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The tip of the iceberg: Three case studies of spill risk assessments used in environmental impact statements

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ABSTRACT

Environmental impact statements (EISs) are based on science produced about specific project proposals, which results in a large body of grey literature. Spill risk estimates are part of that body of work. This is a critique the spill risk models cited in EISs for proposed drilling on the Alaskan Coastal Plain, the Pebble Mine transportation corridor, and Arctic offshore drilling, which are scored against published standards of best practices for ecological risk assessments. After a detailed peer review of Arctic offshore drilling risks, the findings and results from internal and external review processes of those reports are described. The amount of grey literature cited in recent EISs and how the alphanumeric ratings of draft EISs changed in 2017 are shown. Suggestions of how agencies, scientists, and peer reviewed journals can contribute to meaningful review of grey literature in regulatory science are offered.

1. Introduction

Spill research is a fairly young discipline, often produced in highly episodic ways in reaction to spills that occurred near major population centers or otherwise received substantial media attention (Murphy et al., 2016). Most modeling studies in oil spill research are concerned with the fate and effects of oil after it has been spilled and subsequently moves through the environment and organisms. Models, which were initially a very small proportion of the field, have increased to 10–15% of published work in recent decades (Murphy et al., 2016). There are few examples in the peer reviewed literature of models that estimate the risk of an oil or other hazardous material spill occurring (but see Anderson and LaBelle, 1990, 1994, 2000; Eschenbach et al., 2010), and even fewer are specific to the Arctic. Instead, policy decisions about whether and where to pursue drilling or mining are made based in part on research performed by scientists within the Bureau of Land Management (BLM), the US Army Corps of Engineers (USACE), the Bureau of Ocean Energy Management (BOEM), among other federal agencies, and those under contract to them or the project proponents. The research studies by and for these agencies are part of a grey literature that receives some measure of internal review and is subject to public comment via Regulations.gov when included in environmental impact statements (EISs) but which may not withstand the level of scrutiny that would come from peer reviewed scientific journals.

This work reviews three examples of spill risk estimates given in EISs, including a detailed case study of spill risk estimates on the Arctic outer continental shelf (OCS), estimates the amount of grey literature cited in EISs based on a sample of 22 recent EISs, and shows how the Environmental Protection Agency (EPA) has reviewed draft EISs (DEISs) from 2015-2018. I close with suggestions about potential ways regulatory agencies, scientists, and journals could improve the effectiveness of peer review in the EIS process. The case studies reviewed here illustrate: 1. the lack of quantitative spill risks given in section 3.2.11 (Solid and Hazardous Waste) of the DEIS for proposed drilling on the Alaskan Coastal Plain (BLM, 2018b); 2. the unreasonable scales of the spills of diesel and ore concentrate that risks were estimated for along the proposed Pebble Mine transportation corridor, as well as the lack of any chemical reagent spill estimates (AECOM, 2019); and 3. the myriad issues in the fault tree model used to estimate the risk of substantial ($\geq$1000 barrel (bbl)) spills for a drilling project of an expected volume of 4.3 billion bbl (Bbbl) of oil in the Arctic OCS (Bercha Group, 2014b). The most detailed review is of a series of reports prepared by Bercha Group Inc to estimate the risks of substantial oil spills in the Beaufort and/or Chukchi Seas.

All three risk assessment case studies need to estimate the expected number of spills. The approaches to those calculations vary in detail by the size, substance, and source of the spill risk to be calculated. The simplest version of the model is

$$N = RT \qquad \text{Eq. 1}$$

where N is the number of expected spills, R is the spill risk rate for a specified combination of size, substance, and source, and T is the exposure variable that describes the magnitude and length of exposure to

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the risk over the course of the proposed project. (For simplicity, risk rates are treated as constant over time in the case studies shown here.) This model (Eq. (1)) is the starting point in each of the case studies, which have varying amounts of complication in modeling *R* and/or explicit statements of *T*.

2. Case study 1: Alaska Coastal Plain oil drilling

2.1. Background

The Coastal Plain DEIS was largely authored by the BLM, which is required to establish and administer an oil and gas leasing program for the Coastal Plain the Arctic National Wildlife Refuge under Section 20001 of Public Law 115–97. The area under consideration for oil and gas development, more than 1.5 million acres, sits along the Beaufort Sea near the US border with Canada. Section 3.2.11 of the DEIS (BLM, 2018b) details the analysis of solid and hazardous waste risks associated with oil and gas development. Potential impacts "include the generation of solid waste, wastewater, produced fluids, drilling muds, and spills of oil, salt water, and hazardous substances. Analysis of these impacts is tiered from information contained in the GMT2 Final SEIS (BLM, 2018a), and the NPR-A IAP/EIS (BLM, 2012) … Spills can originate from pipelines, storage tanks, production facilities and infrastructure, drilling rigs, and heavy equipment or vehicles. Impacts from spills vary, based on material type, size, and season" (BLM, 2018b). Spill size classes were defined as.

- *Very small* spills, less than 10 gallons
- *Small* spills, 10 to 99.5 gallons
- *Medium* spills, 100 to 999.5 gallons
- *Large* spills, 1000 to 100,000 gallons
- *Very large* spills, greater than 100,000 gallons

2.2. Critique

The only spill risks per unit volume (*R*) in Bbbl of oil produced (BBO) and estimated numbers of spills (*N*) given in quantitative terms in BLM (2018b) were in Section 3.2.6 (Petroleum Resources), in which two sizes of crude oil spills were considered. In that section, *large* spills were defined as those >500 barrels (21,000 gallons), and *small* spills were defined as anything less. The *large* crude oil spill rate of 0.65 spills per BBO produced was based on North Slope spill data from 1985-2010, citing BLM (2012). The *small* crude oil spill rate of 187 spills per BBO produced was based on North Slope data from 1989-2009, also citing BLM (2012). Production estimates in this section varied from 3.4 to 9.3 BBO, with commensurate estimated numbers of *small* and *large* spills ranging from 636 to 1739 spills and 2 to 6 spills, respectively. These estimates were not repeated or referenced in the Solid and Hazardous Waste section of BLM (2018b), which used different spill size definitions.

The remainder of this case study is focused on the Hazardous and Solid Waste section (3.2.11) of BLM (2018b). In lieu of numerical estimates, Section 3.2.11 of BLM (2018b) cited several previous documents, many of which "tier from" or "incorporate by reference" earlier BLM EISs and other documents (ADEC, 2007; BLM, 2012, 2014, 2018a). BLM (2018b) implied that quantitative predictions are not possible and cited only qualitative spill risks. Specifically, "spills are not a planned activity and are unpredictable in cause, location, size, time, duration, and material type (Mach, et al., 2000). Table 3-15, taken from the Alpine Satellite Development Plan EIS [BLM, 2004, reproduced as Table 1], describes the relative rate of occurrence for spills from main sources" (BLM, 2018b).

Although Section 3.2.11 of BLM (2018b) did not show any quantitative estimates for the number of spills expected, project specific spill numbers are calculable based on the estimated risk rates and a range of production volumes cited directly and indirectly in BLM (2018b) (Eq. (1), Table 2). Estimated spill risk rates vary by substance spilled, volume spilled, and by the time frame over which the data were collected but were all reported in per unit of oil produced. The list of spill risk estimates per BBO (Table 2) are a compilation of those previously cited for comparison purposes, and not an endorsement of them for use in the current DEIS (BLM, 2018b) for the Coastal Plain. It was unclear from BLM (2018b) how much oil is predicted to be produced. BLM (2018b) Appendix B ("Reasonably Foreseeable Development Scenario for Oil and Gas Resources …") contains several potential volumes (Table 2).

Calculating the number of expected spills is straightforward once both *R*, the spill risk rate per BBO, and *T*, the production volume (in BBO), values are known. As shown in Eq. (1), the expected number of spills is the product of those quantities. The relative occurrence rates in Section 3.2.11 of BLM (2018b) (Table 1) describing the risks of *large* spills as *low* to *very low* are based on comparisons against the occurrence rates of smaller spill size classes and are not informative to decision-makers. Even using a relatively small estimate of BBO production, such as the Van Wagener (2018) mean production estimate of 3.4 BBO, approximately 10–14 *large* spills of crude oil are expected, depending on the spill rate per BBO used. Furthermore, more than 3300 spills of all substances and sizes could be expected, including 110–127 *large* spills (Table 2). If more than 3.4 BBO are produced, the expected numbers of spills would increase proportionally. Similarly, if using more current spill data results in different spills rates per BBO, the estimated numbers of expected spills would change.

Table 2 merely serves as an example of how BLM could come up with the simplest estimate, consistent with its own previous methodolgy, of the number of *large* spills that would occur on the Coastal Plain if this project were to go forward. None of these are "good" answers to what the expected number of spills will be. The data cited in BLM (2018b) are at least nine years out of date. The BBO to be produced is not clearly specified. No standard deviations have been included with any of these estimates. BLM should use a comprehensive and up-to-date spill data set, such as the one available from the Alaska Department of Environmental Conservation (ADEC, 2019), with current production estimates to first estimate spill risk rates and then calculate the numbers of expected spills of various sizes given a range of production volumes for this proposed project. These calculations are only one piece of any cumulative effects analysis. They do not include spills that have already occurred or any other drilling or other projects that have negative environmental impacts happening in the same geographic region.

3. Case study 2: Pebble Mine transportation corridor

3.1. Background

The Pebble Mine DEIS was produced with the USACE (2019) as the lead agency. While the risks of tailing pond failures are of obvious concern, there are other spill risks associated with the potential mine, especially along the transportation corridor. As described in the DEIS (USACE, 2019), the 83 mile long transportation corridor from the mine site to a port on Cook Inlet consists of:

- A 30-mile private two-lane unpaved road from the mine site to a ferry terminal on the north shore of Iliamna Lake
- An 18-mile lake crossing utilizing an ice breaking ferry to a ferry terminal on the south shore of Iliamna Lake
- A 35-mile private two-lane unpaved road from the south ferry terminal to the Amakdedori Port
- Lightering of concentrate between Amakdedori Port and offshore lightering locations for loading onto bulk carriers

Port facilities are expected to handle "annual vessel traffic of up to 27 concentrate vessels and 33 supply barges … The port site will include shore-based and marine facilities for the shipment of concentrate,

Table 1
Reproduction of Table 3–15 from the Coastal Plain DEIS (BLM, 2018b). This table is a reproduction of one that appeared as Table 4.3.2–2 in BLM (2004).

Tables 3–15 Relative Rate of Occurrence for Spills from Main Sources

Source Pipeline	Spill Size				
	Very Small (< 10 gallons)	Small (10–99.5 gallons)	Medium (100–999.5 gallons)	Large (1000–100,000 gallons)	Very Large (> 100,000 gallons)
Produced fluids	H	H	M	L	VL
Salt water	H	H	M	L	VL
Diesel	H	M	L	VL	0
Sales oil	M	M	M	L	VL
Bulk storage tanks and containers of pads	L	L	L	VL	0
Tank vehicles	H	M	L	VL	0
Vehicle and equipment operation and maintenance	VH	VH	M	VL	0
Other routine operations	VH	VH	H	L	VL
Drilling blowout	VL	VL	VL	VL	VL
Production uncontrolled release	VL	VL	VL	VL	VL

Notes.
VL = Very low rate of occurrence.
VH = Very high rate of occurrence.
L = Low rate of occurrence.
M = Medium rate of occurrence.
H = High rate of occurrence.
0 = Would not occur.

freight, and fuel for the Project. The shore-based facilities will include separate facilities for the receipt and storage of containers for concentrate and freight. Other facilities will include fuel storage and transfer facilities, power generation and distribution facilities, maintenance facilities, employee accommodations, and offices" (USACE, 2019).

Spill risks along the transportation corridor include diesel, ore concentrate, and chemical reagents. Although it was not shown, the underlying model for the number of spills along the transportation corridor is straightforward. The number of *large* spills expected if this project scenario were to be carried out is

$$N_T = \sum_i \sum_j R_{ij} T_{ij} \qquad \text{Eq. 2}$$

where

N_T = number of *large* spills along the transportation corridor,
R_{ij} = risk of spilling > 1000 gallons of substance i per unit exposure for source j (ex. risk of spilling diesel from a tanker truck per truck mile-year), and
T_{ij} = total units of exposure for substance i from spill source j (ex. number of truck mile-years diesel will be transported).

Similar equations could be set up for *small* and *medium* spills. The USACE (through AECOM (2019)) needed to estimate the substance and transportation mode specific risk rates (R_{ij}), multiply them by their associated exposure variables (T_{ij}), and find their cumulative expected number of *large* spills. The T_{ij} values vary across the proposed alternatives and result in different overall estimates of spill risks. If a substance is not moved by a specific transportation type, then its $T_{ij} = 0$. For example, in USACE (2019) diesel is expected to be moved via tanker trucks, a lake ferry, and marine barges, but not via pipeline. Therefore, $T_{diesel,\ pipeline} = 0$ and $R_{diesel,\ pipeline}$ does not need to be estimated.

An estimated 16 million gallons of diesel are to be used annually at the Pebble Project (USACE, 2019). Instead of coming by pipeline as modeled in EPA (2014), diesel would be transported by marine tanker barge, trucks, the Iliamna Lake ferry, and a second set of trucks to the mine site. The marine barges are slated to be double-hulled marine barges, with four deliveries per year of 4 million gallons each. Unloading those deliveries would take an expected three days each. The diesel would be transported in 6350-gallon tanks and stored in four holding tanks of 1.25 million gallons. Trucks bringing diesel to the mine can carry three tanks each, or 19,050 gallons per trip. Getting 16 million gallons to the mine every year would require approximately 840 driving trips each year (AECOM, 2019). The number of expected *large* diesel spills, N_{diesel}, can be modeled as

$$N_{diesel} = \sum_j R_{diesel,\,j}\, T_{diesel,\,j} \qquad \text{Eq. 3}$$

where j includes tanker trucks, marine barges, the Iliamna Lake ferry, storage at the port, and transfers between the marine barges and storage at the port, transfers between the port storage and tanker trucks going to the ferry, transfers between trucks and the ferry, and between the ferry and trucks going to the mine. This does not consider offloading the tanker trucks at the mine, or bulk storage at the mine site.

Pebble Mine would primarily produce copper and gold ore concentrate, with an estimated 2400 wet tons to be transferred from the mine site every day by truck and ferry. Trucks would haul three containers at a time, with each container holding carrying 724 ft^3 of concentrate, weighing 76,000 lbs (38 tons), for a total of 228,000 lbs (114 tons) of concentrate per trip. Once at the marine port, containers of ore concentrate would be loaded onto lightering barges and then onto bulk carrier vessels in Cook Inlet. "A total of 10 trips by lightering vessel would be required to load each bulk carrier, which would remain at anchor for 4 to 5 days … The peak production rate of copper-gold concentrate would require transporting a total of approximately 22,800 specialized bulk shipping containers by truck, ferry, and barge each year. Annually, there would be an estimated 27 bulk marine vessels anchored at the lightering locations, for a total of 108 to 135 days" (USACE, 2019). One alternative includes transporting the ore concentrate by pipeline from the mine site to the port. The number of expected *large* ore concentrate spills, $N_{ore\ conc}$, analogous to N_{diesel}, with j including tanker trucks, the Iliamna Lake ferry, the ore pipeline, lightering barges, and marine barges, as well as transfers between trucks and the Iliamna Lake ferry, between the ferry and trucks to Cook Inlet, between trucks and lightering barges, and finally from lightering barges to marine barges, would be the sum of vessel specific $R_{ore\ conc,\ j}T_{ore\ conc.,\ j}$. $T_{ore\ conc,\ j}$ would depend on which alternative was being

Table 2
Expected number of spills expected under oil and gas development of the Coastal Plain in various size classes using spill rates per BBO cited directly and indirectly and estimated production volumes (in BBO) (BLM, 2018b).

		Coastal Plain oil production scenarios mentioned in BLM (2018b)				
Production estimate source		USGS 95% CI upper bound	Mean estimate	90% recoverable volume	USGS 95% CI lower bound	Van Wagener (2018)
Production estimate volume (BBO)		15.16	10.35	9.315	5.92	3.4
Reference cited	Spill rate per BBO	Expected number of spills = Spill rate per BBO x BBO				
Crude oil, > 1000 gallons						
BLM (2004) Volume 1	3.23	49.0	33.4	30.1	19.1	11.0
ADEC (2007) - all listed data	4.13	62.6	42.7	38.5	24.4	14.0
ADEC (2007) - data after 1995	2.91	44.1	30.1	27.1	17.2	9.9
BLM (2012) Volume 6 App. G	3.42	51.5	35.2	31.7	20.1	11.6
Crude oil, > 100 bbl						
Mach et al. (2000) - Alaska	5.29	80.2	54.8	49.3	31.3	18.0
Mach et al. (2000) – Alaska, Canada	6.22	94.3	64.4	58.0	36.8	21.2
ADEC (2007) – all listed data	2.18	33.0	22.6	20.3	12.9	7.4
ADEC (2007) – data after 1995	0.97	14.7	10.0	9.0	5.7	3.3
Crude oil, > 500 bbl						
Mach et al. (2000) – Alaska	0.93	14.2	9.7	8.7	5.5	3.2
Mach et al. (2000) – Alaska, Canada	1.23	18.6	12.7	11.4	7.3	4.2
BLM (2004) Volume 2 App. 9	0.23	3.5	2.4	2.1	1.4	0.8
ADEC (2007) – all listed data	1.21	18.3	12.5	11.3	7.2	4.1
ADEC (2007) – data after 1995	0.48	7.3	5.0	4.5	2.8	1.6
BLM (2012) Volume 6 App. G	0.65	9.9	6.7	6.1	3.8	2.2
Crude oil, > 1000 bbl						
Mach et al. (2000) – Alaska	0.39	5.9	4.0	3.6	2.3	1.3
Mach et al. (2000) – Alaska, Canada	0.54	8.2	5.6	5.0	3.2	1.8
ADEC (2007) – all listed data	0.24	3.6	2.5	2.2	1.4	0.8
ADEC (2007) – data after 1995	0	0	0	0	0	0
All substances, all volumes						
BLM (2004) Volume 1	990	15,009	10,247	9222	5861	3366
ADEC (2007) – all listed data	1088	16,488	11,257	10,131	6439	3698
All substances, > 1000 gallons						
BLM (2004) Volume 1	36.4	551.7	376.6	339.0	215.4	123.7
ADEC (2007) – all listed data	37.4	566.7	386.9	348.2	221.3	127.1
ADEC (2007) – data after 1995	32.3	489.4	334.1	300.7	191.1	109.8

evaluated and could be 0 in alternatives where a given transportation mode (or transfer point) was not relevant.

The chemical reagents listed that would require transportation to the proposed mine site are calcium oxide, sodium ethyl xanthate, diesel, sodium hydrogen sulfide, carboxy methyl cellulose, methyl isobutyl carbinol, sodium silicate, and anionic polyacrylamide (USACE, 2019). The quantities in which they would be used were not specified but are large enough that "reagents would be transported to the mine site … in 20-ton shipping containers" (USACE, 2019). It is expected that the proposed project would have an annual vessel traffic of up 33 supply barges (USACE, 2019). Four of those supply barges may be bringing in 4 million gallons of diesel each, so the quantities of reagents to be transported would still require about 30 barge loads per year. Like $N_{ore\ conc}$, the number of expected *large* reagent spills, $N_{reagent}$, can be modeled similarly to N_{diesel}, where j includes tanker trucks, marine barges, the Iliamna Lake ferry, storage at the port, and transfers between the marine barges and trucks going to the ferry, transfers between trucks and the ferry, and between the ferry and trucks going to the mine. This does not consider offloading the tanker trucks at the mine, or bulk storage at the mine site.

3.2. Critique

As shown in the Coastal Plain case study, in other DEISs spill risks are evaluated by defined size classes *small*, *medium*, *large*, and *extra large*. The Pebble Project DEIS instead only defined five spill scenarios: > 3000 gallons of diesel from a tanker truck; ~3850 gallons of copper-gold ore concentrate from a pipeline; 5700 gallons of copper-gold ore concentrate from a tanker truck; and > 300,000 gallons of diesel from a marine barge or lake ferry (USACE, 2019). The spills they modeled are well above the threshold to qualify as *large* in other EISs, so the spill rates and probabilities of *large* spills occurring are underestimated.

USACE (2019) and AECOM (2019) only gave quantitative estimates for five spill rates, and there were problems with each them. The spill rates of diesel and of ore concentrate from tanker trucks used different roads as analogs, both of which have small sample sizes (partly because of the geographic specificity and partly because they only consider spills with exceptionally large volumes). The diesel spill risk rate equated risks on Dalton Highway with the proposed Pebble Mine roads and based the estimated spill rate on a single spill. The spill risk of ore concentrate was based on 17 spills in 23 years of data in ADEC (2019) from Red Dog Mine. Although the selected data set resulted in the smallest of several estimated risk rates per truck-mile, AECOM (2019) estimated that a spill of 5700 gallons of ore concentrate from a truck is expected ~2.5 years. The ore pipeline spill risk estimates were based on spill risks rates of petroleum products, which may have different characteristics than ore concentrate, particularly in terms of corrosion potential. AECOM (2019) took the EPA's estimated pipeline risk rate (EPA, 2014) and multiplied it by 10% to make it match the Canadian National Energy Board's rate, claiming that being in a remote area would lead to far fewer spills due to third party accidents. The modeling to find the risk rate for spills >300,000 gallons from a marine barge uses BOEM's estimated rates of spills >42,000 gallons, >420,000 gallons, and >1,050,000 gallons (ABS Consulting, 2016) in an overly complicated and mathematically unjustified attempt at curve fitting in which the "observed" rates were wrong in both their *x*- and *y*-coordinates and four observations were used to fit a two parameter model. Overall, the modeling for the $R_{diesel,\ barge}$ answered the wrong question with the wrong data using the wrong technique. The same spill risk rate estimate was used for both $R_{diesel,\ barge}$ and for estimating an upper bound for $R_{diesel,\ ferry}$ even though the largest amount of diesel the ferry is expected to carry at a time is 57,150 gallons.

