Oil Fate & Transport Discussion
FINAL

ExxonMobil Silvertip Pipeline Spill
Yellowstone River, MT

Requested by EPA – OSC

Prepared by NOAA Emergency Response Division (ERD)
July 22, 2011

Introduction

On July 15, 2011 EPA requested that NOAA assist in describing the fate and transport of the oil from ExxonMobil's Silvertip Pipeline spill that occurred on July 01, 2011 in the Yellowstone River near Laurel, MT. Determination of fate and transport is critical to effectively scale and direct response efforts to areas where recoverable quantities of oil may be found. This report represents ERD's efforts to describe the expected initial fate and transport of the oil based on the review of available acquired data and field observations, documented physical and chemical processes, and comparison to findings from previous spills.

It should be noted that this discussion was not intended to address the question of oil budget estimates. Such estimates are exceedingly difficult to generate without huge uncertainties largely because most input parameters are effectively un-measureable. Instead, the focus of this discussion was to answer the following question: How far downstream from the spill site might recoverable oil be expected to occur?

We expect that oil would be found within 100 nm downriver of the source for both surface recoverable oil and subsurface oil. We do not expect recoverable oil to be found in the water column or on the bottom of the river. For buried oil, recoverable quantities may be found in depositional areas along the receding river within 100 nm of the spill site.

Oil spill trajectory analysis for coastal spills is almost always a two dimensional problem whereas river spills are usually more of a three dimensional problem due to several hydraulic differences between coastal or open water and riverine systems. In this incident, the question becomes a particularly complex three dimensional problem due to the high volume flows, shear forces, and turbulence involved as well as the local bathymetry, turbidity conditions, etc. Attempts have been made in this and past incidents to apply open water trajectory models to river systems, but the results have limited accuracy. Given these complexities, an operational model does not presently exist to answer the above question with reliable accuracy and on a response time-frame (hours to days).

The US Geological Survey (USGS) estimated mean river speeds at the spill site to have been approximately 6 knots at the time of release. With that, one could estimate that a hypothetical pollutant particle might travel 150 nm within 24 hours and 250-300 nm within 48 hours. Over time, however, the utility of such a hypothetical particle becomes less and less useful to responders because oil weathers and interacts with its surroundings.

We therefore must use our knowledge of the oil, the weathering and transport processes involved, experience from other oil spills in riverine settings and incident-specific observations to date to attempt to estimate the distance that recoverable quantities of oil may have traveled.

The Spill & Related Conditions

At approximately 11:00 PM on Friday, July 1 a break occurred in a 12-inch pipeline owned by ExxonMobil that resulted in a spill of blended crude oil into the Yellowstone River approximately 20 miles upstream of Billings, Montana. According to the company's estimates 1,000 barrels of oil entered the river, which was in flood stage, before the pipeline was shut down.

The oil is described as a blend of Elk Basin Heavy and Wyoming Asphaltic Sour crudes and estimated to have an API° of 23.1 (s.g. of 0.915). This oil will float easily, except when currents pull small droplets below the surface or when the oil interacts with enough sediment to become heavier than the surrounding water. The Wyoming Asphaltic Sour Crude oil has high sulfur content and will be very aromatic (this is consistent with early SCAT field observations). Limited data on this blended oil's properties was available at the time of this report. Further data on viscosity, and percent of saturates, aromatics, resins, and asphaltines would have added to discussions of some weathering mechanisms.

The pipeline break occurred at the bottom of the river releasing oil directly into the water. At the time, the Yellowstone River gauging station at Billings Montana read approximately 13.88 feet; almost 6 feet above normal and a foot above flood stage. Water levels increased to a maximum of 13.95 feet (July 2nd), declined to around 12 feet (July 4th) and rose again to 13 feet (July 7th; Figure 1).

