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Fast prediction of the evolution of oil penetration into the soil immediately after an accidental spillage for rapid-response purposes

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Accidents involving spillages of oil onto the ground surface have the potential to create serious problems in terms of both soil and groundwater contamination. If appropriate emergency actions can be taken immediately after the spillage occurs, then any potential damage and future remediation costs can be limited. Estimation of the approximate time at which the oil will reach the groundwater is very important for emergency response.
In this paper, we present a rapid, simplified technique for predicting the evolution of oil penetration into soil after an accidental spillage onto the ground. In particular, the proposed model is suitable for calculating the maximum potential penetration depth, both in the period immediately after the spill, and over the subsequent few hours. In the method, surface spreading, surface evaporation and seepage mechanisms of the spilt oil are taken into consideration. The method could be used as a decision support tool by emergency services, helping to determine the most appropriate response for individual incidents. An example of an application is presented and the influence of various environmental and geological parameters is discussed.

1. Introduction

In recent years there has been an increasing number of accidents involving oil spillage on land and this is becoming one of the most significant management problems for the emergency services. Accidents include fuel spillages (diesel, gasoline, jet fuels, home heating oils, etc.) from road or rail tanker transport.
In order to estimate the evolving disposition of spilt oil it is important to have sufficiently accurate estimates of the rate of pool spreading over the ground surface, the rate of penetration into the soil and the time at which the oil might reach the water table. For many spills there is a 'window of opportunity' within which prompt and effective actions will minimise soil contamination and avoid groundwater contamination.
The extent of this window of opportunity after a spillage is often very short, hence it is likely that only very basic information about the accident location and the release scenario will be available to emergency teams. In situations where it is possible to prevent groundwater contamination after an oil spillage on land, it is important to take early, appropriate actions. An initial estimate of the extent of the sub-surface contamination (area and depth) is, therefore, of great importance when taking any

decisions on emergency action. Emergency response teams and planners would benefit from a rapid method of predictive estimation that can support the decision making and the choice of any necessary preventative measures. Useful estimation methods must be operable even with very limited initial information, but must allow users to construct a sufficiently accurate representation of the local situation, taking into account factors related to environmental conditions (wind, temperature, soil moisture, permeability of soil, topography of site, etc.) to ensure the selection of appropriate actions.

2. The problem of oil spillage onto ground

The problem of soil and groundwater contamination from oils has been largely studied from the point of view of restoration – in particular, the US-EPA (USA) the ASTM (USA) and APAT (I) have developed many tools for evaluation and to support decision making in the medium or longer term after spillage or leakage.

Many studies have been completed for petroleum hydrocarbon mixtures in soils, but in the majority of cases the source has been from leaking underground storage tanks, which produce relatively small and continuous sources. Important studies on the protection of groundwater from oil pollution were documented for the CONCAWE programme (CONCAWE, 1979). Numerous models for contaminant distribution are currently available: there are examples for long-term surveys and for site specific cases. Such models tend to require good access to data and are typically so complex that they do not fit well in situations with scarcity of input data, and with the requirement of simplicity and rapid response times which apply in the immediate management of accidents.

There are a few models which have been developed for use by rescue services and which focus on large accidental spills that occur on land. In 2003 Pacific Northwest National Laboratory (PNNL-USA) completed a specific review on the status of models for land surface spills of non aqueous liquids (Simmons and Keller, 2003) and no rapid predictive tools were found. S.Halmemies et al. (2003) made laboratory experiments to determine both seepage velocities and short term oil retention capacities of different soil types. The Swedish rescue services developed very basic tools for the assessment of chemical spillages on land and implemented them in a graphical information system (RIB, 2004).

These projects, together with other recent work on evaporation of oils (Fingas, 2004) and on predicting the surface spreading of oil spilled on ground (Grimaz et al., 2007), have allowed us to define a simplified predictive method. The research presented in this paper was carried out as part of a joint research project between the University of Udine (I) and the Queen's University of Belfast (UK) and was financed by the Friuli Venezia Giulia Region, Italy (Progetto D4). Only part of the study is presented here.

3. Simplified method for prediction of the window of opportunity

Oil spills on a permeable soil surface undergo three main processes that control the extent of the spill and the subsequent environmental impacts. These processes are surface flow, infiltration and evaporation.

