Analysis of Frequency, Magnitude and Consequence of Worst-Case spills from the Proposed Keystone XL Pipeline

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Executive Summary

TransCanada is seeking U.S. regulatory approval to build the Keystone XL pipeline from Alberta, Canada to Texas. The pipeline will transport diluted bitumen (DilBit), a viscous, corrosive form of crude oil across Montana, South Dakota, Nebraska, Kansas, Oklahoma and Texas. As part of the regulatory process, the National Environmental Policy Act (NEPA) requires an assessment of the potential environmental impacts of a pipeline spill. The Clean Water Act (CWA) also requires TransCanada to estimate the potential worst-case discharge from a rupture of the pipeline and to pre-place adequate emergency equipment and personnel to respond to a worst-case discharge and any smaller spills. The Keystone XL environmental assessment documents (e.g., Draft Environmental Impact Assessment) as well as the environmental impacts documents for the previously built Keystone pipeline, can be found on the US State Department web site. It is widely recognized that the environmental assessment documents for the Keystone XL pipeline are inadequate, and that they do not properly evaluate the potential environmental impacts that may be caused by leaks from the pipeline (e.g., USEPA 2011a). The purpose of this paper is to present an independent assessment of the potential for leaks from the pipeline and the potential for environmental damage from those leaks.

The expected frequency of spills from the Keystone XL pipeline reported by TransCanada (DNV, 2006) was evaluated. According to TransCanada, significant spills (i.e., greater than 50 barrels (Bbls)) are expected to be very rare (0.00013 spills per year per mile, which would equate to 11 significant spills for the pipeline over a 50 year design life). However, TransCanada made several assumptions that are highly questionable in the calculation of these frequencies. The primary questionable assumptions are: (1) TransCanada ignored historical data that represents 23 percent of historical pipeline spills, and (2) TransCanada assumed that its pipeline would be constructed so well that it would have only half as many spills as the other pipelines in service (on top of the 23 percent missing data), even though they will operate the pipeline at higher temperatures and pressures and the crude oil that will be transported through the Keystone XL pipeline will be more corrosive than the conventional crude oil transported in existing pipelines. All of these factors tend to increase spill frequency; therefore, a more realistic assessment of expected frequency of significant spills is 0.00109 spills per year per mile (from the historical data (PHMSA, 2009)) resulting in 91 major spills over a 50-year design life of the pipeline.

The CWA requires that TransCanada estimate the “worst-case spill” from the proposed pipeline (ERP, 2009). TransCanada’s calculation of the worst-case spill from the proposed Keystone XL pipeline was not available at the time of this assessment, so an assessment of the methods used by TransCanada for the existing Keystone pipeline and a comparison of the results of those methods with the methods recommended in this analysis were made. The worst-case spill volume at the Hardisty Pumping Station on the Keystone (the original pipeline will be referred to as simply the Keystone pipeline while the proposed pipeline is the Keystone Xl pipeline) pipeline predicted using methods recommended in this analysis was 87,964 barrels

(Bbl), while the worst-case spill predicted using TransCanada's methods was 41,504 Bbl (ERP, 2009). The difference is a factor of more than 2 times. The primary difference between the two methods was the expected time to shut down the pumps and valves on the pipeline. TransCanada used 19 minutes (TransCanada states that it expects the time to be 11.5 minutes for the Keystone XL pipeline). Since a very similar pipeline recently experienced a spill (the Enbridge spill), and the time to finally shut down the pipeline was approximately 12 hours, and during those 12 hours the pipeline pumps were operated for at least 2 hours, it is clear that the assumption of 19 minutes or 11.5 minutes is not appropriate for the shut-down time for the worst-case spill analysis. Therefore, worst-case spill volumes are likely to be significantly larger than those estimated by TransCanada. The worst-case spill volumes from the Keystone XL pipeline for the Missouri, Yellowstone, and Platte River crossings were estimated by this analysis to be 122,867 Bbl, 165,416 Bbl, and 140,950 Bbl, respectively. In addition, this analysis estimated the worst-case spill for a subsurface release to groundwater in the Sandhills region of Nebraska to be 189,000 Bbl (7.9 million gallons).

Among numerous toxic chemicals that would be released in a spill, the benzene (a human carcinogen) released from the worst-case spill into a major river (e.g., Missouri River) could contaminate enough water to form a plume that could extend more than 450 miles at concentrations exceeding the Safe Drinking Water Act Maximum Contaminant Level (MCL) (i.e., safe concentration for drinking water). Therefore, serious impacts to drinking water intakes along the river would occur. Contaminants from a release at the Missouri or Yellowstone River crossings would enter Lake Sakakawea in North Dakota where they would adversely affect drinking water intakes, aquatic wildlife, and recreation. Contaminants from a spill at the Platte River crossing would travel downstream unabated into the Missouri River for several hundred miles and affect drinking water intakes for hundreds of thousands of people in cities like Lincoln, NE; Omaha, NE; Nebraska City, NE; St. Joseph, MO; and Kansas City, MO, as well as aquatic habitats and recreational activities. In addition, other constituents from the spill would pose serious risks to aquatic species in the river. The Missouri, Yellowstone, and Platte Rivers all provide habitat for threatened and endangered species including the pallid sturgeon, the interior least tern, and the piping plover. A major spill in one of these rivers could pose a significant threat to these species.

The benzene released by the worst-case spill to groundwater in the Sandhills region of Nebraska would be sufficient to contaminate 4.9 billion gallons of water at concentrations exceeding the safe drinking water levels. This water could form a plume 40 feet thick by 500 feet wide by 15 miles long. This plume, and other contaminant plumes from the spill, would pose serious health risks to people using that groundwater for drinking water and irrigation.

Introduction

TransCanada is seeking U.S. regulatory approval to build the Keystone XL pipeline from Alberta, Canada to Texas. The pipeline will transport diluted bitumen (DilBit), a viscous, corrosive form of crude oil across Montana, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. As part of the regulatory process, TransCanada is required by the National Environmental Policy Act (NEPA) to evaluate the potential environmental impacts of a pipeline spill. The Clean Water Act (CWA) also requires TransCanada to estimate the potential worst-case discharge from a rupture of the pipeline and to pre-place adequate emergency equipment and personnel to respond to a worst-case discharge and any smaller spills. The Keystone XL environmental assessment documents (e.g., Draft Environmental Impact Assessment) as well as the environmental impacts documents for the previously built Keystone pipeline, can be found on the US State Department web site. It is widely recognized that the environmental assessment documents for the Keystone XL pipeline are inadequate, and that they do not properly evaluate the potential environmental impacts that may be caused by leaks from the pipeline (e.g., USEPA, 2011a). The purpose of this paper is to present an independent assessment of the potential for leaks from the pipeline and the potential for environmental damage from those leaks.

In addition to evaluating potential environmental damage from pipeline leaks, TransCanada is required by law to pre-position emergency equipment and personnel to respond to any potential spill. This paper does not address these requirements. However, an independent assessment of TransCanada's emergency response plans for the previously built Keystone pipeline was done by Plains Justice (Blackburn, 2010). This document clearly shows that the emergency response plan for the Keystone pipeline is woefully inadequate. Considering that the proposed Keystone XL pipeline will cross much more remote areas (e.g., central Montana, Sandhills region of Nebraska) than was crossed by the Keystone pipeline, there is little reason to believe that the emergency response plan for Keystone XL will be adequate.

Since spills from these pipelines will occur, and since they will be extremely difficult and expensive to clean up (likely tens to hundreds of millions of dollars), it is imperative that TransCanada be required to be bonded for these clean-up costs before any permits are granted. This proposed requirement is supported by the recent Enbridge spill, where a smaller crude-oil pipeline leak released crude oil into a tributary of the Kalamazoo River, and early clean-up costs, as reported in Enbridge's annual report, have exceeded $500 million (Enbridge, 2011).

