16 March 2017

PRELIMINARY SEDIMENT TRANSPORT STUDY

Kingston Inner Harbour
Kingston, Ontario

Submitted to:
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REPORT

Report Number: 1661792-002-R-Rev0-3000

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1.0 INTRODUCTION

Public Works and Government Services of Canada (PWGSC) has retained Golder Associates Ltd. (Golder) to provide a preliminary sediment transport study for the Transport Canada and Parks Canada water lots within Kingston Inner Harbour, Ontario. The study is being conducted in conjunction with the development of a conceptual remedial options analysis for the Kingston Inner Harbour. The scope and cost estimate for this study are outlined in Golder's Proposal for the development of conceptual remedial options analysis for the Kingston Inner Harbour – Transport Canada and Parks Canada Waterlot, Kingston, Ontario dated 27 July 2016. This proposal was prepared in response to the PWGSC Statement of Work (SOW) dated 18 July 2016 (PWGSC, 2016).

1.1 Background

Golder has been involved with the environmental assessment of the Kingston Inner Harbour (KIH) indirectly since 2009 and directly since 2010. The assessment has consisted of characterizing both the spatial extent and magnitude of contamination and the effects of contaminants on the environment. Multiple rounds of field studies and desktop evaluations of risks to humans and aquatic life have been conducted. These studies have identified that a potential ecological and human health risk could be present via contaminated sediments located within the Harbour.

KIH is comprised predominantly of water lots that are separately administered by Parks Canada and Transport Canada (Figures 1 and 2). The Parks Canada and Transport Canada water lots are located in adjacent portions of KIH between Belle Island and the LaSalle Causeway (Figure 2). Due to the potential risk of the contaminated sediments across water lot boundaries and the lack of data regarding local sediment transport and distribution, a preliminary sediment transport study was requested.

1.1.1 Objectives

The overall objective of the preliminary sediment study is to gain a basic understanding of the behavior of sediment within KIH in order to supplement the previously collected physical and biological data in assessing the ongoing risk of contaminants. This assessment was conducted on the current state of the harbour and no future conditions were included. The potential effects of climate change (e.g., changes in water levels in the harbor and Lake Ontario, changes in duration and thickness of ice cover, changes in runoff on Cataraqui River, changes in intensity, direction and duration of storm winds) were not included in this scope.

The assessment was carried out by the following tasks:

- Conduct a preliminary analysis of available data and information.
- Describe the physical processes affecting the harbour.
- Assess sediment delivery to Kingston Inner Harbour.
- Prepare a geomorphic summary of Kingston Inner Harbour with respect to sediment transport including the frequency and depth of disturbance.

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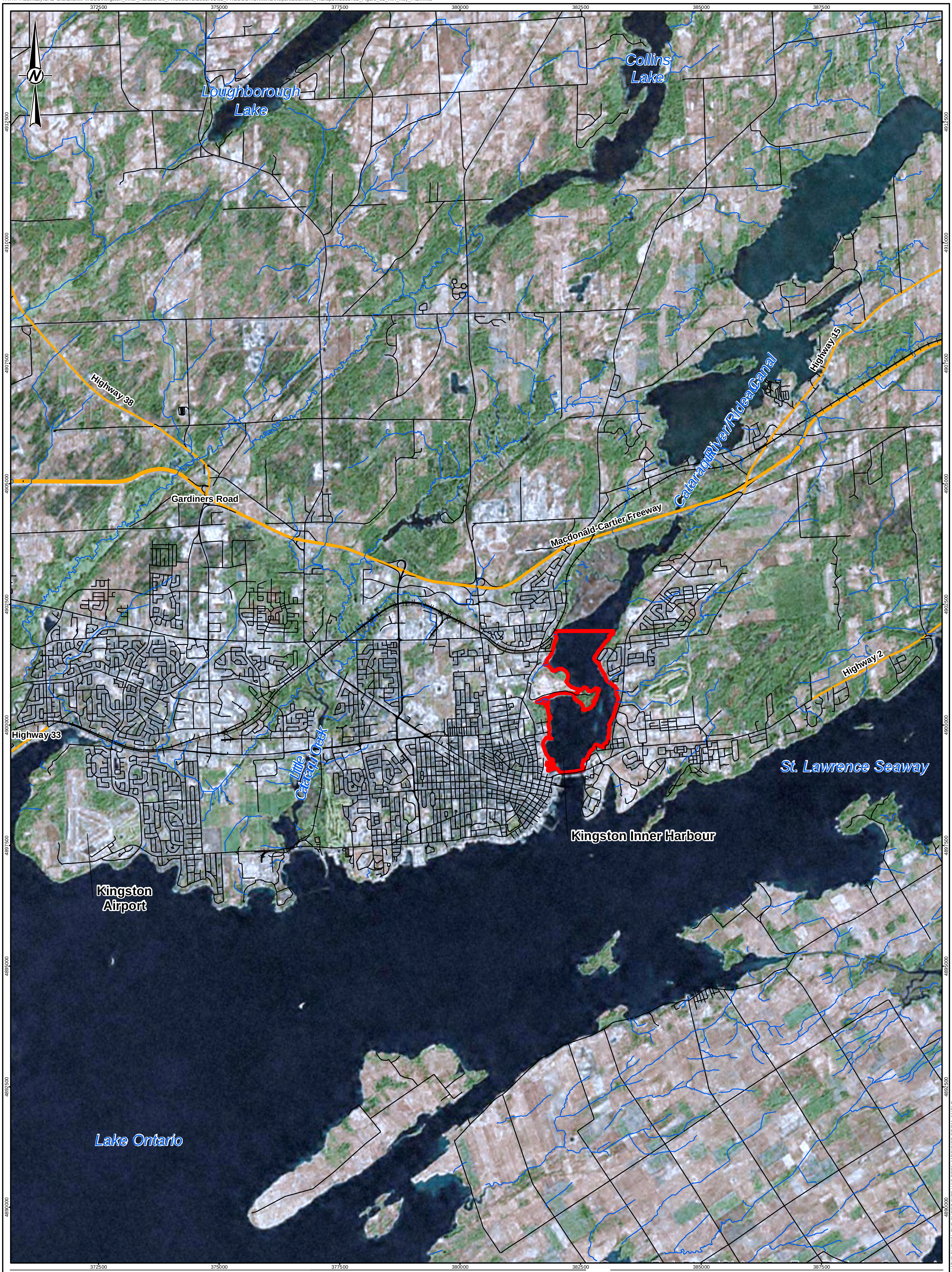

LEGEND

- KINGSTON INNER HARBOUR
- HIGHWAY
- ROAD
- RAILWAY
- WATERCOURSE

0 1,500 3,000

1:75,000 METERS

REFERENCES

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3. PROJECTION: UTM ZONE 18 DATUM: NAD 83

CLIENT
PWGSC

PROJECT
KINGSTON INNER HARBOUR
KINGSTON, ONTARIO

TITLE
KEY PLAN

CONSULTANT

Golder Associates

YYYY-MM-DD	2017-01-03
DESIGNED	SS
PREPARED	JP
REVIEWED	
APPROVED	

PROJECT NO.	PHASE	REV.	FIGURE
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LEGEND

- FEDERAL WATER LOT BOUNDARY
- APPROXIMATE LOCATION OF NAVIGATIONAL CHANNEL
- STORM SEWER OUTFALL
- STORM SEWER (APPROXIMATE)
- HIGHWAY
- ROAD
- RAILWAY
- WATERCOURSE

0 300 600

1:15,000 METERS

REFERENCES

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3. PROJECTION: UTM ZONE 18 DATUM: NAD 83

CLIENT
PWGSC

PROJECT
KINGSTON INNER HARBOUR
KINGSTON, ONTARIO

TITLE
SPATIAL DOMAIN OF SEDIMENT TRANSPORT STUDY AREA AND WATER LOT BOUNDARIES

CONSULTANT

Golder Associates

YYYY-MM-DD	2017-01-03
DESIGNED	SS
PREPARED	JP
REVIEWED	
APPROVED	

PROJECT NO.	PHASE	REV.	FIGURE
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1.2 Methods

The preliminary sediment transport study included an assessment of geomorphic indicators and sediment transport to evaluate the patterns of sediment transport within KIH. The depth and frequency of sediment disturbance was also assessed using various desktop techniques. It involved the collection and review of existing data relevant to site, measurements, and previous hydraulic studies including the following:

- Review of historical aerial photographs (as available from the City of Kingston website; CoK, 2016) to identify historic indicators of geomorphic drift and sediment transport patterns.
- Review of near shore bathymetric and topographic data from Canadian Hydrographic Services and from bathymetry data collected during sampling activities, to assess the effect of nearshore shallow water on the sediment transport regime of KIH.
- Due to the poor quality of available bathymetric survey data for KIH, only a qualitative estimation of disturbance of bed sediments by wash from vessel propellers was conducted.
- Review of wind records in the vicinity of project site.
- Review of water level and hydrology records from Canadian Hydrographic Services at Kingston and for the Cataraqui River, including evaluation the coincidence of high water and storm wave events on the embayment (i.e., water level regime).
- Review of reports on previous sediment studies carried out within KIH.

The wind records were analysed to develop winds with various periods at the site for use in the wave hindcast. A one-dimensional wave hindcast model as applied to estimate nearshore wave conditions. The wave regime at the Site was analyzed based on the local fetch lengths, water depths, and wind duration controls on wave heights and periods.

Data reviewed was used to analyse the current condition of the harbour and used to estimate rates of sediment transport and deposition.

This report summarizes the results of the wind/wave analysis, the data review and analysis, and briefly summarizes how readily sediment in the area is re-suspended, the typical depths of sediment disturbance and which direction sediments may move once mobilized.

