# Pipelines and Parks: Evaluating External Risks to Protected Areas from the Proposed Northern Gateway Oil Transport Project

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RESEARCH ARTICLE

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# Pipelines and Parks: Evaluating External Risks to Protected Areas from the Proposed Northern Gateway Oil Transport Project

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**ABSTRACT**: Protected areas increasingly face degradation from both internal and external stressors. One increasingly relevant external threat is oil contamination, which has well documented negative impacts on terrestrial and aquatic ecosystems. To evaluate such potential threats in environmental management, risk analysis has expanded as a discipline. Here, we derive a risk index for protected areas in British Columbia, Canada, that are located downstream from the proposed Northern Gateway pipeline along its 680 km route across the province. Using a Geographic Information System (GIS) approach, our risk model incorporates both the probability of oil – once spilled – contaminating a park and the consequence of such exposure. We identified 34 protected areas located downstream and potentially at risk. Two were within 50 meters of the proposed pipeline route. Of downstream parks, we found that some were at twice the risk of others. In general, higher risk parks were not any closer to the pipeline but were, on average, of larger areas. The Fraser River watershed, which hosts British Columbia's most economically valuable salmon runs, contained the most parks at risk. From an environmental impact assessment and park management perspective, our results can help identify and evaluate the potential adverse effects of pipeline ruptures. The information can be used to determine, systematically, which parks most urgently require spill response plans and where baseline environmental monitoring might be best deployed. Given that oil transport, a rapidly growing enterprise, is only one of many stressors that threaten natural areas, decisions concerning industrial proposals benefit appreciably from risk analysis.

*Index terms:* Enbridge Northern Gateway Project, external threats, oil pipeline, protected areas, risk analysis

## INTRODUCTION

The establishment and maintenance of protected areas (or parks) is a primary means by which managers prevent extinction and loss of ecological function that stems from habitat destruction elsewhere (Pimm 2001; Hockings 2003). Protection of ecological function and habitat is achieved through both permanent reservation and effective management (Bruner et al. 2001; Dudley 2008). Increasingly, however, evidence is emerging that the ecological integrity of many parks is degrading from both internal and external stressors (Liu et al. 2001; Locke and Dearden 2005; Cameron 2006; Dearden and Rollins 2009; Auditor General of British Columbia 2010).

Whereas internal threats like vehicular collisions and recreational impacts might be evaluated with existing policy, external threats to protected areas are particularly problematic because activities beyond park boundaries are not usually subject to park jurisdiction (Giesser 1993; Lockwood et al. 2006). Park boundaries cannot always constrain the diffuse nature of many human-caused influences on natural systems. Protected areas are part of larger ecological systems that are influenced by inputs from nearby systems (e.g., Cameron 2006; Timko and Satterfield 2008; Darimont et al. 2010). Planning for marine parks, for example, has identified important 'downstream' land-to-sea stressors such as siltation or contaminants from agriculture or industrial logging that can alter the function of the near-shore environment (Stoms et al. 2005; Tallis et al. 2008; Halpern et al. 2009).

Ruptures and spills from petroleum pipelines, which are common and often severe, are another downstream process that can affect parks. Within Canada, a 10 to 1000 $m^3$ spill has occurred on average every 16 years per 1000 km section of pipeline (National Energy Board 2010). Van Hinte et al. (2007) calculated that the average spill between 1992 and 2002 among eight major spill events in Canada was 9814 barrels, with the largest spill being over 25,000 barrels. As a result, pipelines can have large downstream effects within and beyond protected areas (Oilwatch 2004; Van Hinte et al. 2007; United States Environmental Protection Agency 2011). Resultant contamination can lead to reductions in survivorship across a wide range of taxa, species diversity, and productivity in terrestrial and aquatic ecosystems (e.g., Kinako 1981; Vinson et al. 2008; Vosyliene et al. 2008).

