ANALYSING SEDIMENT PROPERTY TRENDS FOR THREE COASTAL BAYS IN NOVA SCOTIA USING KRIGING

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this Research Paper.

I authorise Ryerson University to lend this Research Paper to other institutions or individuals for purposes of scholarly research.

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ABSTRACT

Coastal ecosystems are potentially impacted by the presence of aquaculture. The benthic environment becomes suboxic as feces are deposited, resulting in reduced biodiversity. Sediment property measures of this impact include sulphide concentration, redox potential, percent water, and total organic content. The sediment properties for three bays on the Eastern Shore of Nova Scotia were sampled with sediment grabs. Ordinary kriging models specific to each bay were generated using the Geostatistical Analyst in ArcGIS and applied to produce trend estimates. The sulphide concentration and redox potential samples for each bay required log transformation in order to produce statistically valid results. The tools available within Geographic Information Systems enable the generation of interpolated surfaces that are more interpretable than basic point maps. Geostatistical modelling is scarce in aquaculture planning despite its ability to define boundaries, habitats, and undertake constraint mapping to exclude unsuitable areas. Kriging analysis provides an additional tool for aquaculture managers and provides insight into aquaculture site selection, and in this case offers baseline sediment property trends for this region.

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LIST OF ACRONYMS

ASE – Average Standard Error

CH – Country Harbour

DFO – Fisheries and Oceans Canada

ESRI – Environmental Systems Research Institute

GIS – Geographic Information Systems

NHE – Normal Hydrogen Electrode

MPE – Mean Prediction Error

MJ – Marie-Joseph Harbour

NAD – North American Datum

NSFA – Nova Scotia Fisheries and Aquaculture

RDP – Reduction-Oxidation Discontinuity Potential or Redox Potential

RMSPE – Root Mean Square Prediction Error

SAOB – Sulphide Anti-oxidant Buffer

SRMSPE – Standardised Root Mean Square Prediction Error

TB – Tor Bay

UTM – Universal Transverse Mercator

Chapter 1: Introduction

Management of coastal ecosystems requires detailed knowledge of habitats and resources in demand by a variety of users (Grant et al., 2005). Among these activities, aquaculture has the potential to impact coastal ecosystems, with respect to cumulative impacts and the carrying capacity of the environment (Grant et al., 2005). Cultured shellfish, such as blue mussels (*Mytilus edulis*), excrete nutrients, consume oxygen, and in the case of suspension-feeders deplete seston (suspended food particles consisting of phytoplankton and detritus) and phytoplankton (Cranford et al., 2003; Grant et al., 2007b). Waste products such as feces from farmed mussels are deposited to the benthic environment where they degrade and deplete oxygen, leading to a suboxic benthos and reduced biodiversity (Grant et al., 1995; Grant et al., 2005; Otero et al., 2006; Grant et al., 2007a). Otero et al. (2006) consider areas of high mussel aquaculture concentration (such as Tracadie Bay, Prince Edward Island or Ria de Arousa, Spain) to be human activities that have the greatest impact on natural cycles of elements and the ecology of these regions. Sediment property measures of this impact include sulphide concentration, redox potential, percent water, and total organic content (Nilsson and Rosenberg, 1997; Wildish et al., 2003). These impacts may extend beyond the immediate area (ie. footprint of impact) of the leased farm resulting in broader effects on the regional ecosystem (Wildish et al., 2004b; Grant et al., 2007a). Wildish et al. (1999) and Wildish et al. (2001b) have determined gradients of effect for sulphide concentration and redox potential from normal to anoxic (reducing environment) from which managers at Fisheries and Oceans Canada (DFO) and Nova Scotia Fisheries and Aquaculture (NSFA) identify potentially aquaculture related benthic environmental effects (Table 1).

Table 1: Characterisations of effect along an organic enrichment gradient (increasing from left to right) based on geochemical measures (Wildish et al., 1999; Wildish et al., 2001b).

Geochemical Measure	Group			
	Normal	Oxic	Hypoxic	Anoxic
Sulphide Concentration (μM)	< 300	300 - 1300	1300 - 6000	> 6000
Redox Potential (mV)	> +100	0 - 100	-100 - 0	< -100

1.1 Habitat Mapping

Habitat mapping has gained prominence with regard to biodiversity, landscape ecology, and marine protected areas in the context of coastal resource use and ecosystem services (Morrison et al., 2001; Roff et al., 2003; Hewitt et al., 2004). Geographic Information Systems (GIS) have been applied in many areas of coastal zone management, but use in aquaculture has been somewhat limited to modelling of carrying capacity or impact (Pastres et al., 2001; Bacher et al., 2002; Pérez et al., 2002; McKindsey et al., 2006; Sequeira et al., 2008). The majority of these studies have been conducted around finfish, eg. Atlantic salmon (*Salmo salar*), sites and not bivalve aquaculture leases. For example, Corner et al. (2006) predicted total carbon settlement to the sediment from beneath finfish farm sites using GIS dispersion models and contouring capabilities.

Applications of habitat mapping include both detailed views of single sites (e.g. bays) as well as broader views of multiple sites (Nath et al., 2000; Hewitt et al., 2004). In Canada, GIS has been used for aquaculture management in both Nova Scotia and British Columbia. In Guysborough County, NS a custom MapInfo GIS interface was written for the Guysborough County Regional Development Authority (GCRDA, 2008) to allow constraint mapping of suitable aquaculture sites for selected species. In British Columbia, a custom ArcView GIS tool was developed to assess beach and open water aquaculture site capability for the entire BC coast (Land Use Coordination Office, 2008). Carswell et al. (2006) also quantitively inventoried the aquaculture infrastructure for Baynes Sound, BC. The most extensive use of GIS for aquaculture site selection has been conducted by Pérez et al. (2003a), Pérez et al. (2003b), and Pérez et al. (2005) in Tenerife, Canary Islands, Spain using several factors including water quality.

1.2 Kriging

GIS analytical tools such as geostatistical modelling (i.e. interpolation) can provide insight into the effects of mussel aquaculture on the benthic environment. GIS models have previously been used to map freshwater and coastal sediment properties, such as metal concentration, beyond areas limited to direct physical sampling (Forsythe et al., 2004; Forsythe and Marvin, 2005; Ouyang et al., 2005; Ouyang et al., 2006). However mapping of geochemical sediment properties such as sulphide concentration and redox potential from marine and aquaculture ecosystems are uncommon, but insightful where conducted (Nilsson and Rosenberg, 1997; Corner et al., 2006).

Kriging methods were initially developed by D.G. Krige, a South African mining geologist (Lloyd, 2007). These interpolation methods utilise statistical models that incorporate autocorrelation among measured sample points to predict outside the range of known data values (Johnson et al., 2001; Lloyd, 2007). Kriging aims to minimise the error variance by finding optimal weights to assign to the available data in order to predict unknown values at any location (Lloyd, 2007).

Ordinary kriging interpolation is the most effective and flexible geostatistical method in comparison to other models, such as Inverse Distance Weighting (IDW), as the prediction results can be statistically validated, providing a measure of the probable error associated with the estimates (Forsythe et al., 2004; Forsythe and Marvin, 2005). Cross-validation is used to measure the accuracy of the prediction and indicates whether a true representation of the modelled phenomena can be mapped (Johnston et al., 2001; Jakubek and Forsythe, 2004). This requires that for all points, cross-validation sequentially omits a point, predicts its value using the rest of the data, and compares the measured and predicted values (Fortin and Dale, 2005; Lloyd, 2007). The validity of the interpolations is indicated by the values for the Mean Prediction Error (MPE), Root Mean Square Prediction Error (RMSPE), Average Standard Error (ASE), and Standardised Root Mean Squared Prediction Error (SRMSPE). In order for the model to be statistically validated, values for MPE should be close to 0, RMSPE and ASE should be as small as possible and similar to each other, and SRMSPE should be close to 1 (Johnston et al., 2001). If the ASE is greater than the RMSPE, then the variability of the prediction is overestimated; if the ASE is less than the RMSPE, there is an underestimation of the variability of the predictions. If the SRMSPE is greater than 1, there is an underestimation of the variability of the predictions, and if the SRMSPE is less than 1, overestimation is the result (Johnston et al., 2001; Forsythe et al., 2004).

Although kriging is a robust predictor and does not require that data be normally distributed (Johnston et al., 2001; de Smith et al., 2007), models that violate the cross-validation values are not statistically valid. It is best if the data are normally distributed, removing any skewness or outliers, in order to create confidence intervals, thus requiring transformation in some cases (de Smith et al., 2007). Forsythe et al. (2004) showed non-valid statistics for kriging prediction surfaces of sediment metal contamination in Lakes Erie and Ontario. Their solution was to normalise the data through log transformation and report these findings in Forsythe and Marvin (2005).

With kriging, spatial variability is estimated through modelling the semivariogram; equal to one-half of the variance between paired sample differences taken at some fixed or "lag" distance apart (de Smith et al., 2007; Ritter and Leecaster, 2007). Thus the semivariogram can be used to assess the errors associated with the degree of spatial autocorrelation predictions (Ritter and Leecaster, 2007). The best fit model for the prediction then can be identified with empirical functions, whether spherical, exponential or Gaussian and its associated parameters such as lag distance, and other neighbourhood statistics (de Smith et al., 2007). Other neighbourhood statistics include the major and minor axes, the number of points involved in the interpolation, orientation and anisotropy. Anisotropy is a directional bias that can be attributed to a number of physical effects (de Smith et al., 2007); for example in sediment sampling, circulation patterns may affect sedimentation rates resulting in depositional or resuspension environments (Forsythe et al., 2004; Forsythe and Marvin, 2005). One of the advantages of kriging is that it is straightforward to model anisotropy (Lloyd, 2007). A study of the semivariogram as well as the application of cost or objective functions can determine the optimal sampling grid (sample number and spacing) for future studies (Ritter and Leecaster, 2007).

Numerous studies on contamination, both for land-based soils and coastal/in-land waters have relied on classic statistical analyses (Buccolieri et al., 2006; Pekey, 2006; Terrado et al., 2006). Current research in sediment contamination is predominantly kriging based (Forsythe et al., 2004; Li et al., 2004; Forsythe and Marvin, 2005; Ouyang et al., 2005; Ouyang et al., 2006; Sun et al., 2006). Some studies used an IDW method to interpolate heavy metal concentrations in soil on Hong Kong Island (Lee et al., 2006), in Hong Kong coastal waters (Zhou et al., 2007) and trace metals in soils, surface and sub-surface waters in the National Capital Territory, Delhi (Kaur and Rani, 2006). A previous study by some of the authors of Lee et al. (2006) in Kowloon Peninsula on the same contaminants using identical sampling methods employed kriging as their interpolation method as opposed to IDW (Li et al., 2004). Although these studies have focused on contamination from metals and not geochemical sediment properties as proposed for the current research, they interpret the results similarly.

1.3 Study Sites

The Nova Scotia coastline has the potential for extensive mussel aquaculture development due to its under-utilised bays and estuaries. Unlike finfish aquaculture depositional effects, which have been studied extensively (Corner et al., 2006; Sutherland et al., 2006), the effects of bivalve farming are less understood and documented (Grant et al., 2005). Questions such as: (1) What is the extent of depositional bottom effects? (2) What is the impact of deposition on sediments? (3) Does mapping of the effects provide an indication of environmental impact? (4) How are these types of data utilised? arise from the effects of extensive mussel farming on the ecosystem. To answer these questions sediment properties (sulphide concentration, redox potential, percent water, and total organic content) for three different bays on the Eastern Shore of Nova Scotia in Guysborough County (Country Harbour, Marie Joseph Harbour, and Tor Bay) where mussel aquaculture is present and/or planned were sampled in July and August 2005 (Figure 1).

The three bays were chosen as study test sites due to their topographical and hydrological differences. Country Harbour (CH) is a relatively protected long, narrow fjord-like bay with a high level of activity due to shipping, aquaculture operations, recreational use, and ferry crossing (Figures 1 and 2). A small mussel lease (approx. 7 ha shown in green in Figure 2) is under review by NSFA nearshore. Marie-Joseph Harbour (MJ) is a small bay open to ocean influences, but protected by large islands (Figure 1), and consists of a large mussel aquaculture operation with a lease expansion under review (lease in green in Figure 3). In contrast to the smaller harbours, Tor Bay (TB) is the largest bay in Guysborough County, and is very open to ocean influences (Figure 1). The bay does not currently have expansive mussel aquaculture operations, nor are any leases under review in this area and a hypothetical lease (shown in green in Figure 4) was outlined as part of the larger study project not discussed here. None of the bays sampled here exhibited indications of hypoxic or anoxic stages, but ranged mostly within the normal and oxic ranges as outlined in Table 1.

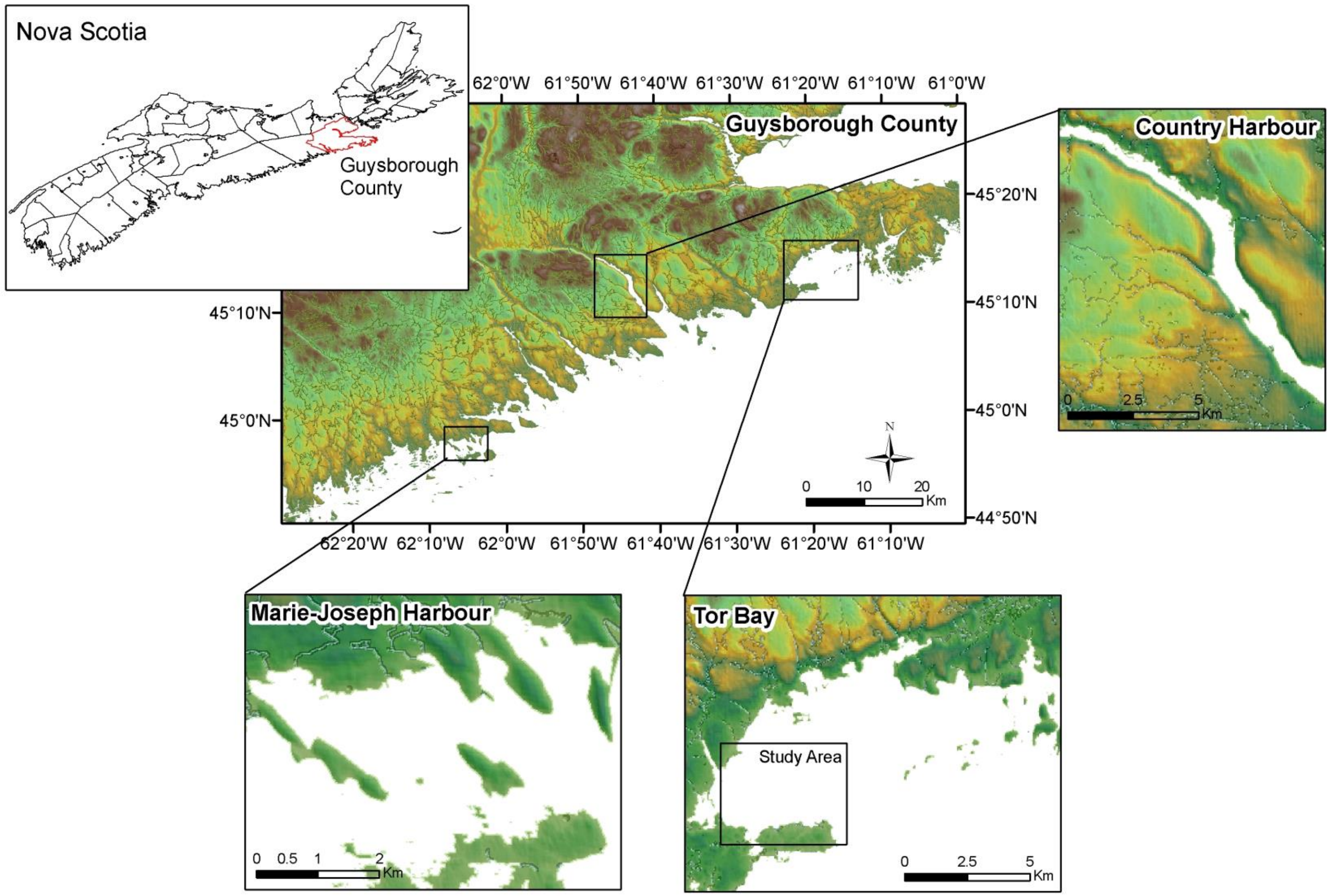

Figure 1: Guysborough County, Nova Scotia site selection with study bays, Country Harbour, Marie-Joseph Harbour and Tor Bay.

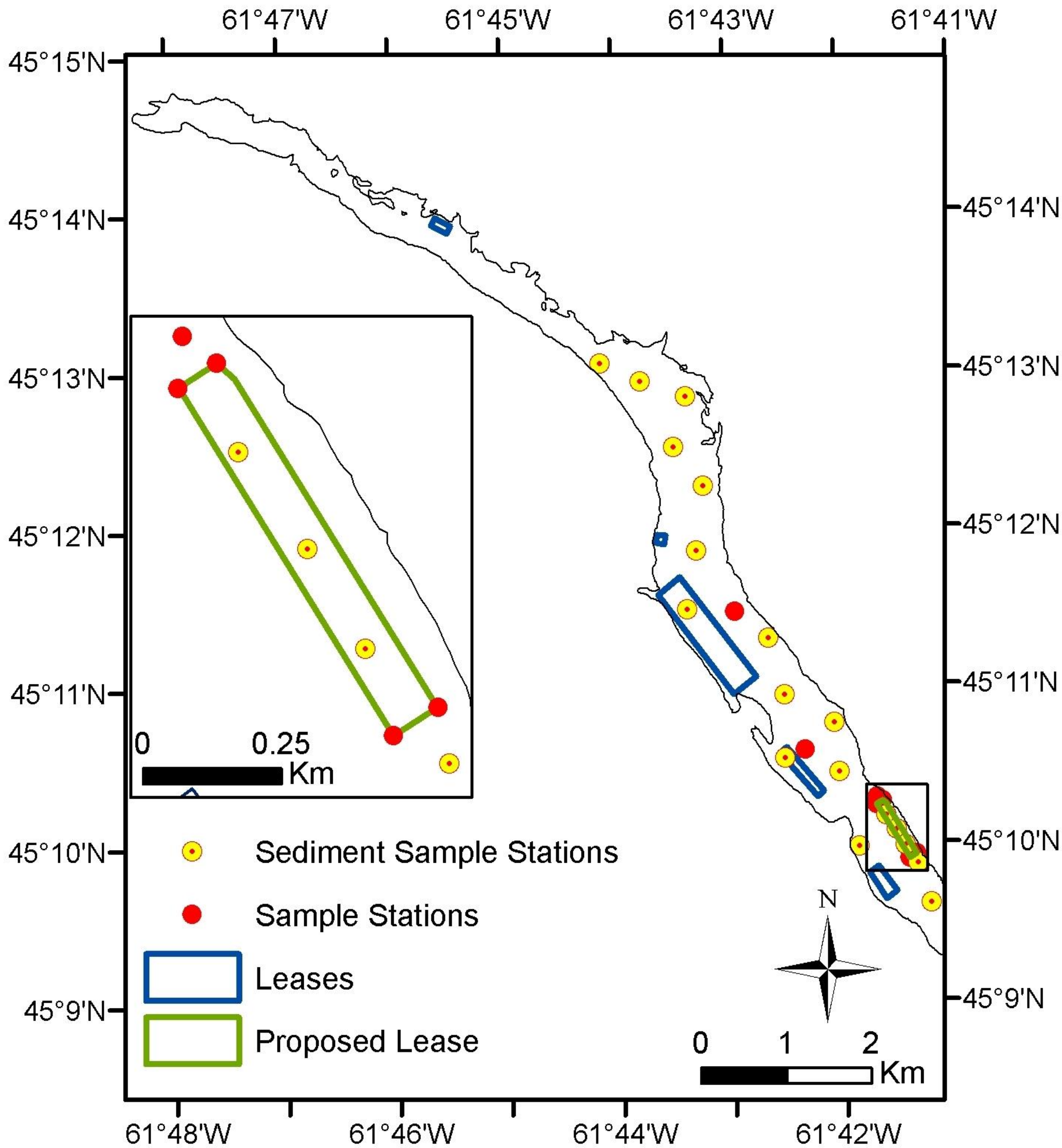

Figure 2: Sampling stations for Country Harbour. Inset shows lease under review at the time of the study, with sampling stations in accordance to DFO environmental assessment guidelines.

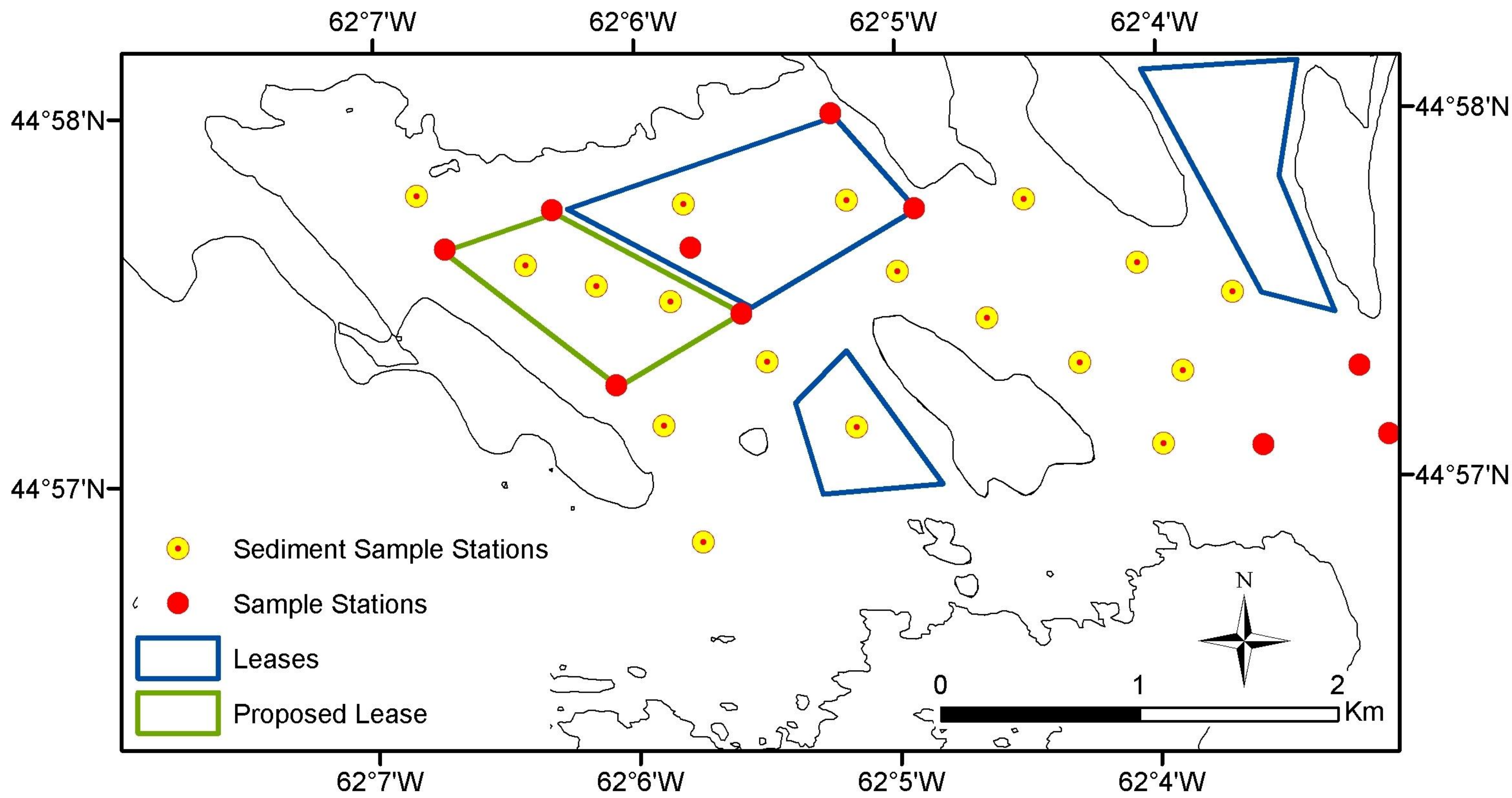

Figure 3: Sampling stations for Marie-Joseph Harbour with sampling stations in accordance to DFO environmental assessment guidelines.

