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Article

Geovisualization of Mercury Contamination in Lake St. Clair Sediments

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Abstract: The Laurentian Great Lakes of North America contain approximately 20% of the earth's fresh water. Smaller lakes, rivers and channels connect the lakes to the St. Lawrence Seaway, creating an interconnected freshwater and marine ecosystem. The largest delta system in the Great Lakes is located in the northeastern portion of Lake St. Clair. This article focuses on the geovisualization of total mercury pollution from sediment samples that were collected in 1970, 1974 and 2001. To assess contamination patterns, dot maps were created and compared with surfaces that were generated using the kriging spatial interpolation technique. Bathymetry data were utilized in geovisualization procedures to develop three-dimensional representations of the contaminant surfaces. Lake St. Clair generally has higher levels of contamination in deeper parts of the lake, in the dredged shipping route through the lake and in proximity to the main outflow channels through the St. Clair delta. Mercury pollution levels were well above the Probable Effect Level in large portions of the lake in both 1970 and 1974. Lower contaminant concentrations were observed in the 2001 data. Lake-wide spatial distributions are discernable using the kriging technique; however, they are much more apparent when they are geovisualized using bathymetry data.

Keywords: mercury; contamination; sediment; kriging; bathymetry; geovisualization; Lake St. Clair

1. Introduction

The Laurentian Great Lakes of North America are made up of five major water bodies that contain approximately 20% of the world's fresh water resources. Canada and the United States rely heavily on these lakes, making up about 84% of North America's water supply and approximately 90% of the United States water supply [1,2]. There are numerous threats to the productivity, health, and sustainability of water resources in the Great Lakes Basin. This is due to the interrelationship of lake and river ecosystems. Among the worst threats are chemical spills and dumping, habitat destruction from land use change and climate change, and the introduction of invasive species disrupting ecological functions and the food chain [2]. Among the Great Lakes are smaller lakes, rivers and channels that connect these water bodies to the St. Lawrence Seaway, creating an interconnected freshwater and marine ecosystem. Lake St. Clair (Figure 1) is a small lake located in the northwestern portion of the Lake Erie Basin that connects Lake Erie and Lake Huron via the St. Clair River and the Detroit River.

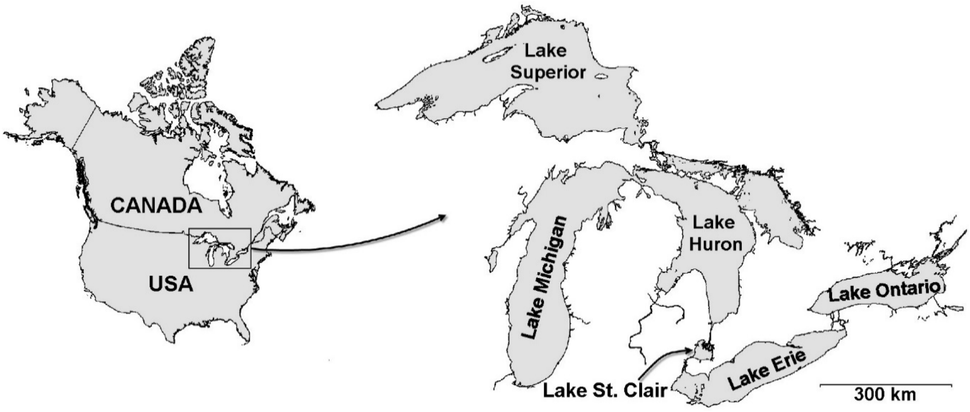

Figure 1. The location of Lake St. Clair.

Lake St. Clair has elevated levels of various contaminants in the water and sediment column including lead, mercury, polychlorinated biphenyls (PCBs), cadmium, and several chlorinated compounds due to the long history of petroleum and industrial manufacturing along the St. Clair River [3]. Among these contaminants, mercury can be claimed as the most notable as it is considered a persistent toxic substance by the Canadian Environmental Protection Act due to its ability to bioaccumulate, reduce fertility, impede biological development, and have lethal effects on human and marine life at high concentrations [4].

