Fate and Transport Modelling of Uranium in Port Hope Harbour

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Abstract

Fate and transport modelling of contaminants in Port Hope Harbour and near-shore Lake Ontario was undertaken in support of an ecological and human health risk assessment. Uranium concentrations in the Harbour and near-shore Lake Ontario due to groundwater and storm water loadings were estimated with a state-of-the-art 3D hydrodynamic and contaminant transport model (ECOMSED). The hydrodynamic model was simplified to obtain a first estimate of the flow pattern in the Harbour. The model was verified with field data using a tracer (fluoride). The modelling results generally showed good agreement with the tracer field data.

1. Introduction

Fate and transport of contaminants seeping into the Harbour and near-shore Lake Ontario through groundwater and storm water were undertaken in support of a Site Wide Risk Assessment (SWRA) of the Port Hope Conversion Facility (PHCF) (see [1]). The Risk Assessment in PHCF is presented in companion papers (see [2] and [3]). A 3D hydrodynamic and contaminant transport model was used to estimate the dilution ratios between groundwater and storm water loadings to concentrations in various locations in the Harbour and near-field Lake Ontario and derive contaminant concentrations at receptor locations for the SWRA.

2. Hydrodynamic Modelling

ECOMSED is a state-of-the-art, three-dimensional, time-dependent, hydrodynamic, sediment transport and contaminant transport model [4]. The hydrodynamic model has successful applications to oceanic, coastal, river and estuarine waters. The orthogonal-curvilinear grid was created with the mesh generator CCHE2D v3.2 [5]. The computational domain consists of 11009 cells with 8 sigma layers in the vertical direction. The 8 sigma layers are spaced from the surface to the bottom as follows: 0.05, 0.1, 0.3, 0.5, 0.7, 0.9, 0.95 and 1.0. The spatial resolution of the grid in the turning basin and Harbour channel is 506 and 216 cells, respectively. The typical grid size (dimensions) of the cell in the turning basin is 4 m x 16 m. Figure 1 shows the computational domain.

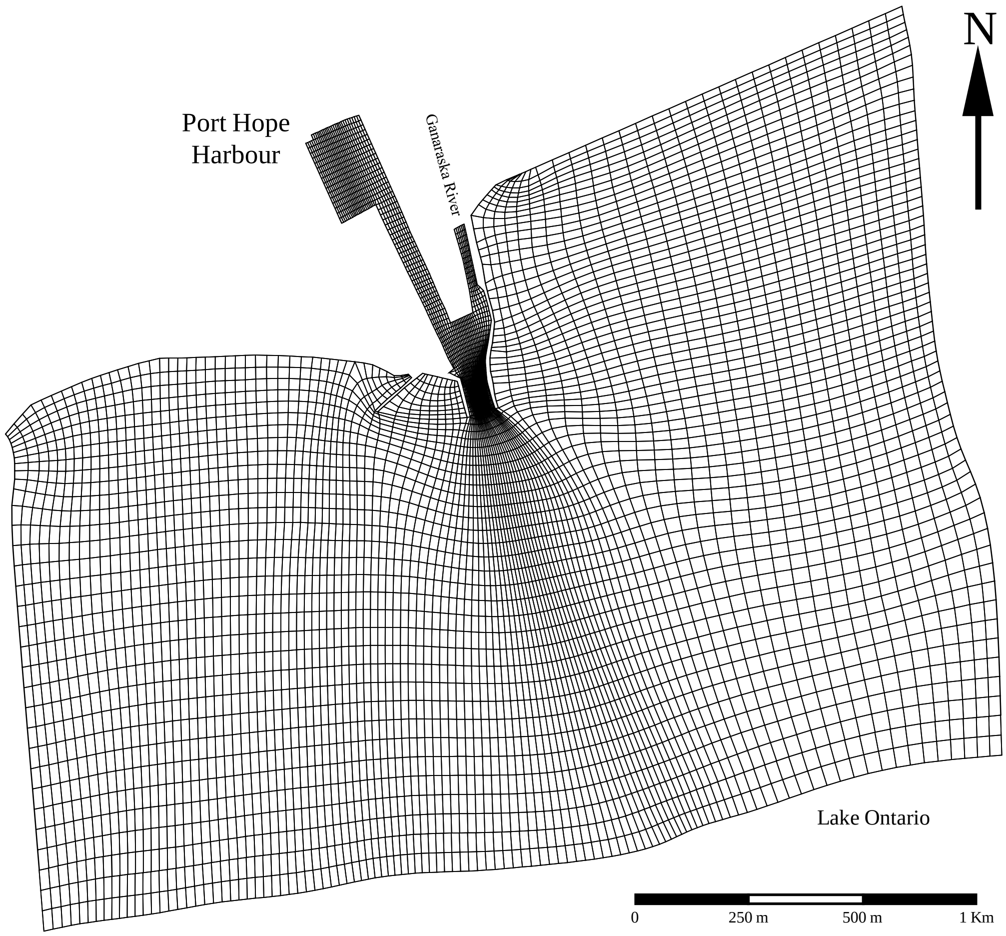


Figure 1   Computational Domain

Several simplifying approximations were made to develop a first estimate to the hydrodynamic characteristics of the flow in the Harbour, river mouth and near-shore Lake Ontario. These included: a) an eight (8) sigma layers model was selected based on its reasonable vertical resolution and optimum computational time, b) the buoyancy effect in the Harbour due to temperature differences between the flow in the Harbour and outflows (cooling water) was neglected, c) salinity effects were neglected, d) heat exchange between water and air was neglected, and e) the computational mesh (see Figure 1) was tilted to account for the two typical current directions (west-south-west and east-north-east currents) near-shore Lake Ontario. A mean annual simulation was adopted as an approximation of the dynamic process as follows: a) long-term mean annual flow of Ganaraska River, b) mean annual flow of cooling water outflows and supply, c) long-term mean annual level at Lake Ontario, d) mean annual wind speed in the Harbour and near-shore Lake Ontario, and e) mean annual currents near-shore Lake Ontario.

