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Investigations into Ship Induced Hydrodynamics and Scour in Confined Shipping Channels

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ABSTRACT

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Deep draft ships transiting through confined channels can significantly alter surrounding hydrodynamic conditions. Drawdown is a long-period motion, in the order of 30 to 150s, caused by the ship displacing water from the channel. The long-period character of the drawdown wave causes relatively large near-bed currents which are capable of inducing significant rates of sediment transport.

The Burlington Shipping Channel is a confined channel, 88m wide and 800m long, which connects Hamilton Harbour to Lake Ontario. Significant scour levels have been observed near the entrances to the channel and along the nearby sheet-pile channel piers. A series of investigations have been undertaken to determine the extent of scour and the magnitude of the forces causing scour. Investigations discussed in this paper include bathymetric and hydrodynamic data collection and numerical modelling using the ship wake and drawdown model *SGH* (Ship-Generated Hydrodynamics).

Hydrodynamic data was collected for seven ship movements to investigate hydrodynamic forces contributing to the scour. The applicability of simulating drawdown using a two-dimensional depth-averaged ship drawdown model such as *SGH* has been investigated. The model achieved a good level of calibration, particularly in the mid-sections of the channel and near the western entrance. The investigations have confirmed the validity of using sophisticated ship models such as *SGH* to investigate complex hydrodynamic and scour processes associated with deep draft ships transiting through confined channels. These models are capable of realistically simulating the spatial variation in sediment transport potential in confined channels and could be used to assist in the design of appropriate channel protection.

ADDITIONAL INDEX WORDS: *Numerical modelling*

INTRODUCTION

Deep draft ships transiting through confined, shallow water bodies can significantly alter the ambient hydrodynamic conditions. These impacts are observed through two main processes; wake and drawdown. Wake is the term given to the stern and bow waves generated by a moving ship. The waves propagate away from the ship and generally have periods of less than 10s. The character of wake waves is influenced by the vessel profile and the ship speed.

Drawdown is the observed decrease in water level surrounding the ship as it moves through the channel and is primarily caused by the ship's displacement of the channel cross-section (HERBICH and SCHILLER, 1984). A feature of drawdown is the long period nature of the waveform. Although the amplitude of the drawdown wave may not be large, the period of this wave can be between 30 to 100 seconds. The orbital motion associated with the drawdown wave is relatively uniform through the water column and current speeds near the sea bed can be large. The surge wave generated by drawdown in confined channels is a function of ship speed, depth under the ship, drawdown height and blockage ratio (MAYNORD, 2004). The blockage ratio is the wetted cross-section of the ship relative to the channel.

Wake and drawdown can interact with the surrounding shoreline and bed material and shoreline erosion and scour due to ship movements has been observed at numerous sites.

Hamilton Harbour is a large port facility in the Great Lakes system and a major industrial centre of Ontario, Canada. The port is situated in a naturally enclosed basin separated from Lake Ontario by a narrow channel, the Burlington Shipping Channel. Recent studies have showed that sections of the Burlington Shipping Channel bed have been significantly scoured. In response, a series of data collection, engineering and numerical modelling investigations have been undertaken to investigate; the causes of scour, magnitude and spatial variation in the physical forcing causing scour and potential stabilisation techniques. The study has focussed on ship induced drawdown which causes long period wave motion because wake is of only secondary importance at the Burlington Channel due to the sheet pile edge treatment of the channel.

BURLINGTON SHIPPING CHANNEL

Hamilton Harbour is a 2,150 ha protected body of water located on the western shoreline of Lake Ontario. It is located approximately 60 km southwest of Toronto and is a major industrial centre of Canada. Hamilton Harbour is the busiest Canadian Port on the Great Lakes. It handles over 700 ship passages and 12 million tons of cargo each year.

Hamilton Harbour evolved with Lake Ontario during the glacial retreat approximately 9,500 to 12,500 years ago (GILBERT, 1994). Prior to 1823, a sand spit separated Hamilton Harbour and Lake Ontario with a shallow channel to the north of the present channel (O'CONNNOR, 2002). The Burlington Shipping Channel was constructed in 1823 and is 88m wide with a design depth of approximately 9.5m to chart datum (CD). The channel is constructed with vertical sheet pile. The bed material within the channel and surrounding areas is generally a medium grain sand.