Worst-Case Spill

One of the requirements of the CWA is to calculate the worst-case potential spill from the pipeline. An assessment of the potential worst-case spill from the Keystone pipeline was conducted by TransCanada; however, some of the methods and assumptions in that assessment are in question. The primary focus of this paper is to provide an independent assessment of the worst-case spill from the Keystone XL pipeline and to compare that to the assessment done by TransCanada.

<u>Spill frequency</u>

To support understanding of the potential impacts due to releases from the pipeline, an assessment of the likely frequency of spills from the pipeline is made. TransCanada calculated the likely frequency of a pipeline spill for the Keystone XL pipeline in the Draft Environmental Impact Statement (ENTRIX, 2010) using statistics from the Pipeline and Hazardous Materials Safety Administration (PHMSA). Nation-wide statistics from PHMSA for spills from crude oil pipelines show 0.00109 significant (i.e., greater than 50 Bbl) spills per mile of crude oil pipelines per year. When this rate is applied to the Keystone XL pipeline with a length of 1,673 miles, the expected frequency of spills is 1.82 spills per year (0.00109 spills/mi* 1,673 mi). Adjusting the nation-wide PHMSA data to only include data from the states through which the Keystone XL pipeline will pass results in a frequency of 3.86 spills per year for the pipeline length (ENTRIX, 2010).The state-specific data are more applicable to the Keystone location; however, the smaller state-specific data base might over-estimate spill frequency. Therefore, the frequency of 1.82 per year is adopted as the best available value for this assessment. Assuming a design life of 50 years for the pipeline, 1.82 spills per year results in 91expected significant spills (i.e., greater than 50 barrels) for the Keystone Pipeline project. According to the TransCanada Frequency-Volume Study of the Keystone Pipeline (DNV, 2006), 14 percent of the spills would likely result from a large hole (i.e., greater than 10 inches in diameter). Using the 14 percent value, the 91 expected spills during a 50-year lifetime for the pipeline would result in 13 major spills (i.e., from holes larger than 10 inches in the pipeline).

However, TransCanada diverged from historical data and modified the estimate of the expected frequency of spills from the pipeline (DNV, 2006). The company's primary rationale for reducing the frequency of spills from the pipeline was that modern pipelines are constructed with improved materials and methods. Therefore, TransCanada assumed that pipelines constructed with these new improved materials and methods are likely to experience fewer leaks. The revised expected frequency for spills was reported in the Frequency-Volume Study (DNV, 2006) to be 0.14 spills/year over the 1,070 miles from the Canadian border to Cushing, OK. This value was adjusted to 0.22 spills per year for the total 1,673 miles of pipeline, including the Gulf Coast Segment (ENTRIX, 2010). Using the 0.22 spills/year, TransCanada predicted 11 spills greater than 50 barrels would be expected over a 50-year project life.

This reduced frequency estimated by TransCanada is probably not appropriate for a couple of reasons. First, the study of the revised frequency ignored some of the historical spill data; i.e., the spill cause category of "other causes" in the historical spill data set (DNV, 2006). The "other causes" category was assigned for spills with no identified causes. Since this category represents 23 percent of the total spills, this is a significant and inappropriate reduction from the spill frequency data. In addition, the assumed reduction in spill frequency resulting from modern pipeline materials and methods is probably overstated for this pipeline. TransCanada used a reduction factor of 0.5 in comparison to historical data for this issue. That is, according to TransCanada, modern pipeline construction materials and methods would result in half as many spills as the historical data indicate. However, the PHSMA data used in the TransCanada report were from the most recent 10 years. Therefore, at least some of the pipelines in the analysis were modern pipelines. That is, the initial frequency estimate was calculated in part with data from modern pipelines; therefore, a 50 percent reduction of the frequency estimates is highly questionable based on the data set used. More importantly, DilBit, the type of crude oil to be transported through the Keystone XL pipeline will be significantly more corrosive and abrasive than the conventional crude oil transported in most of the pipelines used in the historical data set. The increased corrosion and abrasion are due to 15 – 20 times the acidity (Crandall, 2002), 5 – 10 times the sulfur content (Crandall, 2002), and much higher levels of abrasive sediments (NPRA, 2008) compared to conventional crude oil. In addition, the high viscosity of DilBit requires that the pipeline be operated at elevated temperatures (up to 158^{o}F for DilBit and ambient temperature for conventional oil) and pressures (up to 1440 psi for DilBit and 600 psi for conventional oil) compared to conventional crude oil pipelines (ENTRIX, 2010). Since corrosion and pressure are the two most common failure mechanisms resulting in crude oil releases from pipelines (DNV, 2006), increased corrosion and pressure will likely negate any reduced spill frequency due to improvement in materials and methods. Although pipeline technology has improved, new pipelines are subject to proportionally higher stress as companies use this improved technology to maximize pumping rates through increases in operational pressures and temperatures, rather than to use this improved technology to enhance safety margins.

Also, TransCanada relies heavily on "soft" technological improvements, such as computer control and monitoring technology, rather than only on "hard" improvements, such as improved pipe fabrication technology. Whereas "hard" technological improvements are built into pipelines, "soft" improvements require an ongoing commitment of monitoring and maintenance resources, which should not be assumed to be constant over the projected service life of the pipeline, and are also subject to an ongoing risk of error in judgment during operations. As demonstrated by the spill from Enbridge's pipeline into the Kalamazoo River, as pipelines age maintenance costs increase, but pipeline company maintenance efforts may be insufficient to prevent major spills, especially if operators take increased risks to maintain return on investment. Moreover, TransCanada assumes that future economic conditions will allow it to commit the same level of maintenance resources from its first year to its last year of operation. Given future economic uncertainty, this is not a reasonable assumption. It is reasonable to assume that decades from now TransCanada or a future owner will likely fail to commit adequate maintenance resources, fail to comply with safety regulations, or take increased operational risks during periods of lower income. Overtime, PHMSA should assume that the risk of spill from the Keystone XL Pipeline will increase due to weakening of "soft" technological enhancements. Over the service life of the pipeline it is not reasonable to rely on TransCanada's "soft" technological improvements to the same extent as built-in "hard" improvements.

The TransCanada spill frequency estimation consistently stated the frequency of spills in terms of spills per year per mile. This is a misleading way to state the risk or frequency of pipeline spills. Spill frequency estimates averaged per mile can be useful; e.g., for extrapolating frequency data across varying pipeline lengths. However, stating the spill frequency averaged per mile obfuscates the proper value to consider; i.e., the frequency of a spill somewhere along the length of the pipeline. Stating the spill frequency in terms of spills per mile is comparable to acknowledging that although some 33,000 deaths from automobile accidents occur annually in the U.S., the average annual fatality rate across 350 million people is only 0.000094; therefore, fatalities from automobile accidents are so rare as to be unimportant. In other words, it is of little importance to know the risk (frequency) of a release in any particular mile segment (frequency per mile); rather it is important to know the risk of a release from the pipeline. As shown above, the expected number of spills for the pipeline over the pipeline lifetime ranges between 11 and 91 spills, depending on the data and assumptions used.

In summary, there is no compelling evidence to reduce the frequency of spills because of modern materials and methods. The increased corrosiveness and erosiveness of the product being transported will likely cancel any gains due to materials and methods improvements and soft technological safeguards will likely become less effective over time. Moreover, the modified frequency stated by TransCanada should not have been reduced by omitting an important failure category. The frequency of spills should have been stated as frequency of spills across the pipeline length per year and per pipeline lifetime. Therefore, the best estimate for spill frequency is the value from the PHSMA historical data set resulting in 1.82 spills/yr or 91 significant spills over the pipeline lifetime. Table 1 compares the predicted number of spills over the lifetime of the pipeline computed from TransCanada's assumptions and from historical data.