3. Contaminant Transport Modelling

The 3D contaminant transport model simulates the development of an incremental contaminant plume in surface water due to groundwater and storm water loadings from the PHCF into the Harbour. The contaminants in the cooling water circulation were also included in the model. The model has been implemented for the main Contaminants of Potential Concern COPCs (uranium U, fluoride F, ammonia, zinc Zn and arsenic As) as part of the SWRA [1]. In this paper, the results of uranium are presented. The uranium transport simulation was initiated after 7 days of flow simulation to ensure steady-state flow conditions. Steady-state uranium concentrations in the Harbour are achieved at 35 days of simulation.

Several approximations were made to develop a first estimate to the contaminant concentrations in the Harbour, river mouth and near-shore Lake Ontario. These included: a) the contaminants U and F were assumed as nonreactive with a first-order-decay rate equal to zero, b) the focus of the contaminant transport simulation was incremental concentrations due to groundwater and storm water loadings from Cameco PHCF, c) background concentrations for U and F were assumed as zero, d) the groundwater contaminant plume was assumed to freely seep through both the timber crib and the metal sheet pile towards the Harbour; the metal sheet was assumed to be corroded allowing the contaminants to pass through it, e) loadings from the south Centre Pier and north side of the Harbour were not included in the model and f) loadings of U and F from the Ganaraska River were assumed to be negligible (except for those originating from Cameco loadings; cooling water circulation was considered in some simulations). A mean annual simulation was adopted as an approximation of the dynamic process as follows: a) constant groundwater loading to the Harbour based on groundwater plume concentrations near the Harbour walls, b) constant storm water loading to the Harbour and c) mean annual cooling water loading of the outflows and supply.

3.1 Verification of the Model using a tracer (F)

The comparison of model results to field data for fluoride (F) is useful for verifying the model results. Fluoride is a tracer associated with PHCF operations and does not interact significantly with sediments.

The measurements of uranium and fluoride at several water sampling locations in the Harbour were provided by Cameco (see [6] and [7]). The water sampling locations near the Harbour walls are shown in Figure 2. Additional water sampling locations far from the walls in the turning basin, Harbour channel, off the Centre Pier and near-shore Lake Ontario are shown in Figures 3 and 4.

Three criteria were used in the estimation of the agreement between model and measurements based on three ratios: 1.15, 1.3 and 1.5. The agreement was set equal to Y when the ratio (model to measurement or measurement to model) was below 1.15, 1.3 or 1.5. The modelled concentrations used in the estimation of the agreement correspond to the model with groundwater (GW), storm water (STW) and cooling water (CW) loadings which produces high concentrations in the Harbour.

In general, the modelled fluoride concentrations show good agreement with the measurements near and far from the Harbour walls. The results of the verification are explained below.

1) Turning Basin: Tables 1 and 2 summarize the comparison of model concentrations to measurements near and far from the Harbour walls. Near the Harbour walls, there is very good agreement (ratio below 1.15) with measurements. Far from the Harbour walls, there is reasonable agreement (ratio below 1.3) with measurements (based on one sampling campaign).

2) Harbour Channel and off the Centre Pier: Tables 3 and 4 summarize the comparison of model concentrations to measurements near and far from the Harbour walls. Near the Harbour walls, there is very good agreement (ratio below 1.15) with measurements. Far from the Harbour walls, there is reasonable agreement (ratio below 1.3) with measurements (based on one sampling campaign).

3) West Beach near-shore Lake Ontario: the model concentrations are a factor of 60 (WSWc model) to 230 (ENEc model) lower than the measurements. However, the measured concentrations are also very low (120 ug/L).

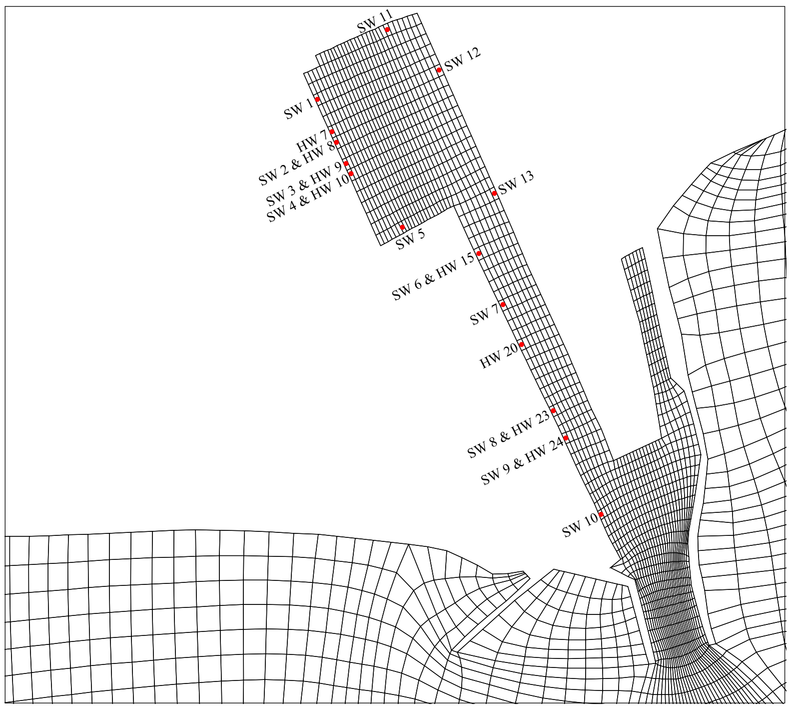


Figure 2   Location of Measurements near the Harbour Walls (HW and SW)

