austin Adams, M.Sc., EP, Tony Gallo, M.Sc., P.Biol., EP
Re: Fluvial Geomorphology Baseline Assessment – West Duffins Creek and Duffins Creek Pickering and Ajax Flood Control Dykes Rehabilitation Class Environmental Assessment

1. Introduction

Palmer was retained by KGS Group Ltd. (KGS), on behalf of the Toronto and Region Conservation Authority (TRCA), to complete a fluvial geomorphology baseline assessment of West Duffins Creek and Duffins Creek in support of the Class Environmental Assessment (EA) for Remedial Flood and Erosion Control Projects for the rehabilitation of the Pickering and Ajax flood control dykes. Palmer was also retained to complete an ecology baseline assessment, which was provided to KGS under a separate cover. The fluvial geomorphology baseline assessment provides the foundation on which to assess the magnitude of net positive and negative effects in the evaluation of alternative solutions later in the EA process. As well, the fluvial geomorphology assessment helps ensure any future dyke rehabilitation plans anticipate and proactively accommodate future channel migration along West Duffins Creek and Duffins Creek.

A summary of methods (Section 2) is followed by an overview of the physical setting and historical changes (Section 3); a description of channel morphology near the Pickering and Ajax Dykes (Section 4); an overview of erosion and deposition risks (Section 5); and a summary of the fluvial geomorphology baseline assessment (Section 6). Historical aerial photography used for our assessment are provided in **Appendix A** and additional channel migration rates beyond those provided in the main body of the report are provided in **Appendix B**.

1.1 Background

In order to reduce the risk of flood damage within the Duffins Creek watershed in Pickering and Ajax, a two-dyke flood protection system was constructed in the mid 1980s to protect urban areas up to the 500-year flood event. The Ajax Dyke (340 m long) was constructed in 1984 and the Pickering Dyke (1,150 m) was constructed in 1985 (**Figure 1**). The Pickering Dyke was constructed alongside an anthropogenically straightened section of channel without regard for the risks associated with inevitable readoption of a meandering channel pattern. Erosion scars and erosion protection works now punctuate the northern flank of the dyke, where meanders have redeveloped and encroached.

In 2009, TRCA commissioned a fluvial geomorphology assessment and level of service study of Duffins Creek and the dykes (Geomorphic Solutions – Sernas Group Ltd., 2009). As part of the 2009 fluvial geomorphology assessment, rapid assessments (RGA, RSAT) were completed, meander belt widths were established, and detailed geomorphic and hydraulic data were collected along West Duffins Creek adjacent the Pickering Dyke. Recommendations of the 2009 assessment included further geotechnical and hydraulic investigations within the vicinity of the dykes.

Recent geotechnical assessment (Valdor Engineering Inc., 2018a) indicated that the dykes were constructed with non-cohesive soil and that the dykes do not meet current engineering design standards and factors of safety. Furthermore, recent hydraulic assessments of West Duffins Creek and Duffins Creek have determined that the Pickering Dyke provides protection up to the 100-year flood event and the Ajax Dyke provides protection up to the 50-year flood event (Valdor Engineering Inc., 2018b). TRCA has initiated a Class EA for Remedial Flood and Erosion Control Projects to identify a preferred remedial solution.

1.2 Study Area

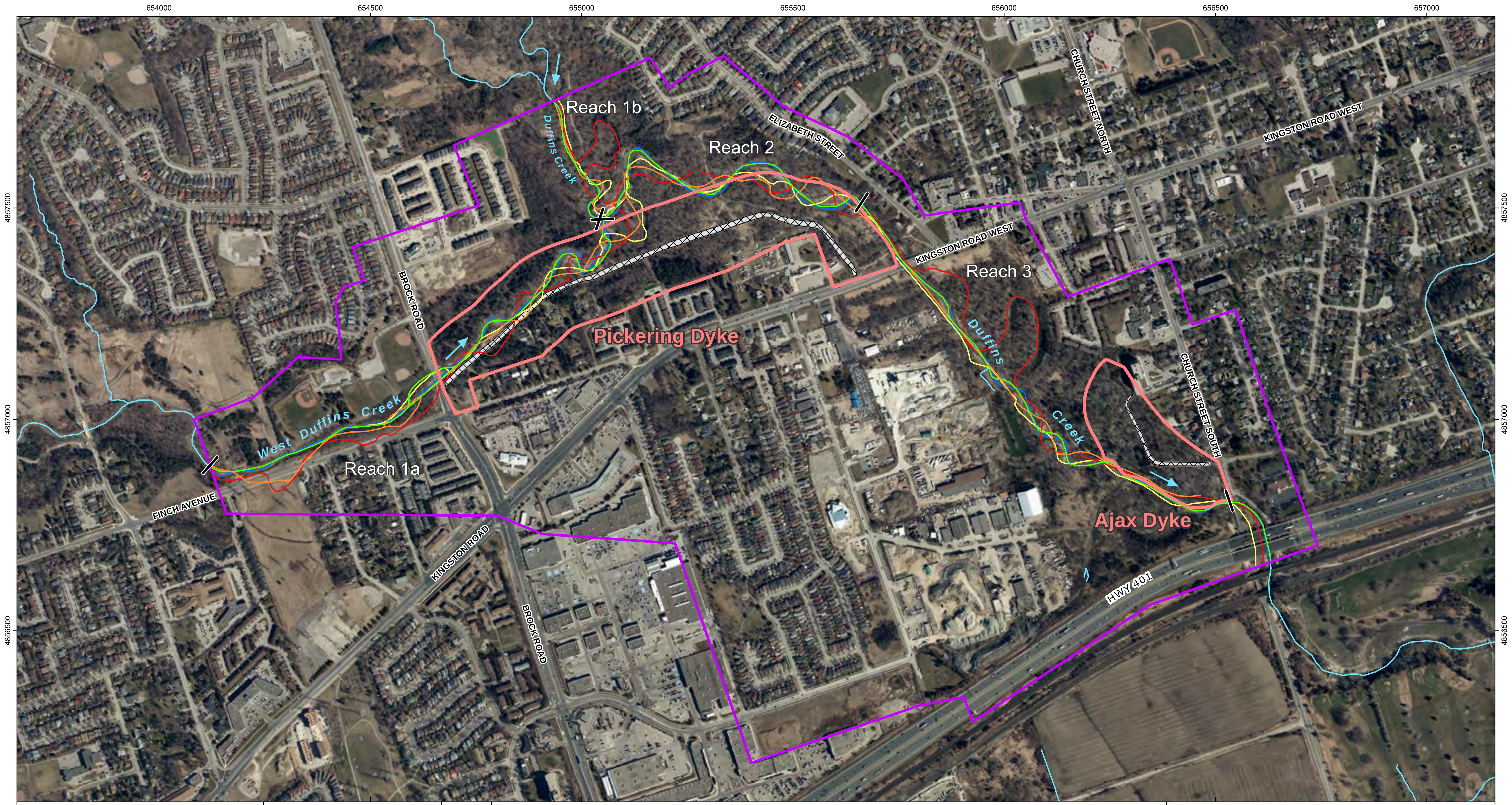
Two direct study areas (Pickering Dyke and Ajax Dyke) and a larger Indirect Study Area were established by TRCA for the Class EA (**Figure 1**). The Indirect Study Area, located within the Duffins Creek Watershed, contains reaches of Duffins Creek and West Duffins Creek. As well, the Indirect Study Area lies within both the City of Pickering and Town of Ajax. Both dykes are located on land owned by TRCA.