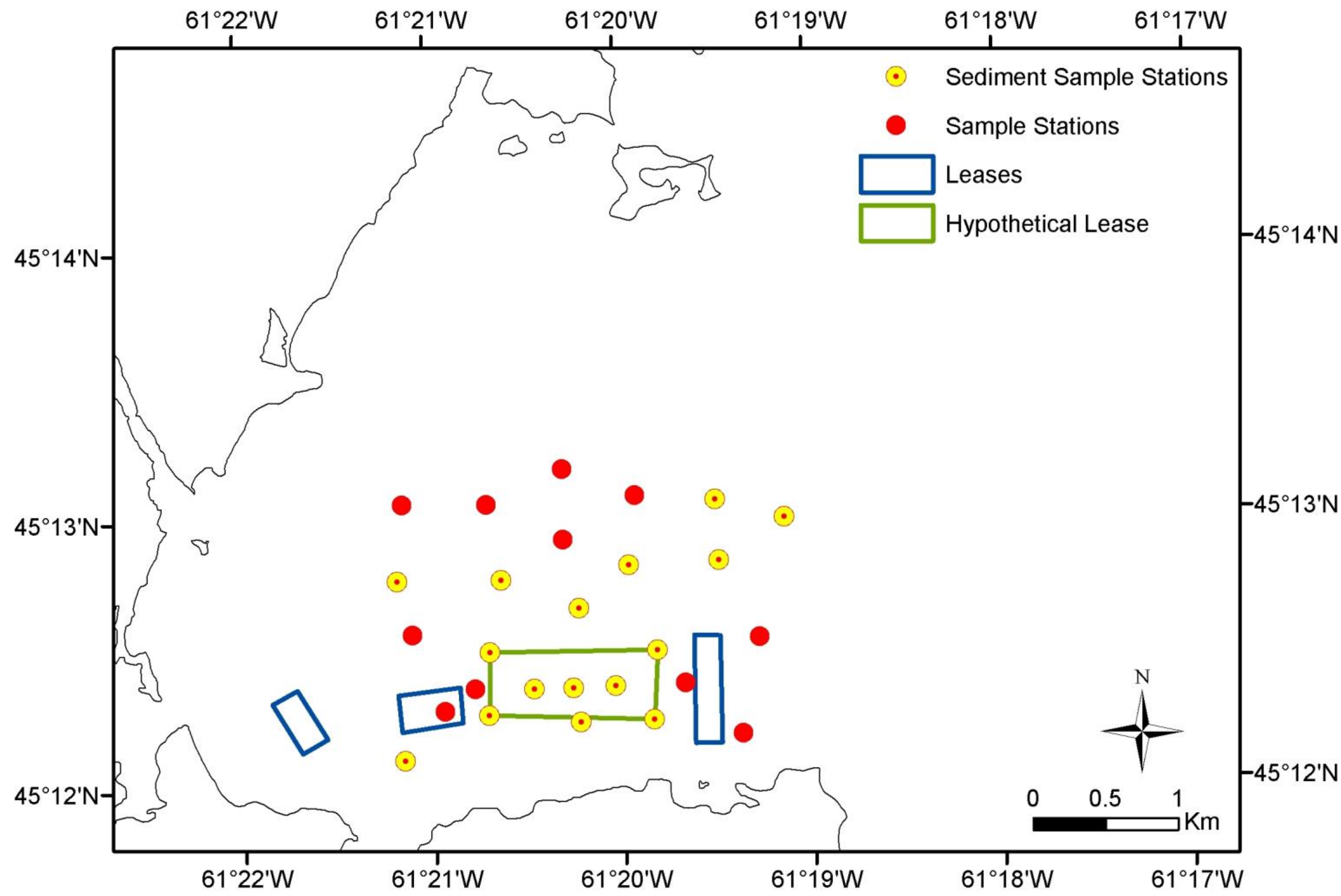

Figure 4: Sampling stations for Tor Bay with hypothetical lease in green, with sampling stations in accordance to DFO environmental assessment guidelines.

In order to standardise the scaling of the bays, the total number and placement of stations for all three sites were planned by placing a 500 m grid within the area of interest. This also included the three sample stations within the lease or proposed lease of interest along its longest axis, the four corners of the lease, and three reference stations. This plan is in accordance with DFO's environmental assessment mandate for aquaculture site monitoring by individual farmers and NSFA as determined by DFO's Habitat Management Division. This mandate requires that underwater videography of the bottom be taken at each corner of the lease, and three reference stations be taken beyond the lease but within similar depths and sediment types. Thus more stations were planned for other parts of the project beyond sediment sampling. Those stations that were sampled for sediment are shown in yellow in Figures 2-4. Some of the stations planned for sediment sampling did not result in any samples due to bottom type characteristics, and these are shown in red in Figures 2-4. For example several stations along the northern edge of the study site in TB (Figure 4) and three stations to the east of MJ could not be sampled due to the hard bottom (cobble, boulders), or the presence of seagrass beds interfering with the sediment grab mechanism, thus resulting in a reduced sample size. Total sediment sample stations were 18 for CH and MJ Harbours and 16 for TB.

1.4 Objectives

The objectives of this research were to use ordinary kriging interpolation, a geostatistical method, to model sediment property trends in these areas and attempt to answer the questions outlined in Section 1.3. This is in response to knowledge that interpretation and mapping of point-based sediment measurements without the application of interpolation methods does not allow for spatial trends to be fully analysed (Forsythe et al., 2004;

Forsythe and Marvin, 2005). The paper discusses the sediment property model results per bay, as they are correlated to each other, and also interprets the results in response to bottom type.

Chapter 2: Data and Methodology

2.1 Data

In July and August of 2005, a field program was implemented on the eastern shore of Nova Scotia, in Guysborough County, to expand the application of mapping and GIS into the process of aquaculture site evaluation. As part of this program, sediments within the bay and within aquaculture leases were sampled and analysed for sulphide concentration, redox potential, percent water content (porosity) and total organic content. *In situ* remote sensing surveys using an echosounder (Biosonics Inc.) were also conducted to determine bottom type. These were verified with underwater videography. The field portion of the project was conducted using boats operated by DFO and NSFA.

2.2 Sediment Sampling

Sediment was grabbed with Ekman Grabs (n = 3 per station; Figure 5), and the interfacial sediments (top 2 cm) was sampled with a 5cc syringe per grab in accordance to previously determined and accepted methodology in mariculture monitoring (Hargrave et al., 1995; Hargrave et al., 1997; Hargrave et al., 1998; Wildish et al., 1999; Wildish et al., 2001a; Wildish et al., 2003). Samples were frozen and analysed for sulphide concentration and redox potential within 72 hours in the laboratory in accordance to the methods described in Wildish et al. (1999) and improved in Wildish et al. (2004a).

2.2.1 Sulphide Concentration

High concentrations of sulphides in interfacial sediments are a result of anaerobic respiration (the breakdown of organic material in the absence of oxygen) indicating the presence of sulphur reducing bacteria (Otero et al., 2006). In marine sediments *Beggiatoa*

Figure 5: Sediment sampling using an Ekman Grab. Occasionally samples could not be obtained due to interference of seaweed and hard bottom types.

species are predominant, which produce large algal mats that appear milky white on the sediment surface indicating organic enrichment (Fenchel and Bernard, 1995). The sediment is characterised by a strong rotten egg odour. Sulphide concentrations were determined by an OrionR silver/silver sulphide electrode with a combined calomel electrode as reference, standardised with sodium sulphide stock solution, in a fixed 1:1 ratio of sample/standard [sulphide anti-oxidant buffer (SAOB)] (Wildish et al., 1999). Sulphide concentration is measured in micro-molars (μM) and the value is proportional to the concentration.

2.2.2 Redox Potential

Redox potential [referring to the reduction-oxidation discontinuity potential (RDP)] is a measure used to determine whether conditions are aerobic (favouring oxidation) or anaerobic (favouring reduction). Redox potentials standardised with Zobells solutions were measured using a combined reference and platinum electrode containing 3 - 4 Molar potassium chloride solution (Wildish et al., 1999). Redox is expressed in millivolts (mV) at ambient temperature relative to a Normal Hydrogen Electrode (NHE), and is inversely proportional to the value. A reducing environment is favoured with negative redox potential, indicating high organic matter (Rufino et al., 2004).

2.2.3 Percent Water and Total Organic Content

Percent water or porosity was measured by difference in dry weight and wet weight after drying the collected sediments in a 60 °C oven for 24 hrs. The dried sediments were sub-sampled and ashed in a high temperature muffle furnace (520 °C) for 6 hours. Total organic content was determined from the difference in weight of dried and ashed samples, calculating the amount of labile and refractory carbon burned at high temperature.

2.3 GIS Analysis and Statistics

All GIS and statistical analyses were conducted using ArcGIS v. 9.2 (ESRI, 2008). All georeferenced data were converted to ESRI shapefile format with a NAD83 UTM Zone 20N projection and mapped. Data used in the mapping were i) vector (polygon) representing plan view spatial extents of CH, MJ, and TB, ii) vector (polygon) representing plan view spatial extents of existing and hypothetical aquaculture lease sites in CH, MJ, and TB, iii) vector (point) data of sampling stations with processed sediment characteristic data. The best fit ordinary kriging models and spatial interpolations were determined with the Geostatistical Analyst available in ArcGIS. The interpolated surfaces were exported as raster images and clipped according to spatial extents of the bays, if required. Small scale spatial patterns are shown as a result of classifying quantiles (n = 5 classes).

2.4 Modelling and Variograms

For this research, models specific to each bay sampled were generated and mapped using the ordinary kriging geospatial analysis technique in ArcGIS and applied to produce trend estimates. The estimation surfaces provide valuable information that can be used to analyse the spatial distribution of sediment property trends and the ecological impact of mussel farming on the ecosystem. The resulting surface trends are contrasted against proportional point based maps of sediment properties. Preliminary investigations of the data indicate no ecological effect of mussel farming on the environment, but these data provide valuable baseline information for future comparisons as aquaculture activities develop. The research applies known and acceptable analytical methods to the relatively literature poor milieu of GIS and aquaculture effects.

In an effort to determine the best fit ordinary kriging interpolation for each bay, a series of models were tested using the Geostatistical Analyst Wizard in ArcGIS with the log transformed sulphide concentration parameter. The log transformed sulphide concentration values were used as proxy for establishing the kriging models, as generally the sediment property values were not normally distributed, owing to only 18 stations in CH and MJ, and 16 stations in TB. The ordinary kriging models interpolated the total number of stations with sediment characteristic data. Neighbourhood search parameters included major and minor axes, anisotropy, minimum and maximum points, and orientation of the model. For each model simulation, the prediction errors for semivariograms of three different functions (Spherical, Exponential, and Gaussian) were determined, and the best model of the three was chosen for the final prediction. In all cases, the model results were the same, potentially due to the gridded nature of the sampling strategy and the small number of sampled locations, and thus the spherical function was chosen for final predictions. Once the best fit model was derived for each bay using the log transformed sulphide concentration parameter as proxy for all sediment property measures, those settings were used to generate prediction errors for all other sediment characteristics.

2.4.1 Country Harbour

The different models tested for the log transformed sulphide concentration parameter for Country Harbour are shown in Table 2, and ordinary kriging prediction errors associated with the spherical function for each model are shown in Table 3. The best model fit for CH was Model 6, with a SRMSPE of 1.005, indicating a slight underestimation of the prediction. This model was chosen for the final interpolations for CH sediment characteristics.

Table 2: Ordinary kriging model neighbourhood parameters using log transformed sulphide as proxy for sample stations in Country Harbour.

		Neighbourhood Search Size					
	Sample Size	Major Axis (m)	Minor Axis (m)	Anisotropy	Maximum # of Points	Minimum # of Points	Orientation
Model 1	18	5953.85	0	0	5	1	4 sectors, 45 degrees
Model 2	18	5953.85	5953.85	9	5	1	4 sectors, 45 degrees
Model 3	18	1000	500	325	5	1	4 sectors, 45 degrees
Model 4	18	2000	1000	325	5	1	4 sectors, 45 degrees
Model 5	18	2000	1000	155	5	1	4 sectors, 45 degrees
Model 6	18	3000	1000	155	5	1	4 sectors, 45 degrees

Table 3: Prediction errors for the tested model parameters on log transformed sulphide for Country Harbour.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Model 1	0.008453	0.2476	0.243	0.03325	1.017
Model 2	0.004156	0.2441	0.2417	0.01654	1.009
Model 3	-0.002387	0.2887	0.262	-0.006272	1.109
Model 4	0.001535	0.2661	0.2496	0.005187	1.059
Model 5	0.007556	0.2646	0.2506	0.02701	1.052
Model 6	0.0001738	0.2469	0.2456	0.00	1.005

2.4.2 Marie-Joseph Harbour

Similarly to CH, the log transformed sulphide concentration parameter was used to determine the best fit ordinary kriging model. The comparison between models is shown in Table 4 and the resulting prediction errors for the spherical function for each model are indicated in Table 5. For Marie-Joseph Harbour, Model 6 was also chosen with an SRMSPE prediction error of 0.9942, indicating a slight overestimation of the prediction. Although Model 1 also showed an SRMSPE value close to 1, it was felt that the major and minor axes and anisotropy in Model 6 better reflected conditions for the bay than Model 1.

Table 4: Ordinary kriging model neighbourhood parameters using log transformed sulphide as proxy for sample stations in Marie-Joseph Harbour.

	Sample Size	Major Axis (m)	Minor Axis (m)	Neighbourhood Search Size Anisotropy	Maximum # of Points	Minimum # of Points	Orientation
Model 1	18	3866.46	0	0	5	1	4 sectors, 45 degrees
Model 2	18	3866.46	0	0	5	1	4 sectors
Model 3	18	1000	2000	9	5	1	4 sectors, 45 degrees
Model 4	18	1000	2000	9	5	1	4 sectors
Model 5	18	2100	1500	265	5	1	4 sectors, 45 degrees
Model 6	18	2050	1670	265	5	1	4 sectors, 45 degrees

Table 5: Prediction errors for the tested model parameters on log transformed sulphide for Marie-Joseph Harbour.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Model 1	0.004398	0.2855	0.2849	0.01356	1.005
Model 2	0.004206	0.2915	0.284	0.01106	1.027
Model 3	0.000221	0.2993	0.2882	-0.002271	1.046
Model 4	0.007135	0.301	0.2891	0.01746	1.047
Model 5	0.005856	0.2903	0.2862	0.01636	1.017
Model 6	0.0001734	0.2833	0.2859	-0.003171	0.9942

2.4.3 Tor Bay

In Tor Bay, the log transformed sulphide concentration measurements were used again to determine the best fit model for ordinary kriging. Tor Bay is a much larger bay and is less affected by parameters such as anisotropy, thus only three models were generated. These models are shown in Table 6 with their resulting spherical function prediction errors in Table 7. In this case, Model 3 was chosen as the best fit with an SRMSPE value of 0.9921, indicating a minor overestimation of the prediction.

Table 6: Ordinary kriging model neighbourhood parameters using log transformed sulphide as proxy for sample stations in Tor Bay.

	Neighbourhood Search Size						
	Sample Size	Major Axis (m)	Minor Axis (m)	Anisotropy	Maximum # of Points	Minimum # of Points	Orientation
Model 1	16	2522.1	0	0	5	1	4 sectors, 45 degrees
Model 2	16	2522.1	2522.1	9	5	1	4 sectors, 45 degrees
Model 3	16	2000	1000	300	5	1	4 sectors, 45 degrees

Table 7: Prediction errors for the tested model parameters on log transformed sulphide for Tor Bay.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Model 1	-0.02088	0.5198	0.5366	-0.03873	0.9703
Model 2	-0.02134	0.5217	0.5366	-0.04094	0.9731
Model 3	-0.03118	0.5402	0.5498	-0.04971	0.9921

Chapter 3: Results

The results are discussed within each bay, as the sediment property trends are correlated to each other and spatial trends are not necessarily due to similar processes across bays.

3.1 Country Harbour

The untransformed sediment characteristic results of the ordinary kriging spherical model predictions for Country Harbour are indicated in Table 8. Both the porosity and organic content predictions are valid, showing RMSPE and ASE values below 20, but the sulphide concentration and redox potential prediction errors are not statistically valid, with RMSPE and ASE values greater than 40 for sulphide concentration and greater than 60 for redox potential, respectively. In response these characteristics were log transformed and remodelled using the same neighbourhood parameters as the untransformed values, according to Model 6 parameters (Table 2). These data are shown in Table 9, and indicate statistically valid results, with minor underestimation in both cases of the prediction.

Table 8: Prediction errors from ordinary kriging model 6 applied to sediment characteristic parameters for Country Harbour sample stations.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Sulphide Concentration	-0.118	45.79	46.18	0.00	0.994
Redox Potential	0.1596	62.57	60.7	0.00	1.02
Porosity	-0.01985	4.939	5.099	-0.01	0.9589
Organic Content	-0.02833	2.206	2.056	-0.01	0.9701

Table 9: Prediction errors from ordinary kriging model 6 applied to log transformed sulphide concentration and redox potential values for Country Harbour sample stations.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Log Sulphide Concentration	0.0001738	0.2469	0.2456	0.00	1.005
Log Redox Potential	0.002344	0.1959	0.1854	0.01	1.036

3.1.1 Sulphide Concentration

The spatial pattern identified by the kriging model for the sulphide concentration showed small scale variation within two classes ranging from 77.9 to 118.7 µM (Figure 6). This statistically invalidated model shows a patch of slightly higher sulphide concentrated sediments bisecting the bay. When the model is reapplied to log transformed sulphide concentrations in order to validate the prediction, the pattern dissolves and introduces a long patch of lower concentrated sediments towards the north, reducing the high sulphide sediments to a sliver along the southern coastline (Figure 7).

In contrast to the model prediction that can interpret between points showing a fairly uniform sulphide concentration distribution in CH, the proportional point based map does not indicate any spatial patterns (Figure 8). The distribution of concentrations values varies from north to south, and even within leases (Figure 8 inset). It can be seen, however, that the original values for the kriging model ranged from 30.4 to 161.1 µM, but these are smoothed out of the prediction to show a more uniform distribution (Figure 7).

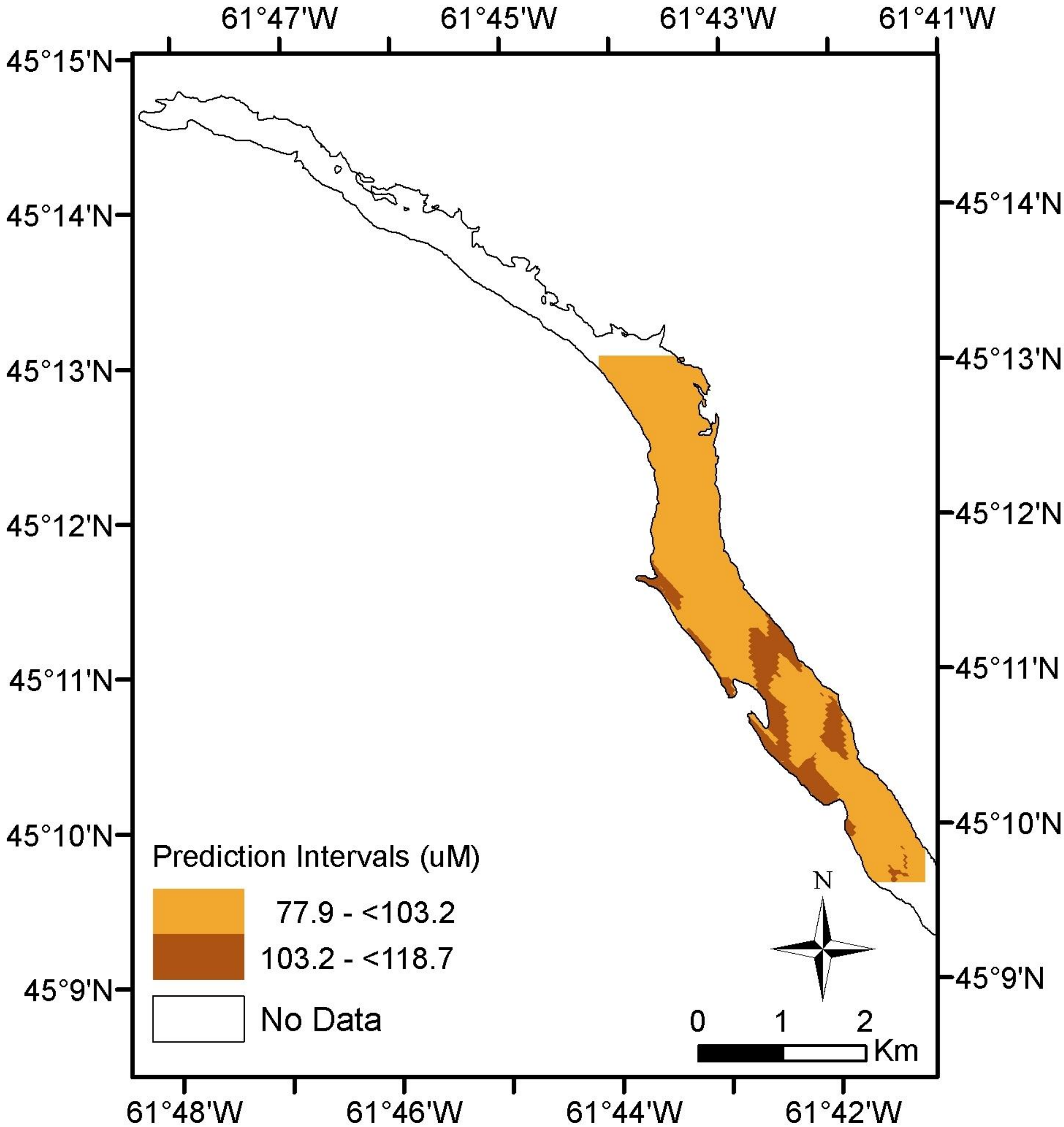

Figure 6: Spatial distribution of sulphide concentration in Country Harbour.