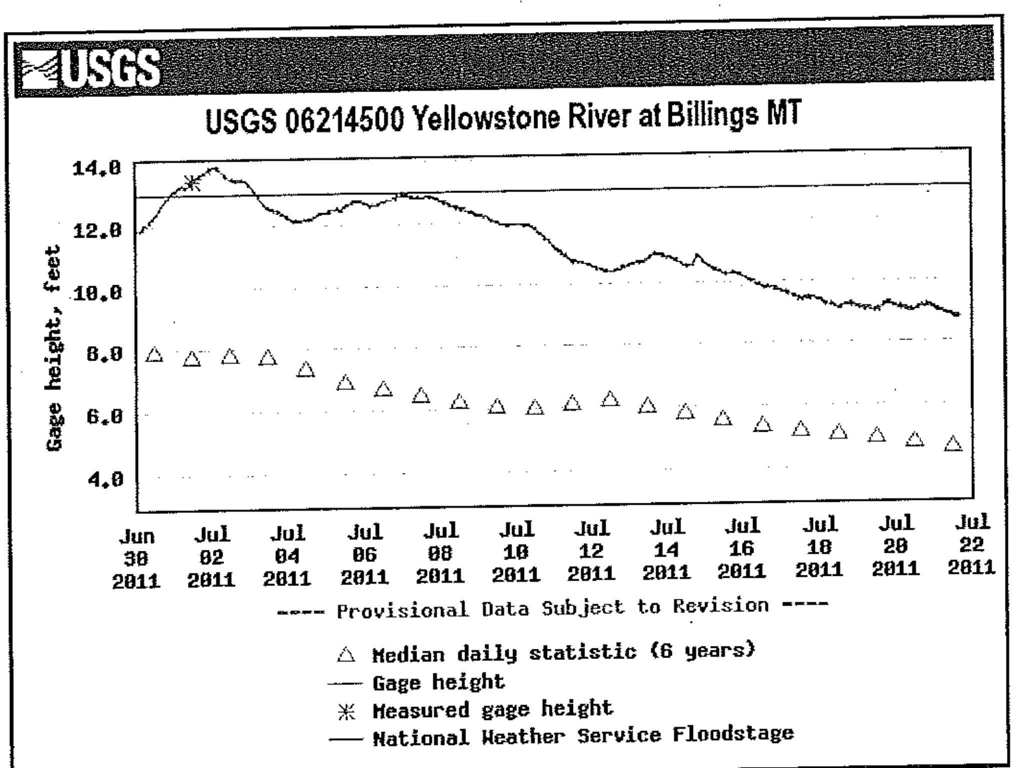

Figure 1. USGS Yellowstone River gage data at Billings, MT (Station 06214500)

The river's flow rate range during the first 24 hours of the spill was estimated to be between 61,700 and 66,700 cfs (USGS Montana Water Science Center) and mean river velocities of about 10ft/sec (~6 knots; USGS phone conversation).

Winds in the vicinity of the spill were initially from the south-southeast at 2-6 miles per hour during the first three (3) hours of the spill, after which the light winds switched to the west-northwest at 5 miles per hour. Winds of 2-5 miles per hour persisted for much of the daytime on July 2nd, varying in direction from the west-northwest to the west-southwest. (NWS Forecast Office, Billings)

Oil trajectory estimates using a computer model (OilMap) were attempted by contractors in the first few days of this spill, but we do not know what the model inputs were and it is unclear from the limited available information whether the modeled estimates were confirmed by field observations (i.e. overflights). Furthermore, early oil transport predictions are less helpful in this discussion than the actual field observations that followed.

Oil observations reviewed for this discussion included overflight information collected on July 3-4 (information collected on July 2nd was not located), oil mapping overflights conducted by the Operations Section on July 4-18 and shoreline oiling information collected by SCAT teams as of July 20th. Oil reports submitted from the public were difficult to locate two weeks after-the-fact and therefore were not reviewed for this report.

Oil Transport in Rivers

Given the complexities of a flooding Yellowstone River, there are a number of technical issues that are important to understand first about the physical processes affecting the movement and spreading of the oil in rivers overall.