Table 1: Predicted Number of Spills from Keystone XL Pipeline Over a 50-Year Lifetime.

	TransCanada Estimate	Estimates Using Historical Data
Spills per year per mile	0.00013[a]	0.00109[a]
Pipeline spills per year	0.22[b]	1.82[b]
Pipeline spills per 50-year lifetime	11[c]	91[c]
Pipeline spills from > 10 inch hole	1.54[d]	12.74[d]

(a) ENTRIX, 2010

(b) spills/year-mile *1673 miles

(c) spills/year* 50 years of pipeline lifetime

(d) spills/lifetime * 14percent spills from > 10 inch hole

<u>Most Likely Spill Locations</u>

Crude oil could be spilled from any part of the pipeline system that develops a weakness and fails. Likely failure points include welds, valve connections, and pumping stations. A vulnerable location of special interest along the pipeline system is near the side of a major stream where the pipeline is underground but at a relatively shallow depth. At these locations, the pipeline is susceptible to high rates of corrosion because it is below ground (DNV, 2006). Since the pipeline is below ground, small initial leaks due to corrosion-weakened pipe would potentially go undetected for extended periods of time (e.g., up to 90 days) (DNV, 2006) providing conditions for a catastrophic failure during a pressure spike. In these locations, pressures would be relatively high due to the low elevation near the river crossing. In addition, major leaks at these locations are likely to result in large volumes of crude oil reaching the river.

In addition to river crossings, areas with shallow groundwater overlain by pervious soils (such as the Sandhills region in Nebraska) where slow leaks could go undetected for long periods of time (e.g., up to 90 days) (DNV, 2006), pose risks of special concern.

<u>Worst Case Spill Volume</u>

The volume of a spill is calculated in two parts: the pumping rate volume and the drain-down volume. The pumping rate volume is the volume of crude oil that is pumped from the leaking pipe during the time between the pipe failure and stoppage of the pumps. The time to shut down the pumps after a leak can be divided into two phases: the time to detect the leak, and the time to complete the shut-down process. The pumping rate volume also depends on the size of the hole in the pipe and the pressure in the pipe. The drain-down volume is the volume of crude oil that is released after the pumps are stopped, as the crude oil in the pipe at elevations above the leak drains out. The following sections explain how the pumping rate volume, the drain-down volume, and the total spill volume are calculated.

<u>Pumping Rate Volume</u>

The pumping rate volume is calculated as:

$$PRV = PR * (DT + SDT)$$

Where:

PRV = pumping rate volume (Bbl)

PR = pumping rate (Bbl/min)

DT = detection time (time required to detect and confirm a leak and order pipeline shut-down (min))

SDT = shut-down time (time required to shut down pumps and to close valves (min))

TransCanada's Frequency-Volume Study (DNV, 2006) states that detection of a leak in an underground pipeline section can range from 90 days for a leak less than 1.5 percent of the pipeline flow rate to 9 minutes for a leak of 50 percent of the pipeline flow rate. The 90-day time to detection is for a very slow leak that would not be detected by the automatic leak detection system. The 9 minute time to detection is for a leak that is large enough to be readily detected by the leak detection system. However, this time estimate is questionable because, as has been shown by experience, it is difficult for the leak detection system to distinguish between leaks and other transient pressure fluctuations in a pipeline transporting high viscosity materials such as DilBit. For example, in the Enbridge pipeline spill, signals from the leak detection system were misinterpreted, and up to 12 hours elapsed between the time of the leak and final pipeline shut-down (Hersman, 2010). During the 12-hour period between the initial alarm and the final shut-down, the pipeline pumps were operated intermittently for at least two hours. It should be noted that the location of the Enbridge spill was a populated area where field verification of the leak should have been quick and easy. Indeed, local residents called 911 complaining about petroleum odors (likely from the leak) 10 hours before the pipeline was shut down. In the case of the Keystone XL pipeline, leaks could occur in remote areas (e.g., central Montana, or the Sandhills region of Nebraska) where direct observation would only occur by sending an observer to the suspected site; this could take many hours.

TransCanada states that the time to complete the pipeline shut-down sequence is 2.5 minutes (ERP, 2009). Therefore, using TransCanada's time estimates, for a 1.5 percent leak, the total time between leak initiation and shut-down could be up to 90 days, and for a large (>50 percent) leak, the total time between leak initiation and shut-down would be 11.5 minutes (ERP, 2009).

However, given the difficulty for operators to distinguish between an actual leak and other pressure fluctuations, the shut-down time for the worst case volume calculation should not be considered to be less than 30 minutes for a leak greater than 50 percent of the pumping rate. This would allow for 4 alarms (5 minutes apart) to be evaluated by operators and a 5th alarm to cause the decision to shut down. In addition, the time to shut down the systems (pumps and valves) would require another 5 minutes. The assumption that the decision to shut the pipeline down can be made after a single alarm , as is suggested by TransCanada(ERP, 2009) is unreasonable considering the difficulty in distinguishing between a leak and a pressure anomaly. The ability to make the decision to shut down the pipeline after 5 alarms is likely a reasonable "best-case" assumption. However, this "best-case" does not describe the "worst case" conditions that are being assessed here. Rather, the worst case should consider confusing and confounding circumstances where a shut-down decision is not clear and where the leak site is remote and not verifiable in a short time period. The total time is then considered to be between 30 minutes (a best-case scenario) and 12 hours (the time for the Enbridge final shut-down) from leak initiation to shut-down. Considering that the Keystone XL pipeline will cross extremely remote areas and that verification of a leak could take many hours, a shut-down time of 2 hours (i.e., the time the pumps were operated during the Enbridge shutdown process) is a reasonable time for the worst-case analysis.

Therefore, for the worst-case spill for a large leak, a shut-down time of 2 hours is assumed. With a maximum pumping rate of 900,000 Bbl/d, and a shut-down time of 2 hours, the pumping rate volume is 75,000 Bbl (900,000 Bbl/d * 1 d/24 hr* 2 hr). This pumping rate volume (75,000 Bbl) is used in the calculation of the total worst-case spill volume for all high-rate leaks (i.e., greater than 50 percent flow-rate).

The worst-case spill for a small leak could occur where the pipeline is buried and in a remote location (such as central Montana or the Sandhills region of Nebraska), and where direct observation would be infrequent. According to TransCanada documents (DNV, 2006), a slow leak of less than 1.5 percent of the pumping rate could go undetected for up to 90 days. However, since pipeline inspections are scheduled every few weeks, it is likely that the oil would reach the surface and be detected before the entire 90 days elapsed. Assuming that the pipeline is buried at a depth of 10 feet and that the 1.5 percent leak (75,802 ft^3/d) is on the bottom of the pipe, oil would fill the pore spaces in the soil mostly in a downward direction, but it would also be forced upward toward the surface. Assuming that the oil initially fills a somewhat conical volume that extends twice as far below the pipeline as above it, the oil would emerge at the surface within about one day (volume of a cone 30 feet deep with a base diameter of 30 feet is 7,068 ft^3). Therefore, the leak would likely be detected in 14 days during the next inspection (assuming bi-weekly inspections). A 1.5 percent spill at a pumping rate of 900,000 Bbl/d over 14 days would result in a release of 189,000 Bbl (7.9 million gallons).