In Canada, the potential impact of pipelines is of increasing concern due to growing global demand for petroleum and the rapid expansion of the Alberta tar sands. This region hosts the world's third largest proven

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oil reserve. There, bitumen – a heavy and viscous hydrocarbon – is recovered from the sand and water matrix in which it is embedded by surface mining or by steam injection. The associated network of pipelines and the volume of oil transported in Canada are expanding briskly. Between 1990 and 2001, Canada's oil and natural gas pipelines experienced a 44% and 88% growth rate in volume of transported materials, respectively (Canadian Energy Pipeline Association 2002). Over the next decade, proposed projects, and upgrades of existing pipelines within Canada, could increase the volume of oil transported by over 400,000 additional barrels per day (Van Hinte et al. 2007; Canadian Association of Petroleum Producers 2011).

With a growing network of pipelines and some non-zero probability of rupture, prudent management of parks and other sensitive areas can benefit from an evaluation of risk. Risk can be quantified as a function of the *probability* of an event occurring and the *consequence* of that event (Farrar et al. 2009). Risk management has been central to social and governance development over the past 10,000 years (McDaniels and Small 2004). Risk analysis has expanded as a discipline to address the role that uncertainty and precaution should play in our management decisions. In the context of oil transport, identifying areas where risk might be greatest, for example, provides managers the opportunity to plan how resources for spill responses might be distributed over space. Such results from risk assessments might be particularly important for park managers and policy makers, who are responsible for safeguarding society's conservation investments in the form of protected areas.

Here we use a risk analysis framework to assess the potential risks posed to parks in British Columbia (BC), Canada, by the proposed Enbridge Northern Gateway project. The proposed development would comprise one of the largest oil pipelines in North America and would transport more than 79,000,000 liters of petroleum daily (500,000 barrels). The pipeline would extend 1172 km from Bruderheim, Alberta, to Kitimat, BC (Van Hinte et al. 2007; Enbridge Incorporated 2010; Figure 1). The proposed project includes two parallel pipelines, one an eastward flowing structure carrying condensate (a natural gas product used to thin bitumen [crude oil from the Albertan Tar Sands] for transport) and a second flowing westerly to transport the mixture of condensate and bitumen (Enbridge Incorporated 2010). Although the pipeline would directly avoid all protected areas in BC, 34 parks are downstream of the proposed route. Twenty one (total area = 2400 km$^2$) are located within 200 km. This $5.5 billion project is currently being evaluated by the National Energy Board of Canada, which has solicited information by the proponent and teams of interveners. Here we contribute to this process by developing a risk index to: (1) rank each protected area in BC in order of relative risk posed by the proposed pipeline and; (2) identify watersheds of particularly high ecological and societal value that are potentially at risk.

## METHODS

### Site Description

Owing to the varied terrain and climates of the landscape, BC hosts the greatest biodiversity in the country (Francis 2000). About 14% of the land base is protected (Della Sala et al. 2001; Dearden and Rollins 2009; Province of British Columbia 2011). Although crossing parts of neighbouring Alberta, the largest portion of the route (approximately 670 km) bisects BC and crosses a wide variety of landscapes, including the Rocky Mountains, the Interior Plateau, and the Coast Mountains (Figure 1). This portion of the pipeline would include 591 water crossings, 532 of which are fish bearing (Enbridge Incorporated 2010).

### Data Analysis

We identified 11 major watersheds – as defined by the BC government's Basemapping and Geomatic Services Branch (http://www.basemaps.gov.bc.ca) – that intersect the proposed pipeline project. Within these, we identified 34 protected areas that are downstream and potentially at risk from oil contamination. We determined downstream parks by tracing the downstream route through stream networks; intersection points between the pipeline and the stream network were assigned as source nodes, and park boundaries were assigned as destination features.

To rank the relative risk posed by the Northern Gateway project to each of these 34 downstream parks, we created a risk index. Similar to models used to create risk indices for weather-related loss events and natural disasters (e.g., Peduzzi et al. 2001; Harmeling 2011), we developed a model that estimates relative risk over a large spatial scale. It provides a quantitative estimate of risk, following an equation commonly employed in the risk analysis literature, which has *probability* and *consequence* components (e.g., Kaplan 1997; Peduzzi et al. 2001; McDaniels and Small 2004; Kirchhoff and Doberstien 2006; Kirchoff et al. 2007; French-McCay et al. 2009): Risk = $f$(consequence, probability). Consequence, a proxy for what is at stake should a spill event occur, had three subcomponents: (1) the "ecological value" of a protected area, (2) its size, and (3) its area-to-perimeter ratio. Probability, an estimate of how likely each park was compared to each other to be subject to a spill, was also comprised of three sub-components: maximum water flow and length of pipeline in the watershed in which a park existed and the distance of the park from the pipeline. Detailed information for each sub-component and how they were calculated is presented in the Appendix.