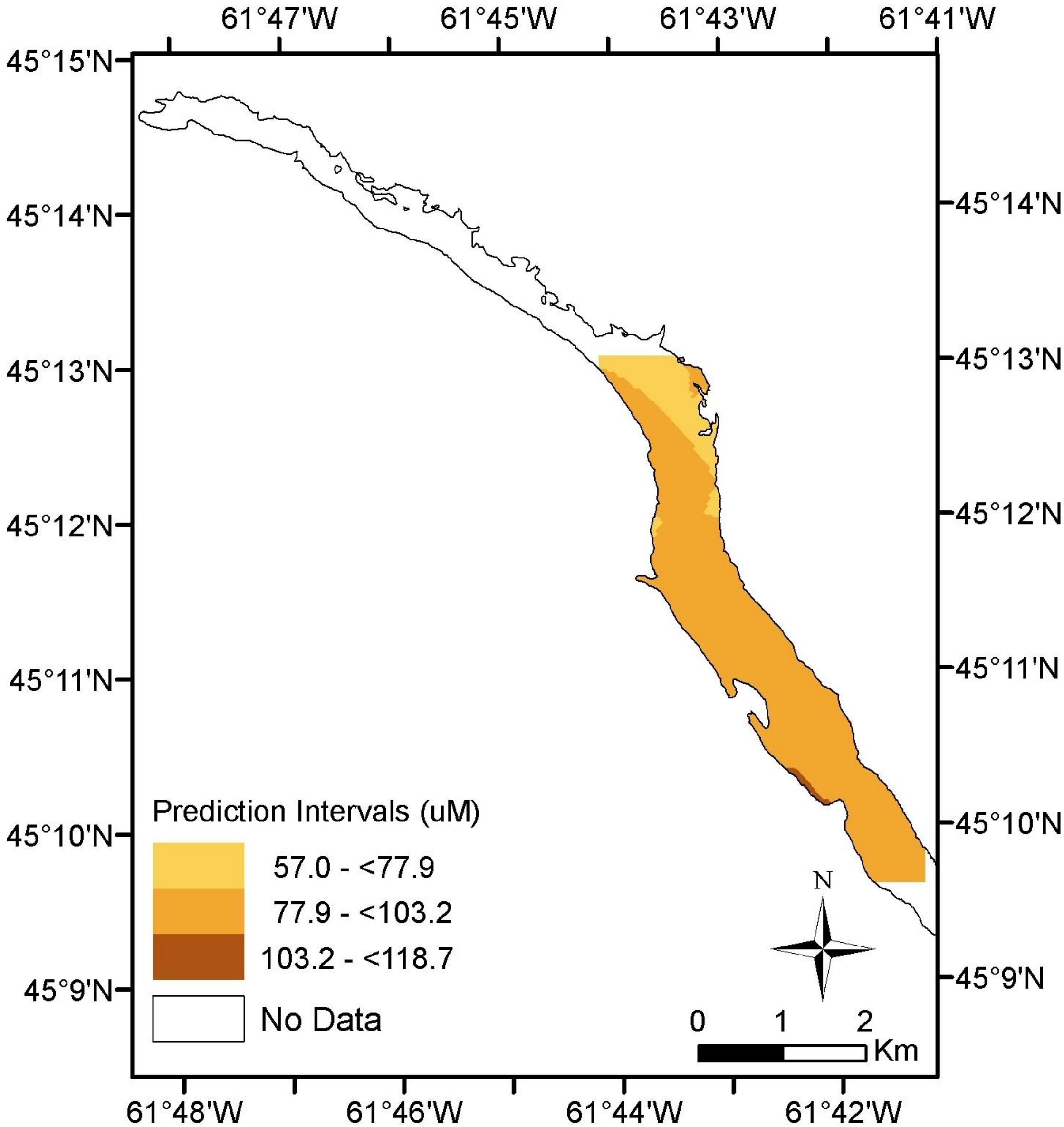

Figure 7: Spatial distribution of log transformed sulphide concentration in Country Harbour.

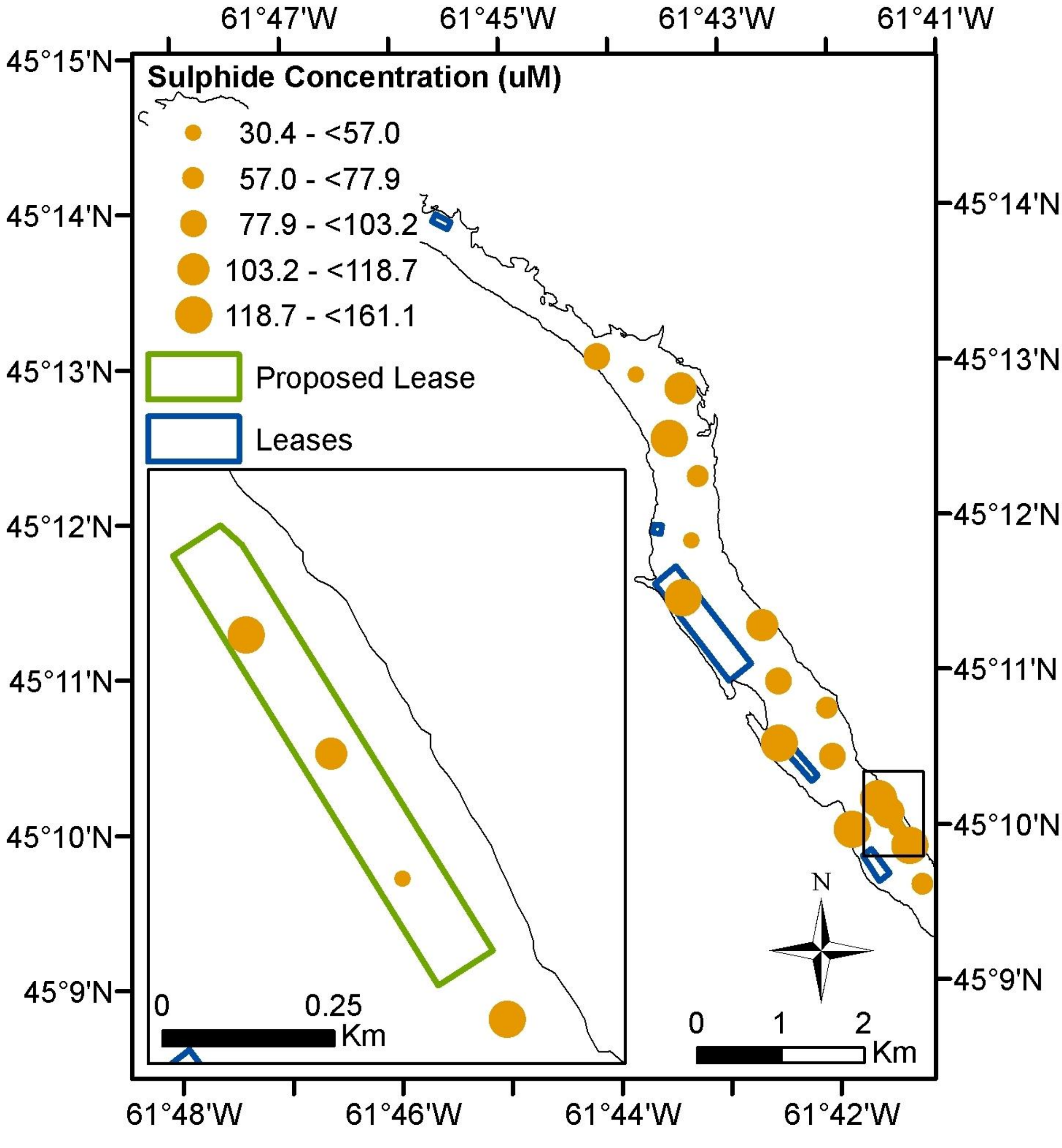

Figure 8: Proportional point based map of sulphide concentration for Country Harbour. Inset indicates proposed lease and DFO environmental assessment sample locations. Legend values also apply to inset values.

3.1.2 Redox Potential

For redox potential, lower values indicate a tendency towards a reducing environment, and the spatial pattern shows that the majority of sediments have a redox potential ranging from 91.7 to 151 mV for both the untransformed and log transformed models (Figures 9 and 10). As the untransformed model is not statistically valid (Table 8), the transformed model more accurately predicts the presence of reduced sediments along the southwestern coastline (Figure 10). Similarly to the sulphide concentration values, the proportional point based map does not indicate any pattern (Figure 11), but does show a slight trend in redox potential along the longest axis of the proposed lease (Figure 11 inset).

3.1.3 Percent Water and Total Organic Content

Percent water and total organic content values did not require log transformation like sulphide concentration and redox potential to statistically validate the model. The prediction model for percent water shows an increasing trend towards the northern end of CH ranging from 56 to 79% (Figure 12). The proportional point based map shows a similar tendency, but not as clearly as the kriging prediction (Figure 13). A similar trend is seen for total organic content, ranging from ~5 to 18%, but with a patch of organically rich sediments in the middle of CH (Figure 14). This observation is supported by the presence of a station with almost 14% organic content in the middle of the bay (Figure 15).

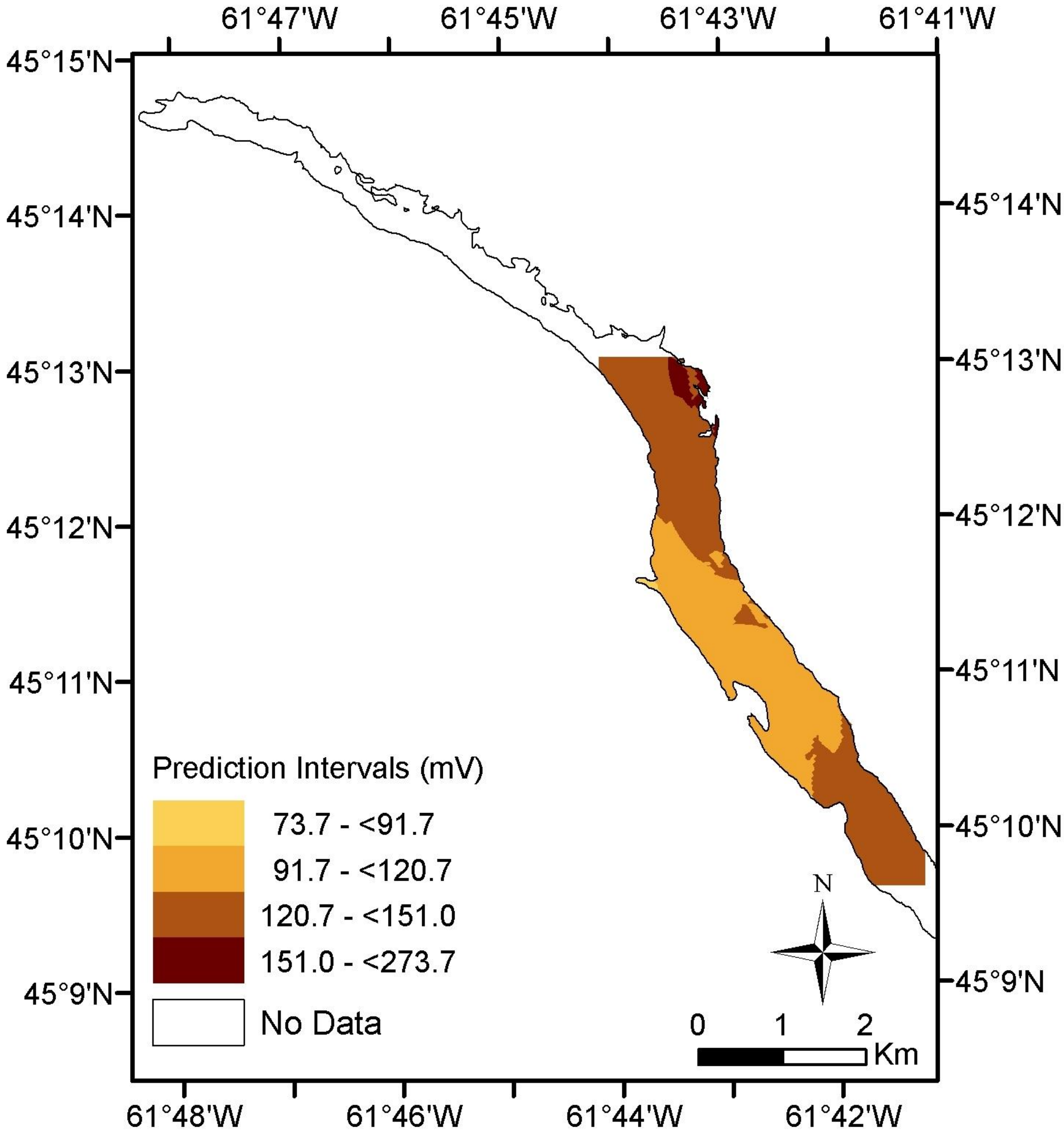

Figure 9: Spatial distribution of redox potential in Country Harbour.

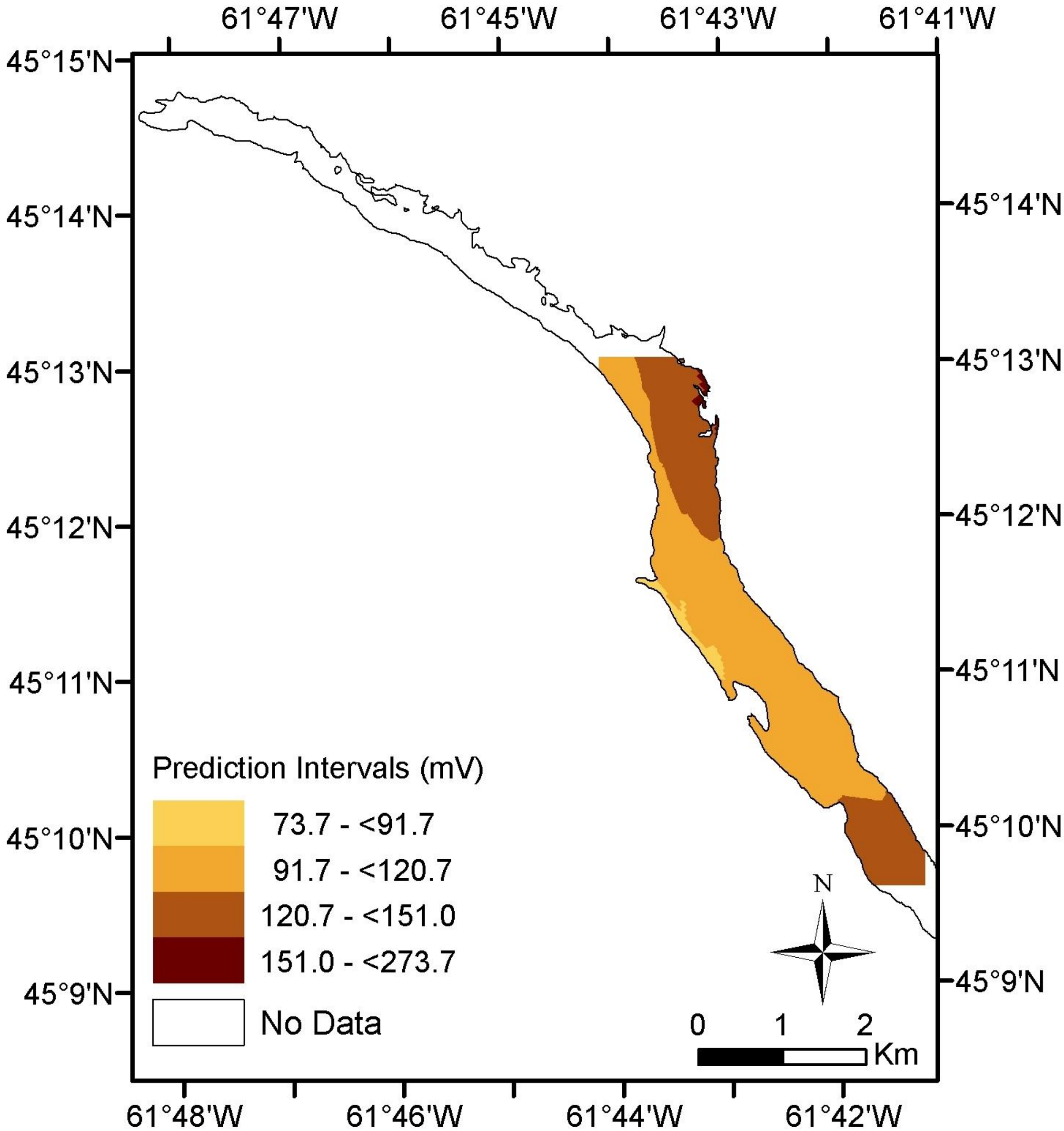

Figure 10: Spatial distribution of log transformed redox potential in Country Harbour.

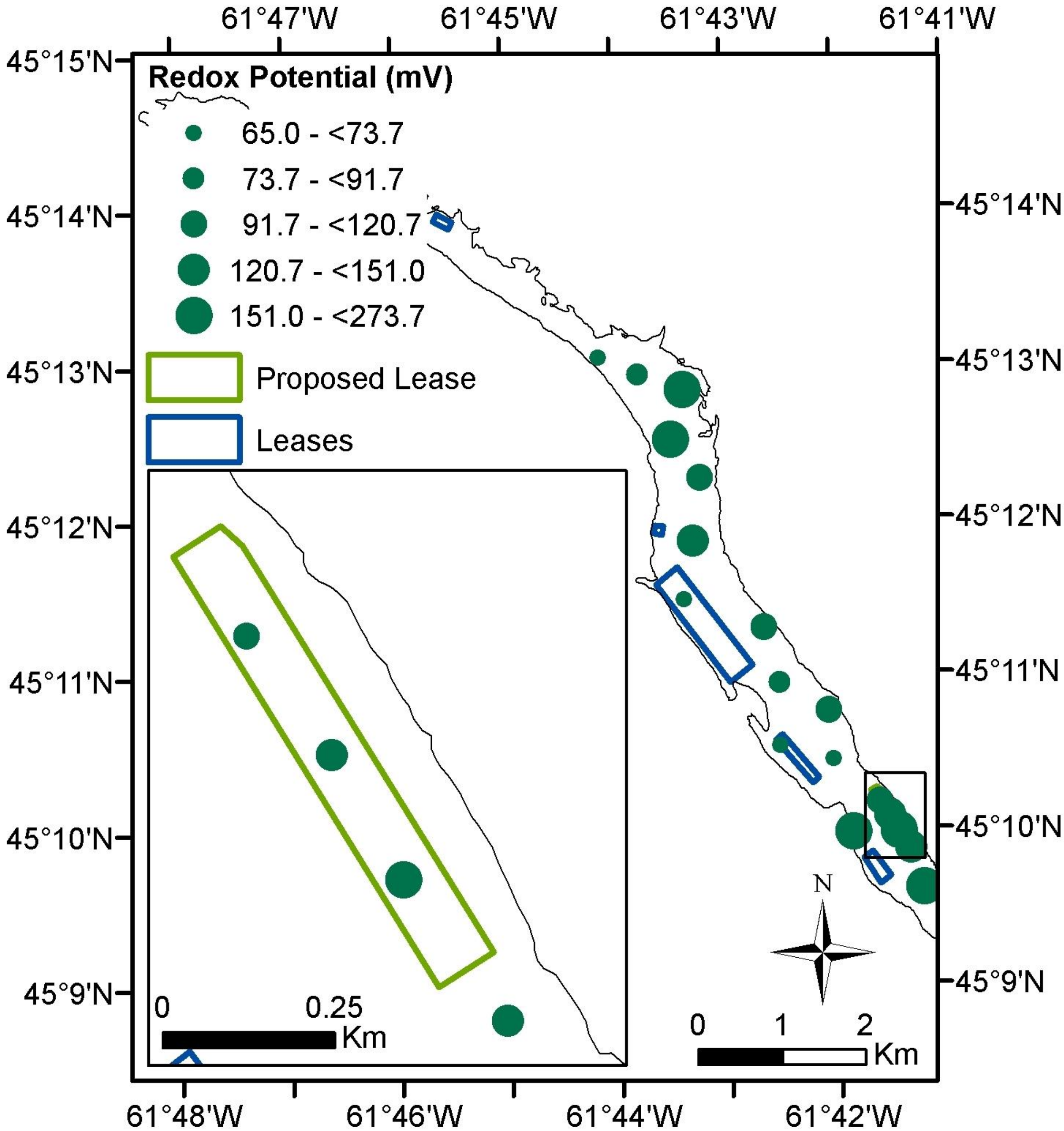

Figure 11: Proportional point based map of redox potential for Country Harbour. Inset indicates proposed lease and DFO environmental assessment sample locations. Legend values also apply to inset values.

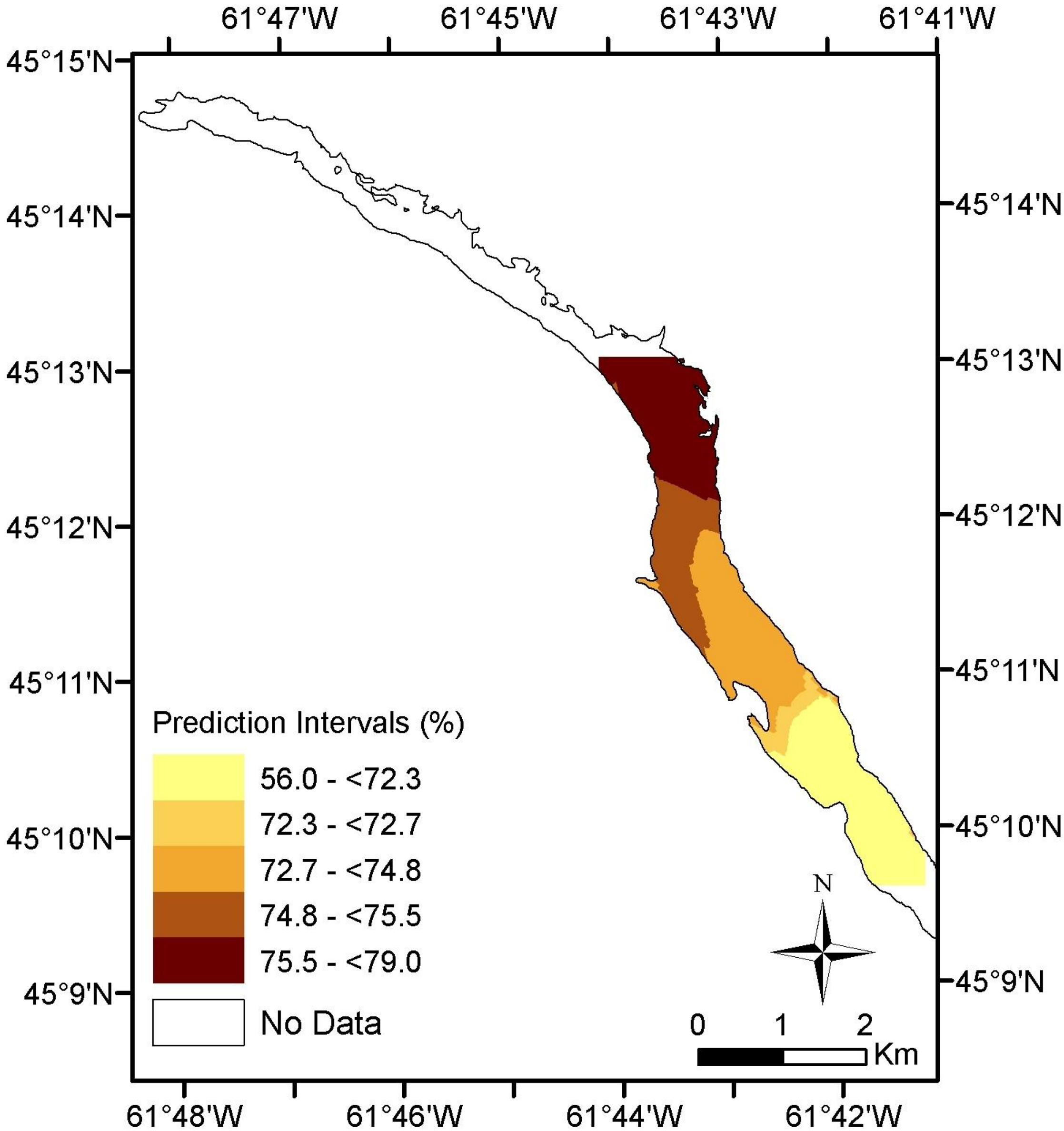

Figure 12: Spatial distribution of percent water in Country Harbour.

