ABSTRACT: A coastal zone oil spill model (COZOIL) was developed to predict the behavior and fate of oil along an arbitrarily varying coastline. This paper describes algorithms for explicit computation of processes controlling behavior of oil in the intertidal zone. Selected sensitivity studies of these algorithms are presented and discussed.

The coastal zone oil spill model described here has been designed to simulate oil spill fates both before and after coastal contact. Multiple discrete batches of oil, or spillets, are used to represent the surface slick. A surface slick is represented by a series of circular spillets, which may become elliptical upon contact with the shoreline. The amount of onshore-offshore foreshortening is governed by a balance between wind stress and gravity spreading forces, and results in alongshore spreading of the spillet. Evaporated hydrocarbons are given no spatial representation, but are simply accumulated from all sources during the simulation. Entrained oil offshore is represented by discrete particles that are advected by the local currents. Inside the surf zone, entrained oil takes on a continuous representation, discretized by an along-shore grid cell. Transport in the surf zone is governed by a classical radiation stress formulation. Incorporation of water into surface oil (emulsification) is simulated offshore. Deemulsification (de-watering) is allowed to occur for oil that is on the foreshore or backshore.

Oil coming ashore may be deposited on the foreshore or the backshore, or carried into coastal lagoons, ponds, or fjords. Oil on the foreshore penetrates into the underlying sediments at a rate dependent on sediment grain size and oil viscosity. Oil may also be carried into the beach groundwater system by wave overwash. Reflotation of surface oil occurs during rising tides. These mass transfer pathways are shown schematically in Figure 1.

Model system overview

The COZOIL model can be conceptually divided into a set of initialization processes, followed by computational and output routines. The most complex portion of the initialization process is the establishment of the geophysical environment in which the simulation will take place. The second important part of the model initialization process centers on the specification of the environmental data used to drive

1. Development of COZOIL was funded primarily by the U.S. Department of the Interior, Minerals Management Service, Alaska Regional Office. William Benjey served as technical contract monitor. The authors are solely responsible for the content of this paper.
(2) Backshore width (m)
(3) Foreshore width (m)
(4) Offshore distance (m)
(5) Backshore slope (rise/run)
(6) Foreshore slope (rise/run)
(7) Offshore depth (m)
(8) Reach orientation (degrees).

The backshore extends from the berm to the dunes, cliffs, or first permanent onshore vegetation. The backshore extends from the berm to the dunes, cliffs, or first permanent onshore vegetation. Parameter 8, reach orientation, is measured in degrees clockwise from true north, standing at the beginning of the reach with water on the left. The offshore distance (parameter 4) and offshore depth (parameter 7) are used to determine the mean bathymetric slope for this reach. The model uses linear interpolation among the offshore depths specified for all reaches to create a discretized representation of the study area bathymetry.

For reach type 8, the model requests 6 parameters:
(1) Pond surface area (m$^2$)
(2) Breachway (entrance) width (m)
(3) Breachway (entrance) depth (m)
(4) Tidal range inside the pond (m)
(5) Fractional flashing value
(6) Freshwater inflow rate to pond (m$^3$/sec)

Flow into and out of coastal ponds and lagoons is computed by simple conservation of mass principles, assuming uniform velocities over the entrance cross section, and neglecting phase lags inside and outside the pond.

The model assumes a uniform wind field over the study area. Since study areas are generally expected to be small (such as 100 km alongshore and 1 to 20 km offshore), spatial variability in the wind field will in general be difficult to resolve from typically available data.

The user can direct the model to compute waves from the wind record, or to read in a wave time series from a prepared file. In either case, the inputs to the computational model are wave height (m), wave period (sec), and direction of propagation. These values are assumed by the model to apply at the offshore (open) boundaries. If the wind record, the model uses the shallow-water, wave-forecasting equations recommended by the U.S. Army Corps of Engineers Shore Protection Manual. The model uses the radiation stress theory of Longuet-Higgins as modified empirically by CERC. An oil slick that has contacted the shoreline may deposit oil on the foreshore if the water level does not exceed the foreshore height associated with that reach. First the model checks to determine that an empirical "holding thickness" has not been exceeded for the coastal cell in which contact has occurred. When the tide is falling, the ratio of the newly exposed beach face to the onshore-offshore radius of the slick determines the fraction of the slick that is deposited.

Oil deposited on a previously clean foreshore carries with it the characteristics of the parent slick: viscosity, density, and boiling point constituents. As additional oil comes ashore at the same location, perhaps from the same or another spill source, the onshore surface takes on the weighted average values of the above characteristics.

