Submerged Aquatic Vegetation Survey in Hamilton Harbour, Lake Ontario, 2016

J. Gardner Costa, R.W.K. Tang, K.E. Leisti, J.D. Midwood, and S.E. Doka

Fisheries and Oceans Canada
Central and Arctic Region (Fisheries Ecology Section)
Great Lakes Laboratory for Fisheries and Aquatic Sciences
867 Lakeshore Road
Burlington, Ontario L7S 1A1

2019

Canadian Technical Report of Fisheries and Aquatic Sciences 3320

Fisheries and Oceans Canada   Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3320

2019

Submerged Aquatic Vegetation Survey in Hamilton Harbour, Lake Ontario, 2016

by

Jesse Gardner Costa, Rex W.K. Tang, Kathy E. Leisti, Jonathan D. Midwood, and
Susan E. Doka

Central and Arctic Region
Fisheries and Oceans Canada
867 Lakeshore Road
Burlington, ON
L7S 1A1

Cat. No. Fs97-6/3320E-PDF, ISBN 978-0-660-31418-1, ISSN 1488-5379

Correct citation for this publication:
Gardner Costa, J., Tang, R.W.K., Leisti, K.E., Midwood, J.D., Doka, S.E. 2019. Submerged Aquatic Vegetation Survey in Hamilton Harbour, Lake Ontario, 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3320: viii + 43 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIX TABLES

LIST OF APPENDIX FIGURES

ABSTRACT

Gardner Costa, J., Tang, R.W.K., Leisti, K.E., Midwood, J.D., Doka, S.E. 2019. Submerged Aquatic Vegetation Survey in Hamilton Harbour, Lake Ontario, 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3320: viii + 43 p.

The Great Lakes Laboratory for Fisheries and Aquatic Sciences (GLLFAS) has been monitoring submerged aquatic vegetation (SAV) in Hamilton Harbour (HH) since 1987, with recent acoustic SAV surveys conducted by GLLFAS in 1992-1996, 2006, 2012, and 2016. The delisting target for the “loss of fish and wildlife habitat Beneficial Use Impairment (BUI #14)” for emergent vegetation and SAV is 500 ha of areal cover for the HH Area of Concern (230 ha specifically in the harbour and Windermere Basin). An SAV model was validated with field data collected in 2016 and was 80% accurate for predicting the presence/absence of SAV, however, accuracy was lower for a separate model used to predict % SAV cover. Field data from transects suggested an improvement (gain) of % SAV cover since 2012; however, model outputs predicted areal SAV extent nearly identical to 2012 calculated estimates, suggesting HH is likely still impaired (below targets). Presence/absence model outputs at different water levels show variation in the potential areal extent from 248-331 ha. Given the large effect high water elevations had on the model (e.g., lowering areal extent by 20%), high water levels in 2017 and likely 2018 may have had a negative effect on SAV bed extents for HH. We recommend that any future surveys of SAV include a stratified random design around the harbour. Using a model validated with data from periodic surveys is a vital tool for the AOC Remedial Action Plan to determine the status of BUI #14 and assess the potential for its delisting, with an ultimate goal of delisting the whole AOC once all BUI targets are met. This report provides recommendations for one set of habitat targets and will serve as another line of evidence in reaching these goals.

RÉSUMÉ

Gardner Costa, J., Tang, R.W.K., Leisti, K.E., Midwood, J.D., Doka, S.E. 2019. Submerged Aquatic Vegetation Survey in Hamilton Harbour, Lake Ontario, 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3320: viii + 43 p.

Le Laboratoire des Grands Lacs pour les pêches et les sciences aquatiques (LGLPSA) surveille la végétation aquatique submergée (VAS) dans le port de Hamilton (PH) depuis 1987, et le LGLPSA a récemment effectué des relevés acoustiques de la VAS de 1992 à 1996 et en 2006, 2012 et 2016. La cible pour la radiation de la désignation « disparition d'habitats de poissons et de la faune - Altération d'utilisation bénéfique (AUB) n^{o} 14 », pour la végétation émergente et la VAS est de 500 ha de couverture de surface pour la zone de préoccupation du PH (230 ha spécifiquement dans le port et le bassin de Windermere). Un modèle de VAS a été validé à l'aide de données recueillies sur le terrain en 2016 et celui-ci s'est révélé précis à 80 % pour prédire la présence ou l'absence de VAS. Toutefois, le degré d'exactitude était moins élevé pour un modèle distinct utilisé pour prédire le pourcentage de couverture de VAS. Les données de terrain provenant des transects semblent indiquer une amélioration (c.-à-d. un gain) du pourcentage de couverture de VAS depuis 2012. Cependant, les résultats du modèle prédisent une couverture de surface de VAS presque identique aux estimations calculées en 2012, ce qui porte à croire que le PH est probablement encore compromis (sous les cibles fixées). Les résultats des modèles de présence/d'absence à différents niveaux d'eau montrent une variation de la superficie potentielle de 248 à 331 ha. Étant donné l'effet important que les élévations des hautes eaux ont eu sur le modèle (p. ex. diminution de 20 % de la superficie), les niveaux des hautes eaux en 2017 et probablement en 2018 pourraient avoir eu un effet négatif sur l'étendue des lits de VAS pour le PH. Nous recommandons que tout relevé futur de la VAS comprenne un plan aléatoire stratifié autour du port. L'utilisation d'un modèle validé à l'aide de données provenant de relevés périodiques est un outil essentiel pour le plan d'assainissement de la ZP afin de déterminer l'état de l'AUB n^{o} 14 et d'évaluer la possibilité de sa radiation, l'objectif ultime étant de radier l'ensemble de la ZP lorsque toutes les cibles relatives à l'AUB sont atteintes. Le présent rapport contient des recommandations pour un ensemble d'objectifs en matière d'habitat et servira de source supplémentaire de données probantes pour atteindre ces objectifs.

INTRODUCTION

Hamilton Harbour, Lake Ontario was designated as an Area of Concern (AOC) in 1987 due to a legacy of anthropogenic development and industry in surrounding watersheds that led to alterations to fish and wildlife habitat and populations, polluted waters, and contaminated sediments. To support the delisting of this AOC, the Hamilton Harbour Remedial Action Plan (RAP) identified a series of Beneficial Use Impairments (BUI) that needed to be addressed, and outlined specific targets for each BUI. From a fisheries perspective, targets for the two most relevant BUIs (*Degradation of fish and wildlife populations* and *Loss of fish and wildlife habitat*) are largely focused on the littoral zone, which has been defined as underwater areas less than 2 m in depth that can support aquatic vegetation (HH RAP 2004). This type of habitat primarily occurs along the shoreline of the Harbour with the exception of the eastern margins and south shore, with more substantive areas near Carroll's Bay and Cootes Paradise (situated at the western end of the harbour). Due to this restricted distribution, the littoral zone represents only a small fraction of the available habitat within the harbour (8.9% by surface area and 14.8% by volume, at a water level datum of 74.2 m above sea level), with the remainder classified as pelagic and benthic habitats. As such, submerged aquatic vegetation (SAV) in these littoral edges plays a critical role for fish habitat in Hamilton Harbour.

Submerged aquatic vegetation is an important component of aquatic ecosystems that affects the physical and chemical nature of their local environment by: anchoring substrate to reduce sediment transport; reducing turbidity caused by the resuspension of sediments by winds; and influencing nutrient and oxygen cycling (Carpenter and Lodge 1986; Kalff 2002). SAV provides food and habitat for birds, mammals, invertebrates, reptiles, zooplankton, periphyton, and fish (Kalff 2002). For fishes, SAV provides spawning, nursery, and adult habitat for numerous species (e.g., Largemouth Bass [*Micropterus salmoides*], Northern Pike [*Esox lucius*], and Pumpkinseed sunfish [*Lepomis gibbosus*]); it is both a refuge from predation through the provision of cover and serves as habitat for macroinvertebrates, a source of food for some fishes (Gilinsky 1984). The presence of SAV has been found to positively influence fish abundance (Chick and McIvor 1994), growth rates (Werner et al. 1983) and fish community structure (Weaver et al. 1997). Randall et al. (1996) concluded that sites with SAV had greater densities of fish and greater species richness than unvegetated sites in three bays in eastern Ontario.

Requirements for both SAV density and extent form part of the delisting objectives for Hamilton Harbour (HH) RAP Beneficial Use Impairment *XIV Loss of Fish and Wildlife Habitat.* Delisting objectives for the Harbour were developed that included metrics for the areal extent of SAV cover. The current targets for emergent vegetation and SAV are 500 ha for Hamilton Harbour, Cootes Paradise, Windermere Basin, and Grindstone Creek combined; this target does not include water level scenarios or Secchi targets (HH RAP 2012) (Figure 1 for map). The Great Lakes Laboratory for Fisheries and Aquatic Sciences (GLLFAS) has been monitoring SAV in HH since 1987 and was a contributor to the Stage 1 Report *Environmental Conditions and Problem Definition*.

Additional acoustic SAV surveys were conducted by GLLFAS annually from 1992 to 1996, 2006 and in 2012. The objectives of this report are to summarize the findings from the 2016 survey and analyze trends in % SAV cover, distribution, and composition in HH to place the data in context with proposed delisting objectives. Cootes Paradise, Windermere Basin, and Grindstone Marsh were not surveyed and were therefore excluded in the discussion of the collected data; however, the status of SAV coverage is important for the assessment of the BUI for the RAP.

METHODS

STUDY SITE

Hamilton Harbour is an embayment located at the western end of Lake Ontario and is bounded by the Burlington shipping canal under the Skyway Bridge to the east and Cootes Paradise to the west. The south shore of HH is heavily industrialized and largely armoured. Although the total surface area of the bay is large (2150 ha), much of HH is shallow with a mean and maximum depth of 13.7 m and 27 m, respectively. For the purposes of this study, the survey area was defined as the entire area of HH excluding Grindstone Creek, Cootes Paradise and Windermere Basin, though in future assessments, Windermere Basin will be included in areal calculations of SAV for H (Figure 1).

PERCENT SAV COVER, EXTENT, AND SPECIES COMPOSITION

The same 33 historical transects that have been used since 1992 were surveyed again between August 22nd and 30th, 2016. These transects are located throughout the non-industrial areas of HH, starting at the nearshore in approximately 1 m water depth and moving offshore (perpendicular to shore) to at least 100 m beyond the edge of the SAV bed (Figure 1). Echosounding was conducted using a BioSonics MX habitat system with a 205 kHz, 8˚ single-beam transducer (Seattle, WA, USA). Metrics derived from these data were:

1) Percent (%) SAV cover: 2-dimensional density of SAV along a transect

2) Maximum depth of colonization: deepest depth where SAV is present on the transect (typically last plant)

3) Bed extent: length of transect from fixed nearshore point to the last plant on the transect

4) Calculations of percent volume inhabited (PVI): percentage of the water column SAV occupies (% SAV Cover * plant height / water depth) (Søndergaard et al. 2010)

All acoustic data were analyzed using BioSonics Visual Habitat software (v2.0.3.9824) In addition to the reference transects, supplementary echosounding included at least two other nearshore-to-offshore transects and a zig-zag transect that traced the edge of the SAV bed (Figure 2).

Point sampling of SAV was also collected along reference transects via haphazard rake tosses to ground-truth the hydroacoustics and determine species composition. During the survey, presence and % cover of SAV (sparse [<25% SAV cover], moderate [25-75% SAV cover], dense [>75% SAV cover]) were visually estimated and recorded in relation to the hydroacoustic ping number; since these data were collected concurrently with the hydroacoustic survey, they were used to provide a rough validation of the hydroacoustic output of % SAV cover.

ANALYSIS

The acoustic data were analyzed using BioSonics Visual Habitat software, version 2.0.29744 (BioSonics 2015) to determine bottom depth, % SAV cover and SAV height. Default software parameters were used with the exception of -38 dB for the rising edge threshold for bottom detection, a plant detection length criterion of >15 cm and maximum plant depth of 10 m (though based on past surveys we had no expectation of vegetation beyond 6 m). Vegetation less than 15 cm in height was observed; however, this height threshold was necessary for the hydro-acoustic assessment to distinguish vegetation from soft sediment. Following the interpretation of the hydroacoustic data, results were summarized (mean ± standard deviation, quartiles etc.) for water depth, % SAV cover, and height of SAV. Although all transects were analyzed, results are only shown for the labelled transects in Figure 1. Summary data for all other transects can be found in the appendix.

All the outputs were scrutinized and manually adjusted to address issues such as incorrect delineation of bottom depths due to dense SAV and fish schools near the bottom identified as SAV. The point sampling undertaken during the survey played a critical role in verifying maximum depths of SAV colonization (max depth of colonization was determined from the sonagram). The results from Visual Habitat were imported into ArcMap and the bed extent (lengths of continuous vegetation on the reference transects) were determined by measuing from a shoreline layer (gaps of <90 m where SAV was absent were included). Mean % SAV cover was calculated for each ping's % cover calculation for start to the edge of the bed extent of each transect. Boxplots illustrating the mean, 25th and 75th quartiles of both % SAV cover and SAV height by depth range (1 m increments) were created using the reference transects and all supplementary echosounding data. SAV point data were plotted in ArcGIS to allow for a spatial assessment of SAV height and cover.

ESTIMATION OF SAV ACREAGE USING THE HAMILTION HARBOUR SAV MODEL

To support assessment of fish habitat in HH, a SAV model was developed to predict and map the location and distribution of SAV in HH (Doolittle et al. 2010). Primary inputs to the model include: elevation, slope, and effective fetch with the output % SAV cover.

% SAV Cover = 86.3783 + (-0.7201 * [PERCENT SLOPE]) + (-10.4607 * [DEPTH]) + (-0.0099 * [EFFECTIVE FETCH @270º]) + ([DEPTH] - 2.3082) * ([DEPTH] -2.3082) * -3.3981 + ([DEPTH] - 2.3082) * ([EFFECTIVE FETCH @270º] - 1299.6220) * 0.0026

Grid cells with a depth > 5.75 m, Secchi values of <= 0.6 m, and areas with predicted <1% plant cover were assigned as 0% SAV cover. Secchi data was taken from a GIS layer with Secchi polygons. The polygons were based on point samples; however, metadata for the layer is currently unavailable. The Secchi layer has been included in the appendix (Figure A1). We applied this model to three scenarios: high-water (75.7 m) maximum colonization (ideal conditions, no Secchi cut-off), chart datum (74.2 m) maximum colonization (ideal conditions, no Secchi cut-off), and chart datum (74.2 m with Secchi cut-off of 0.6 m) maximum colonization. The predicted areal coverage of SAV (Hectares) was calculated for each of the predictive models.

MODEL VALIDATION

The accuracy of the HH SAV Model was evaluated using the 2016 SAV acoustic transect data collected for this report. Data from the SAV acoustic transects were consolidated with layers from the HH geodatabase (Doolittle et al. 2010). For each transect point from the survey data, a 5 m buffer zone was generated using ArcGIS to attach geo-information from the closest grid point. Depths from the 2016 acoustic transect data were used for the analysis; however, we also calculated a secondary depth for all transect points. These secondary depths were corrected for mean daily water levels from the Burlington survey buoy (Station # 13150) and converted to elevations using the HH digital elevation model (DEM) extracted from the HH geodatabase.

Model prediction accuracies were determined *a priori* and compared based on 1) SAV presence / absence, and 2) % SAV cover. SAV presence was defined using two thresholds and analyzed separately, where >= 1% and >= 5% cover were defined as SAV presence for both transect and predicted % SAV cover. *In situ* 1% or 5% SAV densities are very sparse (one or a few plants per m^2); however, for modelling purposes the presence of any SAV signifies a potential for SAV to grow in that area. A model is deemed sufficiently accurate if >80% of data are predicted correctly (Tang et al. in prep., Midwood et al. in prep.). Measures of model accuracy for SAV presence / absence were then assessed using six accuracy indices, including: Area Under Curve (AUC) for a Receiver Operating Characteristic (ROC), omission rates, sensitivity, specificity, proportion correctly identified and Cohen's Kappa (R accuracy {SDMTools}).