A variety of different bulk carrier ships frequent Hamilton Harbour. The size of ships in the Great Lakes is limited by the capacity of the structures which facilitate vessel movement between the lakes and the Atlantic Ocean. In general, the ship specifications are relatively uniform due to the size constraints of the St Lawrence Seaway. The most common ship type is the SeawayMax class which are the maximum sized vessel allowed in the St Lawrence Seaway. The maximum dimension of ships in the St Lawrence Seaway are:-

- Length: 225.5m,
- Beam: 23.7m, and
- Draft: 8.1m.

Certain sections of the seaway can accommodate larger ships however; these ships are unable to pass into the Atlantic Ocean. Depending on water levels, ships can move through some inner sections of the St Lawrence Seaway (including Hamilton Harbour) with a draft up to 9.5m.

SHIP DRAWDOWN IN CONFINED CHANNELS

Drawdown caused by deep draft ships in confined channels has been widely observed and studied. SCHIJF (1949) developed the concept of the limiting speed in confined channels. This concept results in a self-propelled ship not being able to exceed a speed where the flow velocity (ship speed plus return velocity under the ship) is equal to the celerity of a gravity wave.

A number of analytical methods have been developed from the initial work of SCHIJF (1949) to estimate peak long period currents due to ship movements including PIANC (1987) and MAYNORD (1996). These methods have been shown to provide reasonable estimates of velocities and drawdown height away from the ship when applied to channels with simple cross-sections, for example rectangles or trapeziums. In these cases, the decay of the surge wave can be neglected. The analytical methods are unable to evaluate ship effects near channel transitions (MAYNORD 2004).

In recent years, considerable effects have been undertaken to develop numerical tools to investigate ship effects on spatial scale. STOCKSTILL and BERGER (1999) documented an extension of the finite element model HIVEL2D to investigate ship effects. The 2D shallow water equations were modified to include the ship hull as a pressure source. The depth-averaged approximation can be made because the wavelength of the surge wave is in the same order of magnitude as the ship length, which is much greater than the depth in most navigation channels. The HIVEL2D drawdown model has been shown to produce good estimates of currents speeds and surge wave heights in a number of studies including STOCKSTILL and BERGER (1999), STOCKSTILL and BERGER (2001) and MAYNORD (2004).

STUDY APPROACH

A number of investigations were undertaken in 2005 and 2006 to study ship hydrodynamics and associated scour along the Burlington Shipping Channel. Those relevant to this study are briefly described below.

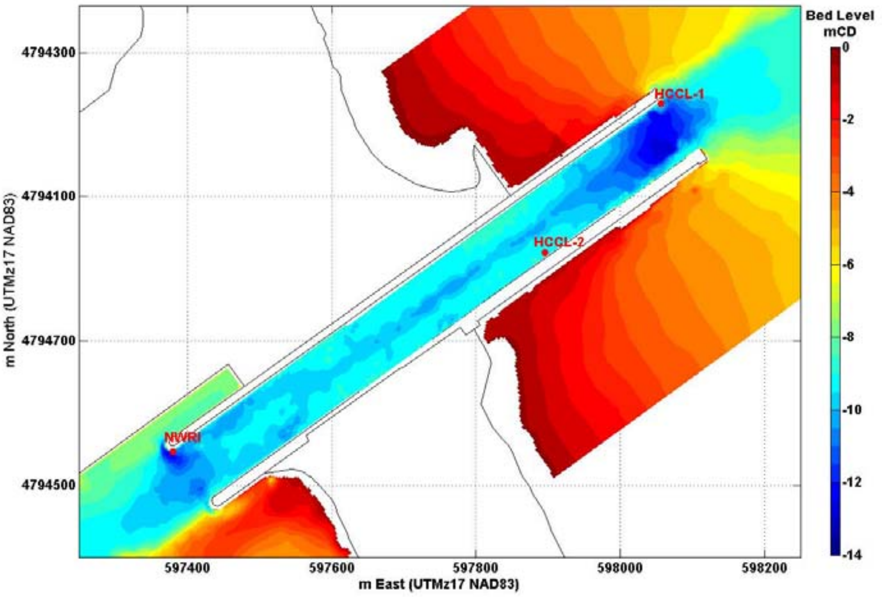

Figure 1. Burlington Shipping Channel Bathymetry, May 2005 (Scour areas are shown in dark blue).

Site Data Collection

Bathymetric and hydrodynamic data was collected to examine the extent of scour and the physical forcing contributing to it. Figure 1 is produced from bathymetric survey conducted in May, 2005. Areas in dark blue indicate depths up to 14mCD, which is significantly greater than the design depth of the channel.