### Model form

To examine the spatial variation in risk among all candidate parks, we first calculated quartiles for all six variables (EV, AREA, A/P, FLOW, LENGTH, DISTANCE; see Appendix). For all but DISTANCE, we assigned quartiles a categorical value of low, medium-low, medium-high, and high based on the magnitude of the original observations. Inverse rankings were assigned to the DISTANCE quartiles, owing to the negative relationship between a park's distance from the pipeline and the probability of impact. To standardize the contribution of each

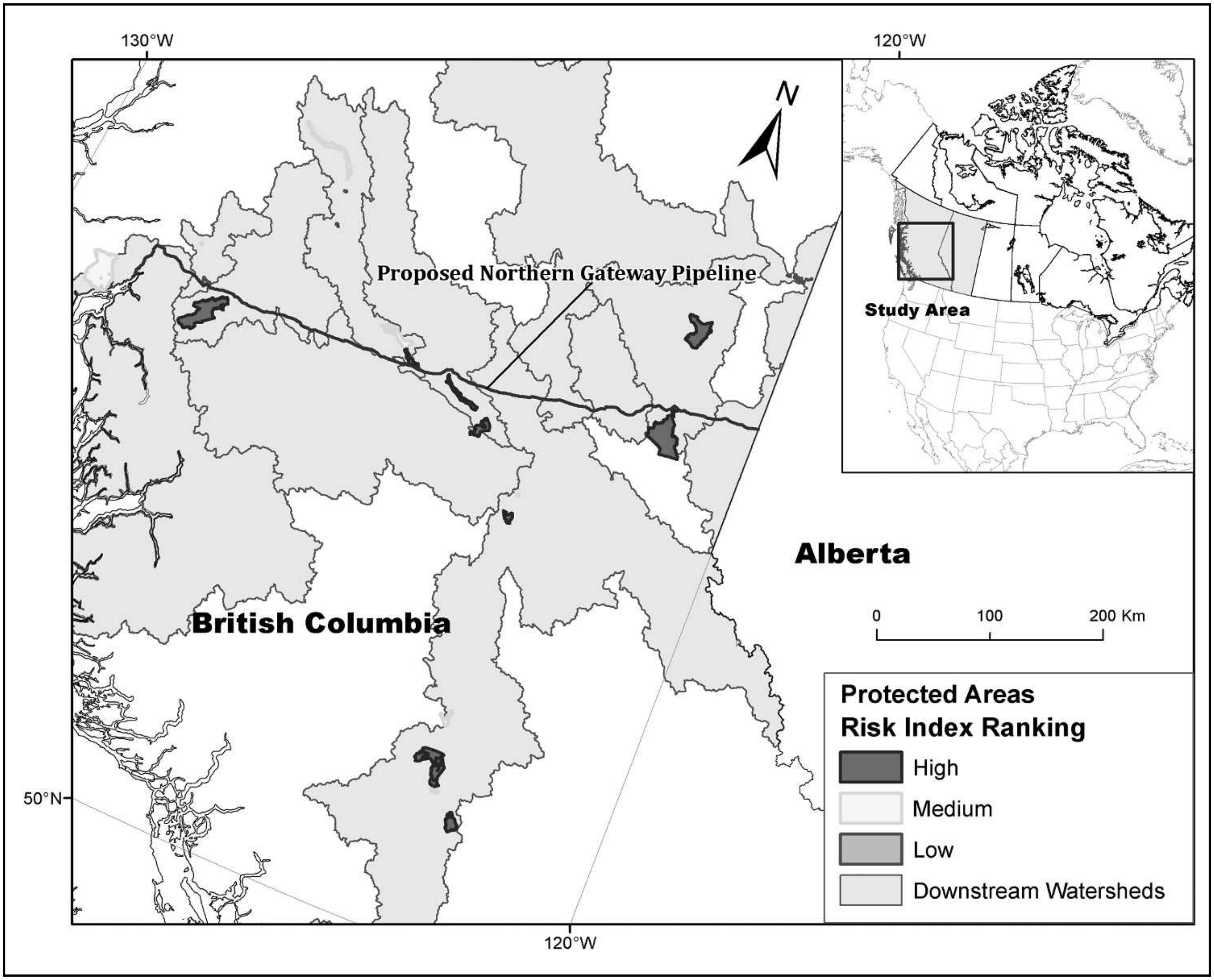

**Figure 1: Downstream protected areas (n = 22) relative to the proposed Northern Gateway pipeline route in British Columbia, Canada. Parks coded in grayscale shades according to their risk ranking (note: some are too small to resolve at this scale). Risk index ranking is based on 3 classes of quantiles: High (rankings 1-2), Medium (rankings 3-6), and Low (rankings 7-10). Shown also are 11 major watersheds intersected by the BC portion of the proposed pipeline.**

variable to the model, we then assigned numerical analogues as follows: low = 1, medium-low = 2, medium-high = 3, and high = 4.

We explored three alternative model forms to combine scores from the six variables. An additive model simply added the assigned numerical category for all six variables, giving equal weight to each. A multiplicative model multiplied the sum of the numeric categories for both the probability and consequence components. Finally, a scaled multiplicative model normalized the probability term by scaling each probability variable by 12; the resulting scaled probability was then multiplied by the summed consequence component. In all model types, the risk indices assigned the highest values to parks that had the highest cumulative score for risk.

We undertook several steps to assess if our methods of categorizing (i.e., scoring) model inputs and combining them in various model forms had any influence on park risk rankings. Note that because our models were not statistical models with error terms, we did not undertake an information theoretic or similar approach. First, we conducted sensitivity analyses to examine any potential change in rankings if categories other than quartiles were used. Rankings based on two and eight bins yielded identical results to the quartile rankings (i.e., top 10 rated parks were the same across all three bin sizes). Next, we used a pair-wise Spearman's r correlation to test for any correlation between the two components of risk. We found none (r = 0.202, p = 0.37), suggesting that relative rankings were weighted by both probability and consequence. We also conducted a pair-wise Spearman's r correlation (among final park risk scores across model forms).