The pool area can sometimes be directly measured on site after an accident. In order to predict the extent of pool spreading after accidental spillage, Grimaz et al. (2007) proposed a simplified predictive formulae derived from gravity current theory.
Infiltration of spilled oil is an important mechanism by which hazardous hydrocarbons may pollute the groundwater. Most oils act as non-aqueous phase liquids (NAPLs) and their migration in the vadose zone is influenced by the interaction between the three immiscible fluids: air, water and oil. Oil migration in porous media has been the focus of numerous studies. The governing equations for oil infiltration to the vadose zone are nonlinear and coupled with equations describing the flow of water and air. However, for the scope of this work, if we accept that the advective transport process represents the dominant process of infiltration and that the air phase can be assumed to be inactive, the use of greatly simplified equations becomes possible.
Another process operating on the spilt oil is evaporation. Here we use the term oil to encompass a wide range of liquid chemicals that consist of a mixture of different compounds, some of which may be volatile. Both the chemical composition of the oil and the environmental conditions control evaporation of the oil. In a recent study Fingas (2004) shows that oil evaporation is not strictly air boundary layer regulated. This means that a much simplified evaporation equation suffices to describe the process. Estimating the evaporation rate does not require consideration of wind velocity, turbulence level, surface area, thickness or size scale. The only factors important for evaporation are time and temperature. The equation parameters required for an approximate estimation of the evaporation of oils can be derived from readily available distillation data for the appropriate grade of oil.
The model relies on the acceptability of the following assumptions for the short period immediately following a spill:

a) evaporation occurs only from the surface pool until the oil infiltrates into the soil;
b) oil viscosity and density remain constant in the period of interest;
c) advective processes are dominant in infiltration;
d) Darcy's law is acceptable to define the rate of penetration into the soil.

The model assumes the soil is homogeneous and has isotropic hydrogeological characteristics and requires, as input data, the depth of the groundwater table at the site of the accident.

3.1 Extent of pool area

The extent of pool area is the most important parameter for the evaluation. Many of the other parameters depend on the pool size. If an accident has already occurred, it may be possible to make measurements on site. If a prediction is needed, then the formulae proposed by Grimaz et al. (2007) may be used. In particular, for typical scenarios in cases of transport accidents, the following equations (1 and 2) can be used to estimate the area of the pool of oil on flat ground.
For accidents involving a point source (i.e. a hole) with an average constant flow rate of spillage during a finite time:

$$A_{pool} \cong 1.7715 \frac{q \upsilon_{oil}}{g k_i k_{r,NAPL}} \tag{1}$$

for accidents with catastrophic rupture of container or tanks and instantaneous release of oil onto the ground:

$$A_{pool} \cong 2.3782 \frac{Q^{4/5}}{(k_i k_{r,NAPL})^{1/5}} \tag{2}$$

where:
A_{pool} is the area of the pool of oil on the surface [m^2]
q is the flow rate of oil spillage [m^3s^{-1}]
Q is the total amount of oil spilt [m^3]
υ_{oil} is the kinematic viscosity of oil [m^2s^{-1}]
g is the gravitational acceleration [ms^{-2}]
k_i is the intrinsic permeability of soil [m^2]
$k_{r,NAPL}$ is the relative permeability of oil (NAPL) [-]

The values of $k_{r,\ NAPL}$, depending from different grades of water saturation of soil, are shown in Table 1.

Table1 - Relative permeability $k_{r,\ NAPL}$ for different scenarios of accidental spillage

Soil situation	$k_{r,\ NAPL}$
dry - *long time without rainfall in warm regions and in hot seasons*	1.0
slightly wet - *long time without rainfall in other regions or seasons*	0.9
very wet - *from 2 hours to 2 days after strong rainfall*	0.3
completely saturated - *during strong rainfall with ponds on surface*	0.0

3.2 Evaporation

To estimate the volume evaporated from the pool it is necessary to define the time t_{ep} during which the pool remains on the surface. For the case of a pool on a permeable medium it can be considered equal to the time of complete infiltration of the oil into the porous medium.
The time t_{ep} can be estimated using Eq (3) which considers a theoretical depth of oil pool and the oil seepage velocity at complete saturation, using Darcy's law.

$$t_{ep} = \frac{h_{tp}}{v_{p,s}} = \frac{V_{spill}}{A_{pool}} \frac{\vartheta_e}{k_{r,NAPL} K} \frac{\upsilon_{oil}}{\upsilon_w} \tag{3}$$

where the symbols not defined earlier are:
t_{ep} is the estimated duration of the oil pool on the surface [s]
h_{tp} is the depth of the oil pool [m]
$v_{p,s}$ is the velocity of penetration of the oil into soil in oil saturated conditions [ms^{-1}]
V_{spill} is the volume of oil spilt [m^3]
K is the hydraulic conductivity [ms^{-1}]
ϑ_e is the porosity of soil [-]
υ_w is the kinematic viscosity for water [m^2s^{-1}]

Then, in order to estimate the percentage of oil evaporated from the pool in t_{ep} the simplest equations proposed by Fingas (2004) can be used. In particular, Fingas proposed the following equations, for different groups of oils.

