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Using geovisualization to assess lead sediment contamination in Lake St. Clair

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Key Messages

- Geovisualization of contaminated sediment patterns is improved when bathymetry data are included.
- Lead contamination in Lake St. Clair decreased from 1970 to 2001.
- Visual interpretation of 3D surfaces highlights contaminated areas and provides additional information that could be used for remediation planning.

Many communities depend on Lake St. Clair for drinking water and recreational uses. In addition, it is an important transport route for natural resources and manufactured products. The St. Clair River, which flows into the lake from the northeast, is a major source of sediment. The upstream area is known as "chemical valley" due to a large amount of industrial activity located along the river. Sediment sampling surveys were conducted in 1970, 1974, and 2001 by Environment Canada as part of a continuing monitoring program. Two approaches to the representation, analysis, and visualization of lead contamination were used: a two-dimensional Geographic Information System-based approach using kriging and a three-dimensional approach that utilized the interpolated kriging surfaces overlaid on bathymetry data. The results of combining this analytical method with a three-dimensional representation appear to show that Lake St. Clair generally has lower levels of sediment contamination away from the main flow and circulation patterns leading to its Detroit River outlet. Lead levels declined below the threshold effect level in 2001 compared with the higher concentrations seen in 1970 and 1974. In addition, lake-wide spatial distributions are better visualized using the kriging spatial interpolation results when they are overlaid on the bathymetry data.

Keywords: geovisualization, kriging, lead, sediment contamination, bathymetry

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L'emploi d'outils de géovisualisation pour évaluer la contamination par le plomb des sédiments dans le lac Sainte-Claire

De nombreuses communautés utilisent les eaux du lac Sainte-Claire à des fins d'approvisionnement (eau potable) et récréatives. De même, il sert d'axe principal pour le transport des ressources naturelles et des produits transformés. La rivière Sainte-Claire, qui se jette dans le lac depuis le nord-est, déverse d'importantes quantités de sédiments. La zone située en amont abonde de produits chimiques en raison des nombreuses activités industrielles en opération de part et d'autre de la rivière. Des échantillons de sédiments ont été prélevés par Environnement Canada en 1970, 1974 et 2001 dans le cadre d'un programme de surveillance continue. Deux démarches ont été mises en œuvre en vue de représenter, analyser et visualiser la contamination par le plomb : une première s'appuie sur un système d'information géographique à deux dimensions utilisant une modélisation par krigeage, et une seconde à trois dimensions utilisant les surfaces d'interpolation obtenue par krigeage superposées aux données bathymétriques. Cette méthode d'analyse conjuguée avec une représentation en trois dimensions permet d'observer une diminution générale du degré de contamination sédimentaire du lac Sainte-Claire en retrait du courant du chenal principal menant à la décharge de la rivière Détroit. En 2001, les concentrations de plomb ont baissé au-dessous du niveau de l'effet de seuil par rapport aux valeurs plus élevées observées en 1970 et 1974. En outre, une meilleure visualisation des répartitions spatiales du plan d'eau est obtenue grâce aux résultats tirés de l'interpolation spatiale par krigeage lorsque ceux-ci sont superposés aux données bathymétriques.

Mots clés : géovisualisation, krigeage, plomb, contamination sédimentaire, bathymétrie

Introduction

The Great Lakes of North America (Figure 1) contain one-fifth of the world's fresh surface water with only the polar ice caps and Lake Baikal in Siberia containing more (GLIN 2004; Forsythe and Watt 2006). The major lakes (Superior, Michigan, Huron, Erie, and Ontario) are important water sources for many different types of commercial, industrial, and recreational activities. Lake St. Clair is located between Lake Huron and Lake Erie and is considered to be part of the Lake Erie watershed (Great Lakes Commission 2004).