The spill response community has a great deal of experience in ocean and estuarine environments as compared to rivers; though care must be taken in applying physical transport processes across such different water bodies types. In rivers, the currents tend to be strong and the fetch over the water relatively small, so wind effects on vertical mixing of oil movement are usually of secondary importance. Thus, for river spills, the currents and shear dominate the vertical and cross-river distribution processes, with the wind acting to determine which bank of the river the spill will trend. In rivers, the turbulence and shear forces created by currents interacting with the river bottom and banks can move significant amounts of oil below the surface, particularly if the oil is finely distributed as droplets. The high energy mixing in rivers tend to produce spill distributions having higher subsurface oil concentrations than would be expected in marine spills and thus substantial proportions of the spilled oil volume can be more difficult to observe and to act on.

Shear-dominated flows cause another effect that characterizes river spills. The lower speeds along the banks and bottom of a river mean that the surface and center of a river move downstream faster than the flow along its boundaries. This speed differential causes increased mixing resulting in exchange of water and pollutants between the slower, near-bank regions and the faster, center regions of the river. This results in the smearing of a pollutant plume, particularly along the axis of the flow. This difference in current speed is typically the mixing mechanism that spreads a pollutant patch out as it moves down a river. As a result, it controls the shape and size of a pollutant plume and the distance over which a pollutant concentration will remain above a particular level of concern. When a river floods over its banks, the water outside of the banks slows down due to friction. Pollutants in the flooded areas will move downstream slower and will often be left high and dry when the water levels drop. Expect to see pools of oil left behind as the water recedes.

A third consequence of shear-dominated flow is that, although the leading edge of the pollutant distribution may move as a relatively sharp front (at the current speed in the middle of the channel), the tail end of the distribution is continually mixed and smeared. Therefore, the actual pollutant distribution over the first few hours will begin to resemble a comet, i.e. with a relatively distinct front followed by a fuzzy tail. This "holdup" in rivers due to "dead spots" in the flow are discussed by Fischer et al. (1979) and others.

On a long straight channel, water (and pollutant) flow is unidirectional. However, few natural channels are actually straight, and it is necessary to consider the effects of shear boundaries in areas of shoals and, particularly, bends in rivers. As water moves around the bend in a river, centrifugal force tends to pile water up along the outside edge of the turn causing acceleration in main channel current speeds (Figure 2). Near the bottom of the river, the velocity decreases due to friction causing a secondary flow that moves water along the bottom toward the inside of the river bend. To conserve water mass there must then be a weak return flow toward the other side of the river bend throughout the water column but above the bottom friction layer. This secondary flow, when superimposed on the normal, and usually much stronger, down-channel flow produces a slow, helical motion as shown in Figure 3. Its effect can be seen in older river channels where the flow tends to deposit bottom silt and sediments along the inside of river bends with stronger currents along the outer bank of the turns.

From a pollution distribution point of view, the secondary flow helps move oil particles across the shear boundaries and greatly increases the smearing, or dispersion, of the pollutant patch. Thus pollutants tend to spread across channel more rapidly in curving river channels than straight ones and are more dilute relative to what would be expected for straight-channeled rivers. The Yellowstone River is fairly straight compared to older, meandering rivers but the bends that do occur would affect cross-channel spreading to a moderate degree.

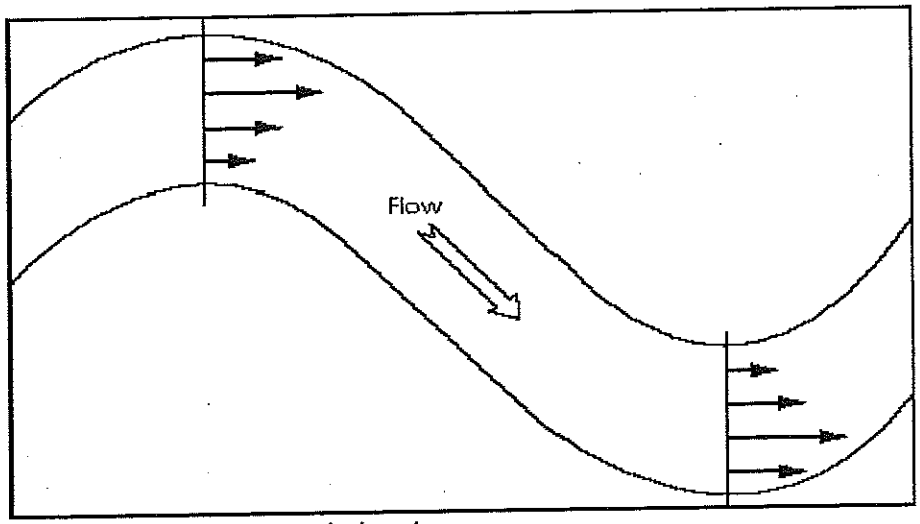

Figure 2. Flow in a meandering river.