2.0 BACKGROUND INFORMATION REVIEW AND ANALYSIS

2.1 Air Photograph Review

Historical air photos and GoogleEarth™ Images for the Project Area were reviewed. The available air photo and satellite imagery record spans the past 68 years (1948 to 2016). The imagery available through GoogleEarth™ spans the period May 2004 to August 2016. The historical air photos and satellite images were examined to assess changes in shoreline morphology, wave patterns captured at the time of photography, and evidence of human activity or changes to the shoreline within the Project Area. The air photos / images were primarily high level photographs, limiting the resolution of observable changes in shoreline location. 'No discernable change' means that based on the scale and resolution of the images, no change between two consecutive images was noticeable or detectable; although changes beyond the resolution of the imagery may have occurred they could not be reliably identified. The air photo/imagery observations and interpretations are summarized in Table 1. Regional locations and features discussed in the air photo review can be found in Figure 1. Features localized to the site can be found in Figure 2.

Table 1: Aerial Photograph Review

Date and Aerial Photograph No. (where available)	Kingston Inner Harbour Description	Key Observations (limited to observable changes in the littoral cell)
1948 A11396:106	Shoreline mostly developed along Anglin Bay north to the Former Lead Smelter. Shoreline is undeveloped along what is currently Douglas Fluhrer but still appears modified.	■ Inferred wave and wind direction: waves visible on Lake Ontario from the SW, wind not discernible.
1953	Only the southern end of KIH is visible in the imagery. South end of KIH a small northerly deflected plume is visible north of Anglin Bay inferred to be storm outflow.	■ Inferred wave and wind direction: waves not visible, wind not discernible. ■ Lighter coloured linear feature is visible in the water north of Belles Island inferred to be navigation channel.
1955	Only the western shoreline of KIH is visible in the imagery. Several drainage channels are visible in Orchard St. Marsh. Plume present north of Anglin Bay appears to be discharging directly east.	■ Inferred wave and wind direction: waves not visible, wind not discernible.
1957	Ice is present immediately south of Bells Island and from the current rowing club location to the south. A small plume is visible at the end of a pier or breakwater south of the former Woolen Mill.	■ Inferred wave and wind direction: wind and waves not visible. ■ Small plume visible along the eastern shore of the upper harbour deflected to the south.

Date and Aerial Photograph No. (where available)	Kingston Inner Harbour Description	Key Observations (limited to observable changes in the littoral cell)
1966	A large sediment plume is visible across the entire Parks Canada waterlot becoming less turbid to the south of former Woolen Mill location and to the east. Plume appears to be deflected into the harbour from the shoreline by the Woolen Mill pier or breakwater at its southern end. Plume appears to follow the shoreline of Belles Island to the north before dissipating south of the Great Cataraqui Marsh.	■ Inferred wave and wind direction: waves not visible, wind not discernible. ■ Some suspended sediment observable in the imagery inferred to be travelling in the Cataraqui River navigation channel east of the Great Cataraqui Marsh. ■ Landfill activities occurring at former landfill location.
1968 A20450:39	Only northeast portion of KIH visible and Bells Park. No discernible change from the 1966 imagery.	■ Inferred wave and wind direction: waves from the east, wind not discernible.
1970	No discernible change from the 1968 imagery.	■ Upper Harbour not visible. ■ Inferred wave and wind direction: waves from the east in Lake Ontario, wind from the north-northeast. ■ Large semi-circular deposit along shoreline north of former landfill location.
1978	No discernible change from the 1970 imagery.	■ Inferred wave and wind direction: waves and wind from the southwest in KIH and the upper Harbour. ■ Landfill and semi-circular deposit appear to have an increase in vegetative cover.
1987 A27169:67	Only southeast portion of KIH and mouth visible. No discernible change from the 1978 imagery.	■ Inferred wave and wind direction: waves from the north-west, wind not discernible.
1990	Small plume deflected to the south along western shoreline from Emma Martin Park and deflected east into the harbour by the Woolen Mill Pier or breakwater.	■ Inferred wave and wind direction: wind and waves from the north. ■ Navigation channel very dark, inferred to be recently dredged. ■ Plume from the Cataraqui River visible passing through the eastern opening in the La Salle Causeway appearing to be deflected slightly south by shoreline currents travelling south-southwest along the north shore of Lake Ontario
1990 A27606:162	Only southern portion of KIH and mouth visible. No discernible change from the 1987 imagery.	■ Inferred wave and wind direction: waves not visible, wind from the east to south east.

Date and Aerial Photograph No. (where available)	Kingston Inner Harbour Description	Key Observations (limited to observable changes in the littoral cell)
1998	No discernible change from the 1990 imagery.	■ Inferred wave and wind direction: waves not visible, wind from the north to northwest.
8 May 2004 GoogleEarth™	No discernible change from the 1998 imagery.	■ Inferred wave and wind direction: wind and waves not visible. ■ 4 vessels observed offshore of Douglas Fluhrer Park within the harbour boundary.
2004	Sediment plume discharging from north of the current rowing club location following shoreline north. Another sediment plume around the Parks Canada waterlot migrating east toward and around Belle Island eventually deflecting to the north.	■ Inferred wave and wind direction: wind and waves from the southwest. ■ Former landfill now a golf course.
29 July 2005 GoogleEarth™	Aquatic vegetation visible above the water along the southern shoreline of the former landfill and in the Parks Canada waterlot	■ Inferred wave and wind direction: wind and waves from the northeast.
2008	No discernible change from the 2005 imagery.	■ Inferred wave and wind direction: waves not visible, wind from the south.
11 July 2010 GoogleEarth™	Only southern portion of KIH visible. Aquatic vegetation visible above the water in the middle of the harbour.	■ Inferred wave and wind direction: wind and waves from the south-southwest. ■ 11 vessels observed offshore of Douglas Fluhrer Park within the harbour boundary. Wake visible only from 1 of 11 vessels.
30 June 2011 GoogleEarth™	No discernible change from the 2010 imagery.	■ Inferred wave and wind direction: wind and waves from the south-southwest. ■ 1 vessel observed offshore of Douglas Fluhrer Park within the harbour boundary.
8 July 2011 GoogleEarth™	No discernible change from the 2011 imagery.	■ Inferred wave and wind direction: wind and waves from the north-northeast. ■ Approximately 11 vessels observed offshore of south Douglas Fluhrer Park within the harbour boundary. Wake visible only from 3 of 11 vessels.
2011	Sediment plume visible heading south along the Cataraqui River navigation channel with plume being discharged out of the mouth of the harbour.	■ Inferred wave and wind direction: wind and waves not visible. ■ Suspended sediment visible in the Cataraqui River and in lakes upstream of Kingston Mills.

Date and Aerial Photograph No. (where available)	Kingston Inner Harbour Description	Key Observations (limited to observable changes in the littoral cell)
2013	Sediment plume visible heading south along the Cataraqui River navigation channel with plume being discharged out of the mouth of the harbour. Plume also present travelling along the western to northern shorelines of KIH.	■ Inferred wave and wind direction: wind and waves from the north-northwest. ■ Suspended sediment visible in the Cataraqui River and in lakes upstream of Kingston Mills.
26 May 2014 GoogleEarth™	No discernible change from the 2013 imagery.	■ Inferred wave and wind direction: waves not visible, wind from the south.
2014	Sediment plume visible heading south along the Cataraqui River navigation channel with plume being discharged out of the mouth of the harbour deflecting to the southeast.	■ Inferred wave and wind direction: wind and waves not visible. ■ Suspended sediment visible in the Cataraqui River and in lakes upstream of Kingston Mills.
3 September 2015 GoogleEarth™	Aquatic vegetation visible above the water over most of the western and northern portions of KIH. A dark straight feature is visible in the water from just north of the rowing club towards Green Bay, following Transport Canada waterlot boundaries.	■ Inferred wave and wind direction: wind and waves not visible. ■ 2 vessels observed; one offshore of south Douglas Fluhrer Park and the other at the mouth of Anglin Bay within the harbour boundary.
28 May 2016 GoogleEarth™	No discernible change from the 2015 imagery.	■ Inferred wave and wind direction: wind and waves not visible.
24 June 2016 GoogleEarth™	No discernible change from the May 2016 imagery.	■ Inferred wave and wind direction: waves not visible, winds from the south. ■ 2 vessels observed near the La Salle Causeway and in navigation channel. Wake visible from both vessels.
3 August 2016 GoogleEarth™	No discernible change from the June 2016 imagery.	■ Inferred wave and wind direction: wind and waves not visible.
16 August 2016 GoogleEarth™	No discernible change from the 3 August 2016 imagery.	■ Inferred wave and wind direction: wind and waves not visible. ■ Aquatic vegetation visible above the water over most of the Upper Harbour and along the Cataraqui River navigation channel.

Key observations from the air photo, orthophoto and satellite imagery review were:

- KIH is located at the mouth of the Cataraqui River where it discharges into Lake Ontario. Most development along the western shoreline of KIH was constructed prior to 1948 including the La Salle Causeway and lock feature along the Cataraqui River.
- Observation of littoral patterns and images indicate the primary source of deposited sediment in the harbour is primarily fine-grained material in suspension from the Cataraqui River. Other primary sources of sediment to KIH include local sediments re-suspended and reworked by waves and currents and local storm water outfalls. Observable sediment accumulation was not identified in the vicinity of the harbour.
- Minor geomorphic indicators of sediment transport were visible along the north shore of Lake Ontario indicating a west to east transport direction outside of the mouth of KIH. Dredging of the navigation channel since at least 1953 has interrupted previously occurring river processes throughout the upper and inner Harbours by directing the main flow of the river through the channel.
- Vessel activity, when observed, was confined to the southern portion of KIH, within the harbour limits as well as the navigation channel. The presence of wakes behind observed vessels were minimal. No vessel activity was identified north of the harbour limit and west of the navigation channel in the available imagery.
- No seasonal variances in sediment transport were observed. However Large-scale suspended sediment plumes appear to follow two clockwise circulation cells, one in KIH and one in the upper harbour.

2.2 Data Obtained from Previous Reports and Regulations

A summary of the pertinent and/or relevant data identified in previous reports that bear on the sediment transport assessment are provided below by source report.

