

OVERLAND FLOW: COMPARISON OF MODELING METHODS

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ABSTRACT

One of the key components of an effective integrity management program is establishing repeatable and defensible processes and analysis techniques. The inclusion of High Consequence Areas in CFR 195 has placed an increased importance on the need for effective pipeline data management and Geographic Information Systems (GIS).

CFR 195 clearly outlines the need for comprehensive identification of High Consequence Areas (HCA) that could be affected directly or indirectly by a pipeline leak or spill. However, expressing this need is much simpler than the rigor required to answer the regulatory requirements in full. The pipeline integrity industry has responded to this need by providing tools and services for modeling spills and overland flow, but unfortunately, the industry available tools and services use vastly different approaches thus providing varying results.

This paper outlines the critical components of a realistic overland flow model and discusses assumptions suitable to overcome typical data quality and availability issues. A portion of this paper also focuses on some of the approaches presently used by industry and discusses each approach in comparison with a comprehensive model.

REGULATORY REVIEW

Regulatory requirements for integrity, risk, and emergency response are converging on the use of Geographic Information Systems to aid in management of assets, data integration, and preplanning of incidents. The inclusion of the High Consequence Areas in CFR Part 195 reiterates the need for GIS involvement to meet regulatory requirements. The Department of Transportation has issued updates to the long standing CFR Part 195 that provide guidance on how pipeline integrity should be performed. The pipeline integrity updates to this regulation require pipeline operators to identify where their pipelines could affect (directly or indirectly) a High Consequence Area. High Consequence Areas include populated areas, unusually sensitive areas (for example, drinking water supplies or ecological areas), and commercially navigable waterways.

More Specifically, CFR 195.452 requires pipeline operators to comply with identifying pipeline segments that could affect an HCA, determining consequences of a failure, and identifying

measures taken to protect the High Consequence Area. Without the capability to model overland flow, it is virtually impossible to inventory properly pipeline segments and affected HCAs therefore making an overland flow model a critical component of regulatory compliance.

Response planning is another area of regulatory concern where overland flow modeling is indispensable. CFR Part 194.107 requires that “each response plan must plan for resources for responding to the maximum extent practicable to a worst case discharge and to a substantial threat of such a discharge” (Department of Transportation, 2003). A realistic overland flow model can be applied to several regulations, for instance, aiding in the analytic requirements of CFR Parts 194 and 195.

OVERLAND FLOW

Although not explicitly stated, overland flow is the analysis expected of pipeline operators in response to the requirements of CFR Part 195 for identifying pipeline segments that could affect High Consequence Areas. In determining HCAs that may be directly or indirectly affected, a geographic information system, if implemented correctly, can provide significant overland flow modeling capabilities. Directly affected HCAs are those found along the pipeline or “online” and are relatively straightforward to determine. Indirectly affected HCAs or “offline” are more challenging to determine and are highly dependent on the overland flow methodology used, hence the importance of choosing and using a comprehensive and defensible overland flow model.

The regulating body governs minimum input criteria for a comprehensive overland flow model. Figure 1 displays regulatory requirements (Department of Transportation, 2003) on the left and model interpretation on the right.

Regulatory Recommendations	Model Considerations
1.Terrain surrounding the pipeline...	1 Digital Elevation Model
2.Drainage systems...	2 Hydrography
3.Crossing of farm tiles...	3 Crossings
4.Crossing of roadways...	4 Crossings and transportation
5.Product characteristics...	5 Fluid properties
6.Physical support...	6 Special Case
7.Operating conditions...	7 Operating conditons
8...Hydraulic gradient...	8 Hydraulic gradient
9...Potential release volume...	9 Potential release volume
10.Potential physical pathways...	10.Potential physical travel paths
11.Response capability ...	11.Response time
12.Potential natural forces...	12.Probability

Figure 1: Regulatory Recommendations versus Model Considerations

From a regulatory perspective recommendations listed in Figure 1 are considered complete, however, there are several factors excluded. Additional factors that should be included in an overland flow model are factors such as surface cover, soil properties, and weather conditions. In accounting for these factors, an overland flow model is able to capture soil absorption, flow resistance, and fluid evaporation.