The integrative risk scores were all highly correlated (additive-multiplicative; r = 0.99; additive-scaled multiplicative r = 0.99; multiplicative-scaled multiplicative r = 1.00; all P < 0.01). Additionally, we inspected how similar the rankings were across all three model types among parks that ranked in the top 10. All three models returned identical top ranked parks. Accordingly, we chose the simple additive approach to compute final risk values for each park. For illustrative purposes, we classified these final risk values into *high* (relative rankings of 1 to 2; i.e., top two parks at risk), *medium* (rankings of 3 to 6), and *low* risk (rankings 7 to 10) categories.

## RESULTS

The 22 downstream parks we evaluated varied in their risk ranking, with most-at-risk parks having risk values twice those of least-at-risk parks (Table 1). The highest risk category contained four protected areas: Monkman Park, Gwillim Lake Park, Stuart River Park, and Fraser River Park. Within this group, the average distance from the pipeline was 102 km compared to an average of 303 km across all parks. Other protected areas in the high risk category, however, were up to 500 km from the proposed pipeline and in the Pine, Stewart, and Fraser watersheds. Many parks clustered near the pipeline route; the Stuart and Zymoetz watersheds contained two parks (Sutherland River and Burnie River PAs) situated only 0.01 and 0.05 km from the proposed pipeline route. The Fraser River, BC's largest watershed, contained the most downstream parks at risk in the province (n = 11). The Zymoetz watershed contained the highest proportion of its parks at risk (0.67; Figure 2).

Compared with lower risk parks, those in the high risk category varied in size but not other features. High risk parks were significantly larger than the medium and low risk parks (average area of high risk = 284.19 km$^2$, medium risk = 120.75 km$^2$, and low risk = 8.35 km$^2$; ANOVA $F_{2,19}$ = 4.08, p = 0.03). There were no significant differences, however, in mean Ecological Value (ANOVA: $F_{2,19}$ = 1.04, p = 0.37) or distance to the pipeline (ANOVA: $F_{2,19}$ = 0.010, p = 0.99) among the risk categories.