All other potential spills were dismissed as unlikely or not consequential. Spill sizes less than the volumes specified in the scenarios listed were not considered quantitatively as risk rates, expected numbers of spills, or cumulative volumes over the course of the proposed project. Among the issues that were ignored are potential spills from lightering barges, spills at any of the transfers between transportation modes, and spills from activities at the port, such as storage facility spills, power generation, or during maintenance activities. In short, the Pebble Project DEIS (USACE, 2019) omitted many potential spill risks along the transportation corridor, only modeled the largest possible volumes from a small number of possible sources (Table 3), and the estimates they have are not statistically justified.

4. Case study 3: Offshore drilling in the Beaufort and Chukchi Seas

4.1. Background

Substantial oil spills (≥1000 bbl) are predicted to have major (widespread, long term, and/or irreversible) consequences for many organisms in the Beaufort and Chukchi Seas (BOEM, 2015a). The 2015 oil spill risk assessment (OSRA) for offshore drilling in the Chukchi Sea contained the estimate that there was a 75% risk of at least one substantial spill and an expectation that there would be one or two substantial spills if the 4.3 billion Bbbl project were to move forward (BOEM 2015a, b). Those values were based on the mean value of a single estimate of λ, the estimated number of substantial spills per Bbbl produced in the Arctic (Bercha Group Inc, 2014b). The estimated risk of drilling in the Arctic was $\lambda = 0.319$ substantial spills per Bbbl produced, while the spill risk if same project were to be completed in the Gulf of Mexico (GOM) or the Pacific (PAC) would have been $\lambda = 0.449$ (Bercha Group Inc, 2014b). The concept, oversight, and funding of the work Bercha Group Inc (2014b) were provided by BOEM under Contract Number M11PC00013.

Bercha Group Inc (2014b) is nearly identical in structure to previous Bercha Group Inc (2002, 2006a, b, 2008a, b) reports that use fault trees and Monte Carlo analyses to estimate the risk of substantial spills, which have been updated as the BOEM oil spill database has grown. This critique reviews the work done by Bercha Group Inc from 2002 to 2014, comparing the data, assumptions, results, and commentary received over time for projected development scenarios in the Beaufort and/or Chukchi Seas. Tables, figures, and pages designated *x.x* are from Bercha Group Inc (2014b) unless otherwise noted. Because there are multiple reports to compare and BOEM cites them in several EISs, this case study is more detailed than the previous two. In the interest of length, many of the technical and computational details from the review are contained in a set of accompanying appendices.

4.2. Mathematical model

The objective of Bercha Group Inc (2014b) was to use existing spill data from the GOM and PAC to estimate the probability of spills of petroleum products in the Arctic in a way that incorporated variation in the input variables, resulted in mean estimates and variances, and allowed for comparison of risks of temperate and Arctic scenarios for spills of various sizes and from a trio sources: pipelines, platforms, and loss of well control (LOWC). Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) used fault trees to describe the oil spill risk and a Monte Carlo process to capture model behavior with variable parameter values. The fundamental concept of the model is that offshore oil drilling in the Arctic will have many of the same risks as offshore oil drilling in the GOM and PAC, but those risks may be at a different scale in the different environment, and that there will be new risks that are unique to the Arctic (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b). Spill causes in both temperate and Arctic scenarios include *impacts* from vessels, *human error*, *weather*, and *mechanical failures*, among others. Arctic specific causes are generally but not exclusively associated with ice, including *ice gouging*, *strudel scour*, and *upheaval buckling*.

The underlying model was not explicitly given in any of the reports (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b) but fairly straightforward conceptually. The number of spills expected if this project scenario were to be carried out in an historic non-Arctic region (N_H) is

$$N_H = \sum_i T_i R_{Hi} = \sum_i T_i \left(R_{Hi} \sum_{j=1}^{n_i} p_{ij} \right) \qquad \text{Eq. 4}$$

where

T_i = total units of exposure for spill source *i* (pipelines, platforms, or LOWC),
R_{Hi} = historic risk per unit exposure for source *i*, and
p_{ij} = proportion of spills from source *i* from historic cause *j* in the GOM and PAC (corrosion, storms, etc.).

Note that $\sum_{j=1}^{n_i} p_{ij} = 1$ for each spill source. To find the number of spills expected for the same scenario in the Arctic (N_A), the historic spill risks are modified and unique risks are added:

$$N_A = \sum_i T_i R_{Ai} \qquad \text{Eq. 5}$$

where the Arctic risks per unit exposure from each source (R_{Ai}) are

$$R_{Ai} = \left(R_{Hi} \sum_{j=1}^{n_i} p_{ij} m_{ij} \right) + \sum_{k=1} a_{ik} \qquad \text{Eq. 6}$$

in which

m_{ij} = modification to the historic causes *j* for each source *i* (e.g. relative likelihood of corrosion to pipelines in the Arctic compared to the GOM and PAC), and
a_{ik} = Arctic unique risks per unit exposure from source *i* from Arctic cause *k* (e.g. pipeline gouging from ice keels).

The risks were calculated per unit exposure (substantial spills per 10^4 pipeline km-yr or per 10^5 well-yr) and then converted to project specific risks per Bbbl produced by aggregating over the total exposure and oil production expected.

Assuming the fault tree model (Eq. (6)) is appropriate, Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) needed to correctly extract the appropriate spills to estimate the historic risk (R_{Hi}) and their causal attributions (p_{ij}) from the historical database maintained by BOEM, estimate the relative risks associated with those spill causes in the Arctic environment (m_{ij}), and estimate the risks of causes unique to the

Table 3
Summary list of exposure variables (T_{ij}) and the five hazardous material spill scenarios (in **bold**) and risk estimates for each scenario, R_S values, estimated for the Pebble Mine transportation corridor (USACE, 2019). No R_{ij} were calculated for any of the standard spill size classes. Transfers between transportation and/or storage vessels are denoted by an x (e.g. storage x tanker truck).

Substance Potential spill source	Exposure description
Diesel	16 million gallons per year
Marine barges	4 per year, each carrying 4 million gallons
	Scenario described: spill of >300,000 gallons $R_S = 1.5 \times 10^{-4}$ per yr
Tanker trucks	Triple tankers, each carrying 3 tanks holding 6,350 gallons for a total volume of 19,050 gallons 840 one-way trips (AECOM, 2019) from the port to the mine (distance varies from 53 to 82 miles depending on alternative chosen)
	Scenario described: spill of >3,000 gallons $R_S = 2.0 \times 10^{-7}$ per truck-mile
Ferry	18 mile lake crossing in Alternative 1; 29 mile lake crossing in Alternative 2; Alternative 3 has no ferry
	Scenario described: spill of >300,000 gallons $R_S < 1.5 \times 10^{-4}$ per yr
Storage	Varies by location; 10,000 to 1.25 million gallon tanks
Marine barges x storage	4 deliveries of 4 million gallons each per year, each requiring 3 days to unload
Storage x tanker trucks	840 one-way trips with 3 tanks pulled by each truck is 2,520 transfer operations from storage at the port to tanker trucks per year
Tanker trucks x ferry	2,520 transfers of full tanks from trucks onto the ferry to cross Lake Iliamna and 2,520 transfers of tanks off the ferry and onto trucks going the remaining distance to the mine site (5,040 transfers per year)
Ore concentrate	876,000 wet tons per year (copper-gold ore concentrate only)
Bulk containers	76,000 lb capacity (38 tons, 724 ft^3, 5,416 gallons) 22,800 bulk containers of ore concentrate per year
Tanker trucks	Haul 3 bulk containers (228,000 lb (16,249 gallon) capacity) 7,684 one-way truck trips per year (AECOM, 2019) (66 miles in Alternative 1; 3 miles in Alternative 2; 82 miles in Alternative 3)
	Scenario described: spill of 80,000 lb (5,701.3 gall) $R_S = 0.78 \times 10^{-6}$ per truck-mile
Ferry	18 mile lake crossing in Alternative 1; 29 mile lake crossing in Alternative 2; Alternative 3 has no ferry
Lightering barges	10 lightering barge loads for each marine concentrate barge ~85 bulk containers per lightering barge trip 3,245 tons per lightering barge trip
Marine concentrate barges	27 concentrate vessels per year, each in port for 4-5 days 32,444 tons ore concentrate per bulk carrier ~850 loads of ore from bulk containers loaded onto each bulk carrier
Tanker trucks x ferry	7,684 (AECOM, 2019) one-way truck trips per year with 3 tanks pulled by each truck is 23,052 transfer operations from tanker trucks to the ferry each year, and then another 23,052 transfers of tanks off the ferry and onto trucks going the remaining distance to the port (46,104 transfers per year)
Trucks x lightering barges	7,684 one-way truck trips per year with 3 tanks pulled by each truck is 23,052 transfer operations from tanker trucks to the lightering barges each year
Light barges x marine barges	270 over water transfer operations per year ~85 containers transferred in each operation ~23,000 bulk container over water transfers per year
Ore pipeline	Alternative 3: 82.3 miles (133 km)
	Scenario described: spill of 54,000 lb (3,848 gall) $R_S = 0.10 \times 10^{-3}$ per km
Ore pipeline x lightering barges	876,000 wet tons per year (copper-gold ore concentrate) transferred to 270 lightering barges
Chemical reagents	Amount varies by reagent
Marine barges	~29 (= 33 supply barges - 4 diesel barges) marine barges per year loaded with 20-ton shipping containers
Trucks	If comparable to trucks hauling ore in triple trailers, this would require ~8,000 truck one-way trips per year; if single trailers are used, the number of one-way trips would triple to ~24,000 per year. (These estimates do not account for any use of airplanes to transport chemical reagents or other supplies.)
Ferry	18 mile lake crossing in Alternative 1; 29 mile lake crossing in Alternative 2; Alternative 3 has no ferry
Storage	Varies
Marine barges x storage	Varies
Storage x trucks	Varies
Trucks x ferry	8,000 to 24,000 one-way truck trips with transfers on and off the ferry is 16,000 to 48,000 truck-ferry transfers per year

Arctic (a_{ik}). Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) allowed for variability in the Arctic fault tree model (Eq. (6)) by repeatedly drawing random values of R_{Hi}, m_{ij}, and a_{ik} from triangle distributions in Monte Carlo simulations to model the mean and variance of the spill risk. A triangle distribution is defined by the parameters specifying its minimum (*Min*), maximum (*Max*), and mode (*Mode*) values, and has an expected value of $(Min + Mode + Max)/3$. Triangle distributions are often used to model expert opinion (Vose, 2008). Triangle distributions are appropriate for situations with sparse data when the three parameters are easy to identify (Bercha Group Inc, 2014b) but are less reliable in situations where the *Max* (or *Min*) is difficult to determine (Vose, 2008).

4.3. Model implementation

4.3.1. Step 1. Compile the data

BOEM maintains a database of offshore spills at least 50 bbl in size of petroleum products and other contaminants that occur on Federal leases in OCS waters (BOEM, 2011). The data span the years 1964–2010 and are a compilation of 336 spills from the PAC and GOM. The available information includes spill dates, locations, sizes, and composition, as well as the facility and company associated with each event. There is also at least one cause listed for each spill. Spill sources are classified as being from pipelines, platforms, including LOWC events, or vessels. BOEM updated the spill database for hurricane caused oil spills that occurred in the 2000s (BOEM, 2018) to show the component spills instead of aggregate total volumes lost from pipelines and platforms due to specific storms.

Bercha Group Inc (2014b) used data from 1972-2010, in which there were 62 pipeline and 124 platform spills of at least 50 bbl of crude or refined petroleum products listed, excluding vessel spills and LOWC. Bercha Group Inc (2002) and Bercha Group Inc (2006a, b) used data spanning 1972–1999 (with 31 or 32 pipeline spills and 21 platform spills), and Bercha Group Inc (2008a, b) used data from 1972-2006 (50 pipeline spills and 74 platform spills) (See Appendix A, Step 1 for a description of other spill types and Appendix B for a list of spills present in the BOEM database that were not used in Bercha Group's models.). Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) compartmentalized the data into separate fault trees by oil spill size class, with pipelines spills having four sizes classes (50–99, 100–999, 1000–9999, and ≥10,000 bbl) for two pipe diameter classes (≤10 in and >10 in), and platforms having two spills size classes (<999 bbl and ≥1000 bbl). The OSRA only modeled the trajectories of substantial spills (BOEM, 2015b). Bercha Group Inc (2014b) based their estimates of those risks on data from 17 substantial pipeline spills and seven substantial platform spills. Bercha Group Inc (2014b) did not aggregate the volumes from spills caused by the same hurricane.

Handling spills by size class is artificial at best. Eschenbach and Harper (2006) show conditional calculations for the risks of substantial spills using the data of all spills ≥50 bbl. The larger data set allows for a better characterization of spill size frequency, and then a subset of those data can be extracted. In this case, Bercha Group Inc (2014b) could have used 62 pipeline spills and 124 platform spills in their fault trees, instead of 17 and seven, respectively, and then found the conditional probabilities that a spill is substantial given that it is ≥ 50 bbl.

4.3.2. Step 2. Estimate historic total spill frequencies, R_{Hi}

Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) first found the historical frequency of spills per 10^5 pipeline km-yr and per 10^4 well-yr based on the number of spills and total exposure in the GOM and PAC. They then modified those historic values in a Monte Carlo process using a triangle distribution with high and low factors and called the resultant spill frequencies the “expected” values for R_{Hi}. There are concerns with Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) methodology for modifying the historical spill frequencies (See Appendix A, Step 2 for more detail about high and low factor calculations and Monte Carlo methods and results.).

Importantly, R_{Hi} will be low for substantial spills due the way hurricane caused spills were considered multiple, independent, smaller events (Table 4). This represents a shift in the way Bercha Group Inc (2014b) handled spills caused by hurricanes from other authors (Eschenbach and Harper, 2006; Anderson et al., 2012) and their own previous work (Appendix A, Step 3). The Poisson model used in the OSRA (BOEM, 2015b) assumes independent events, which does not hold for clusters of spills caused by the same hurricane. Other authors have recommended aggregating the volumes from the spills caused by hurricanes (Eschenbach and Harper, 2006; Anderson et al., 2012), which would have the simultaneous effects of reducing the total number of hurricane spills and increasing their volumes. Had (Bercha Group Inc 2014b) used total volumes for spills attributed to hurricanes, they would have had two additional substantial pipeline spills (from hurricanes Katrina and Rita), bringing the substantial spill count to 19, and a net two additional substantial platform spills (hurricanes Ike, Ivan, Katrina, and Lili added, while three spills from Rita become one aggregate volume), bringing the substantial spill count to nine (Table 4). Aggregating spills caused by specific hurricanes would increase R_{Hi} for substantial spills.

Table 4
Aggregated and component *hurricane* spill counts and volumes.

Hurricane	Year	Total spills attributed (BOEM, 2011)	Spill volume (bbl)		
			Total	Spill volume range, spills <1000 bbl	Spill volumes for spills ≥1000 bbl
Pipelines					
Carmen	1974	1	3500		3500
Andrew	1992	1	2000		2,000[a]
Georges	1998	1	8212		8,212[b]
Ivan	2004	8	3445	95–671	1720
Katrina	2005	5	1247	50–960	
Rita	2005	5	1212	67–862	
Ike	2008	6	2025	56–268	1316
Platforms					
Carmen	1974	2	275		
Jeanne	1980	1	1456		1456
Elena	1985	1	66		
Opal	1995	1	89		
Lili	2002	2	1238	497–741	
Ivan	2004	7	1125	52–510	
Katrina	2005	21	3067	50–380	
Rita	2005	17	7997	51–659	1494; 1572; 2000
Ike	2008	18	3489	50–685	

[a] Attributed to *anchor impact* by Bercha Group Inc (2014b) (Table 5).

[b] Attributed to *mud slide* by Bercha Group Inc (2014b) (Table 5).

4.3.3. Step 3. Assign causes to the spills and find cause-specific spill proportions, p_{ij}, for pipelines and platforms

Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) next task was to assign a cause to each spill and weight each cause by its proportion (p_{ij}) in the fault tree. In most cases in the BOEM spill database a single spill was listed as having multiple contributing factors (BOEM, 2011). Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) reduced these to a single cause for each spill (Table 5). Most recently, all but three of the 24 spills of ≥1000 bbl of oil were assigned to *third party impact* or *natural hazards* (Bercha Group Inc, 2014b). The causes were never formally defined by Bercha Group (or reference made to a definition from BOEM, if any), no specific methodology or reasoning for assigning singular causes was given, and there are inconsistencies in how such assignments were made (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b). A pipeline spill of 2000 bbl of crude on August 31, 1992, and a platform spill of 1456 bbl of crude on November 14, 1980, had nearly identical cause lists, but Bercha Group Inc (2014b) attributed the first to *anchor impact* and the second to *hurricane* (Table 5). Explicit spill cause definitions and a presentation of the logic behind reducing a complex chain of spill causes to a single category would aid the reader and help in comparisons to the assignments by other authors. (See Appendix A, Step 3 for a description of how I compared spill cause listings over time and Appendix C for side-by-side comparisons of Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) cause listings.) Defining spill causes would also aid in comparing Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) categorizations against those of other authors (e. g. Eschenbach and Harper, 2006).

Individual spill cause attributions changed between successive reports. There were seven substantial platform spills listed in Bercha

Table 5
Causation listings for petroleum spills ≥1000 bbl from pipelines and platforms.

Date	Volume (bbl)	BOEM (2011) causation listing	Bercha Group Inc (2014b) causation listing
Pipeline spills			
5-12-73	5000	Equipment failure	Internal corrosion
4-17-74	19,833	External forces, equipment failure	Anchor impact (third party)
9-11-74	3500	Weather, external forces, hurricane	Hurricane (natural hazard)
12-18-76	4000	External forces, equipment failure	Fishing net (third party)
12-11-81	5100	External forces, equipment failure	Work boat anchoring
2-07-88	15,576	Weather, human error, external forces, equipment failure	Anchor impact (third party)
1-24-90	14,423	External forces, equipment failure	Fishing net (third party)
5-06-90	4569	External forces, equipment failure	Fishing net (third party)
8-31-92	2000	Weather, external forces, equipment failure, human error, hurricane	Anchor impact (third party)
11-16-94	4533	External forces, equipment failure	Fishing net (third party)
1-26-98	1211	Human error, external forces, equipment failure	Anchor impact (third party)
9-29-98	8212	Weather, external forces, human error, hurricane	Mudslide (natural hazard)
7-23-99	3200	External forces, human error	Jack-up rig (third party)
1-21-00	2240	External forces, human error, equipment failure	Anchor impact (third party)
9-15-04	1720	Weather, external forces, hurricane	Hurricane (natural hazard)
9-13-08	1316	Weather, external forces, hurricane	Hurricane (natural hazard)
7-25-09	1500	Equipment failure	Anchor impact (third party)
Platform spills			
1-09-73	9935	Equipment failure	Equipment failure
1-26-73	7000	Weather, external forces, equipment failure	Weather
11-23-79	1500	Weather, external forces, collision, equipment failure	Weather
11-14-80	1456	Weather, external forces, equipment failure, hurricane	Hurricane
9-24-05	1572	Weather, external forces, hurricane	Hurricane
9-24-05	2000	Weather, external forces, hurricane	Hurricane
9-24-05	1494	Weather, external forces, hurricane	Hurricane

Table 6
Platform spills of ≥1000 bbl of petroleum listed with their spill volumes and causes over Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b). The total volume attributable to *hurricane* decreased between 2008 (Bercha Group Inc, 2008a, b) and 2014 (Bercha Group Inc, 2014b). Spills in **bold** do not match previous years in either volume or cause or did not carry forward from the previous report.

Bercha Group Inc (2002, 2006a, b)		Bercha Group Inc (2008a, b)		Bercha Group Inc (2014b)	
Volume	Cause	Volume	Cause	Volume	Cause
9935	Equipment failure	9935	Equipment failure	9935	Equipment failure
7000	Equipment failure	**7000**	**Weather**	7000	Weather
1456	Equipment failure	**1456**	**Weather**	**1456**	**Hurricane**
		1500	Ship collision	**1500**	**Weather**
		1536	Hurricane	**1572**	**Hurricane**
		3093	Hurricane	**2000**	**Hurricane**
		6897	Hurricane	**1494**	**Hurricane**
18,391	Total volume	31,417	Total volume	24,957	Total volume

Group Inc (2008a, b) and Bercha Group Inc (2014b), with five changes in causes and volumes (Table 6). In Bercha Group (2008a, b), the total volume of oil spills (from substantial spills) was 31,417 bbl, but in Bercha Group Inc (2014b) the combined volume was 24,957 bbl (Table 6). The spill counts are cumulative, and each of the reports by Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) uses the same starting date. If the spill cause listings across the reports were internally consistent, spill counts and volumes by size class and cause should increase monotonically over time. Instead, the number of spills attributed to *equipment failure* for platforms decreased between Bercha Group Inc (2006a, b) and Bercha Group Inc (2008a, b), as did the counts of *equipment failure*, *collision*, *weather* and *other* between Bercha Group Inc (2008a, b) and Bercha Group Inc (2014b) (Table 7).