MODELING COMPONENTS

In designing a realistic model, consideration must be given to data availability and data quality. Higher quality datasets (i.e. model components) produce results that are more realistic. Availability of quality data is a standard problem in GIS, so any model must be adequately adaptable to account for unavailable data, poor quality data, or for the use of overriding assumptions. A comprehensive model bases its methods on establishing realistic resistance to flow over ground surface and its algorithm creates a continuous surface of fluid flow by accounting for variations in surface cover, directional slope, fluid properties, and other inputs as discussed below.

Digital Elevation Model

The digital elevation model is the main input for any overland flow model. It governs the potential energy available for flow and controls the direction of flow. Wherever possible, breaklines and/or barriers to flow should be included in the elevation surface to ensure flow is properly constrained.

Source Location

Source location is the representation of the spill site and can take the form of a point or linear sources. Point sources are used in the case of localized spills or for predefined locations. Linear sources, typically represented by the pipeline centerline, are advantageous in modeling system wide spills. By calculating overland flow from a linear source all possible occurrences are modeled thus eliminating uncertainty of misclassification of potentially impacted HCAs.

Spill Characteristics

Spill release time and release volume two important characteristics necessary in a comprehensive model. Accounting for spill release time allows operators to include the time required for valve shut-in or emergency response mobilization. Release volume, usually derived from pipeline hydraulics, is not required for general modeling but is imperative for determining the true extent of a spill.

Flow Types

There are several types of flow regimes that must be accounted for within an overland flow model, these being: sheet, flat, and path. Each flow type is heavily dependent on topography and a spill volume may experience any or all of these flows on its course towards an HCA. Accounting for these flow types allows the model to develop a realistic path over which the spill would follow.

Path flow follows the steepest

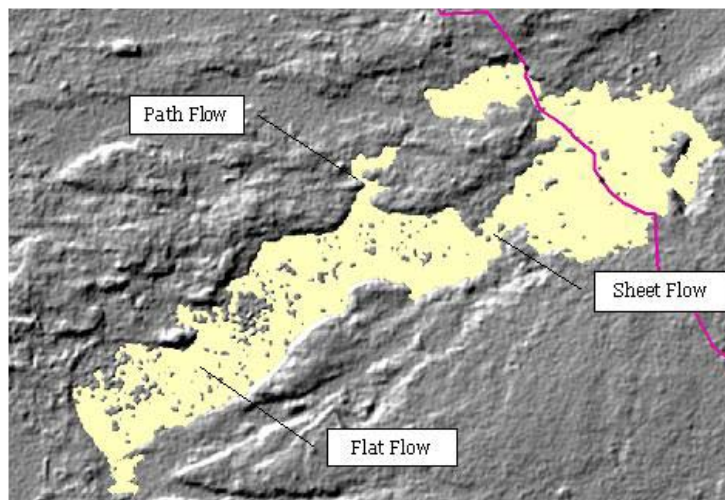


Figure 2: Terrain Dependant Flow Types

downhill path. It occurs over severe or constraining terrain. Sheet flow occurs over terrain that has mild to moderate slope with the flow spreading out proportionally to the slope. Flat flow occurs where the terrain is virtually flat and will tend to spread out in concentric circles.

Surface Flow Resistance Factors and Soil Properties

Surface flow resistance factors act as barriers to flow over the ground surface and are used to account for changes over the landscape in things such as vegetation, anthropogenic features, and hydrography. In the context of overland flow, modeling soil properties related to soil absorption must be included. Differing soil permeability rates leads to varying amounts of liquid absorption and directly affects the spill volume retained in the soil.

Fluid Properties

Density, viscosity, and vapor pressure are all key factor to making modeling results converge towards realism. Viscosity and density account for motion and mass properties of the liquid whereas vapor pressure is important for inclusion in the model when product evaporation is an applicable consideration. By way of example, crude oil is denser and has a higher viscosity than water, therefore it will travel less distance overland than water in the same amount of time.