If the water height exceeds the input foreshore height, then a slick in contact with the shoreline will deposit oil on the backshore. As on the foreshore, the friction of the slick that is deposited is determined by the ratio of newly exposed backshore to slick width, and is again limited by a maximum holding thickness.

Oil fate concepts and algorithms

Offshore, outside the surf zone, COZOIL employs previously developed numerical concepts for oil spill fate simulation. Spreading of a surface slick is computed according to gravity-viscous formulation of Fay and Hoult, as modified by Mackay et al. Evaporation of hydrocarbons from a surface slick is computed using the methods of Payne et al. Entrainment and dissolution represent the only pathways for removal of mass from a surface slick outside the surf zone other than evaporation. The user has two options for oil entrainment algorithms. The first is that proposed by Audunson and modified by Spaulding et al.; the second alternative algorithm is that proposed by Mackay et al. (1980). The emulsification viscosity is allowed to increase for petroleum products according to a "mousse formation" algorithm, also from Mackay et al. Gasoline, kerosene, and light diesel fuel are assumed not to form emulsions with water. Subsurface oil is represented offshore by discrete particles entrained from surface slicks. The initial location of a particle is at a random location under the source slick. at a depth that is a function of wave height. Subsequent transport of the particle is by the superposition of interpolated horizontal velocities, plus random components in both the horizontal and the vertical. Spreading of surface slicks in the surf zone can occur in both along-shore and onshore-offshore directions. Transverse to the shoreline, compression of the slick occurs due to wind and wave/current forces on the slick, and impendance to forward motion by the shoreline. If the wind is offshore, the slick will be transported away from the coast.

Advection in the surf zone is assumed to be dominated by the wave-induced current in the water column, with wind effects superimposed for surface slicks. The model uses the radiation stress theory of Longuet-Higgins as modified empirically by CERC. An oil slick that has contacted the shoreline may deposit oil on the foreshore if the water level does not exceed the foreshore height associated with that reach. First the model checks to determine that an empirical "holding thickness" has not been exceeded for the coastal cell in which contact has occurred. When the tide is falling, the ratio of the newly exposed beach face to the onshore-offshore radius of the slick determines the fraction of the slick that is deposited.

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Oil deposited on the beach foreshore may enter the sediment/groundwater system in two ways, the first by direct penetration and the second by transport in wave overwash. The former process will be simulated using standard fluid-sediment flow algorithms. The second process assumes that waves breaking and overwashing oil on the foreshore will carry with them dissolved and particulate ('water-accommodated') oil. This water-accommodated oil is assumed to travel into the sediments with, and at the same rate as, the water itself. Once within the groundwater system, the transport of oil is assumed to be governed by flushing of the groundwater and equilibrium partitioning kinetics between the adsorbed and water-accommodated phases. Figure 3 shows the conceptual structure of the beach groundwater system used in COZOIL.

The flow of oil from a surface deposit into the underlying sediments is approximated by Darcy's law:

\[
v = \frac{kg\rho(dh/dL)}{\mu} \tag{1}
\]

Where:
- \(v\) = flow velocity (m/sec)
- \(k\) = intrinsic permeability of the sediment (m²)
- \(g\) = gravitational acceleration (m/sec²)
- \(\rho\) = fluid density (kg/m³)
- \(\mu\) = dynamic viscosity (N·sec/m²)
- \(dh/dL\) = pressure head gradient (m/m)

The intrinsic permeability is computed with an equation from Krimbein and Monk (1943):

\[
k = 7.6 \times 10^{-10} (MG)^{2.3} \tag{2}
\]

Where:
- \(MG\) = mean grain size (mm)
- \(\phi\) = inclusive graphic standard deviation (\(\phi\) units).

The actual mass removal rate is then \(dm/dt = \rho h A\). The mass removed from the oil on the foreshore surface by wave overwash is not all carried into the groundwater. Some fraction is carried back into the surf zone with the retreating wave. This oil in the surf zone then becomes further partitioned between the water column and the water surface, depending on the size range of the oil particles relative to the surf zone turbulence. Lacking empirical values for these partitioning coefficients, the model supplies a set of default values and allows the user to alter them if desired.