One of the most heavily industrialized areas in the region is located along the St. Clair River (which drains into Lake St. Clair) and is referred to as "chemical valley" due to the long history of industrial use along the river. In Sarnia, Ontario and within a 25-km radius on the Canadian and American sides of the border, there are 62 industrial

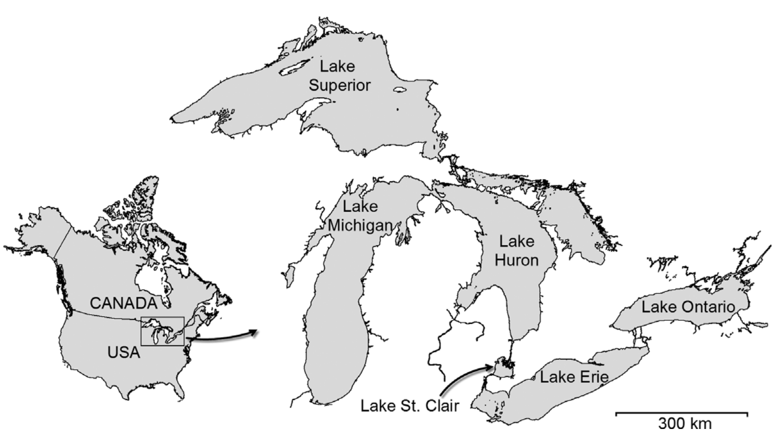

Figure 1
The Laurentian Great Lakes and Lake St. Clair

facilities listed under Canada's National Pollutant Release Inventory (NPRI) and the United States Toxic Release Inventory (TRI) (Ecojustice 2007). These facilities include power generation stations, oil refineries, chemical and pharmaceutical producers, and coal-fired power plants. Since the 1800s when this industrial valley first began to grow, there has been pressure from pollution being released into the river leading to water and sediment contamination within Lake St. Clair. Lead contamination in terrestrial and aquatic environments comes from a variety of these industrial activities and has been plaguing this aquatic system for decades (Sherman et al. 2015).

The Canadian federal government specifies sediment quality guidelines determined through toxicological information in aquatic sediments where adverse biological effects were observed. There are two assessment values: the Threshold Effect Level (TEL) and the Probable Effect Level (PEL). The TEL refers to the concentration below which adverse biological effects are expected to occur rarely, while the PEL defines the level above which adverse effects are expected to occur frequently (CCME 1999). The TEL for lead is 35.00 μg/g while the PEL is 91.30 μg/g.

Lead is a nonessential trace element that is toxic to biological life at elevated concentrations. Adverse consequences include an increase in mortality, decrease in benthic invertebrate abundance and diversity, and abnormal development in species living in areas above the PEL (CCME 1999). The TEL and PEL have been used to study sediment contamination throughout the Great Lakes region (Forsythe and Marvin 2005; Gewurtz et al. 2008; Forsythe et al. 2010; Gawedzki and Forsythe 2012; Forsythe et al. 2015) and particularly in Lake St. Clair (Gewurtz et al. 2007), however the use of three-dimensional (3D) geovisualization of interpolated surfaces performed in this study has not yet been explored. The main reason for this is that bathymetry data for all of the lakes did not become generally available until recently (NOAA 2014). The dataset for Lake Superior has yet to be completed due to funding shortfalls. In this article, 3D refers to the overlay of contamination surfaces that are draped over the bathymetry data.

Limited information can be derived from sediment sample distribution maps. Careful design, implementation, and evaluation of the geovisualization of lake bathymetry together with interpolated contaminant surfaces may help in developing improved representations of contamination patterns, their comprehension by stakeholders, and assist in identifying areas where higher pollution concentrations exist. The overall objective of this article is to utilize spatial interpolation techniques and bathymetry to develop an improved understanding of lead sediment contamination patterns in Lake St. Clair.

Study area

The Lake St. Clair drainage basin encompasses part of the Canadian province of Ontario and the American state of Michigan. A major influence on the Lake St. Clair study area is the St. Clair River. It drains from Lake Huron at approximately the same discharge as the Mississippi River at St. Louis at around 5000m^3/s and is the only outlet for the western Great Lakes: Lakes Michigan, Huron, and Superior (Anderson and Schwab 2011; Hudson and Ziegler 2014).

Lake St. Clair is small when compared to the Great Lakes. It has a surface area of 1114 km^2 compared with Lake Ontario (the smallest Great Lake) at 18 690 km^2 and Lake Superior, which is the largest Great Lake at 82 100 km^2. It is a very shallow lake, averaging 3.0 m deep with a maximum depth of only 6.4 m, compared to Lake Superior's maximum depth of 406.0 m (GLIN 2004; Forsythe and Watt 2006). The lake is a major transport route for large ships and is consistently dredged in order to allow for navigation through the water system between the Great Lakes.