Beginning in the 1960s, elevated levels of mercury in sediments were discovered in the St. Clair River, leading to follow-up monitoring of contamination in fish. In the 1960s and 1970s, fisheries were closed from Lake Huron to Lake Erie, including Lake St. Clair, the St. Clair River, and the Detroit River, causing what has been labelled the "Mercury Crisis of 1970" [5]. Immediate governmental action was taken in response to halt the direct discharge of mercury from the major industries upstream on the St. Clair River [6].

To assist in the protection of aquatic life the Canadian federal government created sediment quality guidelines for freshwater and marine ecosystems [7]. Definitions were developed for a Threshold Effect Level (TEL) and a Probable Effect Level (PEL) for numerous metallic and organic contaminants. The TEL is defined as the concentration below which adverse biological effects are expected to occur rarely while the PEL is defined as the contamination level above which adverse biological effects are expected to occur frequently. The TEL and PEL have been utilized to help assess sediment contamination in rivers and lakes throughout the Great Lakes region [8–13]. Gewurtz *et al.* [14], Gewurtz *et al.* [15] and Jia *et al.* [16] have examined mercury contamination in the St. Clair River, Lake St. Clair and Detroit River corridor. For mercury, the TEL is 0.17 μg/g and the PEL is 0.486 μg/g [7].

This article looks at the change in total mercury (dry weight) contamination found in sediments in Lake St. Clair in 1970, 1974 and 2001. The analyses were performed using the ArcGIS [17] Geographic Information System (GIS) and include the spatial interpolation of contamination patterns across the lake based on sediment survey samples. The changes in distribution are examined temporally and through the use of three-dimensional (3D) bathymetry data for geovisualization. Improved insight for the visual interpretation of contamination patterns can be gained by utilizing 3D analysis compared to two-dimensional (2D) or flat map analyses. Examples of the use of these techniques appear in recent literature including Resch *et al.* [18] who examined the use of bathymetry in a three-dimensional (3D) time series, Alves *et al.* [19] who analyzed oil spill movement and found that bathymetric features have a profound effect on oil spill movement, and Smith *et al.* [20] who highlighted the geovisualization of terrain. Increasing complexity in visualizations is meant to help assess the spatial patterns of mercury contamination throughout Lake St. Clair.

1.1. Study Area

Lake St. Clair has a surface area of approximately 1115 km^2 with a mean depth of 3.7 m. It is bisected by the Canada/USA border from the southwest to northeast. The lake is a main corridor for commercial shipping and a channel in the middle of the lake is continually dredged to the Detroit River outlet at a depth of 8.3 m to accommodate ship traffic [3]. The dredged channel is located just to the northwest of the United States side of the border and it is maintained by the US Army Corps of Engineers. Dredged sediment in Lake St. Clair is disposed of in contained disposal facilities [21,22]. Together, the rivers and channels have been called the Huron-Erie corridor and Lake St. Clair has been called the "Heart of the Great Lakes" [23]. Gewurtz *et al.* [14] also identify the lake as an integral part of the Great Lakes/St. Lawrence Seaway system.

Despite being part of the Lake Erie drainage basin, about 98% of Lake St. Clair water originates from the upper Great Lakes (Superior, Michigan and Huron). The combined drainage area is approximately 146,600 km^2 and the lake-wide water retention time is around nine days. The largest coastal delta system in the Great Lakes is located in the northeastern portion of Lake St. Clair with an area of 620 km^2 [24].

Along the northern portion of the St. Clair River, industrial development has played a major role in dictating the health of the lake and river systems. For example, the Dow chlor-alkali plant opened in 1949, discharging approximately 13.6 kg (30 lbs) per day of mercury to the St. Clair River until 1969 when the effluent jumped to an average of 34 kg (75 lbs) per day (ranging between 21.3 to 88.5 kg (47 to 195 lbs)) [25]. Due to this, the 1970s saw elevated amounts of contaminant loadings into the St. Clair River and Lake St. Clair which still persist in the environment today [6]. Currently there are a total of 62 industrial facilities making up the "Chemical Valley" of Sarnia, which accounts for 40% of Canada's total chemical industry [26]. In 1970, Dow received a commission order to cease the discharge of mercury into the river system, making it less than 0.5 kg (1 lb) per day [25].