For % SAV cover scenarios, measures of model accuracy were assessed using the weighted absolute percentage (WAPE) and the root mean square error (RMSE). WAPE is an alternative to the mean absolute percentage error (MAPE) where zero values (0% SAV cover) are present in the data. RMSE is a measure of goodness of fit, a scale-dependent measurement of error between the predicted and observed values (Singh et al. 2009). RMSE and WAPE are typically used for comparisons among models; however, since there is only one model for HH, we will report these values for future comparisons to any new model but not discuss them greatly within this report.

RESULTS

PERCENT (%) SAV COVER AND PLANT HEIGHT

Maps of % SAV cover (Figures 3-6) were created for 33 historical transects (GPS locations in Table A1), made of reference (n = 13, these sites included point sampling and hydroacoustics) and supplementary locations (n = 20, these sites were just hydroacoustic data). A bathymetric base layer has been included with all maps to provide context to the presence/absence of vegetation. For reference transects, the most extensive SAV beds were found along the north shore of Hamilton Harbour, with the greatest bed extending 287 m offshore at transect 3 (Figure 3; T3). SAV cover was dense along the north shore (>80% for transects 1-15). Although patchier, moderate - dense cover (50-75%) was generally found along the western and southern shores, SAV bed extents were substantially smaller in these areas (generally less than 100 m in length). Transect 19 was completely unvegetated. Although there were only two reference transects on the eastern shore (T31 & T35), % SAV cover was moderately-dense with bed extents of 64 and 134 m, respectively.

The maximum depth of plant colonization varied by transect, ranging from 2.1-5.2 m on reference transects. Table 1 summarizes SAV bed extent, maximum depth of colonization (Z_c), and mean % SAV cover along 12 reference transects in the harbour. Appendix Table A2 summarizes water quality for each of the reference transects at different point sampling locations; there were no clear differences in temperature or conductivity and dissolved oxygen was above 8 mg/L at all sites. These data were included into the report for posterity and are therefore not discussed further.

In all transect areas, mean % SAV cover ranged from 55-94%, though within a transect, % SAV cover had high variabilitiy (Table 1, Table A3). Boxplots of % SAV cover (Figures 7 & 8) and plant height (Figures 9 & 10, Table A4) were binned over depth ranges for all 13 reference transects (T19 had no vegetation therefore there are no graphs). Across all sites, the greatest % SAV cover occurred between 2-3 m water depth, although vegetation was also dense at depths of 1-2 m in transects along the northern shore (T1-T15). Transect T29 (along the south-eastern shore) was most dense at 2-3 m (100%) and did not show any vegetation beyond 4-5 m depth, with a mean % SAV cover of 75 % for the entire transect.

For SAV height, all locations showed a unimodal curve with maximum SAV height between 2-3 m water depth. Generally, sites dominated by *Vallisneria americana* had greater mean SAV height compared to other transects (Figure 11 for relative composition of species). Calculations of percent volume inhabited in (PVI) showed that across all reference sites, plants did not occupy on average, more than 50% of the vertical water column at any site (Figure 12). Table A5 summarizes PVI for all transects and shows variability ranging from 10-20%. T21 (and T19 – but the site was unvegetated) had a PVI of less than 10%. Combined with T21 which also had the second lowest % SAV cover of all the reference transects (55%) field data suggests the western shore was not well vegetated based on model predictions (discussed below).

Point sampling on reference transects detected 10 species throughout the harbour; ranging from 1-4 species along any single transect (Figure 11). *Vallisneria americana* was found at most sites (10 of 12 transects) and was usually the dominant species when encountered. *Myriophyllum spicatum* (invasive species) and *Elodea canadensis* were the only other species encountered at more than 5 transects, usually in relatively small frequencies (<10%). *Potamogeton perfoliatus* seemed to only be encountered along the northeastern shoreline. *Heteranthera dubia* was present in the 2016 survey, as well as the 2012 survey albeit in small quantities (5% relative frequency for the transects it was found in), previously labelled as *Zosterella dubia*. *Stuckenia pectinata* was not previously detetected in the harbour and was found in transect 3.

SAV MODEL PREDICTIONS

Three scenarios were applied using the Doolittle et al. (2010) HH SAV model: maximum potential SAV colonization at high water (75.7 m – no Secchi limitation), maximum potential SAV colonization at chart datum (74.2 m – no Secchi limitation), and maximum potential SAV colonization at chart datum (74.2 m) with a Secchi cutoff of 0.6 m (Figures 13-15). Areal extent of vegation is summarized in Table 2. Given perfect conditions (or lack of limitations from substrate, water clarity, or fetch) figures show the predicted maximum amount of vegetation for Hamilton Harbour. The chart datum scenario gave the highest amount of vegetation at 331 ha of SAV compared to 273 ha for the high-water scenario. Though both figures look similar, the chart datum scenario shows more SAV colonization at the western shore, Randle Reef and the north eastern shore (near Indian Creek); lower water levels allowed colonization further into the harbour.

Figure 15 shows a model output more closely tied to the present-day conditions in the Harbour. Using a minimum Secchi depth cutoff of 0.6 m, the model removed large swaths of vegetation from Carroll’s Bay and Indian Creek, for a total predicted areal extent of 248 ha. Figure 16 overlays our acoustic transect data with the model output to give a sense of how well the model has predicted where SAV may establish. Visually reviewing the output, the Secchi-restricted model appears to be consistent with observations along the northern shore, vegetation cutoffs match up with the predicted bed extents in the model. Indian Creek shows the absence of vegetation in the hydroacoustic dataset, which is in line with the Secchi-restricted model’s prediction. Carroll’s Bay is also unvegetated according to the hydroacoustic data and matches the Secchi-restricted model’s prediction. Just south of Carroll’s Bay predicts large beds of SAV; however, the acoustic data show almost no vegetation, which was also confirmed by field notes (D. Reddick, DFO, pers.comm.). The model predicts patchy SAV on the eastern shore (near transects 31 & 35), which is generally the case, however, there are a few transects from the acoustic data showing the presence of SAV where none was predicted. Lastly, there were no data collected in the southern shore, but it is expected that little to no vegetation is present in the slips or Randle Reef due to, shipping activities, contamination and toxic sediments, or unconsolidated substrate (Doolittle et al. 2010).

SAV MODEL VALIDATION

Survey depth and predicted DEM depth calculated from mean daily water levels at Burlington station showed a general positive linear relationship (Figure 17). Outliers in Figure 18 suggest small errors in the DEM layer in the harbour, and should be corrected for future use. Underestimation of depth was concentrated near Pier 4 in the southern area and overestimation was concentrated at the eastern shore (Figure 18). A frequency distribution of the difference in depth showed a general normal relationship, suggesting predicted depth from the DEM is generally in consensus with the survey depth (Figure 17). In addition, modeling results showed a relatively small RMSE (Table 3), which also suggest water depth predicted using the DEM was generally similar to survey depth, and therefore can be used for future modeling exercises.

For presence/absence model validations, proportion of correctly predicted data ranged from 82% to 83% between the 5% and 1% SAV density thresholds, respectively. The number of correct predictions were identical regardless of whether survey depth or DEM calculated depth were used (Table 3). Cohen's Kappa showed a moderate agreement for the HH SAV model (Table 3). The difference in the number of correct predictions between models with a 5% density threshold and 1% density threshold for SAV presence was small ($n_{\text{difference correct}}$ = 73) relative to the number of total points. For the % SAV cover models RMSE ranged from 30.4 to 30.7 among scenarios with survey depth and calculated DEM depths (Table 3).

DISCUSSION

Previous SAV surveys in Hamilton showed average vegetated transect lengths of approximately 130 m in the north shore (transects 1-12) (Leisti et al. 2016). Since 2012, transects in that sector have grown considerably, ranging from 132 m (HH12) to 287 m (HH3) with a mean of 189.2 ± 52.2 (transects 1-12 only), suggesting improvements in the areal extent of SAV in the northern part of the harbour. Though not as readily apparent, there have been increases in bed extent in the western and eastern shorelines; when the AOC was listed, the western shore was almost completely unvegetated and the eastern shore's transect lengths were <100 m in 2012 (Leisti et al. 2016). On both the eastern and western shore, acoustic data show little to no SAV at the beginning of the transects (HH12, HH15, HH31, HH35) suggesting processes affecting SAV growth associated with the shallow nearshore including wave action (Keddy 1983) and ice scouring Stewart and Freedman 1989) may be preventing the establishment of SAV.

The maximum depth of colonization (Z_c) for SAV was variable across the harbour, but was typically deepest (4.6-5.2 m) northeast of Carroll's Bay (along the northern shore), outside of areas thought to be influenced by turbid inflowing waters from Grindstone Creek (D. Reddick, pers. comm.). Historical surveys showed Z_c at less than 2.0 m around the Harbour (Minns 1992); however, conditions have improved and Z_c had improved (especially on the eastern shore) as of 2012, though no Z_c was greater than 4.0 m (Leisti et al. 2016).

Percent SAV cover was highest around 2-3 m depth in most areas of the harbour, often with sharp declines after 3-4 m; these observations were consistent with SAV surveys in the Bay of Quinte (BQ) in shallow areas with Secchi values between 1-2 m (Gardner Costa et al. 2018). The drop-off of SAV at 3-4 m is likely due to water clarity restrictions; however, we did not collect sufficient clarity data to exclude other potential factors. Exposure, water clarity, and depth (as a proxy for light attenuation) appear to be the main drivers that determine the distribution of SAV in Hamilton Harbour, but there are many other abiotic and biotic factors known to influence SAV growth and establishment (e.g., sediment composition, slope, temperature, current velocity, water chemistry, hydrostatic pressure, and water level fluctuation; Kalff 2002). Since these other abiotic factors were not incorporated into the model, we would not expect perfect agreement between model predictions and field observations; however, the model for Cootes Paradise does consider many of these abiotic factors and found only sand to be a good predictor of SAV (Tang et al. in prep).

Generally, % SAV cover in 2016 was greater compared to previous survey years, where no previous survey showed average % SAV cover above 75%. 2016's data had an average of 81%, though if broken down into sectors the northern shore would fall closer to 90% SAV cover and the eastern and western shores around 60% SAV cover for reference transects. PVI was not caclulated for previous surveys but is a metric that is easily interpreted and has been used to estimate plant biomass (Wood et al. 2012) and indicate the level of eutrophication (weak negative correlation with total nutrients) in European lakes (Søndergaard et al. 2010). The average PVIs for all transects were less than 50% and no pattern was evident across transects. Future studies could use PVI as a metric to see if fish communities differ depending on how much of the water column is occupied by SAV. This could be helpful in the wetland areas of HH including Cootes Paradise.

As mentioned in the Bay of Quinte SAV 2015 report (Gardner Costa et al. 2018), we changed to a newer hydroacoustics system and software for the 2015 survey. The new system also has a slightly wider beam (8^o vs 6^o for the equipment used previously). Since the beam is wider, it would make it more likely to detect vegetation in areas that are sparse or patchy, increasing mean estimates of % SAV cover in these areas. It is unlikely that there would be differences in areas that are heavily vegetated because either system will detect dense patches of vegetation; if there are differences we expect them to be minimal and will not have a large effect on our calculations of % SAV cover. This equipment factor will be examined in the future through field calibration of the new equipment to the old to see if and by how much they differ.

There were more SAV species (10 spp.) recorded in 2016 than in previous years (6-8 spp.; Leisti et al. 2016). *Vallisneria americana* dominated most transects, followed by *Myriophyllum spicatum* and *Elodea canadensis.* These dominant species have always been the most abundant in the harbour; this has been consistent for all previous surveys (Minns 1993, Leisti et al. 2016), suggesting no large shift in SAV communities. These results fall within the lower range from other AOC's SAV surveys (Gardner Costa et al. 2018); however, compared to wetlands such as Cootes Paradise (eight floating, 12 SAV, and 18 emergent vegetation species), the harbour is relatively species poor (Leisti et al. 2016). *Stuckenia pectinata* was newly detected in the harbour albeit rarely in our transects, however, this species is fairly common in the surrounding wetlands, such as Cootes Paradise (A. Court pers. comm.). The Wetland Macrophyte Index (WMI), developed by Croft and Chow-Fraser (2007), is an index used to determine the condition of wetland macrophyte communities. *Heteranthera* is not listed in the paper but *Stuckenia pectinata* is listed as a very tolerant, broad-niche plant species [see table Table 2 from Croft and Chow-Fraser (2007) for tolerance ratings]. It was not within the scope of this report to run the WMI for the harbour but these new species as well as the dominant species (*Vallisneria americana*, *Myriophyllum spicatum* and *Elodea canadensis*) in this survey are listed as tolerant species, suggesting the community is exposed to stressors, only allowing hardy species to establish.

The SAV model outputs presented in this report were calculated indepedently of the field data and show best case scenarios for SAV colonization in the harbour. Figures 13-16 show only the potential areal cover of SAV and should not be used as an actual measure of areal extent related back to the fish habitat BUI. We have calculated areal extent to give an estimate of theoretical maximum amount of vegetation one might measure in the Harbour, which can be used to guide the RAP's delisting targets. The model outputs are informative but do not represent actual conditions. For example, there were no data collected on the south shoreline of the harbour, but there is thought to be little to no vegetation in this area (D. Reddick pers. comm.), which is in contrast to the model predictions; therefore currently, the model overestimates areal extent along the southern shore. Instead of Secchi being the main driver limiting vegetation growth, it is expected that soft, unconsolidated substrates and shipping activities are the reason SAV cannot establish along the southern shore. Contaminants may also play a role in limiting SAV establishment, especially near Randle Reef, however, we have not yet investigated this supposition. Future work should focus on a stratified field design, covering a suite of variables (depth, fetch, substrate, water clarity) across the range of those variables in the harbour. If the model is not deemed accurate enough (>80% accuracy threshold was decided upon *a priori,* though it is up to the RAP to accept our recommendation), then a new model will need to be developed, likely based off current modelling efforts (Tang et al. in prep, Midwood et al. in prep).

Modelling efforts suggest that between 273-331 ha of SAV could potentially establish in Hamilton Harbour. This range is surprising since it suggests that a water level difference of slightly more than 1 m can have a considerable effect (nearly 20% increase from high water to low water levels). Fluctuations in water level can extend the nearshore area (and potential SAV colonization) of the harbour by providing gentler slopes (Duarte & Kalff 1986) into areas with higher Secchi values (Chambers & Kalff 1985). Expanding modelling efforts across a wider range of water depths would help to identify the optimal range of waters depths that would maximize the potential extent of SAV in the harbour. Given water depth limits of SAV on the outer edge of the nearshore, stochastic or consistently high water levels may have a large impact on the areal extent of SAV for the Harbour.

When a Secchi cutoff was overlaid with the model output, predicted areal extent of SAV dropped by 25%. A visual inspection of the data suggested that the model that incorporated a Secchi cut-off was a better match to the field data; this was particularly true in Carroll's Bay and Indian Creek (areas with no vegetation). This result also suggests that the design of transect placement in the harbour is biased towards vegetated areas since we would expect no significant improvement in model accuracy if we removed areas from the model. Future surveys should use a stratified random approach to pick transects. The southern shore lacks acoustic data but we would expect little to no vegetation, suggesting factors other than Secchi such as dredging, sedimentation, steep slopes and deep depths, contaminants, etc. are limiting SAV growth, and that data should be collected along the south in the future to validate the model. The Secchi cutoff was done in GIS rather than incoporated into the model. As Secchi (and other factors that influence SAV growth such as, water clarity and substrate (Kalff 2002) are included in the model, we suspect the model's accuracy will improve. It is important to note that useful Secchi data can be a challenge to collect; point sampling is not representative of Secchi conditions, especially in areas with outflows such as rivermouths. Long-term, high-frequency (hours) sampling is needed to characterize Secchi conditions in the harbour, though this may be logistically infeasible or may not improve accuracy of the SAV model significantly to justify the intensity of sampling.