The most notable change in spill causes over time is the increase in platform spills <1000 bbl attributed to hurricanes Bercha Group Inc (2014b). The total number of platform spills across all cause categories increased by 50 between Bercha Group Inc (2008a, b) and Bercha Group Inc (2014b), but there were 60 more spills attributed to *hurricanes* alone (Table 7).

Segmenting the spills by size classes affected the spill cause p_{ij} values. *External corrosion*, *rig anchoring*, *mechanical connection failure*, *material failure*, and *unknown* causes of pipeline spills were all excluded from the fault trees for substantial spills, as were *human error* and *collision* caused platform spills. While shown on the diagrams (Figures 4.4 and 4.5 in Bercha Group Inc, 2014b), they were assigned 0% probability of occurring. Not having yet caused a spill of that magnitude is not a good reason to say a spill cause has no possibility of doing so in the future. For example, *collisions* were not listed as the cause of any platform spills ≥1000 bbl until Bercha Group Inc (2008a, b), although they had been the cause of smaller spills. (The 1500 bbl spill was reclassified in Bercha Group Inc (2014b) to being caused by *weather* (Tables 6 and 7))

4.3.4. Step 4. Define the modifications to historic causes for the Arctic, m_{ij}

Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) next task was to modify the risks in the Arctic relative to what is expected in temperate water. The text included this caveat: "quantification of existing causes for Arctic effects was done in a relative cursory way restricted to engineering judgment" (Bercha Group, 2002). Bercha Group's (2006a, b, 2008a, b, 2014b) text and qualifying statement about how the Arctic modifications were quantified remained nearly identical, but the triangle distribution parameters varied (Table 8 and 9). None of the reports (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b) cited any research showing why the risks from temperate waters were modified as they were, nor were the parameter changes over time addressed. (See Appendix A, Step 4 for the complete reasoning, one or two sentences per m_{ij}, given by Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) for the specific changes to modify historic risks to Arctic conditions.) In Bercha Group Inc (2014b) the mode m_{ij} values ranged from 0.1 to 0.8, with triangle distribution minimum values from 0.1 to 0.5 and a constant triangle distribution maximum value of 0.9, except for *weather*

Table 7
The number of platform spills by cause have varied over time. Numbers in **bold** are decreases from previous reports.

Cause	Report(s)	Number of spills		
		≥1000 bbl	<1000 bbl	Total
Equipment failure[a]	Bercha Group Inc (2002, 2006a, b)	3	14	17
	Bercha Group Inc (2008a, b)	**1**	37	38
	Bercha Group Inc (2014b)	1	**35**	**36**
Human error[b]	Bercha Group Inc (2008a, b)	0	12	12
	Bercha Group Inc (2014b)	0	13	13
Collision	Bercha Group Inc (2002, 2006a, b)	0	2	2
	Bercha Group Inc (2008a, b)	1	5	6
	Bercha Group Inc (2014b)	**0**	**1**	**1**
Weather[c]	Bercha Group Inc (2008a, b)	2	8	10
	Bercha Group Inc (2014b)	2	**5**	**7**
Hurricane[c]	Bercha Group Inc (2002, 2006a, b)	0	2	2
	Bercha Group Inc (2008a, b)	3	3	6
	Bercha Group Inc (2014b)	4	63	67
Other	Bercha Group Inc (2002, 2006a, b)	0	0	0
	Bercha Group Inc (2008a, b)	0	2	2
	Bercha Group Inc (2014b)	0	**0**	**0**
Total	Bercha Group Inc (2002, 2006a, b)	3	18	21
	Bercha Group Inc (2008a, b)	7	67	74
	Bercha Group Inc (2014b)	7	117	124

[a] Bercha Group Inc (2002, 2006a, b) listed *process facility release*, *storage tank release*, *structural failure*, and *equipment failure* as possible spill causes. Of those, only *equipment failure* was a possible cause given in Bercha Group Inc (2008a, b, 2014b).

[b] *Human error* is not listed as a cause category in the Bercha Group Inc (2002, 2006a, b).

[c] Bercha Group Inc (2002, 2006a, b) have a cause category of *hurricane/storm*. The Bercha Group Inc (2008a, b, 2014b) have *weather* and *hurricane* as separate spill causes.

and *mechanical failures* (Bercha Group Inc, 2014b, Tables 4.5 and 4.8). The (*Min*, *Mode*, *Max*) for *weather* were (1.1, 1.2, 1.3). No changes were made to the p_{ij} for *mechanical failures*; for substantial spills, p_{ij} for *mechanical failures* was 0.

4.3.5. Step 5. Quantify causes unique to the Arctic, a_{ik}

Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) also attempted to incorporate probability distributions for Arctic specific spill causes but demonstrated very little research into modeling the frequency of possible Arctic causes of oil spills. The potential Arctic-specific oil spill risks to pipelines that Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) considered were *ice gouging*, *strudel scour*, *thaw settlement*, *upheaval bucking*, and a catch-all called *other Arctic*. The only Arctic specific risk the Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) showed a quantitative model for was *ice gouging*, and there were significant problems with the way that model (Weeks et al., 1983) was

Table 8
Arctic effect distribution parameters relative to historic values (30–60 m depth, Table 4.5) for pipeline spills have varied over time.

Cause	Report(s)	Arctic Effect Distribution Parameters (% of Historic Values)			
		Min	Mode	Max	Mean
Corrosion					
External corrosion	Bercha Group Inc (2002)	25	50	75	50
	Bercha Group Inc (2006a, b, 2008a, b, 2014b)	10	70	90	56.7
Internal corrosion	Bercha Group Inc (2002)	55	70	85	70
	Bercha Group Inc (2006a, b, 2008a, b, 2014b)	10	70	90	56.7
Third party impact					
Anchor impact	Bercha Group Inc (2002)	5	10	40	18.3
	Bercha Group Inc (2006a, b, 2008a, b, 2014b)	10	50	90	50
Jack up rig or spud barge	Bercha Group Inc (2002)	25	50	75	50
	Bercha Group Inc (2006a, b, 2008a, b, 2014b)	10	50	90	50
Trawl or fishing net	Bercha Group Inc (2002)	5	10	40	18.3
	Bercha Group Inc (2006a, b, 2008a)	10	40	90	46.7
	Bercha Group Inc (2008b, 2014b)	10	50	90	50
Operation impact					
Rig anchoring	Bercha Group Inc (2002)	70	80	90	80
	Bercha Group Inc (2006a, b, 2008a, b, 2014b)	50	80	90	73.3
Work boat anchoring	Bercha Group Inc (2002)	70	80	90	80
	Bercha Group Inc (2006a, b, 2008a, b, 2014b)	50	80	90	73.3
Natural hazard					
Mud slide	Bercha Group Inc (2002)	10	40	70	40
	Bercha Group Inc (2006a, b, 2008a)	10	50	90	50
	Bercha Group Inc (2008b, 2014b)	10	20	90	40
Storm/hurricane	Bercha Group Inc (2002)	25	50	75	50
	Bercha Group Inc (2006a, b)	10	50	90	50
	Bercha Group Inc (2008a)	10	20	90	40
	Bercha Group Inc (2008b, 2014b)	10	40	90	46.7

Table 9
Arctic effect distribution parameters relative to historic values (range shown for all shelf depths) for platform spills have varied over time.

Cause	Report(s)	Arctic Effect Distribution Parameters (% of Historic Values)			
		Min	Mode	Max	Mean
Equipment failure[a]	Bercha Group Inc (2002)	20–60	50–70	70–90	46.7–70
	Bercha Group Inc (2006a, b)	40	70–80	90	66.7–70
	Bercha Group Inc (2008a, b, 2014b)	40	70	90	66.7
Human error[b]	Bercha Group Inc (2008a, b, 2014b)	40	80	90	70
Collision	Bercha Group Inc (2002)	5	10	40	18.3
	Bercha Group Inc (2006a, b)	10	50	90	50
	Bercha Group Inc (2008a)	40	50	90	60
	Bercha Group Inc (2008b, 2014b)	40	60	90	63.3
Weather	Bercha Group Inc (2008a, b, 2014b)	110	120	130	120
Hurricane[c]	Bercha Group Inc (2002)	25	50	75	50
	Bercha Group Inc (2006a, b)	10	50–70	90	50–56.7
	Bercha Group Inc (2008a)	10	20	90	40
	Bercha Group Inc (2008b, 2014b)	10	40	90	46.7

[a] Bercha Group Inc (2002, 2006a, b) listed *process facility release*, *storage tank release*, *structural failure*, and *equipment failure* as possible spill causes. Of those, only *equipment failure* was a possible cause given in Bercha Group Inc (2008a, b, 2014b).

[b] *Human error* is not listed as a cause category in the Bercha Group Inc (2002, 2006a, b).

[c] Bercha Group Inc (2002, 2006a, b) have a cause category of *hurricane/storm*. Bercha Group Inc (2008a, b, 2014b) have *weather* and *hurricane* as separate spill causes.

used. Concerns in the *ice gouging* model used by Bercha Group Inc (2002, 2006a, b, 2008a, 2014b) include the addition of new and different parameters than the cited model, inconsistent values being used in the calculations, computational errors, and a failure to incorporate mean scour depth's exponential relationship water depth (Weeks et al., 1983). (See also Appendix A, Step 5 for details of the *ice gouging* calculations and other Arctic risk estimates, and Appendix D for a partial annotated bibliography and examination of Bercha Group's (2014b) reference section.) Bercha Group Inc (2008b) asserts that at the "deep water [> 30 m] location in the Chukchi, ice gouging does not occur" and did not include it or *strudel scour* as potential spill risk causes.

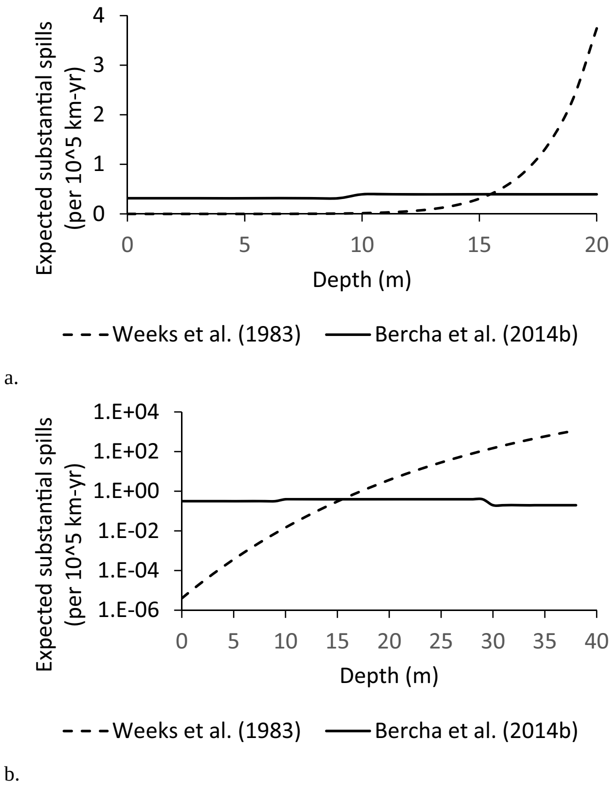

Fig. 1. Comparison of Bercha Group Inc (2014b) and Weeks et al. (1983) estimates of the number of substantial spills per 10^5 km-yr from ice gouging risk, mode values versus water depth for a. water depths of 0–20 m (linear scale) and b. water depths of 0–38 m ($\log_{10}$ scale).

By incorporating water depth into the model of mean scour depth (Fig. 1) and using the assumed amounts of pipeline to be installed at different depths and Bercha Group's (2014b) methodology for finding triangle distribution parameters (see *Step 6*), I calculated that there are 306.6 expected substantial spills from pipelines over the course of the project (Appendix A, Table A9 for calculations), while Bercha Group Inc (2014b) estimated that pipelines would have 0.9 expected substantial spills. The project had an estimated production volume of 4.258 Bbbl, so my estimate of $\lambda_{\text{pipeline, Arctic}}$ is 71.995 per Bbbl (see Appendix A, Step 5 and Table A9 for details), which dwarfs Bercha Group's (2014b) estimate of $\lambda_{\text{pipeline, Arctic}} = 0.21$ substantial spills per Bbbl.

The risk from *strudel scour* is the only other quantity independently estimated with environmental sampling, but few data and no explicit models were given (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b). The platform risks from *ice force* were based on assumptions about engineering reliability, and the remaining Arctic spill risks, *thaw settlement*, *upheaval bucking*, *low temperature*, and *other Arctic* (pipeline and platform), were all modeled relative to other spill risks (Appendix A, Step 5, Table A8). Without more explanation it is hard to assess how reasonable the percentages used to estimate one risk's size relative to another are and how good the models or data being used for the independently characterized risks are. Even if the algebraic expressions in Table A8 are correct, if the values for *ice gouging*, *strudel scour*, and/or *ice force* are incorrect, the remaining Arctic spill risks will also be wrong.

4.3.6. Step 6. The Monte Carlo process and calculating historic and Arctic *R*, *N*, and λ

After finding the "expected" values of R_H for pipelines and platforms, the Monte Carlo simulations incorporated random variation around m_{ij} and a_{ik}, but not p_{ij}, T_i, or production volume (Bercha Group Inc, 2014b). Bercha Group's (2014b) process for defining the *Min* and *Max* values of the triangle distributions to draw from in the Monte Carlo simulations for Arctic unique risks was not clear. Bercha Group Inc (2014b) stated that for small spills caused by *ice gouging* the endpoints of the triangle distributions were "approximately" $0.05{*}Mode = Min$ and $13{*}Mode = Max$. The *Mode* was given as 0.1054 small spills per 10^5 km-yr for pipelines at the 0–10 m depth range. Using Bercha Group's (2014b) rules for finding the range endpoints, (*Min*, *Max*) should be (0.00527, 1.3702), but Bercha Group Inc (2014b) had (0.0087, 1.2841). The reasoning for those calculations of *Min* and *Max*, why the *Min* and *Max* values were "approximately" calculated, and what the methodology was for the rest of the *Min* and *Max* values, which did not follow these general guidelines (data not shown), were not given (Bercha Group Inc, 2014b).

There are other concerns about the Monte Carlo process as performed by Bercha Group Inc (2014b). In addition, the number of iterations performed was low. Bercha Group Inc (2014b) had three water depths, three facility types, four spill size classes, and 51 years of project scenario for a total of 1836 sets of indicators. Bercha Group Inc (2014b) claim to have performed 500 iterations for each of those sets, which "translates into roughly 9 million arithmetic operations to generate the Monte Carlo results". This number is an order of magnitude too high, as 1836 x 500 = 918,000, and seems to conflate the importance of the number of "arithmetic operations" with the number of iterations. Also, the values at the tails of distributions Bercha Group Inc (2014b) generated are too extreme. Using all the minimum and then all the maximum values for m_{ij} and a_{ik} with the given "expected" values of R_H and stated p_{ij} in Eq. 6, I calculated that the range for λ should be (0.099, 0.567) substantial spills per Bbbl produced. The range from Bercha Group's (2014b) simulations was $(-0.011, 0.855)$ substantial spills per Bbbl produced. Both individual project year and life-of-field results show negative values for the minimum risks of spill frequency over time, per Bbbl produced, and spill index (Bercha Group Inc, 2014b, Tables 5.1 and 5.2). This is not mathematically possible when finding the products and sums of non-negative values and indicates that the triangle distributions or other parts of the Monte Carlo simulation were implemented incorrectly.

Table 10
Comparison of Arctic (R_{Ai}) and historic (R_{Hi}) risk of spills ≥1000 bbl per unit exposure over time for pipelines, platforms, and LOWC.

Infrastructure element (unit exposure)	Location, Report				
	Beaufort		Chukchi		
	Bercha Group		Bercha Group		
	(2006a)	(2008a)	(2006b)	(2008b)	(2014b)
Pipeline (per 10^5 km-yr)					
Arctic risks					
0–10 m, <10 in	5.519	5.129	5.518		4.376
10–30 m, <10 in	5.045	5.338	5.044		4.592
30–60 m, <10 in	3.295	3.097	3.294	3.146	3.470
Historic risks <10 in	6.465	6.037	6.465	6.037	4.506
Arctic risks					
0–10 m, >10 in	9.070	7.937	9.070		7.237
10–30 m, >10 in	8.563	8.123	8.562		7.429
30–60 m, >10 in	6.781	5.874	6.781	5.969	6.301
Historic risks >10 in	13.313	11.563	13.313	11.563	10.076
Platforms (per 10^4 well-yr)					
Arctic risks					
0–10 m	0.274	0.390	0.274		
10–30 m	0.288	0.404	0.288		
30–60 m	0.309	0.429	0.309	0.430	0.345
Historic risks	0.360	0.481	0.360	0.481	0.380
LOWC					
Exploration wells (per 10^4 wells)					
Arctic risks					
0–10 m	18.591	18.591	18.591		
10–30 m	21.247	21.247	21.247		
30–60 m	23.904	23.904	23.904	23.904	1.145
Historic risks	26.559	26.559	26.559	26.559	1.273
Development wells (per 10^4 wells)					
Arctic risks					
0–10 m	6.289	6.289	6.289		
10–30 m	7.189	7.189	7.189		
30–60 m	8.086	8.086	8.086	8.086	0.224
Historic risks	8.985	8.985	8.985	8.985	0.250
Production wells (per 10^4 well-yr)					
Arctic risks	1.231	1.231	1.231	1.231	0.016
Historic risks	1.759	1.759	1.759	1.759	0.022

Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) estimated pipeline R_A and R_H decreased over time for most diameters and depths (Table 10). The estimated platform risks per unit exposure were highest in Bercha Group Inc (2008a, b). The most dramatic change in spill risk per unit exposure is for LOWC between the Bercha Group Inc (2008a, b), which cited Holand (1997), and Bercha Group Inc (2014b) estimates, which cited Bercha Group Inc (2014a). Without reviewing Bercha Group Inc (2014a), it is worth noting that the estimated risks of substantial oil spills due to LOWC in the GOM and PAC dropped from 26.559 to 1.273 substantial spills per 10^4 production wells, 8.985 to 0.250 substantial spills per 10^4 development wells, and 1.759 to 0.022 substantial spills per 10^5 production well-yr when citing Bercha Group Inc (2014a), with similar reductions in the estimated risks in the Arctic (Table 10). The most recent risk estimates for the Arctic are lower than their historic counterparts for all types of infrastructure except <10″ diameter pipe in 10–30 m depth range (Bercha Group Inc, 2014b).

In Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) the third chapter is dedicated to delineating the year-by-year number of platforms and miles of pipelines to be used (at specific depths), as well as the anticipated oil production, which have varied over time in scale and location (Appendix A, Step 6, Tables A10 and A11). Life-of-field or total exposure values (T_i) are simply the sums of each type of infrastructure, often depth specific, over the projected timeline. These T_i do not reflect the possibility of any delays or changes to the infrastructure. To the extent that the project does not follow the exact timeline shown, these T_i values will be inaccurate. The estimated production volume does not allow for the possibility of there being more or less oil that can be extracted.

4.4. *Assessing the validity of the fault tree based estimates of R_A, N_A, and λ*

If we accept the premise of the model shown in Eq. (6), the terms in that equation need to be correct or, at least, justified estimates. The R_{Hi} presently focus on a very small subset of spills and undercount substantial spills. The p_{ij} are inconsistent, and, because of the focus on substantial spills, several have artificially been set equal to zero. The m_{ij} were chosen through "cursory" means in Bercha Group Inc (2002), unsupported by research, and while the language concerning them has remained static, the values have not. The a_{ik} are from models that were not applied correctly or were admittedly guesses. The T_i are best case scenarios and assume no delaying events extend the exposure times of the pipelines or platforms. The production volumes did not allow for any variation. Thus, the R_A, N_A, and λ based on this fault tree are meaningless estimates.

Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) estimates of infrastructure specific λ change over time (Table 11) and are often very different from other authors' estimates, which vary by technique, data set, and location under consideration (Table 12). The changes in values (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b) reflect a combination of the evolving set of spills listed in BOEM (2011), variation in the amount of infrastructure required for a given volume of oil to be produced, shifts in the ways the R_{Hi} and p_{ij} were defined and calculated, and changes to how m_{ij} and a_{ik} were assigned. Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) estimates of λ uniformly estimate that the risk of drilling in the Arctic is lower than the risk of allowing a project with the same infrastructure to proceed in the GOM or PAC.

Risks measured per pipeline mile year or platform year may not translate easily to risk per Bbbl produced if the production volume does not require similar amount of infrastructure per Bbbl (Stewart and Leschine, 1986; Givens, 2002; Eschenbach and Harper, 2006, and Eq. (7)).

$$\frac{risk}{infrastructure} \times \frac{infrastructure}{production\ volume} = \frac{risk}{production\ volume} \qquad \text{Eq. 7}$$

One reason Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) have such different estimates of λ than other authors is the lower

Table 11
Scenario specific spill risk per Bbbl produced over time.