1.3 Objective

The objective of a scoped fluvial geomorphology assessment of West Duffins Creek and Duffins Creek alongside the Pickering and Ajax Dykes is to confirm and update the results from TRCA’s previous detailed fluvial geomorphic assessment and level of service study of Duffins Creek and the dykes (Geomorphic Solutions – Sernas Group Ltd., 2009). Furthermore, the fluvial geomorphology assessment will inform the evaluation of proposed alternatives for dyke remediation as part of the EA process and guide the need for erosion protection works.

2. Methods

The fluvial geomorphology of the Duffins Creek watershed was assessed through a combination of desktop and field investigations. We reviewed a number of important background information sources for the study area, including TRCA’s *A Watershed Plan for Duffins Creek and Carruthers Creek* (2003); existing Ontario Geological Survey surficial geology mapping (Ontario Geological Survey, 2010); and LiDAR-derived elevation data and 0.25 m contour topographic data provided by TRCA. Historic and recent aerial photography (1946, 1954, 1967, 1971, 1977, 1978, 1981, 1983, 1988, 1993, 2002, 2018) from TRCA and Google Earth (2002, 2004, 2007, 2009, 2013, 2015, 2016, 2017, 2018) was studied to characterize historical channel conditions and previous anthropogenic disturbances. The aerial photography also provided a basis for forecasting future channel adjustments within the Indirect Study Area.



CLIENT:

KGS GROUP

PREPARED BY:

PALMER ENVIRONMENTAL CONSULTING GROUP INC.

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PROJECT:	Pickering-Ajax Dykes EA		
PROJECT NO.	1903601	REVISION:	1
DATE:	Aug 16, 2019	SCALE:	1:8500
DRAWN:	BE	DATUM:	NAD 1983
CHECKED:	DM	PROJECTION:	UTM zone 17

LEGEND:

▭	Direct Study Area
▭	Indirect Study Area
▨	Dyke
—	Watercourse
—	Reach Break

Historical Channel

—	2018
—	2009
—	1981
—	1967
—	1946

NOTES:
(1) 1981 and 2002 channel delineation were excluded from figure for ease of interpretation.
(2) Study Areas determined by TRCA.
(3) Watercourses and dyke locations provided by TRCA.
(4) Base imagery (2018) provided by TRCA web map service.

Study Areas

Figure 1

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Select historical aerial photography (1946, 1967, 1981, 1988, 2002, and 2009) was georeferenced to the 2018 ortho-imagery using standard georeferencing tools in ArcGIS. Copies of these georeferenced historical aerial photographs are provided in **Appendix A**. At least four control points were used in each case to optimize the spatial match within the study areas. Errors in the georeferenced historical imagery differ slightly across the images but generally do not exceed a few metres in comparison to the ortho-imagery. Channel thalwegs, which are typically the deepest portion of a channel, were approximated in order to support interpretations of patterns in bank erosion and meander dynamics. In the absence of channel bathymetry, the thalweg was inferred to be approximately mid-channel through riffles and near the outer bend of the channel through pools (typically asymmetric in cross-section). The location and morphology of gravel bars, fluvial terraces, and valley walls helped guide the delineation of the thalweg in each set of aerial photography and ortho-imagery. Where possible, the position of the channel thalweg in the most recent imagery at each site was calibrated using field photographs and mapping.

Time-averaged migration rates and trajectories were estimated from the comparative overlay of historical channel planforms. Migration rates were determined for existing meanders that showed systematic channel migration (i.e. continued migration along the same trajectory between years). Rates were considered insignificant for meanders that exhibited adjustments within the margin of georeferencing error (a few metres) or did not exhibit systematic migration. Average annual migration rates were calculated for migrating meanders by dividing the total migration distance along a given trajectory by the elapsed time period. Rates were determined for existing meanders for time periods that showed systematic migration (thus, migration rates were based on different time periods for each meander). Many meanders present in the 2018 imagery are not present in the older imagery due to channel evolution (both natural and anthropogenic). Meanders were labelled numerically based on the 2018 channel planform from upstream to downstream. The comparative overlay analysis we applied facilitates time-averaged estimation of channel migration, assuming progression at a uniform rate. Bank erosion is more likely to occur episodically in response to extreme flows, thalweg adjustments in association with avulsions or bar redistribution, and upstream ice jam breaching. A time-averaged rate effectively smooths the localized and episodic adjustments, but such episodic adjustments become more important as the distance between the channel and the infrastructure decreases.

Field reconnaissance was completed on August 1, 2019 by a Palmer Fluvial Geomorphologist. Flow conditions were slightly above baseflow due to 24 mm of cumulative precipitation over the four previous days as measured at the Oshawa Executive Airport. The purpose of the field reconnaissance was to examine patterns and processes of local erosion, with particular attention given to the two dykes, verify channel reach breaks, observe bed and bank materials, and ground truth aerial photograph-based interpretations. Spot bankfull width and average bankfull depth measurements were made in different geomorphic units (pools, riffles, runs) for each reach during the reconnaissance.

3. Physical Setting and Historical Changes

Duffins Creek originates on the Oak Ridges Moraine and flows southward over the Halton Till Plain, the Lake Iroquois Shoreline, and the Lake Iroquois Plain to its outlet into Lake Ontario in Ajax. The total drainage area of Duffins Creek is 282 km^2 (TRCA, 2003). The upper and middle reaches of the watershed are rural and characterized by well defined, forested valleylands. The lower portions of the watershed (i.e.

south of Taunton Road) are more urbanized (TRCA, 2003). Within the Indirect Study Area, Duffins Creek and West Duffins Creek flow within well-defined, wide valleys. Surficial material along the valley bottoms are primarily modern alluvial deposits. Near the valley margins and atop the valley walls surficial deposits materials are predominately fine-textured glaciolacustrine deposits and silt-textured till (Ontario Geological Survey, 2010).

Over the period of photographic record, land uses within the West Duffins Creek and Duffins Creek catchments have transitioned from predominantly agricultural to predominantly urban. Furthermore, West Duffins Creek and Duffins Creek exhibit a history of realignment and straightening with prominent oxbows persisting in their floodplains (**Figure 1**). Prior to 1954, West Duffins Creek was straightened upstream and approximately 400 m downstream of Brock Road. As well, Duffins Creek is still recovering from previous straightening between 1946 and 1967 immediately upstream and approximately 650 m downstream of Kingston Road. The previously completed geomorphology assessment (Geomorphic Solutions – Sernas Group Ltd., 2009) includes a detailed description of land use changes and anthropogenic alteration to the valley bottoms within the Indirect and Direct Study Areas.