The current HH SAV model was evaluated with the 2016 SAV acoustic survey results. With a cuttoff of acceptibility for SAV models of >80% correctly predicted data, Hamilton Harbour's presence/absence was 82% and 83% accurate for the 5% and 1% SAV density thresholds, respectively. Cohen's Kappa showed a moderate-good agreement for the HH SAV model; Tang et al. (in prep) summarizes the classification of Kappa scores for model evaluation from (Cohen 1960, Fleiss 1971, Landis and Koch 1977). This model is also useful for simple datasets; it's accurate despite lacking other variables important to SAV such as water clarity. If the RAP requires density estimates (% cover) of SAV then it is recommended that a new model be developed that includes additional variables to more accurately estimate SAV in the harbour.

For the % SAV cover models RMSE ranged from 30.4 to 30.7 among scenarios with survey depth and calculated DEM depths (Table 3). These values fall within range of other % SAV cover models from Cootes Paradise (RMSE range 25.5-27.2) (Tang et al. in prep), and Toronto Harbour (RMSE range 23.5-33.3) (Midwood et al. in prep). Based on RMSE and WAPE, the % SAV cover models had a moderate performance when compared with the presence/absence SAV models, this is not surprising as specific SAV density of a given area is hard to predict as coastal SAV growth are often patchy and are hard to predict exact densities. Given the BUI target addresses areal (ha) extent of SAV, the current presence/absence model is likely sufficient to estimate SAV in the Harbour; however, estimates of % SAV cover are likley too inaccurate to reliably use.

CONCLUSION

The 2012 BUI #14 (Fish and Wildlife Habitat) fact sheet of Hamilton Harbour (http://hamiltonharbour.ca/resources/documents/2012_FactSheet14_FW_Habitat.pdf) tracks the progress towards delisting this BUI. The target for aquatic habitat is 500 ha for the harbour and surrounding wetlands (230 ha in HH and Windermere Basin). As per the 2012 fact sheet, the harbour had a calculated extent of 239 ha (for aquatic vegetation, SAV, and emergent vegetation), but the total areal extent was still under 500 ha, showing that the AOC remains impaired but the harbour exceeds the subtarget. The model output scenarios show potential areal extents from 248-331 ha and exclude any potential acreage from Windermere Basin, Cootes Paradise, and Grindstone Marsh, however, the model is likely overestimating % SAV cover on the southern and eastern shores. Though not surveyed in 2016, we measured the area of Windermere Basin to estimate how much vegetation it may add to the harbour. Assuming Windermere Basin and its connecting stream to the harbour is 100% vegetated (since it is a wetland and field crews have confirmed this, D. Reddick, pers. comm.) with either SAV or emergent vegetation, we can expect it to add 15.2 ha to our estimates. Currently, at the model's lowest predicted range of colonization, the model shows little improvement in terms of areal extent since 2012. Given the large effect water depth can have on areal extent (up to 20% according to our model), high water levels in 2017 and likely 2018 may have a negative effect on SAV bed extents for the Harbour. With increased stochastity of water levels, and the predicted fluctuation of SAV bed extent from our models, it may be difficult to accurately assess and calculate areal SAV bed extent without frequent (yearly or bi-yearly) monitoring (Short et al. 2016).

It is recommended the RAP discuss whether areal extent is the appropriate and accurately measurable metric for delisting. The model used in the current report (or subsequent refined models) could guide areal extent targets for the RAP. Applying the model to a range of water level scenarios will determine the maximum areal extent of vegetation at any specific water level (we have only tested two water levels in this report). Targets would then be 230 ha (RAP target) relative to the max areal extent at the current year's water level. Given the calculation for maximum areal extent would be under ideal conditions, the actual target could be proportionally lower, perhaps 80% relative to maximum areal extent at *x* water level. The result would be a more flexible target that is linked to annual water levels. One could also add in a time component that requires the harbour hits the flexible target *x* years in a row.

The presence/absence model is more than 80% accurate and useful for estimates of where SAV will occur in the Harbour, however, currently we cannot accurately estimate SAV densities. It is recommended that the RAP decide on whether the presence/absence model is sufficient, or if development of a new model based on available models, such as Tang et al. (in prep) Cootes Paradise SAV model are needed for density estimates. Since density estimates are not a part of the BUI target, we suggest that the presence/absence model is sufficient for the target. Any future surveys of SAV should include a stratified random design (stratified by depth, exposure, and some measure of water clarity) around the harbour to aid in validation of the SAV model. With a validated model, areal extent can be calculated for the harbour and be measured against the BUI's delisting targets. Ultimately SAV measures are a proxy for fish habitat and the data in this report and future surveys should be compared with fish community estimates (Boston et al. 2016) to show habitat associations of fish and determine if habitat (vegetation at least) is a limiting factor for fish populations. Using a model validated with data from periodic surveys is a vital tool for the RAP to determine the status of the BUI and assess the potential for its delistment, with an ultimate goal of delisting the whole AOC. This report provides recommendations and will serve as another line of evidence towards these goals.

ACKNOWLEDGEMENTS

The authors gratefully acknowledges the able assistance of the field crew consisting of GLLFAS personnel David T. Reddick, Christine Boston, Sommer Abdel-Fattah, and Federal Student Work Experience Program students Abby Wynia, Stephanie Smodis, and Sami Kurani. Jacqueline Dosen of GLLFAS provided maps and formatting using ArcMap. Ja also ran the SAV models using different scenarios. Funding was provided by the Great Lakes Action Plan, administered and led by Environment and Climate Change Canada, which funds research and monitoring in Areas of Concern.

REFERENCES

Best, E.P.H., 1982. The aquatic macrophytes of Lake Vetchen. Species composition, spatial distribution and production. Hydrobiologia 95: 65–77.

Binion G.R., Allen, M.S., Catalano, M.J. and Pine, W.E. III. 2008. Direct and indirect estimates of black crappie size selectivity to a common sampling gear: Potential biases and limitations for assessment. Fish Res. 95: 47-54. doi:10.1016/j.fishres.2008.07.010.

BioSonics 2016. Visual Habitat User Guide. Seattle, WA.

Boston, C. M., Randall, R. G., Hoyle, J. A., Mossman, J. L., and Bowlby, J. N. 2016. The fish community of Hamilton Harbour, Lake Ontario: Status, stressors, and remediation over 25 years. Aquat. Ecosyst. Health 19(2): 206-218. doi:10.1080/14634988.2015.1106290.

Carpenter, S. R. and Titus, J. E. 1984. Composition and spatial heterogeneity of submersed vegetation in a soft water lake in Wisconsin. Vegetatio. 57(2-3): 153–165. doi:10.1007/BF00047313.

Carpenter, S. R. and Lodge, D. M. 1986. Effects of submerged macrophytes on ecosystem processes. Aquat. Bot. 26(3-4): 341-370. doi:10.1016/0304-3770(86)90031-8.

Chambers, P.A., Kalff, J. 1985. Depth distribution and biomass of submersed aquatic macrophytes communities in relation to Secchi depth. Can. J. Fish. Aquat. Sci. 42: 701–709. doi:10.1139/f85-090.

Chick, J. H. and McIvor, C. C. 1994. Patterns in the abundance and composition of fishes among beds of different macrophytes - viewing a littoral-zone as a landscape. Can. J. Fish. Aquat. Sci. 51(12): 2873-2882. doi:10.1139/f94-286.

Croft, M.V., Chow-Fraser, P., 2007. Use and Development of the Wetland Macrophyte Index to Detect Water Quality Impairment in Fish Habitat of Great Lakes Coastal Marshes. J. Great Lakes Res. 33(3):172-197. doi: 10.3394/0380-1330(2007)33[172:UADOTW]2.0.CO;2.

Crowder, A. and Bristow, M. 1986. Aquatic macrophytes in the Bay of Quinte, 1972-82. *In* Project Quinte: point-source phosphorous control and ecosystem response in the Bay of Quinte, Lake Ontario. Edited by C.K. Minns, D.A. Hurley, and K.H. Nicholls. Can. Spec. Publ. Fish. Aquat. Sci. pp. 114-127.Cohen, J. 1960. A Coefficient of Agreement for Nominal Scales. Educ. Psychol. Meas. 20: 37–46. doi: 10.1177/001316446002000104.

Duarte, C. M., Kalff, J. 1986. Littoral slope as a predictor of the maximum biomass of submerged macrophyte communities. Limnol. Oceanogr. 31(5): 1072–1080. doi:10.4319/lo.1986.31.5.1072.

Doolittle, A.G., Bakelaar, C.N., and Doka, S.E. 2010. Spatial framework for storage and analyses of fish habitat data in Great Lakes' Areas of Concern: Hamilton Harbour geodatabase case study. Can. Tech. Rep. Fish. Aquat. Sci. 2879: x + 67 p.Fleiss, J.L. 1971. Measuring nominal scale agreement among many raters. Psychol. Bull. 76: 378–382. doi: 10.1037/h0031619.

Gilinsky, E. 1984. The role of fish predation and spatial heterogeneity in determining benthic community structure. Ecology 65(2): 455-468. doi:10.2307/1941408.

Gardner Costa, J., Leisti, K.E., Midwood, J.D., Doka, S.E. 2018. Submerged aquatic vegetation survey in the Bay of Quinte, 2015. Can. Tech. Rep. Fish. Aquat. Sci. 42 p.

Hamilton Harbour Remedial Action Plan. 2012. 2012 FactSheet14 FW Habitat. http://hamiltonharbour.ca/resources/documents/2012_FactSheet14_FW_Habitat.pdf 2 p.

Kalff, J. 2002. Limnology. Upper Saddle River, NJ: Prentice Hall, 592 p.

Keddy, P. A. 1983. Shoreline vegetation in Axe Lake, Ontario: effects of exposure on zonation patterns. Ecology 64(2):331-344. doi: 10.2307/1937080Landis, J.R., and Koch, G.G. 1977. The Measurement of Observer Agreement for Categorical Data. Biometrics 33: 159. doi: 10.2307/2529310.

Leisti, K.E., Millard, E. S. and Minns, C. K. 2006. Assessment of submergent macrophytes in the Bay of Quinte, Lake Ontario, August 2004, including historical context. Can. Manuscr. Rep. Fish. Aquat. Sci. 2762: ix+84p.

Leisti, K. E., Theÿsmeÿer, T., Doka, S. E., & Court, A. 2016. Aquatic vegetation trends from 1992 to 2012 in Hamilton Harbour and Cootes' Paradise, Lake Ontario. Aquat. Ecosyst. Health 19(2): 219–229. doi:10.1080/14634988.2015.1129257.

Minns, C. K., Cairns, V. W., Randall, R. G., Crowder, A., & McLaughlin, A. 1993. Macrophyte surveys of littoral habitats in Great Lakes' Areas of Concern: The Bay of Quinte, Hamilton Harbour, and Severn Sound - 1988 to 1991. Can. Tech. Rep. Fish. Aquat. Sci. 1936: viii + 60p.

Randall, R. G., Minns, C. K., Cairns, V.W. and Moore, J.E. 1996. The relationship between an index of fish production and submerged macrophytes and other habitat features at three littoral areas in the Great Lakes. Can. J. Fish. Aquat. Sci. 53(S1): 35-44. doi:10.1139/f95-271.

Søndergaard, M., Johansson, L. S., Lauridsen, T. L., Jørgensen, T. B., Liboriussen, L., & Jeppesen, E. 2010. Submerged macrophytes as indicators of the ecological quality of lakes. Freshwater Biol. 55(4): 893–908. doi:10.1111/j.1365-2427.2009.02331.x.

Short, F. T., Kosten, S., Morgan, P. A., Malone, S., & Moore, G. E. 2016. Impacts of climate change on submerged and emergent wetland plants. Aquat. Bot. 135: 3-17. doi: 10.1016/j.aquabot.2016.06.006.

Singh K.P., Basant A., Malik A., Jain G. 2009. Artificial neural network modeling of the river water quality-A case study. Ecological Modelling, 220(6): 888-895.

Stewart, C., Freedman, B., 1989. Comparison of the macrophyte communities of a clearwater and a brownwater oligotrophic lake in Kejimkujik National Park, Nova Scotia. Water Air Soil Poll., 46:335–341.

Weaver, M. J., Magnuson, J. J. and Clayton, M.K. 1997. Distribution of littoral fishes in structurally complex macrophytes. Can. J. Fish. Aquat. Sci. 54(10): 2277-2289. doi:10.1139/cjfas-54-10-2277.

Werner, E. E., Gilliam, J. F., Hall, D.J. and Mittelbach, G.G. 1983. An experimental test of the effects of predation risk on habitat use in fish. Ecology 64(6): 1540-1548. doi:10.2307/1937508.

Wood, K. A., Stillman, R. A., Clarke, R. T., Daunt, F., & O'Hare, M. T. 2012. Measuring submerged macrophyte standing crop in shallow rivers: A test of methodology. Aquat. Bot. 102: 28–33. doi:10.1016/j.aquabot.2012.04.006

TABLES

Table 1. SAV bed extent (transect length (m)), maximum depth of colonization (m), percent (%) SAV cover ± std. dev (and min & max %) for reference transects in Hamilton Harbour.

Transect	SAV Bed extent (m)	Max colonization (m)	Mean % SAV cover	Standard Deviation	Min	Max
1	166.3	2.45	89	21	20	100
3	287.5	4.58	89	22	10	100
6	173.0	3.82	83	25	20	100
9	187.2	4.78	90	23	10	100
12	132.6	3.27	90	21	20	100
15	95.9	5.21	94	18	30	100
19	0.0	0.00	0	0	0	0
21	82.0	4.20	55	33	10	100
25	71.0	3.09	77	35	10	100
26	11.5	3.05	94	10	70	100
29	9.3	4.04	85	20	40	100
31	64.9	2.14	64	28	10	100
35	134.8	2.57	70	32	10	100

Table 2. Total area of SAV modelled for Hamilton Harbour in 2016. This table summarizes 3 modelling scenarios (high water max potential colonization, chart datum water max potential colonization, and chart datum, SAV colonization with 0.6 m Secchi cutoff) and tabulates area (ha) of SAV for 5 classes: 0 (no SAV), 1-25 (sparse), 26-50 (moderate), 51-75 (moderate-dense), 76-100 (dense). Values in red are not included in the "total veg" calculation.

Water Level	**SAV Colonization**	**Percent (%) SAV Cover**	**Area (Ha)**
High	Max	0	1816
		25	41
		50	53
		75	171
		100	7
		Total Veg	**273**
Chart datum	Max	0	1758
		25	50
		50	54
		75	210
		100	18
		Total Veg	**331**
	With Secchi cutoff	0	1842
		25	47
		50	44
		75	146
		100	11
		Total Veg	**248**

Table 3. Model validation and accuracy statistics of the Hamilton Harbour submerged aquatic (SAV) vegetation model using the SAV 2016 survey data. Validation was split between Presence / Absence model under two percentage thresholds (SAV presence threshold) and two different depth calculation methods (Survey depth and DEM calculated depth). Presence/Absence models were evaluated based on the Proportion of correct predictions (Accuracy) and the Cohan's kappa as an indicator for model agreement to the data. For SAV density models, the root mean square error (RMSE) and Weighted absolute percentage error (WAPE) was used instead for model validation.