Region, report	$\lambda_{A,\ Pipeline}$	$\lambda_{A,\ Platform}$	$\lambda_{A,\ LOWC}$	Total = λ_A	Total = λ_H
Chukchi					
Bercha Group Inc (2014b)	0.213	0.099	0.007	0.319	0.449
Bercha Group Inc (2008b)	0.273	0.063	0.151	0.485	0.804
Bercha Group Inc (2006b)	0.304	0.038	0.173	0.516	0.842
Beaufort					
Bercha Group Inc (2008a)	0.288	0.082	0.205	0.579	0.871
Bercha Group Inc (2006a)	0.207	0.071	0.237	0.514	0.728

Table 12
Values of λ have varied over time and by author for different project scenarios and locations. Spill source abbreviations: L = pipelines, F = platforms, and W = LOWC.

Reference	Location	Spill sources	λ
Bercha Group Inc (2014b)	Chukchi	L, F, W	0.319
Bercha Group Inc (2014b)	Historic	L, F, W	0.449
Bercha Group Inc (2008b)	Chukchi	L, F, W	0.486
Bercha Group Inc (2006a)	Beaufort	L, F, W	0.512
Bercha Group Inc (2006b)	Chukchi	L, F, W	0.515
Bercha Group Inc (2008a)	Beaufort	L, F, W	0.579
Eschenbach and Harper (2006); Method 1[a]	Arctic	L, F	0.599
Eschenbach and Harper (2006); Method 2[a]	Arctic	L, F	0.697
Bercha Group Inc (2006a)	Historic	L, F, W	0.728
Bercha Group Inc (2008b)	Historic	L, F, W	0.804
Bercha Group Inc (2006b)	Historic	L, F, W	0.842
Bercha Group Inc (2008a)	Historic	L, F, W	0.871
Anderson et al. (2012); 1996–2010 data	Historic	L, F	1.130
Anderson et al. (2012); 1964–2010 data	Historic	L, F	1.26
Anderson and LaBelle (1990); 1964–1987 data	Historic	L, F	1.27
Anderson and LaBelle (2000); 1985–1999 data	Historic	L, F	1.38
Anderson and LaBelle (2000); 1964–1999 data	Historic	L, F	1.65
Eschenbach and Harper (2006); 1972–2005 data	Historic	L, F	1.66
Anderson and LaBelle (1994); 1964–1992 data	Historic	L, F	1.77
Lanfear and Amstutz (1983); 1964–1980 data	Historic	L, F	2.6

[a] The Arctic estimates from Eschenbach and Harper (2006) do not include any Arctic specific risks, such as ice gouging, strudel scour, etc.

numbers of pipeline km-yr and platform well-yr required to produce a Bbbl in the Arctic relative to the GOM or PAC (Appendix A, Note 6, Table A12). The most directly comparable estimates of λ in the Arctic to come from independent statistical frameworks are from 2006, when both Bercha Group Inc (2006a, b) and Eschenbach and Harper (2006) submitted estimates to BOEM. The Eschenbach and Harper (2006) estimates range from 0.599 to 0.697 substantial spills per Bbbl produced, depending on the statistical method, not including Arctic effects or LOWC in their calculations of λ (Eschenbach and Harper (2006) did model ice gouging risks with the explicit consideration of water depth but did not include that in their overall Arctic spill risk rate estimate.). Bercha Group Inc (2006a, b) estimated that λ = 0.512 in the Beaufort and λ = 0.515 in the Chukchi, including Arctic effects and LOWC.

4.5. *Scoring against standards for scientific writing*

One basic tenet of scientific writing is correct citation of previous works, such that every reference listed is mentioned in the text and vice versa. Further, the works cited should be relevant to the matter they were used in reference to. Bercha Group Inc (2014b) list 63 references, 24 of which were not referred to in the text (Table D1). Of the 39 references cited in Bercha Group Inc (2014b), 13 were by Frank Bercha or Bercha Group Inc. Three works authored by Bercha or Bercha Group Inc were listed in the *References* section (Bercha Group Inc, 2014b) but not cited in the text (Table D1). Most of the 23 remaining works cited were grey literature, such as conference proceedings, reports to various government agencies, or papers prepared for fossil fuel companies. In addition to the mismatch between the listed references and the citations in the text, there are issues with how Bercha Group Inc (2014b) used information from the works they cited. This was most concerning in the section about Arctic unique causes, in which the citations referred to in the text often did not contain the information that Bercha Group Inc (2014b) attributed to those sources (See Appendix D for a partial annotated bibliography.).

4.6. *Other critiques and BOEM's responses*

Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) work has been subject to peer review, including works by Zeh (2002), MBC Applied Environmental Sciences (2005), and Eschenbach and Harper (2006), and commentary submitted via Regulations.gov (BOEM, 2015a), in which some of the issues addressed here were raised. Many of those concerns persist to Bercha Group Inc (2014b), and several other inconsistencies only become apparent when comparing the earlier versions with the more recent ones. BOEM notes that “the Bercha results have been disseminated through several independent peer-reviewed conferences” and “[r]ecent studies, such as Bercha Group Inc, 2014, are structured to include a Science Review Board to perform peer review of the final report” (Geoffrey Wikel, Chief, Branch of Environmental Coordination, and Walter Johnson, Chief, Branch of Physical and Chemical Sciences, personal correspondence dated December 6, 2016).

In general, conference presentations – whether posters or talks – receive less stringent peer review and scrutiny than publications in journals demand but can still highlight important areas that require more work or better explanation. Dr. Frank Bercha presented the fault tree models as they were being developed at the Tenth and Eleventh Information Transfer Meetings for the Alaska OCS Region in March 2005 and January 2009, respectively (MBC Applied Environmental Sciences, 2005, BGES, Inc., 2009). At the 2005 meeting there was a discussion about mean ice gouging depths, especially in water depths greater than 20 m. Dr. Bercha's reply was that he did not remember how the gouge depths were modeled and that his group used a criterion from BP that applied to the Liberty Project (MBC Applied Environmental Sciences, 2005); the Liberty project extends to shallower water depths (6 m, Bercha Group, 2016) than the project considered here (up to 60 m). At the 2009 Transfer Meeting there were still concerns about how difficult it is to model Arctic effects and compute meaningful confidence intervals. There was also a discussion of whether a sample of 36 spills was sufficiently large to break into different categories to model (BGES, Inc., 2009). Issue 25 in Appendix E (Response to Comments) of the final EIS summarizes comments from the federal government, tribal and Alaska Native organizations, state and local governments, environmental organizations, corporations and industry groups, and the general public about the modeled oil spill probability, including one comment that “provided an extensive critique of the Fault Tree analysis” (BOEM, 2015a). That comment included ice scour depths in the Chukchi Sea as one concern among nine listed. BOEM responded that “[t]he fault tree model appropriately covered a range of ice gouge distributions. Ice gouging was modeled as an exponential failure distribution and not a single mean scour depth in the fault tree model” (BOEM, 2015a). To the contrary, mean scour depth was constant in

Table 13
Evaluating the three case studies using Burmaster and Anderson (1994) “Principles of good practice for the use of Monte Carlo techniques in human health and ecological risk assessments.”

Burmaster and Anderson (1994) Principle (lightly edited for length and generalized)	Evaluation of the Coastal Plain EIS spill risk (BLM, 2018b)	Evaluation of AECOM (2019) in the Pebble Mine transportation corridor spill risk analysis	Evaluation of Bercha et. al. (2002, 2006a, b, 2008a, b, 2014b) for spill risks in the Beaufort and Chukchi Seas
1. Show all the formulae used to estimate risks.	Not shown.	Not shown in report text.	Not shown. See *Mathematical model* and *Step 5*.
2. Calculate and present a point estimate of risk using a deterministic risk assessment.	None.	Only provided for five of the possible components of the fault tree individually.	Not shown; I was able to perform this step after explicitly stating Bercha Group's models
3. Conduct a sensitivity analyses of the deterministic risk assessment to identify which variables should receive probabilistic treatment in simulations.	None.	Not shown.	Not shown.
4. In the interest of saving time and resources, be judicious in selecting which variables to treat probabilistically.	Not shown; probably less important now that computing power has increased substantially in comparison to what was available in 1994.		
5. Provide detailed information about input distributions, including a 5- to 10-page justification of the selected distribution based on results in a refereed publication, from new developments, or from elicitation of expert judgment.	None.	The main text ofAECOM (2019) is 14 pp long. The appendices show a variety of potential data to use in modeling with no explanation for the set selected.	Not done. See *Steps 4* and *5* and Appendix A, Notes 4 and 5.
6. Show how the input distributions capture and represent both the variability and the uncertainty in the input variable.	Not shown. Could be gleaned for sources cited directly and indirectly.	Not shown.	Partially done. Tables of triangle distribution parameters were given but not with any physical or research context.
7. Use measured data to inform the choice of input distributions whenever possible, after making sure that the data are relevant and representative to the population, place, and time in the study.	None.	AECOM (2019) tried finding analogs to the Pebble Mine transportation corridor but constricted their selection to tiny sample sizes.	Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) used limited data sets to set parameter bounds (Appendix A, Note 5: *Ice gouging*) and the initial spill cause frequencies (Step 1); no measurements or data were referred to for the m_{ij} distributions.
8. Discuss the methods and report the goodness-of-fit statistics for any parametric distributions for input variables that were fit quantitatively to measured data.	None.	Not shown.	Not shown.
9. Discuss the presence or absence of moderate to strong correlations between or among the input variables.	None.	Not shown.	Not shown. Arctic causes will be strongly correlated due to the way risks for *upheaval buckling*, *thaw settlement*, and *facility low temperature* were calculated (Appendix A, Note 5).
10. Provide detailed information and graphs for each output distribution, including a comparison against the deterministic point estimate.	None.	The pipeline spill risk rates resulting from different reduction factors of the EPA (2014) rate are shown on p. 33.	Shown but without the deterministic point estimate.
11. Perform probabilistic sensitivity analyses for all of the key inputs represented by a distribution in the analysis in such a way as to distinguish the effects of variability from the effects of uncertainty in the inputs.	None.	Not shown.	Not shown.
12. Investigate the numerical stability of the (i) central moments (mean, standard deviation, skewness, and kurtosis) and (ii) the tails of the output distribution of the simulation. The analyst should run enough iterations (commonly $\geq$10,000) to demonstrate the numerical stability of the tails of the outputs.	None.	Not shown.	Bercha Group Inc (2014b) claim they performed 500 iterations to sample from 1836 combinations of parameters (3 water depths x 3 facility types x 4 spill size classes x 51 year project duration).
13. Present the name and the statistical quality of the random number generator used.	None.	Not shown.	Not shown.
14. Discuss the limitations of the methods and of the interpretation of the results.	None.	There is some acknowledgment in AECOM (2019) that the estimated risks are based on very limited data and restricted to the specific scenarios listed. Those caveats are not brought forth in the DEIS (USACE, 2019).	Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) acknowledge that the “quantification of existing causes for Arctic effects was done in a relatively cursory way restricted to engineering judgment,” and that climate change and temporal variations in the parameters have not been incorporated into the model.

Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) and the only parameter that varied was *F*, which had stepwise changes across shelf depth classes. (See Appendix A, Note 5, Tables A6 and A7). There was variation around the *Mode* ice gouge risk from the triangle distributions in the Monte Carlo simulations, but not around the parameters used to calculate the *Mode* risk at each shelf depth. In their report, Eschenbach and Harper (2006) noted that ice gouge risk increases by an order of magnitude for every 5 m of increasing water depth and that Bercha Group Inc (2006a) failed to account for that in their use of the Weeks et al. (1983) model.

5. Common themes across the three case studies

I scored the three spill risk case studies against 14 best practices listed by Burmaster and Anderson (1994) for using Monte Carlo methods to assess human health and environmental risk for a more generalizable evaluation framework that might be helpful for other reviewers of risk assessments (Table 13). All three spill risk estimates fall well short of meeting almost all of them. In reference to spill scenarios along the transportation corridor for the proposed Pebble Mine, AECOM (2019) noted that the expected values they calculated are "fundamentally uncertain and hypothetical." Bercha Group Inc (2014b) briefly acknowledge the lack of researched justification for m_{ij} and the difficulties in modeling most a_{ik}. Those admitted uncertainties were not mentioned in BOEM (2015a), which presented the estimated number of large spillsusing only the mean value for λ. The three case studies are centered around estimating spills in Alaska, but the issues highlighted here likely extend to other risk analyses in other locations.

6. Grey literature in EISs and the role of the EPA

6.1. Proportion of grey literature in EISs

In the United States 78 Federal agencies submitted more than 15,000 EISs from 1987 to 2017 (EPA, 2019). Twenty Federal agencies produced 89.8% of them (Table 14). I conducted a meta-analysis to estimate the proportion of the reports supporting an EIS that is subject to peer review by selecting a recent draft or final EIS produced by each of the Federal agencies listed in Table 14, as well as from two other agencies, the Office of Surface Mining and the US Geological Survey, that are required to submit their findings for peer review based on the OMB definition of significance (see *Discussion*). I collected the references cited from each EIS, concatenated across all volumes and any appendices, removed duplicate citations, and sorted them into four broad categories:

Peer reviewed: These were from recognized peer reviewed journals.

Government authored: Authorship is listed as a government agency, such as BOEM, whether at the city, county, state, or national level. Intergovernmental Panel on Climate Change reports were also included in government documents. Publications from chambers of commerce or websites ending in .com were not.

Outside science: This includes work contracted by government agencies, such as AECOM (2019) and Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b), as well as white papers and industry reports. The quality of the data and methodology may vary widely, as may the quality and amount of review of these works receive. Not all works in this category are publicly available, especially if written under contract to a private entity.

Other: This is a catch-all category for websites, unpublished master's theses and doctoral dissertations, conference proceedings, books, book chapters, correspondence, etc.

Peer reviewed research ranged from 2.1 to 53.4% of the references cited in individual EISs and accounted for 27.6% of the 13,291 citations categorized (Table 15). Government authored science ranged from 14.7 to 79.9% of the works cited in individual EISs and comprised 33.5% of the overall total. Outside science made up 24.5% of the material referred to in the EISs analyzed.

The EPA, and possibly other agencies, base their assessments of project impacts on the draft and final EIS documents, which may span thousands of pages with multiple volumes and appendices (Sheaves et al., 2016, Table 15). Although often voluminous, EISs are summary documents, with many details consigned to appendices or left in the supporting documents. Readers seeing references cited in a document assume that authors citing the work do so correctly in content and context, have read it thoroughly enough to understand its strengths and weaknesses, and give the results appropriate weight in their own work. In general, the citation of an earlier work is a nod to its scientific validity. (Some exceptions to this would occur when the cited work is being used for comparison, as a counterexample, or its flaws are specifically being critiqued.) When a government agency cites research contracted by the agency or the project's proponent in the EIS documents, that agency is giving an implicit stamp of approval to that work.

6.2. EPA evaluation of EISs

The EPA is required to review and comment on draft EISs about major federal actions that could significantly affect the environment, with a comment window that is at least 45 days long (Adams et al., 2013). The number of EISs written per year generally increased from 1987 to 2004, when it reached a maximum of 616, declined to 256 in 2017, and rose to 324 in 2018 (Fig. 2). The EPA has issued comment letters on at least 80% of the draft and final EISs submitted every year since 2003 except in 2017. From 1984 until October 22, 2018, EPA comment letters contained an alphanumeric rating system: a letter code indicating if there is a lack of objections (LO), environmental concerns (EC), environmental objections (EO), or if the proposed project is

Table 14
Twenty Federal agencies are responsible for 89.8% of the EISs produced from 1987-2017.

Agency (Abbreviation)	Number of EISs	Number of EISs with EPA comment letters	Percent of total EISs prepared
Forest Service (USFS)	3522	1898	22.31
Federal Highway Administration (FHA)	2198	1007	13.92
US Army Corps of Engineers (USACE)	1637	864	10.37
Bureau of Land Management (BLM)	1274	702	8.07
National Parks Service (NPS)	823	484	5.21
National Oceanic and Atmospheric Administration (NOAA)	507	300	3.21
Fish and Wildlife Service (USFWS)	480	300	3.04
Federal Energy Regulatory Commission (FERC)	462	284	2.93
Department of Energy (DOE)	411	170	2.60
United States Navy (USN)	372	163	2.36
Bureau of Reclamation (BR)	344	216	2.18
Environmental Protection Agency (EPA)	330	117	2.09
Federal Transit Administration (FTA)	301	203	1.91
United States Air Force (USAF)	298	99	1.89
United States Army (USA)	287	113	1.82
Federal Aviation Administration (FAA)	251	105	1.59
Nuclear Regulatory Commission (NRC)	223	178	1.41
General Services Administration (GSA)	164	67	1.04
Bureau of Indian Affairs (BIA)	159	116	1.01
Minerals Management Service/Bureau of Ocean Energy Management (MMS/BOEM)	133	69	0.84

Table 15
Categorization of works cited source types ordered by decreasing percent from peer reviewed journals within EPA letter grade rating groups.

Agency (Example EIS title; number of pages, including appendices)	Number of references	Percent of references				EPA rating
		Peer reviewed	Government authored	Outside science	Other	
USN (Atlantic Fleet Training and Testing; 3136 pp)	3243	53.4	17.7	14.7	14.2	LO
NPS (Dyke Marsh Wetland Restoration Plan; 282 pp)	193	15.0	46.6	14.5	23.8	LO
NRC (Construction Permit for the Northwest Medical Isotopes Radioisotope Production Facility; 421 pp)	389	2.8	79.9	12.9	4.4	LO
FTA (Chicago Red Line Extension; 9,219 pp)	501	2.6	52.7	19.8	25.0	LO
USFWS (Chokecherry Sierra Madre; 3060 pp)	738	36.3	25.1	27.2	11.4	EC2
MMS/BOEM (Liberty Development Project in the Beaufort Sea; 1273 pp)	2197	40.2	14.7	31.9	13.2	EC2
Office of Surface Mining (Stream Protection Rule; 1267 pp)	121	23.6	33.5	25.4	17.5	EC2
USFS (Granite Creek Watershed Mining Project; 1040 pp)	152	22.4	27.6	25.0	25.0	EC2
NOAA (He'eia National Estuarine Research Reserve; 809 pp)	281	16.7	45.9	24.9	12.5	EC2
USGS (Klamath Facilities Removal, Final EIS; 3068 pp)	1386	13.2	43.8	31.7	11.3	EC2
BLM (Greater Mooses Tooth 1; 1144 pp)	504	11.7	28.0	50.6	9.7	EC2
DOE (Northern Pass Transmission Line Project; 1084 pp)	184	7.6	54.3	23.9	14.1	EC2
BR (Pojoaque Basin Regional Water System; 1262 pp)	462	6.5	57.4	23.4	12.8	EC2
USAF (Proposed establishment and modification of Oregon military airspace training; 626 pp)	150	4.7	74.0	10.7	10.7	EC2
FERC (Mountaineer and Gulf Xpress Projects; 1266 pp)	288	4.5	65.3	18.4	11.8	EC2
USA (Implementation of energy, water, and solid waste sustainability initiatives at Fort Bliss, Texas and New Mexico; 472 pp)	153	3.9	69.9	9.8	16.3	EC2
FHA (US 181 Harbor Bridge; 1560 pp)	358	2.2	50.8	24.0	22.9	EC2
GSA (Public sale of Plum Island Animal Disease Center, Long Island Sound, Suffolk County, New York; 408 pp)	96	2.1	56.3	19.8	21.9	EC2
FAA (SpaceX Texas Launch Site; 916 pp)	245	5.7	61.6	15.9	16.7	EO2
BIA (Osage County oil and gas; 322 pp)	196	5.1	63.3	15.8	15.8	EO2
USACE (Proposed tailings storage facility; 855 pp)	259	2.7	32.0	44.4	20.8	EO3
EPA (Designation of the Atchafalaya River …; 228 pp)	195	19.5	24.6	44.1	11.8	NA
Totals	13,291	3672	4455	3255	1909	
Overall percentage		27.6	33.5	24.5	14.4	

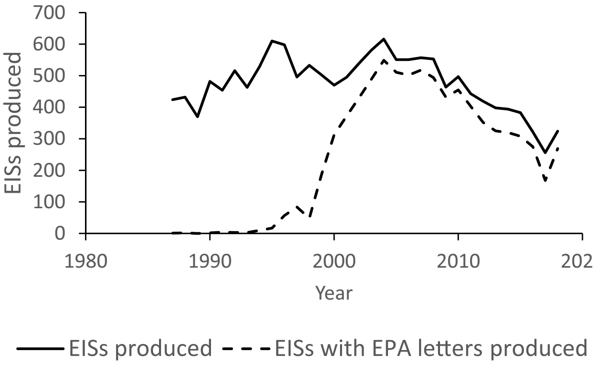

Fig. 2. Number of EISs produced and EPA rating letters submitted between 1987 and 2017.

environmentally unsatisfactory (EU); and a numerical code designating how complete the EIS is, with *1* being adequate, *2* meaning inadequate information in some respects, and *3* indicating inadequate overall (EPA, 2018a, b). The ratings are often accompanied by detailed comments about aspects of the draft or final EIS that require further attention (Adams et al., 2013; EPA, 2018b).