Table 2: Pumping Rate Volume for Various Sized Leaks

Leak as percent of Pumping Rate[a]	Detection and Shut-Down Time	Pumping Rate Volume[d]
<1.5percent	14 days[b]	189,000 Bbl
100percent	2 hours	75,000 Bbl
100percent	11.5 minutes[c]	7,188 Bbl

(a) Design pumping rate for Keystone XL = 900,000 Bbl/d. Calculation of worst-case spill requires 100 percent of pumping rate.
(b) Time between pipeline inspections.(DNV, 2006)
(c) TransCanada's assumed shut-down time (ERP, 2009)

Drain-Down Volume

The drain-down volume is the volume in the pipe between the leak and the nearest valve or the nearest high point. Some oil in locally isolated low spots will tend to remain in the pipe. TransCanada arbitrarily assigned a drain-down factor of 0.6 for the Keystone XL pipeline, meaning that 40 percent of the oil in the draining pipeline at elevations above the leak will be captured in low spots. However, since siphon effects will tend to move much of the oil even in local low spots, the 40 percent retention factor is likely too high for a worst-case analysis. PHMSA regulations require valves to be placed on either side of a major water crossing. If these valves are working, they should limit the amount of crude oil that drains from the pipeline to the amount that is between the valves. However, to calculate a worst case spill, the volume should be calculated assuming that at least some of the valves fail (recall the failures of the safety devices in the recent Gulf oil spill). If the valves fail, the drain-down volume would be limited by the major high elevation points on either side of the leak, with a reasonable adjustment for residual crude oil remaining in the pipeline. For this worst-case analysis, a reasonable estimate for residual crude oil remaining in the pipeline is assumed at 20percent of the total volume of oil at elevations above the leak. All of these parameters are site-specific; therefore, for this assessment, the worst case drain-down volumes will be calculated for several of the river crossings of the Keystone XL pipeline, including the Missouri, Yellowstone, and Platte Rivers.

The drain-down volume is calculated using:

$$DDV = PLDV * DF$$

Where:

DDV = Drain Down volume (Bbl)

PLDV = Pipeline Drain Volume (Bbl) (volume of pipeline either side of the leak to next valve or high elevation point)

DF = Drainage Factor (80percent)

Worst-Case Release Calculation for the Missouri River Crossing

The Missouri River crossing is located at mile post (MP) 89 along the Keystone XL pipeline. The upstream valve is located at MP84, and the downstream valve is located at MP 91. The river is at an elevation of 2,035 feet. Figure 1 shows the elevation profile of the crossing at the Missouri River. Since there are no major high elevations between the river and the valve at MP 84, it is likely that nearly all of the oil in the pipeline between the valve and a hypothetical leak at the river will be siphoned or drained via gravity. If the valve at MP 84 fails, all of the oil in the pipeline between that point and the next valve (MP 81.5) could drain since the pipeline rises gradually in elevation between MP 84 and MP 81 (elevation of 2,225 feet). If the valve on the downstream side of the crossing (MP 91) fails, oil in the pipeline up to the major high point at MP 93 could drain to the hypothetical leak at the river crossing.

There are several scenarios that could affect the drain-down volume. In the worst-case scenario both valves could fail, and the drain-down volume would then be the cross-sectional area of the pipe, times the length of pipeline draining times 80 percent. For this scenario, the length of pipe is 11.5 miles (MP 81.5 to MP 93). The cross-sectional area of the 36 inch pipe is 7.07 ft^2. Thus the drain-down volume is $3.43x10^5$ ft^3 (61,164 Bbls, 2.57 million gallons). However it is highly unlikely that both valves will fail at the same time.

A second scenario would occur if both valves operated correctly but the siphon effect removed the oil from the high point downstream of the valve at MP 84. Under this scenario, the length of drained pipe is 7 miles, and the resulting drain-down volume is $2.09x10^5$ ft^3 (37,230 Bbls, 1.56 million gallons).

A third scenario would occur if both valves operated correctly, and the siphon effect did not remove the oil between the high point at MP 86.5 and the valve at MP 84. In this scenario, the length of drained pipe is 4.5 miles (valve at MP 91 to the high point at MP 86.5), and the drain-down volume is $1.34x10^5$ ft^3 (23,934Bbls, 1.01 million gallons).

A fourth scenario would occur if one of the valves fails. To be conservative, the valve closest to the river will be the assumed failed valve. In this scenario, the drain-down distance would be 9 miles (between the valve at MP 84 and the high point at MP 93). The resulting drain-down volume would be 2.69 x 10^5 ft^3 (9 mi * 5,280 ft/mi * 7.07 ft^2 * 0.8) (47,867 Bbl, 2.01 million gallons).

While the first scenario is very unlikely, valve failure is a reasonable consideration in the worst-case spill analysis. So for the purposes of this analysis the fourth scenario, where one of the valves fails, is used to calculate the worst-case spill drain-down volume for the Missouri River crossing site. Therefore, using the fourth drain-down scenario, the drain-down volume is 47,867Bbls. Adding the pumping rate volume of 75,000 Bbl, the worst-case release volume for the Missouri River crossing is 122,867 Bbl (5.16 million gallons).

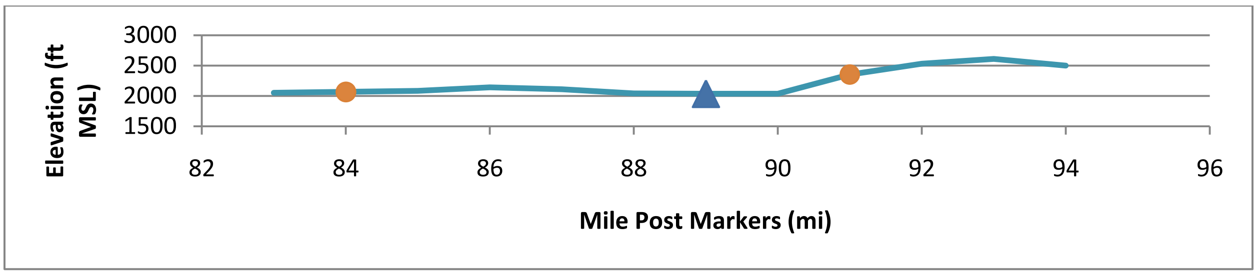


Figure 1: Horizontal profile of surface elevations at the Missouri River crossing. Note that the vertical axis is exaggerated compared to the horizontal axis. Solid circles show locations of pipeline valves. The solid triangle shows the location of the river crossing.

<u>Worst Case Release Volume Calculation for the Yellowstone River</u>

The crossing on the Yellowstone River is at MP 196.5 which is at an elevation of 2,125 feet. The closest upstream valve is at MP 194.5 at an elevation of 2,230 feet. The nearest major high point on the upstream side is at MP 183 at an elevation of 2,910 feet. The closest valve on the downstream side is at MP 200 at an elevation of 2,506 which is also the high point on the downstream side of the crossing. Figure 2 shows the elevation profile for the crossing at the Yellowstone River.

The first scenario for drain-down volume is if all valves work properly. The drain-down volume is 80 percent of the volume between the valves (the cross-sectional area of the pipe (7.07 ft^2) times the pipe length between the valves (5.5. miles)) which equals 1.64x10^5 ft^3 (29,252 Bbl, 1.23 million gallons).

Another scenario considers the volume if the valve at MP 194.5 does not work. In this case, the drain-down volume is the volume of the pipe between the two high elevations which are at MP 183 and MP 200 (17 miles). In this scenario the drain-down volume is 5.07x10^5 ft^3 (90,416 Bbl, 3.80 million gallons).Assuming failure of the valve at mile-post 194.5 is a reasonable assumption for conditions of the worst-case spill volume. The total worst-case volume is then the drain-down volume of 90,416 Bbl plus the pumping rate volume of 75,000 Bbl totaling 165,416 Bbl (6.95 million gallons).