Model	**Depth Calculation**	**SAV presence threshold**	**AUC**	**Omission Rate**	**Sensitivity**	**Specificity**	**Proportion Correct (%)**	**Kappa**	**Correct Predictions**	**Incorrect Predictions**	**RMSE**	**WAPE**
Survey Depth vs Predicted Depth	Survey and DEM calculated										0.61	55.50
SAV Presence/ Absence	Survey	> = 5%	0.84	0.03	0.97	0.72	0.83	0.67	5944	1223		
SAV Presence/ Absence	DEM calculated	> = 5%	0.84	0.03	0.97	0.72	0.83	0.67	5944	1223		
SAV Presence/ Absence	Survey	> = 1%	0.84	0.03	0.97	0.70	0.82	0.65	5873	1294		
SAV Presence/ Absence	DEM calculated	> = 1%	0.84	0.03	0.97	0.70	0.82	0.65	5873	1294		
SAV % cover	Survey										30.50	71.20
SAV % cover	DEM calculated										30.71	71.65

FIGURES

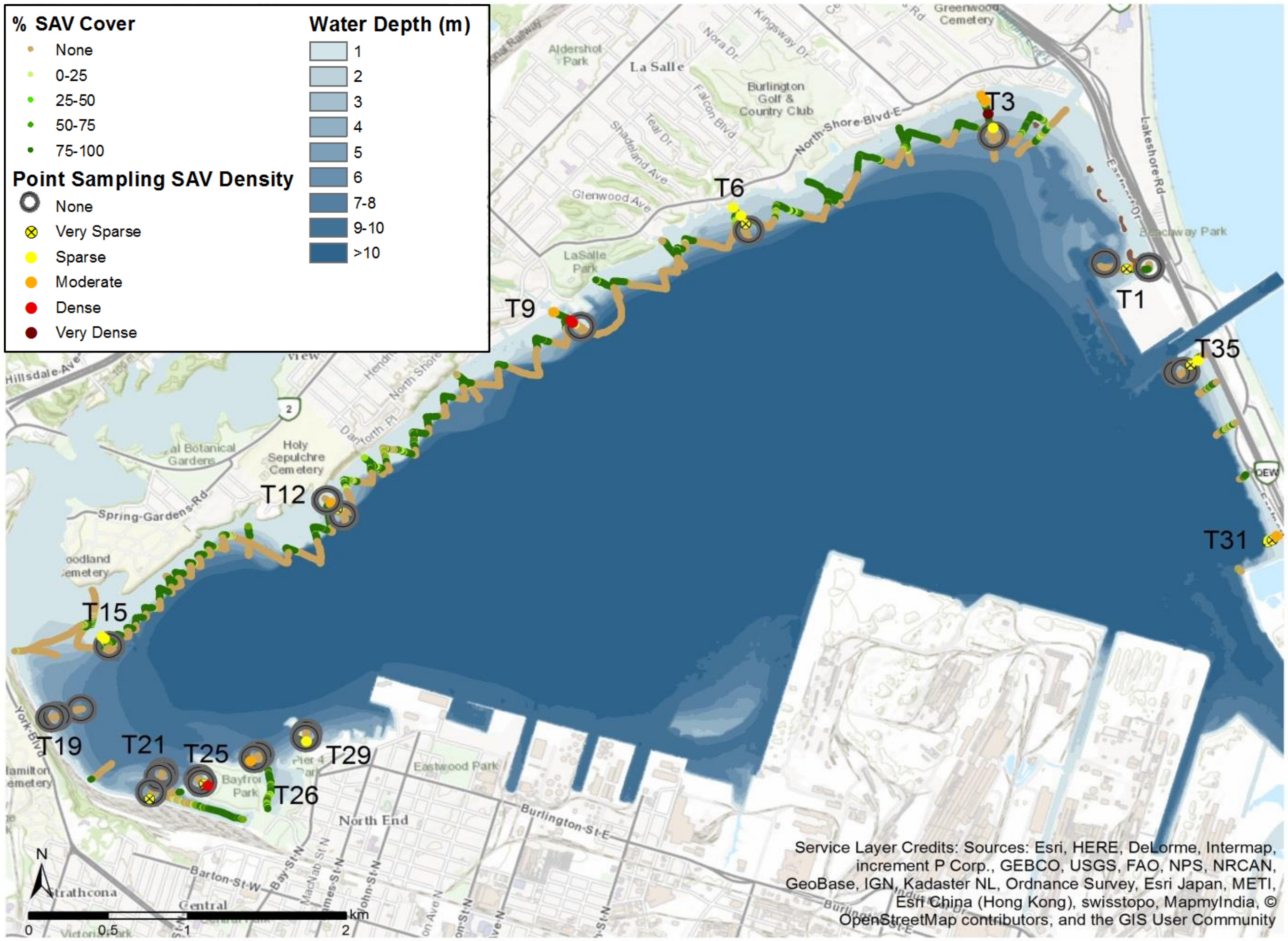


Figure 1. Transects from the 2016 Hamilton Harbour submerged aquatic vegetation (SAV) survey with analyzed data. Only reference transects are labelled. Both % SAV cover (from hydroacoustics) and SAV density (from point sampling) are displayed.

Figure 2. Map showing the zig-zag transects that were run during the 2016 Hamilton Harbour SAV survey in order to detect the edge of the bed. The 2 shades of blue indicate different acoustic files.

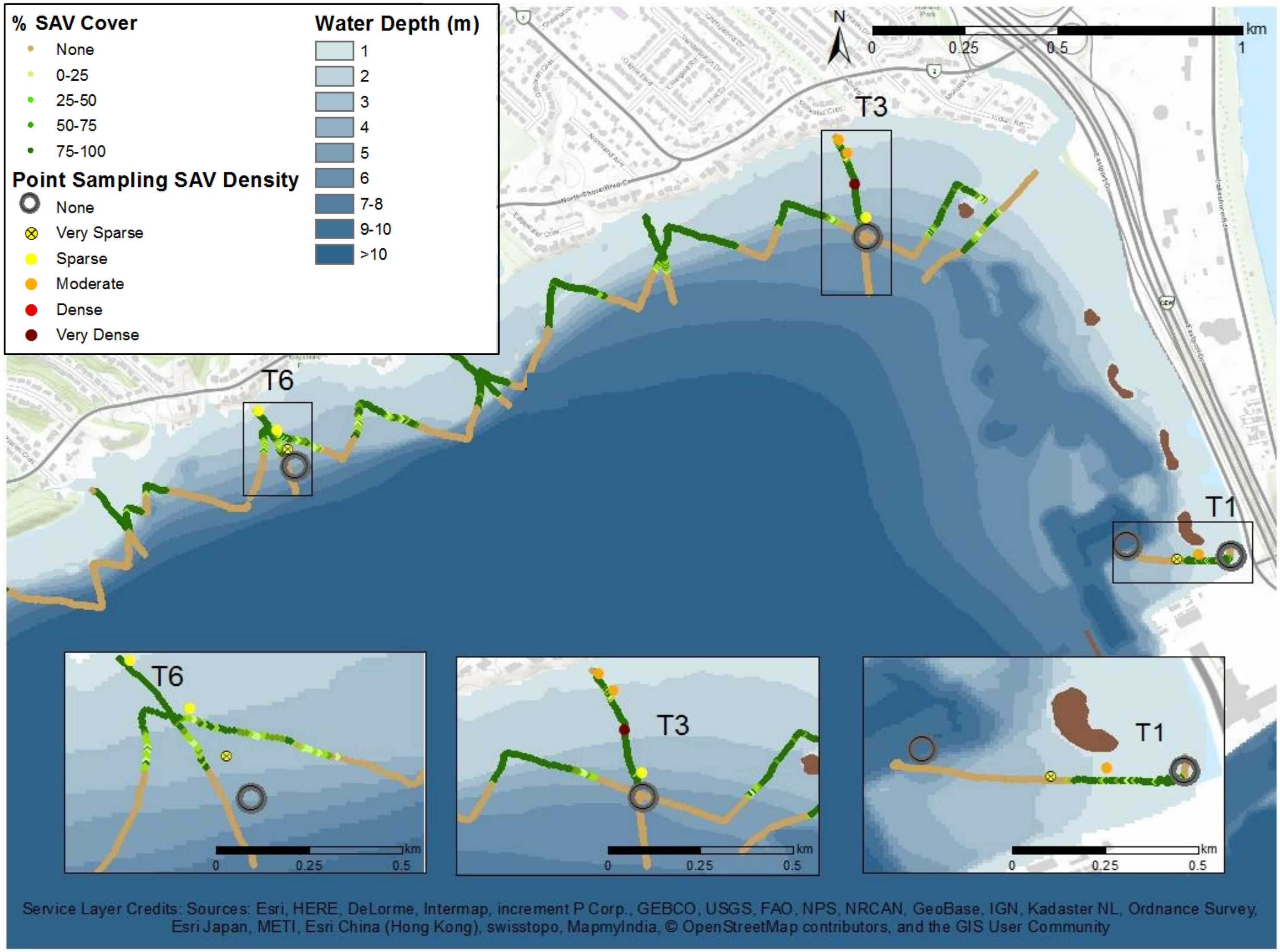


Figure 3. Percent SAV cover and density determined by the analysis of acoustic data from the Hamilton Harbour 2016 SAV survey. Included are the SAV results from the point sampling using a rake toss for transects 1, 3 and 6.

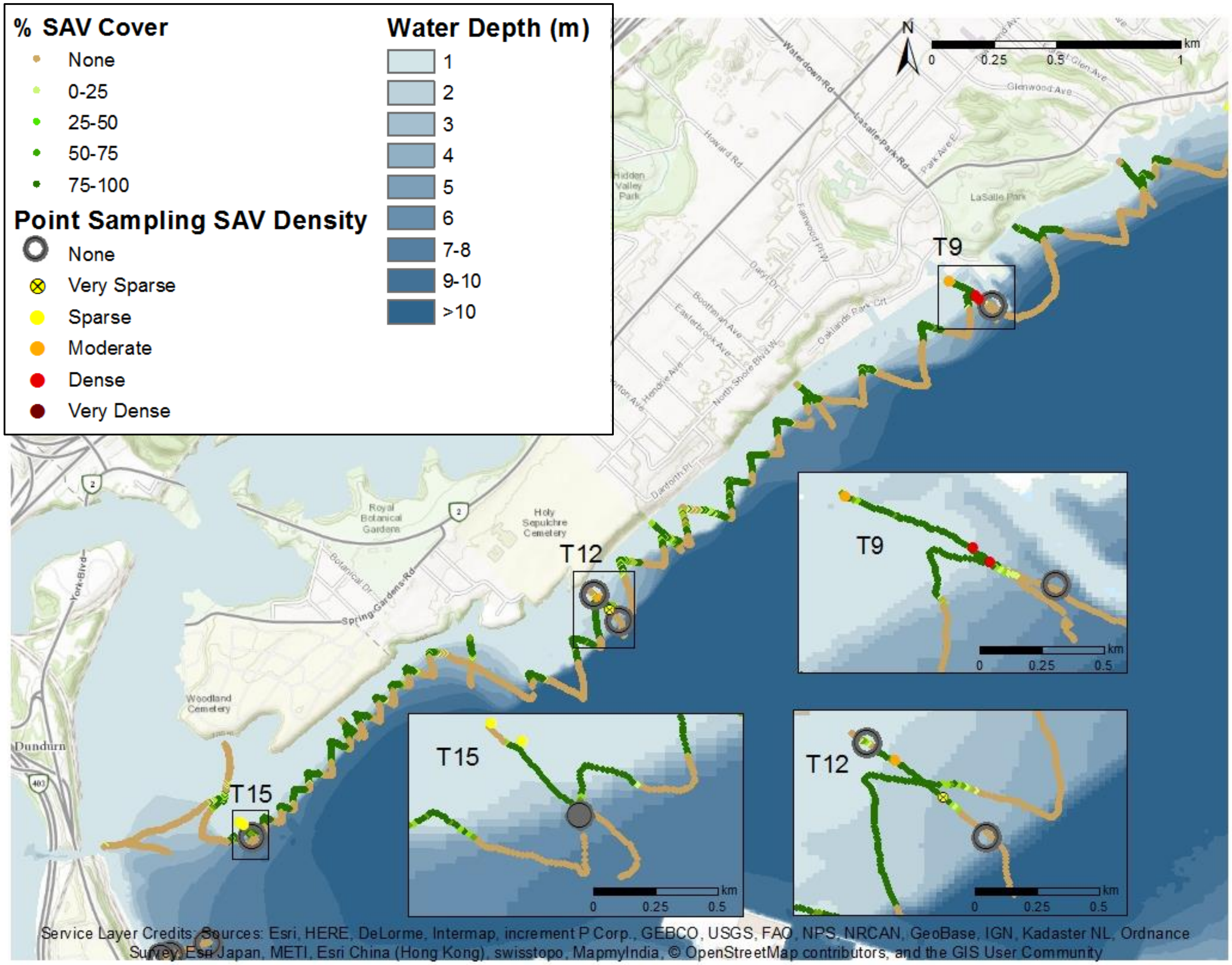


Figure 4. Percent SAV cover and density determined by the analysis of acoustic data from the Hamilton Harbour 2016 SAV survey. Included are the SAV results from the point sampling using a rake toss for transects 9, 12 and 15.

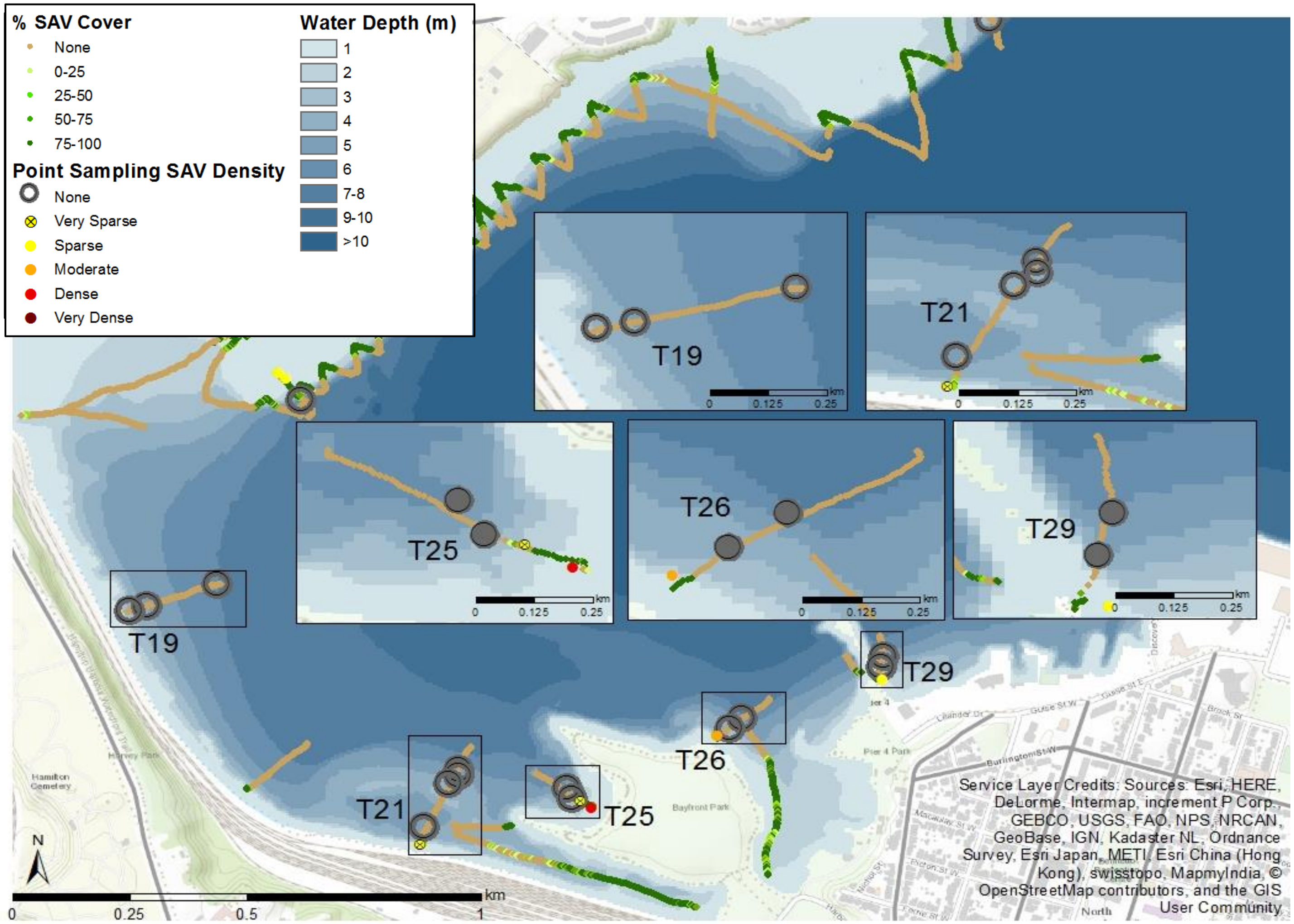


Figure 5. Percent SAV cover and density determined by the analysis of acoustic data from the Hamilton Harbour 2016 SAV survey. Included are the SAV results from the point sampling using a rake toss.

