GIS Method for Calculating Maximum Potential Spill Volume Due to Natural Landforms

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Abstract

GIS can be used in conjunction with ArcObjects to determine the maximum potential spill volume for points along a pipeline. A customized ArcObjects program was created which allows a user to enter a pipeline route and a series of points or valves along the route, a Digital Elevation Model (DEM) to provide the elevation, an interval at which to determine spill volumes and either a static diameter or a defined field for diameter between valves. This tool provided a shapefile output that encapsulates the potential volume of oil spill at each interval along with graphs for each segment of pipeline and corresponding volumes at each interval point with the segment. Using this tool, one can determine potential sites of sensitivity along a path and build a precursor to spill analysis modeling and high consequence area analysis.

Introduction

In the United States, there are currently more than 166,000 miles of pipeline which traverse areas both remote and highly populated (Office of Pipeline Safety, 2007a). These pipelines carry a multitude of chemical products, most of which are hazardous to the health of the environment and the human populace.

Between the years of 1984 and 2007, there were 3,776 accidents contributing to 276 injuries, an estimated cost of property damage of $1.25 billion, and over 3 million barrels of product initially spilled (Office of Pipeline Safety, 2007b). As consumption of oil and gas products rises, the volume of petroleum products moving through the nation's pipelines also increases (Energy Information Administration, 2008). This increase in volume could potentially raises the number of accidents and amount of product spilled per accident, thereby increasing the cost of clean-up and damage to property.

This research examined the ability to estimate the maximum potential spill of a pipeline due to landform changes by creating a custom ArcGIS program using ArcObjects and Visual Basic .NET technologies within the context of a GIS. The program permits users to execute advanced analysis of pipelines to determine areas of high risk and to estimate corresponding potential spill volumes at points along a pipeline. This information can be used to quantify risk along a pipeline, to identify the greatest areas of risk, to aid in engineering structurally preventative measures along the pipeline and to act as an input for spill modeling.

There are numerous methods available to help reduce the spill potential within a pipeline such as stronger materials, better engineering, increased inspections, and better use of

technology. Geographic Information Systems (GIS) is one such method that can be used in a variety of ways to aid in determining the potential amount, severity, and clean-up of pipeline spills.

Methods

Above ground pipelines follow the landscape, or relief of the land. These valleys and peaks influence the volume of spill in such a way that if a break would occur at the lowest point, the maximum spill volume would occur if no structure was in place to prevent the flow of product.

In order to determine the potential volume of spill at any given location along a pipeline, it is necessary to collect data defining the location in the coordinates, the elevation, and the diameter of the pipeline for the point of interest and for all other points on the pipeline. The information that is available is generally limited by pipeline design. Additionally, the model assumes that block values are present and serve as barriers to flow in case of ruptures and spills.

As the analysis involved spatial location, especially with respect to elevation and distances, GIS became the preferential tool in creating the necessary data in an automated fashion. An automated process using ArcObjects and a GIS removed the need for hand-calculation of data and increases the ability to generate accurate assessments more quickly along with increased ability to graphically show results.

Data Acquisition

Data acquisition consisted of capturing the spatial information of the points along a route in a given interval. The application requires the pipeline feature to be represented as a linearly referenced route with event tables which represent block valves along a pipeline. Users are required to provide the application with the linear referencing information necessary to retrieve the spatial information of each point along a line.

Linear referencing was used as it easily allows users to define locations along a line with a measure value, rather than a strict x and y value. This allows intervals to be computed easily and created along the pipeline.

In order to capture the elevation at each point along the pipeline, it was necessary to provide a GRID raster layer with corresponding elevation values of type double or integer. The ability for the program to incorporate a GRID layer allows for finer resolution elevation data to be attained and used. The elevation value was captured from the GRID layer via ArcObjects and custom programming, which eliminated the need for the ArcGIS Spatial Analyst™ extension.

The user is also required to enter information regarding the unit of measurement for the linearly referenced route, the interval at which they wish to estimate spill volumes, the constant diameter for pipelines or a field which contains valid numeric values for the pipeline diameter, and the pipeline diameter units.

Users also must define the output field names for intervals, the elevation, length of pipe contributing to the spill, and volume of spill in cubic feet, along with output directories and naming conventions.