## DISCUSSION

Here we used a risk assessment framework to rank the relative threats the proposed Northern Gateway oil pipeline might present to downstream parks in BC. In doing so, we contribute to the provision of 'adequate and objective information,' a criterion that Van Hinte et al. (2007) assessed as deficient in their evaluation of best practices required for impact assessments related to the growing pipeline industry in North America. Typically, they note, information about potential benefits and costs of proposed projects are presented by the proponent.

Several applied implications emerge from our results. From a park management perspective, our results can alert park managers to the general risk posed by oil transport and development outside park boundaries. Given the determination and resources to plan accordingly, our findings can also prioritize which parks might most urgently require spill response plans and equipment as well as baseline environmental monitoring. Moreover, our findings have identified two protected areas (Sutherland River and Burnie River Parks) that are located within 50 m of the proposed pipeline route, potentially making them susceptible to direct (i.e., non-rupture related) impacts from construction of the pipeline and associated right-of-way.

Given that the Fraser watershed: (1) contains the greatest number of parks at risk in BC, and (2) has the highest mean flow rate (Table 1), the watershed might be of particular relevance to decision-makers. Notably, the Fraser watershed hosts the largest and most economically valuable salmon runs in BC (and indeed, the world; Quinn 2005). All 11 downstream parks in the watershed host spawning areas for at least one salmon species (Fisheries and Oceans Canada, unpubl. data).

Our risk index, a parsimonious metric to assess relative risk, was the first attempt to document the risk posed by the proposed Northern Gateway pipeline to any area in BC. The results returned rankings that would likely differ from naïve predictions based on distance alone. As our model incorporated components of not only probability (for which distance is an intuitive component) but also consequence, our risk rankings suggest that this project poses risk to a greater breadth of parks than consideration of proximately alone would suggest. Conversely, whereas park managers might intuitively assume that parks closer to the pipeline would be at increased risk, our risk analysis suggests otherwise. Several distant protected areas (Fraser River Park and Gwillim Lake Park with probability values reduced by their distance) have higher consequence loadings (such as high Ecological Value, Area, or Area-to-perimeter shape) and, as a consequence, were in the high risk category.

Despite the utility of our preliminary assessment, the unavailability of commercial software that can simulate in detail the dispersion of spilled oil constrained our capacity to build a more sophisticated risk model. We used highest water flow rate in each watershed as a proxy for oil flow. Clearly, water flow rate is important, but several additional variables would also matter – among them: (1) water temperature, (2) ambient temperature, (3) viscosity of spilled material, (4) shoreline vegetation characteristics, (5) substrate material, (6) shape of water body path, and (7) quantity of spill material (Yapa and Shen 1994; Danchuck and Wilson 2010). Additionally, as condensate and diluted bitumen have different dispersion behaviors, scenarios to simulate the spread of different spill compositions need to be conducted to estimate more accurately the potential spatial impact of a pipeline rupture (Jeglic 2004).

Interpretation of our results relies on an understanding of risk as applied to pipeline failures. Here we have estimated the relative risks posed once a spill has occurred, not the probability of a spill occurring. Moreover, the probability component of our model is not an absolute measure of the likelihood of an oil spill affecting a given park. Rather, it indexes the probability of an oil spill affecting a specific protected area relative to all others. In future research, a more sophisticated model could include variables that can contribute to

**Table 1.** **Risk index values from 21 protected areas in British Columbia, Canada, located downstream from the proposed Northern Gateway oil pipeline. Values were calculated from additive combination of six input variables, representing both the consequence of an oil spill and the probability of an oil spill reaching a park. Each variable's score was normalized based on quartiles derived from the magnitude of the original estimate. Ecological value is derived from an integrative dataset of seven proxies that represent the ecological significance of each park.**