The Canadian side of the lake is characterized by wetland areas and agriculture; however, growth in urban and recreational developments has encroached on the wetlands in the United States and they are slowly disappearing (GLIN 2004). The northeastern portion of Lake St. Clair is an extensive delta system, the largest within the Great Lakes Basin (Great Lakes Commission 2004; Forsythe and Watt 2006). Lake St. Clair is fed by five significant inflow channels and three major tributaries (these features can be seen in all subsequent figures) in addition to other low flow tributaries. In 1985, much of this delta system along with the entire St. Clair River to the mouth of Lake St. Clair was designated an Area of Concern (AOC) under the Canada–United States Great Lakes Water Quality Agreement (U.S. EPA 2013). AOCs are defined as areas recognized by the International Joint

Commission where sediment, water, and fish quality have experienced some type of environmental degradation and the objectives of the Great Lakes Water Quality Agreement on water quality standards are not met. As of 2003, despite almost $4 million of remedial action, many activities within the St. Clair River AOC remain impaired, including: fish consumption, degradation of benthos, and loss of fish and wildlife habitat (Environment Canada 2010; CRIC 2013).

Overall, the watershed is home to approximately five million people, all of whom rely in some way on this natural resource. It provides inhabitants with drinking water, recreational resources, aesthetic beauty, and numerous economic advantages. Because of the close association between the human population and the watershed, water quality is tied directly to the residents' quality of life (Great Lakes Commission 2004; Forsythe and Watt 2006; U.S. EPA 2006).

Data

Sediment core surveys were conducted across Lake St. Clair in 1970 (45 samples), 1974 (46 samples), and 2001 (34 samples). The top 3 cm of the sediment was sub-sampled from the core for analyses. A variety of organic contaminants and metals were examined from the cores, along with water depth and pH being measured at each location. The most recent survey was conducted (in part) to assess whether sediment quality had improved. The samples were collected as part of the Environment Canada Great Lakes Sediment Assessment Program (Forsythe 2004; Forsythe and Watt 2006). Bathymetry data (for the creation of the 3D overlays) at a 90-m spatial resolution were obtained from the National Oceanographic and Atmospheric Administration (NOAA 2014).

Methodology

Kriging interpolation methods utilize statistical models that incorporate autocorrelation among a group of measured points to create prediction surfaces (Jakubek and Forsythe 2004). Weights are assigned to measurement points on the basis of distance, in which spatial autocorrelation is quantified in order to weight the spatial arrangement of measured sampling locations (Johnston et al. 2001; Jakubek and Forsythe 2004). Customization of the estimation method to a specific analysis is possible by accounting for statistical distance with a variogram model (Jakubek and Forsythe 2004). Kriging accounts for both the clustering of nearby samples and for their distance to the point to be estimated (Isaaks and Srivastava 1989). Given the statistical properties of this method, measures of certainty or accuracy of the predictions can be produced using a cross-validation process. There are many derivations of the kriging model. Ordinary kriging was chosen for these analyses based on successful applications of this technique in the Great Lakes by Forsythe and Marvin (2005), Forsythe et al. (2010), Gawedzki and Forsythe (2012), and Forsythe et al. (2015).

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 (Forsythe et al. 2004). 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 (Johnston et al. 2001; Forsythe and Watt 2006).

The ArcGIS (ESRI 2012) Geographic Information System (GIS) was utilized to perform the ordinary kriging analyses. Specifically, the Geostatistical Analyst extension was utilized as it allowed for flexibility in deriving the inputs for the interpolations. Two-dimensional (2D) prediction surfaces were generated for the sediment samples that were obtained in 1970, 1974, and 2001. Experimentation was required to determine the optimal parameters (i.e., to obtain the models with the best error statistics). These were determined to be a maximum search radius of 15 000 m, anisotropy of 10 000 m, and the direction was set to 0. Nine categories were utilized with three equal intervals below the TEL, three equal intervals between the TEL and PEL, and three intervals above the PEL (based on the interval increments between the TEL and PEL).

Geovisualization and mapping of bathymetry is an evolving field (Smith et al. 2013; Alves et al. 2014; Resch et al. 2014). While neither geovisualization nor kriging are new, their combination in assessing sediment contamination in lake-bottom sediments is not well documented. Recent examples of the use of geovisualization and/or bathymetry in the literature include Alves et al. (2014) who found that bathymetric features have a profound effect on oil spill movement in the Aegean Sea; Smith et al. (2013) who highlight the use of visual processing, visual interaction, and visual outputs, all of which form part of the geovisualization of terrain; and Resch et al. (2014) who examined the display of bathymetry as a three-dimensional (3D) time series for geovisualization purposes. In this article, after the kriging analyses were performed, the resulting map data were used to create 3D overlay visualizations in ArcScene (part of the ArcGIS software) using the bathymetry data as the base layer.