Equations

Simple equations were used to determine

the spill volume at the predefined locations. The first equation dealt with estimating measure of pipeline. Data was defined in units of distance along the pipeline or a linearly referenced route. As each interval point was created a corresponding measure and elevation value was assigned to it. As spill volumes are dependent on elevation, there were times when all that was known about the interval point were the known points directly above and beneath the determinant point, in terms of elevation, which contributed to the determinant point's potential spill volume, but not the associated spatial information or measure value. In this instance, it was necessary to interpolate the measure (x) and elevation (y) value given the information for the point directly higher with the terms x_1 and y_1 and directly lower using the terms x_0 and y_0. The points bracketing the known elevation value had corresponding measure values as shown in Figure 1 and Figure 2.

$$x = x_0 + (x_1 - x_0)\frac{(y - y_0)}{(y_1 - y_0)}$$

Figure 1. Linear lnterpolation.

The application involved estimating spill volume by using the equation for volume of a cylinder as was necessary in (Figure 3).

Limitations

Throughout the creation of this program, several limitations became apparent. A major limitation of the program was the DEM (digital elevation model), or raster grid underlying the pipeline. For ease of use, only a single DEM was used by the model.
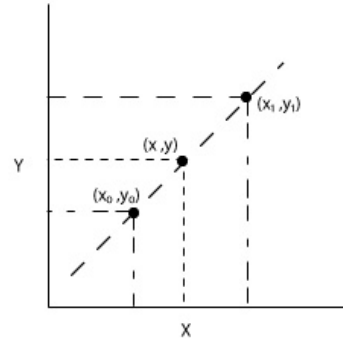

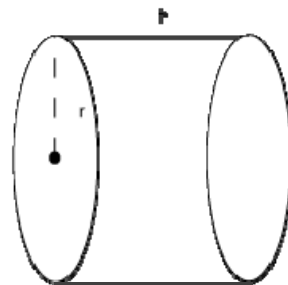Figure 2. Linear interpolation graph.

Figure 3. Volume of a cylinder ($V = \pi r^2 h$).

If a user were to model a pipeline that traversed a continent, all the DEM pieces would need to be preprocessed and combined into a single layer. This limitation could be overcome, in part, by allowing the user to use a Raster Catalog of all the DEMs, or allowing the user to select multiple DEMs and to determine the underlying DEM via spatial location, though this might cause issues in determining which DEM to use for a given point when overlapping grids are present.

Another limitation was within the volume calculation. In order to simplify calculations, the volume calculation does not take into account the angle in which the pipe lies. By ignoring the angle, the potential spill volume was inflated by the volume within the corresponding angle between points within the pipeline. The equation to account for this would be much more complex and would require support of qualified engineers and complicated mathematics.

Process

In order to calculate the potential spill volume of a point on a line, several procedures must be run to create points at defined intervals, extract the elevation data from the underlying raster layer, and calculate the spill volume at each point.

The first step in this procedure was to generate points along a route at the user defined interval. This was accomplished by limiting the user to processing information based on the route model. Routes were defined as linear features that have a corresponding measure value. This measure value may not necessarily be the length defined by the geographic coordinates, but could be custom defined by the user when developing the route. Since the pipelines within the route were linear features with statically declared measure values, a stand-alone table could be generated containing information regarding which pipeline point the analysis was on and a measure value that defined at which location along the route the point should lie. A procedure was created that allowed for rapid creation of this table and populating the measure values and other information.

For each route line

For [beginning route measure] to [ending route measure] step [user defined interval]:
    {function} Locate Point on Route
    {function} Save to table
Next [interval]
Next [route line]

Once this table was created, it was necessary to convert the measure units along the route into real-world coordinates as x and y pairs. Generally, it was easier to use the ArcGIS built in function to post a table as a point event using the ArcObjects IRouteEventProperties interfaces and corresponding class. But attempting to use these interfaces within the project resulted in the sudden exiting of ArcMap. In order to process the measure values to points, each point was individually located along the route and its corresponding real-world coordinates saved to a shapefile as Point Geometry. This resulted in unnecessary overhead but processes without failure. As mentioned earlier, the output of this was an ESRI shapefile with geometry and attributes corresponding to the route at which it came from and the original measure value.

