

A GIS Method for Determining Volumetric Flow in a Riverine Channel

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Abstract

The purpose of this research was to develop a viable method of determining volumetric flow in large rivers using equipment available to a field biologist or university program. The study area was located on a side channel of the Upper Mississippi River near Trempealeau, Wisconsin. Location, depth, and flow velocity data was gathered at various points throughout the study area. This data were then downloaded into Geographic Information System (GIS) software for analysis. Utilizing the tools built into the software, interpolations of depth and velocity data were performed. These interpolations were used to calculate the volumetric flow on a cell-by-cell basis. By summing the volumetric flow through all cells, a total value was attained.

Introduction

Flow in natural river channels is a very complex natural process. Its temperamental and transient nature makes it difficult to model from a scientific standpoint. There are many commercially available flow modeling applications, however they have a couple of drawbacks. First, they tend to be rather expensive when compared to “off the shelf” GIS tools. Secondly, there is often a rather steep learning curve involved in order to obtain satisfactory results.

Flow is very important for determining the physical as well as environmental parameters of the river. Volumetric flow or discharge is normally expressed in terms of volume per unit of time. On the Upper Mississippi River the unit used by the

United States Army, Corps of Engineers is ft^3/s (U.S. Army, Corps of Engineers, 2004). The flow conditions dictate the design of bridges, erosion control projects, and water control structures such as sluiceways. A good understanding of flow allows civil engineers to make sound, cost effective, design decisions. From an environmental science standpoint, flow is also very important. Flow has an effect on all living things within a riverine ecosystem. For example, the habitat where fish can be found is often dictated by the volume and velocity of water flow, with different species behaving differently depending on conditions. It would be desirable to have a relatively inexpensive way of determining the flow characteristics of a particular area of a river or stream. There are some flow data available on the

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Internet from sources such as the U.S. Army, Corps of Engineers. However, most available data of this type tends to be very qualitative in nature, for example the total discharge at a lock and dam. Also, this type of data does not have a spatial component that might provide an indication of how the flow in a river is behaving on a smaller scale. For instance, is the flow evenly distributed across a channel or is most of the flow moving through a proportionally smaller part of the channel? This project is an attempt to develop a methodology for examining flow characteristics in a river channel using relatively inexpensive, “off the shelf” GIS and GPS technology. These technologies also provide a spatial context for examining the data.

Background

Spatial data can be divided into two general types, vector and raster. Vector data consists of points, lines, and polygons and is feature based. Raster data on the other hand is made up of cells, similar to the pixels in a computer display. Each cell in a raster data set has a single value associated with it. Raster data is used to map continuous phenomena such as depth. In this study, raster data were developed using discrete sample points of both depth and flow velocity at various points throughout the study area.

The process of developing raster data sets from sample data points is called interpolation. Interpolation methods can be divided into two groups, global methods and local methods. Global methods use all control points to predict the values at unknown points. Local methods on the other hand use

only a sample of the control points to determine the unknown values (Chang, 2002). Local methods are used for most applications. The three most common local methods are inverse distance weighted (IDW), splining, and Kriging.

Interpolation methods can be further classified as deterministic and geostatistical. Deterministic methods create rasters entirely on the known values of the data. IDW and splining are both deterministic methods. Geostatistical methods include a measure of uncertainty in predicting unknown values. Kriging is a geostatistical method. The advantage of geostatistical methods is that the analyst can also derive a raster showing the certainty of the predicted values.

IDW interpolation assumes that the value at any unknown point is directly proportional to the distance from known sample points. The greater the distance from a sample point, the less influence that point has on the predicted value (Childs, 2004). Overall the IDW method of interpolation is quite robust. One disadvantage of IDW is that it will not predict any values outside the bounds of the known sample points. In other words, the maxima and minima predicted by IDW will be the maxima and minima of the known sample points.

Spline interpolation uses the sample points to determine a mathematical equation that fits the surface through all the known sample points with a minimum of curvature. Conceptually, it is like bending a rubber sheet to fit through all of the sample points (Childs, 2004). Spline interpolations are recommended for smooth continuous surfaces (Chang, 2002). Examples of smooth continuous surfaces are precipitation amounts or

barometric pressure when displayed on a weather map. A major disadvantage of spline interpolations are the tendency for there to be overshoots in data poor areas. Overshoots occur when the interpolation predicts values that are unreasonably beyond the limits of the data.