Analysis and results

The use of geovisualization to assess sediment contamination may help in the identification of contamination patterns and provide a basis for decisions concerning any remediation plans that could be implemented. Areas that have the highest sediment contamination levels (and problems associated with the pollution) tend to be in urban-industrial harbours, embayments, and river mouths (Zarull et al. 1999). The issue is that these areas are normally the spawning/nursery sites for most fish, the nesting and feeding spaces for most aquatic avian fauna, the zones of highest biological activity, and they have the most human contact (Zarull et al. 1999; Forsythe and Watt 2006). Aquatic ecosystems are considered those environments that are most impacted by anthropogenic stressors (Shaker and Ehlinger 2014).

Lead sample distribution

Lead is one of the main pollutants in Lake St. Clair (Environment Canada 2004). The chemical and petroleum industries located upstream on the Canadian side of the St. Clair River are responsible for the majority of the chemical loadings into the lake. There is, however, industrial activity on the American side of the river and the use of lead in gasoline (Newell and Rogers 2003) that also contributed to contamination within the lake. Canadian gasoline regulations that mandated the removal of lead (made under the Canadian Environmental Protection Act) came into force on April 26, 1990 (Environment Canada 2009). In the United States, the phasedown of lead in gasoline occurred in the 1980s (Newell and Rogers 2003).

The dot distribution maps for the 1970, 1974, and 2001 sample surveys are displayed in Figure 2. The intervals used indicate whether the contamination level is below the TEL, between the TEL and PEL, or above the PEL. Some patterns of elevated contaminant concentrations are evident, particularly along the dredging channel in the centre of the lake. However, there is an absence of sediment contamination above the PEL (91.30 μg/g) in all sample years. In addition, based on the 2001 samples there is a decrease in lead contamination through time. Table 1 shows the minimum and maximum contamination levels for each year and a marked decrease by 2001 is evident. A maximum of 29.00 μg/g was determined for the 2001 survey as compared to the 1970 and 1974 maximum concentration levels of 60.00 μg/g and 67.00 μg/g, respectively.

Lead kriging maps

Ordinary kriging techniques were utilized based on the results of Forsythe et al. (2004), Forsythe et al. (2010), Jakubek and Forsythe (2004), and Forsythe and Watt (2006). The kriging technique includes cross validation procedures that provide measures of accuracy for the predictions that are made. The MPE, ASE, and SRMSPE values for all of the kriging analyses are found in Table 2. For each sample year, they are very close to the optimum.

The 2D kriging results for Lake St. Clair for 1970, 1974, and 2001 are presented in Figure 3 while the 3D results are presented in Figure 4. Legend intervals are divided into three groups—below the TEL, between the TEL and PEL, and above the PEL. These three classes are subdivided according to three equal breaks to represent where the kriged results fall in relation to the TEL and PEL. The TEL isoline indicates where the contamination level shifts below/above the TEL. The PEL is not present in any of these maps meaning that lead sediment contamination does not exceed the PEL for ecological degradation for any sample year. The predicted surfaces for 1970 and 1974 produced very reliable cross validation results, which were relatively unbiased and rendered acceptable ASE values of 11.99 and 14.06. The SRMSPE values of 0.97 and

