Using GIS to model transverse mixing of effluent downstream of Bonnybrook Wastewater Treatment Plant, Calgary, Alberta, Canada.

Nuell, D.D., J. A. Vandenberg, and M.C. Ryan.

Abstract

Bonnybrook wastewater treatment plant is the first major point source discharge into the Bow River. Across fifty transects downstream of the outfall, we measured electrical conductivity in-situ and collected samples for laboratory analysis of chloride, nitrate, ammonia, phosphate, and fecal coliforms. Parameters were mapped to determine the extent of transverse mixing. Representing the plume in Universal Transverse Mercator coordinates was problematic due to interpolation methods that do not account for river meanders. We transformed coordinates into a rectilinear system that reduced the errors incumbent with a meandering river. The two-dimensional output facilitated a better understanding of the dynamics of the effluent plume.

Introduction

Modeling of wastewater effluent discharge mixing into a natural river is well documented. Methods of disposal may be very basic such as an outfall at the side of a river or slightly more complex such as under water diffusers. Regardless of method, the mixing, both vertical and transverse, of the effluent upon entering a natural river has been the focus of many research papers (Lau and Krishnappan 1981; McCorquodale et al. 1982).

Understanding the importance of how wastewater effluent dynamically interacts within a natural river can lead to a better appreciation of the sometimes adverse and severe influence on the aquatic biota (Lung 1995). A visual representation of the mixing of wastewater effluent in a river is useful to fully conceptualize the mixing process, observe at what point the effluent reaches the opposite side of the river, and determine the point at which the river is fully mixed.

Geographical Information Systems (GIS) have been used extensively to model diverse geographic phenomena pertaining to the natural environment. The ability of a GIS to assemble a spatially referenced database, and then use this database with a variety of analytical tools to supply answers is key to problem solving if the spatial realm is of importance (Franklin 2001). In the context of wastewater effluent mixing in rivers, the spatial characteristics are of great importance to illustrate the effect on a natural river system.

This paper provides a case study a GIS is used to illustrate the transverse mixing of wastewater effluent discharge into a natural river. A significant contrast in electrical conductivity (EC) between the Bonnybrook Wastewater Treatment Plant (WWTP) and the river upgradient of the outfall makes EC an ideal parameter for mapping. The EC was measured directly in the mixing zone in the river, with global positioning coordinates recorded simultaneously while paddling transects across the river in a canoe (Vandenberg 2004). We combined the EC data and GPS coordinates with a GIS to model effluent mixing in a river as a two dimensional (plan) visualization. In the case study provided, river meanders presented a significant obstacle to interpolation in the modeling process. In addition to providing a visual representation of the effluent plume, the resulting GIS provides a spatial data set that can be used in mathematical model calibration and prediction.

Study Area

The Bow River originates in the Eastern Slopes of the Rocky Mountains. The upper watershed is located entirely within the boundaries of Banff National Park, Alberta, Canada and thus it is largely protected from the impacts of development. The Bow River's water quality upgradient of the City of Calgary is very good (Grasby and Hutcheon 2000) with low levels of wastewater effluent constituents (e.g. chloride, sodium, and potassium upstream) (Grasby et al. 1999).

Drinking water is drawn from the Bow River at the Bearspaw Reservoir immediately upstream of Calgary, Alberta and then discharged as effluent through the Bonnybrook WWTP after treatment (Figure 1). The WWTP is the major treatment plant for Calgary's domestic wastewater, providing tertiary treatment to 400 000 $m^{3}\cdot d^{-1}$. Following upgrades to the WWTP, reduced nutrient levels in the effluent, particularly nitrogen, have resulted in decreased macrophyte biomass (Sosiak 2002), however excessive weed growth remains evident for several kilometers downstream of the WWTP during low flow periods.