EPA ratings and comments do affect the EIS process, at least in the final documents that are submitted. Recently, the EPA assessed its effectiveness in attaining a goal of having the final EISs submitted by agencies address and suggest mitigation for 70% of the impacts identified in the draft versions. Based on a sample of 10 final EISs submitted to the EPA in 2012 and a comparison of them to the draft EISs and the EPA commentary the agencies received (Adams et al., 2013), the EPA achieved its goal. Proposed mitigations in the final EISs included the selection of less environmentally damaging alternatives, measures for mitigation in wetlands, and work explicitly centered on environmental justice (Adams et al., 2013). That success is tempered by the fact the EPA program staff consider their work in the EIS process completed once the final EIS letter is submitted, with little later examination of the Records of Decision or follow-up that mitigation measures and monitoring happen as agreed to, although the EPA may request such information from the lead agencies (Adams et al., 2013). While the EPA makes constructive suggestions and improvements on draft EISs, they have no jurisdiction over the decisions made after final EISs are submitted to the Department of the Interior. Furthermore, the EPA evaluates the draft and final EISs, but not necessarily the underlying documents. If the foundational work is faulty, the rest of the scientific and policy conclusions will also be compromised.

In recent decades, the efficacy of the EPA and the size of the role that science plays in reviewing EISs and making decisions has been doubted (Elliott, 2003). The relative importance of science and politics in decision making may mean that the former is a "charade" in service to the latter (Elliott, 2003). I examined 500 EPA DEIS ratings issued from 2015 and 2018 (Table 16). A χ^2 contingency table analysis of the letter ratings comparing the years (2015, 2016) and (2017, 2018) in the categories of LO, EC1, EC2, and (EO2 + EO3 + 3) showed there was not a homogeneous distribution of draft EIS rankings ($\chi^2_{\text{obs}} = 27.09$, df = 3, $p < < 0.001$, Zar 1984). The proportion of LO rankings was significantly higher in 2017-18 than in 2015-16. DEISs often take years to prepare and compile. While the shift in EPA letter grades could be the result of better prepared EISs in 2017-18, other possible reasons include a change in EPA priorities with the shift in administration or a reluctance of some EPA administrators to be as critical of DEISs as they had been previously.

Draft and supplemental EISs can receive different ratings from the EPA. In the case of the potential Lease Sale 193 in the Chukchi Sea that relied on the Bercha Group Inc (2006b) estimates of oil spill risks, the EPA initially scored the DEIS EC2 in a seven page letter from December 27, 2006, that included the risk of substantial spills as one of the agency's concerns: "According to the oil spill risk analyses presented in the Draft EIS, the chance of a large oil spill greater than or equal to

Table 16
Scores of Draft EISs receiving EPA letter ratings from 2015 to 2018.

Year	*n*	LO	EC1	EC2	EO2	EO3	3
2015	142	37	16	77	8	0	4
2016	160	67	8	73	8	1	3
2017	82	47	3	30	2	0	0
2018	116	63	6	46	1	0	0

1000 barrels (bbl) occurring and entering offshore waters is within a range of 31–51%, which represents a significant risk … EPA is very concerned that the risk to environmental resources, based on the above simplified risk analysis and probability assumptions, from a large oil spill is understated in the Draft EIS." In the final EIS (MMS, 2007), the expected number of substantial spills was 0.51, and the estimated probability of at least one substantial spill ranged from 28-40%, depending on the alternative selected; the EPA reported that the "[former] MMS ha[d] clarified the oil spill probability and risk calculations that it conducted, as well as provided additional explanation of the approach used" (EPA letter dated July 13, 2007). After the *Deepwater Horizon* LOWC, there was great concern about a catastrophic discharge happening in the Arctic, and BOEM prepared draft and final supplemental EISs and a second supplemental EIS after a court ordered revision to the expected amount of oil to be produced. In the second supplemental EIS, the estimated probability of at least one substantial spill occurring increased to 75%, with 1.4 substantial spills expected over the course of the project based on the work of Bercha Group (BOEM, 2015b). Both the revised supplemental and second supplemental draft EISs were rated EC1 by the EPA (letters dated July 8, 2011, and December 16, 2014). (Recall that the numeric part of the rating indicates how complete the EIS is.)

7. Discussion and conclusions

7.1. Grey literature and peer review in regulatory science

After years of oral and written criticism from scientific reviewers and input from many sources via Regulations.gov, "BOEM stands by the use of the oil spill-occurrence rates in the Final Programmatic EIS … [and] believe[s] they would be found to be good estimates when one examines the actual offshore spill occurrences over the past 20 years" (Wikel and Johnson, personal correspondence). This brings up concerns not only about using this estimate of risk, but about the process by which this estimate became the one used. BOEM notes that it has "long considered fault tree analysis to be the most appropriate tool for estimating the potential for oil spills on the Arctic OCS, and has invested considerable resources over the years contracting for and refining fault tree analyses of proposed oil and gas activities in the region. BOEM has worked closely with the Bercha Group … to develop these analyses" (BOEM, 2018). It would be possible to keep the fault tree structure while addressing the points raised in this and other critiques. Why did Bercha Group Inc keep getting contracts to estimate risks using this method without making changes, and how can flawed analyses be corrected?

These questions can be broadened to include other federal agencies. If policy decisions are made based in part on works that are not published in the peer reviewed literature, how is the public to know how well vetted that research is? If a work is credibly critically reviewed but no changes are made in response, what other alternatives are there to inform policy makers and the public about shortfalls in the science? How differently does BOEM handle peer review, if not publication, of their internal and contracted science as compared with other federal agencies?

Policy makers and scientists take peer review of research seriously. The Office of Management and Budget (OMB) recognizes that peer review is essential. OMB has published guidelines to ensure information quality and establish standards for peer review (OMB, 2002, 2005), including the importance of scientific quality, utility, objectivity and integrity, as well as reproducibility of the results by qualified third parties. The stringency of the review, which may extend past peer review for journals, is determined in part by how influential (defined as "the agency can reasonably determine that dissemination of the information will have or does have a clear and substantial impact on important public policies or important private sector decisions") the information is (OMB, 2002). Significant decisions about projects that may have $500 million in regulatory or private sector impact, that are new or precedent setting, or that could be relevant to multiple agencies are supposed to receive the most serious scrutiny (Ruhl and Salzman, 2006). Reviewers are to be selected based on expertise, balance, independence, and in avoidance of conflicts of interest (OMB, 2005). The American Fisheries Society and the Estuarine Research Federation wrote their own report about how to implement best available science for policy and management which lists several steps that are critical to the scientific process, including "statistical rigor and sound logic for analysis and interpretation" and peer review (Sullivan et al., 2006).

All three case studies presented here illustrated problems with risk assessments in EISs by government agencies and the regulatory science performed by contractors. The review of Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) shines a light on one case where internal and external review caught fundamental problems with an important risk estimate and the agency's lack of a meaningful response to those critiques. While this is not an indictment of all grey literature or scientific research conducted by federal agencies, AECOM (2019) and Bercha Group Inc (2014b) embody many issues present in EIS production and review that have been described over the last two decades in the United States and in similar processes around the world. The baseline science and data handling are poor (Fairweather, 1994; Treweek, 1996; Thompson et al., 1997; Benkendorff, 1999; Ayles et al., 2004; Chang et al., 2013). The risk assessment mathematical models are not well justified (Stern, 2013; Sheaves et al., 2016) and then feed into later impact predictions without the level of uncertainties and the kinds of assumptions that were present initial model carrying forward (Ortolano and Shepherd, 1995; Adelman, 2004; Duncan, 2008; Lees et al., 2016). The statistical competence of the authors is questionable (Zhang et al., 2013). In the case of the Bercha Group Inc (2002), the lead author admitted that some of the risk data were given to him by industry (Gerrard, 1993; Benkendorff, 1999; O'Faircheallaigh, 2010; Leung et al., 2016; Sheaves et al., 2016). Peer review and public participation have raised red flags about this work, but the lead agency continues to defend and use it (Jasanoff, 1990; Ortolano and Shepherd, 1995; Lackey, 2006; Ruhl and Salzman, 2006; Hults, 2014; Thompson, 2014; Fraser and Russell, 2016).

"Georgetown University Law Center Professor Steve Goldberg observes: '[R]egulatory agencies are regularly accused of being "captured" by industry, consumer groups, members of Congress, or bureaucratic inertia. They are never accused, however, of being captured by scientists'" (Elliott, 2003). The scientific community needs to ensure that policy makers are not only getting the best possible work to base decisions on, but also that it is presented in a way that makes sense to non-scientists (e.g., give results in terms of N instead of λ). This task becomes more important when federal science advisory boards and agency budgets and personnel face steep cuts. The reality is that, under the timeframe and resource pressures that are currently at play in government agencies, the present state of review of EISs is necessary but not sufficient. The grey literature is too voluminous and technical for most lay people, and this may include agency administrators, to meaningfully review.

7.2. Improving the peer review process

Regulatory agencies, outside scientists, and peer reviewed journals can all play a role in improving the quality of regulatory science used in policy making. Patton and Olin (2006) describe leadership responsibilities for creating an effective peer review system within agencies that begins with an institutional culture in which review is welcomed as a method for strengthening science, progresses through making sure there is enough time and other resources for meaningful review, distinguishes between internal and external review, continues with how the review is structured and how reviewers are chosen, and concludes with how the points from the review are incorporated into the final report. Agencies can also make informal external peer review more effective. Given the size of full EIS documents and the short time period available to submit comments, lead agencies could make it more efficient for scientists with relevant experience to concentrate their efforts in reviewing the documentation underlying an EIS, even if they are not part of the formal internal or external review process. 1. EIS documents can have all the references, including those from the appendices, consolidated in one section. 2. There could be a clear indication, such as the use of asterisks, of which references within an EIS are published in peer reviewed journals and which are grey literature. 3. Research that is submitted in reports by contractors should follow the same formatting guidelines as the overall EIS or scientific literature as much as possible. (This may vary by project, agency, and specific discipline.) 4. The type of review that contracted research receives should be explicitly detailed and accessible to reviewers of the overall EIS, especially in the case of review by the regulatory agency. 5. The regulatory agency or project proponent should ensure that interested parties can obtain and have time to evaluate any impact or risk assessments that do not undergo independent peer review. 6. Non-peer reviewed work should note who paid for the research specific to the project, whether the project proponent, a government agency, or an industry or other advocacy group. This is especially true for impact and risk assessments, where conflicts of interest may abound on both sides.

Better and more transparent agency decisions are arguments for more stringent review of individual reports in the EIS process and of the process itself, but peer review is not a panacea. First, it adds a time and resource burden to regulatory agencies (Ruhl and Salzman, 2006). Meaningful technical review of large and complicated documents might not fit within the review period specified by law, and project proponents are unlikely to want to add another step to the process of project approval, especially one that could lessen the likelihood of that approval. Second, peer review is an imperfect process (Jasanoff, 1990; Patton and Olin, 2006), and one in which agencies could introduce bias through the selection of reviewers (Jasanoff, 1990; Ruhl and Salzman, 2006). Peer review can expose but not fill gaps in data or knowledge (Ruhl and Salzman, 2006) and offers little to the overall process if the comments generated in the review are not given proper attention to improve the research, reports, and decision making (Patton and Olin, 2006). Project proponents may understandably dread "paralysis by analysis," but the time it takes to get the science right may well be worth it when projects and their environmental impacts can last for several decades or longer.

If federal agencies preparing EISs cannot or will not carefully examine works they cite that do not receive formal peer review, it will be incumbent on subject matter experts to stay abreast of the EIS process and offer specific critiques when they are warranted. Specifically, a call to action for scientists includes: 1. Paying attention to what EISs are up for review and the comment periods and deadlines; 2. Reading the sections that best match their expertise or interest/concern; 3. Paying attention to details and supporting research; 4. Checking the math – at least at the deterministic level - especially in papers that have not undergone journal level peer review; 5. Making sure that text of the EIS and the executive summary – which may be all that regulators or policy makers read – accurately capture the underlying science and pointing out when there are inconsistencies in content or context between the different stages; 6. Making specific, targeted comments and submitting them not only on Regulations.gov (or the equivalent systems outside the United States) but also to other agencies, as appropriate.

Receiving unsolicited public comment from qualified scientists will be complicated by several factors. First, being aware of science and proposals up for review requires that scientists look for those cases where they can make meaningful contributions even when not specifically contacted by an agency or advocacy group. Second, comment periods for agency proposals are often relatively brief, often 45–60 days. This is a short window of time to become aware of the availability of science for review, read the relevant portion, and structure a meaningful comment, especially when that effort is unpaid and performed in addition to other professional obligations. Third, EIS documents, like most scientific works, have layers of citations. The spill risks in BLM (2018b) were a nesting doll of citations. Evaluating the transportation corridor spill risks for Pebble Mine required reading not just the DEIS but also AECOM (2019). The review of the Arctic OCS drilling spill risks had its origin in an examination the Draft Final EIS of the Lease for Area 193 in the Beaufort and Chukchi Seas (BOEM, 2015a), in which the OSRA (BOEM, 2015b) was cited. Bercha Group's (2014b) estimate was central to the estimates used in the OSRA but was two levels removed from the original EIS.

There are a few points that would tip reviewing scientists to places that deserve more scrutiny. First, work that only appears in the grey literature may not have had the same level of critique as work that appears in peer reviewed journals, although not all journals have the same levels of review and even very reputable journals can have suspect science slip through on occasion. Second, when a central parameter or conclusion is based on a single work, that could indicate a lack of sufficient research, an ignorance, perhaps willful, of other views, or an emerging area of research that will require replication or other confirmation (Sullivan et al., 2006) and can lead to an inflated sense of certainty about the risk level itself (Stewart and Leschine, 1986). Third, if the work being reviewed comes to conclusions which are very different than those arrived at by other authors and those discrepancies are not addressed explicitly, there may because for closer examination.

As highlighted in the Arctic OCS drilling case study, the lead federal agency may ignore both the EPA's comments and other criticism of their work, and the courts will defer to their expertise. Even within the EPA, science can be and often is overridden by political concerns (Elliott, 2003). Therefore, peer reviewed journals can serve as a final advocate for quality science in the EIS process. Admittedly, critical reviews of grey literature are an unusual form of scientific work. However, when a major problem is found and documented, it is in the best interest of the EIS process and in defense of scientific rigor to publish that critique. As shown through the concerns raised about Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) through multiple channels, agencies may ignore or downplay any criticisms raised, so commentary on Regulations.gov alone may have little weight unless those critiques have been vetted by other scientists and published. Without such outside validation to force agencies to use defensible regulatory science, more suspect research will be used, and the decisions that follow will be worse for it. This is especially important when underlying research is insufficiently reviewed and when agency capture can be an issue. Although a well-constructed and peer-reviewed critique will not be completed and published within the 45–60 day time frame required to submit a comment on Regulations.gov, such a publication may have several merits. First, it shines a light on weaknesses or errors that might otherwise go unreported or be glossed over. Second, publication in a journal can force the values-based discussion about the respective benefits and risks of a project to be based on a more honest assessment of the risks, or at least open the door to a debate about how best to quantify the risks before a decision is made. Third, I expect that relatively few such critiques will need to be published before lead agencies and others who contract science for regulatory purposes know that research will be carefully scrutinized and must be of high quality. Therefore, publication of peer reviews of grey literature may not have to be frequent to be highly effective in increasing the quality of science in the EIS process.

As a scientific community, we need to make sure decisions and policy are being made based on fundamentally sound work by holding agencies, and ourselves, to the highest standards. Greater peer review of EIS documents with a careful eye on how uncertainty and risk are communicated would be a good start to improving this process. Peer review must include not only the EIS documents but also the regulatory research they are based on. Furthermore, when credible and significant flaws are found, there should be an effective forum for making those concerns known. While the scope of regulatory science that needs more extensive review is potentially quite large, the steps outlined here for agencies, scientists, and journals can lead to an improvement of the quality of the science and research used in the EIS process. My hope is that getting the scientific and mathematical underpinnings correct, or at least having a robust debate about them, will lead to a greater understanding of what is known about the risks and impacts of proposed projects, and to more transparent decision making.

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8. Declarations of interest

None.

Author's notes

The author is not and has not been an employee of the Bureau of Land Management, the Bureau of Ocean Energy Management, or the US Army Corps of Engineers. Unless specifically noted, the documents and data referred to in this text are publicly available.

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Appendix F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2019.110613.

Abbreviations used in the Appendices:

BOEM, Bureau of Ocean Energy Management;
GOM, Gulf of Mexico;
LOWC, Loss of well control;
OCS, Outer continental shelf;
OSRA, Oil spill risk analysis;
PAC, Pacific;
QC, Quality control

Appendix A. Further details of the offshore drilling in the Beaufort and Chuckchi Seas case study review

Step 1. Compile the data

Bercha Group Inc (2014b) excluded spills from other years for which there were data (1964–1971, during which there were three substantial pipeline spills and seven substantial platform spills (Eschenbach and Harper, 2006)), spills of other chemicals (such as synthetic base fluid, zinc bromide, and other unspecified “chemical” spills), spills from vessels, LOWC spills, and spills of less than 50 bbl of oil. The result of these exclusions meant that from a listing of 336 spills of at least 50 bbl of contaminants (petroleum and other products) to the OCS for which data are available (BOEM, 2011), 186 pipeline and platform spills merited explicit consideration, of which 24 were substantial spills used in the fault tree models (Table A1, Bercha Group Inc, 2014b). For a list of spills in the database but not considered in the Bercha Group's analyses, see Appendix B.

Step 2. Estimate historic total spill frequencies, R_{Hi}

Triangle distribution concerns

First, the way Bercha Group found low and high factors to estimate the spill frequency variability was difficult to follow. Bercha Group’s (2002, 2006a, b, 2008a, b, 2014b) description for finding the high and low factors has remained unchanged:

> If there were 30 data points, the upper 90% (or high value) was the third highest, while the lower 90% (or low value) was selected as the third lowest, which was invariably zero, as numerous years had no spills. Next the third highest value was divided by the historical value to get the high factor.

The high and low factor in the triangular distributions seem to be based on the number of spills per year (Table A2) but I have unable to reproduce them, and Dr. Bercha did not reply to a request for clarification (personal communication). The difference in the way Bercha Group Inc (2014b) counted spills caused by *hurricanes* from other authors and from their own previous reports (counting the individual incidents and not aggregate volumes from specific storms) could have a large effect on calculating the high factor. In turn this would change the calculations of the mode and expected values for the spill risk.

Second, Bercha Group’s (2002, 2006a, b, 2008a, b, 2014b) use of the word “expected” after they use a triangle distribution is not clear. More details about the Monte Carlo simulation and calculation of the “expected” frequencies in Tables 2.4, 2.7, and 2.9 would be helpful. Was there only one Monte Carlo process per spill source that was then applied across all spill size subcategories for each source? The "expected" values match the means for symmetric distributions (large and huge spills from LOWC from production wells), but do not for asymmetric distributions (Table A3). This issue continues throughout Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) with the Monte Carlo simulations for m_{ij} and a_{ik}, and the "expected values" from triangle distributions with longer tails drift farther away from the mean (Bercha Group Inc, 2014b, Tables 4.4 and 4.7, data not shown).

Third, there is no mention of the number of iterations of the Monte Carlo process used to estimate R_{Hi}.

Although not relevant to calculations of λ, Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) also calculated a spill index, which is the product of spill frequency and spill volume. Bercha Group Inc (2014b) used a series of triangle distributions to characterize volumes for different size classes of spills from pipelines of two diameter categories, platforms, and LOWC (Bercha Group Inc, 2014b, Tables 2.12, 2.13 and 2.14, and repeated in Tables 4.14, 4.15, and 4.16). Bercha Group Inc (2014b) used the historical average spill size within each size class as the mode of the distribution. The maximum spill volumes were defined as 20,000 bbl for pipelines, 10,000 bbl for platforms, and 200,000 bbl for LOWC and "[n]o Arctic effects [were] factored into the spill volume values" (Bercha Group Inc, 2014b). There are several problems with this approach. First, the maximum values artificially truncate the spill volume distributions. The maximum for LOWC is noticeably low following the *Deepwater Horizon* incident. Second, within the spill size classes, the triangle distribution poorly characterizes the relative likelihood of the spill volumes. In general smaller spills are more likely than larger ones, but selection of triangle distributions artificially moves the highest probability to the *Mode* (which does not equal the *Min* in any of the given distributions). Third, by definition, the value of the probability density function (pdf) at the *Min* and *Max* values is zero (when the *Mode* is not equal to either the *Min* or the *Max*). When the entire range of spill size classes is considered together, the successive triangle distributions form a decreasing sawtooth pattern because the pdf is zero at the upper and lower bounds of each size class. Bercha Group Inc (2014b) specify four spill size classes for pipelines and LOWC and two for platforms; the number and bounds of those peaks do not match across spill sources. Finally, Bercha Group Inc (2014b) ignore that working conditions and lack of infrastructure could mean that the spill distribution from the GOM and PAC may underestimate the spill sizes in the Arctic, where ice and lack of recovery or mitigation technology could lead to larger spills and less effective clean up.

Step 3. Assign causes to the spills and find cause-specific spill proportions, p_{ij}, for pipelines and platforms

I matched the spill volumes from Bercha Group Inc (2002, 2006a b, 2008a b, 2014) to the petroleum spill volumes from the BOEM database (BOEM, 2011) by spill source and compared cause attributions over time (Appendix C). There were many discrepancies between platform spills listings in the various iterations of the Bercha Group reports (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b), including spill presence and absence and their cause attributions (Table A4).

In their estimate of Arctic spill risk, Eschenbach and Harper (2006) assigned a larger proportion of pipeline spills due to *operational* and *mechanical* issues, relative to *third party damage* and *hurricanes* than Bercha Group Inc (2006a) did and also attributed a larger fraction of platform spills in the GOM between 1971-2005 to *human error* compared to Bercha Group (Bercha Group, 2006a).