Golder, *Implementation of the Canada-Ontario Decision Making Framework for Assessment of Great Lakes Contaminated Sediment - Kingston Inner Harbour, Ontario*, 2011.

- Sediment distribution within the harbour is coarsest within Anglin Bay fining to the east and north.

Golder, *Transport Canada Waterlot Sediment Investigation, Ontario*, 2014.

- Cores taken from off of Douglas Fluhrer Park did not retain substantial sediments during sampling due to shallow dense clay layer (<30 cm).
- PAHs were found in samples from 0.10 to 1.6 m depths in Anglin Bay and from 0.10 to 0.4 m in the nearshore of Douglas Fluhrer Park and 0.40 to 1.0 m depths offshore of Douglas Fluhrer Park. These were higher concentrations than surface samples taken from the same locations.
- Surface samples typically contained between 24% and 59% sand, 26% to 47% silt and 9.8% to 20% clay.
- Sandy silt to silt was found in depths of 0.4 to 0.7 m with increasing concentrations of fines with depth. Heavy clay was found in depths from 0.7 m to 1.9 m

Malroz Engineering Inc. *Kingston Inner Harbour Data Compilation and Gap Analysis — Great Cataraqui River*. 2003.

- Waves heights reported were estimated by others (Crysler and Latham, 1977; Hall, 1999; Paine, 1983) but are summarized as follows:
  - A fetch of 1,770 m generates 0.15 m wave heights.
  - Wave heights of 0.10 – 0.20 m up to 0.5 m in fall storms can generate currents along the shoreline of 0.5 to 1 m/s.
  - Wave heights of 0.37 m would re-suspend sediments within the harbour.
- Currents reported were also estimated by others (Paine, 1983; Hall, 1999) but are summarized as follows:
  - Maximum river flow conditions generate currents less than 0.15 to 0.18 m/s. These currents are capable of scouring bottom sediments.
  - 0.2 – 0.4 m/s circulation cell currents may cause significant scour.
- Substantial carp population exists within harbour which can stir up bottom sediment.
- Dense weed growth is prominent over most of the inner harbour.

RMC*, Application of the Canada-Ontario Decision-Making Framework for Contaminated Sediments in the Kingston Inner Harbour,* February 2014

- All historical industry that contributed to local contamination with KIH was closed by the mid-1980s.
- Chromium concentrations in surface sediments throughout the harbour are fairly consistent suggesting limited dilution and burial are occurring.
- Concentrations of several contaminants of concern decrease within the harbour from west to east (i.e., further distally away from sources) suggesting potential resuspension and transport to the east.
- Area between Belle Island and the mainland was infilled with dredged sediment from the harbour then used as a landfill.
- Industrial activity contributing to sediment contamination consisted of:
  - Smelting works were conducted between 1879 and 1915 at the former lead smelter.
  - The Tannery operated from 1909 to 1973, discharging chromium, copper, lead, zinc, arsenic and salt into the harbour.
  - A coal plant operated from 1848 to the 1950's. The coal tar contained PAHs.
  - Railway and shipyards operated in Anglin Bay from the early 1900's until the 1980's which included coal yards and ship building.
  - The Belle landfill operated from 1952 until 1974 and is suspected of containing PAH, PCB, metals and pesticide wastes.
  - A waste disposal facility which contained miscellaneous contaminants, topsoil and wastes from the smelter operation operated until 1985.

3.0 CONCEPTUAL MODEL OF PHYSICAL PROCESSES

3.1 Hydrology

The harbour is located at the mouth of the Cataraqui River, which is part of the Rideau Canal system. The Cataraqui River watershed is within the Great Lakes Lowlands and drains an area approximately 910 km^2 (Acres, 1977). The Cataraqui River discharge regime is dominated by a spring (February to March) increase in flows due to snowmelt. Cataraqui River typical flows range from 4 m^3/s to 17 m^3/s up to a maximum estimated flow of 50 m^3/s recorded during a heavy storm (HCCL, 2011). These flows cause the harbour to flush out approximately 76 times per year (RMC, 2014).

Even though the harbour is located at the mouth of the Cataraqui River, its water levels are dictated by those of Lake Ontario. Several changes to the hydrologic regime of Lake Ontario have impacted water level fluctuations within the Harbour. The completion of the St. Lawrence Seaway and lock system in the late 1840's, the completion of the Rideau Canal and lock system upstream in the Cataraqui River in 1832, the construction of the La Salle Causeway across the mouth of the harbour in 1916 and the Lake Ontario Management Plan in the 1960s have all affected the hydrologic regime of the harbour (Dalrymple and Carey, 1990; Malroz, 2003; RMC, 2014). These changes have mostly caused a dampening of water levels and restricted flow in and out of the harbour, thus limiting the modern sediment transport regime by reducing current flows.

3.1.1 Currents

Currents within the harbour have not been well studied. HCCL (2011) as part of an Environmental Assessment for a new crossing of the upper harbour, conducted a hydrotechnical analysis of the upper and lower harbours. As part of their investigation, they conducted some current measurements east of Belle Island as well as modelling the effects of wind on currents. Under moderate to low flows, currents east of Belle Island measured approximately 0.05 m/s. These are typically too low to re-suspend the bed sediments observed within KIH based on comparison with the Shield's criterion[1]. Opposing currents were also observed within the narrows, suggesting the presence of a larger circulation cell between the upper and inner harbours. They observed that wind and surge conditions can produce higher velocities within the harbour than higher flows associated with the Cataraqui River, which would be expected given the overall low annual flows in the Cataraqui River. This would suggest that wind-wave re-suspension is the dominant process of sediment re-suspension. Once the fine sediments are re-suspended they will then be subject to the prevailing current regime.

The modelling results showed that under both light and strong northerly winds, currents will be dominant towards the south. Under southerly winds, surface currents will be dominant toward the north, even in the river channel. The currents in KIH under these southerly winds follow the shoreline around the south end of Belle Island and up into the upper harbour. These patterns were also observed in the sediment plumes in the air photos. Modelled currents were reported as less than 0.45 m/s along the navigation channel, the eastern shoreline and the southern (deeper) portion of KIH. These current speeds are capable of re-suspending silts and sands based on the Shield's criterion. The shallow areas of the northern portion of the Transport Canada Waterlot had currents between 0 and 0.18 m/s while currents were almost 0 in the Parks Canada Waterlot. These current speeds are capable of re-suspending finer sediments but may not re-suspend coarser sediments (e.g., sand-sized sediments).

[1] Shield's criterion is a dimensionless number which is a used to determine the threshold of incipient motion. It is a product of sediment geometry and geochemistry, bed roughness and the resulting turbulence of the boundary layer above the bed.

Several alterations to the shoreline around KIH would have impacted currents and circulation patterns. The area between Belle Island and Belle Park was infilled with dredgeate and then used as a landfill between 1952 and 1974 (Golder, 2011; RMC, 2014). This redirected all flow to east of Belle Island. Also with the construction of the La Salle Causeway and subsequent constriction of flow in and out of the harbour, changes to circulation patterns and flow would have occurred. The constriction of flow in and out of the harbour is suspected to have decreased harbour flushing which has led to an increase in sediment accumulation (RMC, 2014).

3.1.2 Lake Ontario Water Levels

The water levels of KIH are considered to be consistent with Lake Ontario's (Dalrymple and Carey, 1990). Historic daily water level data for Lake Ontario was retrieved CHS (2016) covering the period from 1 January 1962 to 30 September 2016. Golder has conducted a high level assessment of water levels for Lake Ontario at Kingston. Golder calculated values for minimum, mean and maximum water levels at 73.7 m, 74.8 m and 75.8 m, respectively. A summary of those water elevations are included in Table 2. Water levels reported by HCCL (2011) for Kingston Harbour ranged from 74.3 m for average low water to 75.3 m for the average high water level. CHS (2007) reports chart datum as 74.2 m.

Table 2: Summary of Water Elevations

	Reported Water Level (m above sea level, IGLD, 1985)
Recorded high water level (occurred on 11 May 1973)	75.8
Mean Water Level (1 January 1962 to 30 September 2016)	74.8
Chart datum	74.2
Recorded low water level (occurred on 2 January 1965)	73.7

Analysis of the available water data indicates that high water typically occurs on Lake Ontario in early summer months (e.g., June). Periods of high water are typically sustained for several weeks to a couple of months. If the summer water season is taken to last six months then high water conditions typically last for one month out of six.

3.1.2.1 Seiches and Storm Surge

The location of KIH at the eastern end of the lake coupled with southwesterly dominant wind directions make the site potentially prone to short term seiche-induced water level fluctuations and wind set-up. A standing wave in a lake is known as a seiche. It is caused by wind-induced tilting of the water surface. As wind speed decreases, the stress is removed and the water surface is forced back to the still water level (SWL) by gravity. However due to momentum, the water level goes past the SWL and a rocking motion ensues about one or more nodal points. There is a gradual dampening of the oscillation due to gravity and frictional forces, the magnitude of which varies with water depth and complexity of the basin. Seiches are known to occur in Lake Ontario and according to HCCL (2011) can cause water levels to fluctuate from -0.23 m to +0.44 within a few hours. Surges have been recorded as high as 0.7 m historically (HCCL, 2011). Even in winter conditions, short term water level fluctuations can range from -0.25 to 0.47 m.

Due to the short term nature of surge and seiche-induced water level fluctuations, they can create tide-like currents which have the potential to mobilize and transport sediments. No data were identified to quantify currents through the causeway under seiche or surge events, but an initial estimate of average velocity can be made. Assuming the causeway openings have a combined cross-sectional area of 720 m^2, a 0.5 m surge taking 2 hours to drain would result in typical flow velocities of approximately 0.15 m/s at the Causeway, and likely lower within the harbour. However, as these currents are generated by Lake Ontario water level fluctuations, they could potentially induce re-suspension of sediments within the harbour near the inlets through an inrush of water on the rising part of the surge. These re-suspended sediments would potentially be carried up into KIH by the incoming surge. On the falling limb of the surge, the retention of water by the causeway most likely means that coarser re-suspended sediments are retained within the harbour since the rate of release of water would be slowed. Potentially re-suspended fine-grained sediments, e.g., like silt and clay sized materials, could be flushed out into the lake if they remain in suspension near the top of the water column for longer than it takes for the surge to drain back into Lake Ontario.

