GIS Technology Applied to Modeling Oil Spills on Land

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Abstract

Methods used in the application of GIS technology to simulating the movement and fate of oil spills on land and in surface water features are discussed. The discussion will focus on three areas: model input data preparation; model algorithm development, and; model output analysis. The intent is to promote an informed discussion within the GIS community of oil spill modeling in terrestrial and freshwater systems.

Introduction

This paper discusses the development and application of methodologies used to simulate land-based oil spills from pipelines and oil storage facilities. The system has been used to model hundreds of individual spills in a variety of terrains and environments around the world.

Model Input Data

A number of standard data products are required to simulate land based oil spills. Two criteria are important when acquiring input data: 1) get the best available, highest resolution data possible, and; 2) get site-specific data by conducting a site survey. High resolution land elevation rasters and surface water vector data are important because they are the primary control on the path of the spilled oil. Even with the best available data, missing data values and erroneous data occur frequently in the standard data products used to model overland flow. Examples include stream segments in a surface water network that flow in the wrong direction and elevation rasters with erroneous data produced as artifacts of the data generation process. Almost without exception, the small features such as drainage ditches, retaining walls and storm drains that steer the spill over land are not captured in the standard data sets. Supplementing elevation rasters and surface water data sets with land and water features mapped in the field will result in improved model results and are a necessity if an accurate spill path is desired.

The list of required model inputs includes:

Spill location, spill amount and release rate – Spill locations define the spill sites along the pipeline route or at the storage facility. Spill amount and release rate are specified for each pipeline segment or individual spill point.

Elevation Data – Land elevation data in a gridded format defines the land surface over which oil moves. The standard for Digital Elevation Models (DEM) in the U.S. is the National Elevation Dataset (NED) that provides a consistent data product for the entire U.S. at a 30-meter grid cell resolution (ned.usgs.gov). Some areas of the country now have 10-meter grid cell data available, with more areas becoming available all the time. The data can be downloaded via Internet browser or ftp server. Any elevation grid, such as one generated from LIDAR data, can be used where available.

Land Cover Type – Land cover type in a gridded format is commonly used by spill models to calculate different rates of oil loss as oil moves across the surface. The National Land Cover Dataset (NLCD) provides a consistent nationwide land cover data source with 21 individual land cover classifications (www.mrlc.gov). A group of federal agencies, the Multi-Resolution Land Characteristics (MRLC) Consortium, developed the data set from 1992 data and is currently updating the land cover classification system for the US using more recently acquired LANDSAT7 satellite imagery.

Surface Water Network – The National Hydrography Dataset (NHD) provides a standardized source for surface water features in the U.S. that can be used to model movement of contaminants through streams and ponds (nhd.usgs.gov). The NHD provides a network of connected surface water features in vector format and the data necessary to navigate through the network in the downstream direction. A stream velocity must be assigned to each stream reach to control the downstream travel speed of the surface oil. Stream velocities are not part of the NHD and must be obtained form either gauging stations or some other data source. The Enhanced River File maintained by the USGS and US EPA provides a source for velocity values for major streams nationwide.

Oil Characteristics – The physical and chemical characteristics of the spilled oil must be specified in order to calculate evaporative loss. A well documented analytical approach is used to predict the fraction of oil volume evaporated based on the evaporative exposure concept of Stiver and Mackay (1984). The parameters include:

T_o	Initial boiling point (K)
T_G	Gradient of modified distillation curve
A	Dimensionless constant
B	Dimensionless constant

T_o and T_G are the y-intercept and slope, respectively, obtained by linearly regressing a specific oil's boiling point temperature versus the volume fraction distilled.

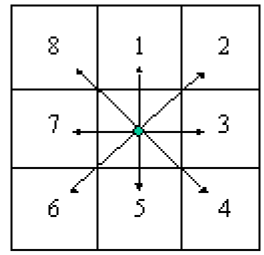
A and B are dimensionless constants determined as the y-intercept and negative slope, respectively, obtained from a linear regression of the natural log of Henry's Law constant versus the boiling temperature.

Environmental Inputs – Wind speed and air temperature are required to calculate oil evaporation. Typically a monthly or seasonal average value for these parameters taken from climatological summaries or models is used. One such source is the National Centers for Environmental Prediction (NCEP) maintained by NOAA (NCEP, 2005) which provides global meteorological data products.