Areas of Concern (AOC) were first designated in 1985 by the Water Quality Advisory Board of the International Joint Commission and are defined as areas where degradation of water, fish or sediment has occurred. This is based on the standards set forth in 1972 by the Great Lakes Water Quality Agreement signed by the Canadian and US governments [27]. The St. Clair River was one of the original 11 designated areas (there are 43 in total), and remains an AOC today, along with much of the delta system at the northeastern end of Lake St. Clair, due to the persistence of mercury and other contaminants in the water, sediment, and fish [28]. As stated by Weis [29], AOCs due to elevated mercury are expected to arise where chlor-alkali plants are located throughout the Great Lakes system. Storm water management plans have also been developed for the lake as governments on both sides of the border treat storm water as a serious pollutant [21].

Development and population growth around the Lake St. Clair region is historically linked to the evolution of the City of Detroit [23] with a population of approximately five million. Despite its key use as a shipping corridor, the lake is also used as a source of drinking water and for recreational purposes such as boating, swimming and fishing [27].

1.2. Data

Sediment core samples were collected by the Environment Canada Great Lakes Sediment Assessment Program in 1970 and 1974, and again in 2001, to assess changes in sediment quality. The number of samples taken differs slightly between years at 45, 46 and 34, respectively. The 1970 and 1974 surveys were conducted based on a 1.61 km (one mile) grid. In 2001, fewer samples were acquired and the sample site locations were selected based on the existing grid, where the lake is deeper, and where it was expected that higher amounts of multiple contaminants would be found. Gewurtz *et al.* [14] state that the lake is generally non-depositional in nature and that the only areas of significant sediment deposition are the deepest waters in the central and east-central region of the lake, which is less impacted by wave turbulence. The top three centimetres of sediment were sampled for numerous metallic and organic contaminants using a mini box core sampling procedure, which has been used in other Great Lakes [14,30,31]. Mercury is the focus of this article because of its high-profile toxicity.

2. Methodology

2.1. Interpolation

The kriging method for spatial interpolation was performed in ArcGIS software (version 10.2) with the Geostatistical Wizard to calculate the lake-wide distribution of mercury. Kriging was chosen over other methods such as Inverse Distance Weighting (IDW) which was used by Dunn *et al.* [32] as it has proven useful in similar lake and river analyses [9–11,33–37]. Specifically, ordinary kriging (spherical model) was used, and it estimates the value of variables at unsampled locations based on the weighted average of the samples around it and also takes into account their spatial relationships, determined through the use of semi-variograms [11,38]. In this case, a minimum of one and a maximum of five nearest neighbours were used to create the prediction surfaces. Since the analysis is based on means, a normal distribution is likely to provide better results for ordinary kriging, and thus the data were log-transformed prior to interpolation to ensure unbiased results. Summary information about each data set can be found in Table 1.

Table 1. Mercury sample summary information for each study year.

Study Year	Minimum (µg/g)	Maximum (µg/g)	Average (µg/g)
1970	0.030	3.640	0.566
1974	0.050	10.280	1.585
2001	0.005	1.194	0.190

The accuracy of kriging predictions is based on the model error statistics. These can be found for these analyses in Table 2. For a kriging spatial interpolation model to provide accurate predictions, the Mean Prediction Error (MPE) should be close to 0, the Average Standard Error (ASE) should be as small as possible (below 20), and the Standardized Root-Mean-Squared Prediction Error (SRMSPE) should be close to 1 [34]. 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, there is an overestimation of the variability in the result [11,12,36–38]. Based on this, the results from these analyses are very representative of mercury contamination across Lake St. Clair.

Table 2. Model error statistics.