3.1.3 Ice Cover

Due to KIH's location in Southern Ontario, winter conditions are such that ice cover during winter months is typical. According to HCCL (2011) KIH is typically ice covered from mid to late December to mid to late April depending on the severity of the winter (NOAA, 2012). Ice can minimize wind and wave generated currents but there is potential for other circulation based currents to exist. River currents from the Cataraqui River, as mentioned in Section 3.1.1 for example, are likely to be present under ice and may contribute to other circulation based currents within the deeper sections of the harbour. Given the protected nature of KIH, ice would tend to form along the shoreline and once thick enough, may freeze directly to the bed in the shallow areas. Ice break up in the spring tends to coincide with high water levels. As the water level increases, ice may float out into the harbour, with bed sediments frozen underneath therefore redistributing these sediments as the ice thaws.

3.2 Bathymetry and Topography

Kingston Inner Harbour is situated on the northeast shore of Lake Ontario at the mouth of the Cataraqui River. Bathymetric data for Kingston Inner Harbour was available through Canadian Hydrographic Services in digital chart form (Chart 1513E; CHS, 2007), as shown in Figure 3. The harbour consists of a shallow u-shaped basin approximately 1.6 km long and 1 km wide. At the southern end of the harbour, the La Salle causeway divides the inner harbour from the outer harbour. The outer harbour is approximately 900 m long and terminates as the mouth of the Cataraqui River, into Lake Ontario. The KIH basin, shallows from its deepest point adjacent to the La Salle Causeway to approximately 1 m depth just south of Belle Island. A very shallow marsh extends from the south end of Belle Island.

According to CHS (2007), the southern end of the harbour was dredged as recently as 1965 to a depth of 5.5 m. The dredge cut runs from the mouth of Anglin Bay on the west side, to the Cataraqui River /Rideau Canal navigation channel to the east. The navigation channel runs approximately south to north, connecting the lock system of the Rideau Canal to Lake Ontario. A dredge cut can also be seen in the aerial photographs which follows a buried pipeline, according to Chart 1513E (CHS, 2007). Available bathymetry dates from 2007 and is therefore at least a decade old. More recent bathymetric data would be required to confirm that water depths have not changed in the intervening years.

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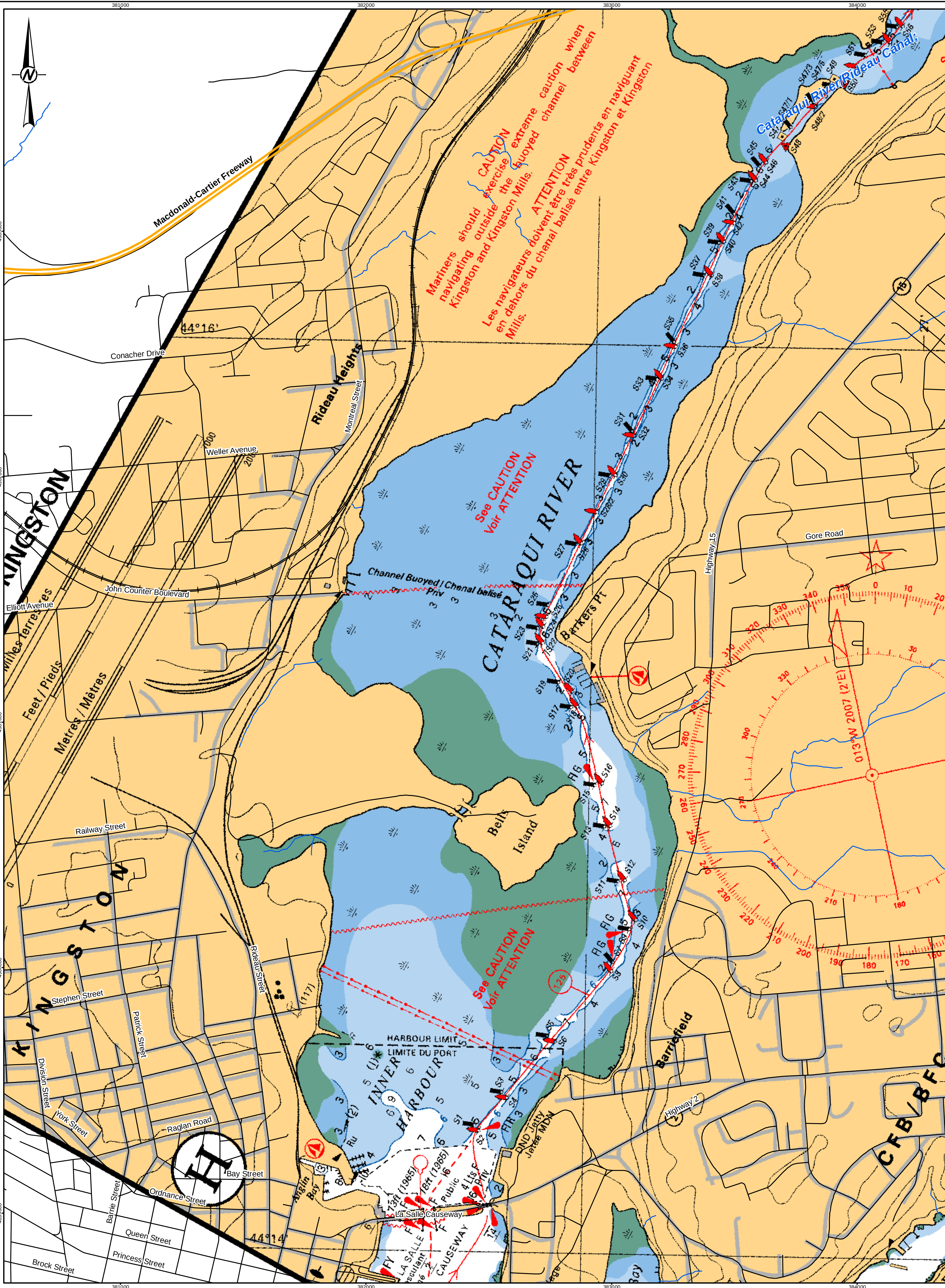

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- ROAD
- RAILWAY
- WATERCOURSE

0 300 600

1:15,000 METERS

NOTE(S)

1. CHART DEPTHS ARE IN FEET.

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3. PROJECTION: UTM ZONE 18 DATUM: NAD 83

CLIENT
PWGSC

PROJECT
KINGSTON INNER HARBOUR
KINGSTON, ONTARIO

TITLE
BATHYMETRY OF KINGSTON INNER HARBOUR

CONSULTANT
Golder Associates

YYYY-MM-DD	2017-01-11
DESIGNED	SS
PREPARED	JP
REVIEWED	
APPROVED	

PROJECT NO.	PHASE	REV.	FIGURE
1661792		A	3

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25mm

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3.3 Geology

The geology in KIH consists of surficial deposits of quaternary and Holocene sediments overlying limestone bedrock. Underlying bedrock is limestone of the Gull River formation (Golder, 2009). Boreholes from previous investigations show a shallow valley within the bedrock where the river channel flows. Depth to bedrock ranges from 3 m on the western side of the harbour to 22 m on the eastern side.

Older sediments overlying bedrock are interpreted as being glaciolacustrine clays deposited in glacial Lake Iroquis (Dalrymple and Carey, 1990). Alternating layers of peat and gyttja overlying the clay suggest cyclical variations in water levels of Lake Ontario over time where peat is formed in shallower waters, and gyttja accumulates in deeper waters. Gyttja accumulation is can be interpreted as a sediment sink environment. Peat within KIH contain an organic content of 70-75% and the inorganic content is silt and clay with mean grain sizes of 0.0155 mm to 0.0055 mm. KIH gyttjas are soft, water rich (>80% w.w.), bioturbated sediments with the same mean inorganic grain sizes as peat (Dalrymple and Carey, 1990). Peat is still present along the surface in the shallow portions of KIH as well as in the marshy areas (RMC, 2014). The surficial layer of sediment in deeper waters (>0.7 m) is comprised of gyttja which has a lower organic content than underlying layers. This may be due to increased sediment inputs from anthropogenic changes in land use within the watershed and therefore a more recent deposit (Dalrymple and Carey, 1990). However, due to the presence of several large lakes in the watershed, limited siliclastic material is supplied to the marsh and harbour (Dalrymple and Carey, 1990).

Figure 4 (RMC, 2014) displays a relatively recent distribution of fine-grained surface sediments across KIH, which are consistent with more recent studies (Golder, 2014). It shows a fining of material from the western side of KIH to the east. An area of silty sand is present offshore of Douglas Fluhrer Park north towards the rowing club. Sandy silt occupies the area east of the silty sand followed by the dominant surface sediment deposit of silty clay as well as a smaller area south east of Belle Island covering part of the navigation channel. Silty clay covers approximately 60% of the bed within KIH. These grain sizes can help to assess sediment transport patterns within the harbour, with fine grained material indicative of low-energy areas of deposition and coarser material in areas of higher-energy.

Sediment recruitment within the Cataraqui River system is expected to be limited due to the low-lying topography and multiple lakes upstream of the harbour making this a sediment limited environment. Coarse sediment recruited upstream of the lock at Kingston Mills may be trapped by Colonel By Lake, whereas fine-grained sediments in suspension were observed to be delivered to the harbour and Lake Ontario. Dredging of the river channel is known to occur for navigation purposes (RMC, 2014). The observed sediment plume from Cataraqui River in the available air photo imagery suggests that the sediments delivered to KIH are primarily deposited within the harbour while a smaller fraction are flushed out into Lake Ontario where they likely settle offshore because accumulations are not observed at the shoreline in the historical air photos. However, the lack of observable dynamic sedimentary features in KIH and in the vicinity of the mouth of Cataraqui River, supports the hypothesis that this is a sediment limited environment. It is likely that the local sediment regime within KIH is dominated by a combination of fine-grained sediments delivered via the Cataraqui River, resuspension of local bed sediments by waves and currents and contribution from local storm water outfalls.