Step 4. Define the modifications to historic causes for the Arctic, m_{ij}

The complete text for each modification from Bercha Group Inc (2014b) wording from pp 4.9–4.11, and Tables 4.4 and 4.7 is in *italics* followed by my comments and questions.

Pipelines

> *External corrosion – Due to the low temperature, limited biological and lowered chemical effects are expected. Coating will be state of the art and high level quality control will be used during pipeline installation resulting in high integrity levels of coating to prevent external corrosion.*

This assertion has little quantitative basis without showing that the temperature is significantly lower in the Beaufort and Chukchi Seas in comparison to the GOM or PAC OCS where the pipelines are already laid and that external corrosion rates are a function of water temperature. It is also difficult to justify the adjustments to the biological and chemical effects in the Beaufort/Chukchi without a comparison to analogous properties of the waters where other OCS development has occurred. What's the average temperature of the oil when it is extracted? Does a gradient from internal to external temperature matter? The assertion that coating will be "state of the art and high level quality control will be used" would be more meaningful if it included an explanation of how that differs from what was done with other pipelines with specific quantitative measurements. What, if any, technological improvements have been made on the engineering and monitoring fronts?

> *Internal corrosion – Additional (above historical levels) inspection or smart pigging is anticipated.*

"Pigging" was not defined, nor were the current inspection levels given. How much more inspection? How is the pigging going to be improved, and how will that improvement be quantified? Does it have to be empirically proven as a requirement of moving forward?

Third party impacts

> *Anchor impact – The very low traffic densities of third party shipping in the area justify a 50% reduction in anchor impact expectations on the pipeline.*
>
> *Jack-up rig or spud barges – Associated or other operations are going to be substantially more limited than they are in the historic data population in the GOM and PAC OCS.*
>
> *Trawl/fishing net – Less fishing is expected in the Beaufort (or Chukchi) Sea.*

Where are the pipelines in the GOM and PAC in relation to shipping routes and fishing areas? How much shipping traffic is there in each location? How much change can we anticipate as more shipping starts to come through the Arctic? If this project extends for decades, this risk factor will not remain static. Mentioning the period that is ice free in a quantitative way would also have helped here. Also, this has the implicit assumption that the risk per ship is the same in the Arctic as it is in the GOM or PAC. It may not be that risk is a linear function of ship traffic. Even if it is proportional to ship traffic, the risks in the Arctic may be different than in more temperate waters.

Operation impacts

> *Rig anchoring – Although it is anticipated that no marine traffic except possibly icebreakers will occur during the ice season, as increased traffic density during the four month open season to resupply the platforms is expected, justifying only a 20% decrease in this failure cause.*
>
> *Work boat anchoring – The same applies to work boat anchoring as to rig anchoring.*

Again, this is something that could be quantified by comparing the number of rigs that are present at other pipeline sites with the number to be used in this scenario, and then adjusting for seasonal constraints as necessary. There may need to be a location specific variable to account for any differences between per ship risk rate in the Arctic as opposed to the GOM and PAC. Operation impacts will also need to include whatever method of resupply would be used when ice precludes boat traffic.

> *Connection failure or material failure – No change was made to account for Arctic effects*.

There were no spills of at least 1000 bbl in either of these categories, and they had no contribution to the Bercha Group's (2014b) fault tree analysis of substantial spills. However, three of 62 pipeline spills were caused by mechanical failures (Table 2.1) and in the future they could cause substantial spills. Also, if cold (either at depth or near the surface) or temperature gradient is a factor for any connections or materials failing, there's a possibility of an increase.

> *Mudslide – A relatively low gradient resulting in limited mudslide potential is anticipated. A gradual increase in the mudslide potential (reflected by smaller decreases in failure frequency) ranging from 90% for [0–10m] shelf water to 80% in [10–29m] shelf and outer shelf water was included to account for the anticipated increase in gradient as deeper waters are encountered.*

What is the difference in gradients in the Beaufort and Chukchi Seas as compared to those in the GOM and PAC? Has a significant correlation been shown between gradient and mudslide risk for oil spills? If so, that factor could be incorporated explicitly in the model, with appropriate statistical consideration of the variability with which it is known. Furthermore, is there an increased risk of mudslides in areas with more seismic activity?

Storms – Considerably fewer severe storms are anticipated on an annual basis in the Arctic than in GOM or PAC, due to damping of the ocean surface by ice cover.

The meteorology of the various areas must be objectively measured to make any meaningful statements here. How do the frequency, duration, size, and intensity of polar lows and other cyclonic storms compare to storms in the GOM and PAC? How were the number and severity of storms in the various areas compared? Frequency per square mile per year? Wind speed? Wave height? Climate change will be a big factor here! Figuring historical and anticipated ice cover into predictions of storm frequency and intensity spanning the next several decades of the project scenario seems a necessary consideration.

For pipelines the most significant modifications to the historic values are posited for *natural hazards* (mean reduction to 40–47% of historic values) and *third party impacts* (mean reduction to 50% of historic values, Table 5) (Bercha Group Inc, 2014b). These are also the categories with the highest numbers of substantial spills and the greatest number of spills of all sizes (data not shown).

Platforms

Equipment failure – State of the art, high QC, high inspection and maintenance requirements. What were the improvements, and how much has that reduced the risk of equipment failure? How is that improvement being measured? What are the risks associated with trying out new technology? What are the quality controls in place at other facilities? How will those in the Arctic differ? What are the inspection and maintenance requirements in the GOM and PAC OCS? What will they be in the Arctic? This needs to be specified before it can be assumed true.

Human error – more qualified personnel. What are the requirements to be more qualified? Will those apply to all personnel? How much more qualification will be necessary to deal with the different environment as opposed to better qualification about offshore drilling in general? Is there some literature about how well humans function physically and cognitively in extremely cold environments that might give us a handle on a better figure here? Eschenbach and Harper (2006), who listed human error as the primary cause of 23 of 78 platform spills in the GOM from 1971-2005, stated "There is absolutely no question that human errors increase in the dark and in the cold … Thus, there is the potential that platform spills due to human error could increase beyond the level experienced in the GOM."

Collision – very low traffic density. This will depend on many factors. These drilling platforms have multiple attendant vessels (Appendix A in Bercha Group Inc, 2014b). A comparison of the number required/proposed attendant vessels in the Arctic to those in the GOM and PAC OCS would be a good initial step, followed by the inclusion of other marine traffic. As the ice season becomes a smaller portion of the year, these numbers will change. How is that accounted for? Furthermore, when boats are not going to the platforms because they are iced in, resupply will happen via some other method. None of the risks associated with those have been addressed here.

Weather – cold temperatures; cycling. This is only category where an increased risk is proposed, and it's a minimal increase. What does "cycling" refer to?

Hurricane – less severe storms. More intensity in deeper water. See comments under "*Storms*" as a pipeline spill risk. What is the distinction in categorizing a spill as being caused by a storm or hurricane? Where in the path of a hurricane does a spill have to occur for the cause to be "hurricane" and not just "weather"? Hurricanes can cover huge amounts of area, but not all at the same level of meteorological severity. An examination of the specific oceanic and atmospheric conditions at each spill site might show if they are causally lumped under hurricane because there was a named storm in the area but that those same weather conditions might have been labeled something else had they occurred without being associated with a named storm. How frequently do comparable winds/waves that are strong enough to cause damage occur in the Arctic, even if true hurricanes do not? Grouping this category by physical characteristics of the weather, rather than by "hurricane" or "storm," might yield a more accurate model of the relative risks in the GOM, PAC, and Arctic.

In Bercha Group Inc (2014b) the most significant modifications to the historic values for platforms are posited for *hurricanes* (mean reduction to

47% of historic values, Table 6), which is the category with the highest number of substantial and total platform spills (Table 3).

LOWC

Bercha Group Inc (2014b) cite Bercha Group Inc (2014a) for the LOWC historical spill frequencies, low and high factors, expected spill frequencies, and spill size distribution and modeled using data from LOWC events from the GOM and North Sea from 1980-2011. Previous versions of the Bercha Group reports (2002, 2006a, b, 2008a, b) used LOWC data from worldwide oil blowouts from 1955-1995. Bercha Group Inc (2006a, b, 2008a, b) also used risk analysis estimates from Holand (1997), which made use of data from the SINTEF (the Foundation for Scientific and Industrial Research, based in Trondheim, Norway) worldwide offshore blowout database. Production wells have $m_{ij} = 0.7$ because of “state of the art, high QC, high inspection and maintenance standard,” while both exploration well drilling and development well drilling have $m_{ij} = 0.9$ due to “highly qualified drilling contractor” and “better logistics support” (Bercha Group Inc, 2014b).

Step 5. Quantify causes unique to the Arctic, a_{ik}

Pipeline risks

Ice gouging. The best documented unique Arctic effect by Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) is *ice gouging*, which was described as “occur[ring] when a moving ice feature contacts the sea bottom and penetrates into it, generally as it moves against a positive sea bottom slope.” Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) cited Weeks et al. (1983). There are multiple problems with Bercha Group’s (2002, 2006a, b, 2008a, b, 2014b) use of the Weeks et al. (1983) model, some based on the selection of parameter values used given the data available (Table A5), some based on the inconsistency of parameter choices between and within versions of the reports (Table A6), and some based on discrepancies between the stated parameter values and resultant estimates (Table A7). The risk of a spill of >50 bbl caused by ice gouging is given as 5.23×10^{-6} per km-yr in the text in Bercha Group Inc (2002), which changed to 5.26×10^{-6} per km-yr in Bercha Group Inc (2006a, b, 2008a, b). No value was given in Bercha Group Inc (2014b).

Weeks et al. (1983) collected extensive data about ice gouges, with more than 20,000 observations at depths from 0-38 m. Barnes et al. (1983) observed more than 2100 gouges in water depths from 0-90 m, with incision depths from 0.2-4 m and incision widths from 0.5-67 m. In comparison Leidersdorf et al. (2001) measured 48 gouges in water 0–12 m deep (Table A5). Nonetheless, Bercha Group’s (2006a, b, 2008a, b, 2014b) mean scour depth matched Leidersdorf et al. (2001) (Tables A5, A6).

The model Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) presented for the number of pipeline failures at a specific burial depth is

$$N = e^{-kx} H_s F T L_p \sin\phi \qquad \text{Eq. A1}$$

where

k = inverse mean of scour depth (m^{-1}),
x = pipeline burial depth,
H_s = probability of pipeline failure given a gouge or hit from an ice keel,
F = scour flux per km-yr,
T = exposure time (yr),
L_p = pipeline length (km), and
ϕ = gouge orientation from pipeline centerline.

The above model is attributed to but does not match the work of Weeks et al. (1983). A similar equation can be constructed from Weeks et al. (1983) using their equations (3) and (8),

$$N = e^{-\hat{k}x} F T L_p \sin\theta \qquad \text{Eq. A2}$$

with three significant differences from Eq. (A1). First, the inclusion of H_s in Eq. (A1) is new, and either came from an unnamed source or is Bercha Group’s (2002, 2006a, b, 2008a, b, 2014b) extension of the previous work. Also, no values for H_s were present in any of the ice gouging papers cited. Second, ϕ and θ are not the same parameter. The Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) model uses ϕ to measure the movement of the ice keel relative to the pipeline orientation and use a value of 45°. Weeks et al. (1983) define θ as a measure of the ice keel movement relative to true north. Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) never show where the 45° they used came from, it does not match the angles presented by others (Weeks et al., 1983, Barnes et al. 1983), and it has the net result of multiplying the risk by approximately 0.70 instead of almost 1 (Eschenbach and Harper 2006). Finally and most importantly, in the Weeks et al. (1983) model, $\hat{k}$ is the inverse of the mean scour depth and is explicitly dependent on water depth:

$$\hat{k} = 9.97e^{-0.04z} \qquad \text{Eq. A3}$$

where z = water depth in m. Weeks et al. (1983) point out, “clearly water depth is a most important parameter in studies of gouging,” with scour depth increasing at greater water depths, but Bercha Group Inc (2002, 2006a, b, 2008a, 2014b) ignored this relationship and have stepwise decreases in F at increasing depth classes (Table A6).

For a given pipeline burial depth, the risk of a spill is highly sensitive to the mean scour depth. For example, the text in Bercha and Cerovŝek (2002) is internally inconsistent, and the average gouge depth changes from 0.4 to 0.2 m, which results in an estimated substantial spill risk decreasing from 174.72 to 0.337 failures per 10^5 km-yr when all the other parameter values stay constant (Table A7). While Bercha Group’s (2002, 2006a, b, 2008a, 2014b) ice gouging risk estimates in 0–10 m deep water do not match my calculations (Table A7), some do match previous calculations from other work on which Bercha was a co-author. The text and tables in Bercha and Cerovŝek (2002) give the substantial spill risk from ice gouging as 0.334 per 10^5 km-yr, a value that matches the estimates from Bercha Group Inc (2002, 2006a, b) (Table A7). When I used the values listed in Bercha and Cerovŝek (2002) with a mean scour depth of 0.2 m, I found the overall spill risk rate to be 0.527 per 10^5 km-yr, which matches the values from Bercha Group Inc (2008a, 2014b) for the 0–10 m shelf (sum of the modes across spill sizes classes in Table 4.4).

Setting aside the differences in the models, the mode risk rates for substantial oil spills I calculated using the equation and parameters given by

Bercha Group Inc (2002, 2006a, b, 2008a, 2014b) do not match the values shown in any year (Table A7). The most significant differences are from the Bercha Group Inc (2002) calculations, where I calculated 279.56 failures releasing at least 1000 bbl oil per 10^5 km-yr at 0–10 m and 139.78 substantial spills per 10^5 km-yr at 10–29 m with $1/k = 0.4$, compared to 0.334 and 0.167 per 10^5 km-yr at those depth ranges (Table A7). Furthermore, issues of consistency are found both within and between versions of their reports. Several parameter values changed between Bercha Group Inc (2002) and Bercha Group Inc (2006a, b) with no explanation, such as mean scour depth (0.4 to 0.2 m), H_s (0.8 to 0.83), and F (4 to 2 scours per km-yr at 0–10 m) (Table A6), but Bercha Group's (2002, 2006a, b) computed risks remained 0.3340 substantial spills per 10^5 km-yr (Table A7). Bercha Group's (2006a, b) reported risks are not internally consistent, with different values given in Chapters 2 and 4. In Bercha Group Inc (2008a) the values of F are specified as 2 and 1.5 per km-yr in Chapter 2 and as 4 and 3.2 per km-yr in Chapter 4 for the 0–10 and 10–29 m depth classes, respectively (Table A6). The other parameters remain constant, but Bercha Group's (2008a) computed values for substantial spill rates are larger for the 10–29 m shelf depth with 0.3953 per 10^5 km-yr than for the 0–10 m depth, where it was given as 0.3162 per 10^5 km-yr (Table A7). Also, while the assumed spill size class distribution stayed constant from Bercha Group Inc (2002) to Bercha Group Inc (2008a), the ratios in the reported risks do not follow those proportions in Bercha Group Inc (2008a). The Bercha Group Inc (2008a) values for F and failures per 10^5 km-yr are inconsistent in Chapters 2 and 4, and the failure rate given in Chapter 4 in Bercha Group Inc (2008a) does not match the corresponding value from Bercha Group Inc (2006a, b) that was supposedly calculated using the same parameter values. In Bercha Group Inc (2014b) no values were given for H_s or ϕ. I performed the same calculations using values from previous reports. The F values decrease from 4 to 3.2 to 1.6 per km-yr across the 0–10 m to 10–29 m to 30–60 m depths, respectively, in the parameter descriptions, but the risks given by Bercha Group Inc (2014b) are greatest for the 10–29 m depth class (Table A7) even though the other parameters remained constant.

Strudel scour. Strudel scour is a depression on the ocean floor which occurs "when water collects on top of the landfast ice, generally from rivers running into the Arctic seas, and drains through a hole in the ice" (Bercha Group Inc, 2014b). The Bercha Group Inc (2014b) mode value for small spills (50–100 bbl) caused by strudel scour was 0.0235 per 10^5 km-yr. Bercha Group's (2002, 2006a, b, 2008a) value for strudel scour risk is more than two orders of magnitude less likely than ice gouging (8.9×10^{-8} vs 5.26×10^{-6} per km-yr, respectively), citing Leidersdorf et al. (2001) among others (Goff et al., 2001, Hunt et al., 2001, Lanan and Ennis, 2001, Owen et al., 2001, and Paulin et al., 2001, but see Appendix D). This is an odd contrast given that Leidersdorf et al. (2001) detail the characteristics of 48 ice gouges and 202 strudel scours observed from 1996-1999 around the Northstar pipelines. Even if only the 15 linear strudel scours were applicable risks, that drop seems too severe. Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) also specify a 100 ft bridge length with 10% conditional pipeline failure probability and the same spill size distribution as for ice gouging, which they say can be used in an equation that is analogous to the one given for ice gouging, but no equation is shown in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) or papers cited therein. The values in the tables in Bercha Group Inc (2008a, b, 2014b) do not match the values in the tables in Bercha Group Inc (2002, 2006a, b), the text from Bercha Group Inc (2002, 2006a, b, 2008a, b), or follow the given spill size class ratio (data not shown). Eschenbach and Harper (2006) estimate that the rate of spills from *strudel scours* is 2.9×10^{-5} per mile-yr (1.8×10^{-5} per km-yr) in shallow water.

Upheaval buckling, thaw settlement, and other Arctic. Bercha Group Inc (2014b) describe *upheaval buckling* in a pipeline as happening when "thermal expansion … causes [the pipeline] to buckle upwards to accommodate the extra length generated from thermal effects" and *thaw settlement* as occurring "when a permafrost lens or formation over which the pipeline was installed melts as a result of the heat generated by the pipeline and ceases to support the pipeline so that the pipeline overburden loads the pipeline and causes it to deflect downwards," citing Miller et al. (2001) for the description of thaw settlement. *Other Arctic* was not explicitly defined but serves as a catch-all category for other unique Arctic effects not specifically named or modeled. While Bercha Group Inc (2014b) offered definitions of *upheaval buckling* and *thaw settlement* "there appears to be no defensible analytical method for calculating the probability of upheaval buckling [or of thaw settlement] of Arctic subsea pipelines in general." The mode risk values for these causes were calculated based on either the risks from spills due to *strudel scour* or a combination of Arctic factors (Table A8). Eschenbach and Harper (2006) estimated that the probability of upheaval buckling is equal to the probability of *strudel scour*, instead of the 20% of *strudel scour* risk that Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) assumed.

Making the ice gouging risk depth specific. As an exercise I applied the Weeks et al. (1983) model with depth specific gouge risks to find a_{ik} for both pipeline diameters at all three depth ranges with the values shown in Table A7 and carried through the associated changes to the *Other Arctic* a_{ik}. I constructed triangle distributions using Bercha Group's (2014b) stated method for the *Min* and *Max* values and found depth- and diameter-specific *ice gouging* risks per 10^5 km-yr. Here the 0.05**Mode* = *Min* and 13**Mode* = *Max* may be roughly justifiable since, as noted by Eschenbach and Harper (2006), the risk related to *ice gouging* increases by an order of magnitude every 5 m deeper out the pipelines are placed, at least to depths of 38 m. The mean value of 2134.4 substantial spills per 10^5 km-yr in the 30–60 m depth range (Table A9) is within the ballpark of spill risk predicted using a mean scour depth of 0.56 m (Tables A5 and A7, Barnes et al., 1983). Given the increase in the risk of *ice gouging* with shelf depth, this project scenario could run the risk of having more than 300 substantial spills from pipelines (Table A9), or $\lambda_{A,\ Pipeline} = 71.995$, as opposed to the 0.213 computed by Bercha Group Inc (2014b) in the Chukchi (Table 11). This method does not account for any changes in burial depth that could be made, incorporate variability in any of the parameters in Eq. (A1), or include the risks from substrate displacement (Lanan and Ennis, 2001, Leidersdorf et al., 2001, Paulin et al., 2001). I did not extrapolate the inverse gouge depth model past the range of data collected by Weeks et al. (1983) or attempt to model the pipeline direction relative to true north at different depths. It is a gross approximation which serves to illustrate the ramifications of not using the selected models correctly or fully incorporating Arctic risks into the fault tree.

Platform risks

Ice force, facility low temperature, and other Arctic. According to Bercha Group Inc (2014b), "some broad assumptions have been made in regard to the likelihood of spills being caused by ice force effects. Specifically, it was assumed that the platforms are designed for a 10,000 year return period with a reliability level of 96%" and that 15% of the spills caused by ice forces on platforms would be substantial. For facility low temperature, the text in Bercha Group Inc (2006a, b, 2008a, b, 2014b) was identical:

> a percentage of historical facility releases was taken. Specifically, it was assumed that the facility low temperature effects will cause small and medium spills at a rate of 6% of that of total historical small and medium spills, and large and huge spills at a rate of 3% of that associated with large and huge historical spills.

but there were differences in whether the risk was a percentage of the *historical process facilities release* rate (Bercha Group Inc, 2002, 2006a, b) or the *historical equipment failure release* frequency (Bercha Group Inc, 2008a, b, 2014b) (as well as no specification of the differences between those terms, if any) and if the rate was 3% or 1% of those risks depending on which chapter the value was in, or if it came from the text or a table. *Other Arctic* again serves as a catch-all term for Arctic risks to platforms that were not otherwise delineated. Calculations for *other Arctic* causes for platform spills changed from 10% of the sum of *ice force* and *facility low temperature* platform risks (Bercha Group Inc, 2002, 2006b) to 5% in Bercha Group Inc (2008b, 2014b) for the Chukchi Sea scenario (Table A8).

Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) cited no models for *upheaval buckling*, *thaw settlement*, and *other Arctic* risks for pipelines, or for *facility low temperature* or *other Arctic* risks for platforms and instead based estimates of those risks on percentages of the estimated risks from *ice gouging* and *strudel scour* for pipelines and *ice force* for platforms (Table A8). Two questions arise from this approach: 1. How reasonable are the percentages used to estimate one risk's relative size compared to another? Eschenbach and Harper (2006) estimated that the probability of *upheaval buckling* is equal to the probability of *strudel scour*, instead of the 20% that Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) assumed. 2. How good is the model or data being used for the risk that is independently characterized? Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) calculated risk values for spills in all size classes caused by *ice gouging* (0.26 to 0.62 failures per 10^5 km-yr at depths >10 m, Table A7) are much smaller than the values I computed (5.8 to 712.1 failures per 10^5 km-yr depending on depth using Weeks et al. (1983), Table A7, and similar calculations by Eschenbach and Harper (2006) (their Table 4.17)). The given *strudel scour* risk modes are orders of magnitude smaller than those (Bercha Group Inc, 2002, 2006a, b, 2008a, b, 2014b). Even if the algebraic expressions in Table A8 are correct, the numerical values will be wrong by the same magnitude that Bercha Group's (2002, 2006a, b, 2008a, b, 2014b) estimates are.

Step 6. The Monte Carlo process and calculating historic and Arctic R, N, and λ

Infrastructure measurement comparisons and calculations of ΣT_i

The proposed infrastructure to produce the oil varied over time (Table A10), as did the potential for LOWC from exploration, development, and production (Table A11). The amount of pipeline and number of platforms proposed to extract a given volume of oil is lower in the Arctic than in the GOM or PAC (Table A12). It should be noted, however, that even having the same definitions of infrastructure is non-trivial, as Bercha Group's (2006a, b) GOM and PAC values do not match those of Eschenbach and Harper (2006). If the risks in the Arctic are to be based on modifications of risks from GOM and PAC historical spills (and not on data from Arctic spills from other nations), having each team working on this analysis start from the same data set of spills (numbers, sizes, and causes) and exposure variables would allow meaningful comparisons of the resultant risk estimates based on the assumptions and methodologies.

Other issues with use of λ in the OSRA

The OSRA uses the $\lambda = 0.319$ substantial spills per Bbbl produced to find there is a 75% chance of at least one substantial spill and then lists the 95% confidence interval for spill frequency as 0.12–0.56 per 10^9 bbl (BOEM, 2015), but those values cut off the most extreme 5% of the distribution from each end, making that a 90% confidence interval (Bercha Group Inc, 2014b, Table 5.2). Based on those endpoints (which may have been determined incorrectly based on the presence of negative values in the lower tail), the 90% confidence interval for having at least one substantial spill over the course of the project scenario ranges from 40 to 91%.

Appendix B. Spills not considered

Multimedia Component 1 is an Excel file with three sheets: *BOEM (2011) database, Bercha Group Inc (2014b) spills,* and *BOEM (2011) Bercha Group Inc (2014b) diff.*

Bercha Group Inc (2014b) used a subset of the BOEM database of spills ≥50 bbl (BOEM, 2011), which included 336 listings from 1964-2010 at the time the Bercha Group Inc (2014b) performed their analyses. Spills of contaminants other than crude and refined petroleum products and of spills with both petroleum products and other chemicals with total volumes of at least 50 bbl are listed in the database. Contaminants other than crude and refined petroleum include but are not limited to synthetic base fluid, zinc bromide, methanol, and unspecified "chemical" spills.

Bercha Group Inc (2014b) did not include spills prior to 1972 in their analyses, nor did they include any spills that did not contain at least 50 bbl of crude or refined petroleum (Table A1). Vessel spills were not part of their fault trees. LOWC spills were considered separately in Bercha Group Inc (2014a). Bercha Group Inc (2014b) considered spills ≥1000 bbl separately from smaller spills. Their fault tree based risk estimates for substantial spills were based on 24 spills (Table A1).

Appendix C. Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) spill listings compared with BOEM spill database (BOEM, 2011)

Multimedia Component 2 is an Excel file with five sheets: All oil spills ≥ 50 barrels, Discrepancies by date, Discrepancies by volume, Discrepancies by type, and Hurricane spills math.

All oil spills ≥ 50 barrels contains the unique ID, volume of crude and refined petroleum spilled, spill date, and cause listing from BOEM for pipeline and platform spills sorted by source and then by spill date. I created columns for the Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011, and 2014b) spill volumes and causes from Tables 2.1 and 2.5 (Bercha Group Inc (2014b) report table numbers; there are corresponding tables in the Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011). I then matched the spill volumes from Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011, 2014b) to the petroleum spill volumes from the BOEM (2011) database. This allowed me to compare cause attributions and see which spills from the BOEM (2011) database were not included in Bercha Group's (2002, 2006a, b, 2008a, b, 2011, 2014b) analysis and try to tease out why they were excluded. I checked that I listed (and found matches for) the correct number of spills shown in each Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011, 2014b) report from each spill source. There are horizontal lines showing the break points of the year ranges (1999 and 2006) for the different database iterations specified in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011, 2014b). Spills where I found no discrepancies across reports are in plain type. Spills for which I found at least one discrepancy are in bold and have an added entry for what the issue is. I extracted the spills in bold to create the sheets *Discrepancies by date, Discrepancies by volume,* and *Discrepancies by type.* (For ease of reading, those spill listings are in plain type in the *Discrepancies* sheets.)

Discrepancies by date, Discrepancies by volume, and *Discrepancies by type* are fairly self-explanatory. I used the *Discrepancies by volume* as a check to see if confusion about multiple listings of a single volume, say 55 bbl, was a matter of errors and mis-assignment on my part. I used the counts of discrepancy types to create Table A4.

Hurricane spills math contains all spills that had the word "hurricane" in the BOEM (2011) cause listing, regardless of Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011, 2014b) cause listing, and all spill volumes listed as being caused by hurricanes in the Bercha Group Inc (2002, 2006a, b, 2008a, b, 2011, 2014b). From those spills, sorted by source and storm name, I was able to determine the number of component spills listed and a total volume for each storm and used those to construct Table 4.

Appendix D. An examination of Bercha Group's (2014b) reference section and select annotated bibliography for citations given for Arctic unique effects

Bercha Group Inc (2014b) list 63 references, 24 of which were not referred to in the text (Table D1). Of the 39 references cited in this report, 13 were by Frank Bercha or Bercha Group. Six of the Bercha Group reports were earlier work for BOEM on this topic (previous fault trees for oil spill risks in the Arctic, updates to the database, and an estimation of LOWC risk (Bercha Group Inc, 2014a). Nine of the Bercha Group reports were conference proceedings or seminars. The last Bercha reference is to a book entitled *Risk Analysis Methods and Applications*. (Three works authored by Bercha or Bercha Group were listed in the *References* section but not cited in the text, Table D1.) Most of the 23 remaining works cited were also conference proceedings, reports to various government agencies, or prepared for fossil fuel companies.

There were 113 references to earlier work in the text of Bercha Group Inc (2014b). Of those, 75 were to Bercha or Bercha Group books, seminars, or papers. The most highly cited non-Bercha (Group) report is Weeks et al. (1983) "Some probabilistic aspects of ice gouging on the Alaskan shelf of the Beaufort Sea" for the US Army Cold Regions Research and Engineering Laboratory, which was referred to four times.

In addition to the mismatch between the listed references and the citations in the text, there are issues with how Bercha Group Inc (2014b) used information from the works they cited. This was most concerning in the section about Arctic unique causes. Here I show the works cited Bercha Group Inc (2014b) in reference to Arctic unique spill risks and how they were previously by Bercha Group Inc (2002, 2006a, b, 2008a, b), the context in which each was used, and then offer a summary and/or text. The citation number from Bercha Group Inc (2014b) is in square brackets, and the reference formatting follows Bercha Group Inc (2014b). Several of the papers listed below are specific to the Northstar Project, which was 9.7 km offshore in the Beaufort Sea in waters up to 11 m deep.

[2] Babaei, M.H., and Sudom, D. "Ice-Seabed Gouging Database: Review and Analysis of Available Numerical Models", Paper No. OTC 24603 in Proceedings of the Arctic Technology Conference – an OTC Event, Houston, Texas, USA, 10–12 February 2014.

Context	Ice gouging
Cited in Bercha Group Inc (2014b).	

Summary This paper summarizes the methodology of 206 runs of 18 numerical modeling studies of ice gouging and scour damage, including important areas for continued research. The database contains information about the mathematical approach, ice keel parameters, soil characteristics, pipe attributes, and keel-soil-pipe interactions used in the models.

[11] Bercha, F.G., and Associates (Alberta) Limited, "Ice Scour Methodology Study", Final Report to Gulf Canada Resources, Calgary, AB, March 1986.

Context	Ice gouging
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b).	

I have been unable to find this report.

[16] Bercha Group Inc., "Alternative Oil Spill Occurrence Estimators and their Variability for the Chukchi Sea – Fault Tree Method ~ OCS Study MMS 2008–036, Final Task 4A.2 Report to US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, March 3, 2008.

Context	Upheaval buckling
Cited in Bercha Group Inc (2014b)	

Summary This is the 2008 version of the fault tree analysis for the Chukchi Sea. There are no models or parameters about upheaval buckling specified or cited other than to assume it occurs 20% as frequently as strudel scour for lack of a "defensible analytical method for calculating the probability."

[17] Bercha Group Inc., "Alternative Oil Spill Occurrence Estimators and their Variability for the Chukchi Sea – Fault Tree Method", Volumes I and II, OCS Study MMS 2006–033, Final Task 1 Report to US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, October 2006.

Context	Upheaval buckling
Cited in Bercha Group Inc (2008b, 2014b)	

Summary This is the 2006 version of the fault tree analysis for the Chukchi Sea. There are no models or parameters about upheaval buckling specified or cited other than to assume it occurs 20% as frequently as strudel scour for lack of a "defensible analytical method for calculating the probability."

[25] Goff, R., Hammond, J., and Nogueira, A. C. "Northstar Sub Sea Pipeline Design of Metallurgy, Weldability, and Supporting Full Scale Bending Tests", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Ice gouging, strudel scour
Cited in Bercha Group Inc (2014b)	

Summary Bercha Group Inc (2014b) include this paper in the list of four papers that constitute the "numerous studies [that] have been conducted on strudel scour." Both ice gouging and strudel scour are defined in the introduction to give context for welding and other tests of pipelines. A brief quantitative description of ice gouging is given.

[29] Hnatiuk, J., and Brown, K. D. "Sea Bottom Scouring in the Canadian Beaufort Sea", 9th Annual OTC, Houston, TX, May 2–5, 1983.

Context	Ice gouging
Cited in Bercha Group Inc (2014b)	

I have been unable to find this report.

[33] Hunt, D.M., McClusky, K.R., Shirley, R., and Spitzenberger, R. "Facility Engineering for Arctic Conditions", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Ice gouging
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b)	
Context	Strudel scour
Cited in Bercha Group Inc (2014b)	

Summary Bercha Group Inc (2014b) include this paper in the list of four papers that constitute the "numerous studies [that] have been conducted on strudel scour." The words "ice gouging" and "strudel scour" never appear in the paper. Environmental conditions (extreme temperatures and freeze/thaw conditions) are mentioned only in the context of the difficulties they present for construction work. The focus of this paper is the planning and engineering of the artificial island to house the pipe rack, pump house, and process and compressor modules.

[35] Lanan, G.A., and Ennis, J. O. "Northstar Offshore Arctic Pipeline Project", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Ice gouging
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b)	
Context	Strudel scour
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b)	

Summary Bercha Group Inc (2014b) include this paper in the list of four papers that constitute the "numerous studies [that] have been conducted on strudel scour." After specifying the basic design of the pipeline system, Lanan and Ennis (2001) briefly describe the risks to pipelines from ice gouging (maximum gouge depth observed over a ten year period was 2 feet; no mean gouge depth was given), permafrost thaw settlement, strudel scour ("survey data show that large/deep strudel scours in the area are rare"), and upheaval buckling. The remainder of the paper is concerned with pipe bending limit state design, welding, construction, and operational requirements.

[36] Leidersdorf, C.B., Hearon, G. E., Hollar, R. C., Gadd, P. E., and Sullivan, T. C. "Ice Gouge and Strudel Scour Data for the Northstar Pipelines", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Ice gouging
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b)	
Context	Strudel scour
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b)	

Summary This report describes the collection of ice gouge and strudel scour data using aerial reconnaissance and surveys of the sea bottom from 1995-1999. "[S]trudel scour, like ice gouging, was characterized by significant inter-annual variation in both frequency and severity." See Table A5 for a summary of the ice gouging data collected. Circular strudel scours had a maximum observed depth of 1.2 m. Linear strudel scours had a maximum observed depth of 0.9 m. Leidersdorf et al. (2001) also include summary data from Barnes et al. (1983).

[39] Miller, D. L., "Hypersaline Permafrost under a Lagoon in the Arctic Ocean", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Thaw settlement
Cited in Bercha Group Inc (2014b)	

Summary In 1996 and 1999 Duane Miller and Associates drilled a total of 57 borings along four offshore routes under a shallow Arctic lagoon (water depth up to 2 m; boring depths of 7–31 m below the sea floor). Ground temperatures were measured in March and April 1996. Other measurements included moisture content, primary classification, shear strength, thaw strain, and salinity. Although Miller (2001) concludes that there are "low thaw strain values for the sediments and a small amount of potential thaw settlement for the buried, heated pipeline" where there is little icy soil under the lagoon, shoals, and barrier islands, no quantitative models were given for anything other than water freezing point as a function of salinity.

[42] MMS (US Department of the Interior, Minerals Management Service, Alaska OCS Region), "Alaska Outer Continental Shelf - Chukchi Sea Oil & Gas Lease Sale 126 - Final Environmental Impact Statement", Vol. II, OCS EIS/EA MMS 90–0095, Anchorage, AK, January 1991.

Context	Ice gouging
Cited in Bercha Group Inc (2014b)	

Summary of use Bercha Group Inc (2014b) include this report as one of the "[v]arious studies [that] have been conducted on the frequency and depth distribution of ice gouges …" but make no further mention of it or any specific information from it. Selected text relevant to Arctic unique effects are given below.

Extracted text

p. III-6 of Volume 1:

At depths shallower than 60 m, linear depressions have been gouged into the seafloor by the keels of drifting ice masses. Ice-gouge densities in the sale area are shown in Figure III-A-10.

Along the coast, areas of high ice-gouge density include the steep slopes of the seafloor in the Barrow Sea Valley or ice-push-sediment ridges, the stamukhi zone, and the shoals adjacent to the capes (Lewbel, 1984). The orientation of the gouges is usually parallel to the isobaths on the steep slopes and shoals, but in water less than 15 m deep the orientation may be random. Between Point Barrow and Icy Cape, the maximum observed gouge-incision depth generally increases slightly from 2.4 m at 12 m of water depth to 2.8 m at 24 m of depth. Below 28 to 30 m, the gouge-incision depth decreases with increasing depth; this decrease may reflect the thin sediment cover, about 1 to 2 m in waters deeper than 30 m, or the presence of bedrock at or near the surface, which would prevent gouges from forming. Reworking of sediments by currents in the stamukhi zone may also eliminate the traces of many ice gouges.

Contemporary ice gouging may be occurring in water at least 43 m deep. In the central part of the Sale 126 area, beneath the ACC in water depths of 43 to 45 m, ice gouges were observed cutting across sand-ripple fields that may be active under present-day current regimes. The currents also transport the sediments that partially or completely fill in the gouges. The reoccurrence interval of ice gouging on the seafloor of the Chukchi Sea is unknown at this time.

p. IV A-12 of Vol. 1:

In the Sale 126 area, sea ice is a principal environmental factor affecting offshore petroleum-resource development. The large lateral forces exerted by moving ice floes and sheets, ridges, floebergs, and ice islands are a major concern in the offshore-facilities design and operation associated with petroleum exploration and development and production. The force that moving sea ice exerts on a structure is limited by the ice strength and the driving-forces magnitude. Sea ice is a heterogeneous substance with many small- and large-scale variations. Sea ice variations are likely to cause stress concentrations and local failures well before the calculated failure loads are reached. Other concerns associated with sea ice include rideup, pileup, override, and seafloor gouging.

[44] O'Connor, M.J, and Associates Ltd., "Preliminary Ice Keel/Seabed Interaction Study", Final Report to GCRI, March 1984.

Context	Ice gouging
Cited in Bercha Group Inc (2002, 2006a, b 2008a, b, 2014b)	

I have been unable to find this report. Bercha Group Inc (2014b) cite it in the context of the likelihood of pipeline damage and/or failure, so I speculate this is where H_s, the probability of pipeline failure given ice gouge impact or hit, was defined and incorporated into the model of the number of spills caused by ice gouging.

[47] Owen, L., Blanchet, D., and Flones, P. "The Northstar Project - Year-Round Production in the Alaskan Beaufort Sea", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Ice gouging
Cited in Bercha Group Inc (2014b)	

Summary "This paper describes the complexity of the permitting, design, and construction of Northstar and subsea pipelines, as well as issues associated with drilling and operational regulatory requirements." Strudel scours, ice gouges, and thaw subsidence were listed as environmental loading conditions to consider, with ice gouging and thaw subsidence considered the more important risks, but no quantitative data about frequency or severity were given.

[48] Paulin, M.J., Nixon, D., Lanan, G. A., and McShane, B. "Environmental Loadings & Geotechnical Considerations for the Northstar Offshore Pipelines", in Proceedings, Volume 1, 16th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Ottawa, ON, August 12–17, 2001.

Context	Strudel scour
Cited in Bercha Group Inc (2014b)	

Summary Bercha Group Inc (2014b) include this paper in the list of four papers that constitute the "numerous studies [that] have been conducted on strudel scour." "The evaluation of and design for unique Arctic environmental loading conditions including ice gouging, offshore permafrost, upheaval buckling, and strudel scour are described … Finite element models were then used to assess pipeline strains as the result of the thaw settlement, ice keel gouging, and strudel scour … [U]pheaval buckling … [which] is not unique to the Arctic environment … was evaluated using industry standard techniques." The maximum observed ice gouge depth was 0.6 m. "The maximum horizontal dimension of any strudel scour was 30 m at the seabed and the maximum depth measured was 1.7 m."

[62] Weeks, W. F., Barnes, P. W., Rearic, D. M., and Reimnitz, E. "Some Probabilistic Aspects of Ice Gouging on the Alaskan Shelf of the Beaufort Sea", US Army Cold Regions Research and Engineering Laboratory, June 7, 1983.

Context	Ice gouging
Cited in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b)	

Summary Weeks et al. (1983) detail the data collection and terminology (dominant gouge orientation, spatial gouge frequency, and gouge depth) and then develop a model of gouge depth frequency and its relationship to water depth. The authors emphasize that "[c]learly water depth is a most important parameter in studies of gouging," with larger gouge depths in deeper water out to the 38-m isobath. The equation used by Bercha Group Inc (2014b) appears to use Weeks et al. (1983) equations (3) and (8), modified by the inclusion of H_s, the change from θ to ϕ, and the change of k from a function of water depth to a constant.

Appendix E. Details about finding T_i and calculating N and λ for historic and Arctic scenarios

Multimedia Component 3 is an Excel document that contains five sheets, one for each year and location given in Table 11.

None of the risks vary as a function of time as Bercha Group Inc (2006a, b, 2008a, b, 2014b) described them. Thus, the sum of the units of exposure over the course of the project scenario multiplied by the mean risk per unit exposure yields the deterministic estimate of the spill risk (number of spills expected (Eq. (5)) and frequency per Bbbl produced) that can be compared to Bercha Group's (2006a, b, 2008a, b, 2014b) mean estimates.

Calculations of λ and N for historic and Arctic project scenarios require having T_i, R_{Hi}, and R_{Ai} values to use in Eq. (4) and Eq. (5), respectively. R_{Hi} and R_{Ai} are given in Table 7 for pipelines, platforms, and LOWC. Table A10 contains T_i for pipelines and platforms. Table A11 gives the T_i for LOWC. Reproducing Bercha Group's (2006a, b, 2008a, b, 2014b) values for λ_{Ai} was straightforward for pipelines and platforms. The LOWC calculations were more complicated in that it was unclear which infrastructure elements were counted in each calculation for the risks associated with exploration wells, development wells, and production wells. Bercha Group Inc (2006a, b, 2008a, b, 2014b) did not give component N_{LOWC} values for the historic or Arctic scenarios or λ_{Hi}, which would have provided a second check on the methodology followed here. I have shown two versions of each calculation of λ: the first has all possible infrastructure included, and the second was the closest I could come to Bercha Group's (2006a, b, 2008a, b, 2014b) values with the simplest change or changes from the complete set of infrastructure listed.

Table A1
A breakdown of the BOEM (2011) list of spills of ≥50 bbl of contaminants from 1964-2010 to the selection of data used by Bercha Group Inc (2014b) for modeling the risks of substantial spills. The risks of substantial spills from pipelines and platforms (non-LOWC) were based on the data in **bold**.