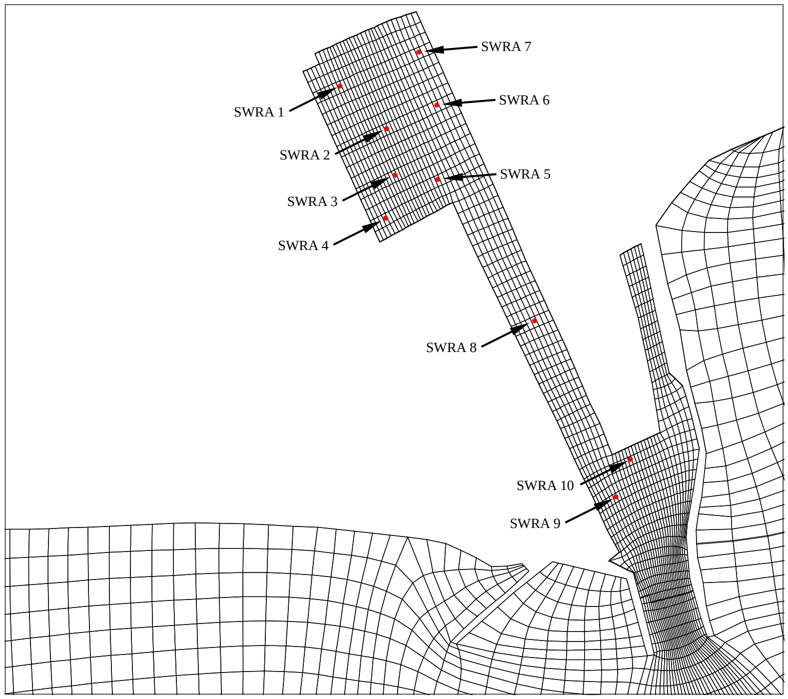


Figure 3 Location of Measurements far from the Harbour Walls (SWRA)

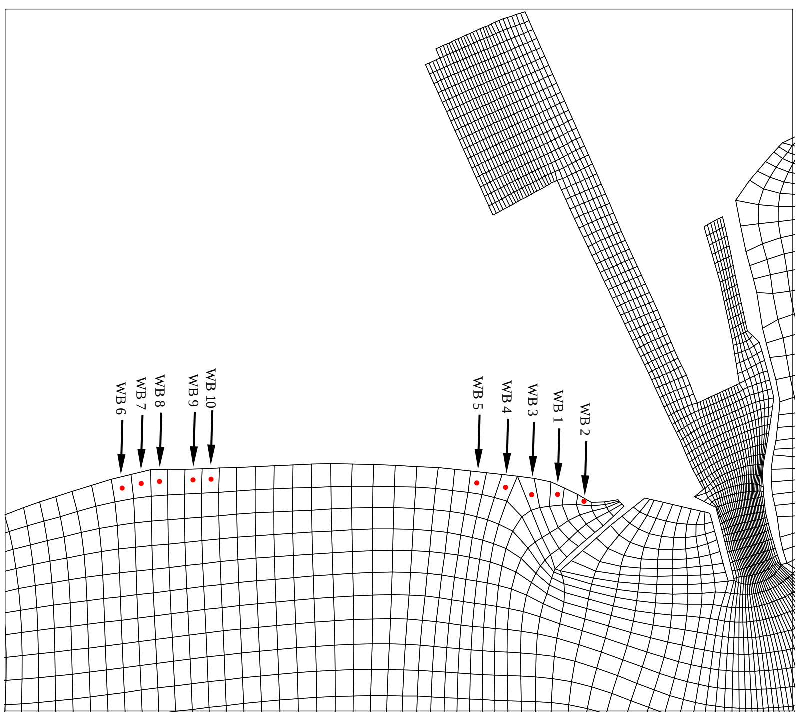


Figure 4 Location of Measurements in the West Beach (WB)

Table 1 Verification of the Model using a Tracer (Fluoride).
Turning Basin - Near the Harbour Wall

Location	WSWc & NNWw Near the Surface	ENEc & ENEw Near the Surface	WSWc & NNWw Near the Bottom	ENEc & ENEw Near the Bottom
SW11	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW1	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW12	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
HW7	(NNY)[12]	(NNY)[12]	N/A	N/A
SW2	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW3	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
HW9-1	N/A	N/A	N/A	N/A
HW9-2	N/A	N/A	N/A	N/A
HW9-3	N/A	N/A	N/A	N/A
HW9-4	N/A	N/A	N/A	N/A
SW4	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW5	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW13	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]

Note:
GW+STW+CW loadings
Y: ratio (model to data or data to model) below a factor of 1.15, 1.3 and 1.5
N: ratio (model to data or data to model) above a factor of 1.15, 1.3 and 1.5
[1]: model above measurement (conservative)
[2]: limited data
N/A: data not available

Table 2 Verification of the Model using a Tracer (Fluoride).
Turning Basin - Far from the Harbour Wall