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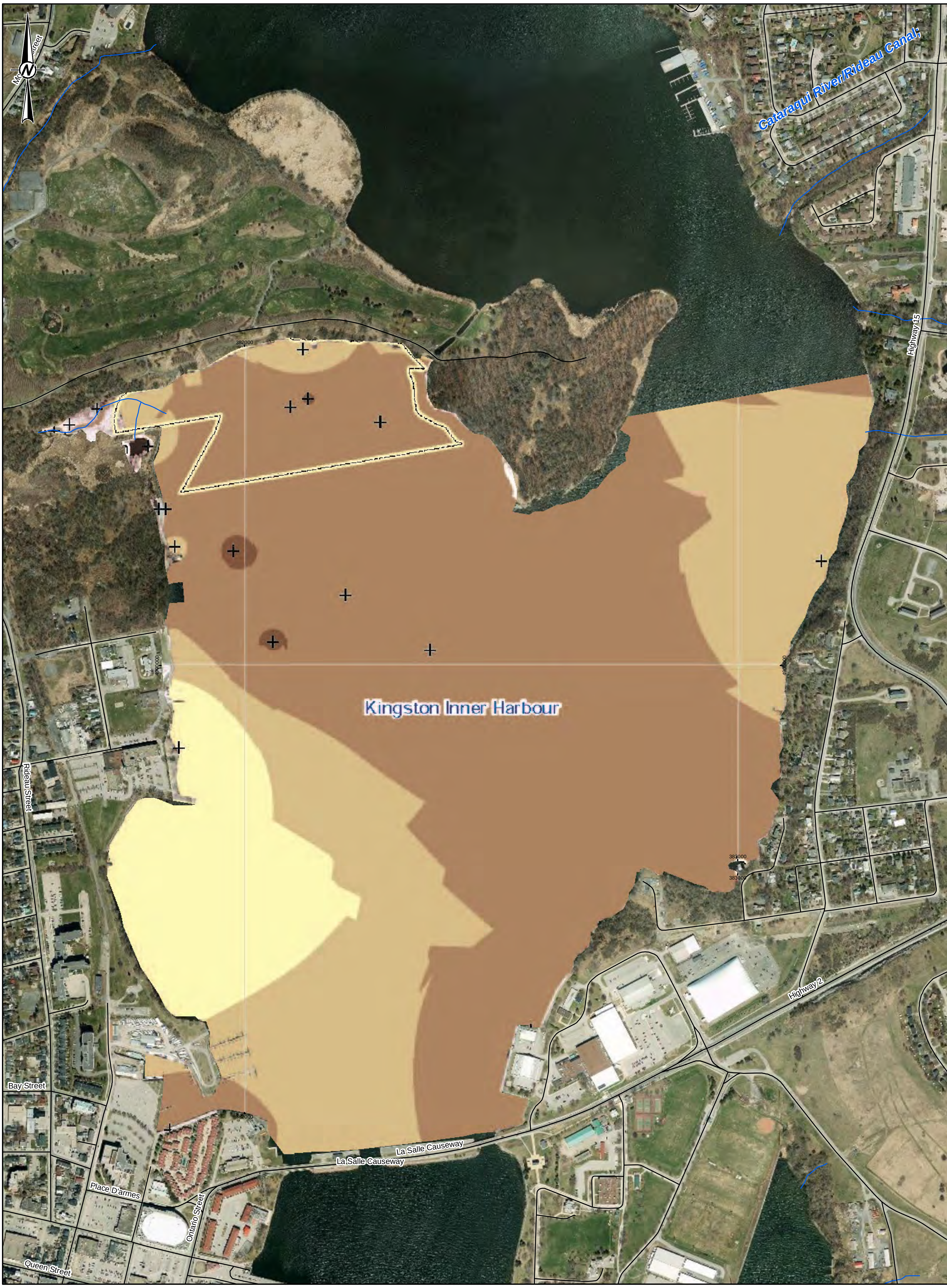

LEGEND

- HIGHWAY
- ROAD
- RAILWAY
- WATERCOURSE
- PARKS CANADA BOUNDARY

GRAIN SIZE

- < 63 SILTY SAND
- 63-81 SANDY SILT
- 81-96 CLAYEY SILT
- >97 SILTY CLAY
- KINGSTON INNER HARBOUR GRAIN SIZE SAMPLE

0 150 300

1:7,500 METERS

REFERENCES

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4. PROJECTION: UTM ZONE 18 DATUM: NAD 83

CLIENT
PWGSC

PROJECT
KINGSTON INNER HARBOUR
KINGSTON, ONTARIO

TITLE
DISTRIBUTION OF FINE-GRAINED SEDIMENTS IN KINGSTON INNER HARBOUR

CONSULTANT

Golder Associates

YYYY-MM-DD	2017-01-11
DESIGNED	SS
PREPARED	JP
REVIEWED	
APPROVED	

PROJECT NO.	PHASE	REV.	FIGURE
1661792		A	4

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25mm

3.4 Wind and Wind-generated Waves

3.4.1 Winds

Historical hourly wind records were obtained for the nearest Environment and Climate Change Canada meteorological station to the site, Kingston Airport (station ID: 6104146). The Kingston Airport station is located approximately 10 km west of the site at 44.2° N, 76.6° W at an elevation of 92.4 metres (m) above mean sea level (msl), approximately 20 m higher than KIH water level (74.8 above msl). Kingston Airport is located directly on the shore of Lake Ontario and is more exposed to southerly winds than Kingston Harbour because it is out of the wind shadow of Simcoe and Wolfe Islands. The airport is also less exposed than Kingston Harbour to southwesterly winds due to the presence of Amherst Island and Prince Edward County creating wind shadows on the airport for full fetch winds along Lake Ontario. This would suggest that estimates of wave heights and wind speeds derived from Kingston Airport data are biased high in KIH for winds from the south and biased low for winds from the southwest. Historical wind data at the Kingston Airport are comprised of two distinct products: (1) hourly data manually logged from 5:00 to 22:00 every day from 1967 until October 2014; and (2) hourly data recorded automatically on a 24-hour basis by a data logger since November 2014 through 2016.

Figure 5 shows wind roses summarizing all wind data collected at the Kingston Airport from May 1967 to July 2016 (50 years) for summer and winter seasons. Summer and winter seasons are broadly defined as the intervals from April to September and from October to March, respectively. Wind roses indicate the direction from which the wind is blowing. Wind direction at the Kingston Airport is primarily from the south during summer and from the west during winter. Wind from the westerly and southerly quadrants (from 135 to 315°) represent 68% and 60% of all wind directions during summer and winter, respectively. Average wind speed during winter is approximatively 20% stronger than in summer (3.9 m/s in summer; 4.8 m/s in winter), but the frequency of wind stronger than 10 m/s in winter is approximatively 5 times greater over the winter months than in summer.

A peaks over threshold (POT) extreme value analysis (EVA) was carried out using wind speeds recorded at Kingston Airport to determine wind speeds for a number of return periods. The analysis involves identifying peak wind speeds associated with independent storm events above relevant wind speed and duration thresholds. The POT method versus the annual maxima method of determining return period conditions is considered more accurate due to the typically larger sample size of the former (Goda, 1988). This analysis also allows for identifying the frequency of storms in a given year which is important to this study as most resuspension events will occur during storm events. The POT analysis involved (Goda, 1988; Leenknecht et al., 1992):

- Sorting the time series wind data into 45° sectors from the predominant directions (southerly, southwesterly, and westerly) to isolate data associated with different meteorological conditions (i.e., belonging to different statistical parent distributions).
- Identifying peak wind speeds associated with independent storm events, based on exceedance of a wind speed thresholds (12 m/s for the winter season and 8 m/s for the summer season) and a minimum duration of 3 hourly records (winter) or 2 hourly records (summer). This resulted in approximately 1 event or more per year between 1967 and 2016.
- Fitting a variety of extreme value probability distribution functions (pdfs), including the Fisher Tippett Type 1 (FT-1) and Weibull distributions, to the wind events.
- Based on the best fit extreme value pdf, return value wind speeds were extrapolated for return periods ranging from 1 year to 100 years.

Return value wind speeds based on the POT analysis are summarized in Table 3 to Table 5 (for summer conditions) and Table 6 to Table 8 (for winter conditions). The determination of wave conditions in winter must consider the extent of ice cover. The POT analysis identified approximately 3 storms per year in the winter and approximately 13 storms per year in the summer. Based on the analysis of water levels, and assuming a uniform distribution of storm events, at least 2 storm events may be expected to occur coincidentally with high water levels on Lake Ontario in a given year. A more detailed analysis of the combined probability of storm events and water levels would need to be undertaken to further refine this analysis. A detailed combined probability analysis was beyond the scope of this study.