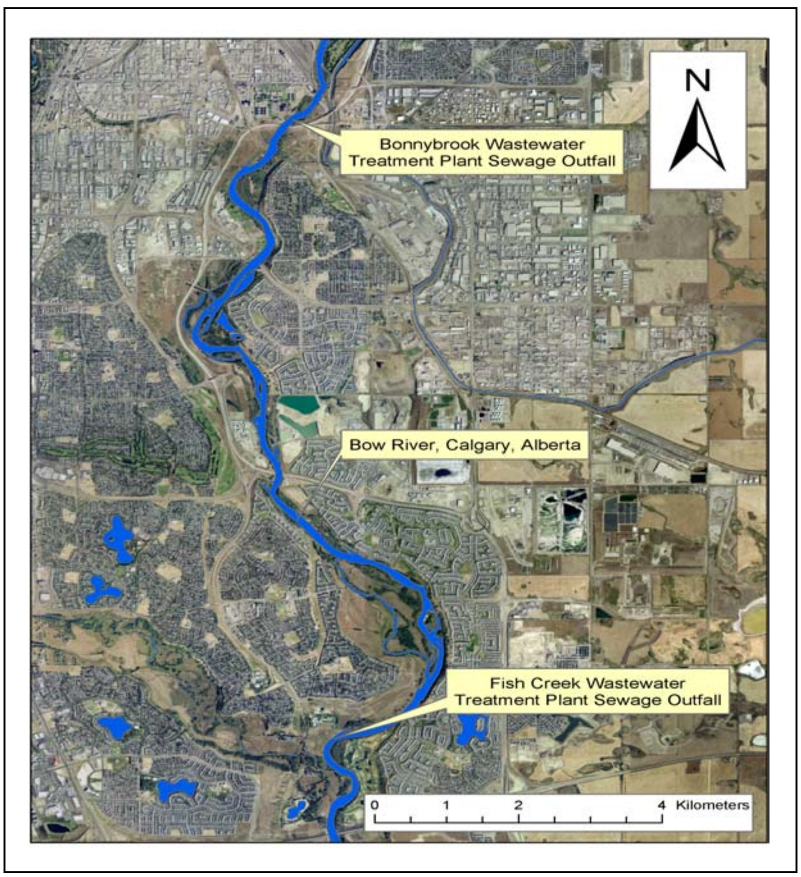

Figure 1. Orthophoto of study area including Bonnybrook and Fish Creek Wastewater Treatment Plants.

Background

Mixing zones are areas within a river system in which effluent is discharged and carried through the water body as a result of the hydraulic characteristics of both the river and effluent (Lung 1995). Wastewater effluent is mixed into a river through both advection and turbulent diffusion (Putz and Smith 2001). The advection process transports the effluent downstream based on the velocity of the water body. Natural rivers have significant velocity gradients in both the vertical and transverse directions (Beltaos 1979) and are therefore difficult to numerically model. Effluent concentrations in the transverse direction are carried through the process of diffusion, where a gradient between areas of high to low concentrations is caused by turbulence. Vertical mixing of the effluent is generally considered to be complete in wide, shallow rivers like the Bow (Farahbakhsh et al. 2002).

Various numerical mixing models have been employed to visualize the transverse mixing zone (e.g. Lau and Krishnappan, 1981; McCorquodale et al., 1983), however these models are primarily based on empirical constants that differ significantly between rivers, and cannot be generalized. Putz and Smith (2001) provided some spatial context by using a Global Positioning System (GPS) to accurately document the exact sample locations along specified transects. However, their results are only extrapolated in a graph format and no two-dimensional visualization of the effluent plume was completed in order to gain a full understanding of the mixing dynamics.

Numerical mixing models, which typically represent rivers as rectilinear shapes, do not consider river geography that can have a significant effect on plume mixing (Lau and Krishnappan 1981). One approach used an orthogonal curvilinear system, where the x-axis traces the bank of the river and the y-axis is the cumulative discharge (Yotsukura and Sayre 1976). The mapping and sampling of real river coordinates (Universal Transverse Mercator (UTM)) allows for a better understanding of how the effluent transversely mixes within a river. The inclusion of spatial river characteristics can include the effects of meanders, islands, and various other geographical phenomena on transverse mixing. These inclusions can be achieved using the real river coordinates (UTM).