In order to determine the potential spill volume along the pipeline, it was necessary to determine the elevation at each point along this line. This program was based on the assumption that elevation values were contained within an ESRI ArcInfo GRID file which spatially overlaid the pipeline.

This program was designed for a simple analysis of spill volume and assumed that the valve is a stop or block valve and it was closed immediately after a loss of pressure. This assumption allowed the program to work on smaller sections with greater ease in calculations, since the largest potential

spill volume occurred between starting and ending stop valves.

A segment for the program was defined as the points along the route that were between the valve and behind the point of interest (to the start of the route) and to the valve ahead (to the end of the route) of the point of interest.

The points for each route were extracted and placed into corresponding segments based on the presence of valves. Each route was represented by a custom class in .NET which held a generic list of segments along with the count in which it occurred and the name of pipeline or route_id. The generic list of segments was formed from a separate .NET class (Appendix 1) that held information about which segment it was in, using the form of an index and a generic list of points that were within the route. The generic points were another class which was built to hold the measures, elevations, length of the spill pipeline in both directions, diameter and volume of spill, along with the OID of the corresponding point in the table (Appendix 1). Each route was then created as a custom class, each segment extracted and added as a class to the route class and further, each point within the segment placed into the segment class within the route. As a minor caveat, some memory related issues could occur if too large a pipeline is processed with an interval too small. This could be minimized by temporarily extracting each segment within a route, one at a time, and then saving back to the generated shapefile.

For each point in the segment, the potential length of pipeline contributing to the spill was found by first computing the forward length of pipeline contributing to the spill potential as shown in Figure 4. Forward,

in this sense, was used to denote that the measure distance values were increasing, from the starting valve to ending valve within the segment. From the determinant point forward, the pipeline length contributing to the spill potential could be found in one of two ways.

The first was if the next point was at a higher elevation. If this was the case, then the forward length was incremented by the difference in measure values from the determinant point to the next and the program moved to the next point.
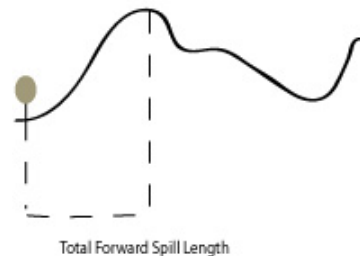

Total Forward Spill Length

Figure 4. Simplified forward spill.

The second option was if the next elevation was lower than the determinant point. In this case it was necessary to continue on through the rest of the points until either the ending valve was reached or a point of equal or higher elevation was found. If a point of equal or higher elevation was located, it was necessary to interpolate the measure value at this elevation. This interpolation was completed using Figure 1 where x_0 and y_0 were the point directly less than the determinant point and x_1 and y_1 were from the point found to be of greater or equal elevation to the determinant point. Once the measure value was interpolated it was added to the measure value of the elevation lower than the determinant point and added to the forward spill potential length as shown in Figure 5.

The process was computed for each point along the length of the segment and a total derived, resulting in the total length of pipeline contributing to spill potential in the forward sense.
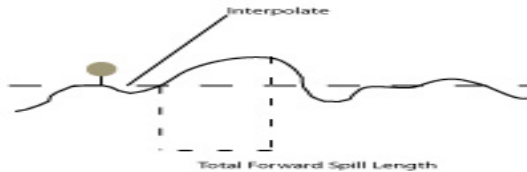

Figure 5. Interpolated forward spill.

After the forward spill length was computed, it was necessary to complete the same for any points behind the point of interest, if any. Because .NET generic lists were used, it was simply a matter of reversing the data in the list by using the built in Reverse() method and processing in the same fashion, switching the order of items in the interpolation for highest point and calculating the measure.

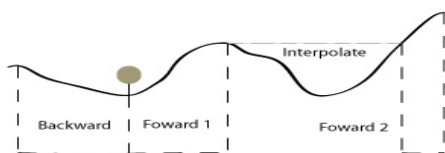The total length of pipe contributing to the spill volume was then

Figure 6. Total spill length.

calculated using the summation of all forward spill lengths added to the summation of all backward spill lengths as shown in Figure 6.

