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DEM simulation of petroleum flux extension and diffusion due to pipeline ruptures in Mexico

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Abstract: Many accidental pipeline ruptures frequently occur in the study region located in the state of Veracruz (Mexico). In relation to the volume involved, the diffusion and extension of the petroleum flux affect this region. For this reason it is necessary to study the eventual extension of the flux when such an event occurs. A high resolution Digital Elevation Model (DEM) is used as a simulation for evaluating the diffusion-propagation of petroleum flux of the Mexican brand in order to assess its consequence at a regional scale.

The DEM is generated by an algorithm introduced by Parrot and Ochoa-Tejeda (2005) which is based on a multi-directional interpolation applied to each point located in a hypsometric slice comprised between two successive contour lines. The decimetre vertical resolution partly eliminates artefacts introducing local breaks in the drainage network. Therefore using contour lines of 20 m interval, a 10 m resolution DEM with a 1/10 m vertical resolution is obtained. In the present case, the motion of oil with thickness is related to viscosity depending on the hypsometric value of the neighboring pixels in such a way that extension is able to invade the region around the pipeline rupture.

The procedure consists in applying to the DEM the following algorithm. From the starting point that corresponds to the localization of the pipeline rupture (blue point in the figure 1), the motion of the petroleum flux which thickness is related to the viscosity depends on the hypsometric value of the neighboring pixels. At each step, pixels that fulfill the requirements are considered as new starting points. The expansion of the petroleum flux depends on possible displacements in an isotropic environment. In such a way that the extension, contrariwise in a simple flooding process, is able to invade the region downstream and upstream as it can be observed in figure 1. Figure 2 illustrates the progression of the pixel filling. Two neighboring pixels (code 2) are filled by the flux. Four neighboring pixels (code 3) are related to the first code 2. The second code 2 gives rise to a unique connection (code 4). Following this procedure, the algorithm takes into account the first code 3 and so on.

The result of the simulation is validated according the observation on the field of a real expansion of to petroleum flux provided by a pipeline rupture. Analysis of the results is focused in two testing cases (Figures 3 and 4). The first one is aimed to show how propagate the petroleum flux into the depression and thereafter to escape following the downstream valley. It is taking account of the viscosity of oil, the soil permeability and the localization of the rupture point. The second one is an alternative way to petroleum flux reaching the sea shore. The simulation corresponds to dry season in a sandy zone so as a high percentage of oil is absorbed.

Discussions and comparison between simulations are based on the field of a real expansion of petroleum flux provided by a pipeline rupture. The results of the simulation are validated according to the example cited above. In all cases the thickness of the Mexican brand is evaluated on a flat surface supposed to be equal to 20 cm. It is also supposed the approximation of the expression of petroleum in an isotropic environment and the soil map is not sufficiently precise to really take into account the porosity rate as a consistent parameter. On the other hand, it is possible to simulate the phenomenon at a regional scale, assuming that all points drawing the pipeline can be affected by such a catastrophic event. The resulting maps can indicate at a regional scale all the zones that are concerned by the phenomenon in relation to the total volume of brand mobilized.

Keywords: *DEM simulation, petroleum flux extension, accidental pipeline rupture, Mexico*

1. INTRODUCTION

In petroleum fields, such as the oil district located in the state of Veracruz (Mexico), accidental pipeline ruptures frequently occur in relation with the bad condition of the pipeline network. This region is regularly affected by such events and the extension of the oil flow released by the pipeline ruptures can cover broad zones according to the volume of crude oil concerned by the incident. Independently that it would be appropriate to improve the state of the pipeline network, it is important to estimate with precision the extension of the zones that can be affected by such a phenomenon in order to define the means necessary for the timely intervention of the emergency power units. For this reason a high resolution Digital Elevation Model (DEM) is used to simulate and quantify the dispersion of the petroleum flux taking into account the viscosity of the Mexican brand and the soil permeability and to estimate the regional consequence of such an incident.

A new algorithm, partly based on different proposed methods used to extract a drainage network from a DEM, has been developed. Generally these procedures use different approaches: scanning the DEM profiles, modeling the stream, searching the maximum of curvature (Peet and Sahota, 1985; Besl and Jain, 1986), using the flux accumulation calculation or the threshold contributing-area method (Jenson and Domingue, 1988). In the present case, the motion of the petroleum flux, whose thickness is related to the viscosity, depends on the hypsometric value of the neighboring pixels. At each step, pixels fulfilling the requirements are considered as new starting points. The expansion of the petroleum flux depends on possible displacements in an isotropic environment. The extension, contrariwise a simple flooding process, is able to invade the region downstream and upstream as it can be observed in figure 1. The blue point in figure represents the localization of the pipeline rupture. On the other hand, the treatment takes into account the local porosity at each point invaded by the petroleum flux, in order to estimate the quantity of oil that can be absorbed by the soil.