The areas of scour are most pronounced across the eastern (Lake Ontario) entrance to the channel. There is also a smaller extent of scour observed surrounding the western (Hamilton Harbour) entrance and along the channel centreline.

In response to the scour observed in Figure 1, a field data collection exercise was undertaken in August to September, 2005 to collect hydrodynamic data from a series of three locations in the channel during the transit of deep draft ships. Acoustic Doppler Current Profiler (ADCP) instruments were deployed at a total of three locations for seven ship movements. The locations are indicated on Figure 1 (HCCL-1, HCCL-2 and NWRI). The ADCP instruments were configured to record currents in 0.3m bins through the water column every 0.5s. Ensembles were averaged every 5s. The dimensions (length, beam and draft) and approximate transit velocity were recorded for each ship movement.

Numerical Model Investigations – *SGH*

Following the field data and desktop engineering studies, an applied research study was undertaken to investigate the ship induced hydrodynamics along the whole channel. The field data provided snapshot information on ship induced forces at particular locations. A suitability calibrated numerical model is able to investigate these forces along the whole channel.

SGH (Ship-Generated Hydrodynamics) is a sophisticated ship wake and drawdown model which is capable of efficiently investigating ship induced hydrodynamics over a large model domain with complex bathymetry. It is a 2D depth-averaged, finite difference model which can simultaneously simulate wake and drawdown processes due to deep draft ships. The motivation behind its development was the need to investigate the combined impacts of drawdown and wake along the St Lawrence River. *SGH* is a proprietary software product of Pacific International Engineering and was developed as part of the sediment transport software SedSim (DAVIES and MACDONALD, 1999). The investigations at Burlington Channel have applied the drawdown module of *SGH* only.

SGH uses the same technique as the US Army Corp of Engineers' model HIVEL2D to model a vessel as a moving pressure field (STOCKSTILL and BERGER, 1999). A spatial representation of the vessel hull is specified. *SGH* consists of two model domains. The first is a temporally varying domain which propagates along with the ship. This domain features high resolution to resolve pressure gradients surrounding the vessel. The results from this grid are superimposed on the overall computational domain and all parameters are solved at each location on the grid. Open or closed boundary can be specified and ambient hydrodynamic conditions, for example currents, can be specified along model boundaries. Energy absorption can be specified within the model to minimise reflections along boundaries. The model is sensitive to the shape of the vessel hull.

A full description of the development of *SGH* including model source terms is contained in MACDONALD and DAVIES (2003).

RESULTS

Field Data

Hydrodynamic data for a total of seven vessel movements were collected between 30th August, 2005 and 2nd September, 2005. Table 1 summarises the ship movements and the locations of the instruments. (Figure 1 indicates the location of the instrument sites). The largest currents were recorded at site HCCL-1 (eastern entrance). Near-bed current speeds were up to 1.6m/s. At sites HCCL-2 (mid-channel) and NWRI (western entrance) current speeds were up to 1.1m/s and 0.8m/s respectively. The velocity profile during the peak of the drawdown was relatively uniform through the water column. Figure 2 is a plot of the velocity in five vertical bins (Bin 1 near-bed, Bin 48 near free-surface) at Location HCCL-1 during the transit of CSL Niagara. A full summary of the data collection exercise is contained in HCCL (2005).

The ADCP current data collected at Burlington Channel was found to be consistent with HERBICH and SCHILLER *(*1984). In all cases, the direction of the peak near-bed current was in the opposite direction to the motion of the ship. The magnitude of observed currents is dependant on the direction of ship motion. At Location NWRI, largest currents were observed during the west bound movement of ships and at Location HCCL-1 largest currents were observed during east bound ship movements. At Location HCCL-2, a significant difference in current magnitudes between east and west bound ships was not observed.