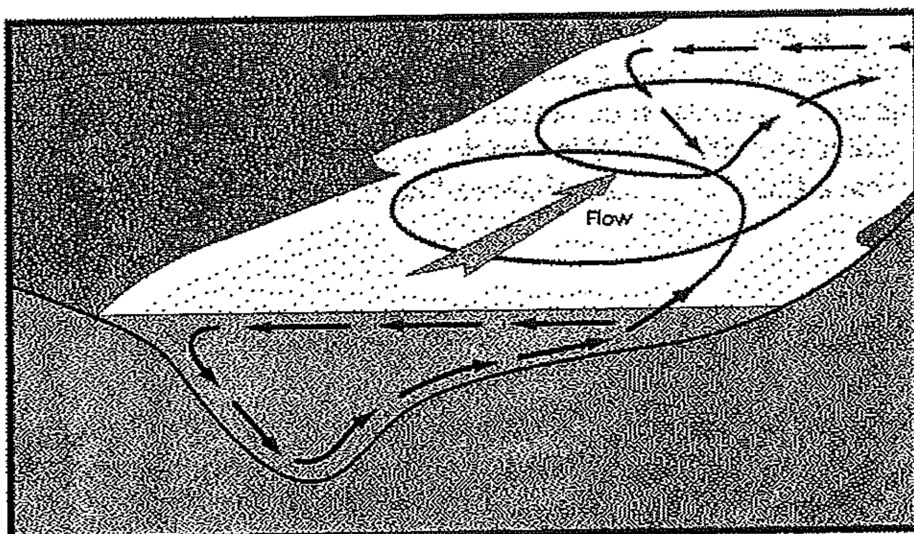

Figure 3. Cross-section of a meandering stream showing secondary flow.

Many cross-channel river profiles are very irregular, with rapids at one extreme and bays at the other. These features either accelerate or decelerate the average flow of water and pollutant downriver and contribute to the shear in the current pattern and significantly increase the along channel spreading of the pollutant distribution.

The overall result of these shear-related features is that subsurface oil caught in the main channel will mix rapidly with cleaner waters and cause pollutant concentrations to decrease rapidly.

Available observations thus far compiled appear consistent with the above discussion. SCAT observations within Operational Division A and shown in Figure 4 show shoreline oiling occurring only along the south side of the main river channel and the outside of the first bend (Segments A-13 & 14). Shoreline oiling is not documented along the north shoreline until Segment A-21 suggesting that oil has undergone some cross-channel spreading.

Fate of the Oil

To reconstruct what may have happened to the oil since its release 2-3 weeks prior to generating this report provides some challenges. At the time of this report, the biggest data gap was the limited amount of available observational data (e.g. "who saw what, where?") from the first 48-72 hrs of the spill. Early observations would be one of the best ways to understand transport times and oil distribution, thus providing overall scale of the recoverable oil problem. Given what is known about the incident-specific river and wind conditions at the time of the Silvertip Pipeline spill, some initial conclusions may be reached involving the fate of oil that followed. It should be noted that discussions occurred while drafting this report between NOAA staff and other technical specialists experienced in evaluating and modeling oil weathering processes in marine and inland spills and there was general agreement on the assumptions used here and many of the conclusions drawn.

Surface oil fate/shoreline oiling

By looking at evaporation rates of similar oils in the NOAA's ADIOS-2 oil weathering model, it is estimated that about 20% of the oil may have evaporated within the first 2-3 days, with most of the evaporation occurring within the first 12 hours.