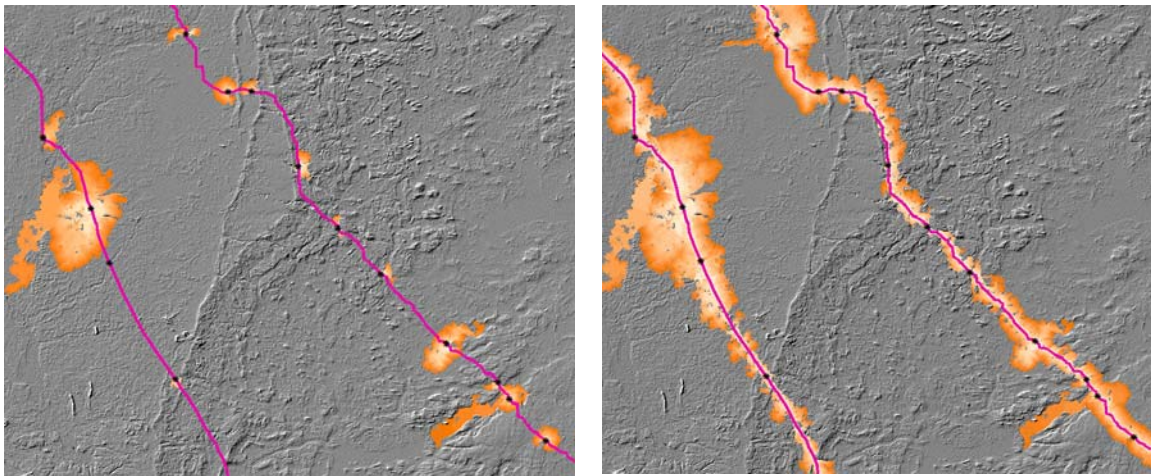


Figure 3: A comprehensive model output. The right represents point flow and the left represents linear flow from a pipeline centerline.

INDUSTRY RESPONSE

Modeling Approach #1

This approach computes downward flow by inspecting a three-by-three cell window to determine the center cells next movement (Figure 4). The steepest downslope neighbor determines flow direction from cell to cell. In this method, flow only occurs if elevation is downhill from the last cell. Any elevation changes causing impedance to flow cause the algorithm to terminate. Examples of elevation impedances include plateaus and pits (or sinks). Separate flow paths can accumulate into a single cell from several upslope cells, but only one flow path can exit this cell. This model can display convergence in valley bottoms, but not divergence in peaks and ridges. (Gallant and Wilson, 2000)

16	20	22
22	23	14
13	17	14

Figure 4: Cell Neighborhood Representation of Flow Direction

Elevation surfaces are susceptible to data pits due to compilation techniques. If this model encounters pits (or sinks) then execution of the model will terminate because there is no further downhill path. In practice these pits can be solved partially for by filling sinks, however, this process alters the digital elevation model through an iterative process and can introduce additional elevation artifacts.

Referring to the comprehensive model components, the Digital Elevation Model is the key input parameter in this model (Figure 5). The only other input used in this algorithm, which is mandatory in every flow model, is the source location as points or lines.