Porosity determines the storage capacity, while permeability indicates the fluid flow capacity of rock, and saturation reflects the porosity occupied by the fluid which infiltrates in the rock. In order to use these parameters, a detailed soil map is required, indicating the porosity rate of each formation.

In the case considered, the soil map is not sufficiently precise to really take into account the porosity rate as a consistent parameter. On the other hand, when the soil is completely saturated, oil infiltration does not occur and the behavior of the flux displacement does not depend on the porosity. After a raining period, the extension of the petroleum flux is then more important than during the dry season.

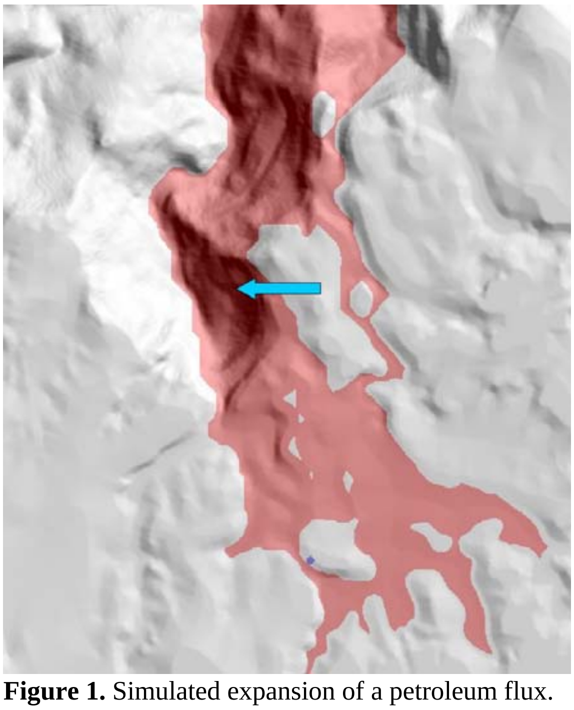

Figure 1. Simulated expansion of a petroleum flux.

2. METHOD

At the present, possibility of storage and advances in computing technology allow using with more precision the square-grid digital elevation models (DEMs). The horizontal and vertical resolutions are sufficient enough to calculate, in an accurate way, different parameters extracted from the DEM surface. The digital terrain analysis (Wilson and Gallant, 2000) allows defining primary attributes such as slope, aspect, plan and profile curvature, and secondary attributes more devoted to estimate the role played by topography in the distribution of soil water or on the susceptibility of landscapes to erosion, for instance.

A 10 m resolution DEM with a decimetre vertical resolution was produced by a multidirectional interpolation (Parrot and Ochoa-Tejeda, 2005), taking into account contour lines of 20 meters interval. The algorithm is based on a multi-directional interpolation applied to each point located in a hypsometric slice comprised between two successive contour lines. Even if this high resolution DEM presents some artefacts inherent to the type of interpolation (that overestimates the number of pixels describing the contour lines), the decimetre vertical resolution partly eliminates artefacts introducing local breaks in the drainage network. In fact, the developed algorithm is able to overcome this handicap: the low zones encountered locally are filled until the level required, and the petroleum flux is able to follow its progression.

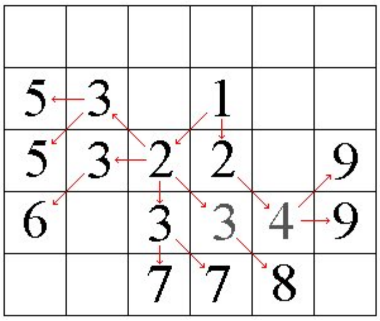

Figure 2. Progressive filling from a starting point (value 1).

The main lines of the algorithm are as follows. Figure 2 illustrates the progression of the pixel filling. Two neighboring pixels (code 2) are filled by the flux. Four neighboring pixels (code 3) are related to the first code 2. The second code 2 gives rise to a unique connection (code 4). Following this procedure, the algorithm takes into account the first code 3 and so on. The calculation is successively applied to each pixel taking into account the recoding order.

The passage of a pixel to its neighbors depends on the altitude of this pixel (Ap) to which the thickness of the flow (Tf) is added. When the altitude of a neighbor pixel is higher than Ap + Tf, oil flow cannot reach this pixel. If the altitude of the neighbor pixel is lower than Ap + Tf but higher than the initial altitude Ap of the pixel source, the layer of oil on the neighbor pixel will be less than the thickness fixed according to the oil viscosity, and will depend on the difference between Ap + Tf and the altitude An of the neighbor pixel. In the last case (An < Ap +Tf and An < Ap), the neighbor pixel will play the role of a source pixel according to its code and its range in the group of pixels, if there are more than one pixel with the same code value (see figure 2).