Given the conditions involved, an understanding of river flow dynamics, the time it would take for oil to have traveled such distances, other river spill examples, and observational data (though somewhat limited) available within the Incident Command Post, it is reasonable to expect that most/all shoreline oiling can be expected within the first 75-100 river miles.

Figure 4. SCAT map of cumulative shoreline oiling within Operational Division A, as of July 20, 2011.

As of the date of this report, the furthest shoreline oiling confirmed by SCAT teams in Segment C-52 was about 67 river miles from the spill site (Figures 5 & 6). On July 3rd an overflight from Billings to Glendive, MT noted and photographed a handful of oil observations within Operational Divisions D & E, to approximate135 river miles from the spill site. The furthest aerial oil observation was noted about 220 river miles from the spill site, located at the beginning of Division G, mid-way between Kinsey and Terry, MT (Figures 7 & 8)* No additional oil sightings were noted during the remainder of this flight to and from Glendive, MT, about 55 river miles further downstream.

Perhaps a reasonable strategy to get a l
of shoreline oiling relatively quickly is to
level shoreline surveys starting at C-52 a
agreed to distance beyond observed oil.
prudent to consider maintaining some le
for public oiling reports further downstre

* NOTE: MT DEQ & NOAA evaluated the subject location and determined that the Division G location was not oil.
Mike Towle
7/26/11

Subsurface oil & deposition

Because no data of subsurface oil (obse
ICP, an estimate can only be attempted
dynamics, the time it would take for oil to
experiences from other river spills. The
the release lead us to expect that physic
both substantial mechanisms limiting an

The turbulence of the flooding Yellowsto
be expected to quickly disperse a large p
small droplets. How quickly this occurre
known. Small droplets of naturally dispe
extended periods of time and move dow
estimated mean current of 6 knots. However, given the high turbulence and dilution potential (1,000bbls in released into 60,000cfs) as well as the shear-induced spreading (along and across channel) throughout the river, we would expect the overall concentration of this naturally dispersed oil to be low overall, patchy in distribution and not recoverable.

Given the high turbidity at the time of release and the opportunity for the oil to interact with river sediments, a portion of oil is expected to have become sediment-laden and sunk. This phenomenon has occurred numerous times and to varying degrees in sediment-laden rivers (Mississippi, Delaware and Kalamazoo Rivers). When this happens the oil moves downstream along the bottom or just off the bottom of the river breaking into smaller and smaller particles due to the turbulence. The form or character of sediment-laden oil then becomes important in considering transport and recoverability.