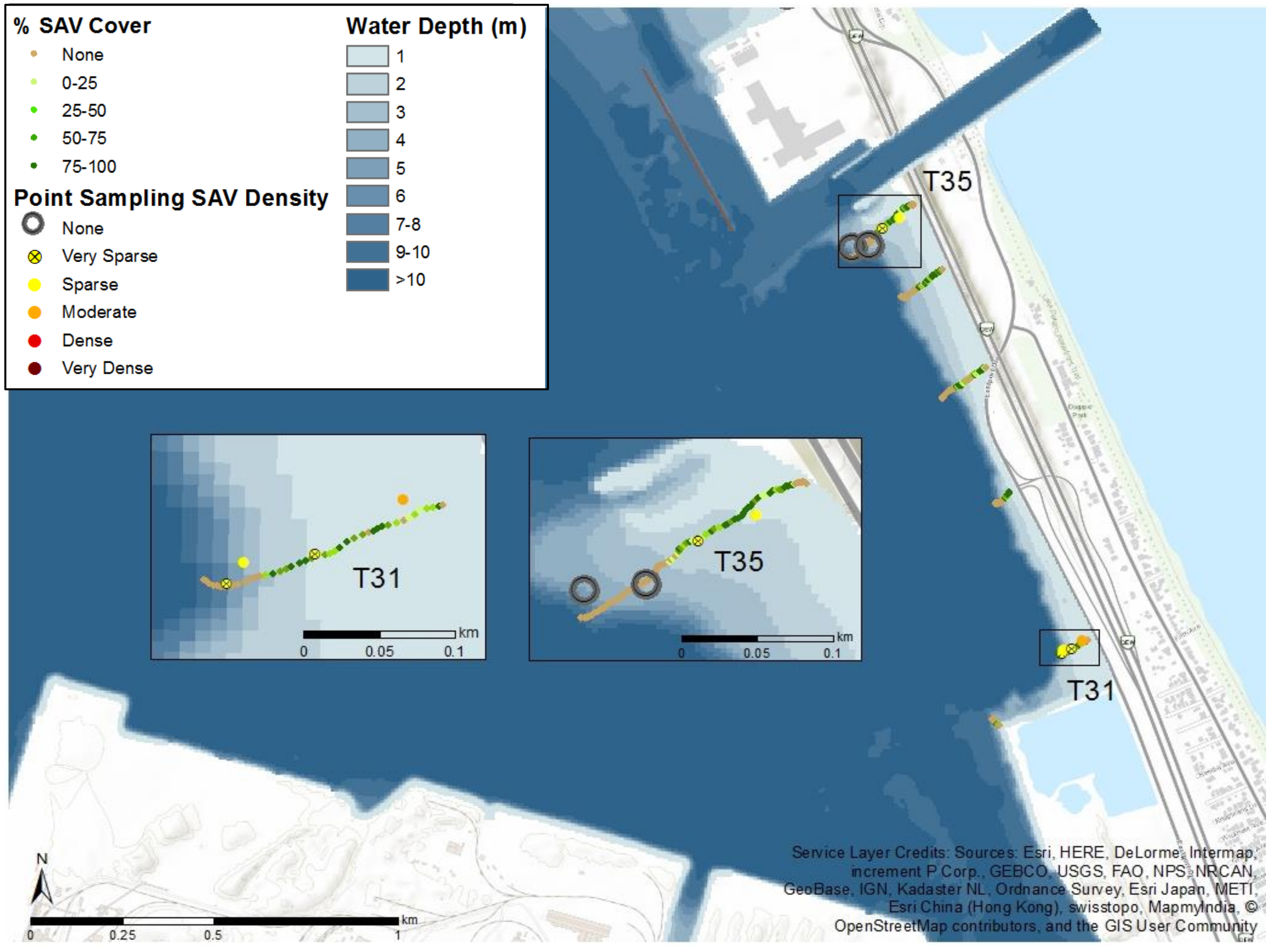


Figure 6. Percent SAV cover and density determined by the analysis of acoustic data from the Hamilton Harbour 2016 SAV survey. Included are the SAV results from the point sampling using a rake toss for transects 31 and 35.

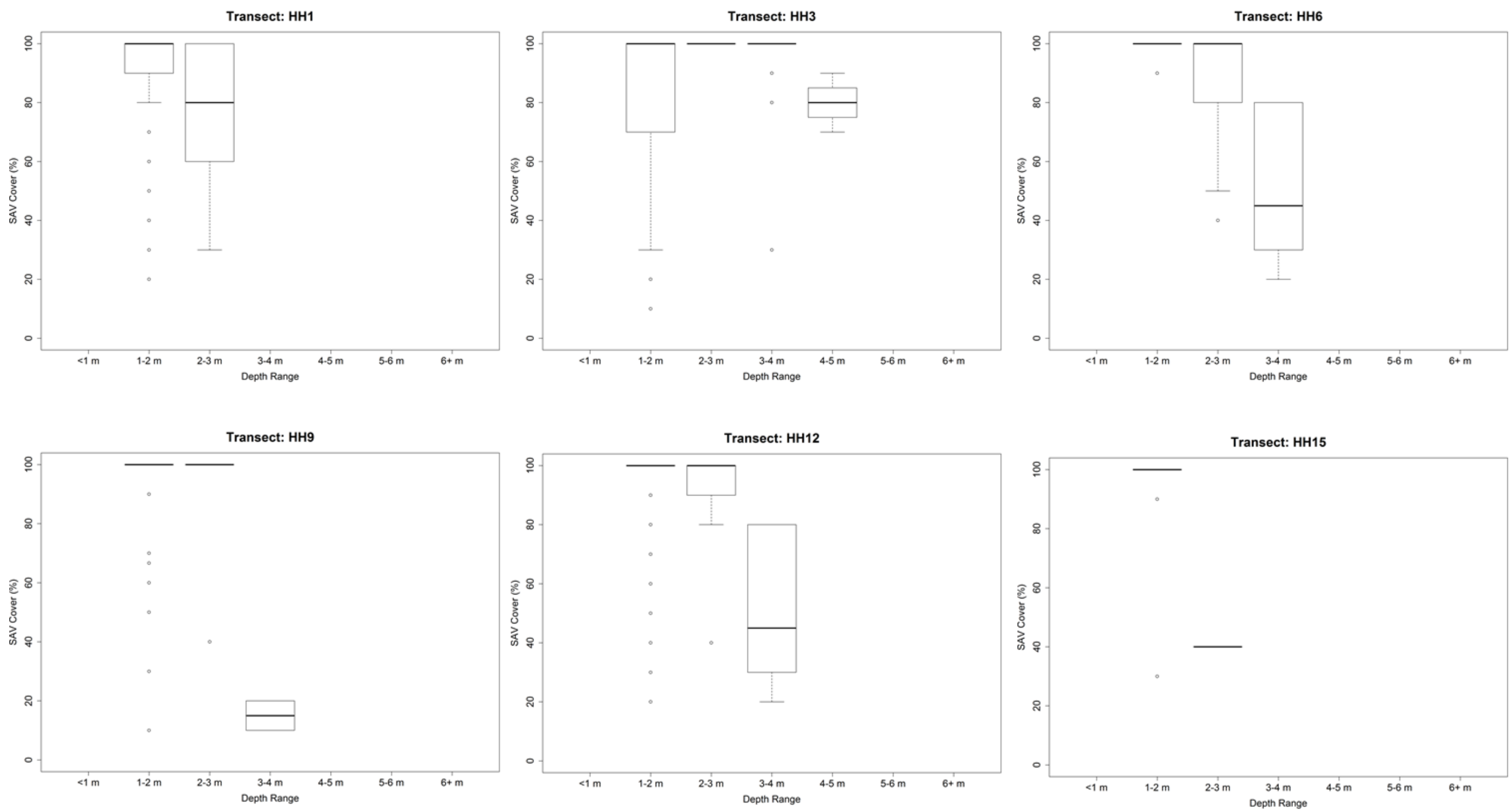


Figure 7. Boxplots by depth range of % SAV cover determined for reference sites (HH1-HH15) in Hamilton Harbour from the acoustic analysis of the 2016 survey data.

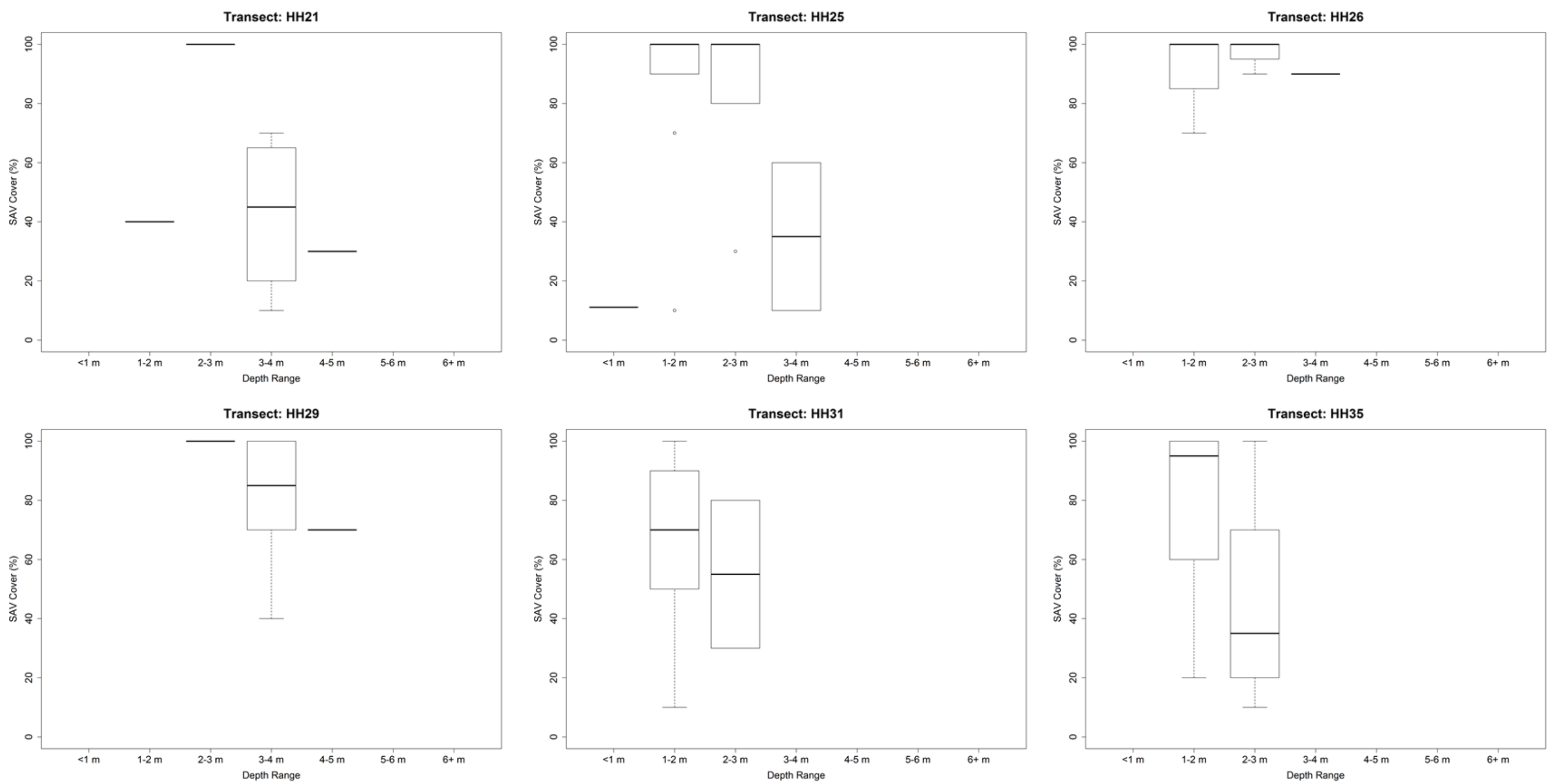


Figure 8. Boxplots by depth range of % SAV cover determined for reference sites (HH21-HH35) in Hamilton Harbour from the acoustic analysis of the 2016 survey data.

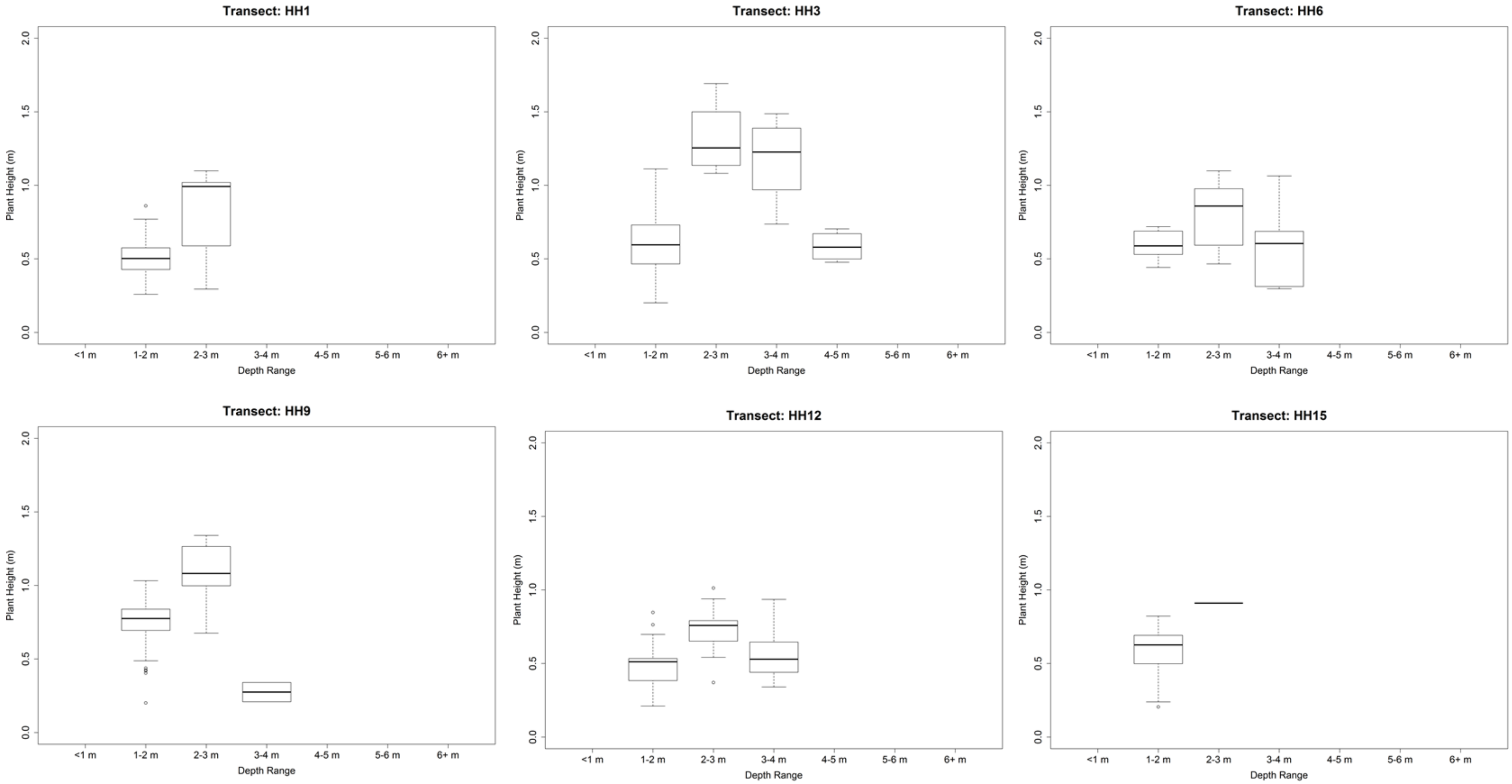


Figure 9. Boxplots by depth range of SAV plant height (m) determined for reference sites (HH1-HH15) in Hamilton Harbour from the acoustic analysis of the 2016 survey data.