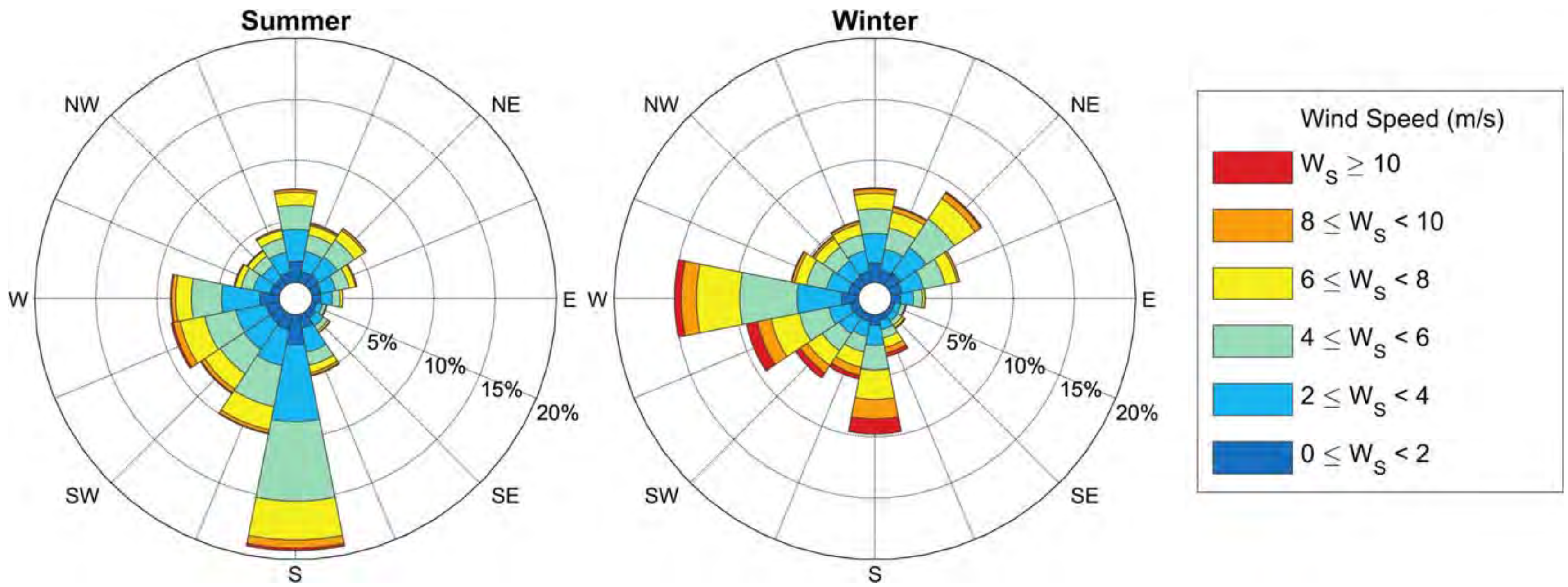

Figure 5: Wind Roses for the Summer and Winter Season from 1967 to 2016 at the Kingston Airport.

Table 3: Return Periods and Associated Wind Speed for the Kingston Harbour Region for Southerly (157.5∘to 202.5∘) Winds during the Summer Season

Return Interval (years)	Wind Speed (m/s)	95% Confidence Interval (m/s)		
1	11.8	11.4	to	12.2
2	12.9	12.4	to	13.5
5	14.4	13.6	to	15.1
10	15.4	14.5	to	16.2
25	16.7	15.7	to	17.7
50	17.7	16.5	to	18.8
100	18.6	17.3	to	19.9

Table 4: Return Periods and Associated Wind Speed for the Kingston Harbour Region for Southwesterly (202.5∘to 247.5∘) Winds during the Summer Season

Return Interval (years)	Wind Speed (m/s)	95% Confidence Interval (m/s)		
1	11.2	10.8	to	11.7
2	12.5	11.8	to	13.1
5	14.1	13.2	to	15.1
10	15.4	14.2	to	16.5
25	17.0	15.5	to	18.4
50	18.2	16.6	to	19.9
100	19.4	17.6	to	21.3

Table 5: Return Periods and Associated Wind Speed for the Kingston Harbour Region for Westerly (247.5∘to 292.5∘) Winds during the Summer Season

Return Interval (years)	Wind Speed (m/s)	95% Confidence Interval (m/s)		
1	10.8	10.3	to	11.3
2	12.0	11.2	to	12.9
5	13.8	12.5	to	15.1
10	15.3	13.6	to	16.9
25	17.2	15.0	to	19.4
50	18.8	16.2	to	21.4
100	20.3	17.3	to	23.4

Table 6: Return Periods and Associated Wind Speed for the Kingston Harbour Region for Southerly (157.5∘to 202.5∘) Winds during the Winter Season

Return Interval (years)	Wind Speed (m/s)	95% Confidence Interval (m/s)		
1	14.1	13.8	to	14.5
2	15.4	14.9	to	15.8
5	16.6	16.0	to	17.3
10	17.5	16.7	to	18.2
25	18.4	17.5	to	19.3
50	19.1	18.0	to	20.1
100	19.7	18.5	to	20.8

Table 7: Return Periods and Associated Wind Speed for the Kingston Harbour Region for Southwesterly (202.5∘to 247.5∘) Winds during the Winter Season

Return Interval (years)	Wind Speed (m/s)	95% Confidence Interval (m/s)		
1	11.7	10.8	to	12.5
2	15.5	14.8	to	16.1
5	17.5	16.5	to	18.6
10	18.7	17.5	to	20.0
25	20.1	18.5	to	21.6
50	21.0	19.2	to	22.7
100	21.8	19.8	to	23.7

Table 8: Return Periods and Associated Wind Speed for the Kingston Harbour Region for Westerly (247.5∘to 292.5∘) Winds during the Winter Season

Return Interval (years)	Wind Speed (m/s)	95% Confidence Interval (m/s)		
1	13.1	12.5	to	13.6
2	15.2	14.6	to	15.8
5	17.1	16.2	to	18.1
10	18.3	17.1	to	19.5
25	19.7	18.2	to	21.3
50	20.7	19.0	to	22.5
100	21.7	19.7	to	23.7

3.4.2 Waves

Wind-waves at the site were calculated using the Automated Coastal Engineering System (ACES) software (Leenknecht et al. 1992) developed by the United States Army Corps of Engineers (USACE) to estimate wind-wave growth over open water and restricted fetches in deep and shallow water. The accuracy of modelled wave heights and periods are ±0.1 m and ±0.1 s. No site specific wave information was identified. The deep water, restricted fetch condition was used for calculating wind-waves generated over fetches associated with each wind direction sector in the Inner Harbour as follows:

- Southerly: 1.6 km
- Southwesterly: 2.1 km
- Westerly: 1.2 km

Return value wind speeds calculated in the EVA were used to evaluate significant wave heights and peak wave periods generated along each fetch. Nearshore wind-generated wave estimates (significant wave height and peak wave period) are provided in Table 9 for each wind directional sector (with return periods of 2, 5, 10, 25, 50, and 100 years), respectively. Wave heights for a ½ year event range from 0.2 m to 0.3 m. For extreme conditions during a 1/100 year event wave heights range from 0.3 to 0.4 m in summer and 0.3 to 0.5 m in winter under winter open water conditions. Ice is typically present in KIH during the winter months. The presence of ice cover would minimize or reduce the generation of waves by winds. For the purposes of this analysis, open water conditions in the winter were assumed as this would be conservative. The largest wave height conditions occur with winds from the southwest predominantly due to the larger fetch length. Waves forming along this direction will reach full size in the northeast corner of KIH near the navigation channel and will deflect currents to the north.

Table 9: Estimated Significant Wave Heights (Hs) and Periods (Tp) for Associated Return Periods for Various Fetch Lengths in the Inner Harbour

		Summer			Winter (assumes open water)		
	Return Interval (years)	**Southerly (157.5 to 202.5)**	**Southwesterly (202.5 to 247.5)**	**Westerly (247.5 to 292.5)**	**Southerly (157.5 to 202.5)**	**Southwesterly (202.5 to 247.5)**	**Westerly (247.5 to 292.5)**
Hs (m)	2	0.2	0.2	0.2	0.3	0.3	0.2
	5	0.2	0.3	0.2	0.3	0.3	0.3
	10	0.3	0.3	0.2	0.3	0.4	0.3
	25	0.3	0.3	0.3	0.3	0.4	0.3
	50	0.3	0.4	0.3	0.3	0.4	0.3
	100	0.3	0.4	0.3	0.3	0.5	0.3
Tp (s)	2	1.6	1.6	1.4	1.7	1.9	1.6
	5	1.7	1.8	1.5	1.8	2.0	1.7
	10	1.7	1.8	1.6	1.8	2.1	1.7
	25	1.8	1.9	1.7	1.9	2.2	1.8
	50	1.9	2.0	1.8	1.9	2.2	1.9
	100	1.9	2.1	1.9	2.0	2.3	1.9

Based on the typical estimate wave heights (0.2 to 0.3 m) and periods (1.5 s to 2 s) presented in Table 9, these waves will interact with the bed in water depths typically less than 2 to 3 m.

As the results from wave hindcast are estimates and based on low resolution bathymetry, field data would need to be collected to validate these estimates and to identify wave propagation and decay into the shallower areas of KIH. The waters of KIH are shallow enough that depth-limited shoaling may be expected to occur, thereby reducing wave heights locally. Detailed analysis of depth-limited shoaling was beyond the scope of this study and would require detailed numerical modelling calibrated to field data to assess these effects.

3.5 Vessel Sediment Disturbance

Prop scour from vessels coming into and out of the harbour may play a role in the resuspension and transport of material from the harbour. Due to the shallow bathymetry and vegetation, most vessel traffic is limited to the navigation channel of the Cataraqui River, the dredged area north of the La Salle Causeway and Anglin Bay.

Beahler and Hill (2003) conducted a study of the impacts of transiting recreational watercraft on the resuspension of surface sediments in a shallow lake. For a bed sediment grain size equivalent to a medium sand (1 mm), near-plane boat speeds of around 8 to 12 m/s created the highest rate of resuspension but the impact of vessel velocity decreased with both increasing and decreasing boat speed. Other variables affecting resuspension include vessel size, water depth and sediment size. To minimize resuspension, Beachler and Hill (2003) recommend water depths of 2.75 m as a minimum for boat activity in waterbodies with medium-sized sand bed sediments and 4.6 m water depth in waterbodies with 50 µm sized silt.