During the data collection exercise, the remnant weather system from Hurricane Katrina moved through southern Ontario. This

Table 1: Summary of Vessel Movements during ADCP Data Collection

						ADCP Instrument Locations		
Name	**Direction**	**Beam (m)**	**Length (m)**	**Draft (m)**	**Ship Velocity (m/s)**	**HCCL-1**	**HCCL-2**	**NWRI**
CSL Niagara	West bound	23.76	225.5	9.5	3	■		
Catherine Desgagnes	East bound	16.92	125.05	7.58	1.7	■		■
CSL Niagara	East bound	23.76	225.5	8	3	■		■
Canadian Enterprise	West bound	23.12	225.5	8	2.7			■
Canadian Enterprise	East bound	23.12	225.5	7.3	3		■	■
Canadian Transport	West bound	23.12	225.5	7.9	3.5		■	■
CSL Tadoussac	East bound	23.76	225.5	8.6	3.4		■	■

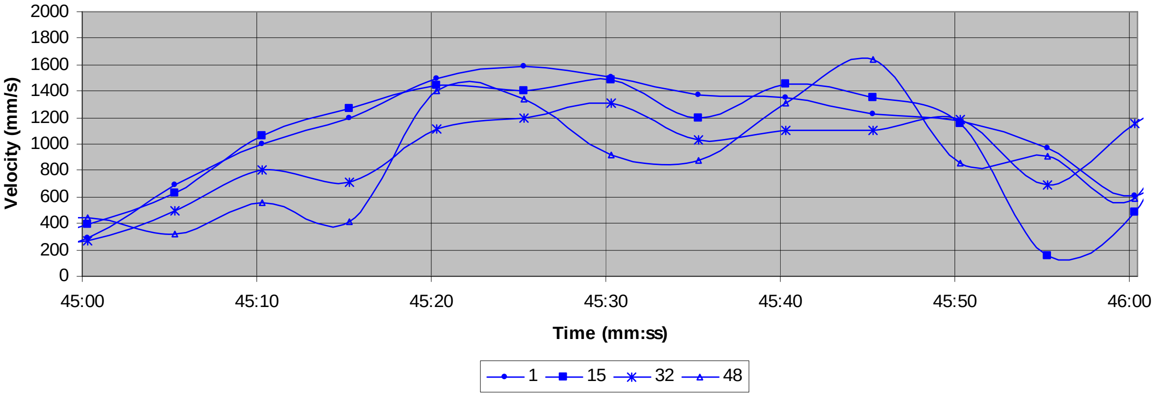

Figure 2. Vertical velocity profile at Location HCCL-1, east bound movement of CSL Niagara (Bin 1 – lower water column, Bin 48 – upper water column.

event produced large waves (approximately 3m) at the entrance to the Burlington Channel and a storm surge of approximately 0.15m. The largest observed currents at the eastern entrance during the storm were significantly lower than during the recorded ship movements.

SGH Model

Model Validity

The *SGH* drawdown model utilises two-dimensional shallow water equations to calculate the wave profile. The assumption has been shown to be valid by STOCKSTILL and BERGER (1999) in the investigation of drawdown in the Mississippi River. The requirement for this assumption to be valid is outlined in Equation 1 where L is the wavelength of the surge wave and d is the channel depth.

$$L >> d \qquad (1)$$

In the study area, the wavelength is much greater than the water depth and therefore the 2D approximation is appropriate. In certain situations, the neglect of vertical accelerations can lead to over prediction of the wave celerity. The ratio of this over-prediction is calculated by Equation 2 which is from WHITLAM (1974).

$$\frac{C_{computed}}{C_{actual}} = \sqrt{1+\frac{4\pi^2 d^2}{3L^2}} \qquad (2)$$

Based on the observed wavelength of the drawdown at Burlington Channel (Table 2), the amount of over-prediction of wave celerity is less than 0.3%. The two-dimensional nature of the *SGH* drawdown model means the solution is not accurate in the immediate vicinity of the vessel. This outcome does not significantly impact of the application of the *SGH* model at Burlington Channel because of primary interest in this study is the characteristic of the drawdown wave along the channel piers, which are situated more than one ship beam from sailing line of the vessels.

Model Setup

A high resolution model of the Burlington Channel has been developed. The model bathymetry has been derived from detailed digital bathymetry model of Hamilton Harbour. The grid domain has the following features:

- Origin: 597000mE, 4793850mN (UTMz17 NAD83),
- Grid dimensions: X=700, Y=200,
- Grid spacing: 3m (x and y), and
- Rotation: +36 degree (from X-axis).

The model extends approximately 650m east and west of the Burlington Channel to allow the model to develop dynamic equilibrium during each simulation before the ship enters the channel. Open boundary conditions along the Hamilton Harbour and Lake Ontario boundaries of the model were specified based on recorded water level measurements during each vessel movement.