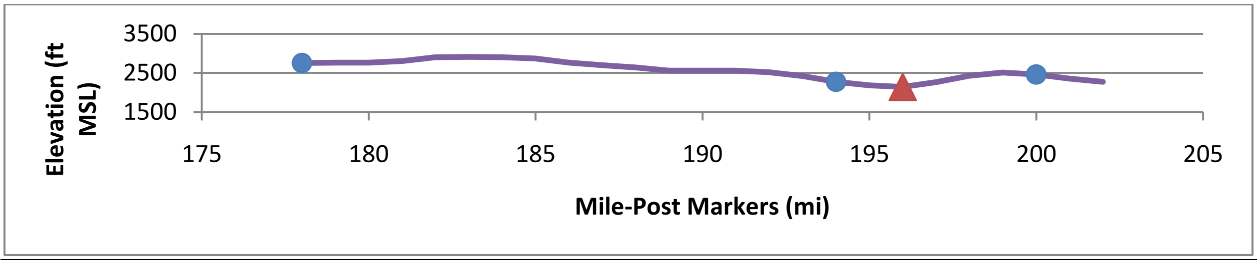


Figure 2: Horizontal profile of surface elevations at the Yellowstone River crossing. Note that the vertical axis is exaggerated compared to the horizontal axis. Solid circles show locations of pipeline valves. The solid triangle shows the location of the river crossing.

Worst-Case Release Volume Calculation for the Platte River, NE

The Keystone XL Pipeline is proposed to cross the Platte River in Nebraska at MP 756.5. There is an upstream valve at MP 747.6 and a downstream valve at MP 765. Figure 3 shows the elevation profile for the crossing at the Platte River. A reasonable worst-case spill scenario is to consider the valve at MP 765 (i.e., closest to the river) to fail. The drain-down volume would then be the pipeline volume between the high point at MP 760 and the valve at MP 747.6. The resulting drain-down volume would be 3.70×10^5 ft^3 (65,950 Bbl, 2.77 million gallons). Adding the pumping rate volume, the worst-case spill at the Platte River crossing would be 140,950 Bbl (5.92 million gallons).

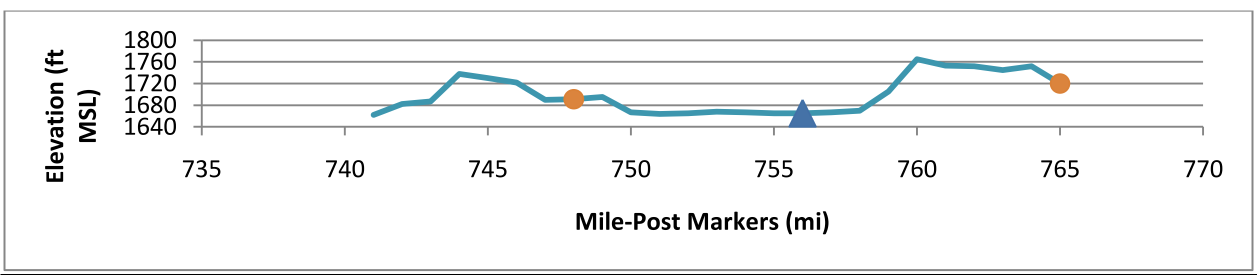


Figure 3: Horizontal profile of surface elevations at the Platte River crossing. Note that the vertical axis is exaggerated compared to the horizontal axis. Solid circles show locations of pipeline valves. The solid triangle shows the location of the river crossing.

Table 3: Worst-Case Spill Volume Estimates.

Location	Estimate from this analysis		
	Pumping Rate Volume (Bbl)	Drain Down Volume (Bbl)	Total Release (Bbl)
Groundwater	189,000[a]	NA	189,000
Missouri River	75,000[b]	47,867[c]	122,867
Yellowstone River	75,000[b]	90,416[c]	165,416
Platte River	75,000[b]	65,950[c]	140,950

(a) 900,000 Bbl/d (Keystone XL design pumping rate)* 1.5 percent leak * shut-down time of 14 days

(b) 900,000 Bbl/d (Keystone XL design pumping rate) * shut-down time of 2 hours

(c) Expected volume to drain from ruptured pipeline after pumps and valves closed

<u>Comparison to TransCanada methods</u>

TransCanada calculated the total Worst-Case Release Volume in a way that appears to be flawed. The worst-case volume was calculated from (ERP, 2009):

$$WCV = ALV + PRV$$

Where:

WCV = worst-case volume (Bbl)

ALV = adjusted line volume (Bbl)

PRV = pumping rate volume (Bbl) i.e., pumping rate (Bbl/min) * time to shut-down (min)

The adjusted line volume was calculated from:

$$ALV = (ILFV - PRV) * 0.60$$

Where:

ILFV = initial line fill volume (Bbl) i.e., the volume of the pipe between the leak and the nearest valve on both sides of the leak.

0.60 = drain-down factor where 60percent of the oil in the pipe will drain after shut-down.

For the Hardisty Pump Station/Regina Pump Station (Keystone pipeline) calculation, the ILFV was stated as 63,346 Bbl. The pumping rate was 662,400 Bbl/day, and the time to shut down was 19 minutes (10 minutes of evaluation of whether a leak had occurred and 9 minutes to shut down the system). This resulted in a PRV of 8,740 Bbl, and an ALV of 32,763 Bbl. The ALV plus the PRV resulted in a total release of 41,503 Bbl.

TransCanada does not explain how the initial line fill volume is calculated. They simply provide a value (ERP, 2009). For the Hardisty Pump Station/Regina Pump Station calculation, they state the value to be 63,346 Bbl. There is no way to verify this value. Whatever method was used, the value should be the pipeline volume between the leak and the high points of elevation on both sides of the leak. TransCanada then, in what appears to be a flawed process, subtracts the pumping rate volume from the initial line fill volume. It is not clear why this subtraction was done. Apparently, TransCanada considered that since the PRV would be pumped out of the pipeline during the leak discovery and shutdown time, that volume of oil would not be still in the pipeline during draining. However, even though the PRV would be removed from the pipeline during shutdown time, an equal amount would be pumped into the draining section. Therefore, the DDV should be calculated as simply the volume of the draining pipeline modified by the fraction of oil trapped in local low points. That is, the PRV should not have been subtracted from the ILFV. The result of subtracting the PRV from the ILFV was then multiplied by 0.60 to account for 40 percent of the oil in the pipe being caught in locally low spots in the pipeline and failing to drain out. Certainly some of the oil in the pipe will fail to drain, especially in locally low spots; however, considering siphon effects, it is very likely that nearly all of the oil will drain even through the locally low spots. Therefore, the 60 percent drain factor is likely to be a significant underestimate of the fraction of oil that will drain. For this worst case spill analysis, a drainage factor of 80 percent is a more reasonable assumption.

Table 4 shows the PRV, DDV, and total worst-case release estimates for the Hardisty Pumping Station on the original Keystone pipeline using methods recommended in this analysis and methods used by TransCanada (ERP, 2009). Note that the PRV values using the method of this paper are much larger than those using TransCanada's method because the assumed shut-down time is much shorter in TransCanada's method (19 minutes compared to 2 hours). The drain-down volumes used for both methods are the reported drain-down volumes from TransCanada's method because sufficient detail was not available in the TransCanada report (ERP, 2009) to allow a comparison of methods.

Table 4: Worst-Case spill volume estimate using the method recommended in this analysis and the method used by TransCanada for the Keystone Pipeline.

	Estimate from this Paper			TransCanada Estimate[a]		
	PRV (Bbl)	DDV (Bbl)	Total Release (Bbl)	PRV (Bbl)	DDV (Bbl)	Total Release (Bbl)
Hardisty Pumping Station	55,200[b]	32,764[c]	87,964	8,740[d]	32,764[c]	41,504

(a) ERP, 2009
(b) Pumping rate volume = 662,400 Bbl/d (Hardisty) * shut-down time of 2 hours
(c) Drain-down volume reported by TransCanada (ERP, 2009)
(d) Pumping rate = 662,400 Bbl/d * shut-down time of 19 min

Impacts from Worst-Case Spill

<u>Impacts to the Air</u>

The primary impacts to the air will be from benzene, hydrogen sulfide, and light molecular weight constituents of the DilBit. The DilBit will be pumped at high temperatures (up to 158°F) and pressures (up to 1440 psi) causing these compounds to volatilize into the air at the site of the spill. The Occupational Health and Safety Agency (OSHA) acceptable concentration of benzene in the air for a workplace is 3.25 mg/m^3 (NIOSH, 1990) for short-term (8-hour) exposures. Since benzene is denser than air, it could accumulate in low-lying areas that are protected from the wind. Under these conditions, the benzene concentration could be above acceptable levels for inhalation. The basements of buildings located above groundwater plumes could also trap benzene gases that exceed safe levels. This could have serious consequences for the occupants of such a building, who may not be aware that a plume of benzene lies beneath the building.