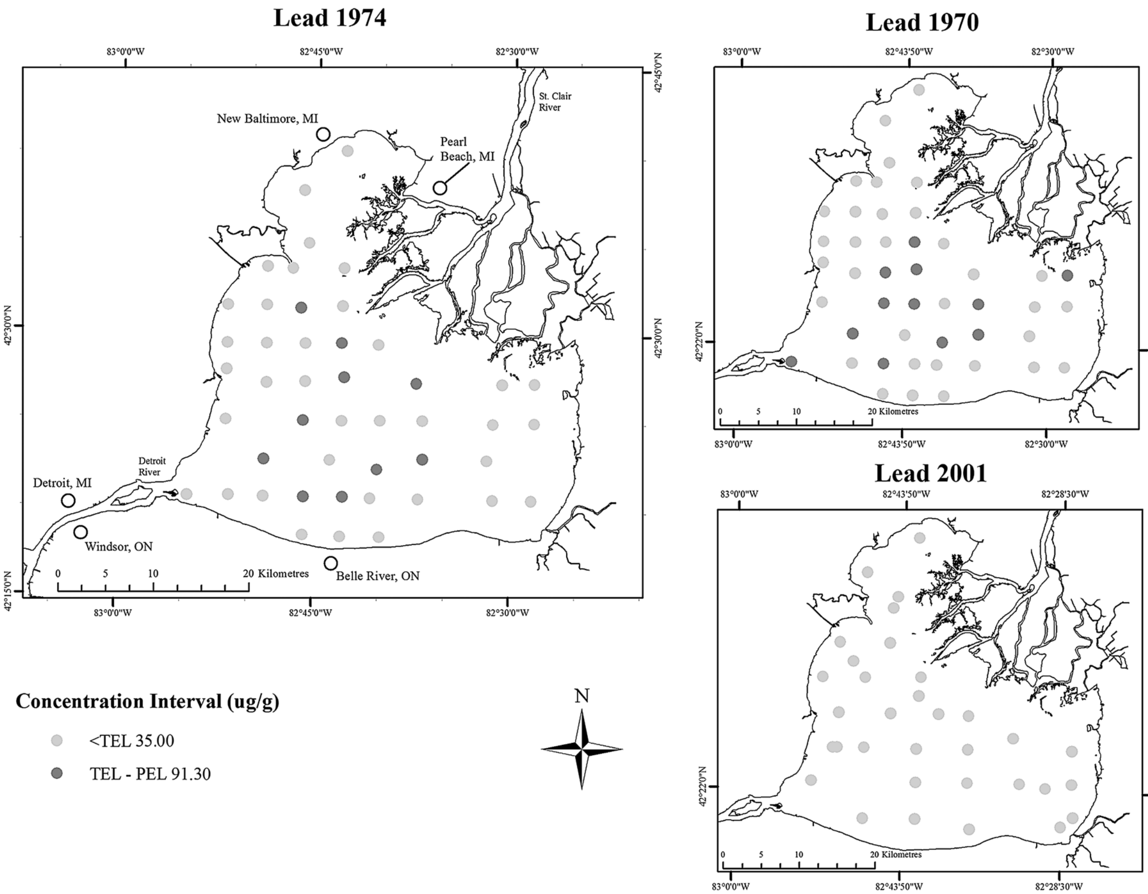

Figure 2
Lead dot map results for Lake St. Clair 1970, 1974, and 2001

0.93 (respectively) indicate that the predictions may be a slight overestimation of generated values. While there are no areas above the PEL, there were areas between the TEL and PEL that were concentrated in the central portion of the lake. The results for the 2001 data analysis are near optimal with a SRMSPE value of 0.98 that is indicative of a very representative estimate. Areas of higher contamination exist in 1970 and 1974. They are found in the deeper parts of the lake where water flow from the

Table 1
Minimum and maximum lead contamination levels for each sample year

Sample Year	Sample Size	Minimum (μg/g)	Maximum (μg/g)
1970	45	8	60
1974	46	7	67
2001	34	0	29

Table 2
Lead kriging cross validation results for Lake St. Clair

Contaminant	MPE	ASE	SRMSPE
1970	0.40	11.99	0.97
1974	0.72	14.06	0.93
2001	0.07	6.18	0.98