Spill description	Number of spills		
	≥50 to <1000 bbl	≥1000 bbl	Total spills
Spills of ≥50 bbl of contaminants (petroleum products and other chemicals) from 1964-2010	289	47	336
Spills of ≥50 bbl of contaminants (crude and refined petroleum products and other chemicals) from			
1964–1971	28	12	40
1972–2010	261	35	296
Spills from 1972-2010			
Crude and refined petroleum products <50 bbl and other chemicals	77	10	87
Crude and refined petroleum products ≥50 bbl	184	25	209
Spills of ≥50 bbl crude and refined petroleum products from			
Vessels	11	0	11
LOWC	11	1	12
Pipelines	45	**17**	62
Platforms (non-LOWC)	117	**7**	124

Table A2
Spills counts by source and year over time based on the BOEM (2011) database of crude and refined petroleum ≥50 bbl and the reported high factors from Bercha Group Inc (2006a, b, 2008a, b, 2014b).

	Number of spills by source				Number of spills by source		
Year	Pipeline	Platform	LOWC	Year	Pipeline	Platform	LOWC
1972	1	0	0	1995	0	3	0
1973	1	4	0	1996	1	1	0
1974	3	3	2	1997	0	1	0
1975	0	1	0	1998	3	1	0
1976	2	1	0	1999[a]	1	0	1
1977	3	1	0	2000	1	2	0
1978	2	1	0	2001	0	1	0
1979	1	3	0	2002	0	2	1
1980	1	6	0	2003	0	1	0
1981	2	3	0	2004	8	6	0
1982	0	3	1	2005	10	30	1
1983	1	6	0	2006[a]	1	6	0
1984	0	2	0	2007	1	0	0
1985	2	6	1	2008	6	18	0
1986	2	1	0	2009	1	2	1
1987	0	0	1	2010[a]	0	1	1
1988	1	3	0	Total	62	124	11
1989	0	2	0				
1990	2	1	0	Bercha Group			
1991	1	1	0			High Factor	
1992	2	0	1	2006[a, b]	2.57	2.88	1.5–2.3[b]
1993	1	0	0	2008[a, b]	2.81	3	1.5–2.3[b]
1994	1	1	0	2014b	2.81	3	1.5–2.3[b]

[a] Bercha Group Inc (2006a, b) used data from 1972-1999; Bercha Group Inc (2008a, b) used data from 1972-2006; Bercha Group Inc (2014b) used data from 1972-2010. The horizontal lines indicate end dates for the different data sets.

[b] LOWC high factors varied for production wells, exploration well drilling, and development well drilling but remained constant across the different report years.

Table A3
Triangle distribution calculations for historical spill frequency variability from Bercha Group Inc (2014b). Large spills are 1000–9999 bbl. Huge + spills are ≥10,000 bbl. Huge spills from LOWC are 10,000–149,999 bbl. Low and high factors, triangle distribution low, mode, and high parameters, and the historical and "expected" values can be found in Bercha Group Inc (2014b) Tables 2.4, 2.7, and 2.9 for pipelines, platforms, and LOWC, respectively.

Infrastructure, spill size	Low Factor	High Factor	Historical	Triangle Distribution Parameters				Bercha Group Inc (2014b) "Exp." = R_{Hi}
				Low	Mode	High	Mean	
Pipeline				Spill risk per 10^5 km-yr				
<10″, Large	0	2.81	3.143	0	0.597	8.832	3.143	3.943
<10″, Huge +	0	2.81	0.449	0	0.0853	1.262	0.449	0.563
>10″, Large	0	2.81	6.247	0	1.187	17.555	6.247	7.837
>10″, Huge +	0	2.81	1.785	0	0.339	5.016	1.785	2.232

(*continued on next page*)

Table A3 (*continued*)

Infrastructure, spill size	Low Factor	High Factor	Historical	Triangle Distribution Parameters				Bercha Group Inc (2014b) "Exp." = R_{Hi}
				Low	Mode	High	Mean	
Platforms				Spill risk per 10^4 well-yr				
Large +	0	3	0.285	0	0	0.855	0.285	0.380
LOWC								
Production				Spill risk per 10^4 well-yr				
Large	0.448	1.545	0.011	0.005	0.011	0.017	0.011	0.011
Huge	0.448	1.545	0.007	0.003	0.007	0.011	0.007	0.007
≥150,000 bbl	0.448	1.545	0.005	0.002	0.005	0.007	0.005	0.004
Exploration				Spill risk per 10^4 wells				
Large	0.439	2.036	0.539	0.237	0.283	1.097	0.539	0.620
Huge	0.439	2.036	0.350	0.154	0.184	0.713	0.350	0.403
≥150,000 bbl	0.439	2.036	0.217	0.095	0.114	0.442	0.217	0.250
Development				Spill risk per 10^4 wells				
Large	0.437	1.76	0.115	0.050	0.092	0.202	0.115	0.122
Huge	0.437	1.76	0.075	0.033	0.060	0.132	0.075	0.079
≥150,000 bbl	0.437	1.76	0.046	0.020	0.037	0.081	0.046	0.049

Table A4
Summary of spill listing discrepancies between BOEM (2011) and Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b).

Discrepancy type(s)	Number of occurrences
Pipeline spills	
Spills with dates prior to 1999 (2) or 2006 (2) not listed until Bercha Group Inc (2014b)	4
Spill with date prior to 1999 not in Bercha Group Inc (2002)	1
Updated spill volume (change noted in BOEM (2011))	1
Total discrepancies	6
Total pipeline spills listed by BOEM (2011) from 1972-2010	62
Platform spills	
Spills from 2006 or earlier in BOEM (2011), that first appear in Bercha Group Inc (2014b) [a]	46
Spills from 1999 or earlier in BOEM (2011), not listed in Bercha Group Inc (2002, 2006a, b) [a]	24
Cause attribution change(s) across two or more of Bercha Group (2002, 2006a, b, 2008a, b, 2014b)	15
In BOEM (2011), listed inBercha Group Inc (2008a, b), then not listed in Bercha Group Inc (2014b)	10
Listed in Bercha Group Inc (2008a, b) with no matching spill in current BOEM (2011) [b]	5
In BOEM (2011), not listed in Bercha Group Inc (2014b) (LOWC that was listed in Bercha Group Inc (2008a, b))	4
In BOEM (2011), not listed in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b)	3
In BOEM (2011), not listed inBercha Group Inc (2002, 2006a, b, 2008a, b, 2014b) (LOWC)	3
In BOEM (2011), not listed in Bercha Group Inc (2008a, b), listed in Bercha Group Inc (2002, 2006a, b, 2014b)	2
In BOEM (2011), not listed in Bercha Group Inc (2014b) after being listed in Bercha Group Inc (2002, 2006a, b, 2008a, b) (LOWC)[a]	1
Updated spill volume?	1
Total discrepancies	114
Total platform spills listed by BOEM (2011) from 1972-2010	145

[a] Spills <1000 bbl caused by hurricanes.
[b] Spills ≥1000 bbl caused by hurricanes.

Table A5
Ice gouging model parameters and spill risk estimates from sources cited at least once in Bercha Group Inc (2002, 2006a, b, 2008a, b, 2014b). Assumed pipeline burial depth = 2.5 m.

Source	Weeks et al. (1983)			Barnes et al. (1983)	Leidersdorf et al. (2001)	Bercha and Cerovŝek (2002)
Years	1972, 1973, 1975–1979			1972–1980	1996–1999	
Number of observations	20,313 across entire depth range			2179	48	
Depth range (m)	5–10	10–30	30–38	0–90	0–12	0–10
Mean scour depth (m)	0.135	0.223	0.391	0.56	0.2	0.4, 0.2
$\hat{k}$ (m^{-1})	7.386[a]	4.480[a]	2.559[a]	1.786	5	2.5, 5
H_s	0.83[b]	0.83[b]	0.83[b]	0.83[b]	0.83[b]	0.5
F (per km-yr)	5.2	5.2	5.2	5.2[c]	5.2[c]	4
θ (degrees)	71–83	97–99	97–99	93	45[b]	45

[a] $\hat{k}$ = 9.97exp(-0.04 x depth) (Weeks et al., 1983) at the depth midpoint.
[b] Using the value from Bercha Group Inc (2006a, b, 2008a, b).
[c] Using the value from Weeks et al. (1983).

Table A6

Ice gouging model parameters and spill risk estimates over time assuming a pipeline burial depth of $x = 2.5$ m. Bercha Group Inc (2002, 2006a, b, 2008a) cited Leidersdorf et al. (2001) for the parameter values. *F* varies by shelf depth in Bercha Group Inc (2002, 2006a, b, 2008a, 2014b) models. Bercha Group Inc (2008b) assumed that "for the present deep water location in the Chukchi, ice gouging does not occur." Numbers in **bold** show where parameters differ from previous versions of the report and where there were internal consistencies in the parameters specified in any given report.

Report(s)	Bercha Group Inc (2002)	Bercha Group Inc (2006a, b)	Bercha Group Inc (2008a)	Bercha Group Inc (2014b)
Shelf depth	0–10 m, 10–29 m	0–10 m, 10–29 m	0–10 m, 10–29 m	0–10 m, 10–29 m, 30–60 m
Mean scour depth (m) = $1/k$	0.4	**0.2**	0.2	0.2
H_s	0.8	**0.83**	0.83	Not given (assume 0.83)
F (per km-yr)	4, 2	**2, 1.5 (Chp 2)** or **1.6 (Chp 4)**	2, 1.5 (Chp 2) or **4**, **3.2 (Chp 4)**	**4, 3.2, 1.6**
ϕ (degrees)	45	45	45	Not given (assume 45)

Table A7

Sample ice gouging mode values per 10^5 km-yr for spills ≥1000 bbl using $N/L_PT = \exp(-kx)\ H_s\ F \sin\theta$ or $N/L_PT = \exp(-kx)\ H_s\ F \sin\phi$ with mean scour depth, H_s, F, and θ or ϕ from different sources (Tables A5 and A6), a mean pipeline burial depth of 2.5 m, and assuming 64% of spills are substantial compared with the values given by Bercha and Cerovŝek (2002) andBercha Group (2002, 2006a, b, 2008a, 2014b).

Source	Depth (m)	Parameter values k or $\hat{k}$ (m^{-1})	F (per km-yr)	H_s	θ or ϕ (degrees)	Pipeline failures per 10^5 km-yr Calculated mode	Mode given in text
Weeks et al. (1983)	5–10	7.386	5.2	0.83	77	0.0026	
	10–30	4.480	5.2	0.83	98	3.742	
	30–38	2.559	5.2	0.83	98	455.74	
Barnes et al. (1983)	0–90	1.786	5.2	0.83	93	3175.79	
Leidersdorf et al. (2001)	0–12	5	5.2	0.83	45	0.728	
Bercha and Cerovŝek (2002)	0–30	2.5	4	0.5	45	174.72	
Bercha and Cerovŝek (2002)	0–10	5	4	0.5	45	0.337	0.3340
	10–30	5	4	0.5	45	0.337	0.1670
Bercha Group (2002)	0–10	2.5	4	0.8	45	279.56	0.3340
	10–30	2.5	2	0.8	45	139.78	0.1670
Bercha Group (2006a, b)	0–10	5	2	0.83	45	0.2800	0.3340
	10–30	5	1.5	0.83	45	0.2100	0.2672
Bercha Group (2008a)	0–10	5	4	0.83	45	0.5599	0.3162
	10–30	5	3.2	0.83	45	0.4479	0.3953
Bercha Group (2014b)	0–10	5	4	0.83	45	0.5599	0.3162
	10–30	5	3.2	0.83	45	0.4479	0.3953
	30–60	5	1.6	0.83	45	0.2240	0.1976

Table A8

Equations for the Arctic unique effect triangle distribution modes for pipelines (substantial spills per 10^5 km-yr) and platforms (substantial spills per 10^4 well-yr) have varied over time and by location. Abbreviations related to pipelines are *IG = Ice Gouging*, *SS = Strudel Scour*, *UB = Upheaval buckling*, *TS = Thaw Settlement*, and *OA = Other Arctic*. Abbreviations related to platforms are *Hist = Historic* process spill rate (Bercha Group Inc, 2008a, b) or *Historic equipment failure* or *facility release rate* (Bercha Group Inc, 2014b), *PF = Process Facility spills* (large), *IF = Ice Force*, *LT = Facility Low Temperature*, and *OA = Other Arctic*.

Report Year, Location				
Pipelines	*UB*	*TS*	*OA*	Total Arctic unique effects expressed algebraically
Beaufort				
Bercha Group (2002, 2006a)	$0.2SS$	$0.1SS$	$0.25(IG + SS + UB + TS)$	$1.25IG + 1.625SS$
Bercha Group (2008a)	$0.2SS$	$0.1SS$	$0.10(IG + SS + UB + TS)$	$1.10IG + 1.43SS$
Chukchi				
Bercha Group (2002)	$0.2SS$	$0.1SS$	$0.25(IG + SS + UB + TS)$	$1.25IG + 1.625SS$
Bercha Group (2006b)	$0.2SS$	0	$0.25(IG + SS + UB)$	$1.25IG + 1.55SS$
Bercha Group (2008b)	$0.2SS_B$[a]	0	$0.10(UB)$	$0.22SS_B$
Bercha Group (2014b)	$0.2SS$	$0.5SS$	$0.10(IG + SS + UB + TS)$	$1.10IG + 1.87SS$
Platforms	*IF*	*LT*	*OA*	Total Arctic unique effects expressed algebraically
Beaufort				
Bercha Group (2002, 2006a)	0.014	$0.1\ PF$	$0.10(IF + LT)$	$1.10IF + 0.110\ PF$
Bercha Group (2008a)	0.014	$0.01Hist$	$0.10(IF + LT)$	$1.10IF + 0.011Hist$
Chukchi				
Bercha Group (2002)	0.014	$0.10\ PF$	$0.10(IF + LT)$	$1.10IF + 0.110\ PF$
Bercha Group (2006b)	0.014	$0.03\ PF$	$0.10(IF + LT)$	$1.10IF + 0.033\ PF$
Bercha Group (2008b)	0.014	$0.01Hist$	$0.05(IF + LT)$	$1.05IF + 0.0105Hist$
Bercha Group (2014b)	0.0135	$0.01Hist$[b]	$0.05(IF + LT)$	$1.05IF + 0.0105Hist$

[a] In Bercha Group (2008b) report *IG*, *SS*, and *TS* were expected to have zero risk possibility in the Chukchi. The value for the *UB* mode in the Chukchi was 20% of the *SS* in the Beaufort (SS_B) (Table 4.4 in Bercha Group (2008a) and Bercha Group Inc (2008b)).

[b] In Bercha Group Inc (2014b) the text has a 3% risk of large spills, but the accompanying table shows a 1% risk.

Table A9
An exercise in calculating depth-specific ice gouging spill risks for pipelines and the effects on the estimated overall substantial spill risk per Bbbl produced using the Bercha Group Inc (2014b) project scenario.

Risk per 10^5 km-yr	Depth			Comment
	0–10 m	10–30 m	30–60 m	
Ice gouging				
Mode	0.0026	3.742	455.738	From Table A7 (Mode risk rates for spills ≥1000 bbl under Weeks et al. (1983) calculations)
Min	0.00013	0.187	22.787	0.05**Mode*
Max	0.0338	48.649	5924.594	13**Mode*
Mean	0.0122	17.526	2134.373	
Other Arctic				
Mode	0.00941	0.376	45.576	10% of all other Arctic unique spill risks
Min	0.00047	0.019	2.279	0.05**Mode*
Max	0.12237	4.892	592.487	13**Mode*
Mean	0.04408	1.762	213.447	
Total Arctic (modified historic and Arctic unique) risks per 10^5 km-yr = R_{Ai}				
< 10″ diameter	2.800	21.676	2350.199	Using mean values for *Ice gouging* and *Other Arctic* shown here with all other risk expected values as calculated and given in Table 4.5 of Bercha Group Inc (2014b)
> 10″ diameter	5.657	24.501	2353.013	
Exposure (mi-yr)				
< 10″ diameter	0	0	630	From Table A10
> 10″ diameter	440	528	7462	
Exposure (10^5 km-yr) = T_{Ai}				
< 10″ diameter	0	0	0.010137	Conversion to same units as risk rates
> 10″ diameter	0.00708	0.008496	0.120064	
Expected number of spills ≥1000 bbl = $R_{Ai} \times T_{Ai} = N_{Ai}$				
< 10″ diameter	0	0	23.82	Risk*unit exposure
> 10″ diameter	0.040	0.208	282.51	
Total expected spills ≥1000 bbl from pipelines in the Arctic = $\Sigma N_{Ai} = 306.583 = N_{A,\ Pipeline}$				
Spills per Bbbl produced (assuming production volume, $V = 4.2584$ Bbbl) = $N_{A,\ Pipeline}/V = 71.995 = \lambda_{A,\ Pipeline}$				

Table A10
Comparison of project scenario timeline, infrastructure, and total units of exposure (T_i) by location and year for pipelines and platforms (Bercha Group Inc (2006a, b, 2008a, b, 2014b) Tables 3.2 and 3.3).

Infrastructure element (exposure units)	Location, Report				
	Beaufort		Chukchi		
	Bercha Group Inc (2006a)	Bercha Group Inc (2008a)	Bercha Group Inc (2006b)	Bercha Group Inc (2008b)	Bercha Group Inc (2014b)
Years of oil production	29	21	25	22	45
Expected production (Mbbl)	1375.6	500.5	1000.5	500.0	4258.4
Total pipeline miles	115	90	120	80	240
Platform wells	206	60	98	50	457
Exploration wells					
0–10 m	7	4			
10–30 m	6	3			
30–60 m	5	2	4	7	40
Production wells					
0–10 m	69	18			
10–30 m	137	18			
30–60 m		24	62	50	457
Pipeline (mi-yr)					
0–10 m, < 10 in					
10–30 m, < 10 in	195				
30–60 m, < 10 in		210	700		630
0–10 m, > 10 in	1050	250			440
10–30 m, > 10 in	790	360	750		528
30–60 m, > 10 in		590	1500	1420	7462
Total	2035	1410	2950	1420	9060
Prod. platform wells (well-yr)					
0–10 m	1014	252			
10–30 m	2541	252			
30–60 m		348	1240	728	12,148
Total	3555	852	1240	728	12,148

Table A11
Comparison of project scenario timeline, infrastructure, and total units of exposure (T_i) by location and year for LOWC (Bercha Group Inc (2006a, b, 2008a, b, 2014b) Tables 3.2 and 3.3).

Infrastructure element (exposure units)	Location, Year				
	Beaufort		Chukchi		
	Bercha Group Inc (2006a)	Bercha Group Inc (2008a)	Bercha Group Inc (2006b)	Bercha Group Inc (2008b)	Bercha Group Inc (2014b)
Delineation/dev'm't wells					
0–10 m	6	4			
10–30 m	11	4			
30–60 m		5	104	8	457
Production platforms					
0–10 m	3	1			
10–30 m	5	1			
30–60 m		1	1	2	8
Production subsea wells					
30–60 m		12	36		
Prod. platforms (well-yr)					
0–10 m	48	15			
10–30 m	100	10			
30–60 m		12	25	32	271
Total	148	37	25	32	271
Subsea wells (well-yr)					
30–60 m		168	720		

Table A12
Exploring choice of exposure variable in estimating spills risks.

Reference	Exposure Variable			Infrastructure required per Bbbl produced	
	10^5 km-yr	10^4 well-yr	Bbbl prod	10^5 km-yr/Bbbl prod	10^4 well-yr/Bbbl prod
Arctic - Beaufort					
Bercha Group Inc (2006a)	0.03274	0.3555	1.3756	0.0238	0.258
Bercha Group Inc (2008a)	0.02269	0.0852	0.5005	0.0453	0.170
Arctic - Chukchi					
Bercha Group Inc (2006b)	0.04747	0.1960	1.0005	0.0474	0.196
Bercha Group Inc (2008b)	0.02285	0.0728	0.500	0.0457	0.146
Bercha Group Inc (2014b)	0.14577	1.2147	4.2584	0.0342	0.285
GOM and PAC (historic)					
1972–1999					
Bercha Group Inc (2002)	2.53903	11.9714	10.132[a]	0.251	1.182
Bercha Group Inc (2006a, b)	1.87183	11.9714	10.132[a]	0.185	1.182
Eschenbach and Harper (2006)	1.846	7.8801	10.132	0.182	0.778
1972–2005					
Eschenbach and Harper (2006)	2.603	10.0087	13.535	0.192	0.739
1972–2006					
Bercha Group Inc (2008a, b)	2.73847	21.2971	13.535[b]	0.202[b]	1.573[b]
1972–2010					
Bercha Group Inc (2014b)	3.34764	24.5486			

[a] Bercha Group Inc (2002, 2006a, b) did not give an estimation cumulative volume of oil produced from 1972-1999. I used the value from Eschenbach and Harper (2006) for that period.

[b] The same as for *a* but no data were available for 2006 Bbbl produced, so I used the total from 1972-2005. The resultant infrastructure needs to produce each Bbbl oil are therefore slightly too high.

Table D1
List of 24 works included in Bercha Group's (2014b) reference section but not cited in the text. Reference order and formatting follow Bercha Group Inc (2014b).

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(*continued on next page*)

Table D1 (*continued*)

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