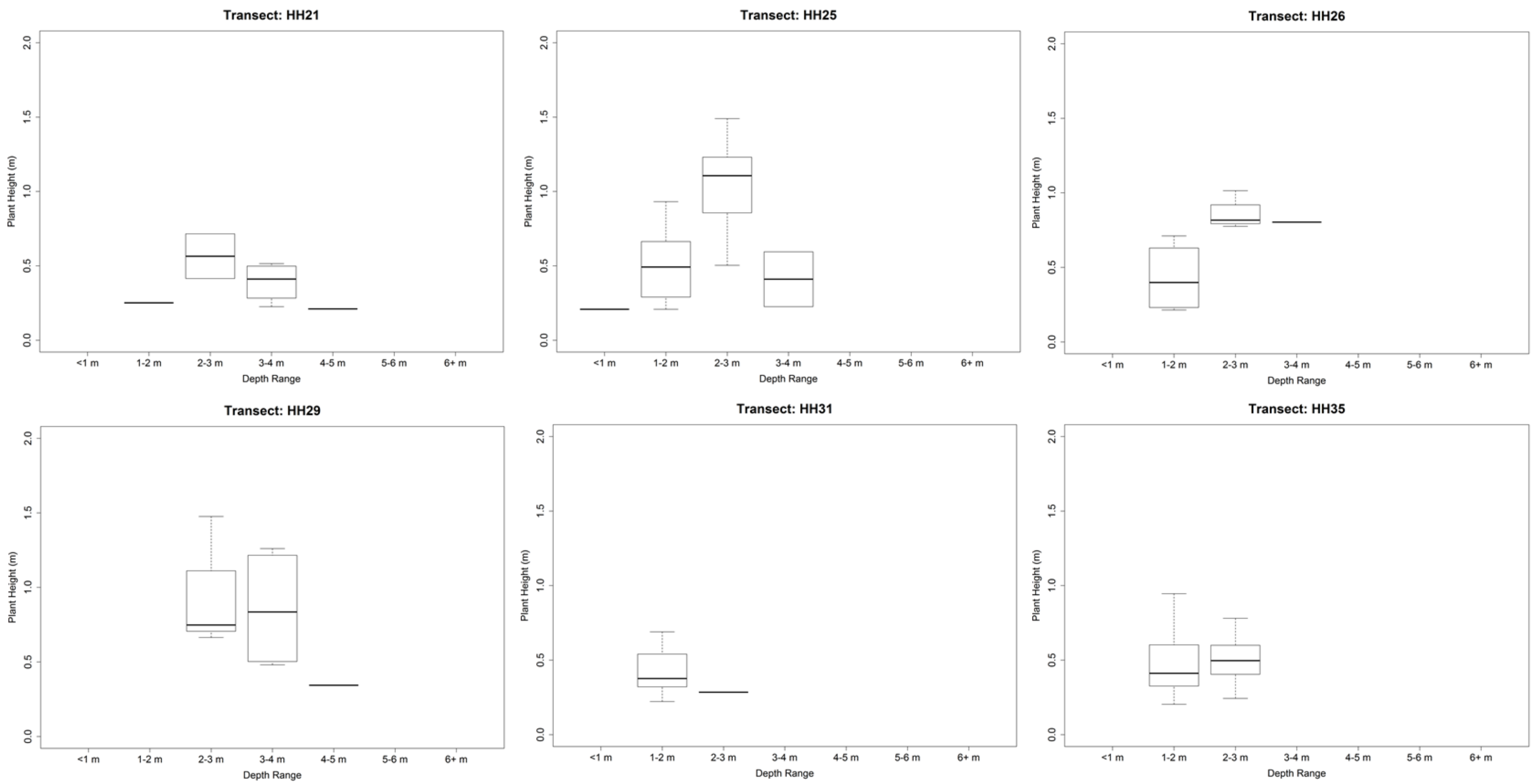


Figure 10. Boxplots by depth range of SAV plant height (m) determined for reference sites (HH21-HH35) in Hamilton Harbour from the acoustic analysis of the 2016 survey data.

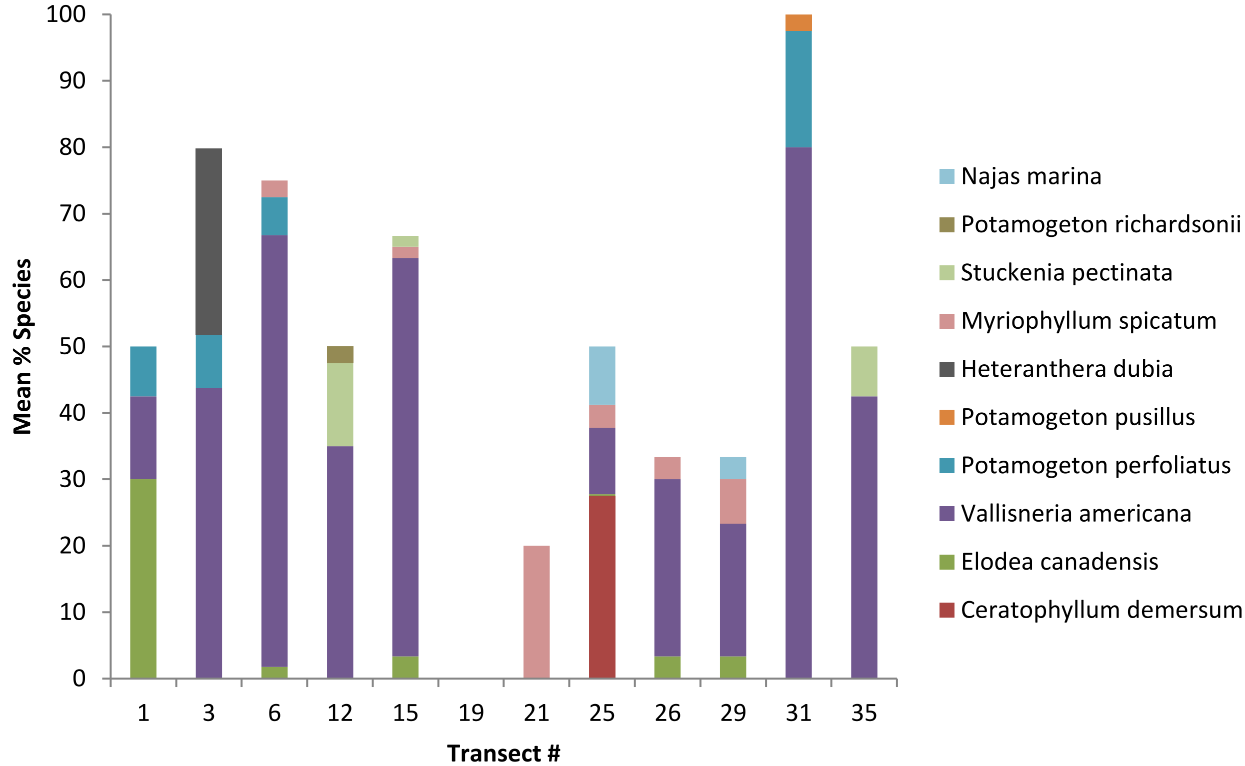


Figure 11. Relative frequency of occurrence of ten SAV species located via point sampling along the reference transects during the 2016 Hamilton Harbour SAV survey.

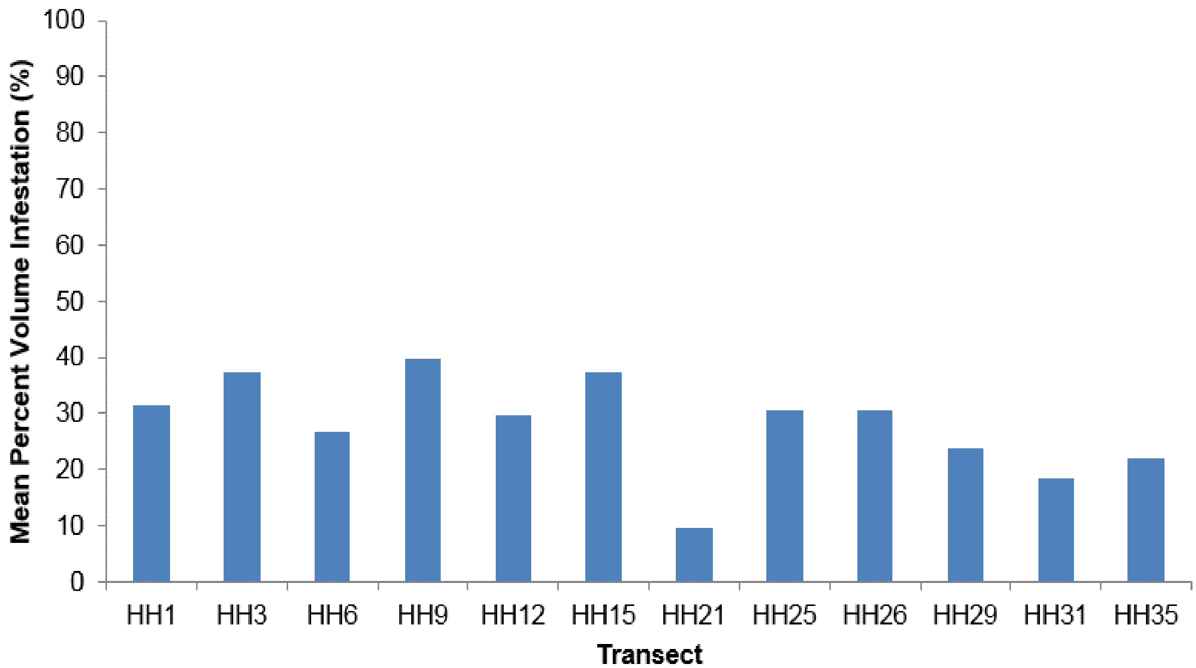


Figure 12. Percent Volume Inhabited (%) for reference transects in the 2016 Hamilton Harbour survey. PVI is a measure of the % of vertical water column plants occupy.

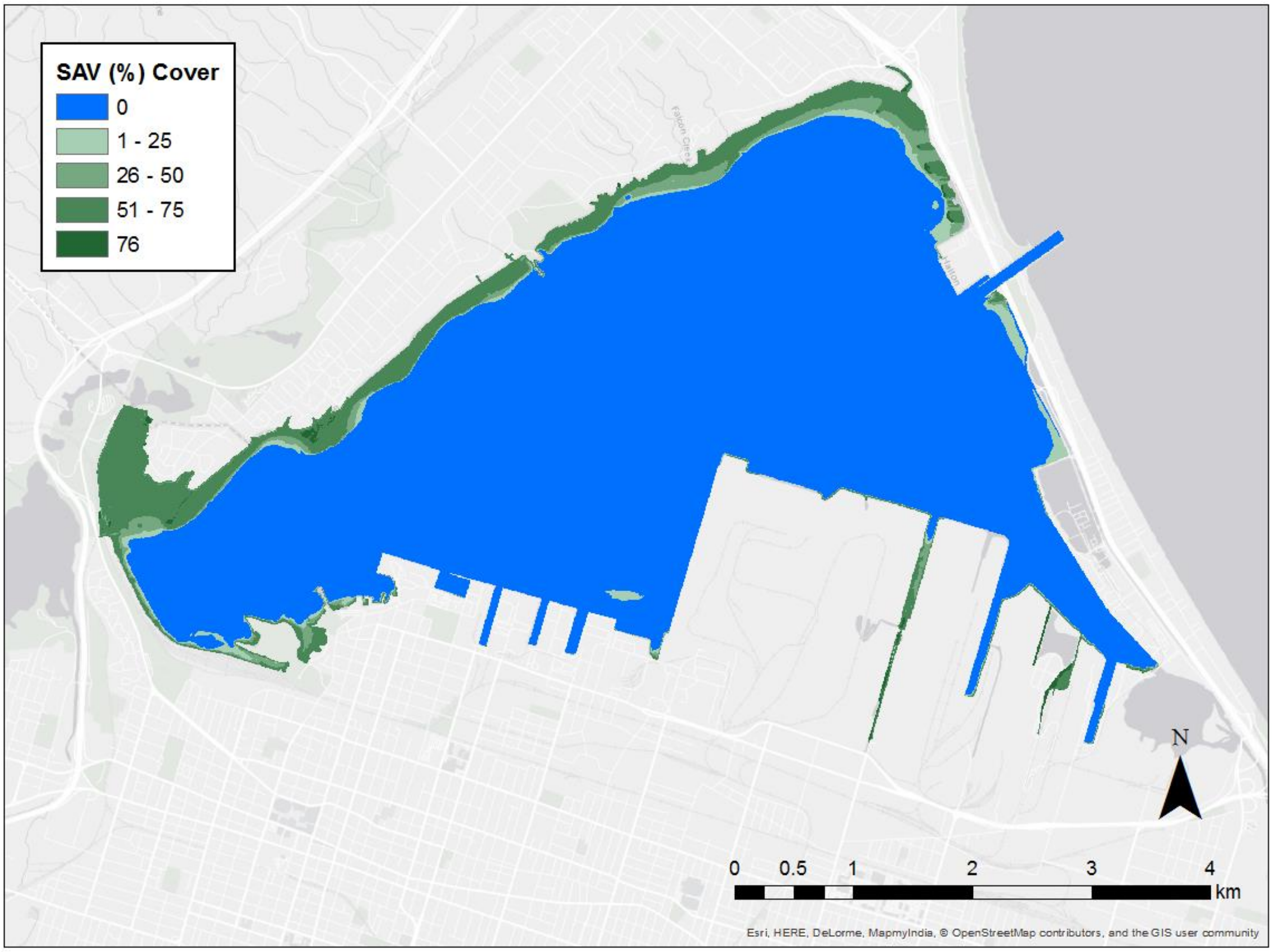


Figure 13. SAV model output for Hamilton Harbour 2016 at high water level with maximum SAV colonization (no Secchi limitations). Water level set at 75.7 m.

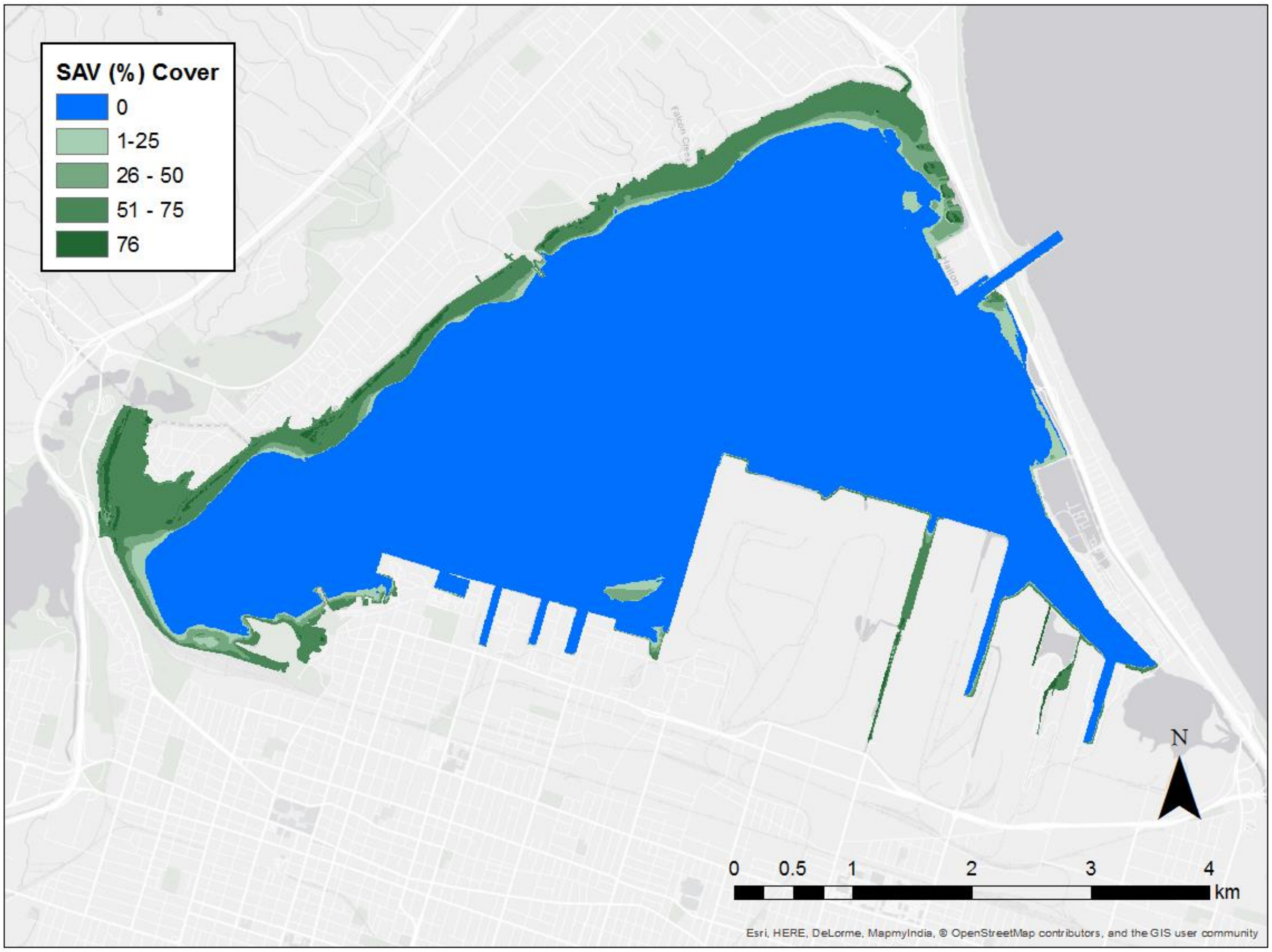


Figure 14. SAV model output for Hamilton Harbour 2016 at chart datum water level with maximum SAV colonization (no Secchi limitations). Water level set at 74.2 m (chart datum).