Study Year	MPE	ASE	SRMSPE
1970	0.017	0.509	1.027
1974	0.026	0.543	0.931
2001	0.003	0.400	0.950
Ideal	~0.000	<20.000	~1.000

2.2. Visualization

Two-dimensional dot map and kriging visualizations were created in the ArcGIS software (version 10.2) using ArcMap, and 3D geovisualization was performed using bathymetry in ArcScene. A 90 m spatial resolution bathymetry model was obtained from the National Oceanographic and Atmospheric Administration [2]. The geovisualization was enhanced by utilizing the software view settings to increase the shadow and depth contrast due to the shallow nature and gradual slopes in the lake. All of the 2D and 3D images were viewed from directly south.

3. Results and Discussion

Initial visualization of the sediment sample locations within the lake as traditional dot maps can be seen in Figure 2. The samples were categorized based on where the values fall within the range of the TEL and PEL. Based on this, 1974 showed the highest levels of mercury contamination in the centre of the lake. Mercury concentrations are greater than the PEL at 24 sample points. This is an increase from the 1970 sample year where there were 14 samples above the PEL, with some between the TEL and PEL and many below the TEL. These seemed to dramatically increase in 1974. The lowest levels of mercury are seen in 2001, where two samples were still above the PEL but had otherwise decreased to between the TEL and PEL. In the northwest section of the lake in all sample years, there were consistently low levels of mercury. Using this two-dimensional visualization technique adequately demonstrates where levels of mercury were highest across the study years; however, only a basic interpretation of why the patterns exist can be determined. This is similar to the proportional circle representation used by Gewurtz *et al.* [14].

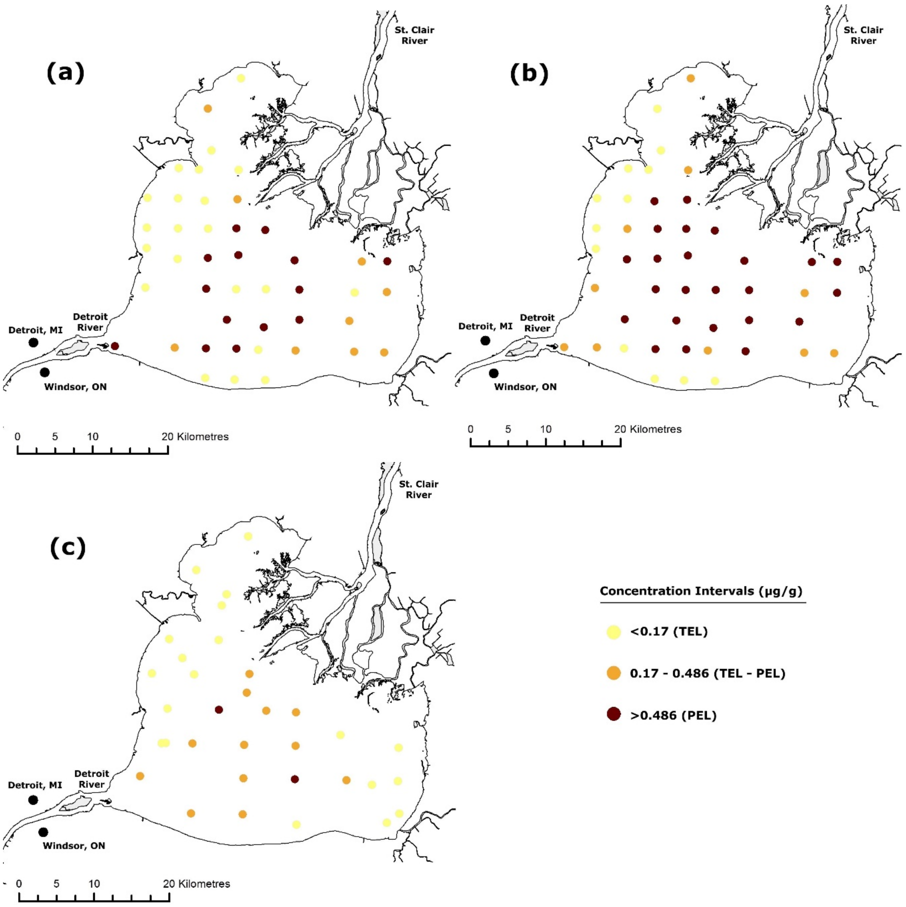

Figure 2. Two-dimensional dot map sample distribution maps: (**a**) 1970; (**b**) 1974; (**c**) 2001.