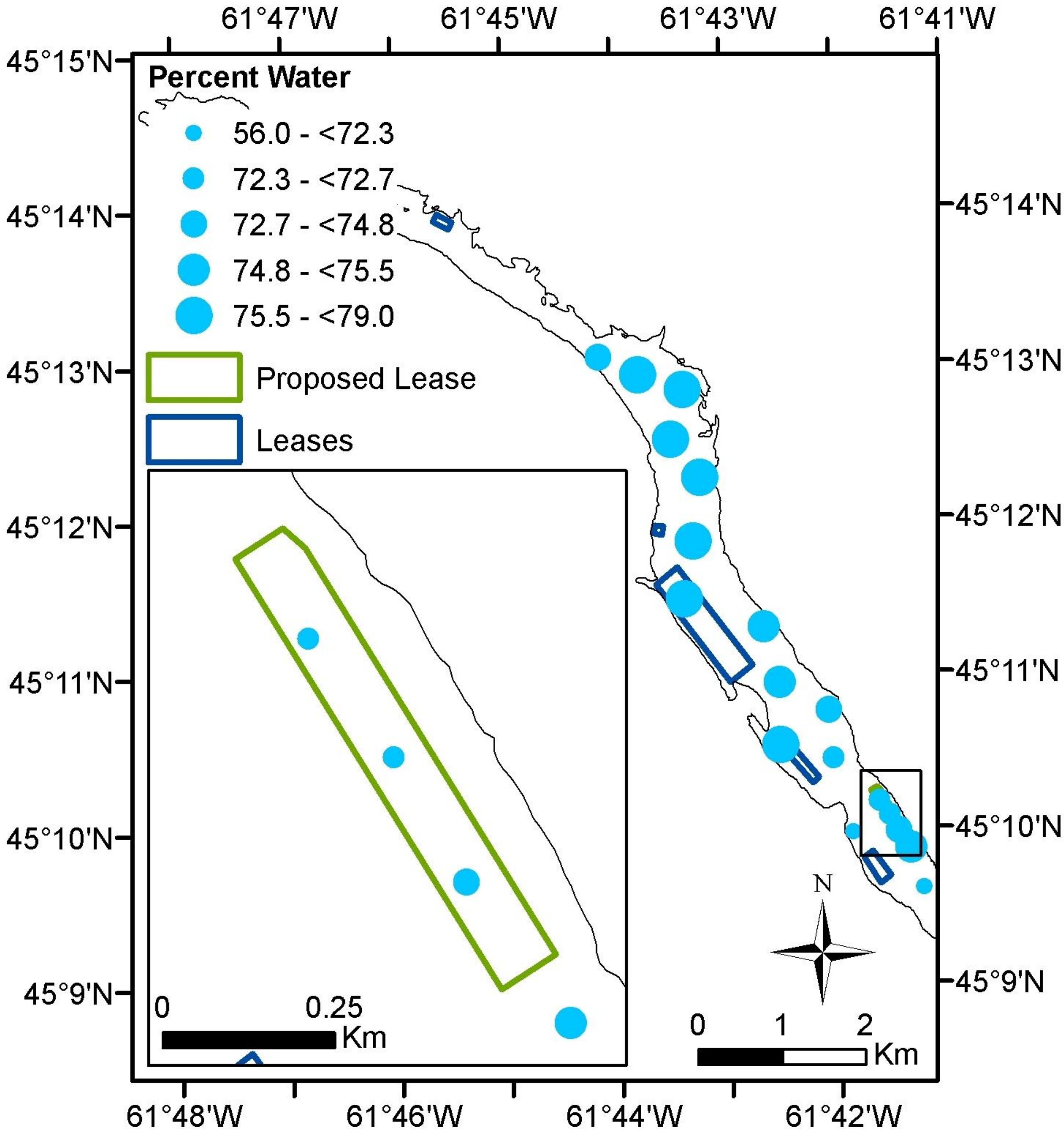

Figure 13: Proportional point based map of percent water for Country Harbour. Inset indicates proposed lease and DFO environmental assessment sample locations. Legend values also apply to inset values.

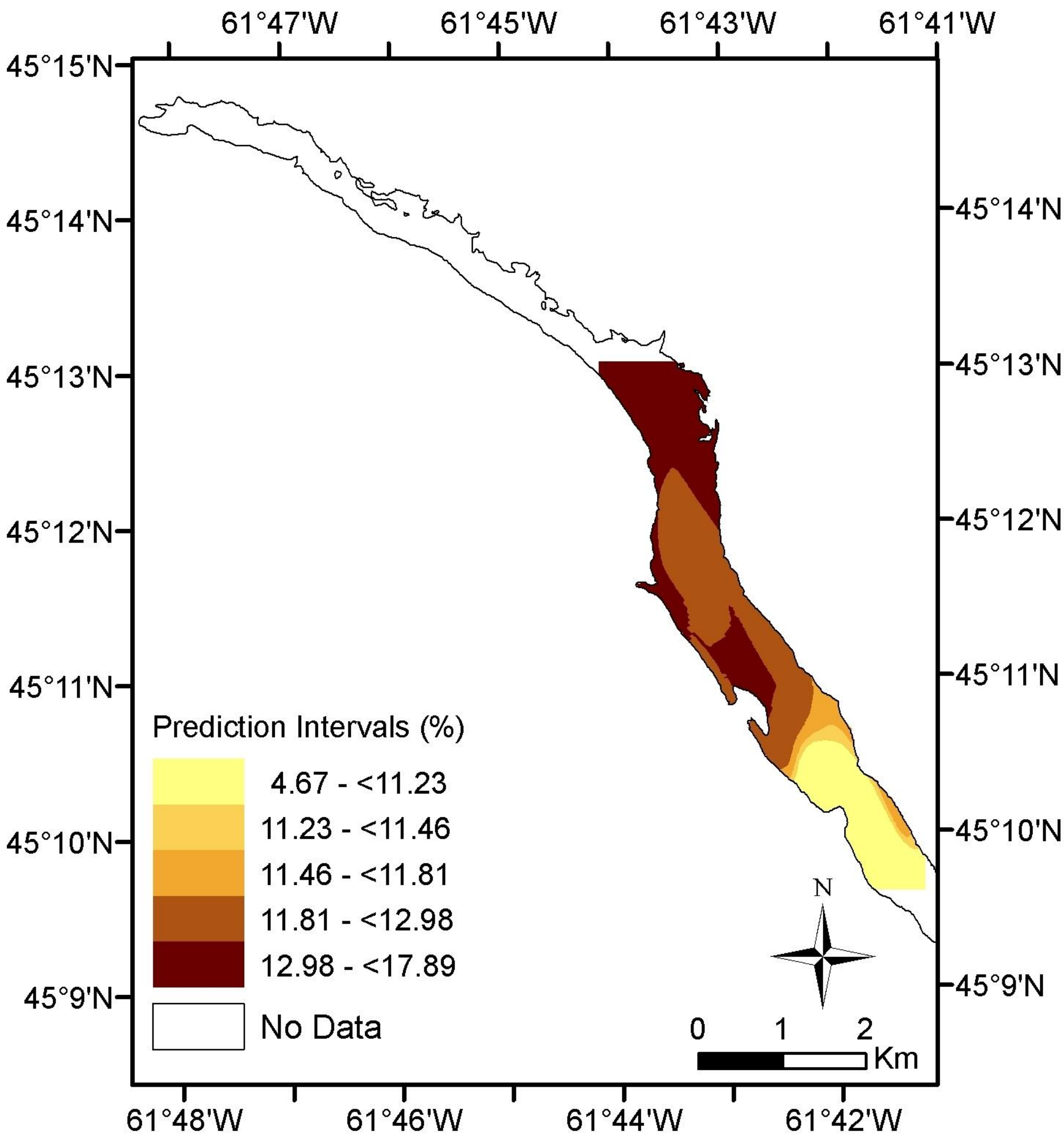

Figure 14: Spatial distribution of total organic content in Country Harbour.

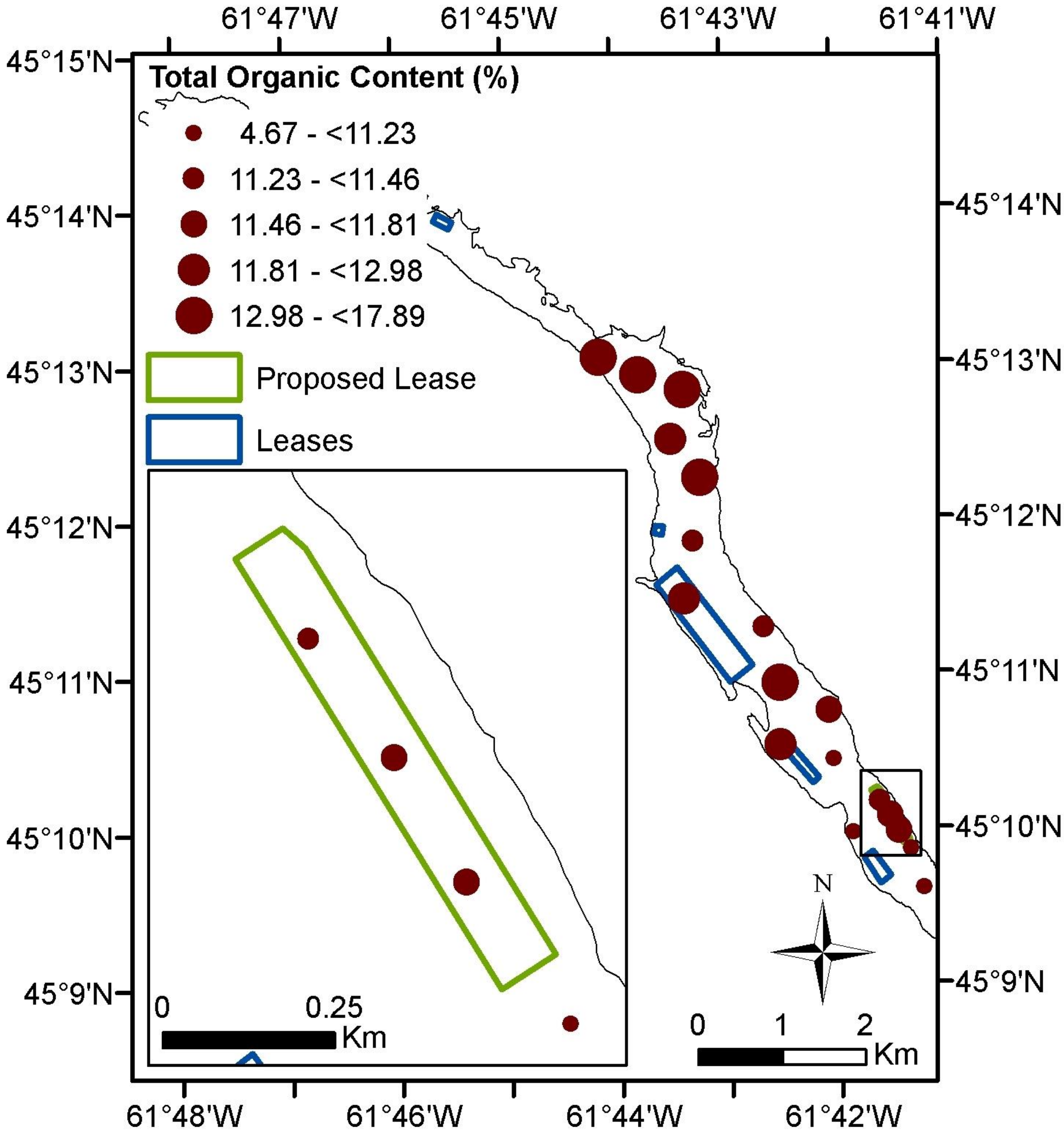

Figure 15: Proportional point based map of total organic content Country Harbour. Inset indicates proposed lease and DFO environmental assessment sample locations. Legend values also apply to inset values.

3.2 Marie-Joseph Harbour

The untransformed sediment characteristic results of the ordinary kriging spherical semivariogram predictions indicated that both the sulphide concentration and redox potential predictions, as for CH, were not statistically valid (Table 10). The RMSPE and ASE for sulphide concentration and redox potential prediction errors were both greater than 20. The log transformed predictions resulted in acceptable RMSPE and ASE prediction values (Table 11). The prediction for the log transformed redox potential and porosity are greatly underestimated, and in contrast the sulphide concentration and organic content predictions are both overestimated, although to a greater extent for sediment organic content. Islands can also influence the results as they act as barriers that interrupt sedimentation and depositional processes.

Table 10: Prediction errors from ordinary kriging model 6 applied to sediment characteristic parameters for Marie-Joseph Harbour sample stations.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Sulphide Concentration	2.199	75.2	81.89	0.02222	0.9224
Redox Potential	-1.008	42.27	37.39	-0.01107	1.107
Porosity	-0.577	7.343	6.189	-0.05936	1.137
Organic Content	0.07147	2.179	2.4	0.0307	0.9207

Table 11: Prediction errors from ordinary kriging model 6 applied to log transformed sulphide concentration and redox potential values for Marie-Joseph Harbour sample stations.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Log Sulphide Concentration	0.0001734	0.2833	0.2859	-0.003171	0.9942
Log Redox Potential	-0.001469	0.1083	0.09357	-0.000587	1.123

3.2.1 Sulphide Concentration

The spatial pattern for sulphide concentration in Marie-Joseph Harbour is slightly different between the untransformed and transformed values. The range of values for the untransformed is higher than that of the log sulphide concentration, ranging from 108.1 to 267 µM compared to 58.9 to 172.3 µM (Figure 16). Interestingly a feature that is present for both sets of data towards the lower southeast part of the bay falls into two different classes (Figures 16 and 17). This pattern for the log transformed values is influenced by the point data map showing a sample station in the immediate area with a sulphide concentration <58.9 µM (Figure 18). This further indicates the invalid results for the model for untransformed sulphide concentration values (Table 10). No specific patterns can be determined from the proportional point map, but similarly to CH within the proposed lease an increase in sulphide concentration along the longest axis can be seen, potentially as a result of circulation patterns or tidal influence within both bays (Figure 18).

3.2.2 Redox Potential

The spatial pattern between the untransformed and log transformed redox potential is similar (Figures 19 and 20), however the validated log redox potential distribution does include the influence of a station within the proposed lease with a high redox potential value (Figure 21). Although bathymetric features are not shown, this station was associated with shallower water that was more oxygenated than other areas of the bay. The eastern part of the bay is also influenced by the open ocean, thus resulting in more oxygenated sediments. This area was also more prevalent to seaweeds and grasses and slightly coarser sediments (personal observation).

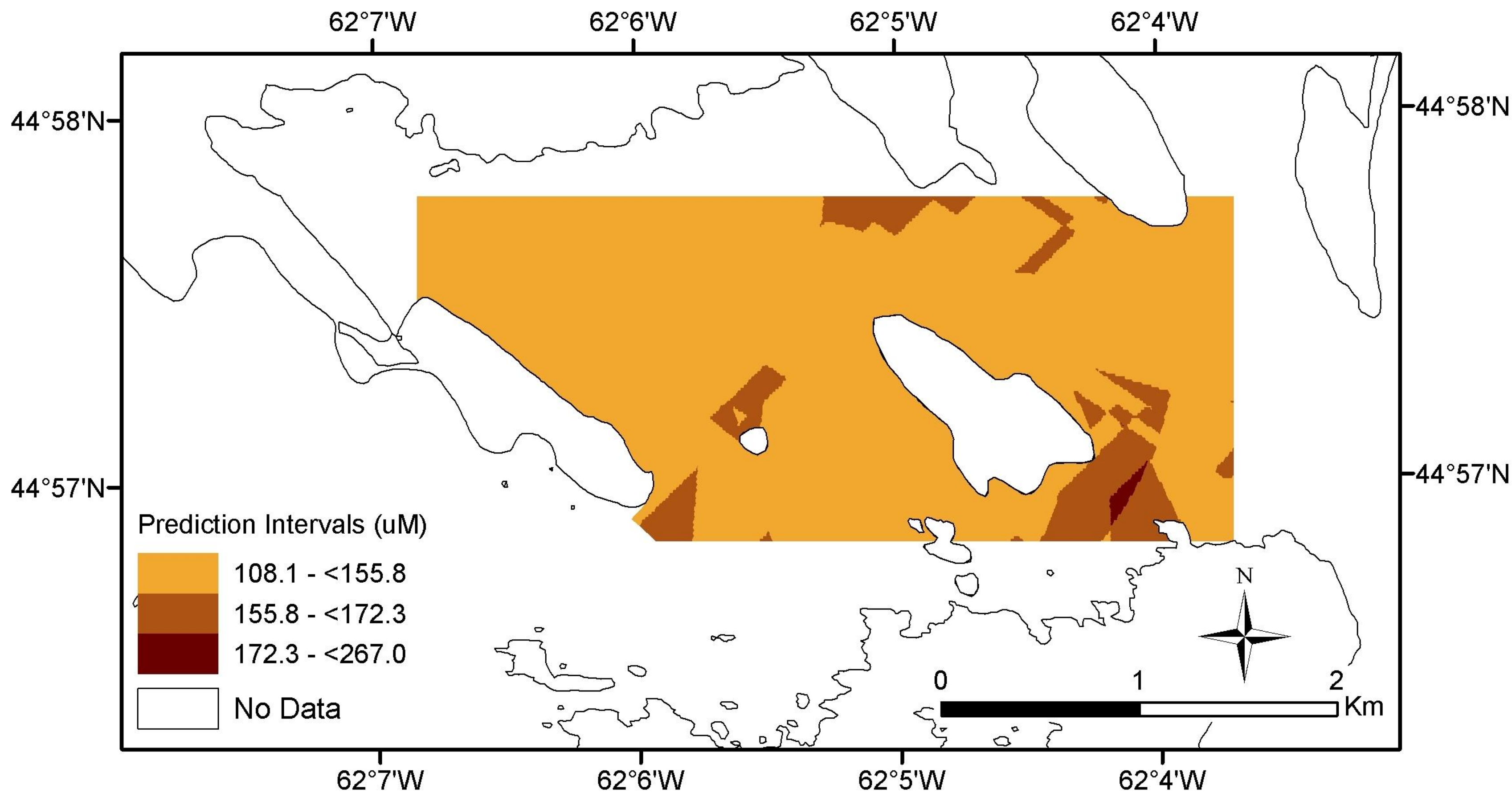

Figure 16: Spatial distribution of sulphide concentration in Marie-Joseph Harbour.

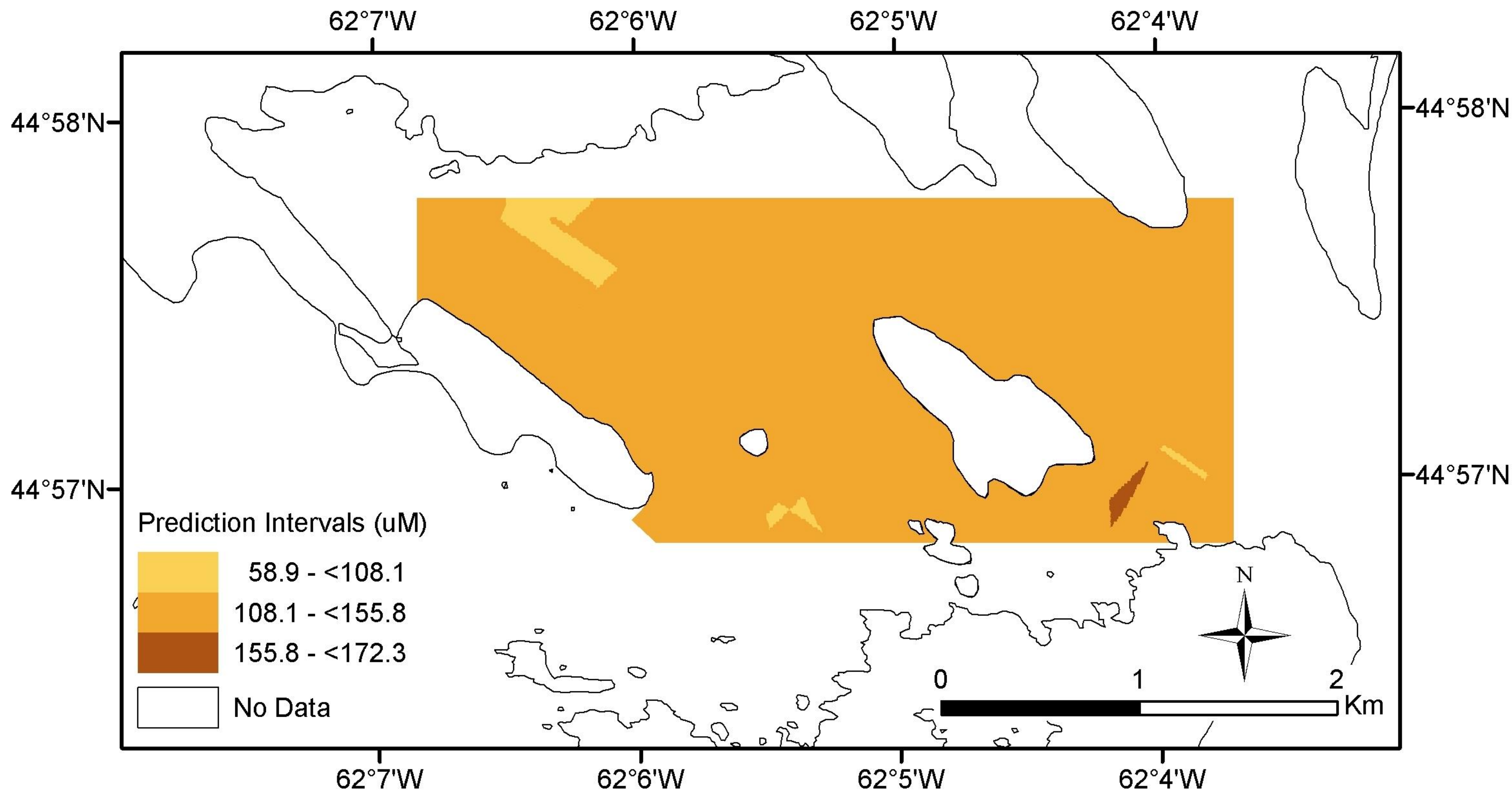

Figure 17: Spatial distribution of log transformed sulphide concentration in Marie-Joseph Harbour.