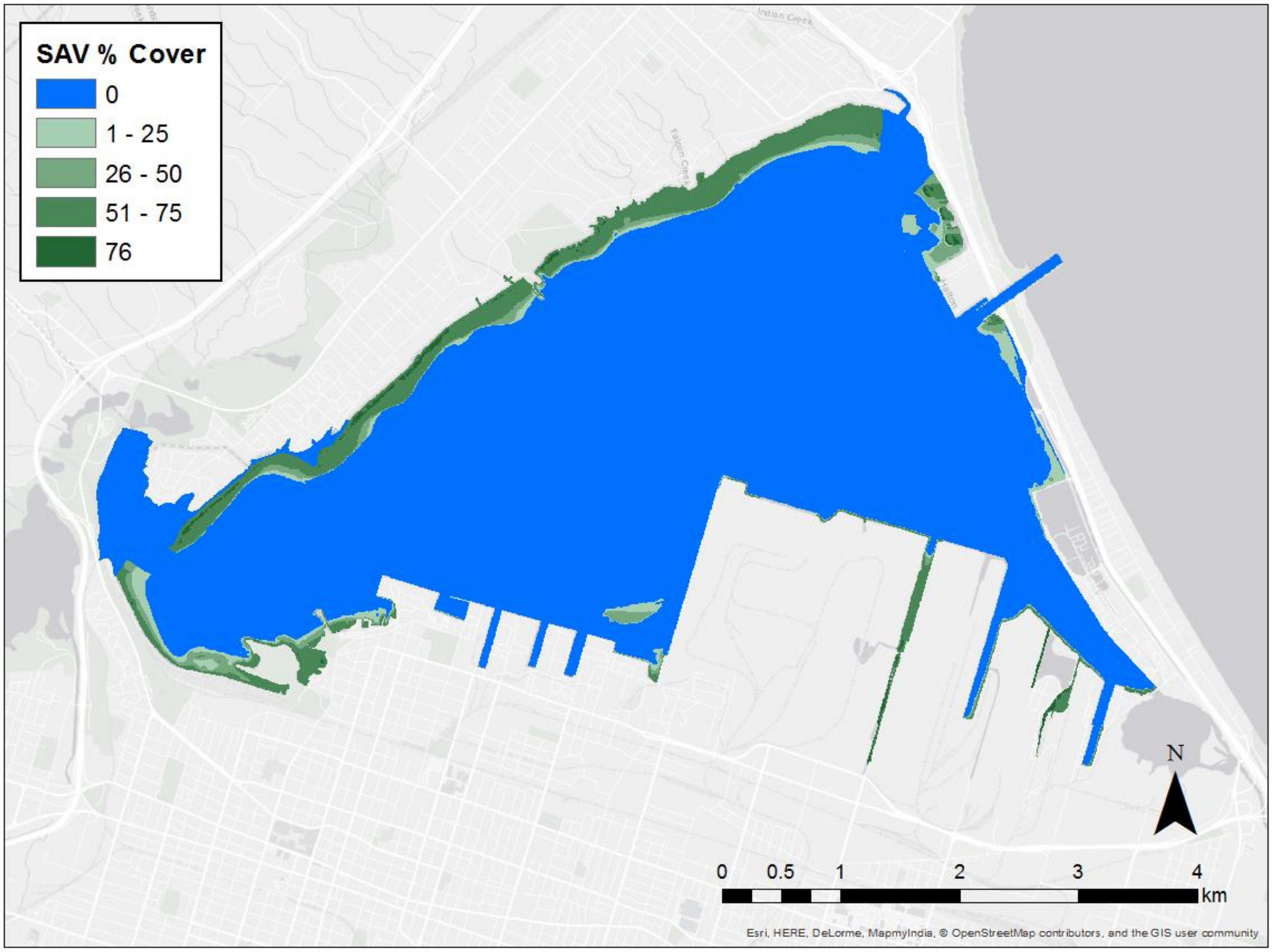


Figure 15. SAV model output for Hamilton Harbour 2016. Water level is at chart datum (74.2) with a Secchi cut-off of 0.6 m (any area with that value or lower is designated as 0% SAV cover in the output).

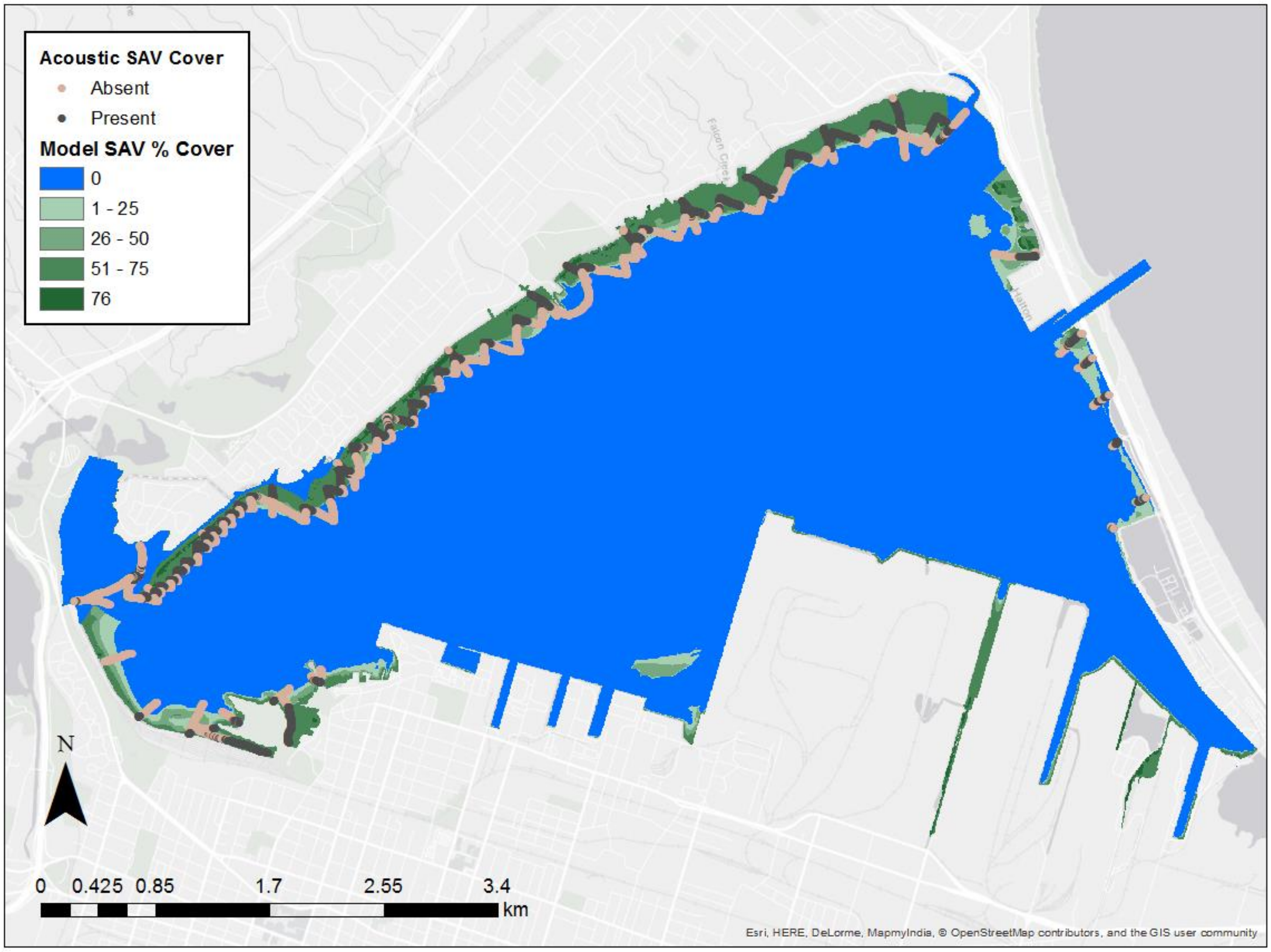
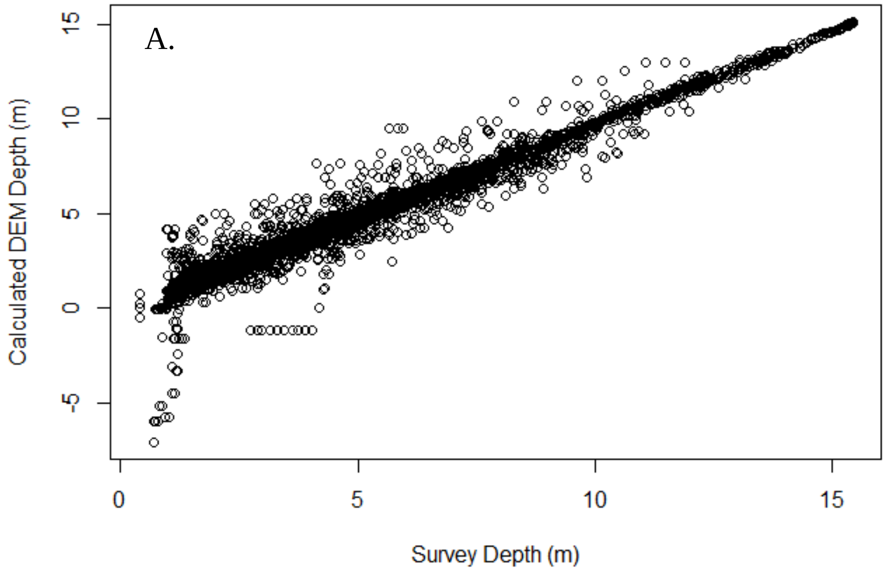


Figure 16. SAV model & acoustic data overlay for Hamilton Harbour 2016. Water level is at chart datum (74.2 m) with a Secchi cut-off of 0.6 m (any area with that value or lower is designated as 0% SAV cover in the output).



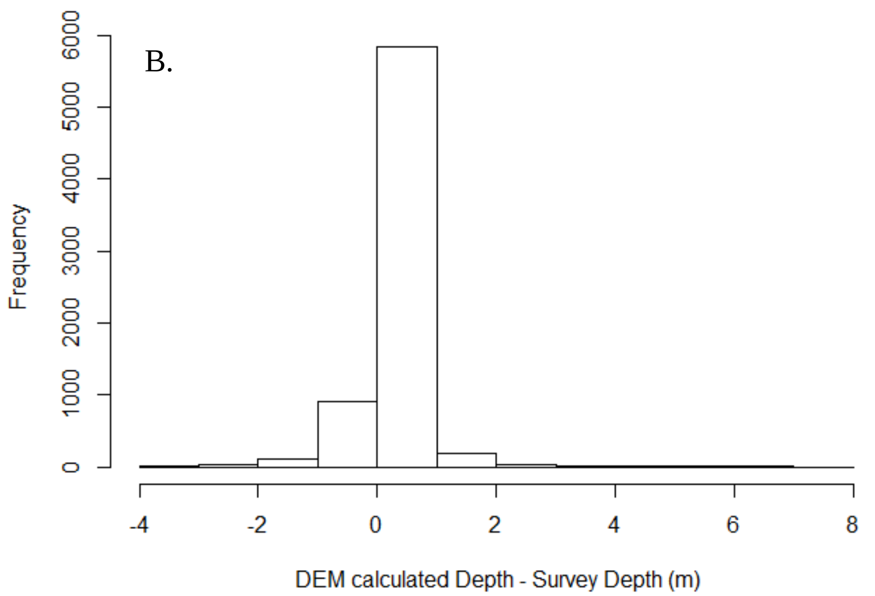


Figure 17. A) Depth (m) from Submerged Aquatic Vegetation (SAV) Survey vs calculated depth from the Hamilton Harbour Digital Elevation Model (DEM; Doolittle 2010). B) Frequency distribution of the difference between SAV Survey Depth and DEM calculated Depth.

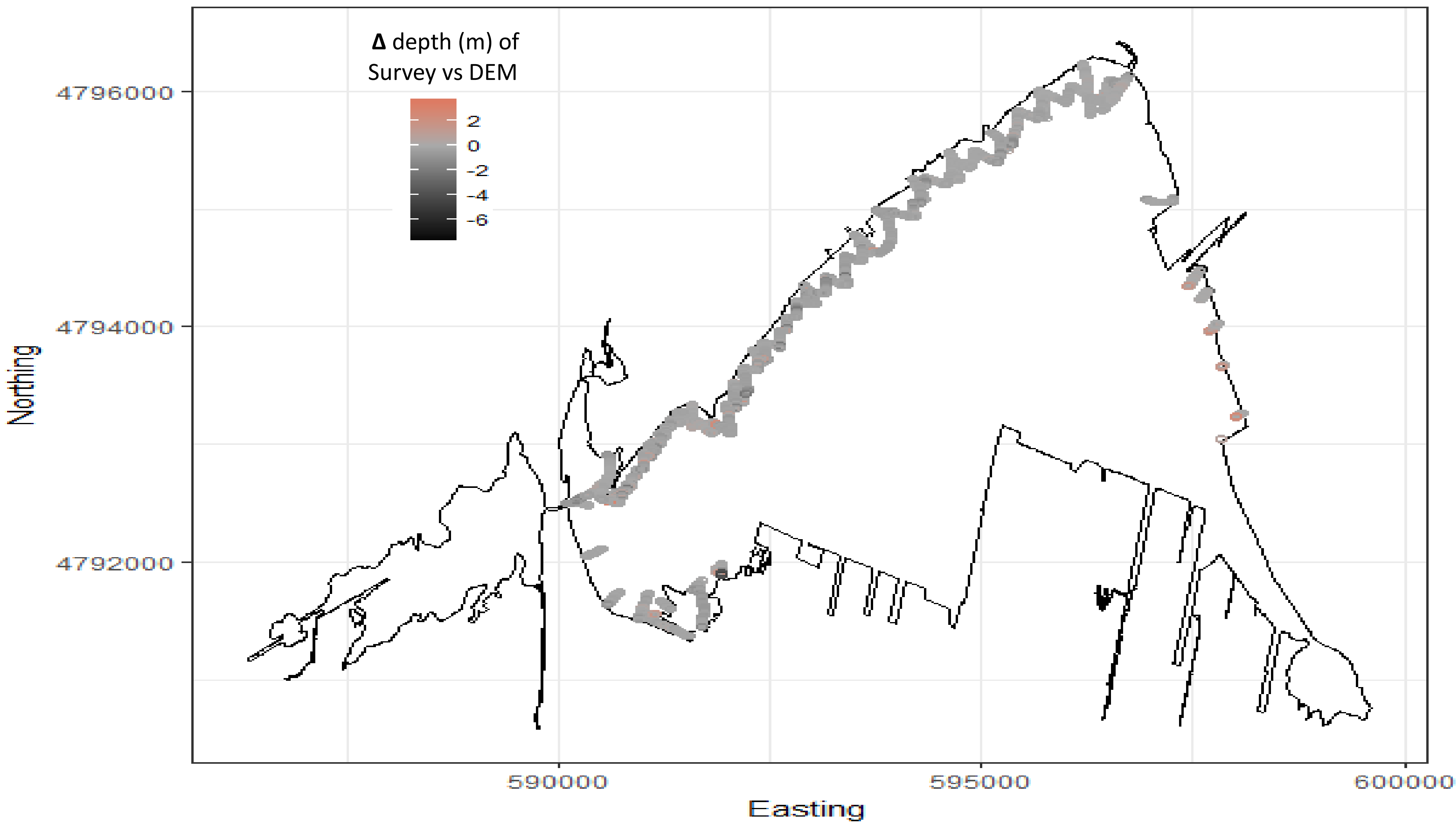


Figure 18. Difference of calculated depth (m) of the Hamilton Harbour Digital Elevation model (DEM) using mean daily water level and 2016 Submerged Aquatic Vegetation (SAV) survey depth. Towards a red gradient indicates an overestimation from the DEM and a black gradient indicates an underestimation

APPENDIX

APPENDIX TABLES

Table A1. GPS locations for all transects in the Hamilton Harbour 2016 survey. “A” denotes the start of a transect, “Z” the end of a transect. Some transect locations are missing.