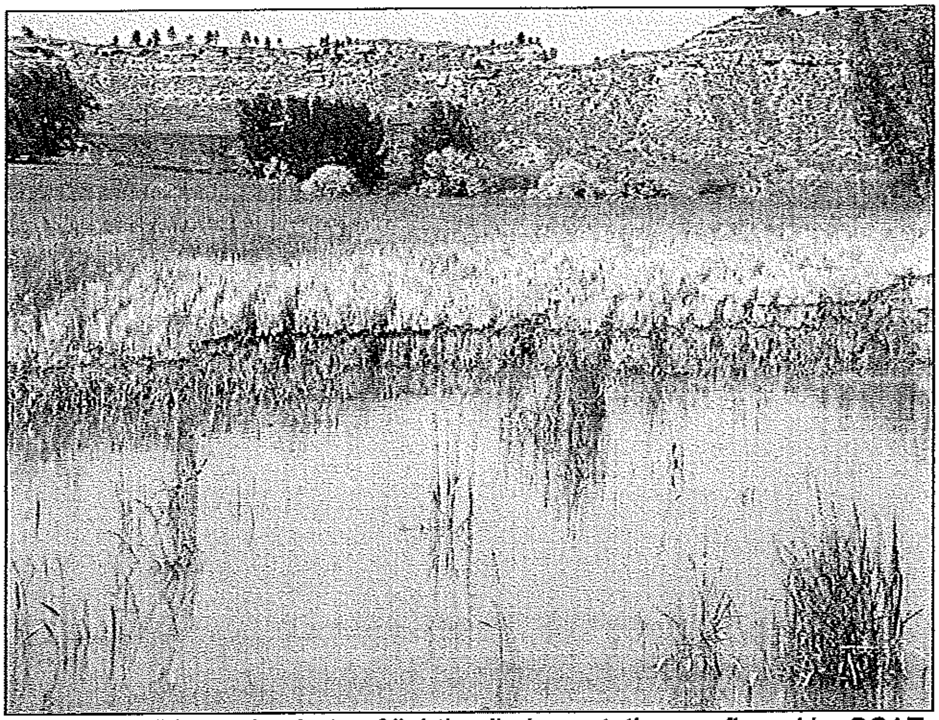

Figure 5. Wide angle photo of lightly-oiled vegetation confirmed by SCAT teams at Segment C-52.

Figure 6. Close-up photo of lightly-oiled vegetation confirmed by SCAT teams at Segment C-52.

Figure 7. Location map showing the furthest aerial observations of oil on July 3rd. The furthest site is approximately 220 river miles from the spill site, at the beginning of Operational Division G. The other observations shown are within about 135 river miles.

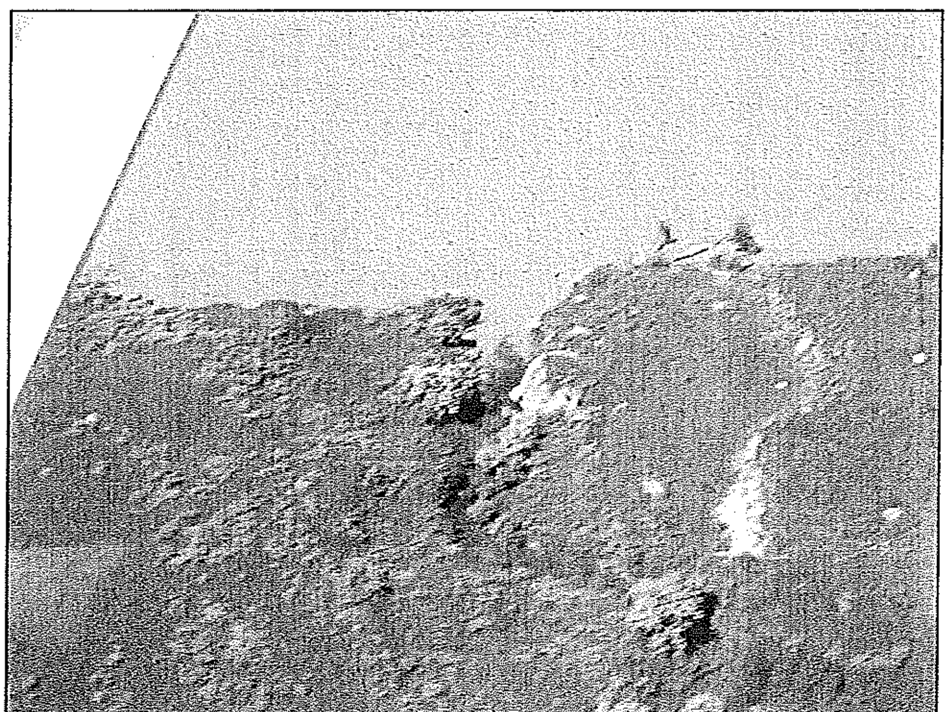

Figure 8. Aerial view of a small pocket of oil found during July 3rd overflight (cropped from original photo). This location is indicated in Figure 7 above.

Given the current speeds, turbulence, volume differential between oil and the receiving waters, and high suspended sediment load it seems more likely that sediment-laden oil would be in the form of small/very small oil particles scattered over a wide area amongst very large volumes of new sediment. Other subsurface oil forms cannot be ruled out however and could conceivably include: 1) "pooled" oil, 2) large discrete oil globs 3) tarballs 4) some combination of these. Regardless of the form, however, turbulence will break oil/sediment particles into smaller and smaller particles over time and distance, causing them to become more widely distributed farther from the source.