| | | | Consequence | | | Probability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rank | Protected Area | Major Watershed | Ecological Value | Area (km$^2$) | Area to Perimeter Ratio | Length of Pipeline (km) | Flow (m$^3$/s) | Distance from Pipeline (km) | Risk Index Value |
| 1 | Monkman Park | Pine | 11.8 | 629 | 4076 | 65.13 | 627.75 | 45.73 | 20 |
| 1 | Gwillim Lake Park | Pine | 15.4 | 325 | 2716 | 65.13 | 627.75 | 205.43 | 20 |
| 1 | Site | Stuart | 20.3 | 210 | 1215 | 51.87 | 303.05 | 3.9 | 20 |
| 1 | Fraser River Park | Fraser | 18 | 49 | 1202 | 64.49 | 4942.14 | 150.84 | 20 |
| 2 | Morice Lake Park | Bulkley | 10.3 | 525 | 2889 | 118.64 | 287.33 | 10.21 | 18 |
| 2 | Sutherland River Park | Stuart | 19.8 | 48 | 1011 | 51.87 | 303.05 | 0.05 | 18 |
| 2 | Churn Creek Park | Fraser | 9.4 | 369 | 1420 | 64.49 | 4942.14 | 435.31 | 18 |
| 2 | Edge Hills Park | Fraser | 12.8 | 118 | 1522 | 64.49 | 4942.14 | 503.81 | 18 |
| 3 | Sutherland River Park | Stuart | 17.9 | 136 | 1235 | 41.44 | 51.78 | 14.96 | 17 |
| 3 | Foch - Gilttoyees Park | North Coast | 9.8 | 611 | 4184 | 86.24 | 47.54 | 106.83 | 17 |
| 4 | Junction Sheep Range Park | Fraser | 6.9 | 48 | 903 | 64.49 | 4942.14 | 390.37 | 16 |
| 4 | Babine River Corridor Park | Babine | 21.9 | 154 | 938 | 41.44 | 51.78 | 177.37 | 16 |
| 5 | French Bar Creek Park | Fraser | 8 | 12 | 552 | 64.49 | 4942.14 | 472.95 | 15 |
| 5 | Fort George Canyon Park | Fraser | 12.5 | 2 | 234 | 64.49 | 4942.14 | 127.62 | 15 |
| 6 | Foch Gilttoyees Marine Park | North Coast | 15 | 1 | 184 | 86.24 | 47.54 | 106.83 | 14 |
| 6 | Swan Creek Park | Zymoetz | 17 | 3 | 411 | 18.09 | 285.1 | 33.26 | 14 |
| 7 | Burnie River Park | Zymoetz | 11.1 | 23 | 972 | 18.09 | 285.1 | 0.01 | 13 |
| 7 | Peace River Corridor Park | Peace | 10.9 | 20 | 545 | 47.58 | 627.75 | 265.13 | 13 |
| 8 | Kiskatinaw River Park | Peace | 13 | 2 | 337 | 47.58 | 627.75 | 270.32 | 12 |
| 8 | Rainbow Alley Park | Babine | 16 | 1 | 196 | 41.44 | 51.78 | 165.32 | 12 |
| 9 | Beatton River Park | Peace | 9.2 | 2 | 219 | 47.58 | 627.75 | 255.25 | 11 |
| 10 | Babine Lake Marine Park | Babine | 8 | 1 | 215 | 41.44 | 51.78 | 131.79 | 10 |