The summation of spill lengths used to determine the volume of potential spill using the cylinder volume

equation (Figure 2) where height (h) is defined as the total length of pipeline. The pseudo-code would be represented similar to the following example:

for each [point] in [pointList]:
  do until stop:
   for each [point+1] in [pointList]:
    if [end]: stop
    if [point].[measure] >= [point+1].[measure]:
     [measure]+= [point+1].[measure] – [point].[measure]
     else:
      {function}FindNextHighestPoint
      {function}InterpolateMeasure
      [measure] += [interpolatedMeasure]
   if {function}InterpolateMeasure or [end]: stop.

Analysis / Case Study

The application works in a variety of situations and for the purpose of demonstration, a demo site was created to show the program output. A pipeline route was created in two segments. The first segment traversed the straight line distance from Red Wing to Rochester, Minnesota and the second segment traversed from Rochester to Winona, Minnesota. The bluffs common to this area provided a wide range in elevation values within a short distance and were ideal to show fluctuations in volume due to natural landforms (Figure 7). DEM, or digital elevation models, show the elevation or relief of the area. For this demonstration application, DEM data was obtained from the Minnesota Department of Natural Resources Data Deli (http://deli.dnr.state.mn.us/) for the counties of Winona, Wabasha, Goodhue and Olmstead. To run the program, a continuous elevation grid was required,
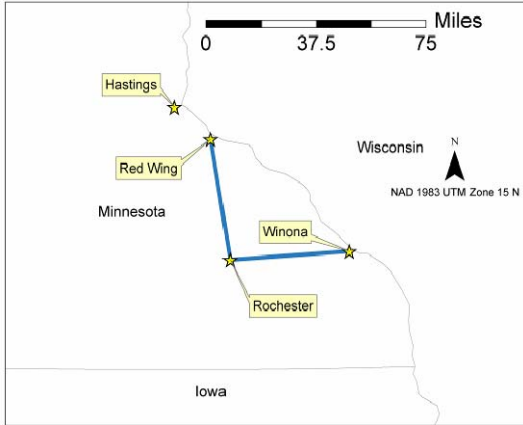
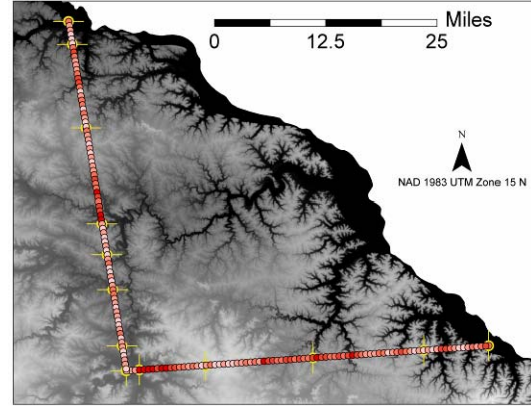Figure 7. Potential spill volume demo project area.

Figure 8. Program output. Points classified as light to dark red correlating to low to high potential spill volume. DEM classified from black to white correlated to low to high elevation values. Valves are shown in yellow. Correlation of higher potential spill elevation in longer valve to valve segments with elevation drop between the valves was shown.

thus a mosaic image was created. The first pipeline segment traversed approximately 39.7 miles, from Red Wing to Rochester, with a diameter defined as 12 inches and the second segment totaled approximately 40.8 miles, from Rochester to Winona with a diameter of 12 inches. Valves were created at random intervals along both pipeline segments. The program was then exercised with an interval of ½ mile (Figure 8).

The program generated 179 potential spill volumes calculated within 2 minutes with a range of 0 to 5316.73 cubic feet. Comparing the potential spill volume to elevation resulted in the following figures: Figure 9 for segment 1 and Figure 10 for segment 5. These figures show the relationship between potential spill and elevation within the constraints of valves.

The change in volume due to elevation can be observed by showing only the segment of pipeline that occurs between the beginning and ending valves on the 5th segment (Figure 11). The following figures depict the potential volume spilled using a dark blue line and the elevation using a light blue line. Potential spill volume at a point is related to the surrounding relief

within the constraints of stop valves. Areas of lower relief have a higher potential for spill. Conversely, areas at higher relief have a lower potential volume of spill for segments of pipeline between the stop valves or start and end points of the segment (Figures 9-12).