Location	WSWc & NNWw Near the Surface	ENEc & ENEw Near the Surface	WSWc & NNWw Near the Bottom	ENEc & ENEw Near the Bottom
SWRA1	(NYY)[12]	(NYY)[12]	(NYY)[12]	(NYY)[12]
SWRA7	(YYY)[12]	(NYY)[12]	(YYY)[2]	(NNN)[12]
SWRA2	(NYY)[12]	(NYY)[12]	(NYY)[12]	(NYY)[12]
SWRA6	(NYY)[12]	(NYY)[12]	(NYY)[12]	(NYY)[12]
HW9-5	N/A	N/A	N/A	N/A
SWRA3	(NYY)[12]	(NYY)[12]	(NYY)[12]	(NNY)[12]
SWRA5	(NYY)[12]	(NYY)[12]	(NNY)[12]	(NYY)[12]
SWRA4	(NNY)[12]	(NNY)[12]	(NYY)[12]	(NNY)[12]

Note:
GW+STW+CW loadings
Y: ratio (model to data or data to model) below a factor of 1.15, 1.3 and 1.5
N: ratio (model to data or data to model) above a factor of 1.15, 1.3 and 1.5
[1]: model above measurement (conservative)
[2]: limited data
N/A: data not available

Table 3 Verification of the Model using a Tracer (Fluoride).
Channel & Centre Pier - Near the Harbour Wall

Location	WSWc & NNWw Near the Surface	ENEc & ENEw Near the Surface	WSWc & NNWw Near the Bottom	ENEc & ENEw Near the Bottom
SW6	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW7	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
HW20	(YYY)[2]	(NNY)[12]	N/A	N/A
SW8	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW9	(YYY)[2]	(YYY)[2]	(YYY)[2]	(YYY)[2]
SW10	(NNN)[23]	(NNN)[23]	(NNN)[23]	(NNN)[23]

Note:
GW+STW+CW loadings
Y: ratio (model to data or data to model) below a factor of 1.15, 1.3 and 1.5
N: ratio (model to data or data to model) above a factor of 1.15, 1.3 and 1.5
[1]: model above measurement (conservative)
[2]: limited data
[3]: model below measurement
N/A: data not available

Table 4 Verification of the Model using a Tracer (Fluoride).
Channel & Centre Pier - Far from the Harbour Wall

Location	WSWc & NNWw Near the Surface	ENEc & ENEw Near the Surface	WSWc & NNWw Near the Bottom	ENEc & ENEw Near the Bottom
SWRA8	(NYY)[12]	(NNN)[12]	(NYY)[12]	(NNN)[12]
SWRA10	(YYY)[2]	(NNN)[23]	(NYY)[23]	(NNN)[23]
SWRA9	(NNN)[23]	(NNN)[23]	(NNN)[23]	(NNN)[23]

Note:
GW+STW+CW loadings
Y: ratio (model to data or data to model) below a factor of 1.15, 1.3 and 1.5
N: ratio (model to data or data to model) above a factor of 1.15, 1.3 and 1.5
[1]: model above measurement (conservative)
[2]: limited data
[3]: model below measurement

3.2 Comparison of Modelled Uranium Concentrations to Measurements

The previous section provided the verification of the model based on fluoride data. The present section compares the modelled uranium concentrations to field data. The uranium was not used for direct verification of the model because it is not a conservative tracer. However, the comparison of model to measurements provided in this section is useful for understanding sources of sinks of uranium and for gaining insight into the fate and transport of this contaminant. In general, the modelled uranium concentrations show very good agreement with the measurements near the Harbour walls and less agreement far from the Harbour walls. The results of the comparison are explained below.

1) Turning Basin: the model concentrations near the surface and near the bottom are shown in Figures 5 and 6. The model shows very good agreement with the measurements near the Harbour walls. Far from the Harbour walls, the model over predicts the concentrations (based on one sampling campaign). This could be the result of variability in the concentrations (e.g., due to flow conditions or cooling water circulation) or it could indicate the existence of a potential sink (such as removal to sediment). However, it should be noted that the model is conservative far from the Harbour walls (i.e., over predicts aquatic concentrations based on a comparison of model results to measurements).

2) Harbour Channel and off the Centre Pier: the model concentrations near the surface and near the bottom are shown in Figures 7 and 8. The model shows reasonable agreement with the field data near the Harbour walls. Far from the Harbour walls, the model over predicts the concentrations (based on one sampling campaign). This could be the result of variability in the concentrations (e.g., due to flow conditions) or it could indicate the existence of a potential sink such as removal to sediment. However, it should be noted that the model is conservative far from the Harbour walls (i.e., over predicts aquatic concentrations based on a comparison of model results to measurements).

3) West Beach near-shore Lake Ontario: the model concentrations are a factor of 3 (WSWc model) to 80 (ENEc model) lower than the measurements as shown in Figure 9. However, the measured concentrations are also very low (0.8 ug/L).

3.3 Uranium Plume in the Harbour

Two scenarios were proposed to assess the minimum and maximum concentrations in the Harbour. The first scenario represents the conditions in the Harbour when the cooling water system is shutdown (no circulation of contaminants); the contaminant plume of this scenario with groundwater (GW) and storm water (SWT) loadings is shown in the top of the figures. The second scenario represents the increase of concentrations once the cooling water system is in operation (circulation of contaminants); the contaminant plume including the cooling water (CW) loading is shown in the bottom of the figures. These two scenarios were considered in the Site Wide Risk Assessment (SWRA) of the Port Hope Conversion Facility (PHCF) (see [1]).

The uranium concentrations were averaged over the depth at each computational cell in the turning basin, Harbour channel and near-shore Lake Ontario. The average uranium concentrations were marked as green and blue in the contaminant plume figure when the concentrations were lower than the Water Quality Guidelines PWQO (Figures 10 and 11).