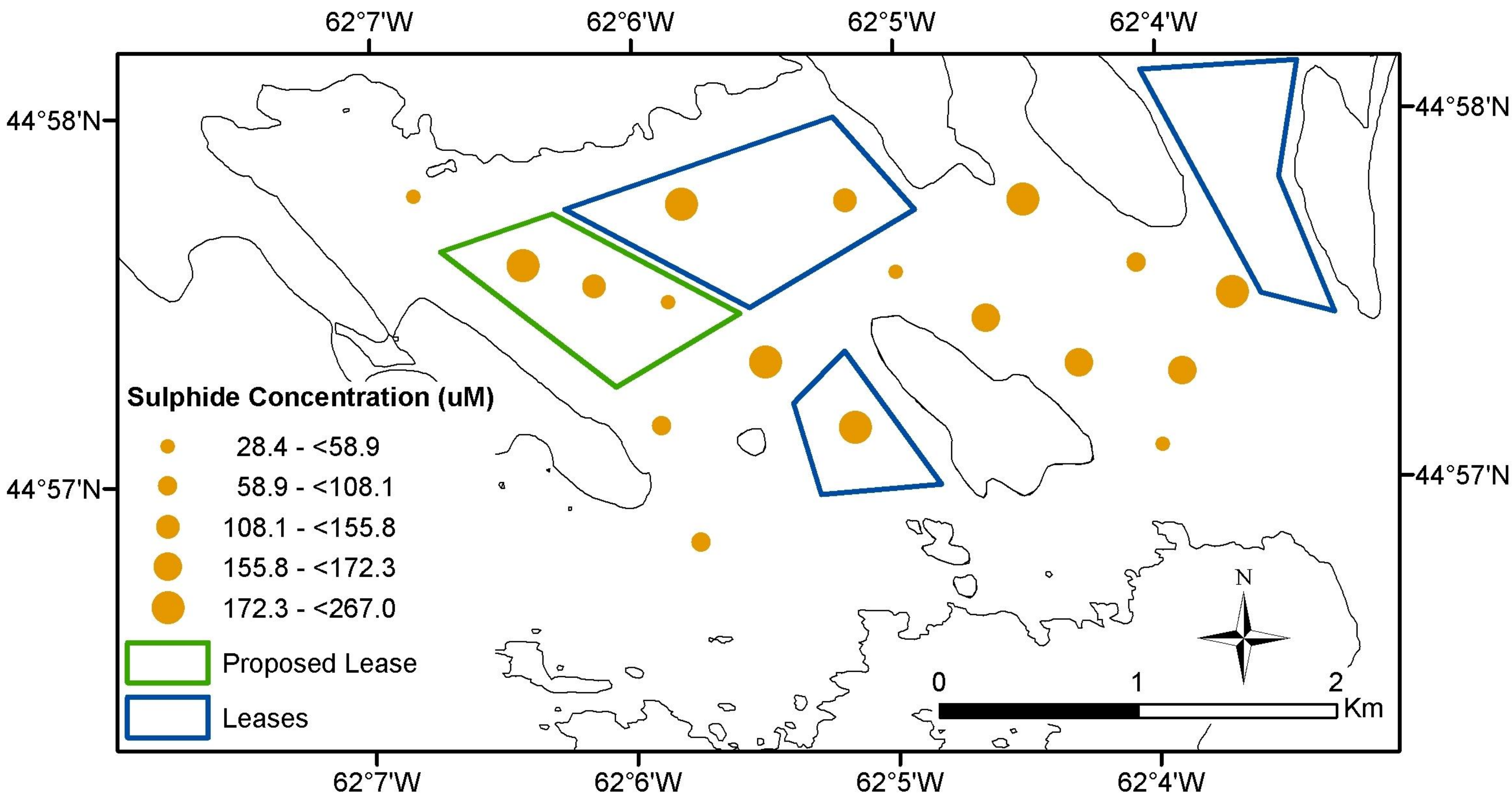

Figure 18: Proportional point based map of sulphide concentration for Marie-Joseph Harbour.

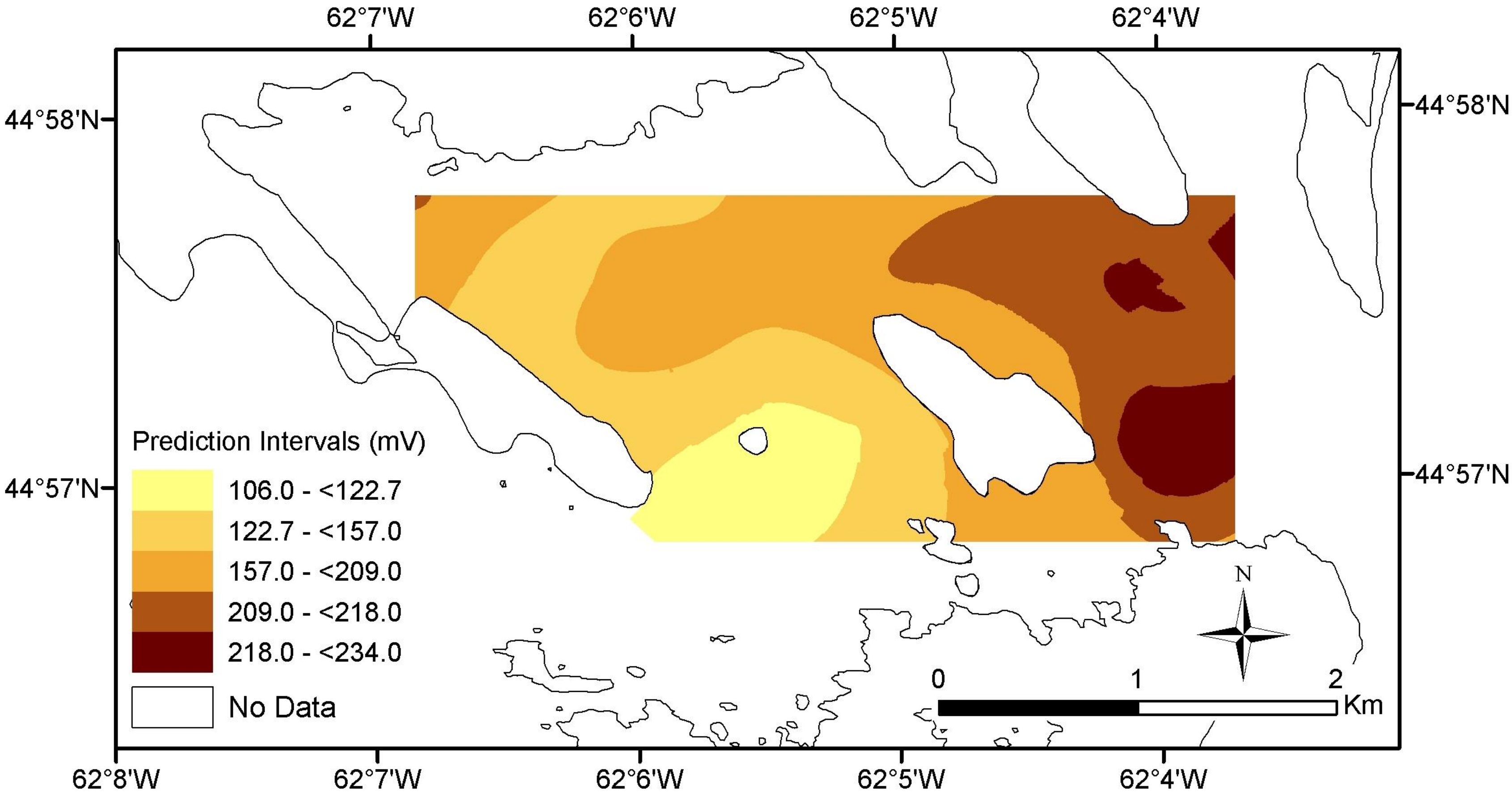

Figure 19: Spatial distribution of redox potential in Marie-Joseph Harbour.

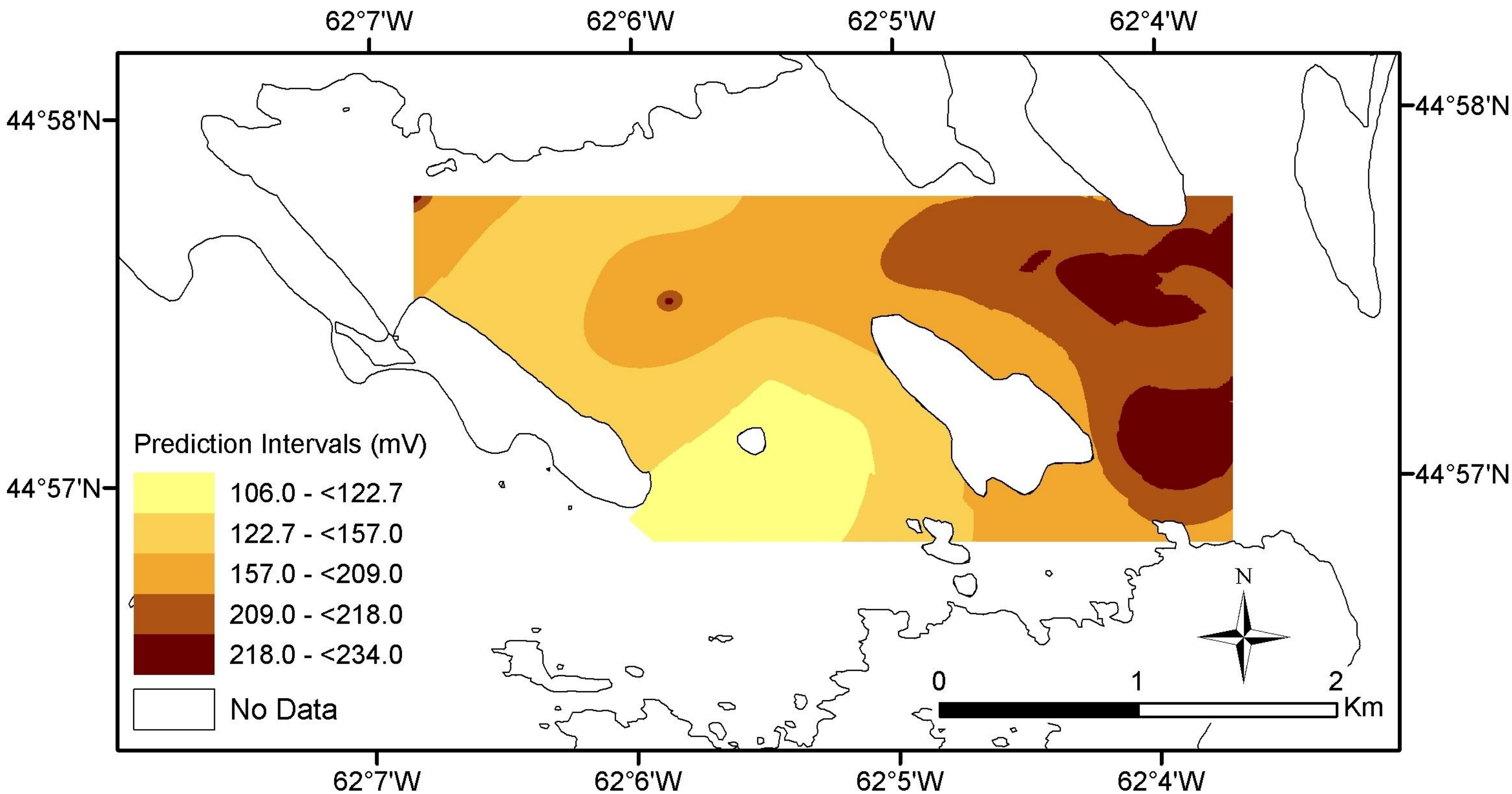

Figure 20: Spatial distribution of log transformed redox potential in Marie-Joseph Harbour.

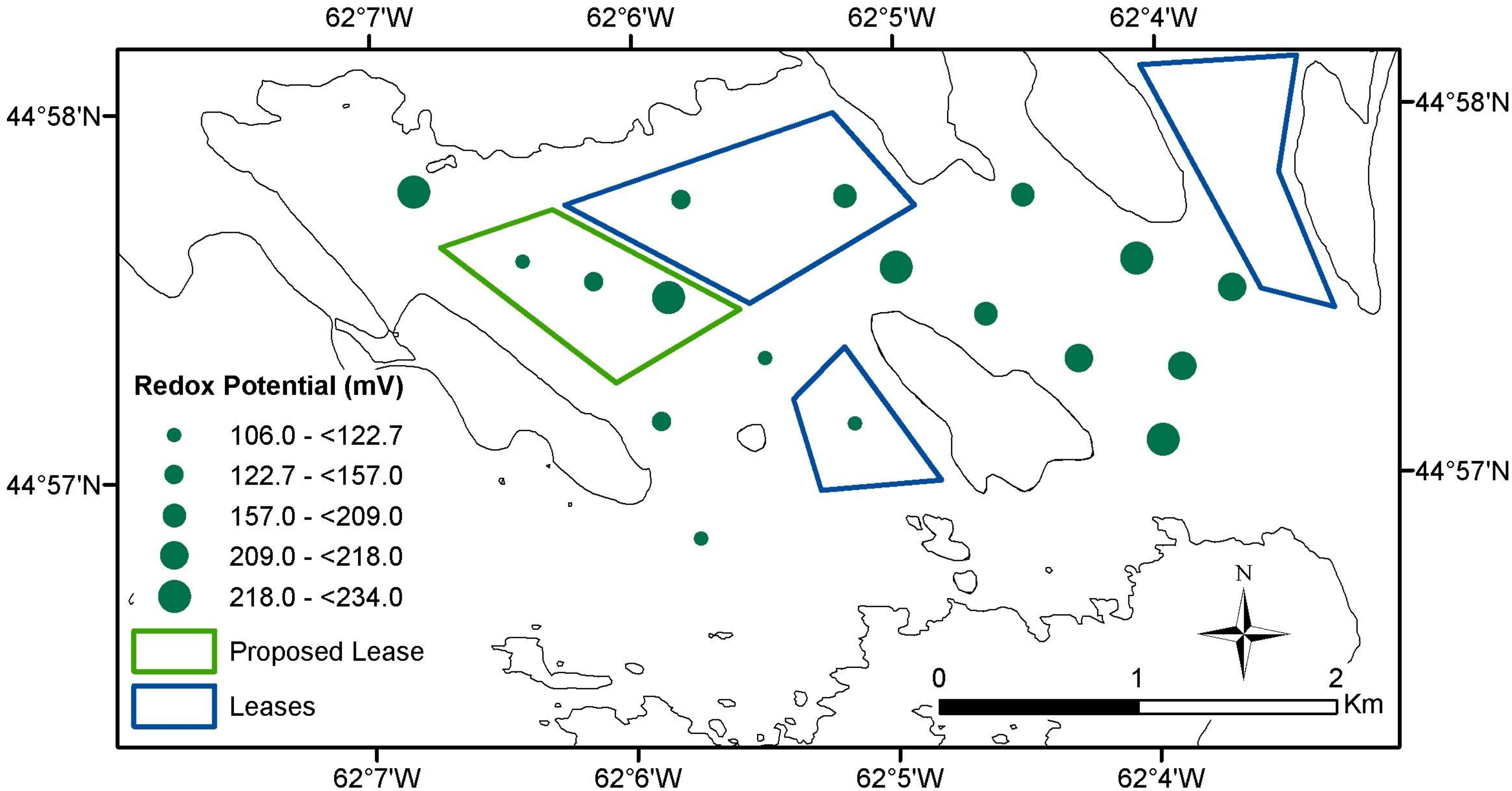

Figure 21: Proportional point based map of redox concentration for Marie-Joseph Harbour.

3.2.3 Percent Water and Total Organic Content

Neither the percent water nor total organic content required log transformation in order to validate the ordinary kriging models. The spatial pattern for percent water in Marie-Joseph Harbour is concurrent with personal observations that those sediments towards the eastern part of the bay are coarser, resulting in less water retention within those sediments (Figure 22). This is also more indicative of suspension environments versus depositional environments in more protected areas of the bay. The spatial pattern can somewhat be identified from the proportional point based map but not as clearly as the spatial distribution shown in the interpolated surface (Figure 23). There is not much difference in the total organic content in all sediments, with only 5% separating the lowest from the highest class (Figure 24). The pattern, however, seems very haphazard towards the northwest part of the bay and is not substantiated by the presence of sampling stations (Figure 25).

3.3 Tor Bay

A similar pattern emerged in Tor Bay where the untransformed sediment sulphide concentration and redox potential predictions were not statistically valid (Table 12). The RMSPE and ASE for sulphide concentration and redox potential prediction errors were both greater than 20, and in the case of sulphide concentration greater than 100. In contrast the log transformed predictions resulted in acceptable RMSPE and ASE values (Table 13). In this case the prediction for the log transformed sulphide concentration and organic content are overestimated, and slightly underestimated for porosity and log transformed redox potential.

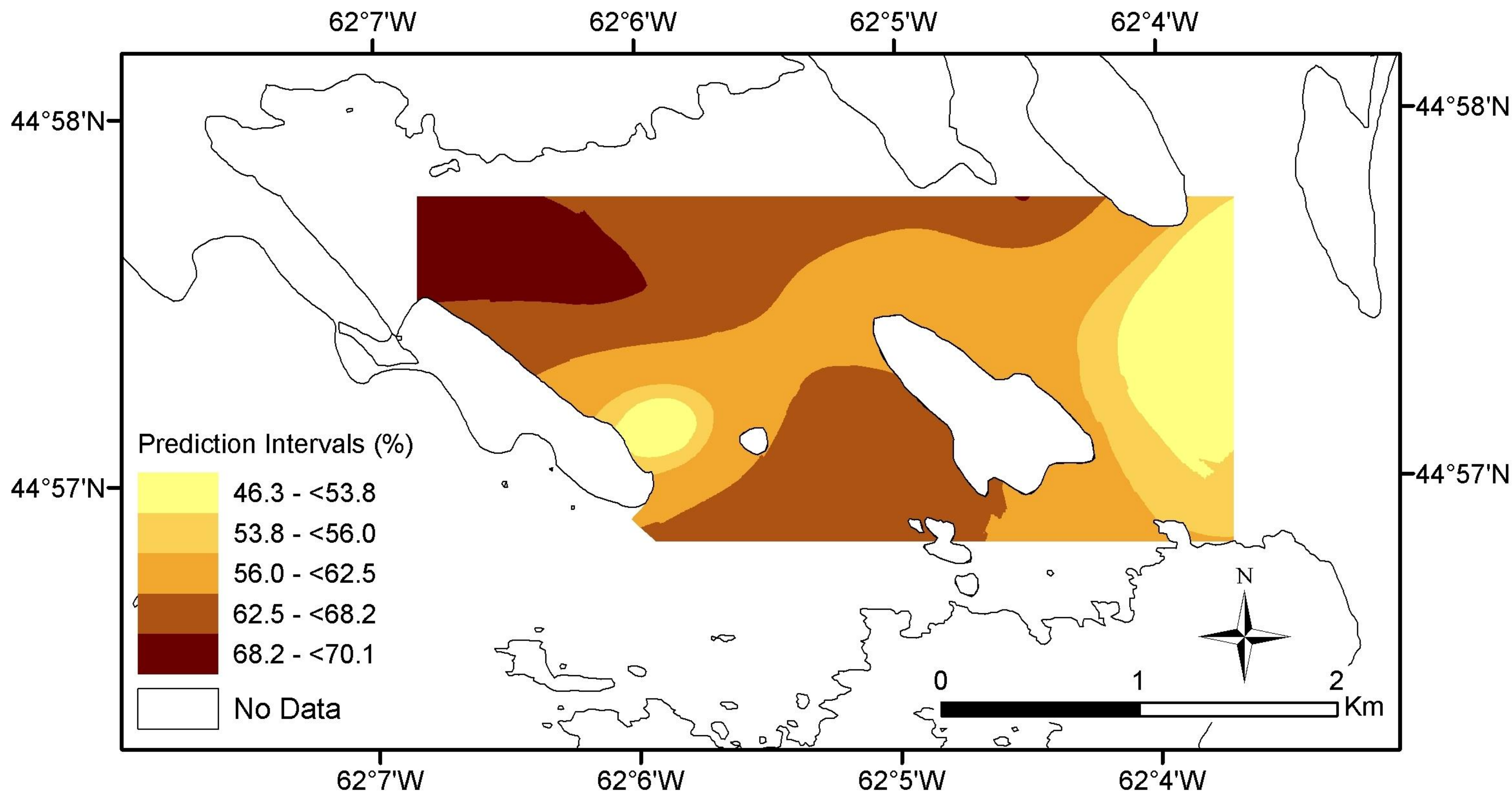

Figure 22: Spatial distribution of percent water in Marie-Joseph Harbour.

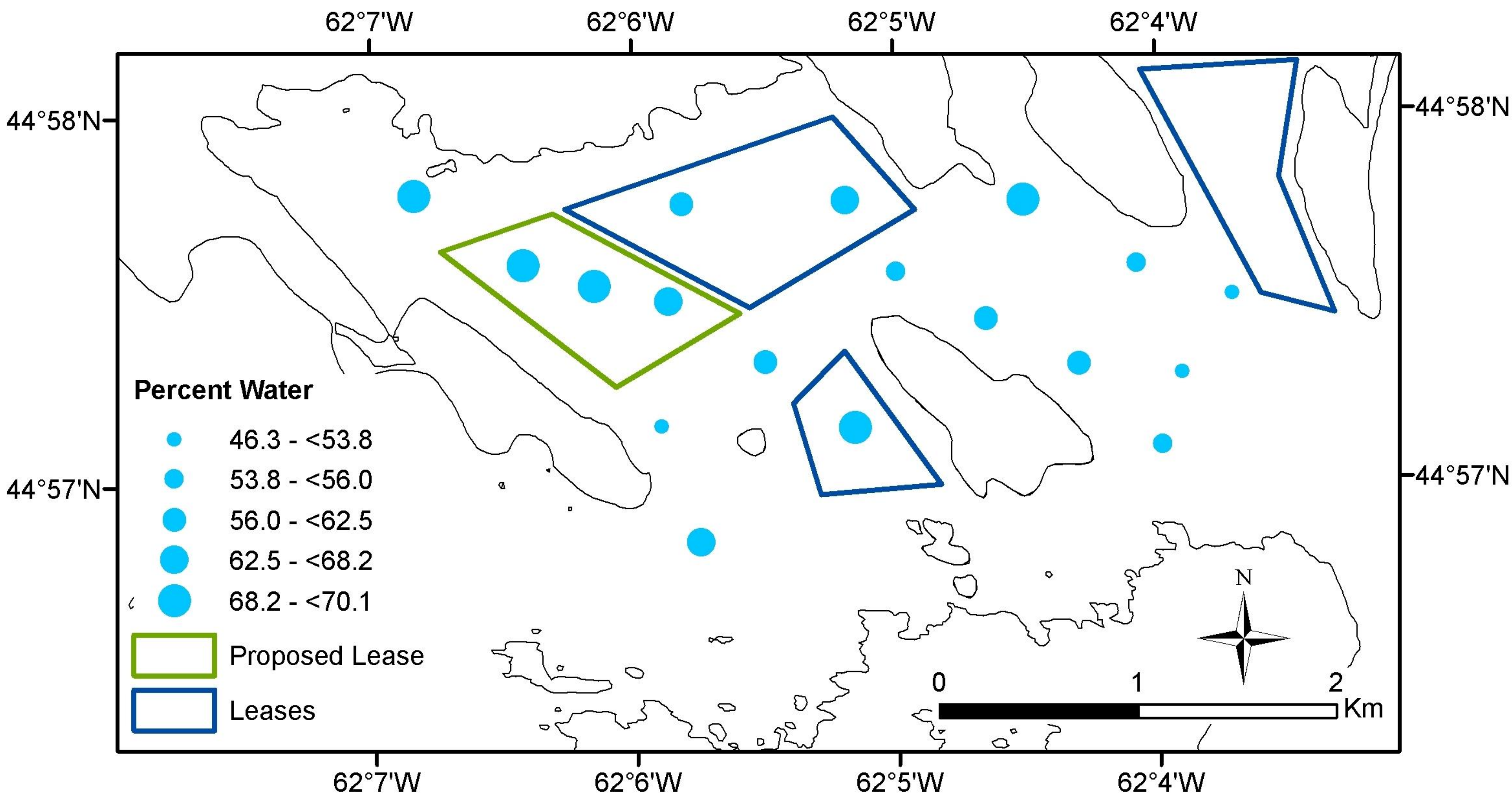

Figure 23: Proportional point based map of percent water for Marie-Joseph Harbour.