This procedure is moderately dependent on the drainage network that plays a minor role when defining the path of the petroleum flux. As illustrated in figure 1, oil runs off the eastern side of the valley and does not follow the drainage network (see arrow). On the other hand, when an endoreic zone is encountered, the algorithm searches the minimum altitude of the flux in this zone in order to fill it. Then a new starting point is defined taking into account the minimum distance between this point and the former starting point and the process restarts mobilizing the remaining volume. The process stops when the initial volume of the petroleum that escaped from the pipeline is null.

3. APPLICATION

Figure 3 corresponds to the studied zone. The altitude is comprised between 0 and 327 meters; the pipeline network is also reported on this map. Analysis of the results is focused in two testing cases (Figures 3 and 4). The first one is aimed to show how the petroleum flux propagates into the depression and thereafter to escape following the downstream valley. It is taking account of the viscosity of oil, the soil permeability and the localization of the rupture point. The second one is an alternative way to petroleum flux reaching the sea shore. The simulation corresponds to dry season in a sandy zone, so as a high percentage of oil is absorbed. The pipeline breaking point is underlined by the diagonal arrow reported in figure 4.

Discussions and comparison between simulations are based on the field of a real expansion of petroleum flux provided by a pipeline rupture. The results of the simulation were validated according to the example cited above. In all cases, the thickness of the Mexican brand was evaluated on a flat surface supposed to be equal to 20 cm. It was also assumed the approximation of the expression of petroleum in an isotropic environment; the soil map is not sufficiently precise to really take into account the porosity rate as a consistent parameter.

The thickness of the petroleum flux depends on the viscosity of the Mexican brand. A thickness of 20 centimetres was defined, but other estimations consider that this thickness can be only equal to 5 centimetres. The simulations operated here took into account these two different estimations. Assuming that 2 millions of m3 escaped from this point, the contaminated surface would be equal to 9.326 km2. One can notice that the depression zone located northwards the rupture point is totally invaded by the flux and corresponds to a surface of 8.725 km2 that needs 1 629 000 m3 for be spoiled. In this zone the thickness of the petroleum flux is comprised between 10 and 20 centimeters. No infiltration occurred as the bottom of this old lake is mainly composed of montmorillonite clays. Thickness of 2.50 meters can be locally observed in the exit valley (see figure 5).