4. Description of Channel Morphology

The Indirect Study Area includes four distinct reaches of West Duffins Creek and Duffins Creek (**Figure 1**). Reach 1a (West Duffins Creek) extends from the upstream limit of historical channel realignment to the confluence with Duffins Creek. Reach 1a is gradually readopting a meandering planform but is confined to the south by Finch Avenue and the Pickering Dyke. Reach 1b (Duffins Creek) extends from the confluence with Urfe Creek downstream to the confluence with West Duffins Creek. Reach 2 extends from the Duffins Creek-West Duffins Creek confluence to the onset of the historical channel straightening upstream of Kingston Road. Reach 3 extends from just north of Kingston Road downstream to Church Street, where the watercourse transitions into a concrete-lined channel. Reach 3 has been straightened but is gradually readopting a meandering planform. The extents of the reaches are similar to the reaches established as part of the previous fluvial geomorphological assessment (Geomorphic Solutions – Sernas Group, 2009). A description of channel morphology and erosional processes along each reach is provided in the subsections below.

Reach 1a

Reach 1a was realigned and straightened prior to 1988 to accommodate the widening and relocation of Finch Avenue, residential development to the south of West Duffins Creek, and the construction of the Pickering Dyke (**Figures 1** and **2**). The planform development is confined to the south by the Finch Avenue embankment and the Pickering Dyke. Reach 1a is readopting an irregular meander pattern; however, the existing meanders are undersized relative to undisturbed and unconfined meanders upstream of the reach or near the downstream extent of the reach (e.g. oxbow near the confluence with Duffins Creek). The 2018 sinuosity of Reach 1a (1.16) is lower than the 1946 sinuosity (1.25) as a result of the historical straightening and realignment (**Table 1**). A large medial deposit upstream of Brock Road has bifurcated flow. Since 2009, most of the flow is conveyed along one channel through the south cell of the Brock Road crossing. Additionally, an avulsion between 2002 and 2004 led to the formation of an oxbow and shifted the confluence with Duffins Creek approximately 45 m upstream.

Upstream of Brock Road, the channel has a riffle-glide bed morphology. The previous straightening and associated bed and bank armouring have led to the formation of these steeper geomorphological units. Downstream of Brock Road, the channel has regained some sinuosity and re-established a pool-riffle bed morphology (**Photo 1**). Two prominent riffles (upstream of M2 and upstream of M4) act as natural grade controls and strongly influence the upstream and downstream energy gradients (**Figure 2**). The formation of medial and lateral gravel bars and overbank sand deposits throughout the reach suggest the channel is likely aggrading, which corroborates the findings of previous geomorphic assessment of the reach (Geomorphic Solutions – Sernas Group, 2009).

Bankfull width and average bankfull depth are approximately 17 m and 1.6 m, respectively (**Table 1**). The cross-sections in the glide and riffle units are nearly symmetrical, whereas the pool units, which are situated near the apices of meanders, are asymmetrical. Two large gravel point bars have formed along the inner bank of M2 and M4 (**Figure 2**). The lack of vegetation colonization and the accumulation of large wood atop these point bars suggest they are frequently wetted. Geomorphic Solutions – Sernas Group (2009) completed a detailed geomorphological survey within Reach 1a as part of its detailed geomorphic assessment. The results of its survey are presented in **Table 2**.

The channel banks are composed of alluvial sands, except where the banks have locally been hardened to prevent channel migration (i.e. near Brock Road crossing, M1, M3, M5). Bed material in the riffles is mostly gravel and cobble. Some lag boulders and reworked riprap from localized erosion protection are present in the riffles. The coarser cobble particles in the riffles are commonly covered in aquatic lichens and mosses, indicating they have not been recently entrained. Bed material in pools is mostly fine gravels and coarse sands. Silty-textured glaciolacustrine sediments are present within an anomalously deep pool along the outer (north) bank of M4 (**Figure 2**). Large sand deposits have formed (i.e. concave-bank benches) along the upstream limb where meanders are locally confined by the Pickering Dyke (M1, M3, M5).

Riparian vegetation is a mixture of young and mature deciduous trees and shrubs. Locally, the riparian areas have been cleared of vegetation between M1 and M3. Large wood is present throughout the reach. Significant accumulations of large wood were observed on the point bars at M2 and M4. Large wood embedded in the riffles upstream of the M2 and M4 stores sediment upstream and locally steepens the channel downstream. At M4, many large wood pieces had been cut with a chainsaw and discarded on the point bar.

Table 1. Summary geomorphic characteristics by reach

Reach	Bankfull Width[1]	Average Bankfull Depth[1]	Bed Morphology	Bed Material Range	Confinement	1946 Sinuosity[2] (m/m)	2018 Sinuosity[2] (m/m)
1a	17	1.6	Run-riffle & Pool-riffle	Coarse sand to boulder	Anthropogenically confined	1.25	1.16
1b	16	1.6	Pool-riffle	Coarse sand to cobble	Locally confined by valley wall	2.04	1.15
2	19	1.8	Pool-riffle	Coarse sand to cobble	Locally confined by valley wall	1.15	1.34
3	22	1.9	Pool-run	Medium sand to gravel	Unconfined	1.38	1.09

1 – average based on spot measurements
2 – sinuosity (m/m) = channel length (m)/valley length (m)

Table 2. Detailed geomorphic survey results from Reach 1a completed by Geomorphic Solutions – Sernas Group (2009)

Channel Parameter	Value
Bankfull gradient (%)	0.48
Channel bed gradient (%)	0.57
Bankfull width (m)	16.4
Average bankfull depth (m)	1.4
Maximum bankfull depth (m)	2.1
Bankfull cross-sectional area (m^2)	20.3
Entrenchment (m)	80
Entrenchment ratio	5
D_{50} (mm)	42
D_{90} (mm)	101
Manning’s ‘n’	0.036
Bankfull Discharge (m^3/s)	60
Average bankfull velocity (m/s)	2.6

Photo 1. Looking downstream at the riffle crest upstream of M2

Reach 1b

Reach 1b was straightened between 1946 and 1954 (**Figures 1** and **2**). A channel avulsion (perhaps anthropogenically induced) immediately upstream of M7 between 1946 and 1954 led to the formation of a large oxbow in the eastern floodplain. Other oxbows formed prior to 1946 are noted within the valley bottom. Since 1967, Reach 1b has readopted an irregular meandering planform. The reach is mostly unconfined, which has allowed it to readopt a sinuous planform. The 2018 sinuosity of Reach 1b (1.15) is considerably lower than the 1946 sinuosity (2.05) due to the large channel avulsion (**Table 1**).

Reach 1b has a defined pool-riffle bed morphology, with pools located near the apices of meanders (**Photo 2**). Small point bars and a medial gravel bar are present in the reach. Bankfull width and bankfull depth are approximately 16 m and 1.6 m, respectively (**Table 1**). The cross-sections in the riffles are nearly symmetrical, whereas the pool units, which are situated near the apices of meanders, are asymmetrical. Localized overbank sand deposits suggest the channel has good connection to its floodplain.