Methods

Field Collection

On October 2, 2003, about 800 EC measurements were collected along 50 transects paddled in a 22 km reach of the Bow River immediately downstream of the WWTP sewage outfall. The location for each point was recorded using a hand held Garmin Etrex GPS receiver with a horizontal accuracy of approximately 7m. Sample transects were pre-selected to coincide with areas where mixing was expected to occur (i.e. before, during, and after river bends, islands, etc.). Water samples were collected for laboratory analysis of chloride, nutrients, and fecal coliforms in an associated study (Vandenberg 2004). The raw data set consisted of GPS coordinates (X, Y) and their associated EC measurement (Z). Analysis of EC presented here is taken between Bonnybrook WWTP and Fish Creek WWTP approximately 15 Km downstream.

GIS Processing

Two modeling methods were applied to construct the GIS analysis in order to determine the transverse mixing of the effluent plume. The first used the UTM X and Y sampling coordinates. The second method 'straightens out the river channel' by transforming the original coordinates into a rectilinear coordinate system. The y-axis is calculated as the longitudinal distance along the river path downstream from the sewage outfall to the center of each sampling transect. The x-axis is the distance between each sample point and the transect end point, located on the western riverbank projected along an axis that is orthogonal to the y-axis using the foot-point method (Farin and Hansford 1998). The western riverbank was maintained as a straight line in the GIS model to minimize plume distortion. The 're-projected' GIS model still represents the changes in the channel width and curvature (meandering).

To perform an accuracy check on the modeled data, a randomly chosen ten percent of the sample points (67 values) were removed from the data before any modeling was begun. After modeling, these removed points were then overlaid onto the model and interpolated values were extracted for those points. Interpolated and observed values at each point were compared. A standard error of regression, with 95% confidence, to find the error in the slope and intercept was performed to test the success of the modeling.

For the first method, the sampling points in the rectilinear coordinate system were used to create a continuous raster surface using the Environmental Systems Research Institute (ESRI) software ArcMap. The major challenge in the creation of the raster surfaces was the generation of an accurate representation of the surface based on the characteristics of the input data (Earth Systems Research Institute 1999). To convert the sample points to a raster surface, Inverse Distance Weighted (IDW) interpolation was applied with the Z value field set as the EC measurement, with a power value equal to 6, and the number of samples set to 100. The output layer was then clipped to the appropriate size of the river width to constrain the modeled surface to the appropriate dimensions. The benefit to using the IDW interpolation is that this method "explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart" (Earth Systems Research Institute 1999). The IDW interpolation was chosen because of the minimal distance between sample points in each transect, and because each point has a local influence upon the interpolation (Earth Systems Research Institute 1999).

The original UTM X and Y coordinates were transformed into a raster surface using the same parameters as outlined for the rectilinear coordinate system, except a barrier polyline was used in this instance to constrain the modeling results to within the river boundaries. Background river EC (as measured upstream of the effluent outfall) was 0.31 $mS \cdot cm^{-1}$. The WWTP effluent was about 0.80 $mS \cdot cm^{-1}$. Values greater than 0.40 $mS \cdot cm^{-1}$ downstream of the effluent outfall were considered to represent the WWTP effluent plume mixing zone, and to determine the longitudinal distance where transverse mixing was complete.

Results and Discussion

Two intriguing results are obtained through the modeling of both coordinate systems. The first model, focusing on the UTM X and Y coordinates (Figure 2), resulted in considerable error surrounding the sample points and transects. Pockets of high and low concentrations fluctuate significantly around river meanders. Upon closer examination of this model (Figure 3), sample points with high values of EC on the western bank are biasing areas that are being extrapolated between transects on the eastern bank. This 'bubbling' effect between transects, as modeled, is not indicative of the actual EC concentration gradient from west to east bank.