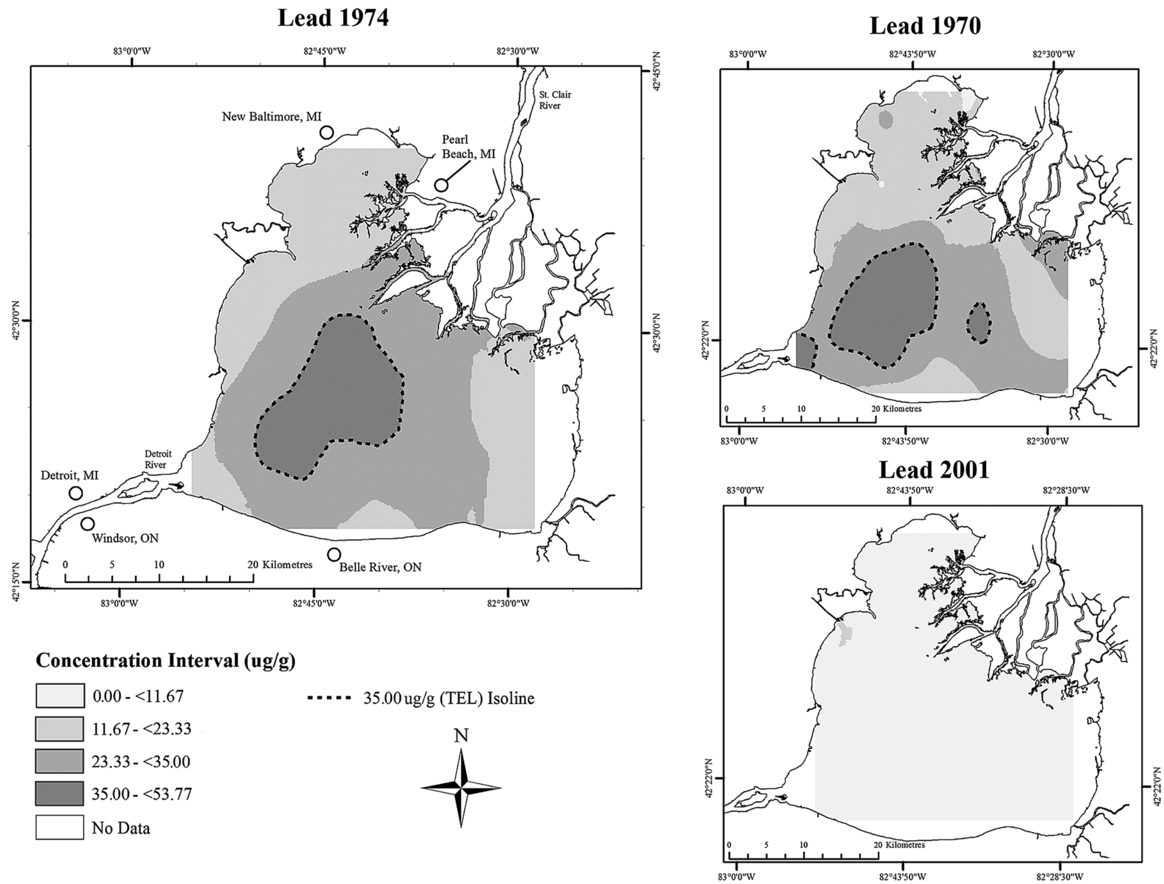

Figure 3
Lead kriging results for Lake St. Clair 1970, 1974, and 2001

St. Clair River to the Detroit River outlet slows and sediment deposition occurs. These patterns are much more obvious in the 3D lake bathymetry patterns (Figure 4) compared with the dot maps and the 2D maps. Lead concentrations above the TEL (in 1970 and 1974) funnel into the dip in the centre of the lake. Specifically, in 1974 the TEL isoline on the west side of the lake falls into the dredged channel, which is a feature not evident in the 2D visualization. In 2001, all parts of the lake had lead levels of approximately 10.00 μg/g that were well below the TEL of 35.00 μg/g, and overall lead levels in sediment have declined significantly since the 1970 samples were obtained. This is an interesting finding and may in part be explained through the removal of lead from gasoline in the 1980s (Newell and Rogers 2003), which was a major source of pollution. The lower contamination levels may also be related to resuspension and transport of lead through the Detroit River into western Lake Erie from dredging disturbances. In addition, the possibility exists that the older, more contaminated sediments may have been buried by less polluted deposits in the intervening period since only the top 3 cm of sediment was analyzed in each survey. The remaining lead concentrations in the lake may be the result of precipitation from coal combustion which was found to be a significant source of lead across the Great Lakes region (Sherman et al. 2015). When the 2D kriging results are compared to the dot