Stop valves are seen in Figure 12, where the potential spill volume drops to zero independent of the elevation. The analysis created does not take in to account failures directly at the stop valves resulting in null or zero values.

Conclusions / Future Usage

The output of this program can be used to identify high risk spill areas by using GIS to display the data on a map, tables to show quantitatively the degree of potential spills, and to allow users to show potential spill within pipeline volumes along with the corresponding elevations through the generated user interface.

At this point the program does not allow for direct modeling of the

7

pipeline to take place. A future addition to the program could allow for users to select any point along the pipeline and generate a potential spill volume.
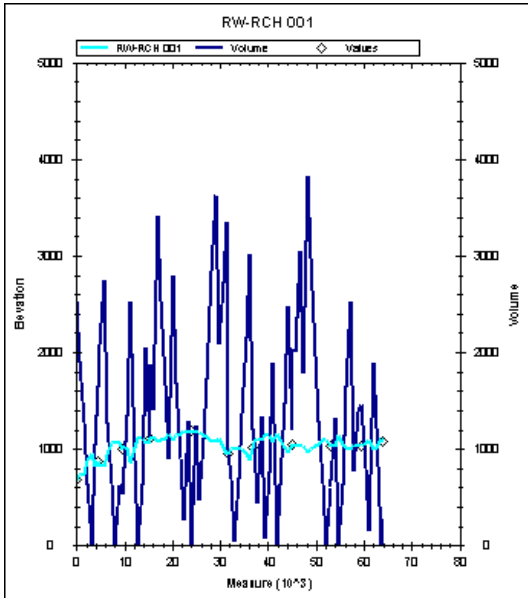

Figure 9. Red Wing to Rochester pipeline. Elevation depicted in light blue, volumes in dark blue, and valves are circles outlined in black. High points in elevation typically correspond to high potential volumes.

In addition, to generating potential spill volumes at known points, a strong potential for this program resides in determining the optimal placements of valves along pipelines. With the advance in computational power, iterations of random locations of valves could be created, and the best scenario chosen to limit the total risk of a given pipeline and to potentially optimize the placement of stop valves. This limits the associated costs of pipeline construction and in spill prevention and spill response.

Neural networks or Bayesian statistics could also be incorporated to determine best scenarios with less computational power. With a spill volume accurately
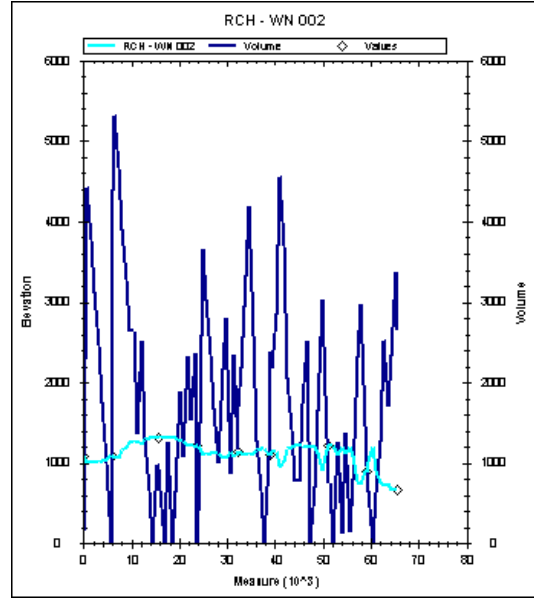