Parameters for each ship movement have been based on observations recorded during the data collection exercise. Vessel hull characteristics have been based on the hull profile of the *Algosoo*. The *Algosoo* is a Great Lakes bulk carrier which has been investigated using the *SGH* model in previous studies (MACDONALD *et al*, 2003). This ship is similar in hull characteristics to the six largest ship movements observed during the data collection exercise. The hull profile of the *Algosoo* was scaled to produce the correct length, beam and draft characteristics of each ship in this study. Analysis of the data collected during each ship movement indicated that the ambient current in the model domain was minimal. Therefore fixed boundary conditions with zero velocity were specified along all open boundaries.

An important consideration in the development of the Burlington Channel model has been the treatment of boundary conditions along the sheet pile piers of the channel. The nature of this type of vertical boundary is that the influence of the boundary layer is an order magnitude smaller than the computational mesh size adopted in this study. A conventional setup of the *SGH* would lead to the adoption of a 'no-slip' boundary condition along the piers. This type of boundary specification creates a physically unrealistic solution from the *SGH* model at this site. The impact of the zero velocity condition along the 'no-slip' boundary propagates a significant distance into the modelled channel. A 'slip' boundary condition was implemented in the Burlington Channel model by allowing the velocity in the direction of the channel piers to be non-zero along the pier.

Model Calibration

Simulations were undertaken for each of the seven ship movements. Figure 3 is a time series plot of model (solid red) and measured (dashed blue) current speed, current direction and water level during the movement of Canadian Transport (west bound) at Location HCCL-2 (mid-channel).

Tables 2 and 3 present quantitative summaries of the current magnitude and water level calibration respectively for all available field data. Location HCCL-2, in the mid-section of the Channel, achieves the best calibration. Location NWRI also achieves reasonable calibration with modelled current magnitudes and water levels within approximately 0.1m/s and 0.1m respectively of measured data. Scour is evident in the vicinity surrounding this location and the model is able to describe the magnitude of the scour forces at this site.

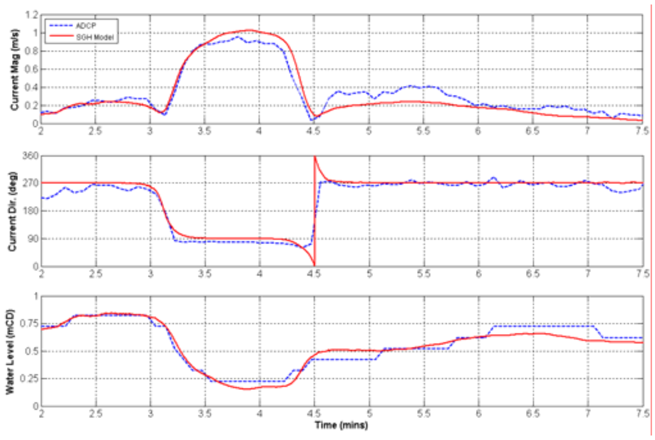

Figure 3. Model Hydrodynamic Calibration at HCCL-2 – Canadian Transport (west bound)

Location HCCL-1 provides the poorest calibration with current speeds on average 0.2m/s to 0.3m/s different to the measured data. At HCCL-1 current speeds were generally under predicted. The poor water level calibration at HCCL-1 is in part a result of the measured data having local wave influences. The data for Location HCCL-1 related to ships which have a different profile to the reference hull (*Algosoo)*.

DISCUSSION

The investigations into ship-induced hydrodynamics at Burlington Channel have confirmed the complex nature of this phenomena. At the Burlington Channel, observed currents at the entrances and mid-sections of the channel indicated that there was significant potential for sediment transport during ship movements. The hydrodynamic data indicates that at the entrances, current magnitude is a function of the ratio between the channel cross-section and the cross-section of the adjoining water body. At the eastern entrance which joins the relatively open water of Lake Ontario, current magnitudes were greater than at the western entrance which adjoins Hamilton Harbour. The surge wave currents are also more complex at the eastern entrance. Considering the streamlines of the return flow at both entrances; at the western entrance they are already partially aligned with channel before the entrance because of the surrounding shoreline. At the eastern entrance the streamlines undergo significant direction changes causing flow acceleration in the vicinity of the entrance. It is likely that three-dimensional processes are more significant at the eastern entrance compared to the western entrance. *SGH* is a two-dimensional model and therefore cannot fully represent this process.