Hydrogen sulfide is another toxic gas that could cause dangerous conditions at the site. The OSHA acceptable concentration for a workplace is 14 mg/m^3 for an 8-hour exposure and 21 mg/m^3 for even a momentary exposure (NIOSH, 1990). The concentrations of hydrogen sulfide in the air are expected to be above acceptable levels in areas near a spill site (Enbridge, 2010) and will likely be a serious health threat to emergency workers, remediation workers, and possibly to local residents.

In addition to toxicity effects, benzene, hydrogen sulfide, and the light molecular weight fractions of the oil could create explosive conditions as they volatilize from the spilled oil. Again, this risk will be greatest in areas that are protected from the wind and where concentrations could reach the explosive limits.

Impacts to Terrestrial Resources

The proposed pipeline will cross numerous types of terrestrial habitats (e.g., upland prairies, lowland prairies, woodlands, northern high plains, etc.) as it passes from Canada to Texas. Each of these habitats is unique in terms of its physical conditions (e.g., soils, climates), biological communities, and human communities. Because the physical, biological, and human conditions are so varied in these habitats, the potential impacts from a spill will be different for each type of habitat and location. Therefore, it is not possible to thoroughly assess the potential impacts to terrestrial habitats in this paper.

In general, a primary negative impact caused by a crude oil spill on land will be burial and smothering of plants and ground-dwelling animals. The spilled DilBit will form a very dense and thick layer over the ground that will kill essentially any organisms that are contacted. This effect will be localized to the immediate area of the spill, and most animals will be able to avoid contact with the oil. However, some animals may inadvertently contact the oil (e.g., birds landing in the oil) and be harmed or killed. In addition, the spill will release toxic constituents such as benzene, hydrogen sulfide, light molecular weight oil fractions, and polycyclic aromatic hydrocarbons (PAHs), all of which will have toxic effects on local wildlife. A significant concern arises when the pipeline crosses habitats of the numerous threatened or endangered species that are found along the pipeline route. Finally, the spill could affect human communities via exposures to the toxic constituents.

Impacts to Surface Water Resources

The primary constituents of concern in surface water are: benzene, PAHs, hydrogen sulfide, and bulk crude oil. The amounts of these constituents in the surface water are affected by several factors including: the concentration of the constituent in the crude oil, the solubility of the constituent, and the turbulence and velocity of the water. Constituents of special concern are benzene and certain PAHs because they are carcinogenic.

Benzene makes up 0.1 to 1.0 percent of DilBit crude oil (Shell Canada, 2008), and it is relatively soluble in water. The amount of benzene that will be dissolved in the water can be estimated from the octanol-water partition coefficient (a measure of how much of a contaminant will dissolve into the water) which is 131.8 for benzene (LaGrega et al., 2001). Using the octanol-water relationship, and assuming that the benzene concentration in the DilBit is 1 per cent(~$1x10^4$ mg/L), results in a benzene water concentration immediately at the oil/water interface of 75 mg/L ($1x10^4$ mg/L ÷ 131.8). This benzene concentration is 15,000 times the MCL for benzene of 0.005 mg/L. Since the temperature of the DilBit will be up to158^{o}F, the actual water concentration at the spill will likely be somewhat higher than this calculation, which is based on an octanol-water partition coefficient for ambient temperatures. The benzene concentration will decrease with distance from the oil/water interface. TransCanada's Risk Assessment calculated that the average (mixed) benzene concentration in surface water for a 10,000 Bbl spill in a 10,000 ft^3/sec stream would be 2.2 mg/L (ENTRIX, 2010); however, this calculated concentration assumes that all of the benzene would be released into the water within one hour (likely over-estimates resulting concentrations) and that the benzene is immediately mixed across the entire stream (under-estimates resulting concentrations). Note that 2.2 mg/L is 440 times the MCL for benzene. In most cases, the benzene will form a plume that travels downstream from the spill site. The concentration in the plume will gradually decrease as it moves farther from the spill site.

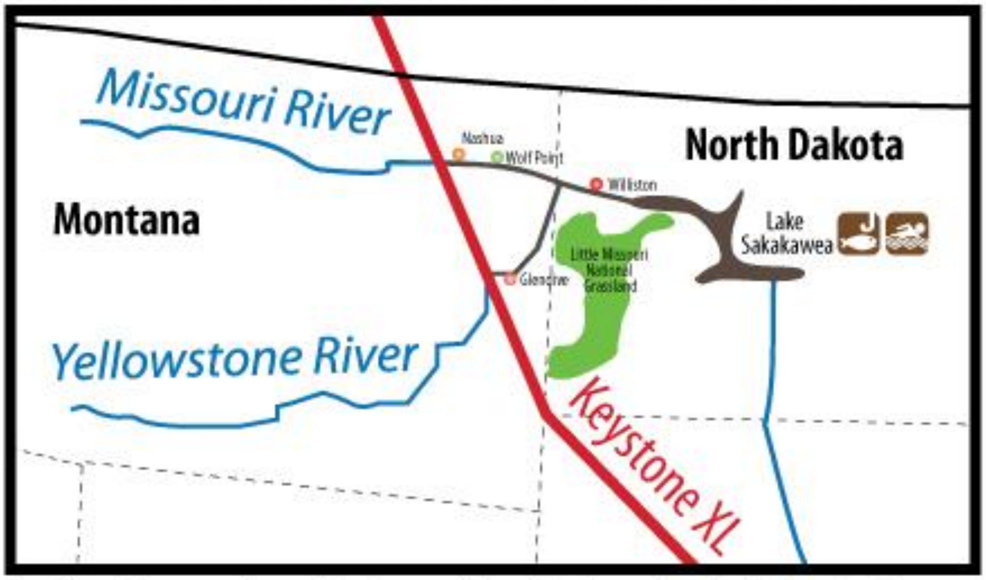
Besides human health risks from contaminated drinking water supplies, benzene also poses risks to aquatic species. The EPA Region III screening water concentration for benzene designed to be protective of aquatic biota is 0.370 mg/L (EPA, 2011b). The predicted benzene concentration at the oil/water interface is 75 mg/L which is 200 times higher than the screening concentration. Therefore, negative ecological impacts due to toxicity are expected, at least in localized areas where benzene is actively dissolving from the oil.