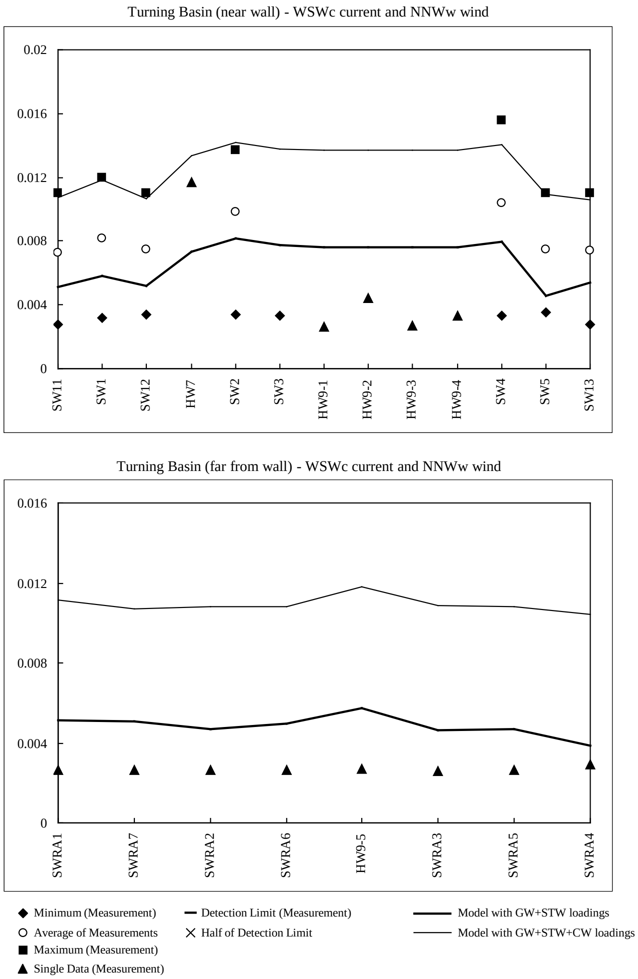


Figure 5 Comparison of Modelled Uranium Concentrations to Measurements near the Surface in the Turning Basin

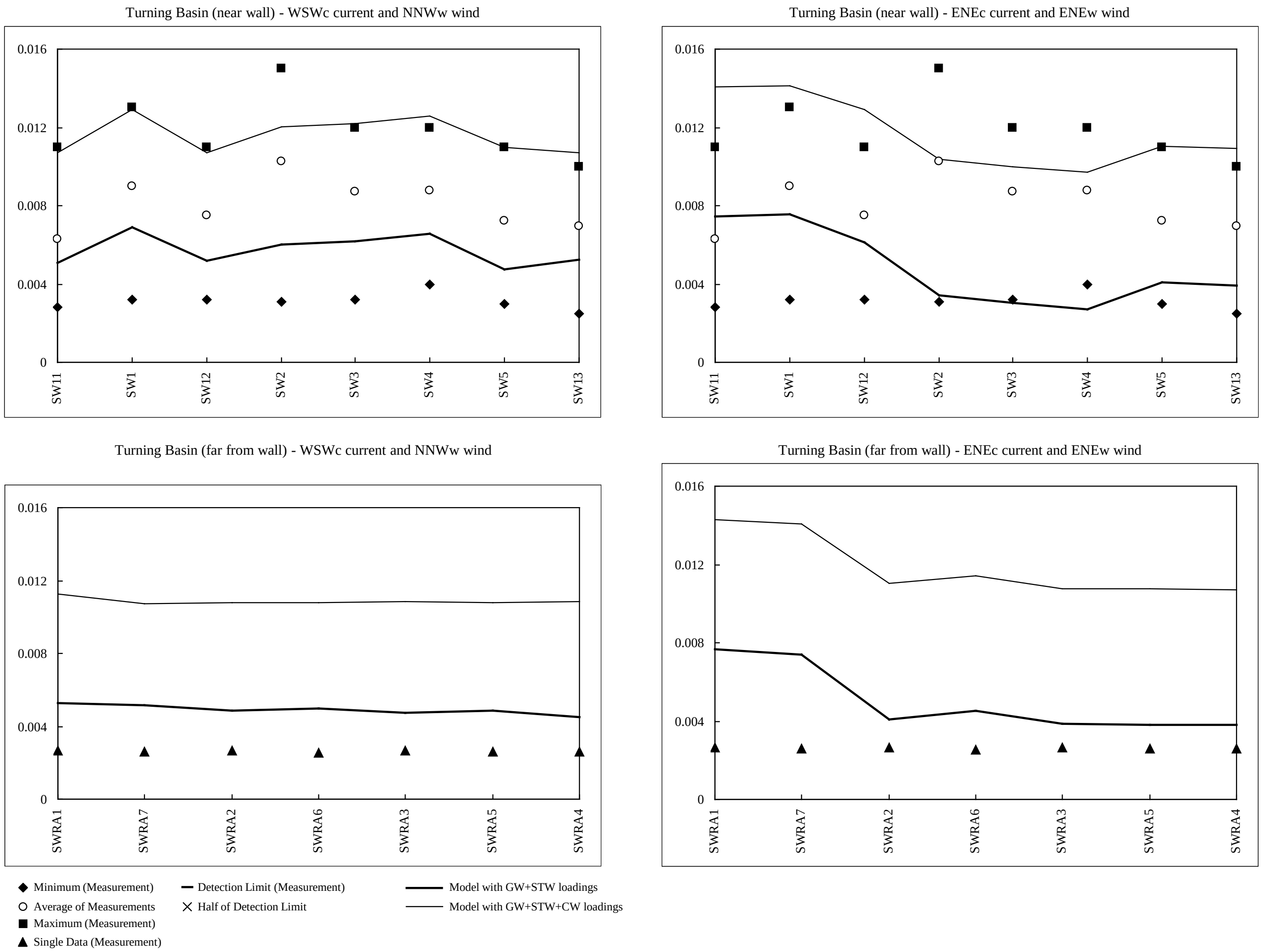


Figure 6 Comparison of Modelled Uranium Concentrations to Measurements near the Bottom in the Turning Basin