To enhance this visualization, two things were done: sample points were interpolated to determine the contamination patterns across the lake (Figure 3), and lake bathymetry was used to create 3D maps showing lake depth with the interpolated kriging surfaces overlaid on top (Figures 4–6). Here the 2D and 3D samples can been seen with the TEL and PEL isolines indicating where contamination has crossed a threshold. The spatial distribution becomes much more intuitive to the movement of sediment when compared to the dot distribution maps; however, the overlay of this on lake bathymetry paints the best picture of why mercury contamination is concentrated in some places (the deeper parts of the lake, the dredged shipping route through the lake and in proximity to the main outflow channels through the St. Clair delta) *versus* others (the periphery of the lake). While this may be intuitive to some readers, geovisualization helps eliminate conjecture as spatial relationships can be observed. It also provides an innovative approach to analyzing sediment contamination distribution patterns.

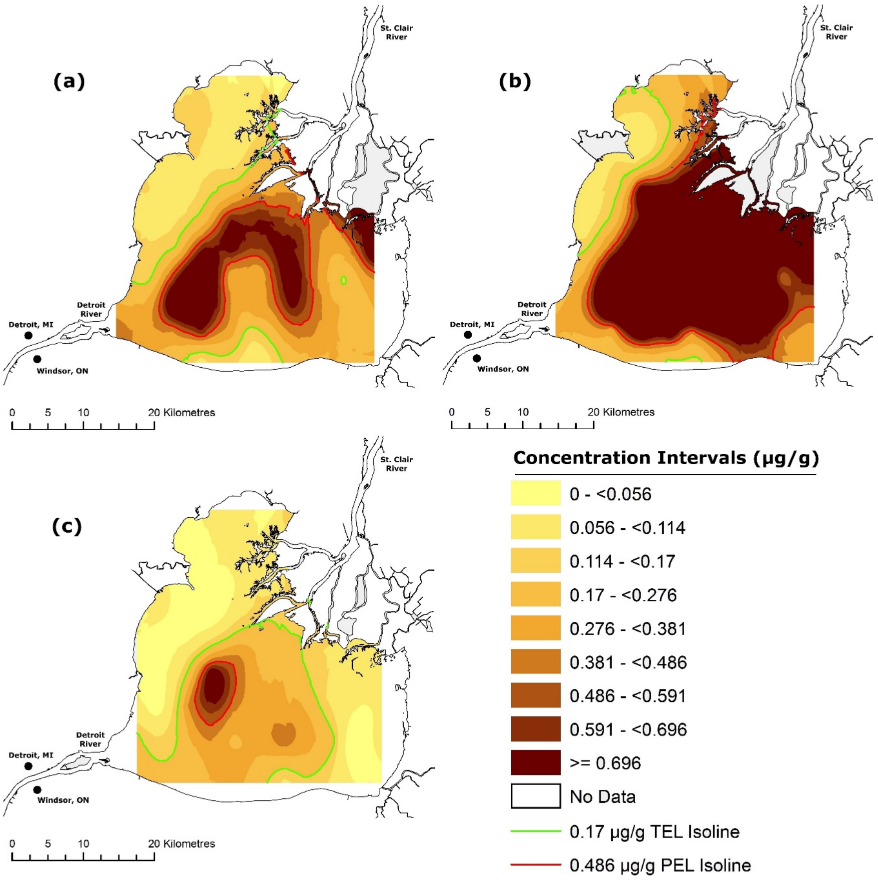

Figure 3. Two-dimensional interpolated kriging distribution maps: (**a**) 1970; (**b**) 1974; (**c**) 2001.