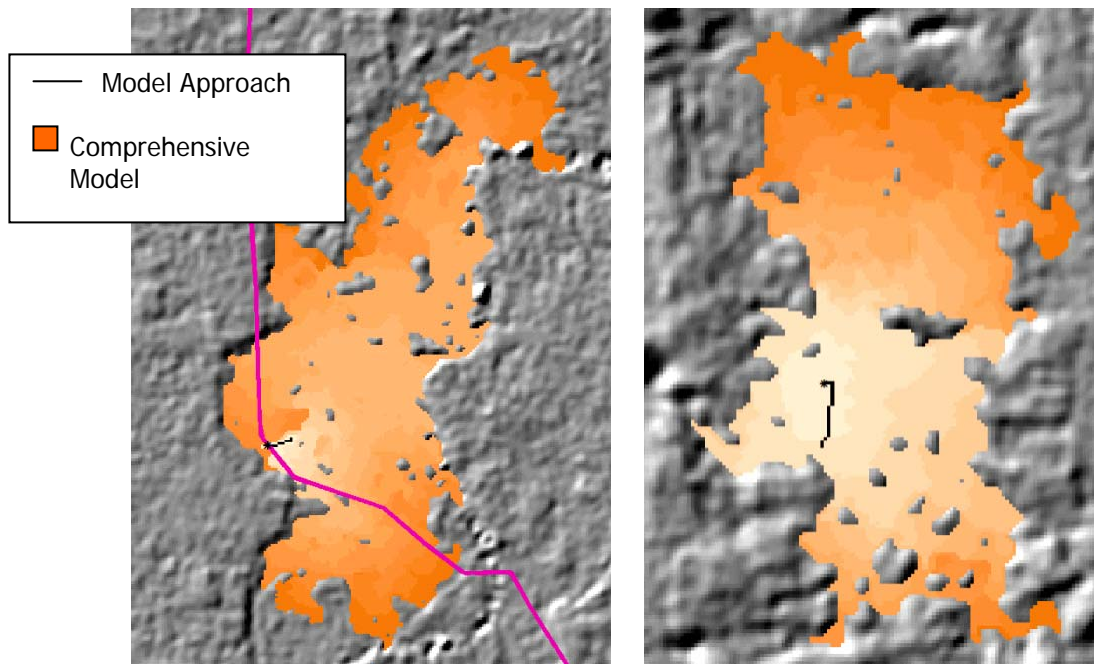


Figure 5: Model #1 Approach compared to a Comprehensive Model Approach

Modeling Approach#2

This method is a combination of vector and raster analysis. It uses raster elevation data to identify locations having elevations lower than the spill source and flags these sites as potentially affected areas. Spills are then permitted to “flow” from the source to the flagged sites using distance and volume as the spill constraints. This approach is less like an overland flow model and more like a simplified spill tracking methodology.

Even though implementation of this model uses vector and raster data, when compared with the components included in the comprehensive model there are many similarities in the inputs. However, the components in this model are captured mostly as assumptions rather than as data sets. For example, ground absorption is governed by soil properties and is applied in a comprehensive model through categorical raster dataset that varies over the study area in accordance with soil variation. However, in this approach, absorption is merely a single value input for the entire analysis.

Modeling Approach #3

This final modeling approach is one that closely resembles the comprehensive model both in terms of implementation and data inputs. One of the important similarities is the ability of this approach to account for flow types thus making the output from this model much the same as that of the comprehensive model; a natural appearance of a liquid overland flow.

Conceptually, this model accounts for instances where a spill may collect or “pool” so that in instances where pits (or sinks) are encountered the algorithm continues to fill the pit until the pool elevation is equal that of its neighborhood. Once this elevation is attained then the pool will spill over the edges of the pit and the overland flow model continues processing as it did before the encountering the pit. As discussed earlier, pits are inherent to digital elevation models and, in most cases, are errors in the dataset. Although the pooling model is valid, its sophistication should not be used to overcome fundamental data errors.

Logistically this model accounts for Fluid Properties, Digital Elevation Model, and time in the same way as the comprehensive model. The major difference between the two models is that the comprehensive model includes surface flow resistance factors.

SUMMARY

Our world is multi-faceted and quite complex and in creating realistic models some level of simplification is necessary. With such extreme consequences of oil leaks or spills, it is imperative that the overland flow model be realistic as well as correct. A comprehensive model is based on methods for establishing realistic resistance to flow over the ground surface, uses proven algorithms to create continuous surfaces of fluid flow while accounting for variations in surface cover, slope, fluid properties, and other inputs. A comprehensive overland flow model should be an integral part of any operator’s integrity management plan.

REFERENCES

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