Latitude	Longitude	Way Point for Transect
43.30918	-79.81098	HH 2A
43.3097	-79.81006	HH 2Z
43.31283	-79.81388	HH 3A
43.30905	-79.81295	HH 3Z
43.3108	-79.82084	HH 4A
43.30901	-79.81958	HH 4Z
43.3078	-79.82741	HH 5A
43.30435	-79.83877	HH 5A1
43.30619	-79.82519	HH 5Z
43.30625	-79.83347	HH 6A
43.30424	-79.83219	HH 6Z
43.30281	-79.83722	HH 7Z
43.30223	-79.84365	HH 8A
43.30096	-79.84238	HH 8Z
43.30015	-79.84714	HH 9A
43.29877	-79.84518	HH 9Z
43.29641	-79.85498	HH 10A
43.29644	-79.85494	HH 10A1
43.29504	-79.85312	HH 10Z
43.29134	-79.86221	HH 11A
43.29041	-79.86091	HH 11Z
43.28889	-79.86539	HH 12A
43.28772	-79.86377	HH 12Z
43.28735	-79.87131	HH 13A
43.28547	-79.87156	HH 13Z
43.28438	-79.87793	HH 14A
43.28372	-79.87713	HH 14Z
43.2806	-79.88304	HH 15A
43.27982	-79.88213	HH 15Z
43.28345	-79.88401	HH 16A
43.2815	-79.88372	HH 16Z
43.2799	-79.88971	HH 18A
43.27962	-79.88651	HH 18Z
43.27582	-79.88709	HH 19A
43.27568	-79.88704	HH 19B
43.27643	-79.88474	HH 19Z
43.27207	-79.88391	HH 20A
43.27304	-79.88233	HH 20Z
43.27092	-79.87925	HH 21A

Latitude	Longitude	Way Point for Transect
43.2729	-79.87821	HH 21Z
43.27131	-79.87674	HH 24A
43.27138	-79.87838	HH 24Z
43.27161	-79.87467	HH 25A
43.27232	-79.87624	HH 25Z
43.27309	-79.87156	HH 26A
43.27389	-79.87008	HH 26Z
43.27435	-79.86746	HH 28A
43.27466	-79.86795	HH 28Z
43.27425	-79.8671	HH 29A
43.27492	-79.86701	HH 29Z
43.28377	-79.79417	HH 30A
43.2839	-79.7943	HH 30Z
43.28595	-79.79117	HH 31A
43.28561	-79.79204	HH 31Z
43.28959	-79.79364	HH 32A
43.28936	-79.79411	HH 32Z
43.2929	-79.79452	HH 33A
43.29213	-79.79581	HH 33Z
43.29525	-79.79585	HH 34A
43.29448	-79.79719	HH 34Z
43.29676	-79.7968	HH 35A
43.29565	-79.79886	HH 35Z

Table A2. Water chemistry collected at reference sites in Hamilton Harbour (2016). Data were collected during point sample collection to verify plant species.

Transect	Site	Depth (m)	Code	Latitude	Longitude	Temperature (°C)	DO (mg/L)	Conductivity (μs)	Secchi Depth (m)	Turbidity
1	1	9.6	722	43.30255	-79.80457	24.0	10.89	514.7	1.1	4.03
1	4	0.6	725	43.30227	-79.80094	24.6	12.12	513.0	Bottom	6.79
3	1	5.1	726	43.301033	-79.8129	24.0	11.09	528.5	1.2	4.08
3	5	0.4	730	43.31277	-79.81374	25.5	13.63	503.9	Bottom	3.32
6	1	4.1	731	43.30482	-79.83205	23.7	10.48	527.3	1.5	2.08
6	4	1.2	734	43.30619	-79.83321	24.4	13.57	529.2	Bottom	1.51
9	4	1.3	261	43.30003	-79.8473	23.7	9.88	551.4	Bottom	1.87
9	1	4.8	258	43.29914	-79.84521	23.8	10.5	523.4	1.1	5.64
12	1	3.5	262	43.2879	-79.86398	23.2	9.91	521.2	1.8	1.58
12	4	1.0	265	43.28884	-79.86518	23.4	10.55	518.2	Bottom	1.64
15	1	4.8	266	43.2802	-79.88231	22.8	8.71	521.1	1.5	0.96
15	3	0.4	268	43.28075	-79.88283	23.3	10.05	520.0	Bottom	2.71
19	1	6.2	269	43.2764	-79.88457	22.6	8.71	518.9	2	0.79
19	3	3.2	271	43.27589	-79.88689	23.0	8.62	522.3	2.2	0.81
21	5	2.8	276	43.27093	-79.8793	22.3	8.65	524.6	Bottom	0.57
21	1	5.8	272	43.27251	-79.87829	22.5	8.55	521.2	2.3	0.59
25	1	5.1	277	43.27208	-79.87544	23.2	8.85	524.8	2.1	1.43
25	4	0.6	280	43.27166	-79.87477	24.3	12.28	507.8	Bottom	6.6
26	3	2.1	283	43.27312	-79.87143	22.5	8.88	518.5	Bottom	0.62
26	1	5.9	281	43.2735	-79.87079	22.6	8.92	518.8	2.1	0.51
29	1	6.0	284	43.27474	-79.86704	22.7	9.4	522.1	1.9	1.22
29	3	2.1	286	43.27425	-79.86705	22.8	9.37	521.8	Bottom	1.12
31	2	2.0	288	43.28565	-79.79191	25.1	11.85	540.3	0.8	NR
35	1	3.8	291	43.29586	-79.79888	24.7	11.99	531.2	0.8	6.82
35	4	0.9	294	43.29659	-79.79723	25.7	12.39	525.9	0.5	9.46

Table A3. Mean % SAV cover for all transects in the Hamilton Harbour 2016 survey. * denotes reference transects.

Transect	Mean % SAV cover	Standard Deviation	Min	Max
HH1*	88.9	21.0	20	100
HH2	70.7	32.0	10	100
HH3*	89.1	21.7	10	100
HH4	90.7	20.6	10	100
HH5	97.9	10.5	10	100
HH6*	82.8	24.8	20	100
HH7	96.2	10.4	60	100
HH8	93.6	17.7	10	100
HH9*	89.7	22.9	10	100
HH10	88.6	25.5	10	100
HH11	86.6	21.2	20	100
HH12*	89.8	20.8	20	100
HH13	82.8	27.0	10	100
HH14	95.9	13.4	40	100
HH15*	94.2	18.4	30	100
HH16	60.0	37.3	10	100
HH18	26.0	18.2	10	50
HH20	70.0	37.9	10	100
HH21*	55.0	33.4	10	100
HH22	80.6	28.0	10	100
HH24	91.1	23.2	30	100
HH25*	76.9	34.9	10	100
HH26*	94.4	10.1	70	100
HH27	74.1	26.6	10	100
HH28	72.1	30.7	10	100
HH29*	85.0	20.1	40	100
HH30	58.0	19.2	30	80
HH31*	63.7	28.2	10	100
HH32	90.8	21.1	30	100
HH33	55.9	35.8	10	100
HH34	79.6	27.1	20	100
HH35*	69.5	32.2	10	100
HHSAVEdge1	84.4	25.6	10	100
HHSAVEdge2	92.9	19.9	10	100
HHSAVEdge3	86.1	24.6	10	100
HHSAVEdge4	93.2	20.1	10	100
HHSAVEdge5	76.6	25.4	10	100

Table A4. Mean SAV height (m) for all transects in the Hamilton Harbour 2016 survey. * denotes reference transects.

Transect	Mean SAV height (m)	Standard Deviation	Min	Max
HH1*	0.53	0.17	0.26	1.10
HH2	0.78	0.32	0.24	1.43
HH3*	0.93	0.39	0.20	1.69
HH4	0.81	0.33	0.21	1.56
HH5	0.96	0.32	0.26	1.74
HH6*	0.68	0.21	0.30	1.10
HH7	0.62	0.25	0.26	1.54
HH8	0.67	0.36	0.23	1.72
HH9*	0.76	0.21	0.20	1.34
HH10	0.54	0.26	0.21	1.62
HH11	0.32	0.05	0.26	0.54
HH12*	0.51	0.16	0.21	1.01
HH13	0.96	0.40	0.42	1.70
HH14	0.74	0.48	0.20	1.96
HH15*	0.59	0.19	0.20	0.91
HH16	0.43	0.12	0.21	0.59
HH18	0.24	0.03	0.22	0.29
HH20	0.49	0.15	0.23	0.69
HH21*	0.39	0.17	0.21	0.72
HH22	0.56	0.20	0.23	1.17
HH24	0.71	0.33	0.42	1.41
HH25*	0.65	0.38	0.21	1.49
HH26*	0.66	0.27	0.21	1.01
HH27	0.65	0.19	0.24	1.11
HH28	0.51	0.31	0.24	1.01
HH29*	0.84	0.38	0.34	1.48
HH30	0.24	0.02	0.21	0.26
HH31*	0.43	0.15	0.22	0.69
HH32	1.04	0.31	0.40	1.42
HH33	0.47	0.25	0.22	1.17
HH34	0.54	0.22	0.29	1.11
HH35*	0.48	0.18	0.20	0.95
HHSAVEdge1	0.95	0.32	0.20	1.80
HHSAVEdge2	0.85	0.35	0.21	1.72
HHSAVEdge3	0.58	0.25	0.21	1.45
HHSAVEdge4	0.99	0.31	0.20	1.91
HHSAVEdge5	0.46	0.15	0.21	0.86

Table A5. Mean Percent Volume inhabited (PVI) (%) for all transects in the Hamilton Harbour 2016 survey. * denotes reference transects.

Transect	Mean Percent Volume inhabited (%)	Standard Deviation	Min	Max
HH1*	31.6	10.4	3.6	48.3
HH2	22.0	17.2	1.0	61.7
HH3*	37.5	17.2	1.5	62.5
HH4	40.3	16.6	0.6	62.1
HH5	43.6	11.0	0.6	64.1
HH6*	26.7	14.2	2.1	47.3
HH7	37.2	9.7	13.9	58.6
HH8	35.8	12.6	1.3	61.1
HH9*	39.8	14.5	0.6	59.1
HH10	29.2	12.4	0.9	56.4
HH11	22.9	6.1	5.1	36.6
HH12*	29.8	10.6	2.7	47.2
HH13	37.1	20.9	3.1	64.4
HH14	38.6	14.7	7.8	68.7
HH15*	37.3	10.8	5.8	47.6
HH16	20.9	15.0	1.5	40.6
HH18	3.6	2.4	1.5	7.5
HH20	15.3	10.4	0.8	27.1
HH21*	9.7	10.5	0.6	32.7
HH22	17.3	10.0	0.6	40.1
HH24	30.1	11.8	4.6	41.6
HH25*	30.6	19.6	0.7	57.9
HH26*	30.7	9.3	15.2	41.2
HH27	23.9	13.5	1.3	53.0
HH28	20.8	12.0	0.7	41.9
HH29*	23.8	16.1	6.0	54.1
HH30	6.0	2.4	3.2	9.8
HH31*	18.4	13.1	1.8	44.4
HH32	43.2	19.1	7.4	60.8
HH33	17.3	14.1	1.9	48.7
HH34	25.6	12.4	2.8	44.9
HH35*	22.0	13.0	1.0	52.1
HHSAVEdge1	35.3	18.6	0.6	63.2
HHSAVEdge2	39.0	15.0	0.4	62.9
HHSAVEdge3	28.8	12.5	1.1	60.6
HHSAVEdge4	44.0	14.4	0.4	68.1
HHSAVEdge5	24.5	11.6	1.7	48.8

APPENDIX FIGURE

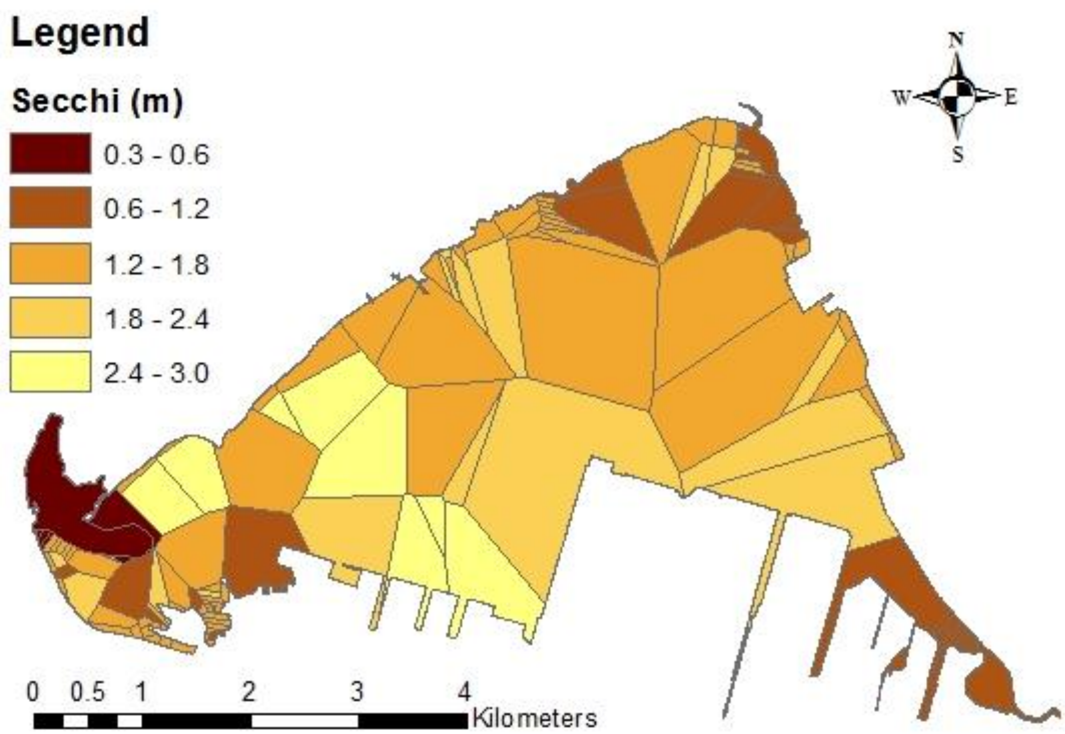


Figure A1. Secchi zones of Hamilton Harbour. Zones were interpolated and classified from point sampling data.