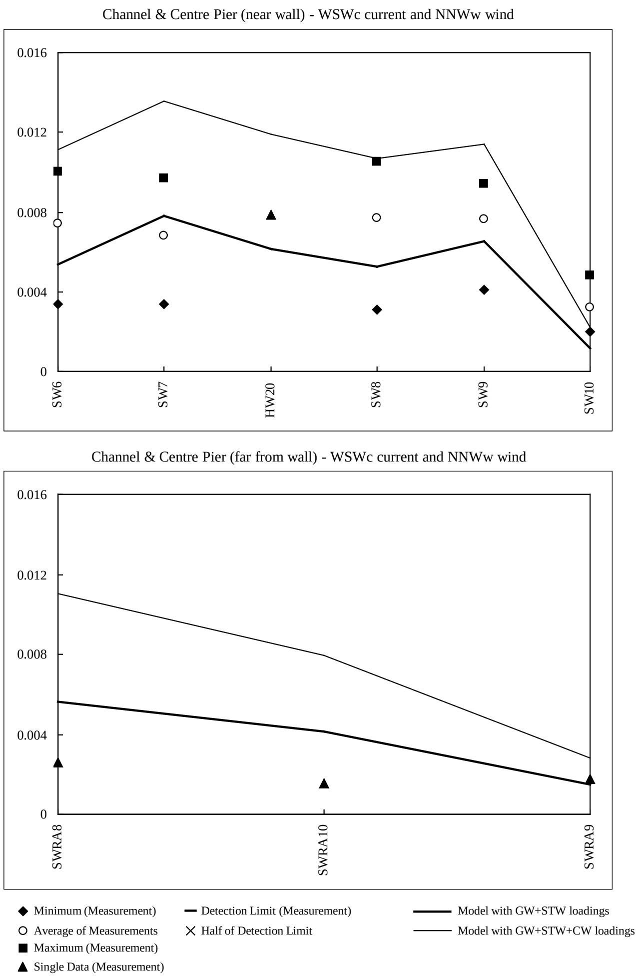


Figure 7 Comparison of Modelled Uranium Concentrations to Measurements near the Surface in the Harbour Channel

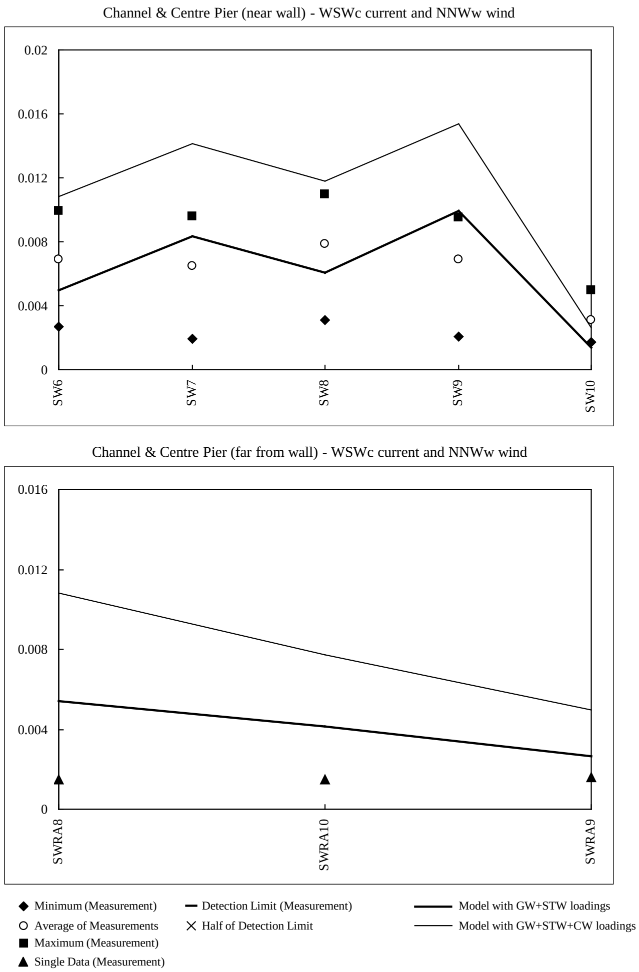


Figure 8 Comparison of Modelled Uranium Concentrations to Measurements near the Bottom in the Harbour Channel