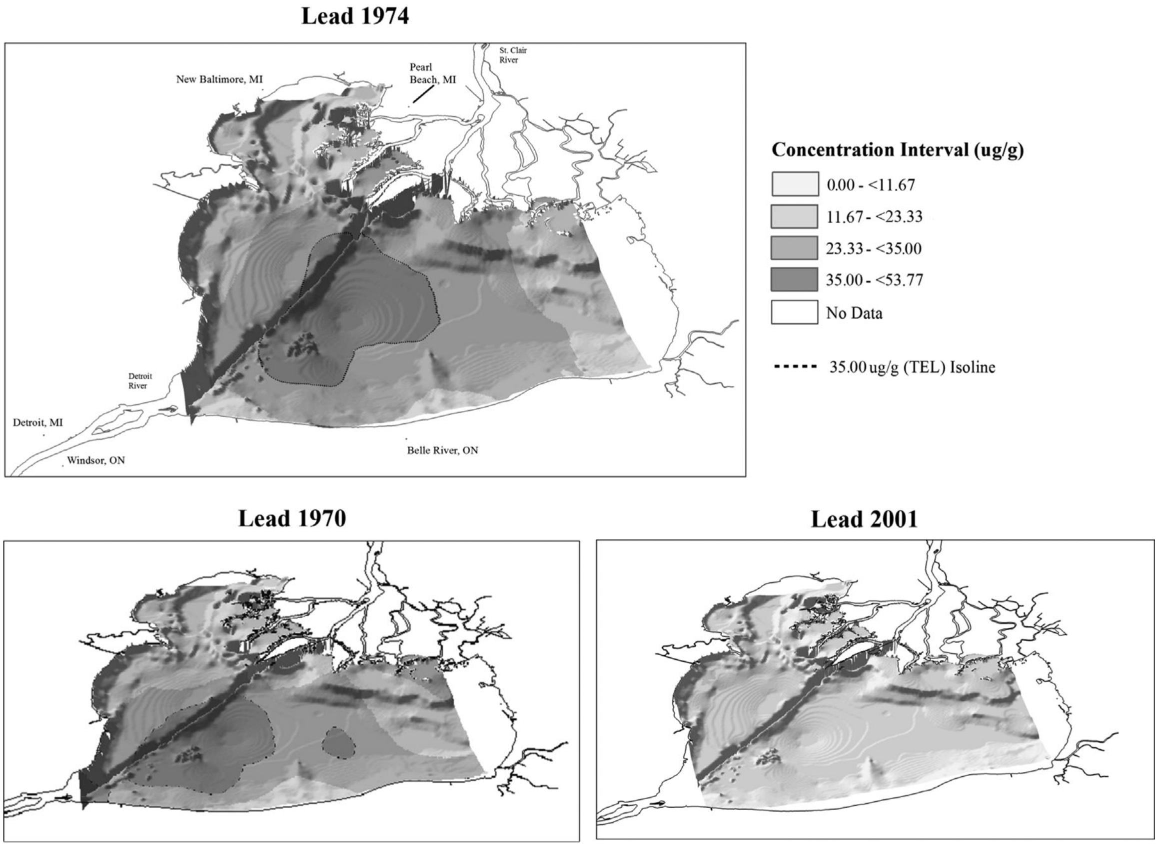

Figure 4
Three-dimensional bathymetry with lead kriging results for Lake St. Clair 1970, 1974, and 2001 (greys appear darker due to bathymetry shading)

distribution maps, it is evident that geovisualization likely provides an improved representation of spatial contamination patterns. The relationships are well defined and it is possible to identify which parts of the lake contain contaminated areas when evaluated together with the TEL and PEL guidelines. When comparing the 2D sample distribution maps with the 3D kriged visualizations, an improved understanding of sediment contamination patterns can be acquired.

Conclusion

The use of the ordinary kriging spatial interpolation technique and 3D geovisualization software allowed for sediment contamination patterns in Lake St. Clair to be identified. Traditional dot maps provide limited information concerning the areal extent of pollution. Deeper parts of the lake in the main flow path from the St. Clair River to the Detroit River were more contaminated than other parts of the lake which became much more evident through analysis of the 3D geovisualizations. The kriging results were all statistically valid with appropriate error statistic results.

The pollution levels identified in this article reveal that lead contamination has markedly improved with no areas of the lake above the TEL for the most recent 2001 data set. From 2000 to 2009, almost $4 million was invested in cleaning up the St. Clair River AOC. A portion of the contaminated sediment was removed and industries affecting it have modified their use and disposal of toxic chemicals and waste pollutants (Environment Canada 2010). The recent cleanup of the St. Clair River AOC has most certainly had a direct effect on Lake St. Clair downstream. The results from 1970 and 1974 may be indicative of historically high amounts of contamination that are still contained within lake sediments. Continued research and remediation programs concerning Lake St. Clair would be of great benefit to aquatic life and the well-being of communities that surround and use the lake since lead is not the only contaminant of concern in Lake St. Clair. Information regarding lead contamination patterns has been generated that may be useful in the development of future sediment surveys and in scientific outreach.

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