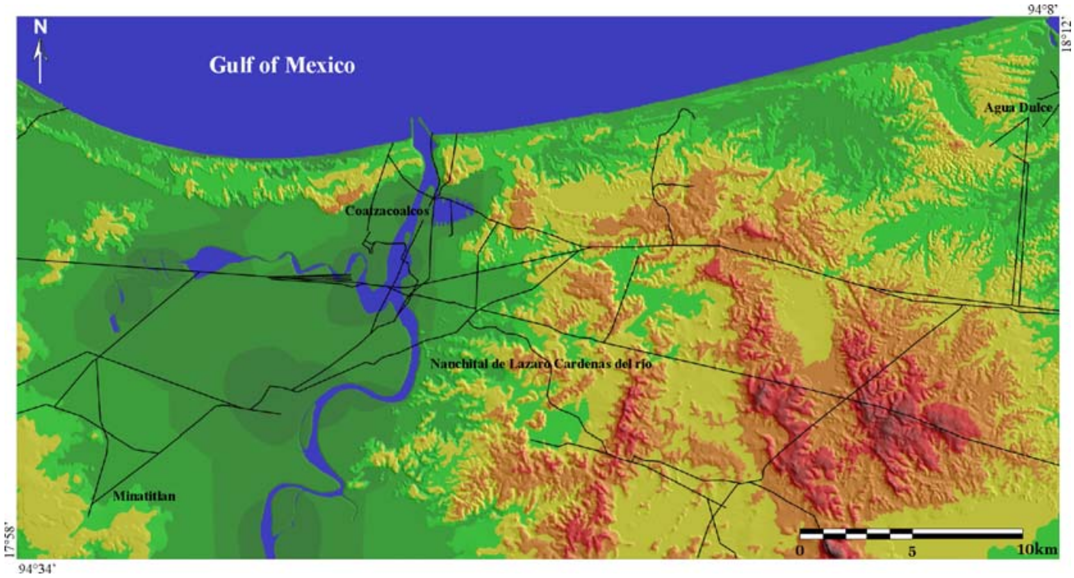

Figure 3. Pipeline network reported on the DEM of the studied region

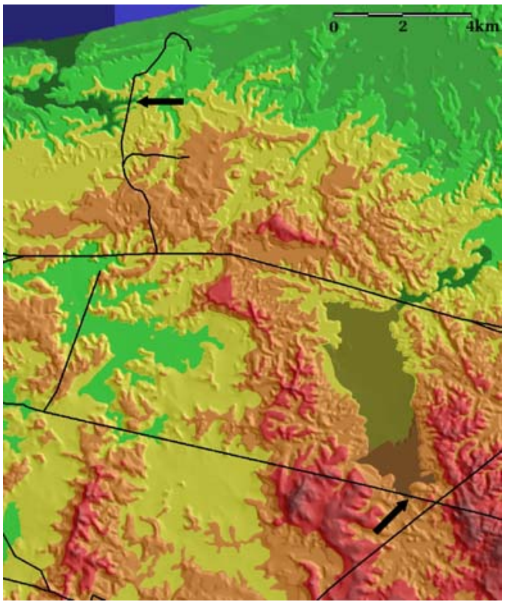

Figure 4. Localisation of the two examples and extension of the disaster areas.

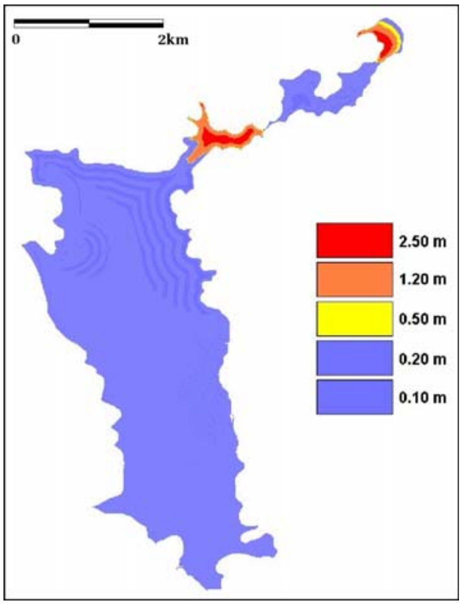

Figure 5. Thickness of the petroleum flux in the affected zone.

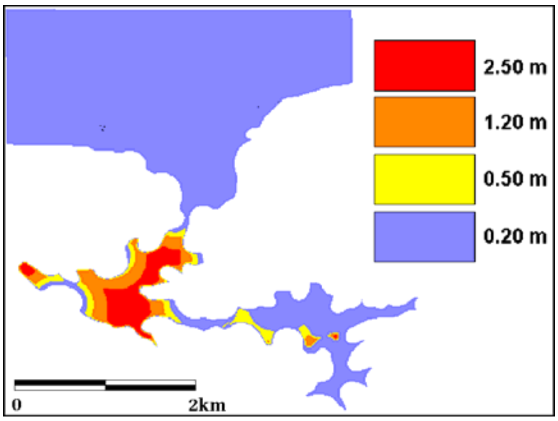

Figure 6. Thickness of the petroleum flux in the case of the second example.

The same volume of oil is mobilized by the second event. The starting point is located in the NE part of the study zone. The pipeline breaking point is marked by a horizontal arrow in figure 4. In this case the petroleum flux reached the sea shore filling the valley until reaching the beach. It is interesting to notice that the surface of the contaminated region is only equal to 5.4 km^2 as the flux crosses a region essentially formed by sand and gravels where the infiltration is relatively high. On the other hand, thickness of more than 3.3 m can be observed in the valley (see figure 6). In this last example, when assuming that the initial thickness is equal to 5 cm, 600 000 m3 are enough to reach the sea shore.

The surface of the contaminated zone is more or less equal to the difference, depending only on the level reached by the flux in the valley and the gullies. The definition of the thickness depends on precise relationships between this parameter and the viscosity of the material. Nevertheless, it is possible to simulate the diffusion and extension of the petroleum flux affecting this region by means of a high resolution DEM.

4. CONCLUSION

One can assess in an accurate way the diffusion and extension of a petroleum flux. This is particularly important in a region where many accidental pipeline ruptures frequently occur due to the bad condition of the pipeline network. The algorithm presented here has been developed with such a goal. The significance of the result depends on the high resolution DEM quality and moreover on its vertical dynamic scale.

In the present case, the vertical resolution corresponds to a decimetre resolution, sufficient enough to follow the extension of a petroleum flux that has a thickness of at least 5 centimetres.

In forthcoming investigations concerning this problem, it is envisaged to extend these treatments to the whole area by successively simulating a rupture in each point of the pipeline network in order to obtain the map of all the regions which are prone to be affected by these events.

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