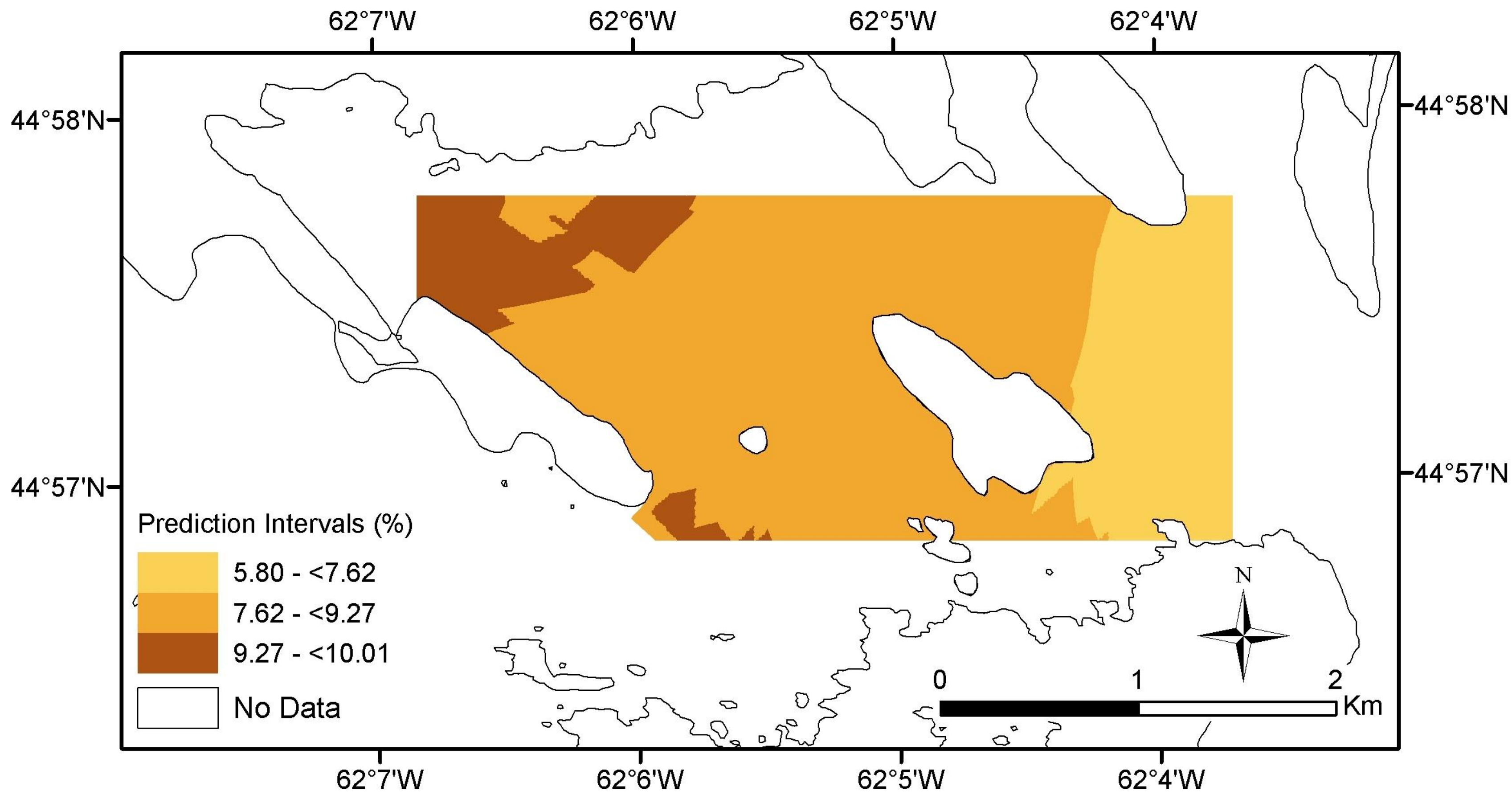

Figure 24: Spatial distribution of total organic content in Marie-Joseph Harbour.

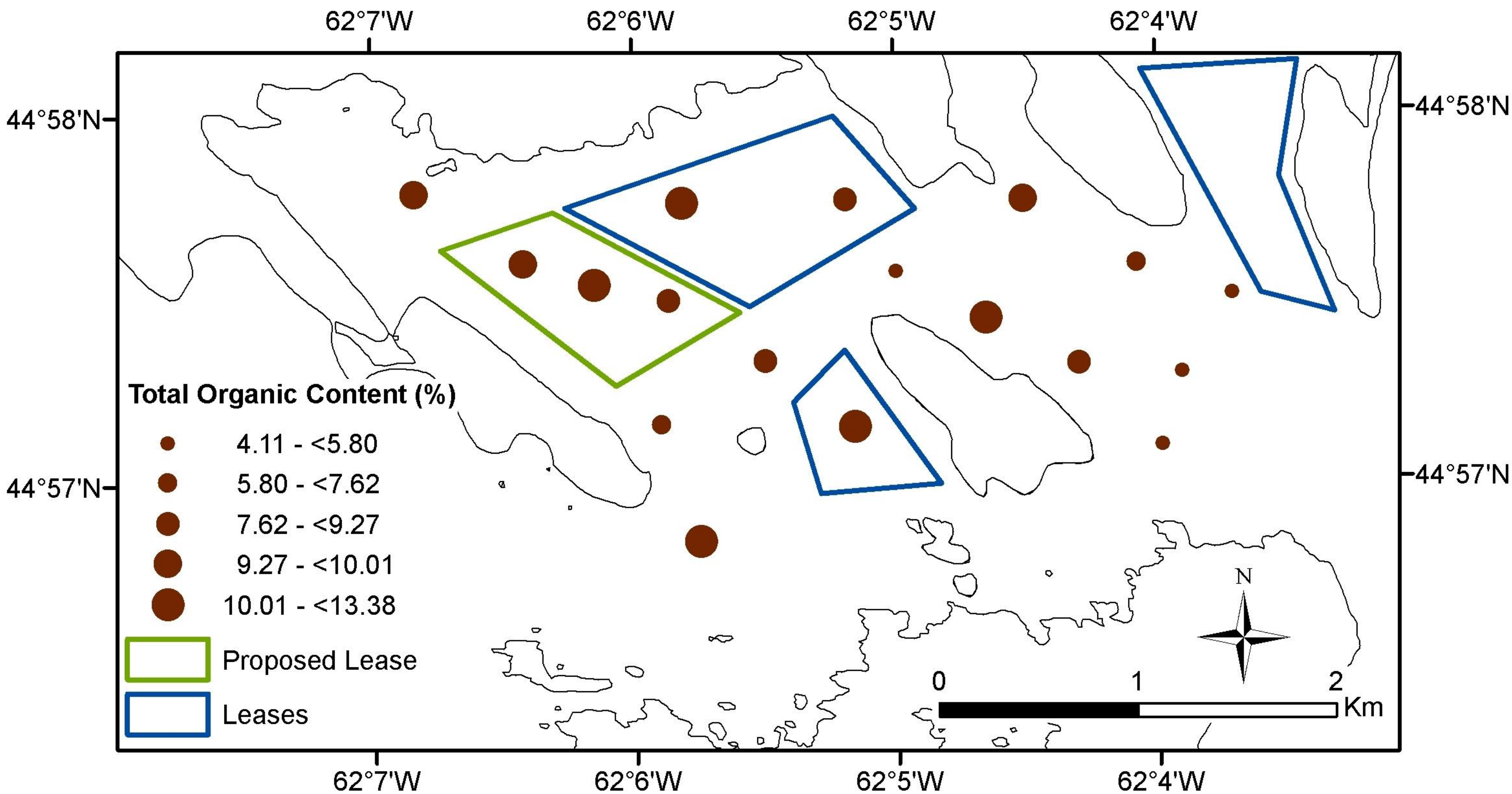

Figure 25: Proportional point based map of total organic content for Marie-Joseph Harbour.

Table 12: Prediction errors from ordinary kriging model 3 applied to sediment characteristic parameters for Tor Bay sample stations.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Sulphide Concentration	-7.938	181.1	177.6	-0.03964	1.036
Redox Potential	-1.075	42.18	42.6	-0.02138	1.008
Porosity	-0.4387	6.381	6.169	-0.04277	1.026
Organic Content	0.04211	1.059	1.174	0.03234	0.9201

Table 13: Prediction errors from ordinary kriging model 3 applied to log transformed sulphide concentration and redox potential values for Tor Bay sample stations.

	Mean Prediction Error	Root Mean Square Prediction Error	Average Standard Error	Standardised Mean Prediction Error	Standardised Root Mean Square Prediction Error
Log Sulphide Concentration	-0.03118	0.5402	0.5498	-0.04971	0.9921
Log Redox Potential	-0.003863	0.1473	0.1501	-0.022	1.004

3.3.1 Sulphide Concentration

Due to the spatial extent and nature of bottom type in TB, there were fewer samples than in CH and MJ. This results in generalised spatial patterns with kriging interpolation. The spatial trend for sulphide concentration only shows a few areas with values ranging from 58.4 to 98.3 µM (Figure 26). With the log transformed sulphide concentration, a pattern evolves where the concentration increases towards the northeast (Figure 27). The spatial distribution is sharp edged for both the untransformed and transformed values, potentially due to the nature of the sampling grid. The proportional point distribution map (Figure 28) shows three stations towards the northeast that account for the trend as shown by the log transformed sulphide, although this model smoothes the estimation within the hypothetical lease that included the highest value (657.1 µM) seen in all three bays.

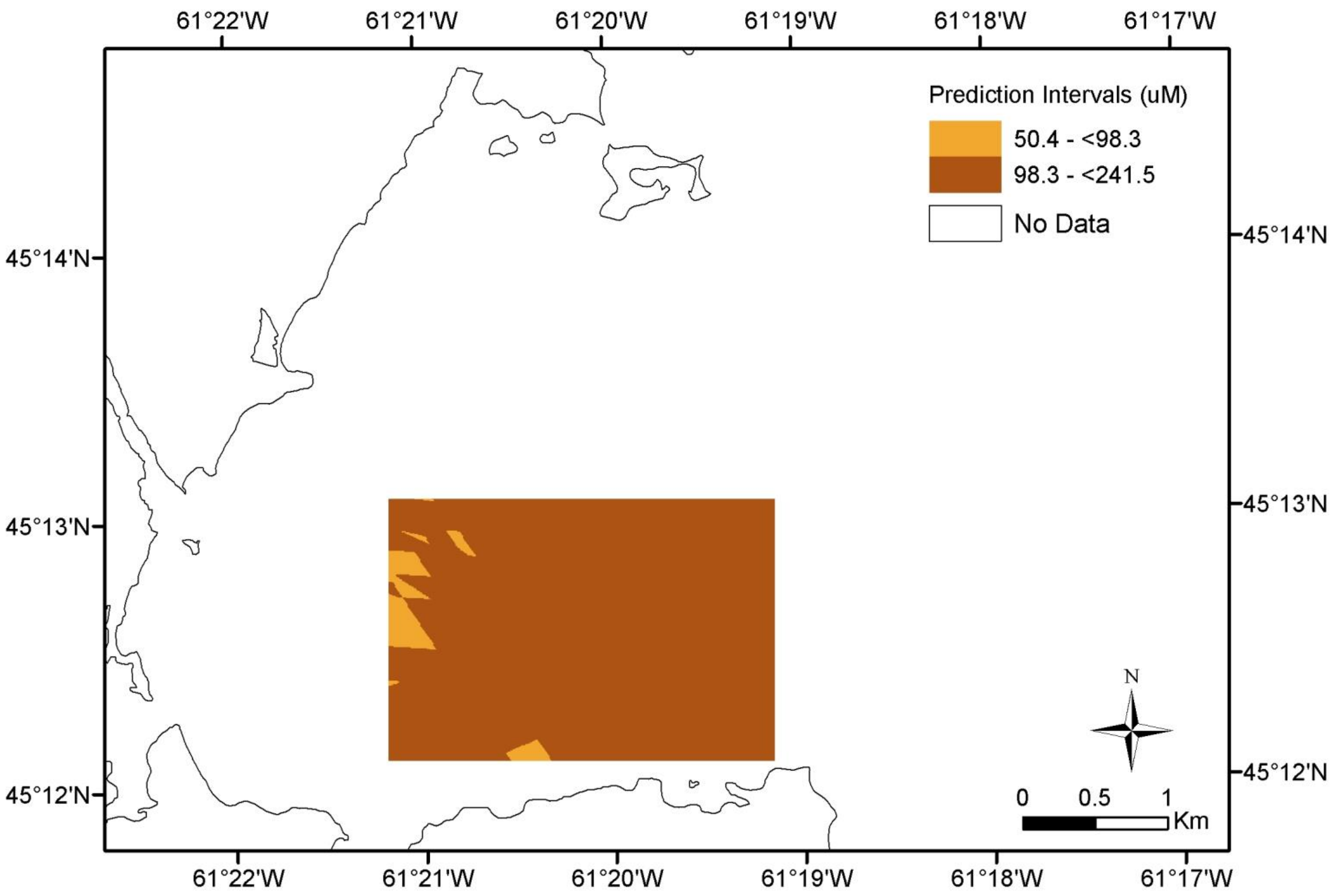

Figure 26: Spatial distribution of sulphide concentration in Tor Bay.

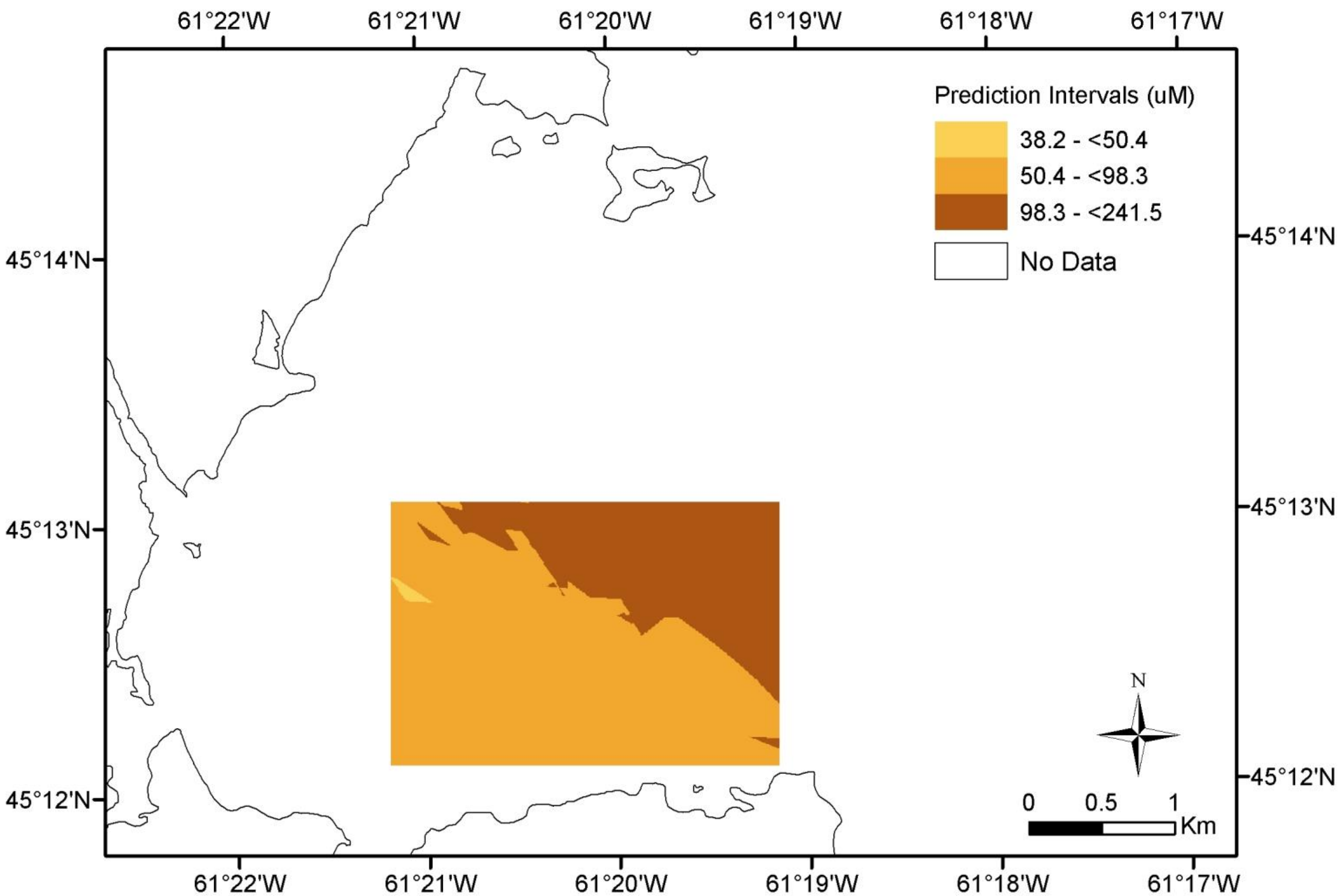

Figure 27: Spatial distribution of log transformed sulphide concentration in Tor Bay.

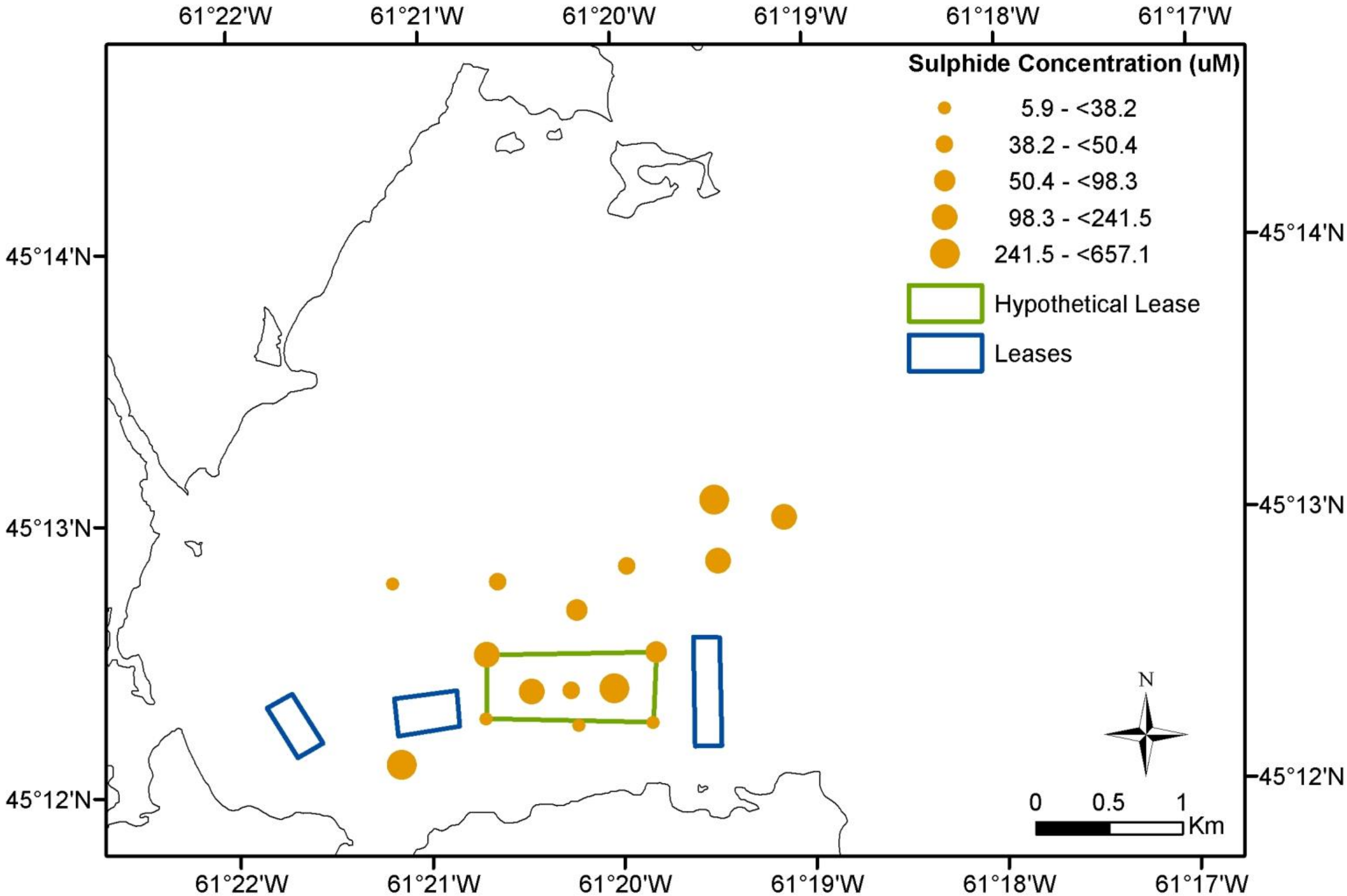

Figure 28: Proportional point based map of sulphide concentration for Tor Bay.

3.3.2 Redox Potential

No pattern emerges from untransformed redox potential values, but as the model is invalidated (Table 12), this is expected (Figure 29). With log transformation, an interesting spatial distribution occurs (Figure 30). The diamond-like patterns towards the northwest are artefacts of the model, as no stations were sampled in the immediate area (Figure 31). By default, the ArcGIS Geostatistical Analyst interpolates within the area of the north/south and east/west extent of all sample points, thus interpolating even where no stations were sampled (Johnston et al., 2001). It is possible that alteration of the nugget could have improved the spatial distribution, but experimentation indicated no change in the spatial distribution. This is potentially a result of low number of sample stations (n = 16). The main result is the presence of sediments with redox potentials within the 155 to 181 mV range in the centre of the study area (Figure 30).