The channel banks are composed of alluvial sands. Bed material in the riffles are mostly gravels and some cobble. Bed material in pools are mostly fine gravels and coarse sands. Bed material in Reach 1b is finer than that in Reach 1a. Riparian vegetation is a mixture of young and mature deciduous trees, coniferous trees, and shrubs. Large wood is present throughout the reach.

Photo 2. Looking downstream in Reach 1b at a pool, vegetated point bar and large wood upstream of M7

Reach 2

In the 1946 imagery, Reach 2 appears to have been recently straightened (**Figures 1** and **2**). Removal of riparian vegetation led to over-widening. Since 1946, the reach has been mostly undisturbed and has re-adopted an irregular meandering pattern with large meander amplitudes relative to those along Reach 1a and Reach 1b. The sinuosity of Reach 2 has increased over time (**Table 1**). Reach 2 is unconfined, which has allowed the formation of the well-developed meanders. Meanders have migrated both laterally and longitudinally (i.e. down-valley). Systematic channel migration and extension of meander M10 has occurred over the entire period of photographic record. Migration was arrested in 2016 when the outer bank of the apex of M10 was armoured with boulders and woody debris to protect the nearby walking trail.

Reach 2 has a defined pool-riffle bed morphology, with pools located near meander apices (**Photo 3**). Large point, medial and lateral gravel bars are present throughout the reach. The large gravel deposits could be sourced from the channel avulsion that occurred near the West Duffins Creek-Duffins Creek confluence between 2002 and 2004. Some localized overbank sand deposits are present; however, the reach appears to be more entrenched than upstream reaches (i.e. floodplain is less accessible).

Bankfull width and bankfull depth are approximately 19 m and 1.8 m, respectively (**Table 1**). The cross-sections in the riffles are nearly symmetrical, whereas the pool units, which are situated near the apices of meanders, are asymmetrical. The channel banks are mostly composed of alluvial sands. Ice-marginal glaciolacustrine sediments are present along the outer (south) bank at M11 (**Figure 2**). Bed material in the riffles are mostly gravel and cobble. The coarser cobble particles are commonly covered in aquatic lichens and mosses, indicating they have not been recently entrained. Bed material in pools is mostly fine gravels and coarse sands. Riparian vegetation is a mixture of young and mature deciduous trees, coniferous trees, and shrubs. Large wood is present along the channel periphery throughout the reach.

Photo 3. Looking downstream from pedestrian bridge (M11) at pool (foreground) and riffle (background)

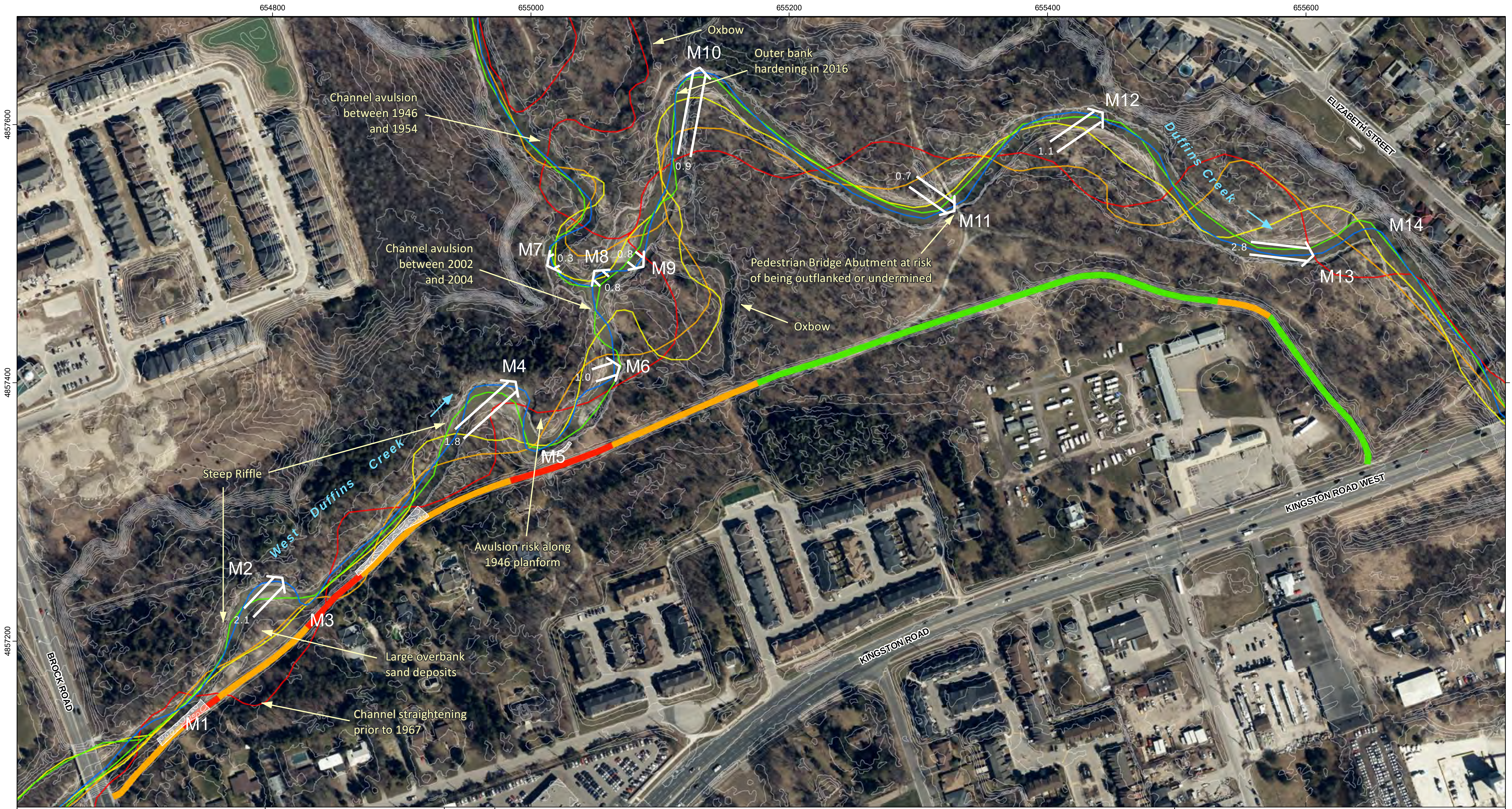
Reach 3

Prior to 1954, Reach 3 had an irregular meandering planform with large meander amplitudes relative to those along upstream reaches (see 1946 planform in **Figure 1** and **Figure 3**). Reach 3 was straightened between 1954 and 1967, which coincided with residential and industrial development along both sides of the channel. Since 1967, Reach 3 has been gradually readopting an irregular meander pattern; however, the 2018 sinuosity (1.09) is still notably lower than then 1946 sinuosity (1.09, **Table 1**). The channel is locally confined on the west in the mid to lower portions of the reach by industrial development and is locally confined on the east in the upper portion of the reach by residential development. This confinement has slowed meander development relative to the unconfined Reach 2. Downstream of Church Street South (i.e. downstream reach break) the channel is lined with concrete, which limits channel migration in the lower portion of Reach 3.