Figure 2. Modeling electrical conductivity using the UTM coordinates between Bonnybrook and Fish Creek WWTP's.

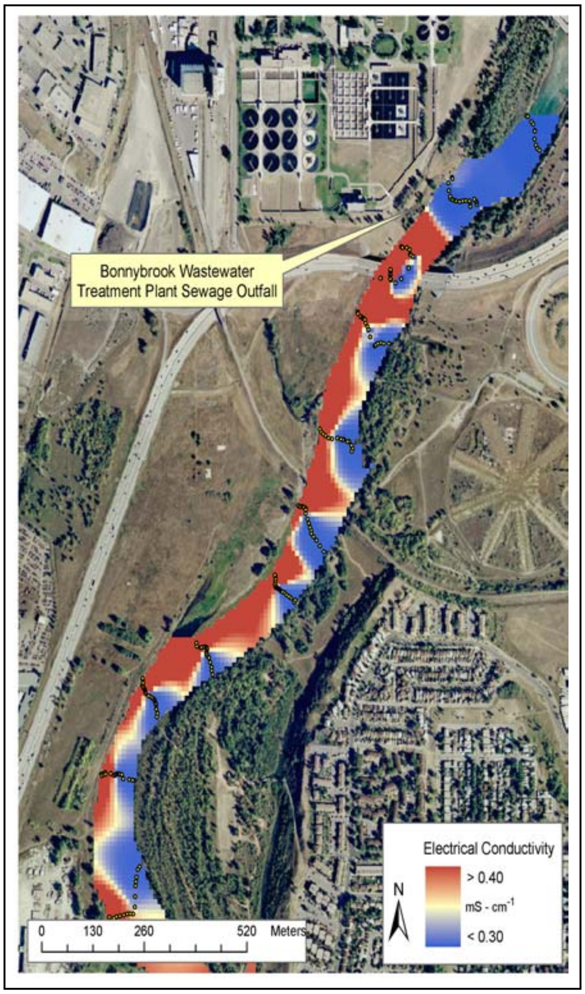

Figure 3. Magnification of the upper reach of the study area to illustrate the 'bubbling' effect between transects.

During a meander, sample points located on the western and eastern banks on two successive transects can be stretched farther apart on one end and brought closer together on the other (Figure 4). Interpolation of the area between the stretched points would result in the area being misrepresented, leading to the 'bubbling' effect seen in the model.