3.3.3 Percent Water and Total Organic Content

The range of percent water in TB is greater than that of CH and MJ, ranging almost 30%. Kriging interpolation shows a clear southwest trend towards increased percent water, with a patch of less porous sediments in the lower southeast part of the spatial extent, although this is only due to two stations along the hypothetical lease (Figure 32 and 33). The spatial pattern for total organic content is very linear, with decreasing organic content towards the northeast (Figure 34). As the range is very small, from 0.33 to 4.25%, the small scale variation is not important. The long patch of organically richer sediments along the southern coastline is attributed to those stations associated with the hypothetical lease (Figure 35).

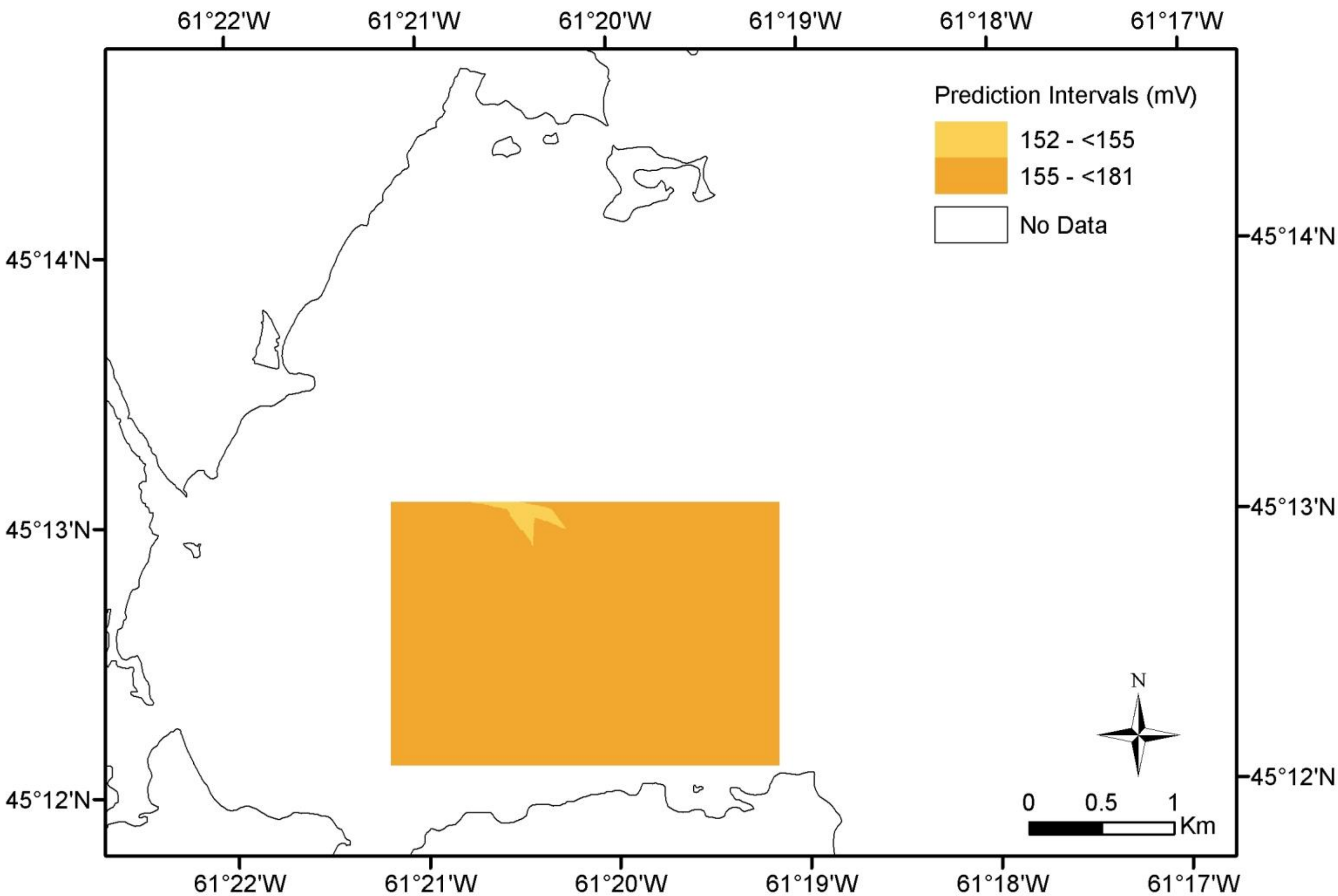

Figure 29: Spatial distribution of redox potential in Tor Bay.

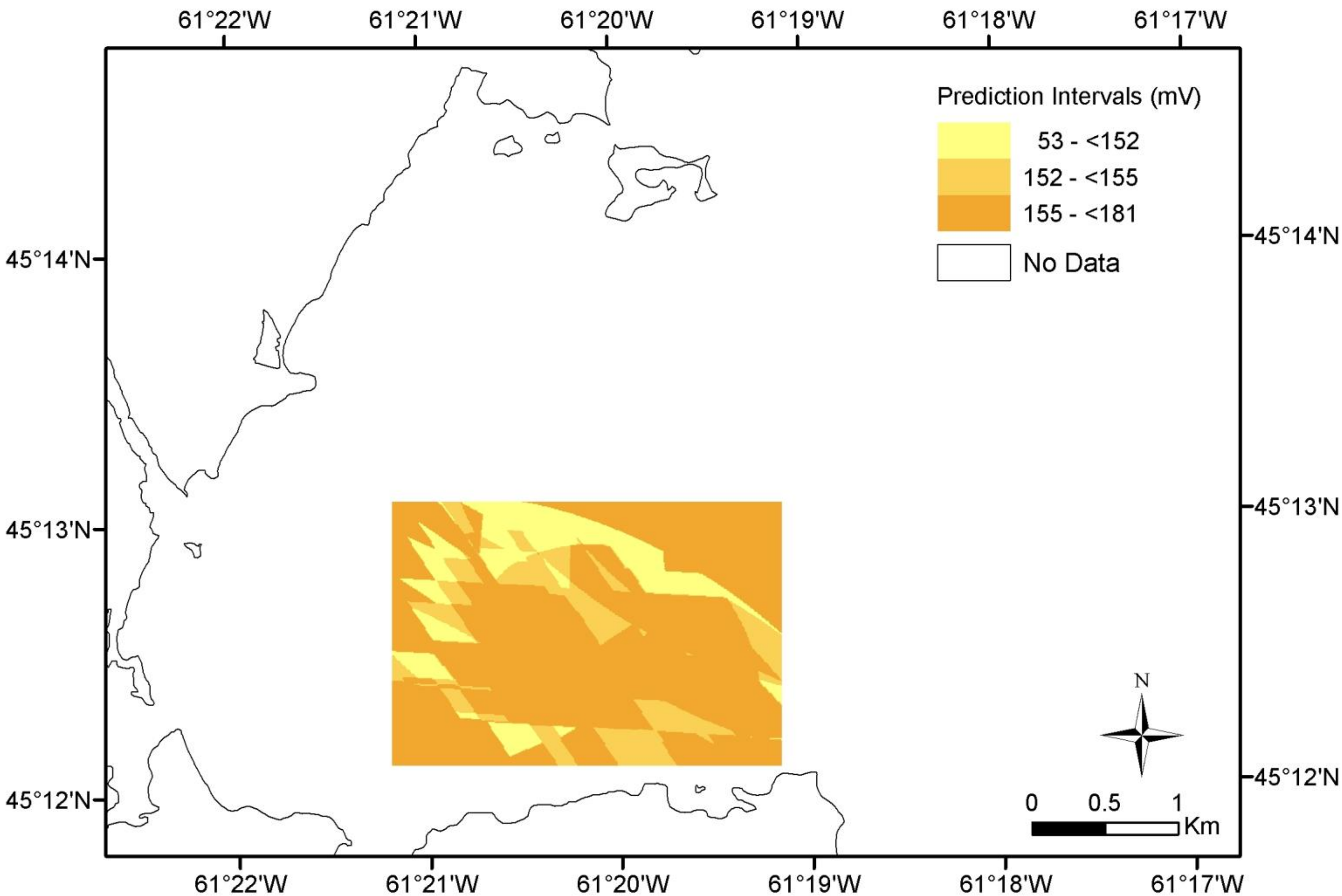

Figure 30: Spatial distribution of log transformed redox potential in Tor Bay. The diamond shaped patterns are artefacts of the model and low sample station number and are not representative of actual spatial patterns.

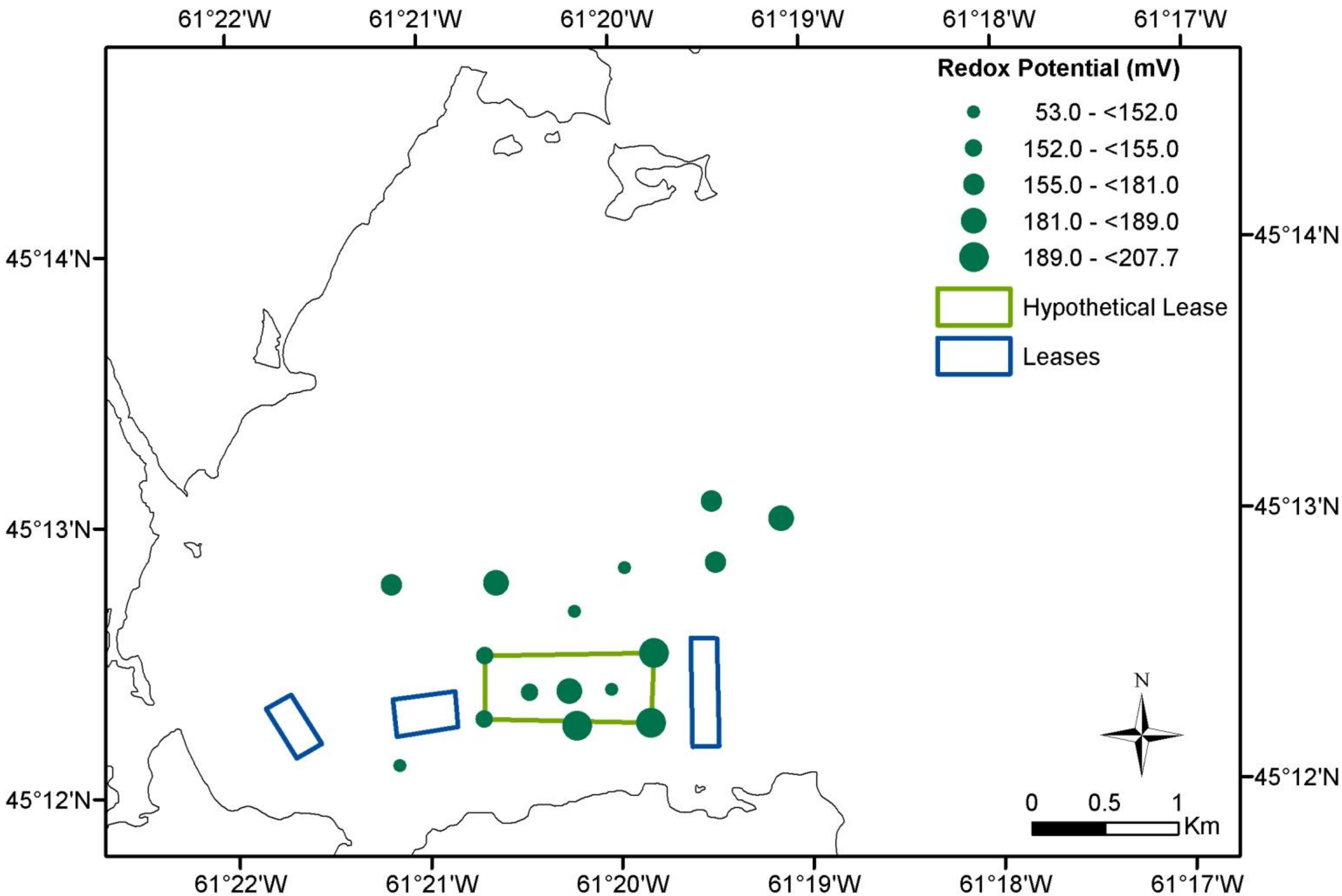

Figure 31: Proportional point based map of redox potential for Tor Bay.

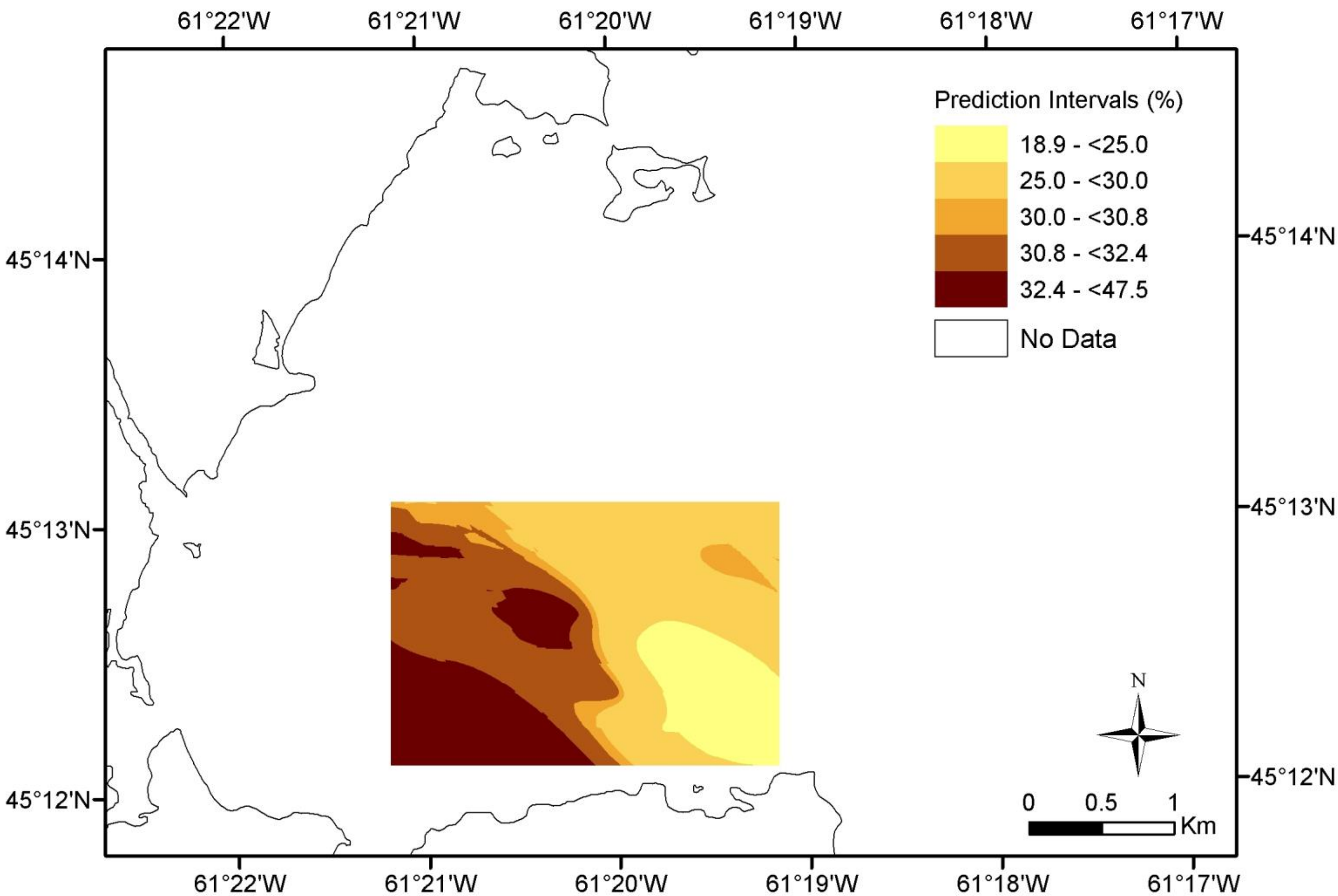

Figure 32: Spatial distribution of percent water in Tor Bay.

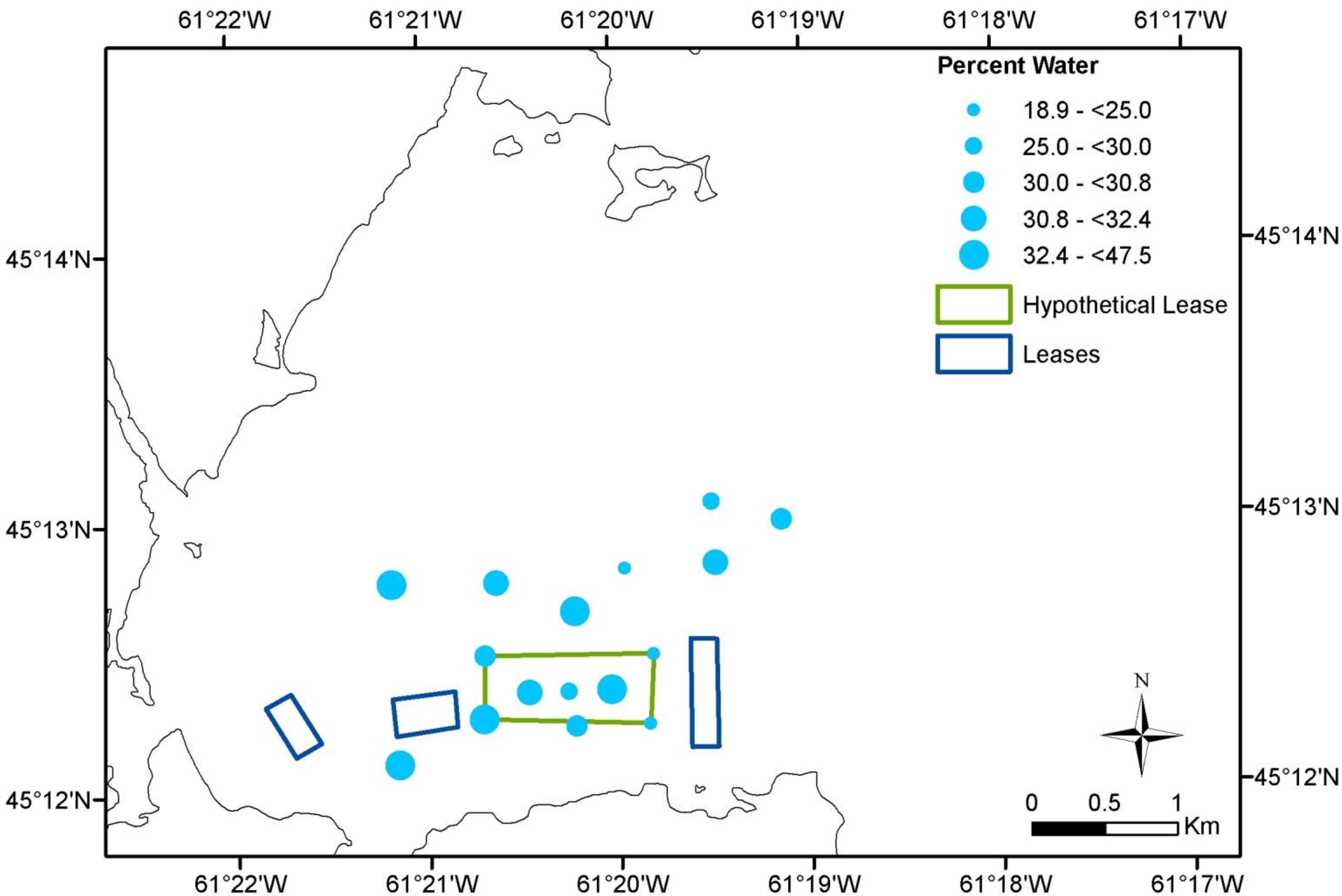

Figure 33: Proportional point based map of percent water for Tor Bay.

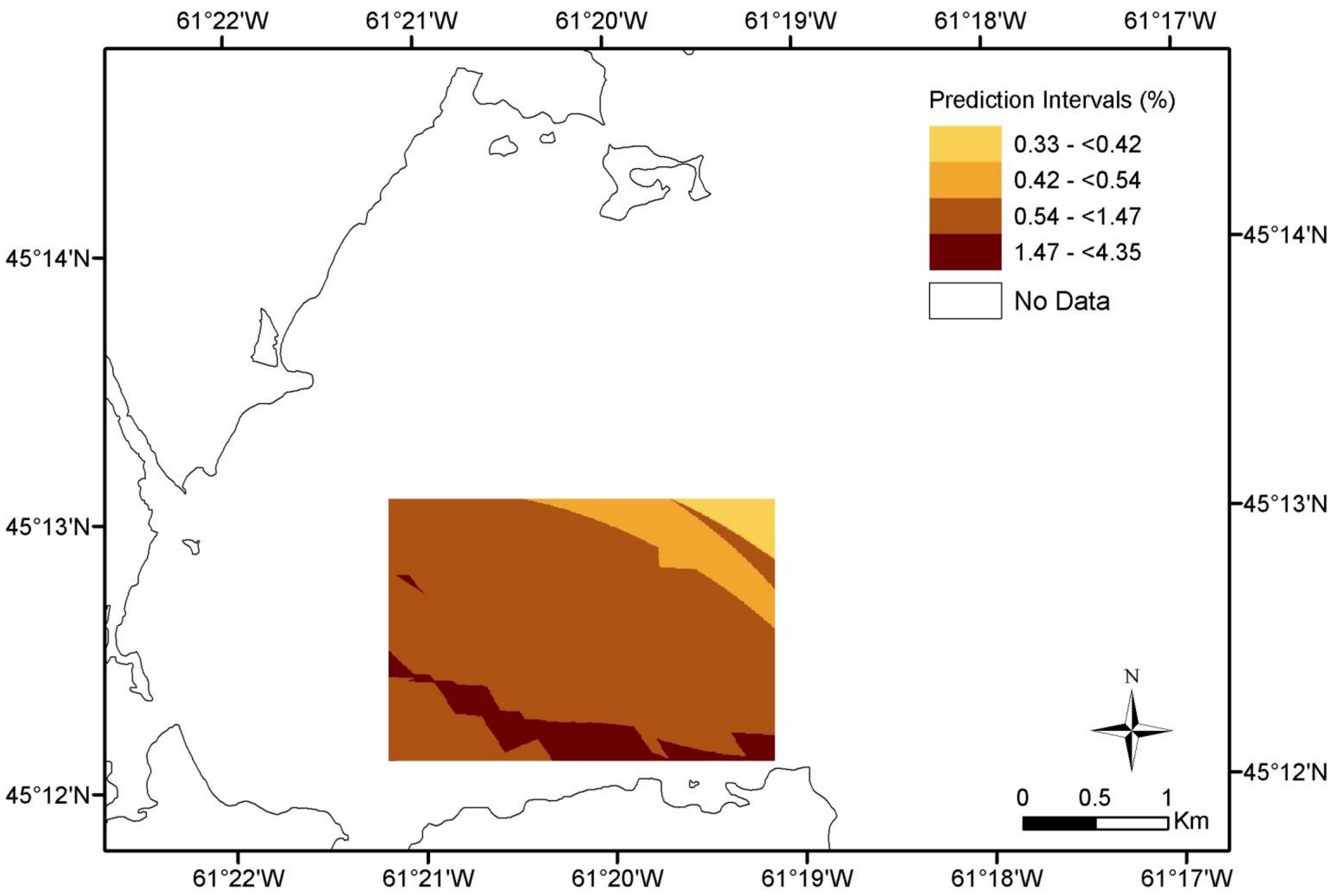

Figure 34: Spatial distribution of total organic content in Tor Bay.