Reach 3 has a pool-run bed morphology, with pools located near apices of meanders. The overall gradient of the reach is less than that of the upper reaches. Point, medial and lateral sand and/or gravel bars are present throughout the reach (**Photo 4**). Sand has deposited along the toes of the banks throughout the reach. Some localized overbank sand deposits are present; however, the reach appears to be more entrenched than upstream reaches (i.e. floodplain is less accessible). A Water Survey of Canada (WSC) concrete structure at M20 (which is also a barrier to sea lamprey) is a grade control (**Figure 3**). Downstream of the WSC structure, the outer bank is armoured with a vegetated geo-cell wall. A grade control structure in the 1967 aerial photograph (i.e. soon after channel straightening) approximately 250 m downstream of Kingston Road is not observable in more recent imagery.

Bankfull width and bankfull depth are approximately 22 m and 1.9 m, respectively (**Table 1**). The cross-sections in the runs are nearly symmetrical, whereas the pool units, which are situated near the apices of meanders, are asymmetrical. The channel banks are composed of alluvial sands and silts. Bed material in the runs is mostly gravel. Bed material in pools is mostly fine gravels and coarse sands. Riparian vegetation is a mixture of young and mature deciduous trees and shrubs. Large wood is present along the channel periphery throughout the reach.

Photo 4. Large wood on outer bank and large fine gravel/coarse sand point bar (looking upstream)



CLIENT: KGS GROUP

PREPARED BY: Palmer™

PROJECT:	Pickering-Ajax Dykes EA		
PROJECT NO.	1903601	REVISION:	2
DATE:	Jan 08, 2020	SCALE:	1:2800
DRAWN:	BE	DATUM:	NAD 1983
CHECKED:	DM	PROJECTION:	UTM zone 17

LEGEND:

⇨ Meander Migration Trajectory and Rate (m/yr)

▨ Existing Riprap Protection

— 0.5 m Contour

Dyke Erosion Risk

🟩 Low

🟧 Moderate

🟥 High

Historical Channel

— 2018

— 2009

— 1988

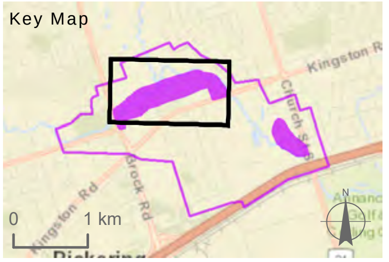
— 1967

— 1946

NOTES:

(1) 1981 and 2002 channel delineation were excluded from figure for ease of interpretation.

(2) Base imagery (2018) provided by TRCA web map service.



Pickering Dyke

Figure 2

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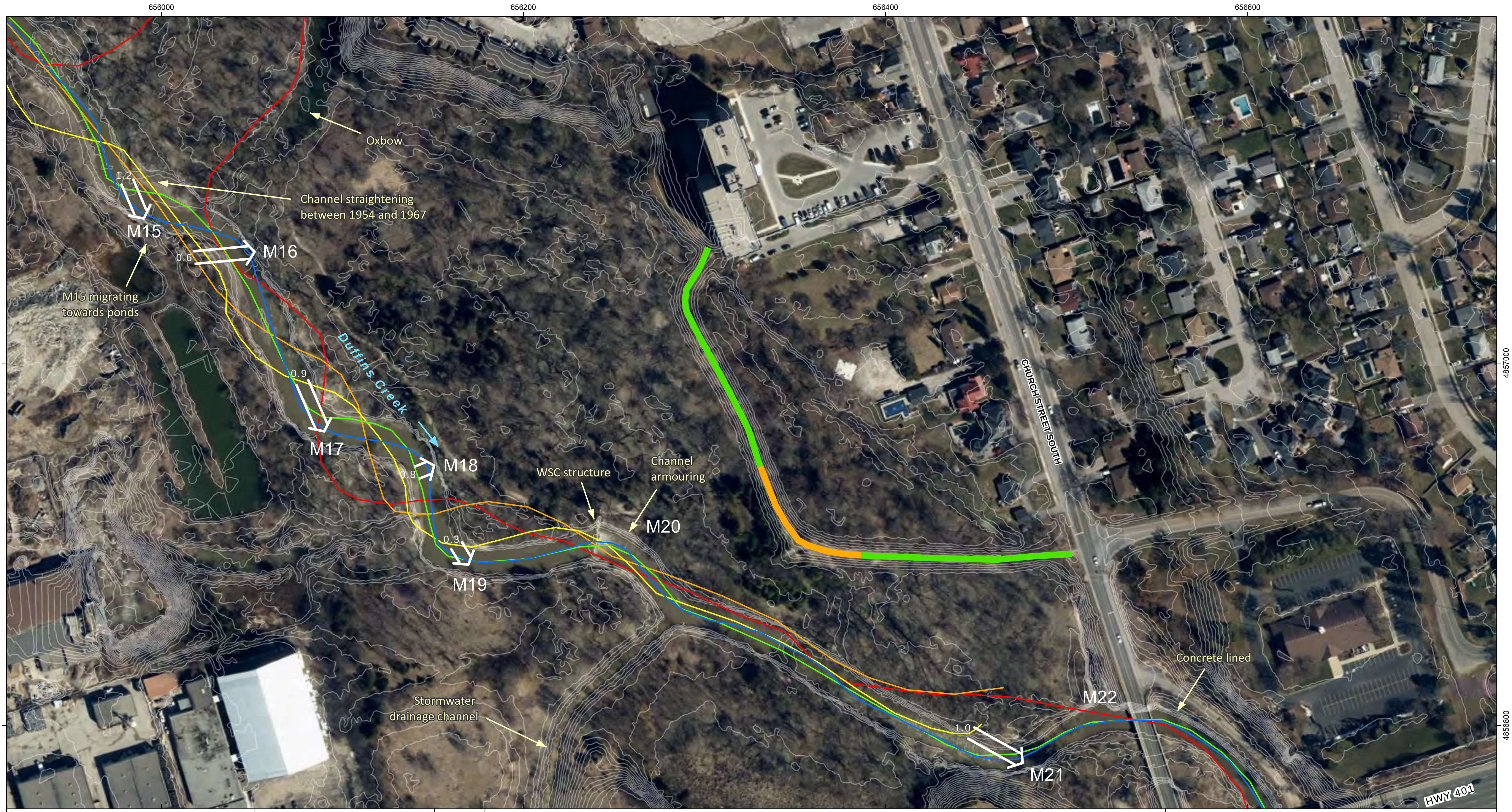

CLIENT:

KGS GROUP

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PROJECT:	Pickering-Ajax Dykes EA		
PROJECT NO.	1903601	REVISION:	1
DATE:	Aug 16, 2019	SCALE:	1:2000
DRAWN:	BE	DATUM:	NAD 1983
CHECKED:	DM	PROJECTION:	UTM zone 17

PREPARED BY:

PALMER ENVIRONMENTAL CONSULTING GROUP INC.