The Burlington Channel *SGH* model overall produced a good representation of the observed peak current speed conditions at three locations along the channel piers. The accuracy of the *SGH* model of the Burlington Channel is similar in magnitude to that reported by MAYNORD (2004) with a HIVEL2D of a confined

Table 3: Correlation Coefficient (R^2) and Root Mean Square Error (m/s) for the modelled and measured current magnitudes.

		HCCL-1		HCCL-2		NWRI	
Name	**Direction**	**R^2**	**RMS Error (m/s)**	**R^2**	**RMS Error (m/s)**	**R^2**	**RMS Error (m/s)**
CSL Niagara	West bound	0.83	0.24				
Catherine Desgagnes	East bound	0.67	0.23			0.26	0.10
CSL Niagara	East bound	0.77	0.33			0.62	0.05
Canadian Enterprise	West bound					0.83	0.11
Canadian Enterprise	East bound			0.84	0.20	0.71	0.10
Canadian Transport	West bound			0.96	0.09	0.67	0.11
CSL Tadoussac	East bound			0.97	0.31	0.63	0.12

Table 4: Correlation Coefficient (R^2) and Root Mean Square Error (m/s) for the modelled and measured water levels.

		HCCL-1		HCCL-2		NWRI	
Name	**Direction**	**R^2**	**RMS Error (m)**	**R^2**	**RMS Error (m)**	**R^2**	**RMS Error (m)**
CSL Niagara	West bound	0.23	0.17				
Catherine Desgagnes	East bound	0.46	0.15			0.87	0.07
CSL Niagara	East bound	0.62	0.11			0.92	0.03
Canadian Enterprise	West bound					0.91	0.08
Canadian Enterprise	East bound			0.81	0.13	0.84	0.05
Canadian Transport	West bound			0.94	0.06	0.95	0.10
CSL Tadoussac	East bound			0.79	0.15	0.90	0.07

channel. Calibration at Locations NWRI and HCCL-2 is generally better than at HCCL-1. Overall the two-dimensional assumption of the *SGH* model has been shown to be valid; which is demonstrated by the good level of hydrodynamic calibration in the mid-sections of the channel and near the western entrance where scour has been observed.

The calibration process confirmed that the *SGH* model is sensitive to specification of the vessel hull profile. In these investigations, a common hull profile was adopted for all seven calibration simulations, and the hull was simply scaled to represent the correct draft, beam and length characteristics. The adopted hull profile was based on the Great Lakes bulk carrier the *Algosoo*. The calibration between the model and observed data was generally the best during Ship Movements 4 to 6 which are associated with two vessels (*Canadian Transport* and *Canadian Enterprise*) most similar in characteristics to the *Algosoo*. The *Catherine Desgagnes* hull profile differed significantly from the adopted profile which is reflected in the poorer calibration of the model during this ship movement.

The observed scour patterns at the entrances to the Burlington Channel are consistent with observations near channel constrictions. Extensive research into scour near open channel constrictions including STRAUB (1934), GILL (1981) and MOLINAS *et al* (1988) have shown that scour is concentrated at the upstream end. This is consistent with the long-term scour pattern in the Burlington Channel being a result of the largest observed currents at each entrance. That is, when flow is directed into the channel. In the mid-sections of the channel there is an absence of significant scour, with the exception of the channel centreline caused by propeller induced turbulence. The field data and model results indicate that currents in the mid-sections of the channel are approximately equal in magnitude but act in opposite directions depending on ship direction. Within the mid-sections of the channel, scour is most evident along the channel centreline which is caused by propeller induced currents. The data collection and modelling investigations undertaken in this study suggest that ship generated surge waves do not cause significant scour in the middle sections of the Burlington Channel because ships transiting in opposite directions cause forces of similar magnitude but which act in opposite directions.

CONCLUSIONS

The investigations into ship hydrodynamics and scour at Burlington Channel have highlighted the significant sediment transport potential which can be induced by ships transiting through confined channels. Hydrodynamic data indicated that at channel entrances, current processes can be complex and magnitudes are significantly higher than in the mid-sections of the channel due to flow acceleration.

The *SGH* model achieved a good level of calibration, particularly in the mid-sections of the channel and near the western entrance. This study has confirmed the validity of depth-averaged drawdown models such as *SGH* to investigate ship induced hydrodynamics and scour potential. Hydraulic transitions, such as strongly confined channel entrances like the eastern entrance of the Burlington Channel are best investigated through field observations due to the complex hydrodynamic processes surrounding these areas. An applied application of models such as *SGH* is to assist in the design of appropriate channel protection along confined channels.

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