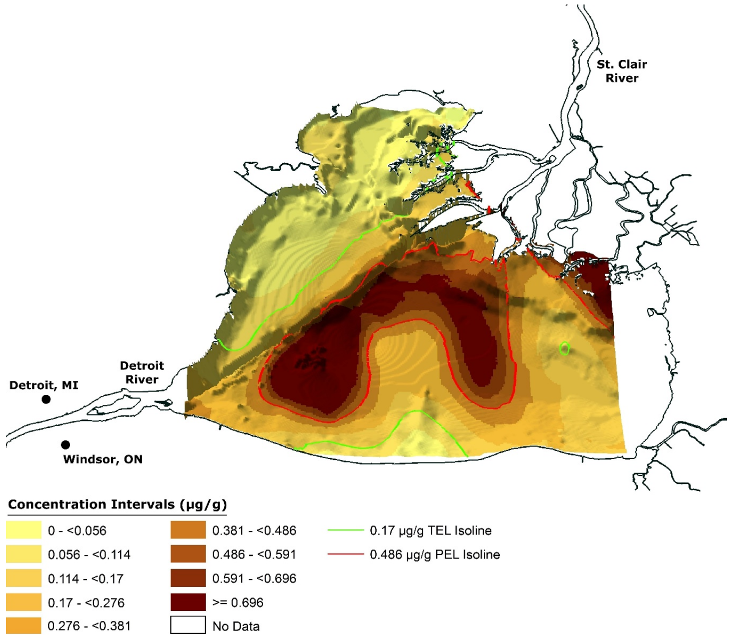

Figure 4. Three-dimensional interpolated kriging distribution map for 1970.

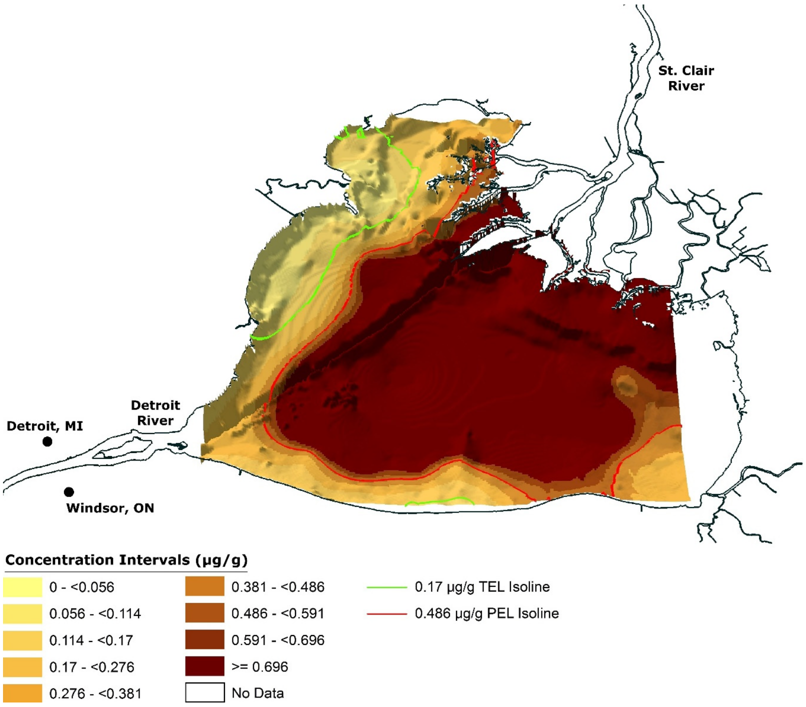

Figure 5. Three-dimensional interpolated kriging distribution map for 1974.