LEGEND:

⇨ Meander Migration Trajectory and Rate (m/yr)

0.5 m Contour

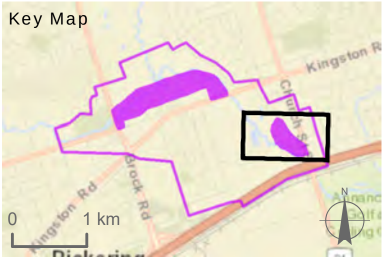
Dyke Erosion Risk

🟩 Low
🟧 Moderate
🟥 High

Historical Channel

2018
2009
1988
1967
1946

NOTES:
(1) 1981 and 2002 channel delineation were excluded from figure for ease of interpretation.
(2) Base imagery (2018) provided by TRCA web map service.



Ajax Dyke

Figure 3

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5. Erosion Risks and Sediment Deposition Zones

Erosional processes pose a risk to the integrity of infrastructure situated near or under alluvial gravel-bed channels, especially in urban areas (Ashmore and Church, 2001). Existing and future erosion risks to both dykes are documented in the following subsections. As well, depositional processes can impact flow conveyance and reduce the hydraulic capacity of both the main channel and the floodplain. Thus, deposition can influence channel migration processes and induce channel avulsions (i.e. a rapid shift in channel position).

5.1 Pickering Dyke

5.1.1 Erosion Risk

Rates of channel migration were documented at 14 meanders (**Figure 2**) near the Pickering Dyke. Time-averaged rates and the associated time period in which the meander displayed systematic channel migration are detailed in **Table 1**. Migration rates for individual time periods (e.g. 2002 to 2009) are documented in **Appendix B**. Four existing meanders do not display systematic channel migration due to confinement by the Pickering dyke itself (M1, M3, M5) or by a valley wall (M14). High migrations rates were observed at M2 and M4 in Reach 1a and M13 in Reach 2. Both M2 and M4 are downstream of two prominent riffles that steepen the channel as it enters the meanders. Review of aerial imagery and field reconnaissance indicate the riffles have migrated, which has led to the subsequent down-valley migration at M2 and M4.

Table 3. Channel migration rates and trajectories near Pickering Dyke

Meander ID	Migration rate (m/yr)	Time Period[1]	Trajectory[2]	Lateral or Down Valley Migration?
M1	Confined by dyke	Not applicable	Not applicable	Not applicable
M2	2.1	2002 to 2018	NE	Down valley
M3	Confined by dyke	Not applicable	Not applicable	Not applicable
M4	1.8	1988 to 2018	NE	Down valley
M5	Confined by dyke	Not applicable	Not applicable	Not applicable
M6	1.0	2002 to 2018	ENE	Lateral
M7	0.3	2002 to 2018	WSW	Lateral
M8	0.8	2009 to 2018	NW	Lateral
M9	0.8	2009 to 2018	SE	Lateral
M10[3]	0.9	1946 to 2018	N	Both
M11	0.7	1967 to 2018	SE	Lateral
M12	1.1	1981 to 2018	NE	Lateral
M13	2.8	2002 to 2018	E	Down valley
M14	Confined by valley wall	Not applicable	Not applicable	Not applicable

1 – the time period of systematic migration from which the rate and trajectory were estimated
2 – cardinal direction
3 – outer bank is locally hardened

Geomorphic Solutions – Sernas Group Ltd. (2009) assessed five meanders (M2, M3, M5, M10, M11) near the Pickering Dyke as part of its detailed assessment. Similar to this current assessment, Geomorphic Solutions – Sernas Group Ltd. (2009) determined meanders M3 and M5 were confined by the dyke and not migrating. At M5, Geomorphic Solutions – Sernas Group Ltd. (2009) calculated a down-valley migration rate of 0.95 m/yr between 1978 and 2008. The current assessment documented a migration rate of 2.1 m/yr from 2002 to 2018 (the period that displayed systematic migration), suggesting channel migration is accelerating at M2. At M10, Geomorphic Solutions – Sernas Group Ltd. (2009) calculated a lateral migration rate of 0.64 m/yr between 1954 and 2008, which is slightly less than the migration rate (0.9 m/yr) calculated as part of the current assessment for 1946 to 2018. At M11, Geomorphic Solutions – Sernas Group Ltd. (2009) calculated a lateral migration rate of 0.57 m/yr and a longitudinal migration rate of 1.17 m/yr between 1954 and 2008. The current assessment documented a migration rate of 0.7 m/yr, which is less than the longitudinal migration rate calculated as part of the previous assessment. The south bank pedestrian bridge abutment, which is now exposed, may be slowing migration.

Based on historic and existing morphological conditions, the Pickering Dyke was divided into one of three erosion risk categories:

- **Low** – the channel is greater than 50 m from the dyke and it is unlikely to migrate or avulse within 50 m of the dyke in the next 25 years
- **Moderate** – the channel is within 50 m of the dyke or has the potential to be within 50 m of the dyke in the next 25 years as a result of channel migration or avulsion
- **High** – the channel abuts the dyke or has the potential to abut the dyke in the next 25 years as a result of channel migration or avulsion

Three high risk areas were delineated at M1, M3, and M5 (**Figure 2**). These are consistent with erosion areas documented in the previous geomorphic assessment (Geomorphic Solutions – Sernas Group, 2009). The previous assessment noted failing erosion control blankets, localized soil loss and scour at these three sites. Review of aerial photography and site photographs from the previous assessment reveal growth of riparian vegetation on or near the dyke at all three encroachment sites. Riparian vegetation and associated root networks could increase the shear resistance of the bank to erosion. However, the vegetation could also locally displace the stone comprising the erosion protection. Although active erosion was not observed during field reconnaissance, erosion is expected at or near these locations in the future based on reach-scale planform adjustments. As well, toe erosion of the valley wall is likely to occur at M14 at a rate that could be estimated based on detailed site assessment.

During the recent field reconnaissance, the boulder revetment at M1 was intact and young deciduous trees and shrubs were growing atop and in the voids of the boulder revetment (**Photo 5**). The channel thalweg was located closer to the north (i.e. opposite) bank, which temporarily reduces erosion potential along the dyke. The energy gradient was low due to the prominent downstream riffle crest, which acts as a natural grade control. Some bank/dyke scour was noted at the downstream extent of the existing erosion protection. Lowering of the downstream riffle crest or a shift in the position of the thalweg adjacent the dyke could increase the erosion potential along the dyke at M1.