The majority of KIH bed sediments are silt-sized and the average water depths is approximately 1.5 m. It is assumed that the majority of KIH is a low speed or no wake zone due to shallow water depths and marked areas for navigation. Re-suspension of bed sediments due to vessel activity could be a concern in shallow waters within KIH where vessels operate. Based on observations made from the aerial imagery, no vessels were observed north of the harbour limit and vessel traffic was typically limited to areas within the harbour limits (see Figure 3) and the navigation channel which are typically in water depths of 1.5 m or deeper. Therefore, vessel resuspension is expected to be limited to shallow water areas immediately adjacent to primary navigation routes. Vessel resuspension is not expected to be a concern away from navigation routes.

3.6 Aquatic Vegetation

The presence of aquatic vegetation can be indicative of areas of reduced flow within a waterbody and of stabilized sediments. Golder (2011) reported the following vegetation present in KIH: Eurasian watermilfoil, coontail, pondweeds and eelgrass. The increased presence of cattails and Eurasian watermilfoil are associated with the accumulation of sediments related to human-induced hydrological changes. According to Dalrymple and Carey (1990) portions of KIH that are deeper than 1.7 m water depth are typically devoid of vegetation. Based on the bathymetry shown in Figure 3 and the observations in the air photos, the northern two thirds of the harbour (north of the harbour limits), and east of the navigation channel is well covered with aquatic vegetation and was devoid of vessel activity. Vegetation helps to reduce currents by creating friction and also stabilize sediments with their root systems.

3.7 Bioturbation

The process of bioturbation can be a major contributor to the resuspension and/or redistribution of previously buried contaminated sediments. The global mean of typical disturbance from bioturbation occurs to a depth of 0.10 m (Boudreau, 1998). Maximum depths of disturbance due to bioturbation of 0.15 m can occur in highly depositional environments (White and Miller, 2008). Carp are a typical bottom-feeding fish present in the Great Lakes which bioturbate sediments. Carp can disturb sediments up to a maximum depth of 0.13 m (5 inches; Avista Utilities, 2015). A detailed analysis of species-specific bioturbation was beyond the scope of this study but the carp data can be used as a reference value.

3.8 Contaminant Distribution in Sediments

Several contaminants of concern including poly-aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), chromium, arsenic, and lead can be found across KIH. Concentrations are typically highest nearest to the source and decrease with distance (RMC, 2014). PAHs and PCBs are fairly widespread and are present in both surface and subsurface sediments so they are not a particularly good indicator of transport or deposition. However chromium, arsenic and lead appear to have been released over a discrete time period so may be helpful in determining current rates of sedimentation.

Chromium contamination is suspected to have been released from the tannery which operated from 1903 to 1973. Surface (top 0.20 m) concentrations of chromium were relatively uniform, ranging from 500–1,500 ppm. The highest concentration of chromium in KIH was found in a sewer core take in the storm sewer discharge channel near the Orchard Street Marsh at a depth of 0.20 to 0.25 m. Chromium concentrations were lower in the surface sediment samples taken from the same location (RMC, 2014). Sediments found in the sewer channel would be prone to resuspension and transport by currents induced by storm sewer runoff and may not be representative of transport and depositional conditions found in the harbour itself. The next highest concentration was found in a core sample from the mouth of the storm sewer discharge at depths ranging from approximately 0.40 m to 0.55 m. A trend of maximum chromium concentrations occurred in all cores from 0.20 to 0.55 m. If the presence of chromium in the cores at 0.55 m corresponded with the opening of the tannery in 1903, the resulting sedimentation rate would be 0.0048 m/year in the northwest corner of the Parks Canada waterlot.

Maximum lead concentrations were found at depths similar to chromium ranging approximately from 0.40 to 0.60 m. Lead is suspected to have originated from the smelter which operated from 1879 to 1916. If the presence of lead in the cores at 0.60 m corresponded with the opening of the smelter in 1879, the resulting sedimentation rate would be 0.0043 m/year which is similar to the sedimentation rate calculated from the chromium deposits. The Woolen Mill is the suspected main source of arsenic to KIH. It operated from 1882 to 1966. Concentrations of arsenic were high in three samples in the nearshore vicinity of Douglas Fluhrer Park at depths from 0.10 m to 0.40 m. Maximum concentrations of arsenic appear to get deeper as you move offshore with the next closest sample exceeding from 0.40 m to 0.70 m and the furthest offshore sample from 1.0 m to 1.3 m. This would suggest that offshore transport is occurring to settling areas due to currents and washing of the nearshore by the small harbour waves. Sedimentation rates here should be calculated from the deepest sediment sample, so the sample least likely to be disturbed by prop scour, bioturbation, wave action and/or currents. If the sample from 1.0 to 1.3 m, corresponded with the opening of the Woolen Mill in 1882, the resulting sedimentation rate offshore of Douglas Fluhrer Park is approximately 0.009 m/year.

4.0 SEDIMENT TRANSPORT REGIME

The sediment transport regime for KIH is complex. Figure 6 graphically summarizes littoral circulation within the harbour which contributes to sediment transport. No site specific information related to sediment resuspension under wave events was identified during the data review. Field data collection of turbidity and wave heights would be needed to further evaluate the minimum threshold of wave activity that generates sediment re-suspension.

River processes dominate along the eastern side of the harbour, typically flowing to the south along the navigation channel. Prior to construction of the causeway, limited longshore sediment transport along the north shore of Lake Ontario likely delivered sediment to the harbour as well as the sediments delivered by Cataraqui River. These processes are now partially restricted due to the La Salle Causeway limiting flow both in and out of the harbour. A reduction in the frequency of flushing within the harbour and anthropogenic land use changes are both contributing to an increase in sedimentation within the harbour.

Distribution of contaminated sediments within the harbour suggest transport to the north and east, some moving clockwise around the harbour. Review of the aerial photography shows sediment plumes moving in a clockwise moving circulation cell which backs up this hypothesis. The trajectory of suspended sediments, as shown in the aerial photographs, carried by the Cataraqui River appear to deflect off the La Salle Causeway, some being discharged into the lake, the rest travelling towards Anglin Bay. Distribution of fine-grained sediments, as shown in Figure 4, suggests that the presence of the coarser sediment load offshore of Douglas Fluhrer Park (silty sand) is the result of currents removing the finer particles and carrying them east and south into the centre of KIH. This theory is partially supported by the presence of high concentrations of contaminants from historical sources at or near the surface of sediments in this vicinity.

Resuspension due to bioturbation may occur at depths reaching a maximum of 0.15 m. Sediment re-suspension by waves is typically limited to water depths less than 2 m to 3 m. These re-suspended sediments would be entrained into the circulation cell under prevailing currents where they would typically be transported towards the Parks Canada waterlot and deposited in the highly vegetated and shallow region south of the former Belle landfill due to a local decrease in velocities (HCCL, 2011).

Dominant wind and therefore wave directions in KIH are from the west, southwest and south. Sediments most likely to be entrained in waves would be in the Parks Canada waterlot due to its water depth. In summer, the dominant southerly winds would drive re-suspended sediment up into the harbour away from the causeway. A wave shadow from the causeway would mean limited wave development immediately north of the causeway. Wave resuspension would occur at a point north of the causeway where wave growth generates near bed currents sufficient to mobilize sediment as water depths become shallower with distance northwards from the causeway. In winter, dominant westerly and southwesterly winds would drive re-suspended sediment across the harbour towards the navigation channel. Wave generation at the western and southwestern shorelines of KIH would be limited in winter because the winds would need some distance of open water to blow across in order to generate waves. The western and southwestern shorelines are where the majority of contamination occurs. The maximum wave heights would occur near the eastern and northeastern shorelines in the winter. Under ice cover conditions, these wave heights are less likely to occur. Therefore sediments along these shorelines are not very likely to be re-suspended due to wind generated waves during the winter. A detailed analysis of the duration of under-ice conditions was beyond the scope of the present study. A detailed analysis would need to include assessment of shore-fast ice, floating ice platforms, and partially frozen conditions to evaluate the effect of ice conditions on sediment re-suspension.

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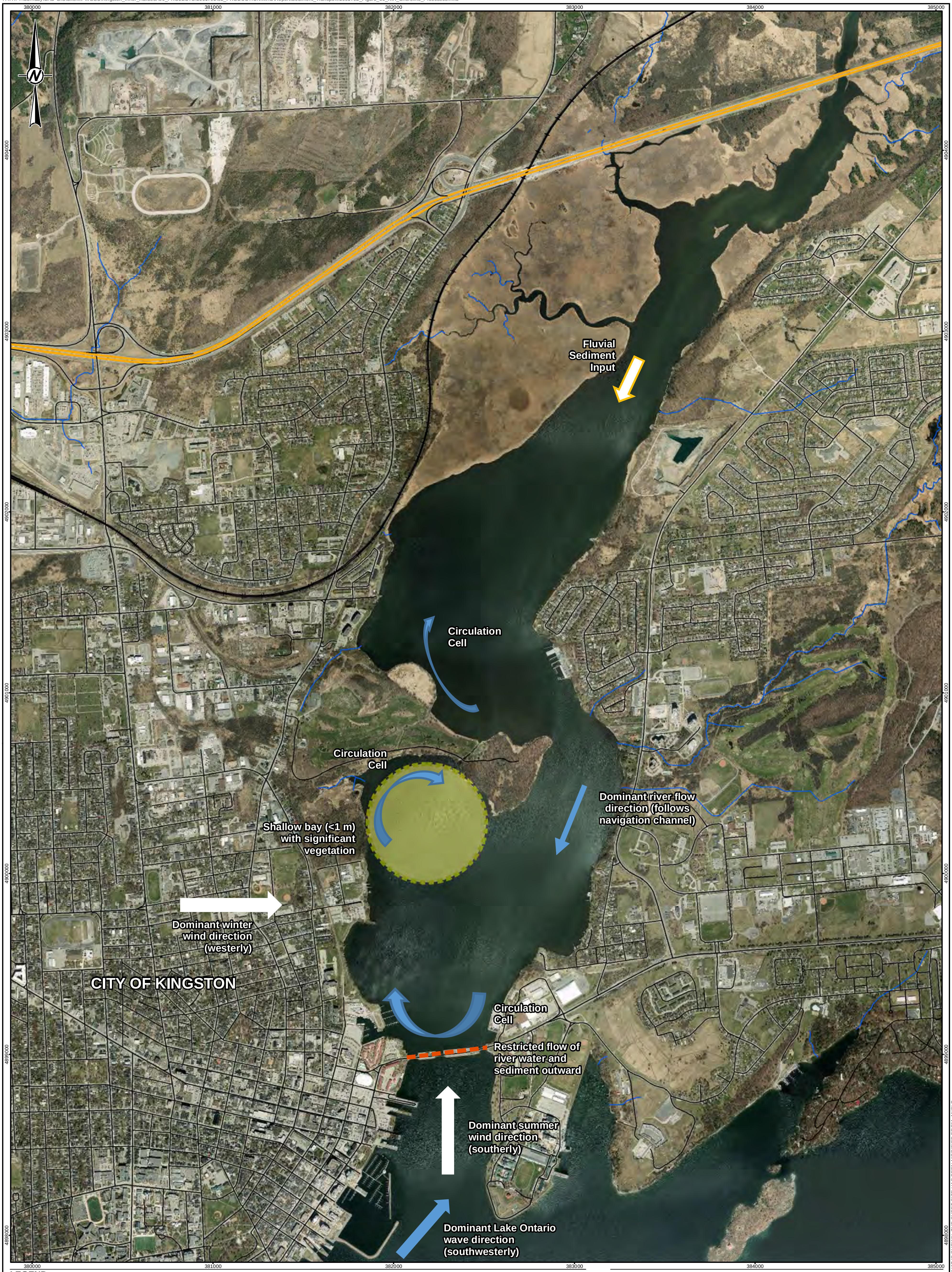