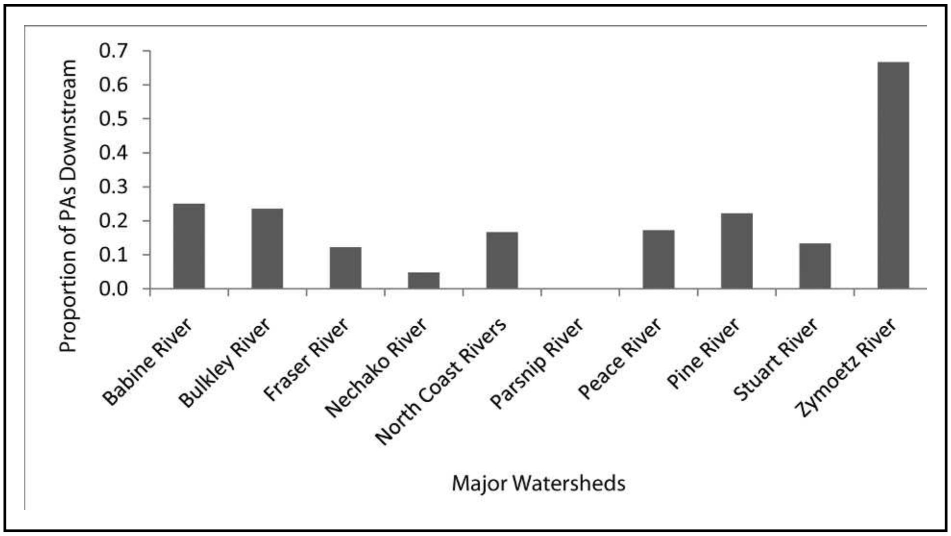

**Figure 2. Proportion of protected areas within major watersheds in British Columbia, Canada, that area potentially at risk (i.e., downstream) from the proposed Northern Gateway pipeline.**

the probability of a spill occurring. These include: construction methods and materials, materials transported, age of pipeline, and geography of landscape (Etkin 1999; Young et al. 2004).

If flowing water bodies are a major mode of transport for spilled oil, why do we expect parks that do not contain major water bodies, or extend far beyond them, to be at risk? Available evidence suggests that a spill can affect a greater spatial extent than solely waterways. The riparian zone, as the interface between aquatic and terrestrial ecosystems, is exceptionally vulnerable to pipeline oil spill contamination (Lytle and Peckarsky 2001). Extending from this area, however, oil contamination can potentially harm terrestrial ecosystems through both the biological (movement of individuals for feeding or reproduction) and geophysical (movement of matter through gravity, fine scale hydrological systems, etc.) connectivity that unites the terrestrial and aquatic ecosystems (Beger et al. 2010). This connectivity across fine to large scales can lead to contamination by polyaromatic hydrocarbon (the primary chemical of concern in crude oil) in terrestrial organisms (Brandt et al. 2002; Smith et al. 2007). For example, an experimental study on herring (*Clupea pallasii*) and great black backed gulls (*Larus argentatu* and *L. marinus*) found that petroleum can transfer from an adult's feet and plumage to an incubating egg, which negatively affects reproductive success to such a degree as to impact populations significantly following a spill (Lewis and Melecki 1984). Similarly, in earthworms (*Eisenia fetida),* which comprise a primary food source for many terrestrial birds and mammals (Malcolm and Shore 2003), survival rates have been shown to be negatively correlated to hydrocarbon contamination (Saterbak et al. 1998). Finally, as evidence from recent oil pollution suggests, the dynamics of catastrophes from oil pipeline and extraction structure failure are unpredictable. For example, shutting off and cleaning up the British Petroleum spill in the Gulf of Mexico in 2010 was considerably delayed and complicated by human error, equipment malfunction, weather events, and their interaction (Safina 2011). Similarly, a 2011 Exxon Mobil rupture on the Yellowstone River, Montana, was thought to be the result of unpredictable erosion of stream banks caused by unusually high water levels (Reardon 2011). Similarly unpredictable processes might lead to oil contamination in BC areas not yet obvious.

Oil transport and its associated risks we outline above is only one of many industrial activities that will increasingly threaten natural areas as demand for resources grow. Accordingly, policy makers, who weigh these risks against their benefits, can increasingly benefit from risk analysis decision tools. Our straightforward risk indexing approach integrates information across a large spatial scale to create a snapshot of potential risk that is easy to interpret. Similar methods can be applied to a variety of management-decision portfolios. The interpretation of results and the subsequent decisions, however, occur within the arena of societal values (McDaniels and Small 2004).

Protected areas' managers are among those decision-makers that can benefit from risk analysis frameworks. Park management now includes ecological triage as protected areas increasingly become habitat islands degraded by cumulative within- and trans-boundary disturbances. At establishment, most parks are embedded in a benign matrix. As disturbances accumulate, however, the landscape matrix becomes more hostile, and the ecosystem structures and functions of the embedded parks are impaired by human-caused stresses (Carroll et al. 2004). Accordingly, political and societal deliberation over large industrial proposals, such as the Northern Gateway pipeline, might choose to incorporate this broad perspective into decision making.