Modeling Methodologies

Land based spills travel down slope over land and most often end up in a stream or other surface water feature. Two fundamentally different modeling approaches are required to simulate a land based spill that enters a surface water feature. Oil flow over land is governed by the physical nature of the land surface and the degree of slope over which it flows. Once the oil reaches a stream or lake its flow is governed by surface currents, requiring a different modeling approach. The overland model calculates an oil mass balance that includes losses from oil adhesion to land over the oiled path, the formation of small puddles, oil pooling in large depressions on the land surface, and oil evaporation to the atmosphere. The water transport model moves oil on the water surface at a defined velocity and calculates oil lost to the shore from adhesion and oil evaporation to the atmosphere.

Calculating the Spill Path over Land



Starting at the spill location, the model determines the steepest descent direction in the eight adjacent cells of the elevation grid. The oil moves to the neighboring cell with the lowest elevation. This process repeats successively until a flat area or depression is reached. In a flat area, the model searches the minimum distance path to a next lowest cell (i.e. looks beyond the eight adjacent cells) and moves the spill to that cell. In a depression area, the depression is filled before the spill continues down slope. Overland flow of the oil continues until the path reaches a stream or other surface water feature, or until the total spill volume is depleted from loss to the land surface and evaporation. The final spill path forms a chain of channels and pooled sections. A channel section is where no pooling occurs and the width of the spill path is dependent on the slope of the land surface. A pooled section consists of an area of one or more contiguous elevation grid cells that form a depression in which the spilled product has collected.

As the oil flows down slope, oil mass is lost through adhesion to surface vegetation, puddle formation on the ground surface and pooling in depressions. The rate of oil loss to these processes is dependant primarily on the physical characteristics of the land surface (vegetation type, land cover, soil type, slope) and the characteristics of the spilled product.

Different land cover types retain different amounts of oil as a spill passes over the land surface. Oil is lost as it adheres to surface vegetation, rocks and soil, and as it puddles in small depressions. The volume of oil retained along the oiled path from the adherence and puddle processes is defined as the path length times the path width times a constant oil thickness. The oiled path width is related to the slope of the land surface as determined from the elevation grid.

The constant oil thickness is specified for each land cover type defined in the land type grid. Each cell in the land type grid is assigned an oil loss thickness so that as oil traverses the land the loss to each land type is calculated. This loss value varies between 2 and 200 millimeters for the range of land cover types typically encountered. These oil loss rates are based on surface hydrologic studies (ASCE 1969, Kouwen 2001, and Schwartz et al 2002).

Separate from adhesion and puddle losses, oil lost to pooling on the land surface is the volume of oil retained within depressions defined in the land elevation grid. The oil lost to the ground is the sum of adhesion, puddle formation and pooling. Total oil loss during a spill simulation includes losses to the ground plus evaporative loss to the atmosphere (described below).

The velocity (V) of the leading edge of the spill as it travels over the land surface is determined by the slope of the land surface using Manning's Equation:

$$V = 1/n \, R^{2/3} \, S^{1/2}$$

Where R is the hydraulic radius and S is the slope, and n is a dimensionless number that characterizes the flow resistance. Assuming n is 0.05 and R is 0.122m:

$$V = 4.92\ S^{1/2}\ \text{(meter/sec)}$$

Because the elevation grid defining the land surface is not of sufficient resolution to define channels that direct the path of the oil, the path geometry is defined for all spills. The width of the flow path increases as the slope of the land surface decreases and the path width decreases with increasing land surface slope. Path width is typically around one meter and can not exceed the dimension of the land elevation grid cells.

Water Transport
Once the spilled oil enters a stream it is transported through the stream network at a velocity defined by the speed and direction of surface currents in each stream reach. While in the stream network, oil is lost by adhesion to the shore and by evaporation to the atmosphere. A maximum total travel time and stream velocity controls the distance traveled downstream. Travel times are typically defined in spill response plans as the time required to respond to and stop a catastrophic release. Oil is modeled to travel downstream until all available oil is lost to the shoreline or to evaporation, or the simulation reaches the maximum downstream travel time.

When oil encounters a lake the slick will spread across the lake surface until it covers the entire lake or it reaches a minimum thickness. If the minimum thickness is reached, spreading stops and the oil travels no farther. The minimum thickness can be varied according to the oil type. If oil covers the lake surface before reaching the minimum thickness it continues down any out-flowing streams at the surface current velocity specified for the stream reach.