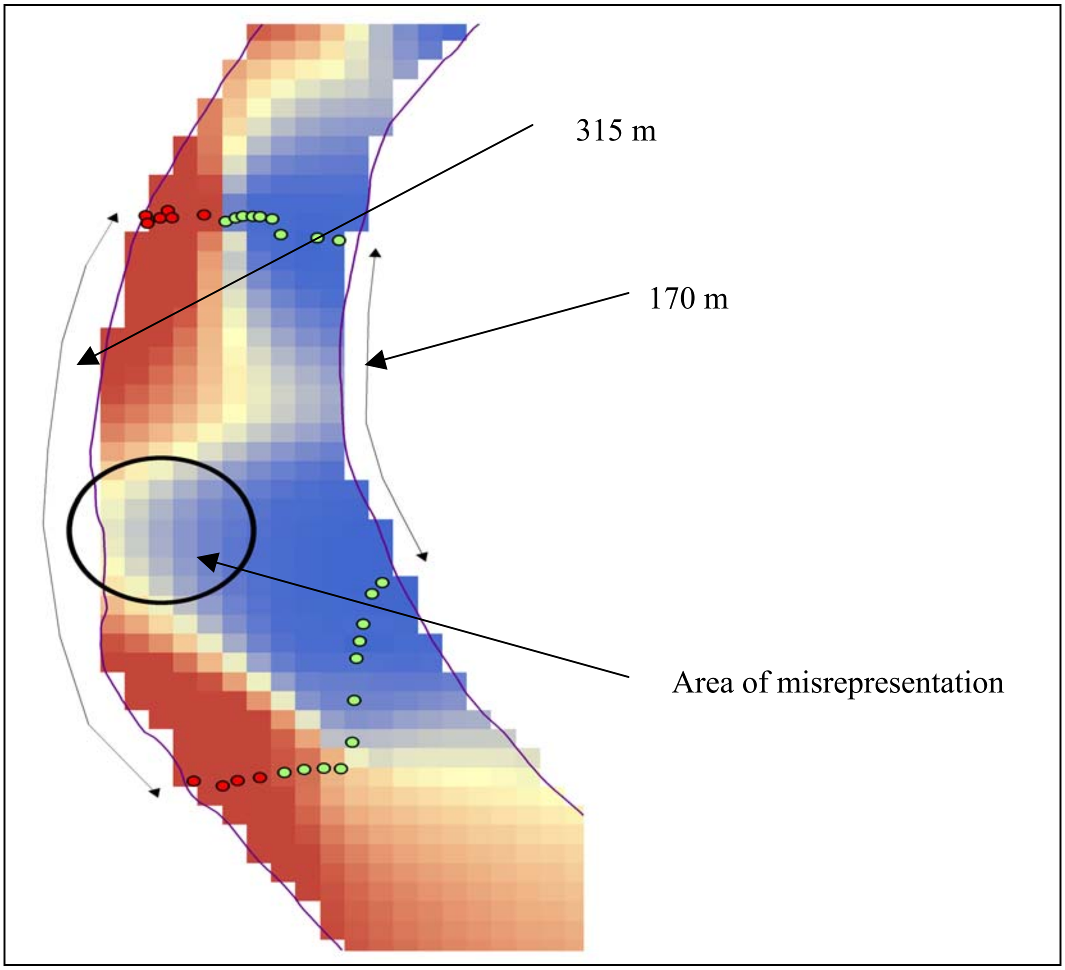

Figure 4. Example of misrepresentation due to a meander in the river.

The second method, using the rectilinear coordinate system, yielded more representative results than using the original X and Y coordinates. The model shows that the effluent, upon entering the river, remains close to the western bank and does not reach the eastern bank until approximately 12 Km downstream (Figure 5). When considering the meanders of the river, converting the coordinates to a rectilinear system removes the error introduced when modeling with the original X and Y. The "bubbling between transects" observed with the first model has been removed, and a more accurate representation of effluent travel downstream is achieved (Figure 6).

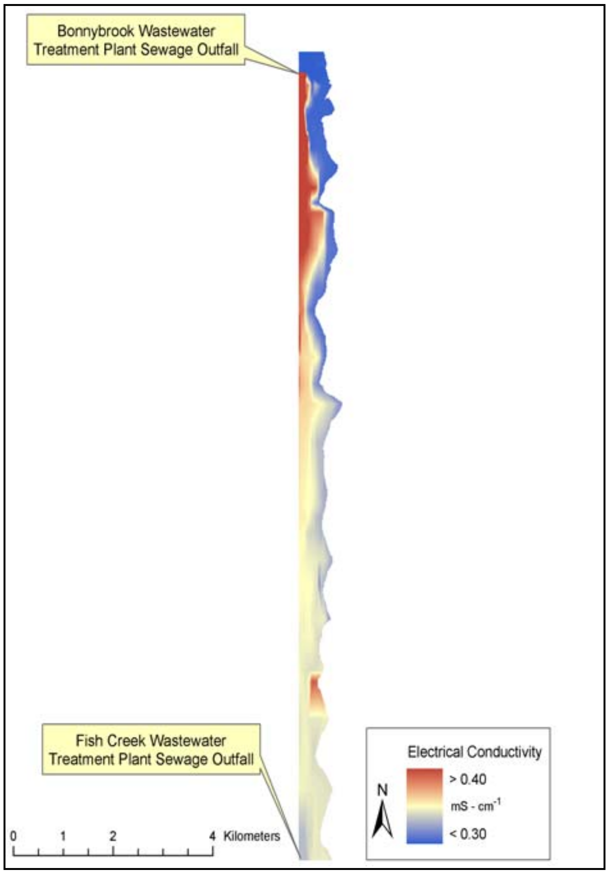

Figure 5. Modeling electrical conductivity using the rectilinear coordinate system between Bonnybrook and Fish Creek WTP's.