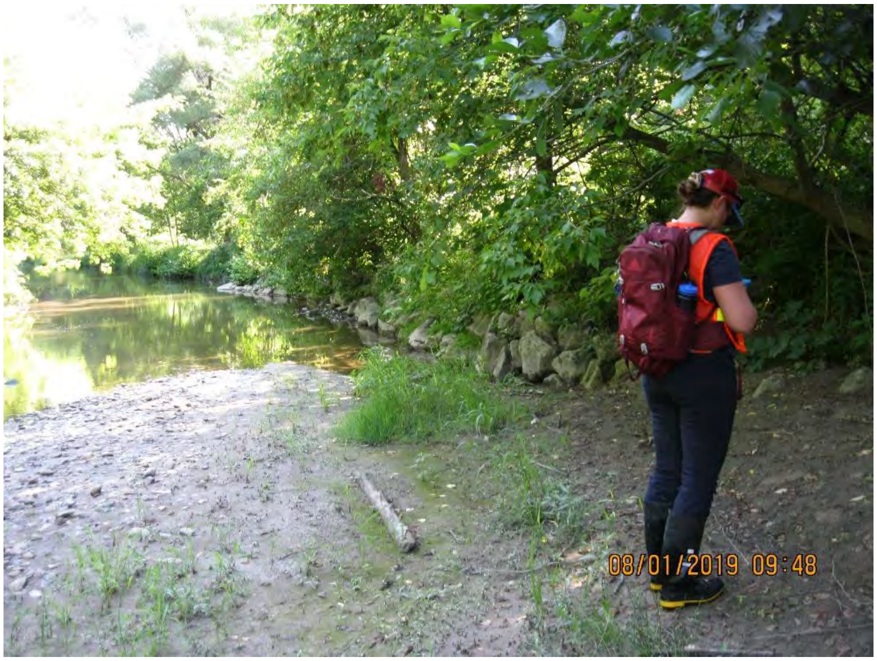

Photo 5. Looking downstream at sand deposition (foreground), low gradient pool unit (background) and the boulder revetment at M1 (right)

Similar to the energy gradient at M1, the energy gradient along M3 is low due to a prominent downstream riffle crest, which acts as a natural grade control. The boulder revetment along the downstream limb of M3 is intact and young deciduous trees and shrubs are growing atop and in the voids of the boulder revetment (**Photo 6**). Previous bank/dyke erosion was observed upstream of the boulder revetment near the upstream limb of M3, but recent down-valley channel migration of M2 has reduced the erosion severity at this site and has caused notable sand deposition adjacent the erosion. Lowering of the downstream riffle crest could increase erosion potential along the dyke at M3.

Photo 6. Looking upstream at boulder revetment (left) and sand deposition (background) near M3

Many boulders in the localized revetment at M5 are displaced (**Photo 7**). The structure is less extensive than the erosion protection at M1 and M3. A down-valley shift in channel position could result in the thalweg abutting an unarmoured section of the dyke. Rapid channel migration at M4 has reduced the radius of curvature at both M4 and M5, which can increase erosion potential along both meanders. A large, high-relief sand deposit has formed at the upstream limb of M5 (concave-bank bench).

Photo 7. Looking upstream at the boulder revetment (left) and large sand deposit (centre and background)

The rapid down-valley migration at M2 and M4, and associated reduction in radius of curvature (i.e. ‘tighter’ bends), could induce a channel avulsion near M3 and M5, respectively (**Figure 2**). In particular, a channel avulsion at M4/M5 could occur along the persistent topographic depression of the 1946 channel alignment. Avulsions and/or continued rapid channel migration could result in the channel abutting the bank/dyke downstream of existing erosion protection.

The large oxbow east of M6 is unlikely to be readopted in the short term because of the existing position of the Duffins Creek-West Duffins Creek confluence. If the oxbow is reoccupied, however, erosion protection will likely be required where the oxbow is within 10 m of the dyke (i.e. location of the 50” flap valve). Downstream of the oxbow, Duffins Creek is sufficiently far from the dyke that erosion risk remains low. At M11, continued outer bank migration could undermine or outflank the south bank abutment of a pedestrian bridge (**Figure 2**, **Photo 8**). At M13, the channel is rapidly migrating and the dyke is within 35 m of the channel. However, based on the down-valley migration trajectory, the channel is unlikely to migrate closer to the dyke.

Photo 8. Actively eroding south bank of Duffins Creek (M11) in front and upstream of a pedestrian bridge abutment (looking upstream)

5.1.2 Sediment Deposition Zones

Overbank sand deposition occurs throughout Reach 1a, Reach 1b, and Reach 2, suggesting high flows have good connection to the floodplain. In particular, a large overbank sand deposit was observed during field reconnaissance and in recent aerial imagery atop the south bank between M1 and M3 (**Figure 4**). Concave bank benches are present where the channel abuts the Pickering Dyke (e.g. M3 and M5). Gravel point, lateral, and medial bars are present throughout Reach 1a, Reach 1b, and Reach 2. Notable gravel bar deposits include the large point bars at M2 and M4, where the channel is actively migrating, and the lateral and medial bars downstream of the Duffins Creek-West Duffins Creek confluence. The riffles immediately upstream of M2 and M4 are significant deposition areas for gravel and cobble.

Figure 4. Overbank sand deposition between M1 and M3

Reach 1a appears to be aggrading. Reach 1b and Reach 2 are also aggrading but to a lesser degree than Reach 1a, which is consistent with the findings of the previous geomorphic assessment (Geomorphic Solutions – Sernas Group, 2009). Aggradation in the active channel and deposition in the overland areas suggests the hydraulic capacity of the channel and floodplain could be decreasing. Reduction in the hydraulic capacity of the main channel can promote channel avulsions because the floodplain becomes more accessible during floods.

5.2 Ajax Dyke

5.2.1 Erosion Risk

Rates of channel migration were documented at eight meanders (**Figure 3**) near the Ajax Dyke. Time averaged rates and the associated time period in which the meander displayed systematic channel migration are detailed in **Table 2**. Migration rates for individual time periods (e.g. 2002 to 2009) are documented in **Appendix B**. Two meanders did not display systematic channel migration since 1988 (i.e. shortly after the dykes were constructed). M20 is confined by localized channel hardening downstream of the WSC structure. Lateral migration of M22 is hindered by the downstream Church Street South bridge. The other six meanders are migrating both laterally and longitudinally as Reach 3 readopts a more sinuous planform following channel straightening in the mid 20th century.

Table 4. Channel migration rates and trajectories near Ajax Dyke

Meander ID	Migration rate (m/yr)	Time Period[1]	Trajectory[2]	Lateral or Down Valley Migration?
M15	1.2	2002 to 2018	SSE	Down valley
M16	0.6	1967 to 2018	E	Lateral
M17	0.9	1988 to 2018	SSE	Down valley
M18	0.8	2009 to 2018	ENE	Lateral
M19	0.3	1988 to 2018	SSE	Both
M20	Confined by bank protection	Not applicable	Not applicable	Not applicable
M21	1.0	1988 to 2018	SE	Down valley
M22	Confined by bridge inlet	Not applicable	Not applicable	Not applicable

1 – the time period of systematic migration from which the migration rate and trajectory were estimated
2 – cardinal direction

Geomorphic Solutions – Sernas Group Ltd. (2009) assessed one meander (M21) near the Ajax Dyke as part of its detailed assessment. At M21, Geomorphic Solutions – Sernas Group Ltd. (2009) calculated a down-valley migration rate of 1.01 m/yr between 1967 and 2008, which is nearly identical to the 1.0 m/yr migration rate calculated from 1988 to 2018 as part of the current assessment.