For oils belong to group A (for example: gasoline, Jet fuel JP-8 and kerosene):

$$\%E_{groupA} = [0.165(\%D_{180}) + 0.045(T - 15)]\ln(t) \tag{4}$$

for oils belong to group B (for example: diesel):

$$\%E_{groupB} = [0.0254(\%D_{180}) + 0.01(T - 15)]\sqrt{t} \tag{5}$$

where
$\%E$ is the percentage (by weight) of oil evaporated
$\%D_{180}$ is the percentage of oil distilled at 180°C
T is the environmental temperature [°C]
t is the time of evaporation [minutes]

If it is acceptable to assume that the oil density remains constant during the initial period after the spill, the volume evaporated can be estimated using the following equation:

$$V_E = \%E_{oil,t_{ep}} \cdot V_{spill} \tag{6}$$

where
V_E is the volume of oil evaporated [m^3]
$\%E_{oil,tep}$ is the percentage calculated using Eq. (4) or (5) at t_{ep} for oils of group A or B
t_{ep} is the time calculated using Eq. (3)
V_{spill} is the volume of oil spilt [m^3]

3.3 Penetration into vadose zone
The spilt oil will not only tend to spread out over the surface of the soil and evaporate, but will also penetrate into the ground (unless it is impermeable).
This downward penetration may be arrested in three ways:
- the threshold of residual saturation has not been reached;
- an impermeable layer in the path of the oil is reached;
- the water table is reached.

Residual saturation may be defined as the minimum saturation which a fluid has to attain in order to move in a porous medium (or alternatively the threshold below which it is no longer able to move). It is a non-dimensional parameter and can be expressed as retention capacity, R. Typical values of R for different types of soils are presented in Table 2.
The maximum depth of penetration of the NAPL in the unsaturated or vadose zone can be estimated using Eq.(7) (CONCAWE, 1979):

$$D_{MP} = \frac{V_{spill} - V_E}{A_{pool} R \xi} \tag{7}$$

where the symbols not defined earlier are:

D_{MP} is the maximum depth of penetration of NAPL into the unsaturated zone [m]
R is the retention capacity [-], from Table 2
ξ is a parameter that depends of the viscosity of the fluid [-], from Table 3.

Table 2 - Retention capacity coefficient R for different types of soils (after CONCAWE, 1979)

Soil typology	Retention capacity – R ($m^3_{NAPL}\ m^{-3}_{soil}$)
Stone - Coarse gravel	5×10^{-3}
Gravel - Coarse sand	8×10^{-3}
Coarse sand - Medium sand	15×10^{-3}
Medium sand - Fine sand	25×10^{-3}
Fine sand - Silt	40×10^{-3}

Table 3 - Parameter ξ for different types of fluids (after CONCAWE, 1979)

Fluid	ξ parameter
Low viscosity (e.g. gasoline, petrol)	0.5
Medium viscosity (e.g. kerosene, gasoil, paraffin and diesel)	1.0
High viscosity (e.g. light fuel oils)	2.0

If D_{MP} is greater than the depth of the groundwater table (more precisely, the depth of the capillary fringe, D_{CF}, which is the groundwater depth, D_{GW}, minus the capillary rise, H_{CR}) then the groundwater may become contaminated. It may be useful to estimate the length of time between the occurrence of the spill and penetration of the oil to the groundwater. This gives a 'window of opportunity' for action to prevent the groundwater contamination.
We can make an estimate using Darcy's velocity of penetration, taking into account the reduced section in which the flow can occur due to the retention effect.
In particular, the arrival time of the NAPL at the target depth, t_{AT}, can be calculated as:

$$t_{AT} = \frac{D_{TG}}{v_{p,un}} = \frac{D_{TG}}{\frac{k_{r,NAPL} K}{\vartheta_e - R} \frac{\upsilon_w}{\upsilon_{oil}}} \tag{8}$$

where the additional symbols not defined earlier are:
t_{AT} is the arrival time of the NAPL at the target level [s]
D_{TG} is the depth of target level [m]
$v_{p,un}$ is the velocity of penetration of the oil into unsaturated zone [m s^{-1}]

If $D_{MP}<D_{CF}$ then oil does not reach the capillary fringe. In this case, water pollution occurs only indirectly; by dissolution of soluble components of the oil from the contaminated soil layer when water permeates through the upper contaminated zone and subsequently down to the water table. The window of opportunity in this case will be different. Water velocity and retardation factor must be taken into consideration in the calculation.