Oil that has penetrated the surface sediments via Equation 3 and remains above the mean water table (Figure 3) may be removed to the...
surf zone if the beach is subject to erosion by the present wave field. A basic assumption here is that the presence of the oil will not appreciably alter erodibility of the beach sediments. Following Sunamura and Horikawa, \[ G_Q = \frac{(H/Lo)(\tan\beta)^{2.7}}{(Da/Lo)^{0.67}} \] Beach erosion is assumed to occur for \( G_Q > 18 \), accretion for \( G_Q < 4 \), and equilibrium in between.

The COZOIL model incorporates a relatively simple representation of oil in the beach groundwater system, a representation that nonetheless reproduces the observed behavior relatively well. The oil is partitioned between two phases, one of which is trapped by the sediments (an “adsorbed” phase), and one that is transported with the groundwater (a “water-accommodated” phase). We assume an equilibrium partitioning between oil in the adsorbed and water-accommodated phases (e.g. Thibodeaux):

\[ \frac{C_w}{C_a} = K_p C_s F_c \]
The mass removed per tidal cycle is then

\[ F_{\text{w}} = S_r \cdot P \cdot C_{\text{w}} \]  

(7)

Where:  \( S_r \) and  \( P \) = the specific yield and porosity of the sediment.

Evaporation of the foreshore follows the same computational procedures as on the water surface. Surface oil entering coastal lagoons or deposited on the backshore evaporates at the mean rate for oil on the beach during each timestep. This approximate procedure conserves both computer storage and processing time, while retaining a realistic evaporation rate governed by the oil type spilled.

Oil on the beach face (foreshore surface) or on the backshore that has not penetrated the sediments may be refloated on a rising tide. As oil is refloated from the foreshore surface, it is combined with an existing spillet if one is present at that coastal location. In this case, the characteristics of the spillet become the mass-weighted characteristics of the spillet plus the newly refloated oil. If a spillet does not exist at the coastal cell where refloation is occurring, a new spillet may be formed.

Water that has become incorporated into oil during the process of emulsification may be released from oil-water mousse deposited on the beach face. The rate of release, or de-emulsification, depends on the stability of the mousse. Detailed investigations by Berridge et al.\(^2\) evaluated mousse formation and stability for several crude oils and five petroleum products. In general, the crude oils investigated formed relatively stable emulsions, whereas the refined products (such as diesel, kerosene, and gasoline) did not form emulsions at all. The set of characteristics governing emulsion stability appears to be sufficiently complex to warrant a separate study. Here we simply assume a first order process for the loss of water from stranded mousse:

\[ y = y_0 e^{-bt} \]  

(8)

Where:  \( y \) = fraction of water in oil at time  \( t \)  \( y_0 \) = initial fraction of water in oil  \( b \) = constant.

Sensitivity studies

**Spreading in the surf zone.** An equation for spreading/compression of oil slicks in the surf zone was developed as part of this project. The equation balances wind stress normal to the shoreline against the gravity/viscous spreading force to determine the rate of change of the onshore/offshore (minor) axis of the slick as a function of time. The longshore (major) axis increases according to the same rate equation used offshore. The dynamic behavior of the minor axis of a 100 m\(^3\) oil slick under the influence of various onshore wind speed is shown in Figure 4b. For these test cases, the slick was initiated with a thickness of 1 cm and a radius of about 56 m. A minor axis length of 1 m was also specified. At a wind speed of 1 m/sec, the time for the onshore/offshore axis to reach this limit is about an hour, versus about 15 minutes at 4 m/sec (Figure 4a). At 15 m/sec the time to reach a 1-m minor axis length is about 4 minutes. It should be noted that these tests are independent of any other processes in the model. The surf-zone wave field associated with 15 or 20 m/sec winds, for example, would rapidly entrain surface oil into the water column, so that consideration of foreshortening rates at these higher wind speeds becomes somewhat irrelevant.

**Penetration rates.** Penetration of oil into various sediment types is computed via Darcy’s law and an equation for intrinsic permeability as a function of grain size. Model tests were performed to demonstrate penetration rates as a function of sediment type and oil viscosity. Note that the penetration equations are being solved in these tests for an infinite sediment, neglecting the presence of groundwater, which is accounted for in the model. Figure 5a shows penetration depth as a function of time for a light diesel fuel in five sediment types. For comparison, data from a laboratory test of an equivalent viscosity oil in Canadian borrow pit sands\(^10\) is shown. The penetration rate for sand matches the data quite well. The rates for other sediments are qualitatively as expected relative to the rate for sand.