If a spill of 150,000 Bbl (i.e., in the range of predicted worst-case spill volumes) were to occur in a stream with a flow of 10,000 ft^3/sec and a velocity of 3 ft/sec (e.g., the Missouri River below Fort Peck dam has a flow of 9,225 cfs, and the Yellowstone River at Miles City, MT has a flow of 11,180 cfs (USGS, 2009)), the mass and resulting plume of the benzene in the water could be characterized as follows. Assuming that benzene makes up 1.0percent of the DilBit, 150,000 Bbl of DilBit would contain approximately 2.3×10^5 Kg of benzene (150,000 Bbl * 42 gal/Bbl * 3.788 L/gal * 1 Kg/L * 0.01). If 80 percent of the benzene is lost via volatilization and product removal during and immediately after the spill, 4.77×10^4 Kg of benzene would remain in the stream. This benzene would dissolve through time into the water from the DilBit mixture. To be released into the water, the benzene in the mass of crude would have to diffuse to the oil/water interface. Since the composition of DilBit is variable and since the thickness of the crude mass is case-specific (i.e., depends on turbulence, temperature, etc.), it is not possible to predict precisely the rate at which the benzene will diffuse to the oil/water interface; however, a reasonable assumption would be that 5percent of the benzene would reach the oil/water interface per day. If this assumption is too high, these calculations will over estimate the water concentrations but underestimate the duration of the negative impacts, and if it is too small, the opposite will be true. Assuming 5percent of the benzene is released into the water per day, over 2.3 million grams of benzene will be released to the water per day. This will result in a water concentration of 0.09 mg/L (2.3×10^6 g/d * sec/10,000 ft^3 * 1d/86,400 sec *1,000 mg/g * 35.3 ft^3/m^3 * 0.001 m^3/L) once the contaminant plume completely mixes across the entire width of the stream (several miles downstream of the spill). This concentration exceeds the MCL of 0.005 mg/L by 18.8 times. As the benzene plume migrates downstream, the concentration will decrease because of processes such as degradation and volatilization. Reported half-lifes of benzene in surface water range from 1 to 6 days (USEPA, 1986). Assuming a half-life of 3 days, a stream velocity of 3 ft/sec, and a tributary contribution of 20 cfs/mi (the measured value for the Missouri River downstream of the proposed crossing (USGS, 2009)), the plume would reach over 450 miles before its concentration would drop to the MCL and be safe for public water intakes. The plume length was modeled using a series of 10-mile long river reaches with first-order decay ($k=-0.231 d^{-1}$) and increased flow of 200 cfs/10 mi reach.

Contaminants from a release at the Missouri or Yellowstone River crossing would enter Lake Sakakawea in North Dakota where they would adversely affect drinking water intakes, aquatic wildlife, and recreation. Contaminants from a spill at the Platte River crossing would travel downstream unabated into the Missouri River for several hundred miles affecting drinking water intakes for hundreds of thousands of people (e.g., Lincoln, NE; Omaha, NE; Nebraska City, NE; St. Joseph, MO; Kansas City, MO) as well as aquatic habitats and recreational activities. In addition, other constituents from the spill would pose serious risks to humans and to aquatic species in the river.

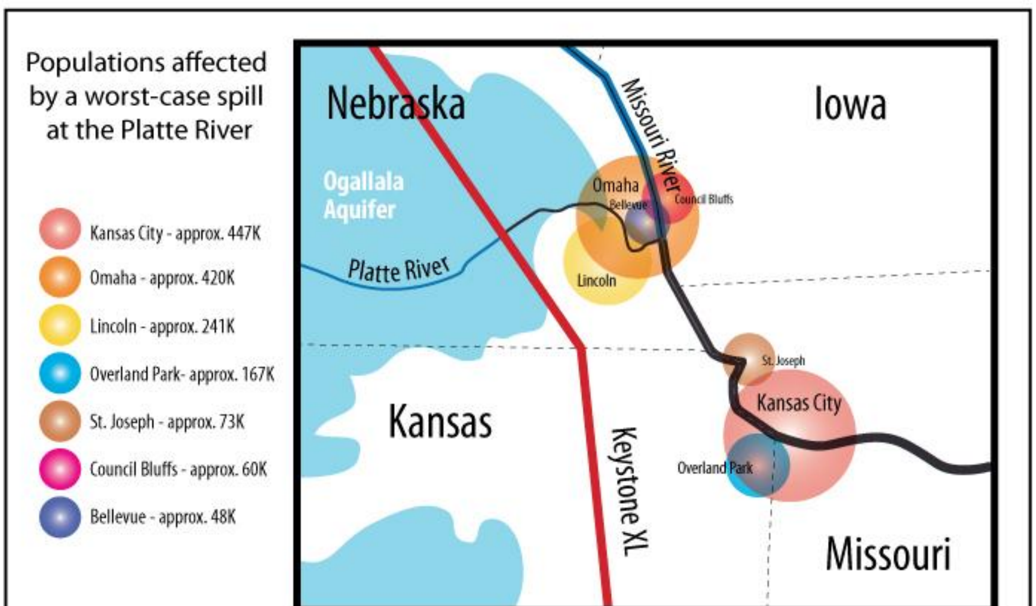
Map 1:

Worst-case spill at the Missouri River or Yellowstone River crossing.



A spill at either crossing could release millions of gallons of crude oil into the rivers and extending downstream as far as Lake Sakakawea, polluting drinking water, and threatening endangered species and recreation areas.

Map 2:



Population estimates based on available data from the U.S. Census Bureau, http://quickfacts.census.gov.
Circles representing these cities are for illustrative purposes and are not to scale.

Of course other assumptions (e.g., shorter half-life) would give somewhat different results. For example, assuming that benzene makes up only 0.3 percent of DilBit and that 10 percent of the benzene is released per day, the calculated plume length would be reduced to around 200 miles. However, since the case-specific details are not known at this point, the precise impacts cannot be calculated; however, it has been clearly shown that if a worst-case spill occurs in a major stream, the impacts would be serious, far-reaching, and long-lasting, and claims to the contrary should be challenged.

The concentrations of PAHs (e.g., benz(a)pyrene) are not specified in the Material Safety Data Sheet(MSDS) for DilBit (Shell Canada, 2008). Also, the risk assessment done for the pipeline (ENSR, 2006) discusses the presence of PAHs, but doesn't detail specific concentrations. Therefore, this analysis will assume that PAHs make up 2 percent of DilBit, and that benz(a)pyrene (BaP) makes up one-tenth of the PAHs or 0.2 percent of the DilBit. This is likely an underestimate. PAHs are not as soluble or as mobile in surface water as is benzene. Much of the released PAH mass will sorb to sediments and remain closer to the location of the spill. However, they will be transported downstream with suspended solids and sediments, and the PAH fraction that does dissolve will form a plume and also be transported downstream. Since they are less soluble and mobile than benzene, PAHs pose less of a threat to municipal water intakes. Using the octanol-water coefficient for benz(a)pyrene (BaP) of 1.1×10^6 (LaGrega et al., 2001), the BaP concentration at the oil/water interface would be 0.0018 mg/L (1.8 µg/L). This concentration exceeds the MCL for BaP of 0.0002 mg/L by a factor of about ten; however, this concentration would be quickly reduced as the plume mixes in the stream. Therefore, based on the assumption that PAHs make up 2percent of the DilBit, drinking water is probably not significantly threatened from release of PAHs.

However, PAHs are toxic to aquatic organisms. The EPA Region III water quality criteria for benz(a)pyrene to protect aquatic species is 0.015 µg/L (EPA, 2011b). In addition, there are several other PAHs with water quality values to protect aquatic species (e.g., benzo(a)anthracene (0.018 µg/L), fluoranthene (0.04 µg/L), and naphthalene (1.1 µg/L)) that are likely to have concentrations that exceed water quality criteria in a major spill. Therefore, the estimated concentration of PAHs is approximately 100 times the allowable level for protection of aquatic life.

Hydrogen sulfide is very volatile, and much of it will likely volatilize to the air during a major spill. However, some of the hydrogen sulfide will dissolve into the surface water and cause toxic effects to the aquatic biota. The EPA Region III screening water concentration protective of aquatic species is 2.0 µg/L. Since the hydrogen sulfide will quickly volatilize, it is expected that these toxic effects will be limited to areas near the spill.

Bitumen, which makes up most of the DilBit, is more dense than water, so it will sink to the bottom and smother any aquatic plants or sediment-dwelling organisms. These effects will be limited to the immediate area of the spill and are expected to pose a significant risk primarily if the stream is the habitat to threatened or endangered species. Since the Missouri, Yellowstone, and Platte Rivers all provide habitat to threatened and endangered species, including the pallid sturgeon, interior least tern, and piping plover, these impacts should be considered potentially significant.