4. Application to a real case of accidental oil spillage onto ground

In the summer of 2004 in Idaho State (US) a tank truck overturned and a large quantity of jet fuel (JP-8) spilt onto soil beside the roadway where the accident occurred.
This accident was studied by researchers from the PNNL (Keller et al, 2005). They observed an area of the wetted soil beside the road of about 153.3 m^2. The ground was flat and sandy with a porosity of 0.3 and a permeability of 1×10^{-6} cm^2. The spillage duration was estimated to be about 123 s with an average flow rate of 61.54 l/s for a total of 7570 litres of JP-8 (2000 US gal) spilt. The viscosity of JP-8 jet fuel is 2.05 cP, and the density is 0.84 kg/l. Therefore, JP-8 will have a lower conductivity than water, with JP-8's saturated liquid conductivity in this sand being about 0.04 cm/s. The percentage of JP-8 that distills at 180°C, $\%D_{180,}$ is about 15%.
The simplified model has been applied to this scenario for the estimation of the window of opportunity for the emergency services. Groundwater depth was assumed to be 3 m and the capilliary rise about 40 cm. The results of cases with different water saturation conditions of soil and environmental temperature at the time of the accident were compared. The results and comparasons are shown in Figure 1.

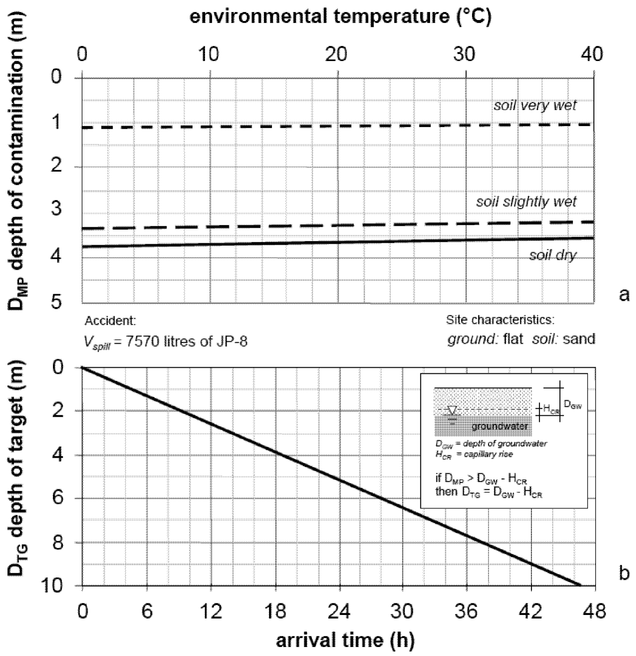

Figure 1 – (a) maximum depth of oil penetration into the soil for different scenarios (b) time of arrive at depth of target

Considering a depth target of 2.60 m, the window of opportunity for the emergency service to act to prevent groundwater contamination is just over 12 hours. In the case of soil completely saturated with water (after heavy, pounding rainfall) the area of surface spreading is larger and the depth of contamination is smaller. The penetration depth remains above the capillary fringe. In this case, groundwater contamination could occur by dissolution of soluble compounds and the retardation factor R_{dp} must be considered (a typical factor for benzene is R_{dp} = 1.5). The arrival time of infiltrating water at the target depth is about 9 h and 10 min. Therefore, considering the retardation factor and assuming that water infiltration continues during all that period of time, the window of opportunity results in about 13 hours and 40 minutes from the start of water infiltration.

5. Conclusions

The model presented here permits a fast prediction of the evolution of the rate of oil penetration into soil and can be used to estimate a window of opportunity for emergency action. Computations can be made using basic algebraic methods, by spreadsheets or simple computer programs, without resorting to numerical methods. The approach taken here suggests some important considerations in terms of strategy. It demonstrates that the larger the area of pool, for the same volume spilt, the shallower is the zone of soil contaminated. It also shows which of the environmental conditions are more important in determining the degree of contamination in soil and groundwater. The more (water) saturated the soil, the larger is the surface pool and the smaller the depth of penetration of the oil into the ground. The larger the percentage of oil evaporated from the pool area the more limited is the volume of surface penetration by oil and the smaller is the depth of soil contaminated. Fingas' experiments show that time and temperature are the only important environmental factors in the oil evaporation process. Therefore, on hot days the potential penetration is smaller than in cold seasons or at night. Also, when evaporation rate is high, there is a risk of vapour concentration in air exceeding the minimum for flammability. The simplicity of the model presented here suggests the potential to incorporate the calculations into a GIS system and thereby to provide a useful tool for emergency planning purposes.

6. References

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