Kriging is a geostatistical method of interpolation. It was originally developed by South African mining engineer, D.G. Krige for determining the orientation of veins of ore underground. Kriging assumes that the spatial variation is neither totally random nor totally deterministic (Chang, 2002). Kriging begins with the spatially correlated portion of a surface, combines it with any trend in the data, and then adds a random error term. An advantage to Kriging is that a raster containing the certainty of the predicted values can be generated. It should probably be avoided for data sets exhibiting random behavior, because it will attempt to fit trends that simply are not present.

Study Area

The area chosen for study is a back slough area of the Mississippi River. The area is at approximately mile 718 of the Upper Mississippi River between Trempealeau Mountain and the Burlington Northern Santa Fe railroad trestle at the mouth of the Trempealeau River. The study area is bounded on the north by the Burlington Northern Santa Fe railroad right of way, and on the south by an island (Figure 1). The flow through the study area is from West to East. The main channel is to the south of the island. This area is the simplest form of a control volume. The volume entering the control volume is equal to the volume leaving, and also equal to the flow across any cross section within the

study area. By comparing the flow at various cross sections within the study area, the viability of the flow measurement procedure can be evaluated.

Data Collection

Data was collected on August 20, 2004 over a period of several hours. Data was gathered by anchoring the boat at each data collection location.



Figure 1. Study Area, for reference Trempealeau Mountain is in the Northwest corner. The study area is approximately 650 feet (200 m) wide at the downstream end.

At each location a GPS waypoint was collected for spatial reference using a Garmin e-Trex Legend GPS. The depth and velocity of the flowing water was collected at each point. The depth was taken using an Eagle depth finder. A solid-state flow meter was used for measuring the flow velocity. The velocity measurement was taken at a depth approximately equal to 60% of the depth in order to obtain the average overall flow velocity (Hynes, 1970). Thirty-four sample points were taken in this manner throughout the study area (Figure 2).

Data Preparation

Utilizing the Minnesota DNR Garmin

Extension, the waypoints were downloaded from the GPS into an ESRI shapefile. Once the shapefile was created, the depth and velocity data were manually entered in the shapefile's attribute table. The data were then added to a personal geodatabase in order to work with it using ArcGIS. The data was projected from Latitude/Longitude, WGS 84 into the Wisconsin State Plane (southern). The sample data points were then brought into an ArcMap map document and then laid over a digital orthophoto of the area for reference.

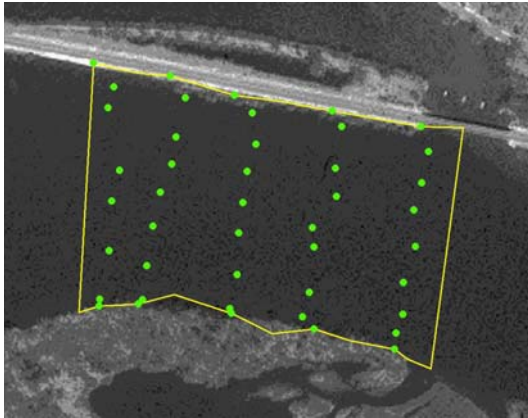


Figure 2. Sample point locations within study area. The study area is approximately 650 feet (200 m) wide at the downstream end.

Analysis

The main analysis task involved using the ArcGIS Spatial Analyst to create bathymetric and flow velocity rasters. (Figures 3 and 4) In both figures the darker color corresponds to higher values. Trial and error were used to determine which interpolation algorithm was best. Splining and Kriging produced very unpredictable results. The Inverse Distance Weighted (IDW) algorithm for creating the surfaces gave the best results. IDW with a polynomial power of 3 and a 1-foot cell size was eventually used. The 1-foot (0.3048

meter) cell size was a good compromise in that it provided good resolution while smaller cell sizes did not produce an appreciable visual change in the results by comparison.

The bathymetric readings had a maximum of 17.5 feet (5.334 meters). The minimum flow reading was 0.06 feet per second (0.018 meters per second), while the maximum flow velocity reading was 0.67 feet per second (0.204 meters per second). (Figures 3 & 4).

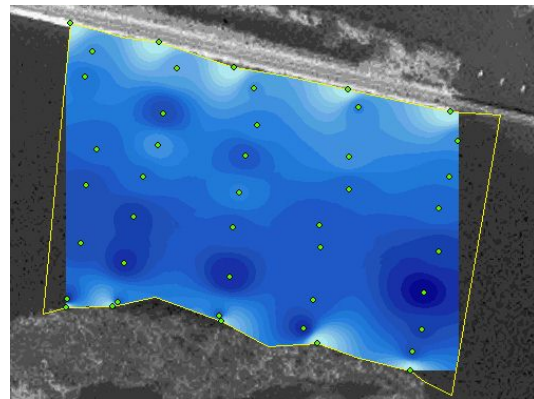


Figure 3. Depth Raster in feet. The darkest blues indicate the deepest water to a maximum of 17.5 feet (5.334 m).