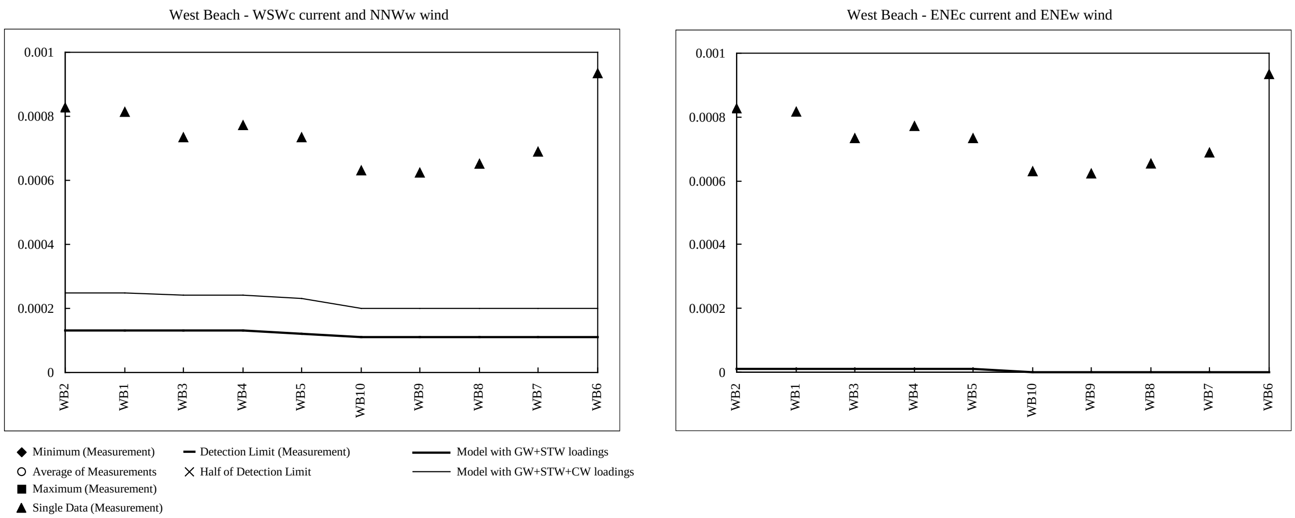
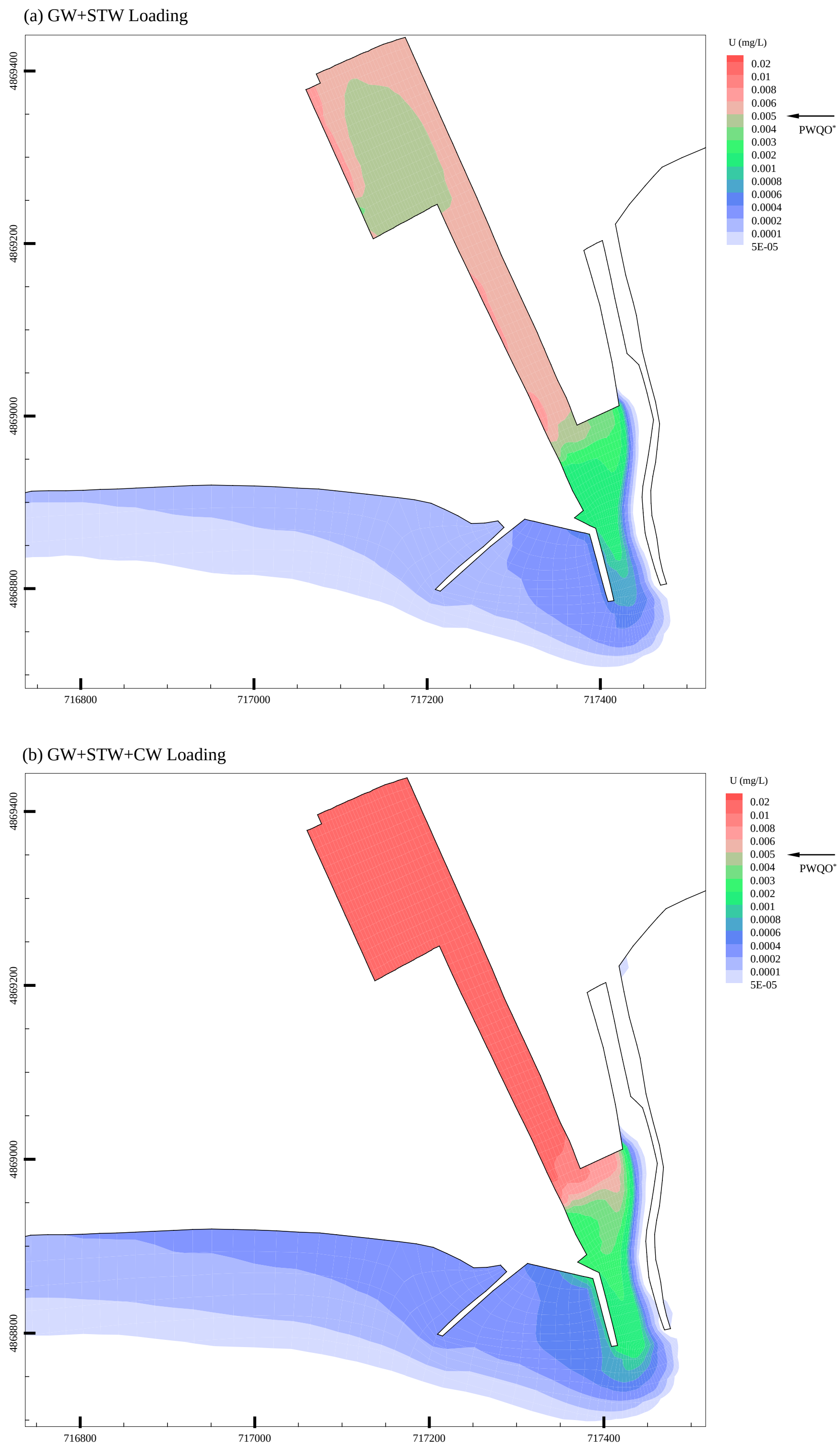


Figure 9 Comparison of Modelled Uranium Concentrations to Measurements near the Surface in the West Beach

The interim PWQO for uranium is 5 ug/L [8]. The distribution of depth-averaged uranium concentrations for the model with WSWc current and NNWw wind and the model with ENEc current and ENEw wind is shown in Figures 10 and 11.