Table 5: Benzene Plume Development for Spill of 150,000 Bbl into a 10,000 cfs Stream.

	Estimate From This Analysis
Spill Volume	150,000 Bbl
Stream Discharge	10,000 cfs
Fully Mixed Concentration[(a)]	0.09 mg/L
Ratio of Concentration to MCL [(b)]	18.8
Length of Plume > MCL [(c)]	450 miles
Duration of Release to Water [(d)]	20 days

(a) mg/sec benzene release to stream ÷ L/sec of flow (10,000 cfs = 283,286 L/sec)
(b) fully mixed concentration ÷ 0.005 mg/L
(c) assumes half-life of 3 d; velocity of 3 ft/sec;
(d) assumes 5percent of benzene is released from DilBit mass per day

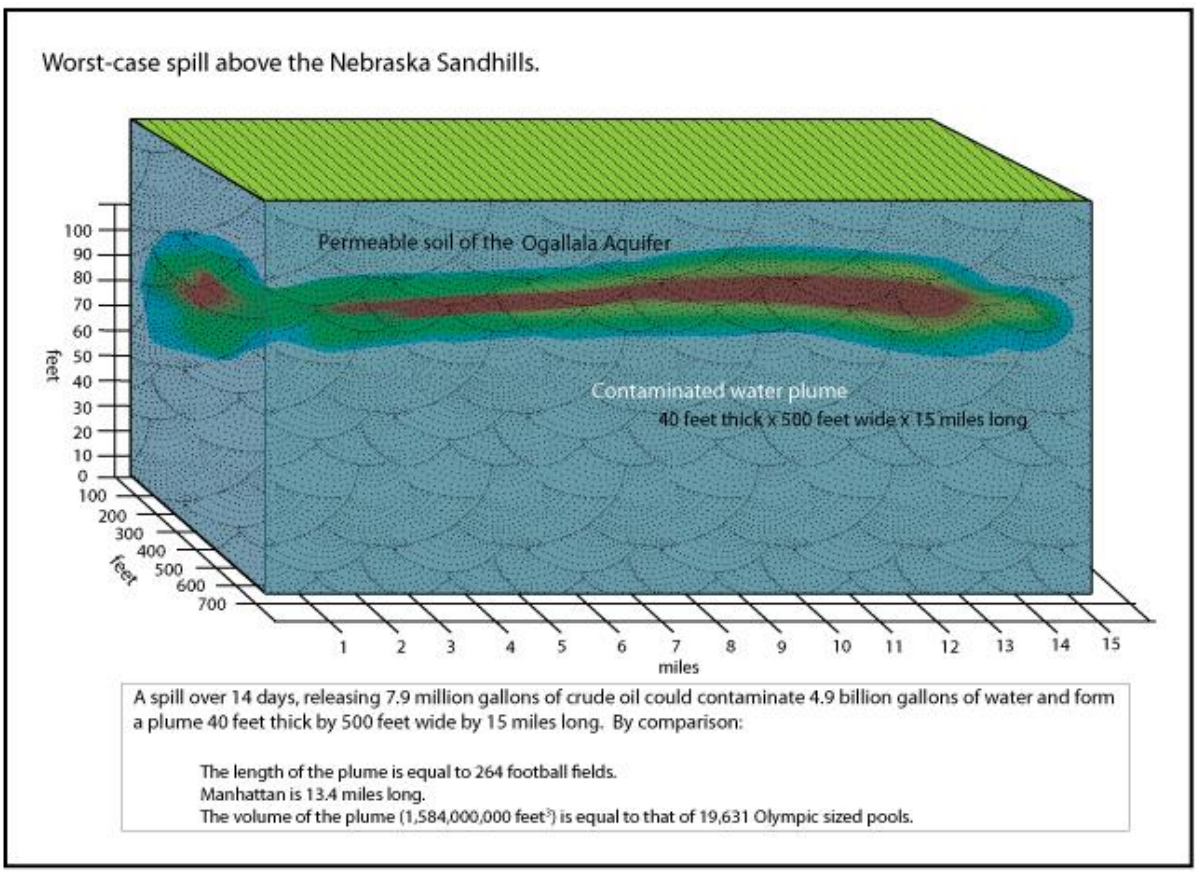
Impacts to Groundwater Resources

The primary constituent of concern for a spill into groundwater is benzene. Since DilBit is very viscous, the bulk crude oil will not likely migrate through the soil to groundwater in large quantities. However, if a small, underground leak remains undetected for an extended period of time, a large amount of benzene will be released with the DilBit. The released benzene could then be transported to groundwater via infiltrating rainwater. According to a TransCanada publication "Frequency-Volume Study of Keystone Pipeline" (DNV, 2006), a leak of 1.5 percent of total flow could remain undetected for 90 days. For this analysis, the discovery and shut-down time is assumed to be 14 days which corresponds to the time between pipeline inspections. At the design flow rate of 900,000 Bbl/d, a 1.5 percent leak would release 189,000 Bbl (7.9 million gallons) of DilBit in 14 days. Since DilBit is 0.1 to 1.0 percent benzene, this would result in a release of up to 79,380 gallons of benzene.

A spill of the magnitude of 189,000 Bbl of DilBit would occupy approximately 2.65×10^6 cubic feet of subsurface sands with a porosity of 0.4 (189,000 Bbl * 5.61 ft^3/Bbl ÷ 0.4). Assuming that theDilBit mass occupies a somewhat cylindrical volume and that the aquifer is 20 feet below the pipeline, the DilBit would spread to an area approximately 335 feet in diameter (335 feet diameter X 30 feet high). A reasonable worst-case 100-year, 24-hour storm would deposit 6 inches of rainwater on the site. In the Sandhills of Nebraska, nearly all of this water would infiltrate. Six inches of water infiltrating onto a contaminated area of 8.8×10^4 ft^2 (335 feet diameter) results in 4.4×10^4 cubic feet of water (8.8×10^4 ft^2 * 0.5 ft infiltrating water) contacting the DilBit. Using the octanol-water partition coefficient of 131.8 (LaGrega et al., 2001), the benzene concentration in the infiltrating water would be approximately 75 mg/L.

The 4.4x10^4 cubic feet of water at a concentration of 75 mg/L equates to 9.35x10^7 milligrams of benzene. Thus, this storm would transport 9.35x10^7 milligrams of benzene to the groundwater. Once in the groundwater, the benzene plume would migrate down-gradient, potentially to down-gradient water supplies or basements where it could pose a cancer risk to residents. The 9.35x10^7 milligrams of benzene in the groundwater, if evenly distributed (not likely) could pollute 1.9x10^{10} Liters (4.9x10^9 gallons) of groundwater at the MCL, enough water to form a plume 40 feet thick by 500 feet wide by more than 15 miles long (assuming porosity of 0.4) at the MCL. These plume dimensions are given for illustrative purposes only. The actual dimensions of a groundwater plume cannot be determined with the available information. Of course, the benzene would not be evenly distributed; however, the plume would still be many miles long. In addition, future storms would transport additional benzene to the groundwater increasing the size of the plume.

Figure 4:



The worst-case site for such a spill is in the Sandhills region of Nebraska. The Sandhills are ancient sand dunes that have been stabilized by grasses. Because of their very permeable geology, nearly 100 percent of the annual rainfall infiltrates to a very shallow aquifer, often less than 20 feet below the surface. This aquifer is the well-known Ogallala Aquifer that is one of the most productive and important aquifers in the world.

Table 6: Benzene Plume from a189,000 Bbl Spill to Groundwater.

Volume of released DilBit (Bbl)	189,000
Volume of benzene in spill (gal)	79,380
Mass of benzene dissolved in groundwater (mg)	9.35×10^{7}
Volume of contaminated water > MCL (gal)	4.9×10^{9}
Equivalent plume dimensions	40 feet X 500 feet X 15 miles

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