The calculations were based on the basic flow equation of:

$$Q = vA$$

Where:

Q = volumetric flow rate

v = velocity, and

A = cross-sectional area.

Since the area term can be written in terms of cell size and depth the working equation becomes:

$$Q = v(\text{depth} * \text{cell size}).$$

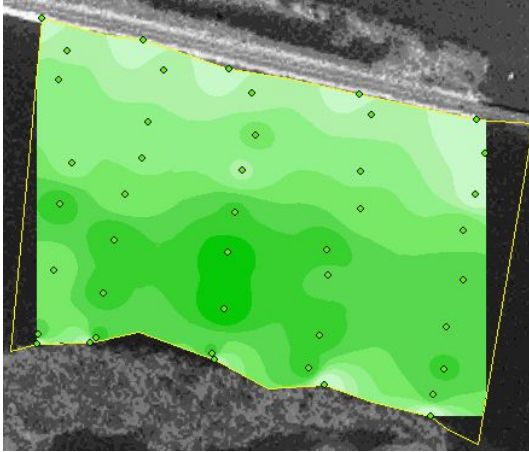


Figure 4. Flow Velocity Raster in feet per second. Dark green indicates the fastest velocities at a maximum of 0.67 feet per second (0.204 m/s), light green indicates the slowest velocity, with a minimum of 0.06 feet per second (0.018 m/s).

The next step was to draw cross sections through the study area. Each cross section was drawn as a graphic and converted to raster. The resulting raster was then used as the analysis mask for the subsequent calculations. Q was calculated on a cell-by-cell basis within the analysis mask. Using the map calculator, a final calculation raster was calculated. The value of each cell was equal to the volumetric flow through that cell. By summing the cell values over the entire cross section, the total flow across the cross section was determined. The map calculator expression was as follows:

$$[Q \text{ Raster}] = [v \text{ raster}] * [depth \text{ raster}] * cell \text{ size}$$

Originally, the intent was to use cross sections at various angles and then include a term in the flow calculation to resolve the flow into components normal and parallel to the given cross section. This, however, proved impossible due to the nature of raster data and cells of the cross section becoming stacked one

behind the other at any angles other than straight North to South or East to West. With this in mind, all cross sections were drawn North to South with the flow assumed to be approximately West to East (Figure 2). An overall map showing the magnitude of flow through a given cell was also produced. This was accomplished by performing the same calculation for the entire area. This map gives an idea of the magnitude of the flow at all areas within the study area, and thus shows where the water is traveling through the study area. This map is qualitative rather than quantitative in nature. The darker areas represent areas of higher flows (Figure 5).

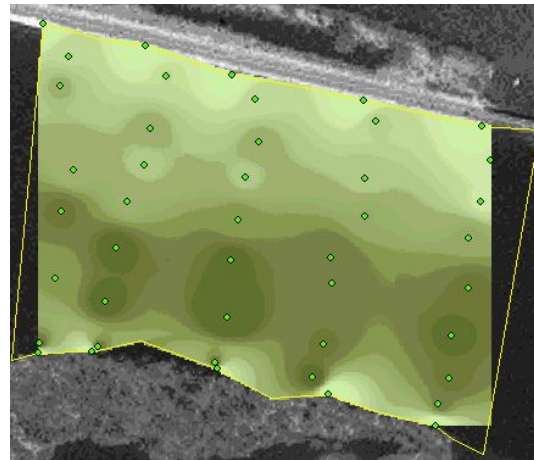


Figure 5. Volumetric Flow, Q Raster in ft³/s. The darkest olives indicate the most volumetric flow per cell to a maximum of 3.91 ft³/s (0.111 m³/s).

Results

The volumetric flow results for five cross sections of the study area are shown in Table 1. The mean flow for these five cross sections was 2740.3 ft³/s (77.6 m³/s). The maximum calculated flow was 3129.8 ft³/s (88.6 m³/s).

Table 1. Calculated Flow at Each Cross Section

Cross Section No.	Calculated Flow Ft ³ /sec (m ³ /sec)
1	2733.1 (77.3)
2	3129.8 (88.6)
3	2815.4 (79.7)
4	2521.1 (71.3)
5	2502.2 (70.8)

The lowest calculated flow for the five cross sections was 2502.2 ft³/s (70.8 m³/s). Figure 6 illustrates the location of the cross sections within the study area.