Based on historic and existing morphological conditions, the Ajax Dyke was divided into erosion risk categories (**Figure 3**). Most of the dyke is considered low risk because the dyke is greater than 50 m from the channel and there are no signs of migration toward the dyke. The dyke is locally within 40 m of the channel, however, the bank protection at M20 will hinder channel migration towards the dyke. M15 is migrating towards the stormwater ponds in the western floodplain. Migration of the channel into the ponds and the potential avulsion that could result would drastically alter channel dynamics and sediment supply downstream in the vicinity of the dyke. Migration of M15 should be monitored. The Church Street South crossing controls the channel location near M22 and, thus, channel migration is not expected at M22 unless the crossing is modified/replaced.

5.2.2 Sediment Deposition Zones

Numerous sand and/or fine gravel lateral and point bars are presented throughout Reach 3. Sand is deposited near the toe of banks throughout Reach 3 and locally atop the banks.

6. Summary and Recommendations

A fluvial geomorphology baseline assessment of West Duffins Creek and Duffins Creek alongside the Pickering and Ajax Dykes was completed in support of the Class EA for Remedial Flood and Erosion Control Projects for the rehabilitation of the Pickering and Ajax flood control dykes. The assessment built upon a previously completed fluvial geomorphology assessment (Geomorphic Solutions – Sernas Group, 2009). Our fluvial geomorphology assessment included both desktop and field analyses. Comparative overlay analysis was completed using a series of aerial photographs to document historic and recent (post-2009) planform adjustment near Pickering and Ajax Dykes. As well, time-averaged rates and trajectories of bank erosion were established as a basis for forecasting erosional risk to the dykes.

Both West Duffins Creek and Duffins Creek exhibit a history of realignment and straightening. Both watercourses are recovering from the previous straightening and are gradually readopting a meander pattern, a process that is expected to continue for decades. The Pickering Dyke was constructed alongside this relatively straight section of channel without regard for the risks associated with inevitable readoption of a meandering channel pattern. West Duffins Creek abuts the Pickering Dyke at three sites (M1, M3, M5). Bank erosion was noted at these sites as part of the previous detailed fluvial geomorphological assessment (Geomorphic Solutions – Sernas Group Ltd., 2009). Localized riprap displacement and erosion was observed at these sites during the 2019 field reconnaissance. Future erosion is expected at these three sites based on channel trajectories and the position of the channel thalweg. Continued channel migration and/or avulsions could increase the erosion risk at additional sites along Pickering Dyke (see 'Moderate' risk locations on **Figure 2**). The majority of the Ajax Dyke is set back sufficiently far from Duffins Creek that it has limited interaction with fluvial erosion and is not subject to the same erosional risks (**Figure 3**).

To adequately protect the dykes from fluvial erosion and better understand fluvial risk, the following actions are recommended:

- Replace and extend the riprap protection at M1, M3 and M5. The current riprap is locally displaced/failing and needs to be further extended upstream and/or downstream. The extent of the riprap at the three sites should encompasses the 'High' risk line segments, at a minimum.
- Incorporate bio-engineering (e.g. live stakes, brush layers) into the erosion protection to increase hydraulic roughness and improve aquatic habitat.
- Conduct comparative overlay assessments every 5 years to monitor the proximity of the watercourse to both dykes. The overlay assessment will help determine the need for erosion protection in the 'Moderate' risk segments.
- Install simple benchmarks (e.g. wooden stakes) along the Pickering Dyke to monitor proximity of the watercourse to the dyke. The distance from the stake to the top of bank of the watercourse should be measured every 1 to 2 years.
- Complete a detailed geomorphological and engineering assessment of the watercourse near the pedestrian bridge in Reach 2 to determine appropriate erosion mitigation to protect the southern abutment.

7. Certification

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Appendix A

Historical Aerial Photos


Year: 1946
1:9,000
N


Year: 1967
1:9,000
N


Year: 1981
1:9,000
N
81.04. MTRCA 4 1-60 -
181


Year: 1988
1:9,000
N
NF 13123 152,90


Year: 2002
1:9,000
N


Year: 2009
1:9,000
N


Year: 2018
1:9,000
N

Appendix B

Meander Migration Rates

Appendix B. Migration rate (m/yr) by time period

Dyke	Meander ID	1946 to 1967	1967 to 1981	1981 to 1988	1988 to 2002	2002 to 2009	2009 to 2018	Minimum	Maximum
Pickering	1	0.3	0.4	Confined	Confined	Confined	Confined	0.3	0.4
	2	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	2.1	2.1	2.1	2.1
	3	Anthropogenic	Confined	Confined	Confined	Confined	Confined	NA	NA
	4	Anthropogenic	Unsystematic	Unsystematic	1.0	4.5	1.0	1.0	4.5
	5	Anthropogenic	Confined	Confined	Confined	Confined	Confined	NA	NA
	6	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	2.3	0.0	0.0	2.3
	7	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	0.4	0.2	0.2	0.4
	8	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	Unsystematic	0.8	0.8	0.8
	9	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	Unsystematic	0.8	0.8	0.8
	10	1.0	1.0	1.5	0.7	0.9	0.4	0.4	1.5
	11	Unsystematic	1.7	0.2	0.1	0.6	0.6	0.1	1.7
	12	Unsystematic	Unsystematic	3.7	0.8	0.4	0.1	0.1	3.7
	13	2.2	3.2	Unsystematic	Unsystematic	1.6	3.7	1.6	3.7
	14	Unsystematic	Unsystematic	Unsystematic	0.9	Confined	Confined	0.9	0.9
Ajax	15	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	0.7	1.5	0.7	1.5
	16	Anthropogenic	0.1	0.8	0.7	0.1	1.4	0.1	1.4
	17	Anthropogenic	Unsystematic	Unsystematic	1.3	0.2	0.8	0.2	1.3
	18	Anthropogenic	Unsystematic	Unsystematic	Unsystematic	Unsystematic	0.8	0.8	0.8
	19	Anthropogenic	Unsystematic	Unsystematic	0.5	0.4	0.0	0.0	0.5
	20	Anthropogenic	Unsystematic	Unsystematic	0.7	0.4	Confined	0.4	0.7
	21	Anthropogenic	Unsystematic	Unsystematic	1.4	0.8	0.6	0.6	1.4
	22	Confined	Confined	Confined	Confined	Confined	Confined	NA	NA

Anthropogenic - the channel was anthropogenically altered

Unsystematic - the observed channel migration was unsystematic

Confined - the channel was confined by anthropogenic features or valley wall/terraces

NA - not applicable