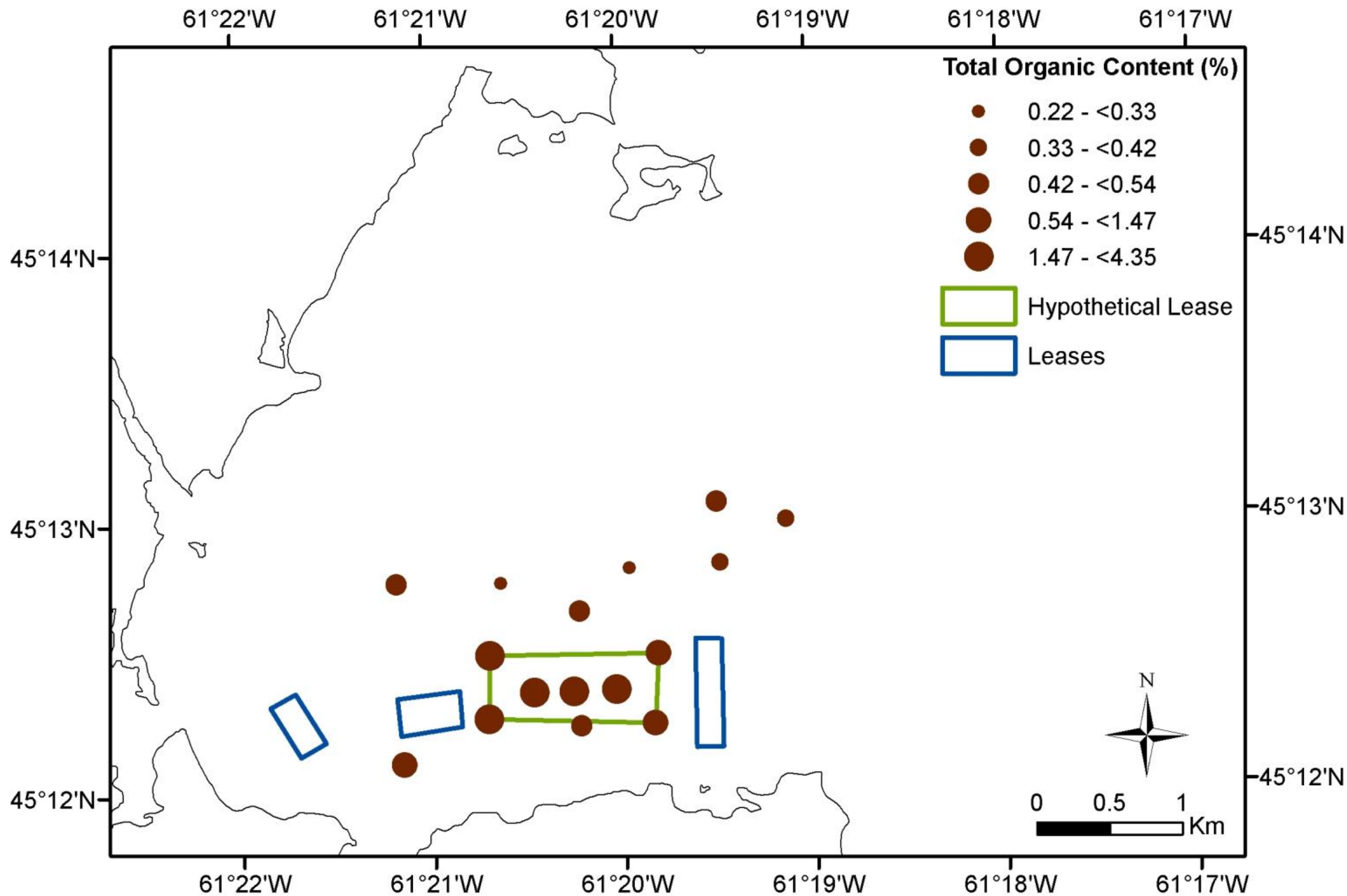

Figure 35: Proportional point based map of total organic content in Tor Bay.

Chapter 4: Discussion

The goals of this research were to determine the environmental effects of mussel aquaculture on the benthic environment as well as to determine whether interpolation using kriging can provide further information on the ecosystem. The environmental effects of mussel aquaculture in this region are minimal (See Section 4.1), and mapping of these data provides insight into small scale variations of sediment properties within each bay.

4.1 Environmental Effects

The spatial patterns identified for sulphide concentration and redox potential for all three bays indicate some small scale variation potentially related to bottom type (See Section 4.2). These small scale variations do not indicate any current environmental effects of mussel aquaculture in these regions according to the organic enrichment gradient derived by Wildish et al. (1999) and Wildish et al. (2001b) (Table 1). The highest value for sulphide concentration, 657.1 μM, was found in TB, and the highest redox potential 273.7 mV was in CH. There are no standards by which managers use percent water or total organic content to determine environmental effects, however organic content is closely related to sulphide concentration and redox potential, with greater organic content indicating reducing environments (Otero et al., 2006).

In CH, the northern part of the bay is more oxygenated, potentially due to river input. Lower concentrations of sulphide and high redox values are present in this area (Figures 7 and 10), however total organic content is high (Figure 14). Although this is counterintuitive, total organic content is complicated by bottom type (See Section 4.2), and the difference between ~4 and 18% may not truly be enough to support the relationship. In contrast, the relationship holds up somewhat in MJ, where high values of redox potential (Figure 20) are supported by lower values of total organic content (Figure 24). The pattern does not hold in TB, but the range of organic content values is minimal and potentially affected by bottom type (See Section 4.2, Figures 27, 30 and 34).

Although the results here do not indicate any environmental impact, these data are of value to managers and aquaculture operators. The aquaculture monitoring program has been implemented by NSFA, and for the last 5 years has collected a large database of sediment property measures for Guysborough County and other parts of Nova Scotia. Although currently these data are confidential and unavailable to the public, the potential exists to map temporal trends for those areas visited yearly. With the frequency of expansion in mussel aquaculture in the Maritimes, especially in Guysborough County, these results provide important baseline information for future research on the effects of this industry on coastal ecosystems. This type of information can contribute to the site selection for the future development of mussel farms in this region, in similar fashion to Pérez et al. (2003a), Pérez et al. (2003b), and Pérez et al. (2005).

4.2 Bottom Type

Rudimentary interpolations using ordinary kriging of bottom type measurements show the distribution of sediment types in all three bays (Figures 36 - 38). The interpolation was done on a categorical scale (1, 2, or 3) for sediment bottom type identifying mud, sand, and gravel/hard bottoms, respectively. The interpolation was reclassed into the three main bottom types, as intermediate bottom types such as sandy mud could not be identified by echosounding nor verified through calibration. These data were collected with a mounted echosounder transducer (DT-X 120 kHz, Biosonics Inc.; www.biosonics.com) along transects within the bays, and further calibrated from underwater videography of stations identifying the echo signature of three main bottom types using Biosonics Inc.'s Visual Bottom Typer software. This method is similar to one used by Hewitt et al. (2004) to map marine soft-sediment communities.

These interpolations are not meant to provide concrete results on bottom type as such, as the data are categorical in nature. However they provide a simplistic view that can be used to loosely interpret the results from the sediment characteristic kriging models. Sediment type, due to effective particle size and surface area, is directly related to sediment properties (Otero et al., 2006; Como et al., 2007). With larger sediment types, there is an increasing likelihood of oxygenated and organically-poor environments due to decreased surface area (Otero et al., 2006; Como et al., 2007).

The majority of CH is mud, with small transitions to gravel/hard bottom along the coastline (Figure 36). The upper part of the bay is characterised by sand supporting lower sulphide concentrations and higher redox values (Figure 36), however the expected relationship dissolves with total organic content (Figure 14). A potential reason is that organic matter like biological debris (shells, seaweeds and seagrasses) are likely to accumulate in sandy environments, thus biasing the total organic content measures. The bottom is MJ is mostly mud (Figure 37), and the variability shown in sediment properties is more likely a result of oceanic influence that cannot be interpreted here. Although from personal observation, the eastern part of the bay was closer to a sandy mud than pure mud, with the presence of seagrasses, which could account for the lower redox potential values in that area (Figure 21). Tor Bay did not contain areas of mud, but was characterised by sand and gravel/hard sediments (Figure 38). Many of the stations initially planned for sampling could not be completed due to the inability to grab sediments. The relationship is harder to determine in TB as higher sulphide concentrations and lower total organic values are associated with the harder bottom type (Figures 28, 35 and 38). The kriging model for redox potential (Figure 30) seems to be associated with bottom type, but it is difficult to interpret.

Although the relationship between particle size and sediment properties is generally true, it can be complicated by other factors. Hydrodynamics of the bays will influence greatly the oxygen content of water and therefore the sediments, as well as determine whether a depositional or suspension environment. There are no models of circulation available for the three bays studied here, and as such the results can only be generalised from bottom type measures. The presence of other matter such as marine debris or seaweeds and grasses may also influence sediment properties. These can only be discussed from personal observation or from limited underwater video unavailable for this research.

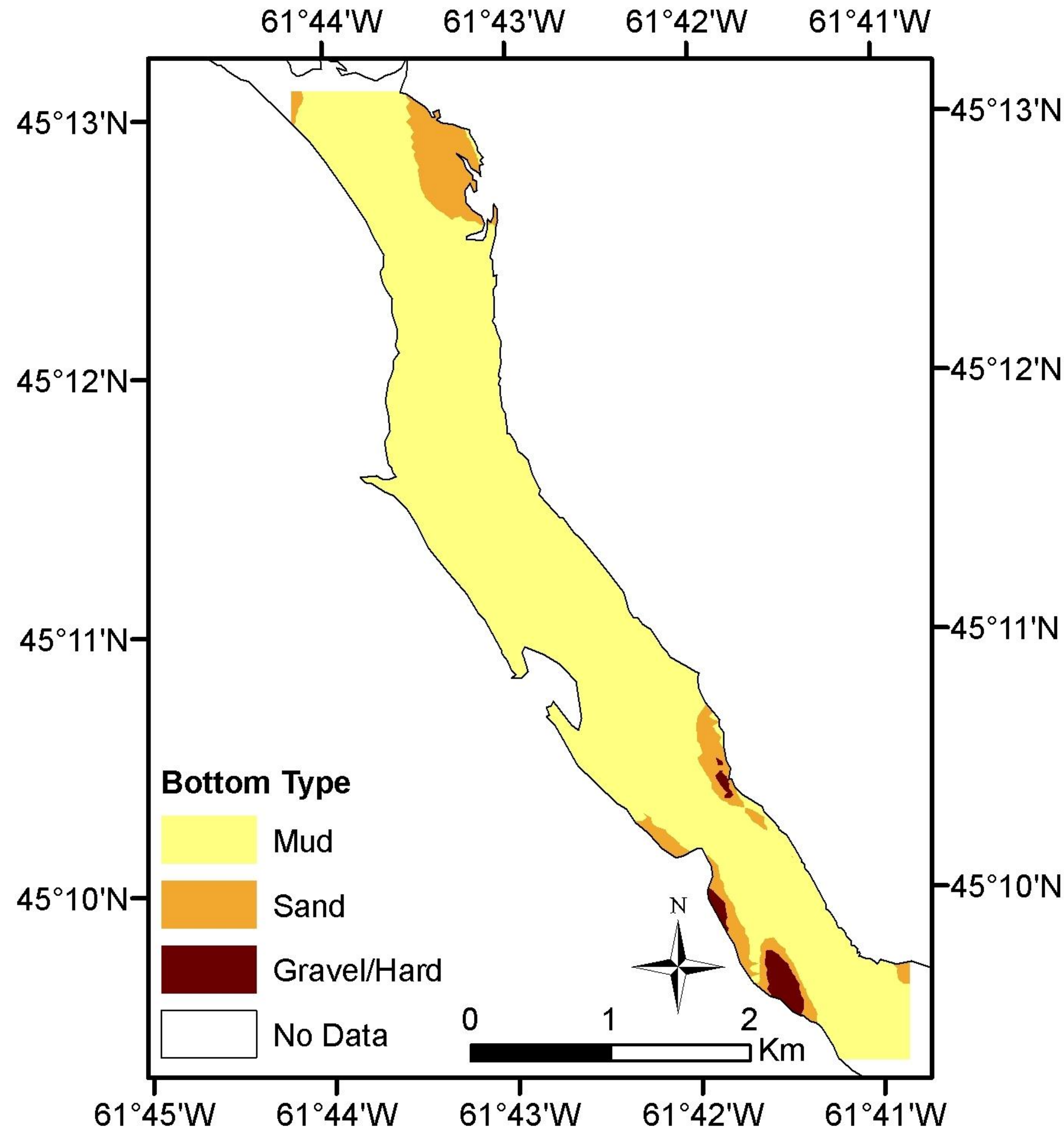

Figure 36: Bottom type for Country Harbour as determined from underwater video calibration of echosound transducer transects signals.

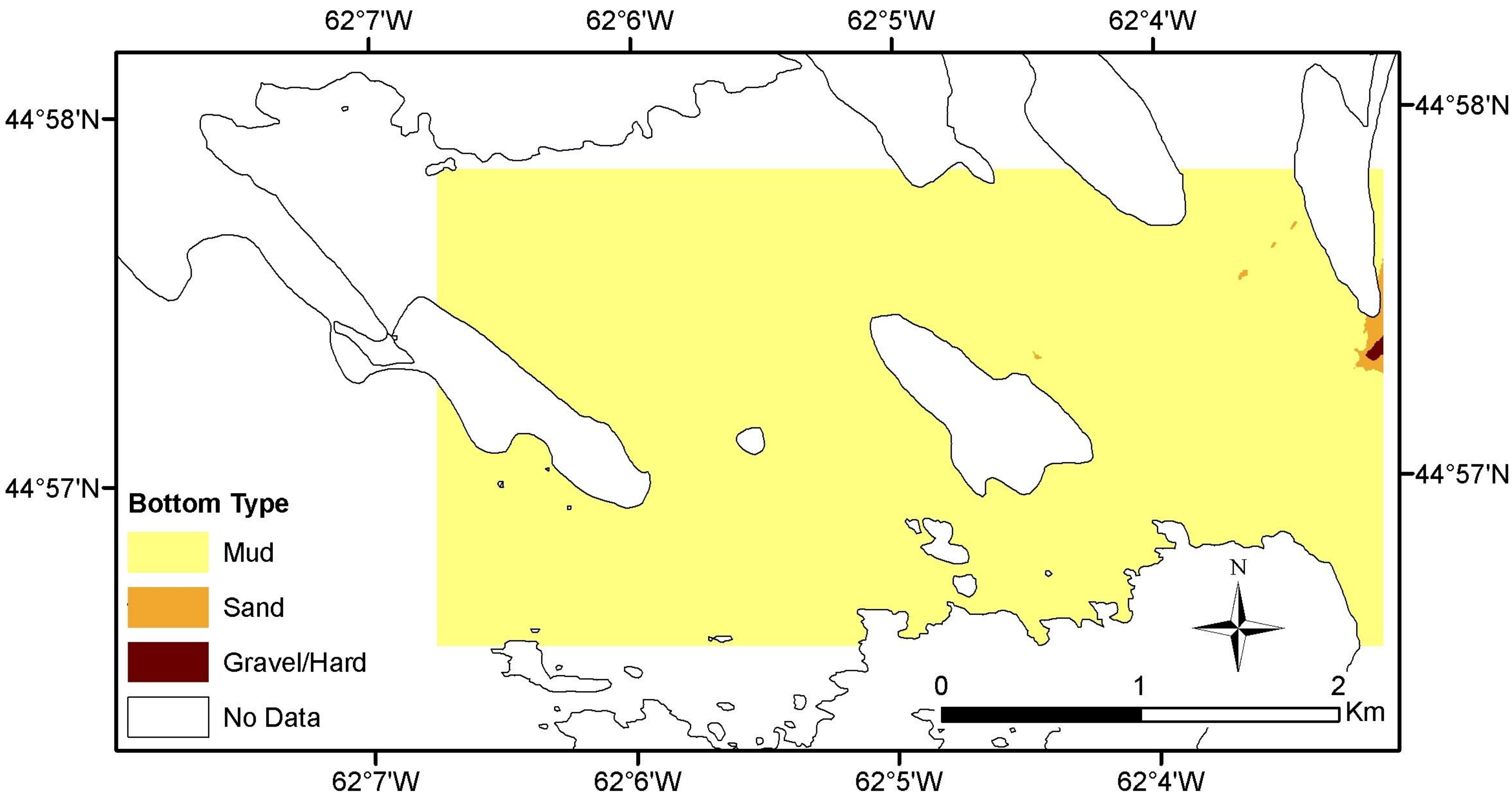

Figure 37: Bottom type for Marie-Joseph Harbour as determined from underwater video calibration of echosound transducer transects signals.

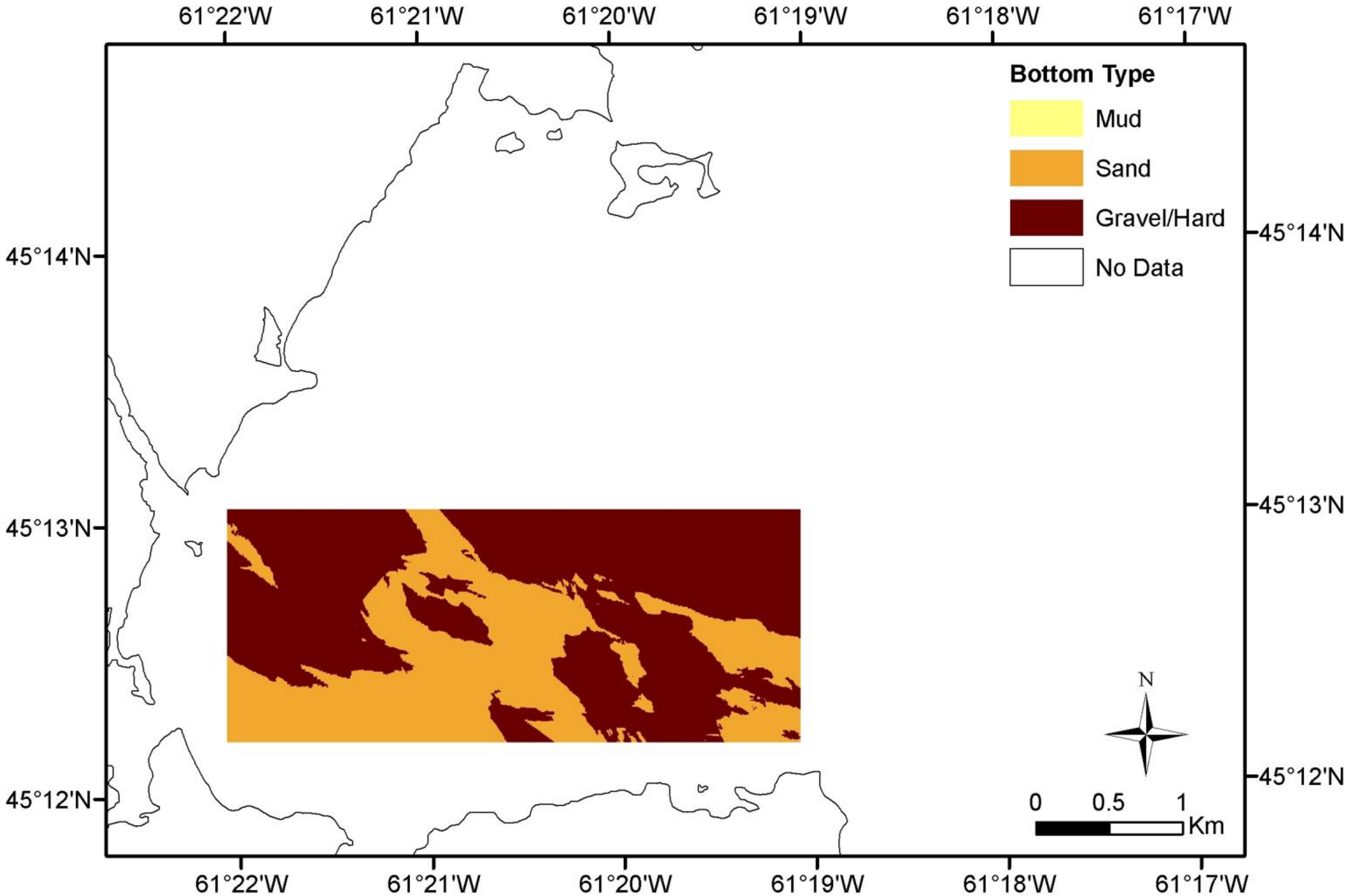

Figure 38: Bottom type for Tor Bay as determined from underwater video calibration of echosound transducer transects signals.

Chapter 5: Conclusions

The advantages of kriging interpolation over other types of interpolation and geostatistics are well known, interpreting surfaces beyond sampled points (Jakubek, 2002; Forsythe et al., 2004). Point based mapping does not interpret spatial trends beyond those areas sampled (Forsythe et al., 2004) and the majority of sediment property studies are dominated by kriging geostatistics (Forsythe et al., 2004; Li et al., 2004; Forsythe and Marvin, 2005; Ouyang et al., 2005; Ouyang et al., 2006; Sun et al., 2006). It is applying these geostatistical models to ecosystem level geochemical sediment properties associated from aquaculture effects that is novel. There are only a few applications of GIS to marine sediment geochemical properties of this nature in the literature (Pérez et al., 2002; Corner et al., 2006; Como et al., 2007). Managers and operators are better equipped to make informed decisions regarding ecosystem health and aquaculture operations when provided further information on ecosystem spatial trends, as demonstrated in this study.

It is the validation of the statistical nature of kriging that is valuable to research hypotheses. The cross-validation of variogram prediction errors is a powerful motivator for utilising these types of statistical analyses for spatial trend determination. Results can be further validated through ground-truthed sampling, although in the case of this research, could not be accomplished. Problems that arose from the kriging of these data were the inability to utilise the cross-validation of the variogram. The error was due to the small sampling pool, which resulted in identical statistics regardless of the model used. In CH and MJ, only 18 stations had sediment property data, and only 16 stations in TB were sampled. Unfortunately this was due to sampling design and inability to sample some bottom types, and cannot be resolved at this time. Fortin and Dale (2005) explain that sample size is one of the most important decisions that confront scientists, and in the context of spatial analysis the choice is guided by the minimum requirement for subsequent spatial statistics and analysis. The minimum recommended sampling number to detect significant spatial autocorrelation is 30, but if the pattern is very strong can be as few as 20 (Fortin and Dale, 2005). The choice of the number of samples is compounded by effects of spatial scale combining aspects of spatial extent and sampling grain (Fortin and Dale, 2005; Lloyd, 2007). For this research, these decisions were circumvented by purposely using a 500 m grid to separate stations, to resolve the scaling and underlying surface variability within the three bays (de Smith et al., 2007). With the occasional inability to sampling the sediment properly due to the nature of bottom type, this resulted in a reduced sampling pool for all three bays. It was beyond the scope of this research to attempt increasing the sampling number, but the possibility exists to pool data from previous and future sampling efforts, with the assumption that temporal trends are insignificant. This will not be possible unless NSFA allows public access to these data, which are currently proprietary.

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