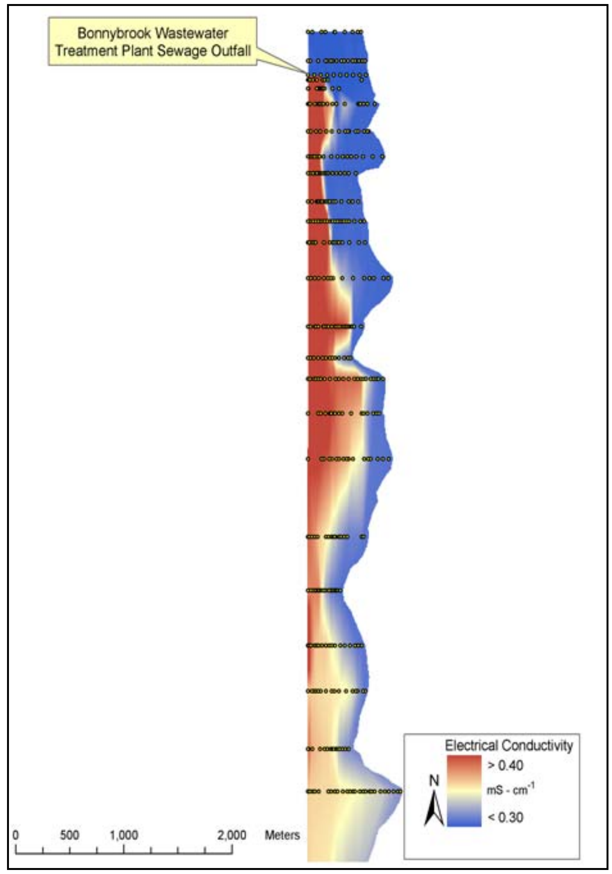

Figure 6. Magnification of the upper reach of study area to illustrate the effluent gradient from west to east bank of the river.

Comparison of the two modeling results shows that the rectilinear coordinate system best exemplifies effluent travel and mixing downstream of the sewage outfall. When creating a raster surface, the bounding interpolation area will equal the maximum extent of the sample points in each cardinal direction. Thus, by converting the original X and Y coordinates into a rectilinear system, the raster surface has less of an area to interpolate and therefore less chance of modeling error. The rectilinear coordinate system also removes the error of a meander from the first model and from the overall interpolation of results.

Statistical analyses were performed to verify the accuracy of interpolated points. For both the UTM and rectilinear coordinate system, the same 67 randomly chosen points were removed from the dataset. The EC values at these points were then generated by ArcMap by interpolating from remaining points. The standard error of regression was used to find the error in the slope and intercept as a measure of the accuracy of each method within the 95% confidence interval. When the interpolated values from the UTM coordinate system are regressed against the measured values, the best fit line is

$$y = 0.91 \pm 0.03\, x + 0.03 \pm 0.01$$

which shows that there is a statistical difference between true and interpolated values (Figure 7). In contrast, when the interpolated EC values from the rectilinear coordinate system are regressed against the measured values, the best fit line is

$$y = 0.99 \pm 0.02\ x + 0.006 \pm 0.01$$

which shows that there is no statistical difference between true and interpolated points using this method (Figure 8). The standard error of regression analysis shows that the model created through use of a rectilinear coordinate system produces a more accurate representation of the transverse gradient over the model for the UTM coordinate system.