LEGEND

- SHALLOW AREA
- FLUVIAL SEDIMENT INPUT
- WATER FLOW/WAVE DIRECTION
- CIRCULATION CELL
- DOMINANT WIND DIRECTION
- BARRIER
- HIGHWAY
- ROAD
- RAILWAY
- WATERCOURSE

0 400 800

1:20,000 METERS

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3. PROJECTION: UTM ZONE 18 DATUM: NAD 83

CLIENT
PWGSC

PROJECT
KINGSTON INNER HARBOUR
KINGSTON, ONTARIO

TITLE
SHORELINE PROCESSES

CONSULTANT

Golder Associates

YYYY-MM-DD	2017-01-03
DESIGNED	SS
PREPARED	JP
REVIEWED	
APPROVED	

PROJECT NO.	PHASE	REV.	FIGURE
1661792		A	6

4.1 Sediment Delivery Yield Assessment

Measured values of sediment load were not available for the Cataraqui River, therefore several techniques were used to estimate the sediment delivery yield to KIH. Estimations of sedimentation rate were derived from contaminated sediment core data with the historical source information to determine rates of deposition over time as discussed in Section 3.8. Values were also derived from Manion *et al.* (2010), Dalrymple and Carey (1990) and Church *et al.* (1999).

Based on Church et al. (1999), calculations of approximate yield based on watershed size can be completed. The Cataraqui River watershed is predominantly within the Great Lakes Lowlands and drains an area approximately 910 km^2 (Acres, 1977). According to Church *et al.* (1999) the estimated sediment yield range for watersheds of this size within the Great Lakes Lowlands is approximately 0.1 x 10^6 Kg/year to 0.2 x 10^6 Kg/year. Applying an assumed density of 1,400 Kg/m^3 for unconsolidated estuarine sediments (Whitehouse, 2000), suggests that the watershed could deliver between approximately 76 m^3/year and 130 m^3/year of sediment to the harbour. The area of KIH is approximately 1.6 x 10^6 m^2 resulting in sedimentation rates of 0.000046 to 0.000079 m/year.

Upon reaching Kingston Harbour, most sediment carried in the river loses momentum due to the opening of the navigation channel due to dredging adjacent to the La Salle Causeway and opposing dominant currents from Lake Ontario, therefore dropping out of suspension or being transported via the circulation cell within the harbour.

Manion *et al.*, (2010) conducted a study looking at the mercury contamination in sediments within the Cataraqui River. Core dating from an undisturbed core at the mouth of the Orchard St Marsh outfall resulted in a 0.21 m core estimated to be between 35-40 years old. This results in a sedimentation rate of 0.0052 m/year which is comparable to the sedimentation rates for chromium and lead, which came from samples in the same area as the dated core in Manion *et al.*, (2010).

The sedimentation rate calculated for top gyttja layer ranged from 0.11 – 0.72 mm/year as determined by Dalrymple and Carey (1990). This sedimentation rate was determined for the top gyttja layer sampled by Dalrymple and Carey (1990). The top layer was carbon dated and is considered to have been deposited over approximately 1,500 years. This is probably the reason for this underestimating sedimentation rates. Several sources have suggested that sedimentation rates have increased within KIH since anthropogenic alteration of the watershed has taken place.

Table 10 presents the summary of results of the annual sediment volume estimate and the annual sedimentation rates. Where the sedimentation rate was calculated first, an area of 1.6 x 10^6 m^2 was used as the aerial extent of KIH to calculate the annual sediment volume estimate.

Table 10: Results of Sediment Delivery Calculations

Method/Source	Annual Sediment Volume Estimate (m^3/year)	Annual Sedimentation Rate (m/year)
Core dating (Manion *et al.*, 2010)	8,683	0.0052
Sedimentation Rate (Dalrymple and Carey, 1990)	181 to 1190	0.00011 – 0.00072
Chromium Contamination (RMC, 2014)	7,939	0.0048
Arsenic Contamination (RMC, 2014)	14,886	0.009
Lead Contamination (RMC, 2014)	7,112	0.0043
Average regional clastic sediment yield (Church *et al.,*1999)	76 - 130	0.000046 to 0.000079

Based on the results summarized in Table 10, there appears to be good agreement between the sedimentation rates calculated from the core dating, and chromium and lead contamination. These values are estimated to be locally high due to the presence of the outfall in this area. If these rates were in fact representative, a total of approximately 0.5 m of sediments would have been deposited over the past century. However, based on this assessment, there is no indication that that rate of deposition is occurring and it is considered to be high. It is possible that the sedimentation rate determined by arsenic contamination is accurate for that location, as it was determined from a deeper location than the other 3 examples and therefore may be an area of increased deposition within the harbour. This is expected based on the assessment of the reworking of local material and offshore transport seen at this location, which is offshore of Douglas Fluhrer Park. If the Manion *et al*., 2010, chromium and arsenic sedimentation rates are all considered high, and Church *et al*., 1999 is considered low, the Dalrymple and Carey (1990) sedimentation rate is inferred to be the most representative across the entire KIH. Regardless, all of the sedimentation rates are extremely small confirming KIH is a sediment-limited environment. It is unlikely that adequate sediment is available within the system to bury or dilute existing areas of surface sediment contamination.

5.0 KEY FINDINGS

The key findings of this assessment are:

- The shoreline and hydraulic processes at Kingston Inner Harbour have been modified since the early 1800's.
- The presence of the La Salle Causeway is creating a partial sediment trap for sediment being transported along the river.
- The dominant sediment source within the littoral cell that contains KIH is a combination of fine-grained sediments delivered via the Cataraqui River, resuspension of local bed sediments by waves and currents and contribution from local storm outfalls.
- The harbour is dominated by wind generated currents from the west, southwest and south as well as river currents moving to the south. Strong winds can generate localized currents which result in sediments being transported both to the north and south, as found with the dispersal of contaminants within the harbour. However the dominant current results from southerly and southwesterly winds generating a clockwise circulation cell, which would dominate suspended sediment transport. This agrees with the patterns of contaminated sediment dispersal observed within the harbour.
- Surface sediments with the harbour are susceptible to re-suspension through bioturbation to a maximum depth of 0.15 m. The potential for sediment re-suspension by bioturbation would occur predominantly in the summer and early fall.
- Surface sediments within the harbour are also susceptible to re-suspension by southerly-generated wind waves in water depths of less than 2 m to 3 m. The frequency of wind-generated wave events that may result in sediment re-suspension is approximately 13 times per year in the summer and 3 times per year during the winter. At least 2 of these summer events may be expected to coincide with high water levels on Lake Ontario in a given year. The winter events are likely to be minimized due to the presence of ice. The exact correspondence between wave events and re-suspension would need to be confirmed with field data.
- The estimated rate of sedimentation ranges from approximately 0.00011 – 0.00072 m/year within the harbour indicating a sediment-limited environment. These low rates of sedimentation are unlikely to be adequate for burial or dilution of contaminated sediments.

6.0 RECOMMENDATIONS

- To validate the interpretation of sediment re-suspension within KIH, future studies could be undertaken including Field data collection of bathymetric survey to confirm water depths and the presence of shallow areas within KIH.
- Field data collection of wave, current and turbidity data to confirm the threshold event for re-suspension within KIH.
- Field data collection to confirm sedimentation rates within KIH.
- Collection of detailed bathymetry to validate water depths and harbor bed morphology as it pertains to the re-suspension of potentially contaminated sediments.
- Detailed combined probability analysis of water levels and storm events affecting KIH.
- Detailed numerical hydrodynamic modelling of KIH to develop estimates of sediment dispersal distances and deposition rates.
- The potential effects of climate change (e.g., changes in water levels in the harbor and Lake Ontario, changes in duration and thickness of ice cover, changes in runoff on Cataraqui River, changes in intensity, direction and duration of storm winds) should be evaluated in detail to determine their significance relative to the review carried out under this study.

7.0 CLOSURE

We trust that this report meets your present needs. Should you have comments or questions, please contact the undersigned at 250-419-4950 or by email at mtidd@golder.com.

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