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**Appendix.**

**Appendix.** Explanation and calculation of Consequence and Probability components of Risk Model.

*Consequence*

Consequence is defined as the impact that would occur if the potential event – in this case a pipeline failure – were to occur. As a proxy for consequence, we estimated the ecological significance of each protected area. This was comprised of three variables: (i) an “ecological value” (“EV”) metric, which is an integrative measure of the ecological significance of each park; (ii) area (“AREA”) to account for the size of the park, owing to the established relationship between patch size and diversity and/or ecological function (e.g. MacArthur and Wilson 1967; Fahrig 1997; Bender et al. 1998; Gascon et al. 2000); and (iii) area-to-perimeter ratio (“A/P”) to account for the shape of the park and the potential for negative “edge effects,” whereby ecological disturbances can penetrate into protected areas along edges (Murcia 1995; Woodroffe and Ginsberg 1998).

We calculated these variables in the following way. EV was computed as a mean value of an amalgamated raster data set of Ecological Value of Intact Forest Landscapes created by Global Forest Watch Canada (GFWC; 2010). In their calculations of EV, GFWC included seven key features thought to contribute to overall ecological value of each 1 km2 pixel, including: soil organic carbon, net biome productivity, presence of wetlands, lakes and rivers, presence of old-growth forest, species diversity (amphibians and reptiles, birds, mammals, trees), and presence of key focal species (e.g. woodland caribou, grizzly bears, etc.). Derived for forested areas only, data were absent for 12 of the 34 downstream parks. The excluded parks, however, were very small, averaging 1.4 $km^2$ compared with an average of 149.5 $km^2$ for the included parks. As a result, only 0.5% of all downstream protected area in BC was excluded. AREA and A/P were calculated from the park polygons projected in a BC Albers projection.

*Probability*

We defined probability as the likelihood that an upstream pipeline failure would impact a given park (and not that a particular region of the pipeline would fail in the first place). We used three variables to estimate probability: (i) maximum flow within each watershed (FLOW) containing a downstream protected area, which accounts for the rate at which oil would travel in waterways downstream; this is because flowing water bodies are a major mode by which spilled oil contaminates other areas (Danchuk and Wilson 2010; Enbridge Incorporated 2010; United States Environmental Protection Agency 2011); (ii) length of pipeline within each watershed (LENGTH) containing a park (pipeline spill frequency predictions are measured according to pipeline length; National Energy Board 2010); and (iii) distance from the pipeline (DISTANCE) of each PA to account the fact that, all others things equal, spilled oil is less likely to reach more distant parks.

We calculated these variables as follows. FLOW was determined based on a daily average flow rate of the highest stream order within each watershed, averaged for the month of June over the previous 25 years (Environment Canada 2011). We selected June because the highest monthly flows within BC are observed then. LENGTH was calculated by clipping each pipeline segment by watershed boundaries and was assigned to all parks within that watershed. Finally, to calculate the minimum DISTANCE from the pipeline to each protected area, we conducted a network analysis of the streams within the Pacific and McKenzie drainage units (Atlas of Canada 2008). We used park edges (for parks intersected by the stream network) and park centroids (for those not intersected) as origin points in this calc-

*Continued*

**Appendix (Cont'd).**

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ulation. Thirty-five meter pipeline interval points were used as destination features in the network analysis. In cases when multiple distances were generated, we selected the shortest distance.

Data and other limitations compelled us to make several assumptions in our probability estimate. First, due to lack of empirical data on pipeline rupture likelihood, we assumed all locations were equally likely to fail. Second, because flow data for the Smokey River did not exist, we excluded candidate parks (n = 5, total area = 1,028 km$^2$) within this watershed from the analysis. Third, we used water flow velocity (FLOW) as a proxy for oil flow velocity. This approach does not incorporate other factors that mediate oil flow (e.g. water temperature, ambient temperature, viscosity of spilled material, shoreline vegetation characteristics, substrate material, shape of water body path, and quantity of spill material; Yapa and Shen 1994; Danchuck and Wilson 2010), which can affect adhesion and evaporation of oil (Owens and Henshaw 2002). A fine-scale oil modeling software package incorporates many of these elements (OILMAPLANDTM, Applied Science Associates, Limited). Despite multiple attempts, however, we were not permitted to purchase it from its vendor.

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