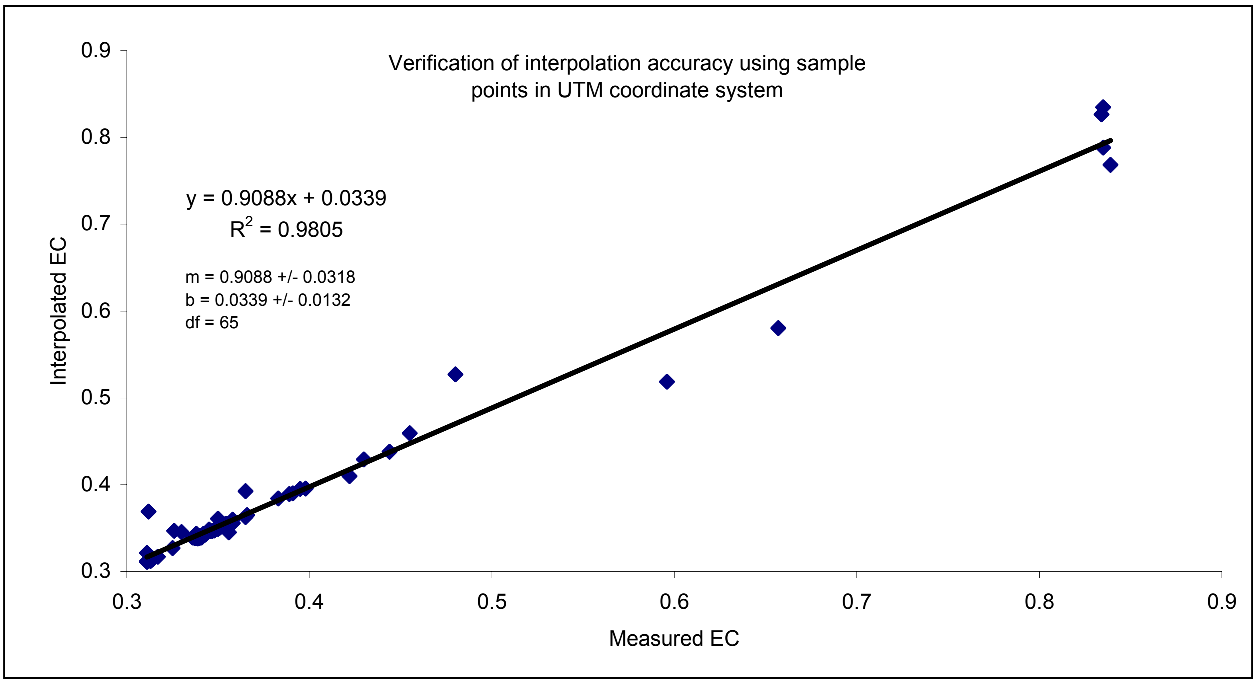

Figure 7. Accuracy assessment using standard regression for the UTM coordinates comparing observed versus interpolated electrical conductivity.