Oil loss to stream shorelines occurs as oil is transported downstream by surface currents. Five different stream shore types are defined, each with a specified bank width and oil loss thickness. Oil volume lost to the shoreline is calculated as the length of the shoreline oiled times the specified bank width times the thickness. Typical shoreline loss values are shown below:

Shore Type	**Shore Width (m)**	**Oil Thickness (mm)**
Bedrock	0.5	1 – 4
Gravel	1	2 – 15
Sand/Gravel	2	3 – 20
Sand	5	4 – 25
Marsh	20	6 – 40

Evaporation
Oil evaporates as it spreads over land or water. The most volatile hydrocarbons (low carbon number) evaporate most rapidly, typically in less than a day and sometimes in under an hour (McAuliffe, 1989). The spill model uses the Evaporative Exposure model of Stiver and Mackay (1984) to predict the volume fraction evaporated.

Several simplifying assumptions are made that directly affect the amount of oil predicted to evaporate. In general, the rate of evaporation depends on surface area, oil thickness, and vapor pressure, which are functions of the composition of the oil, wind speed and air and land temperature. The mass of oil evaporated is particularly sensitive to the surface area of the spreading oil and the time period over which evaporation is calculated. On the land surface, area and evaporation time are functions of the slope defined by the elevation grid. Steeper slopes cause the oil to travel faster but along a narrower path, while a lower slope slows the speed of advance and increases the width of the oiled path.

In the stream network, oil surface area and evaporation time are functions of the stream surface area (total length of the oiled stream times the average width) and stream velocity. Oil loss to evaporation ceases once the total oil spill volume is released and overland travel stops, or if oil enters a stream, once the stream maximum travel time is reached and flow in the stream network stops. In reality, oil will continue to evaporate from the ground or water surface, increasing the total evaporation amount. This conservative calculation of evaporative loss is consistent with a worst-case scenario approach.

Model Output Analysis

Model outputs are stored in ESRI data formats as polygons representing the spill plume from each individual spill site. Oil mass balance time series data are contained in tables listing oil evaporated, oil retained on the land surface and oil retained on stream and lake shorelines.

Spill plumes can be easily overlain onto input and other data layers in the ArcGIS framework. Before accepting the results, a careful inspection of each plume is necessary to identify erroneous output. Problems resulting from bad data such as incorrect stream flow directions are immediately apparent when the output is mapped. Once problems are identified, causes can be determined and fixed. A subset of spills is then rerun and the results scrutinized for errors. For spills originating from a pipeline where hundreds of individual spill sites are modeled, this process can take some time to complete.

HCA Analysis

As part of their integrity management program, hazardous liquid pipeline operators are required by Department of Transportation Office of Pipeline Safety regulations to identify all pipeline segments that could affect a High Consequence Area (HCA) should a spill from that segment of pipeline intersect a HCA. This basic analysis is done by overlay of the spill plumes with HCA data layers to determine their intersection and identify the source pipeline segment.

Spill Response Contingency Planning

Hazardous liquid pipeline operators and other oil handling facilities develop, maintain and exercise spill response contingency plans. Using land spill model results that show where the oil will go and how long it takes to get there, all within a GIS framework, gives planners a powerful tool to help determine response strategies, stage response equipment and write contingency plans to meet government regulations.

Environmental Permitting

Oil spills from proposed pipelines and onshore processing facilities can be simulated to examine the potential for risk to areas that are of special value or are environmentally sensitive. Spill scenarios can be defined to compare spills occurring in different environments, do sensitivity studies examining the effects of changing different spill parameters, and testing specific spill scenarios to meet environmental permitting requirements.

Risk Analysis

Oil products stored in tanks or transported in pipelines pose a potential risk to the surrounding environment. Determining the level of risk and deciding what actions should be taken to prevent accidental releases involves a number of analysis methods. Oil spill models provide a means to simulate the extent and timing of a spill event from land based facilities to evaluate the level of risk to specific environments.

Conclusions

Model Input Data

The predicted overland travel path is only as good as the elevation data. Even with high resolution gridded data, features that steer oil are only captured with a site visit and field mapping. Land spill model results should be viewed with a clear understanding of how accurately the elevation data capture the land features over which the oil travels.

Model Methodologies

There is a lack of field data on actual spill events sufficient to do model hind casts. More data needs to be collected and more hind casts performed to validate the assumptions being used in the models. For example, are oil loss rates tied to land cover type in the appropriate range?

Analysis using Model Outputs

Land spill models can provide useful information for a number of applications. These include HCA analysis for hazardous liquid pipelines, contingency planning for spill response, environmental permitting and risk analysis.

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