Figure 10. Rochester to Winona pipeline. Elevation depicted in light blue, volumes in dark blue, and valves are circles outlined in black. High points in elevation typically correspond to high potential volumes.
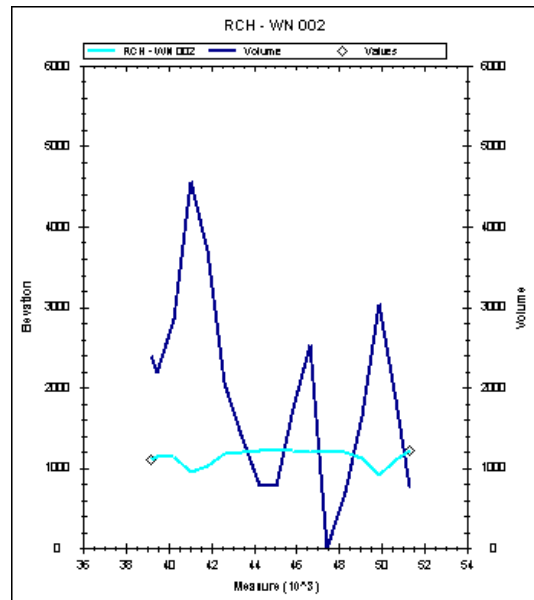

Figure 11. Segment #5 of Rochester to Winona pipeline. Volume spikes correspond to low points in elevation within the single segment. Symbology depicted as described in Figure 9 and Figure 10.

determined it also becomes possible to extend the potential spill volume into a

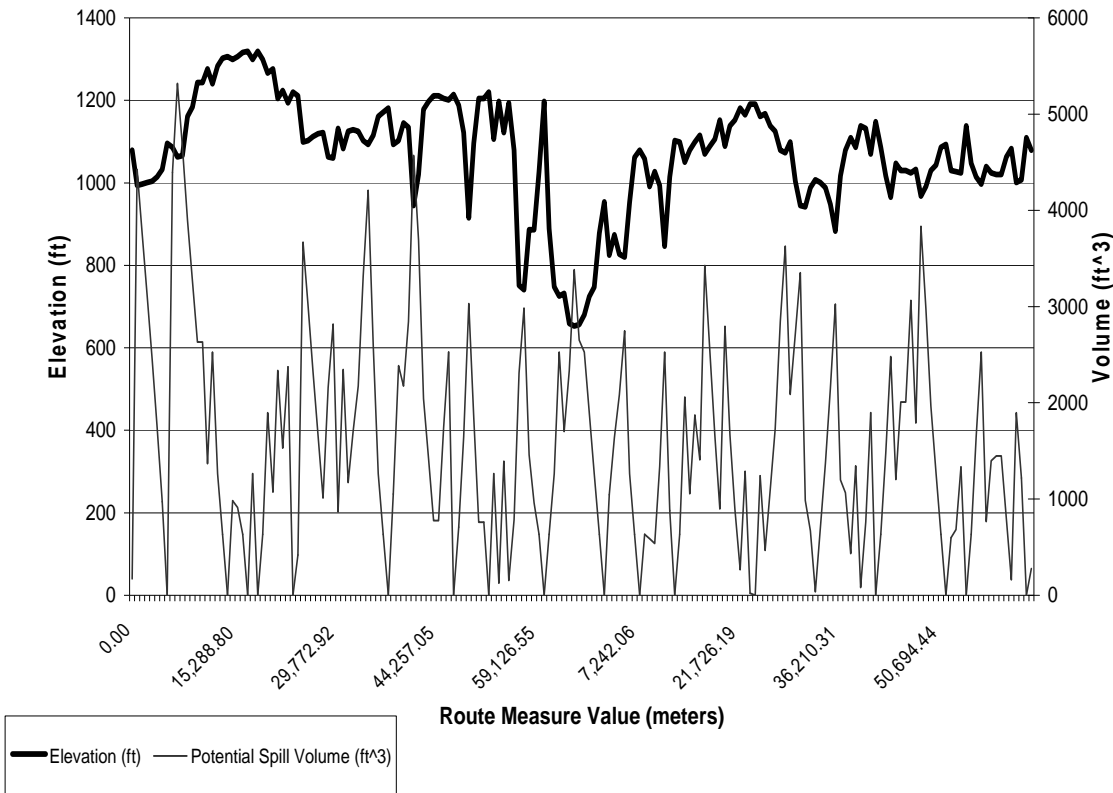## Correlation of Potential Spill Volume to Elevation

Figure 12. Elevation and potential spill volume depicted over route length.

potential plume of spill. Factors associated with the DEM, volume, soil porosity and density of petroleum product could then be incorporated into a spill model constructed for each point or at user defined points.

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Appendix 1. Class diagrams depicting created classes used in data-bound user interface and in volume calculations.