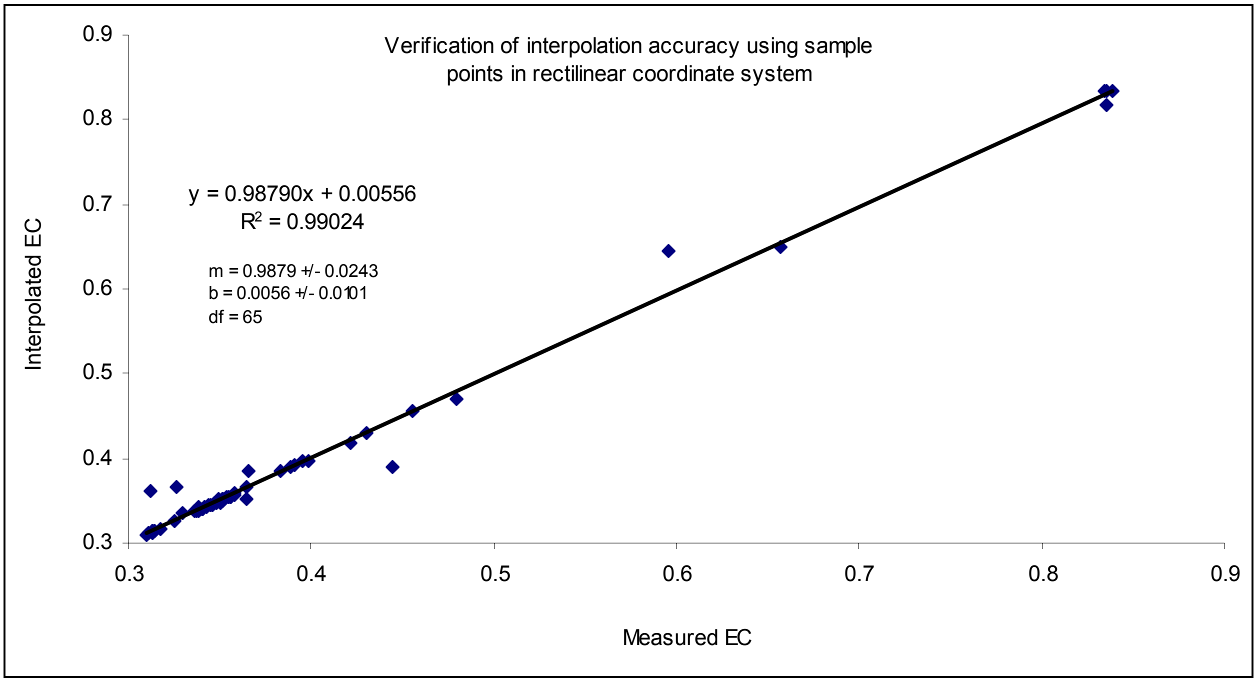

Figure 8. Accuracy assessment using standard regression for the rectilinear coordinate system comparing observed versus interpolated electrical conductivity.

Summary

There are several numerical models that can be used to represent the transverse mixing in natural rivers. However, many of these numerical models, such as a prismatic channel, do not incorporate the spatial characteristics of a natural river. By incorporating our data into a GIS, the spatial characteristics of the sampling regime are included in the final modeling result. Problems occur when attempting to interpolate UTM data into the GIS model, leading to poor results. To overcome this issue in our case study, the UTM X and Y coordinates of the sample points were turned into a rectilinear coordinate system. The rectilinear coordinate system allows for greatly improved modeling of the effluent plume as it travels downstream from the effluent outfall, as supported by the standard error of regression analysis. The GIS model utilizing the rectilinear coordinate system can simulate, with considerable accuracy, the extent of transverse mixing at any point downstream of the sewage outfall so long as a sufficient number of samples are collected along the reach of the river.

Since each river system is unique, using a GIS over a numerical model can give accurate spatial results without having to measure the dynamics of the specific river (i.e., sediment, curvature, etc.) that are included in some numerical models. Using a GIS is an effective tool for modeling and mapping the spatially correlated phenomenon of wastewater effluent mixing in natural rivers.

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Author Information

David D. Nuell, B.Sc.
GIS / RS Technologist
Department of Geography, University of Calgary
Phone: (403) 220-5588
Fax: (403) 282-6561
Email: david.nuell@ucalgary.ca
Web: http://www.ucalgary.ca/~ddnuell

Jerald A. Vandenberg, M.Sc. Candidate
Department of Chemistry, University of Calgary
Phone: (403) 210-9461
Email: javanden@ucalgary.ca
Web: http://www.ucalgary.ca/~javanden

Dr. Cathy Ryan, P. Eng, P. Geol
Associate Professor
Department of Geology and Geophysics, University of Calgary
Phone: (403) 220-2793
Email: cryan@ucalgary.ca
Web: http://www.geo.ucalgary.ca/ryan