Figure 6. Cross Section Locations. The study area is approximately 650 feet (200 m) wide at the downstream end.

The flow values for the five cross sections have a standard deviation of 256.0 ft³/s (7.2 m³/s). The 95% confidence interval was 2740.3 +/- 710.65 ft³/s (77.6 +/- 20.1 m³/s). The mean flow appears to be viable when compared with the flow of approximately 17,000 ft³/s (481.1 m³/s) as determined by the Army Corps of Engineers at Lock and Dam 6 just downstream of the study area (U.S. Army, Corps of Engineers, 2004). This appears to be valid because the width of the study area is only about 25% of the width of the entire river. Also, the main channel, and presumably the majority of the flow, is south of the island on the southern edge of the study area. Also, the Trempealeau River, Cedar Creek,

and Trout Creek all discharge into the Mississippi River below the study area adding their discharges to the total discharge measured at Lock and Dam 6. The 95% confidence interval of +/- 710.65 ft³/s (20.1 m³/s) is disappointing, considering it is approximately 26% of the mean. Since all of the cross sections are on a closed conduit of the flow, there is no flow into or out of the study area that would not be accounted for by one of the cross sections. Therefore, more consistent flow values for each cross section should be expected. There are several possible causes for this much variation between cross sections. First, the bathymetric grid was derived from only 34 data points. This makes errors in the interpolation of the bathymetric surface more likely. An error in the bathymetric grid would have the greatest effect on the calculation of the flow since in the majority of cells it was the largest factor used in the calculation. Also, at the time the flow data was acquired the Mississippi River was at a very low flow condition. This made obtaining reliable flow velocity readings difficult for several reasons. The measured flows were on the extreme low end of the working range of the meter. Also, it was difficult to be sure that the flow meter was correctly turned into the current. Flow direction could also be a source of error. Localized eddies, and other turbulence in the flow could cause error as well.

There are several changes that could be made to improve future work. First, the bathymetric data should be derived from a larger group of points. This would provide a much more reliable bathymetric grid. A better bathymetric survey can be obtained using more of a traverse approach to gathering the depth data. This would

involve using a stop watch to space depth readings out while the boat is moving at a constant speed. Second, the data collection should be performed at a time when the magnitude of the flow velocity is higher, and thus more reliable flow readings can be obtained. An accurate assessment of the flow direction at each point would also be advantageous. This might be accomplished using some type of pressure sensor either integrated with the flow meter or attached to it. The direction data could be used to develop a third raster that could be incorporated into the flow calculations. Since the boat needs to be anchored to obtain the flow data, traverse methods are not a viable method for obtaining a large number of flow velocity readings. Finally, by having a larger number of data points for analysis, interpolations methods other than inverse distance weighted, for example Kriging and splining, will probably become more predictable. This would provide more options for analysis that might give better results.

Conclusions

In conclusion, this method for determining flow in a channel has the potential for success. The pitfall of sparse sample data can easily be overcome, by using a traverse approach to obtaining bathymetric data. A traverse approach would use a stop watch to space depth readings out while the boat is moving. Since in this case, the depth values were numerically at least an order of magnitude higher than the velocity data, this would greatly improve the results. A large sample of velocity data is more difficult to easily obtain because of the fact that the boat needs to be

anchored at each data point. In most cases, velocity will be more predictable and so can be better modeled with fewer data points.

The limitations of raster data may be able to be overcome with further study and analysis. The main concern here would be to eliminate the stacking of cells which occurs when cross sections are not in North-South, or East-West directions. This is a byproduct of how the ArcGIS software converts a line feature into a raster feature. If the stacking issue was eliminated, a geometric factor could be introduced to resolve the flow at each point into components parallel and perpendicular to the cross section. This would improve the results considerably as well.

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References

- Chang, Kang-tsung. Introduction to Geographic Information Systems. McGraw-Hill. New York. 2002.
- Childs, Colin. "Interpolating Surfaces in ArcGIS Spatial Analyst". ArcUser. ESRI. Redlands, CA. July / September 2004.

Hynes, H.B.N. The Ecology of Running Waters, University of Toronto Press. Toronto. 1970.

United States Army, Corps of Engineers. St. Paul District. 2004. www.mvp-wc.usace.army.mil/tmp/19643.png Visited, October 9, 2004.