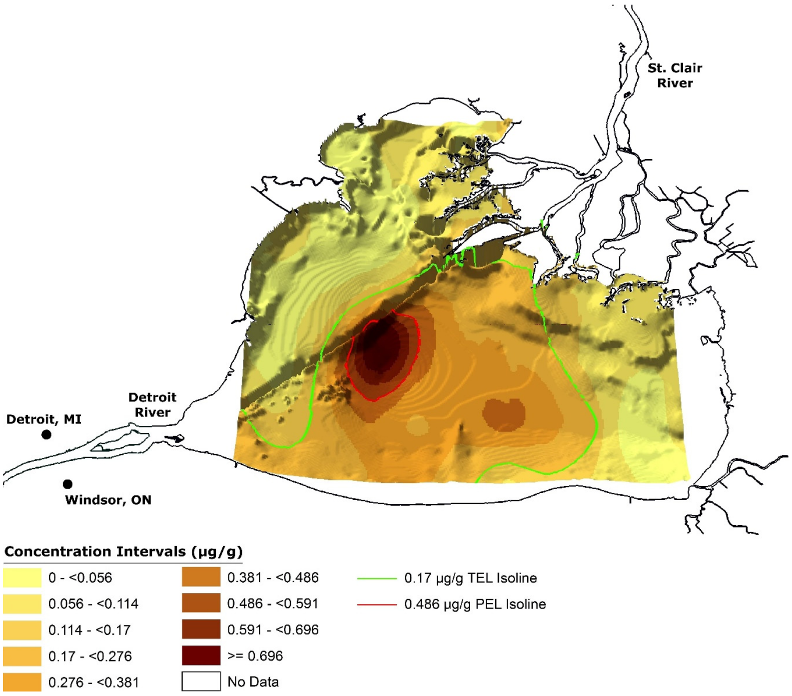

Figure 6. Three-dimensional interpolated kriging distribution map for 2001.

In the centre of the lake in all sample years, mercury is above the PEL. This is the deepest part of the lake, aside from the dredging channel, where sediment accumulates [14]. This is especially evident in 2001, where mercury is above the PEL in the dip of the lake just east of the dredged shipping channel. Additionally, around the edges of the lake where depths are the shallowest, the TEL is seen to fall in each sample year.

Discussion

The northwestern part of the lake near the delta is reportedly less biologically productive, while the southeastern portion is more productive [3]. Retaining walls along the St. Clair River have resulted in a narrow, straight channel which contains very little vegetation. This leads to faster river flows into Lake St. Clair. The water slows as it passes through the numerous channels of the delta system in the northeastern portion of the lake. Highest flow velocity rates have been reported at the top (55%) and middle (40%) portions of the delta, with the lowest flow rates (5%) at the southern-most outlet channel [3]. The dominant wind patterns across the lake follow a west-to-east pattern, creating strong surface currents in this direction [29]. This helps explain why there is less contamination along the northwestern shore of the lake in all sample years as the currents are pushing sediments to the centre of the lake. This also helps explain the concentration of mercury to the east of the dredged channel where flow velocity rates are very low, ultimately allowing sediment to settle and accumulate with minimal disruption from inflow. Redistribution around the lake also occurs due to wakes from personal and commercial shipping vessels [3].

The persistence of mercury as a pollutant is illustrated in the 2001 results. Contamination levels were still found above the PEL despite stringent laws and regulations that have essentially eliminated point source pollution from the "chemical valley" upriver [6]. There is still a significant decline in mercury in 2001 compared to 1970 and 1974; however, this may be explained by the resuspension of sediments into the Detroit River, suggesting that contamination may be moving down through the Great Lakes Basin. Jia *et al.* [16] found that the spatial patterns of mercury contamination in sediments were consistent from the top of the St. Clair River to the lower Detroit River and they suspect multiple sources of mercury along the corridor. Additional support for this finding comes from Forsythe *et al.* [34] who found that there are highly elevated levels of mercury contamination in Lake Erie close to the mouth of the Detroit River. Levels well above the PEL were found in 1971, with decreased levels to around the PEL between 1997 and 1998. There is the possibility that mercury contamination is higher in the lake, as only the top three centimetres of sediment were sampled and more highly contaminated sediment could have been buried; however, Gewurtz *et al.* [14] suggest that erosion, transport, and redistribution are the dominant set of processes for sediments in the lake.

4. Conclusions

Although there has been a decline in mercury across this aquatic ecosystem, it is evident by its continued designation as an AOC that problems continue to persist in Lake St. Clair. Analyzing the issues surrounding sediment contamination using enhanced 3D geovisualization techniques appears to be a superior method for analysis when compared to traditional 2D mapping.

Author Contributions: K.W.F., C.H.M., J.P.W. and D.J.J. conceived, supervised and planned the design of various phases of this study. K.W.F. C.J.V. and J.P.W. established the parameters for the kriging models and implemented the GIS analyses. All authors examined the model statistics, discussed the results and contributed to the writing of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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