Recoverable oil would not be expected to accumulate in substantial amounts in the main river channel due to high currents. Sediment-laden oil is much more likely to settle out in low energy sections of the river, such as deep pools, in ponds left behind as the water level drops, in calm areas behind obstructions like logs or other debris and overflow flats. Some of these accumulations may be prone to re-mobilization during later high water events.

Because there have been no actual observations of submerged or sediment-laden oil in recoverable quantities (though they may become more visible in quiescent areas as water levels continue to drop), it is not yet certain what form(s) sediment-laden oil may have taken and whether recoverable quantities are present. For this reason, a screening-level sunken oil sampling program may be warranted for lower energy areas close to the source to try and locate the various potential forms of sunken oil outlined above. If recoverable quantities of these oil forms are found then appropriate cleanup strategies and endpoints can be developed.

Conclusions

We estimate that approximately 20% of the oil would have evaporated within the first three days. Of the remainder, recoverable quantities of shoreline stranded oil may be scattered within 70-100 miles of the source. Reconnaissance-level boat-based shoreline surveys downstream of Segment C-52 could be an effective way to provide a better estimate. The exact fate and transport of subsurface oil is difficult to estimate at this time without any further data, but due to the river conditions at the time of the spill it is unlikely that large recoverable quantities of subsurface or sunken oil will be found; though it is reasonable to expect some quantities of sediment-laden oil in areas of reduced flow. As various forms of sediment-laden oil may exist in areas of reduced flow, a screening-level sampling program may be warranted to assess the scope and extent of oil in such areas and inform the Response of potentially recoverable quantities.

Some key summary points include the following:

- No operational, oil transport computer model presently exists to estimate how far downstream surface and subsurface oil may travel with any precision and on anything close to a response time-frame (hours to days).
- About 20% of the oil may have evaporated in the first 2 days
- Given an average river flow of 6 knots at the time of release, a hypothetical pollutant particle could have traveled downriver 150 nm over the first 24 hours of the spill; however, this says little about the travel distance of recoverable or even detectable quantities of oil
- Though a portion of oil may have sunk after adhering to sediment given the high turbulence and shear forces involved, much of the subsurface oil would likely be incorporated into small particles rather than larger (possibly recoverable) particles.
- With the Yellowstone River discharge rate of approximately 450,000 gallons/sec at the time of the release and a spill volume of about 40,000 gallons over 1 hr, a high dispersion potential is expected.
- Recoverable quantities of oil can be expected to decrease in quantity and distribution, with increasing distance from the source.
- Oil will strand along river banks with lower elevation, backwater and eddy areas, and in depositional areas of sand and debris

References

Fischer, H. B., E. J. List, R. C. Y. Koh, J. Imberger, and N. H. Brooks. 1979. Mixing in Inland and Coastal Waters. New York: Academic Press. 483 pp.

Overstreet, R and JA Galt. 1995. Physical Processes Affecting the Movement and Spreading of Oils in Inland Waters. HAZMAT Report 95-7. NOAA / Hazardous Materials Response and Assessment Division, Seattle, Washington. 58 pp.

APPENDIX: Data Gaps

Numerous data gaps were identified during the development of this report that would be beneficial in understanding fate and transport of the Silvertip Pipeline oil.

Oil chemistry

Analytical data on oil composition is requested on the total per cent mass for the following

- % saturates/aliphatics
- % aromatics
- % resins
- % asphaltenes

To determine oil weathering, a series of samples analyzed for oil composition over time and space downstream would also be useful.

Oil observations

- Overflight info from the first day (July 2nd) would indicate have how far the oil went before natural dispersion and sinking oil dominated the process. This, along with shore and vessel observation during the first 1-2 days would be the only way to determine how far the leading edge of the floating oil went.
- Overflight observations may also indicate whether the floating oil may have emulsified to some degree, which would affect its volume and overall persistence.
- Shoreline oiling observations over time would help calibrate predictions against chemical and physical properties of oil reacting in the environment. Questions might include:
  - What is the nature of the weathered oil? Is it still sticky, does it have a strong odor?
  - What color is the oil? Has the oil picked up sediment?
  - Is there any oil on the bottom of puddles and pools along the river banks?
  - Does the weathered oil float in freshwater?