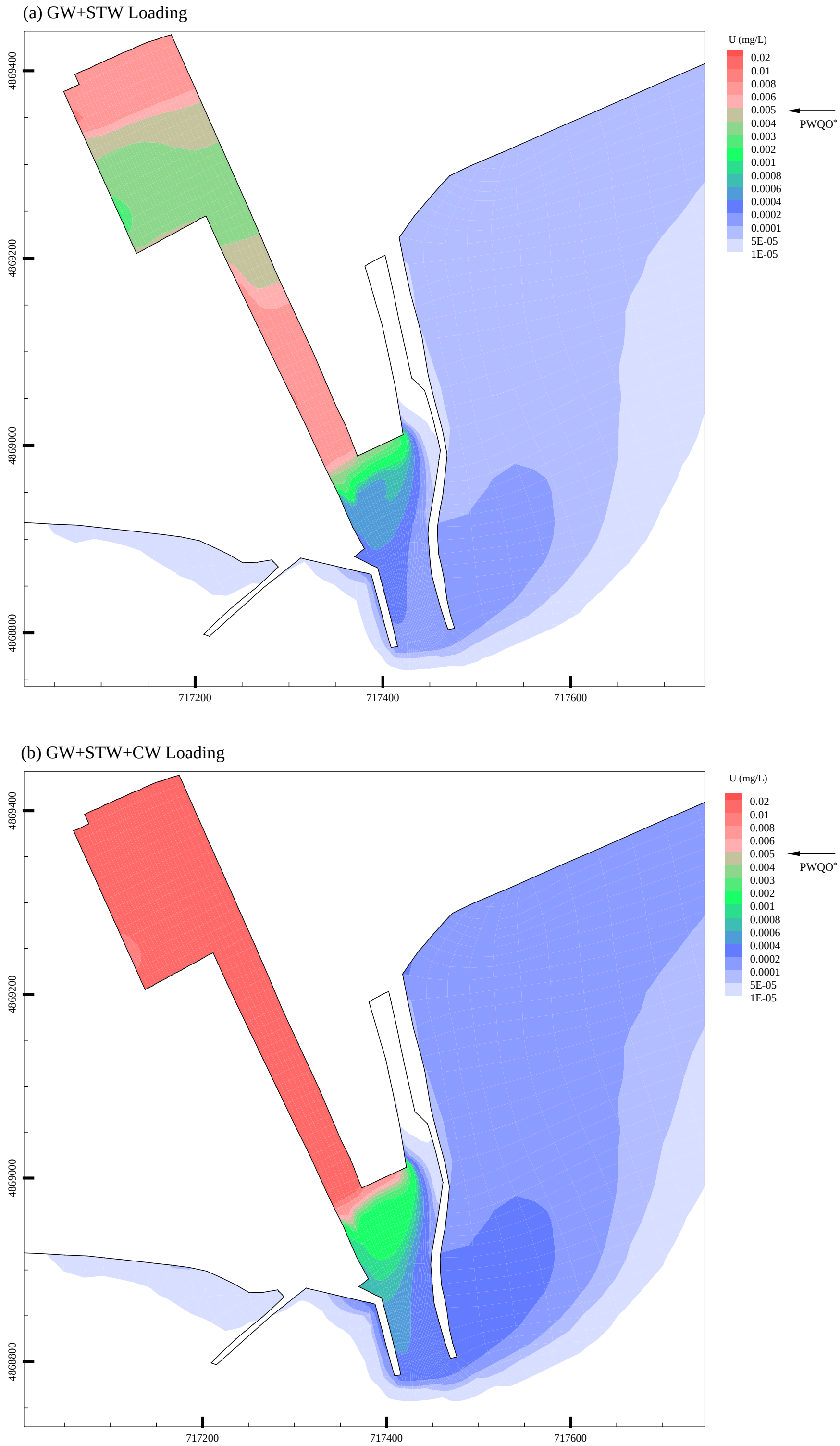
The uranium plume due to groundwater (GW) and storm water (STW) loadings is shown in (a) at the top of Figures 10 and 11. The red color in the figure shows the area where the depth-averaged uranium concentrations are higher than the interim PWQO. These include: the west, east and north walls in the turning basin and the Harbour channel for the WSWc model and the north wall in the turning basin and downstream portion of the Harbour channel for the ENEc model.

The uranium plume due to groundwater (GW), storm water (STW) and cooling water (CW) loadings is shown in (b) at the bottom of Figures 10 and 11. The red color in the figure shows the area where the depth-averaged uranium concentrations are higher than the interim PWQO. These include: the turning basin and Harbour channel. Furthermore, the addition of the cooling water loading into the Harbour increases the uranium concentrations in the tuning basin and Harbour channel above the interim PWQO limit.



Note:
Depth-averaged U in mg/L
PWQO* = 5 ug/L (Interim PWQO)

Figure 10 Modelled Uranium Plume. Model with WNWc Current and NNWw Wind



Note:
Depth-averaged U in mg/L
PWQO* = 5 ug/L (Interim PWQO)

Figure 11 Modelled Uranium Plume. Model with ENEc Current and ENEw Wind

4. Conclusions

The 3D contaminant transport model was verified with a tracer (fluoride) whose results showed good agreement with the field data. The modelled uranium concentrations showed good agreement with the field data near the Harbour walls. However, far from the Harbour walls, the model over predicts the uranium concentrations. This could be the result of variability in the concentrations (e.g., due to flow conditions) or it could indicate the existence of a potential sink (such as removal to sediment). In the west beach near-shore Lake Ontario, the modeled uranium concentrations were considerably low compare to field data which indicates the possibility of additional loadings at this location. However, the field data in this location generally show low uranium concentrations. The circulation of uranium through the cooling water system showed an increase in the uranium concentrations in the Harbour which are higher than the interim PWQO of 5 ug/L.

5. References

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