Figure 5b shows the penetration depths versus time for Prudhoe Bay crude, with a viscosity about three times that of light diesel. After 12 hours, the Prudhoe Bay crude has penetrated to a depth of 1 m versus about 3 m for the light diesel of Figure 5a. Weathered Prudhoe Bay crude, with a viscosity of 350 cp, or 10 times the viscosity of the

![Figure 7](http://example.com/figure7.png)

**Figure 7.** (a) Overall mass balance for Prudhoe Bay crude oil coming ashore on a sand beach (first 6 days) (b) Overall mass balance for Prudhoe Bay crude oil coming ashore on a sand beach (first 90 days) (c) Mass balance for oil associated with the coastal sediments of a sand beach (first 6 days) (d) Mass balance for oil associated with the coastal sediments of a sand beach (first 90 days)
These proportionalities are consistent with the fact that the penetration rate is inversely proportional to the viscosity.

Retention of oil in groundwater system. The retention of petroleum in the beach groundwater system is governed by Equations 5 to 7 described above. The partitioning coefficient $K_p$, is an unknown parameter in this formulation. A series of simulations was therefore performed to allow selection of the value for $K_p$, which results in retentive behavior of the model as shown in Figures 6a, 6b, and 6c. The observations suggest that oil in beach groundwater systems remains detectable for several years after introduction. We estimate from a qualitative evaluation of the information cited above that a half life for oil in a sandy or gravel beach is about six months, or three years in a mudflat. From Figures 6a, 6b, and 6c, we therefore have adopted a value for $K_p$ of 1,000, which the user can adjust.

Whole-model sensitivity tests. A series of model runs was performed to demonstrate overall model behavior for various types of coastal reaches. In each case, a single, uniform, straight stretch of coastline 5 km in length is simulated. One thousand barrels (141 metric tons) of Prudhoe Bay crude oil are released in 24 spills over 48 hours. The release point is 1 km offshore and about midway along the reach. The wind is constant at 5 m/sec, and is $10^\circ$ away from being directly onshore. Only the reach type changes from one test to the next. The mass balance as a function of time for oil coming ashore on a sand beach is shown in Figures 7a, 7b, 7c, and 7d. Since the travel time from the oil release point 1 km offshore is about two hours, the release of spills subsequent to the first is approximately balanced by previous spills arriving at the sandy shoreline (Figure 7a).

This oil is compressed against the shoreline by the wind, which reduces surface area and slows evaporation rates. Oil deposited on the shore does not spread further and is also absorbed into the beach face. These factors combine to reduce the net amount of mass that will evaporate relative to the 20 percent expected for this oil in an offshore simulation.

The tidal signal is clearly discernible in the trace of oil mass on the water surface, the rising tide corresponding to the increase in oil mass on the surface. The longshore currents for this test case are about 6 cm/sec due to waves, plus 2 cm/sec at the surface due to wind. The travel time from the reach midpoint to the boundary, 2.5 km, is therefore about 9 hours for oil at the surface and 12 hours for oil entrained in the surf-zone water column.

During the first 60 hours of the simulation, surface oil leaving the model domain along-shore represents the primary contribution to oil that is “outside” (Figure 7a). In the longer term (for example, 90 days, as shown in Figure 7b), the lower-level contribution from the surf zone becomes the dominant mechanism for oil removal from the study area. Figure 7c shows a detailed mass balance for the oil on the shore. The top trace, “Total Ashore,” corresponds to the trace labeled “Ashore” in Figure 7a. As oil comes ashore, it rapidly penetrates the foreshore surface sediments and, thereafter, begins to enter the beach groundwater system. The Foreshore Surface trace in Figure 7c is 180$^\circ$ out of phase with the oil on the water surface (Figure 7a), since deposition of the beach surface is the opposite of reflation. The modeled half life of oil in the foreshore surface sediments agrees well with the 3 to 5 days estimated by Coastal Science and Engineer-

Figure 8. Overall mass balance for Prudhoe Bay crude oil coming ashore on a tidal mud flat (first 90 days)

Figure 9. Overall mass balance for Prudhoe Bay crude oil coming ashore on a gravel beach (first 90 days)

Summary

A coastal zone oil spill model (COZOIL), capable of detailed resolution of relatively complex coastal topographies, has been developed and tested. This paper has described sensitivity analyses of some of the coastal interaction algorithms. The model has also been subjected to a hindcast test of the Amoco Cadiz oil spill. COZOIL appears to reproduce both qualitatively and quantitatively observed behavior of oil in the coastal zone.

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