Environmental risk-based leak detection philosophy for the Krafla field development in the northern part of the North Sea

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Leaks, leak detection, Krafla, Askja, field, subsea, subsea templates, wells, pipeline, reeling, bundle, SPS, UPP, OSCAR, tolerance criteria, functional requirements, North Sea

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Table of contents

CONCLUSIVE SUMMARY

Equinor is planning for the first major unmanned remote operated field development on NCS. Krafla is located in the North Sea south of Oseberg about 132 km from the coastline of Øygarden municipal in Vestland county, and the water depth in the area varies between 105 and 121 meters. The field is planned with subsea templates at Krafla, Central and Askja, all connected to an unmanned production platform (UPP). The field internal pipelines will be either a reeling concept or a bundle concept. The installations are located close to a defined Sandeel (tobis) area at Vikingbanken (Figure 0-1). DNV has on behalf of Equinor prepared a leak detection philosophy for the Krafla development project.

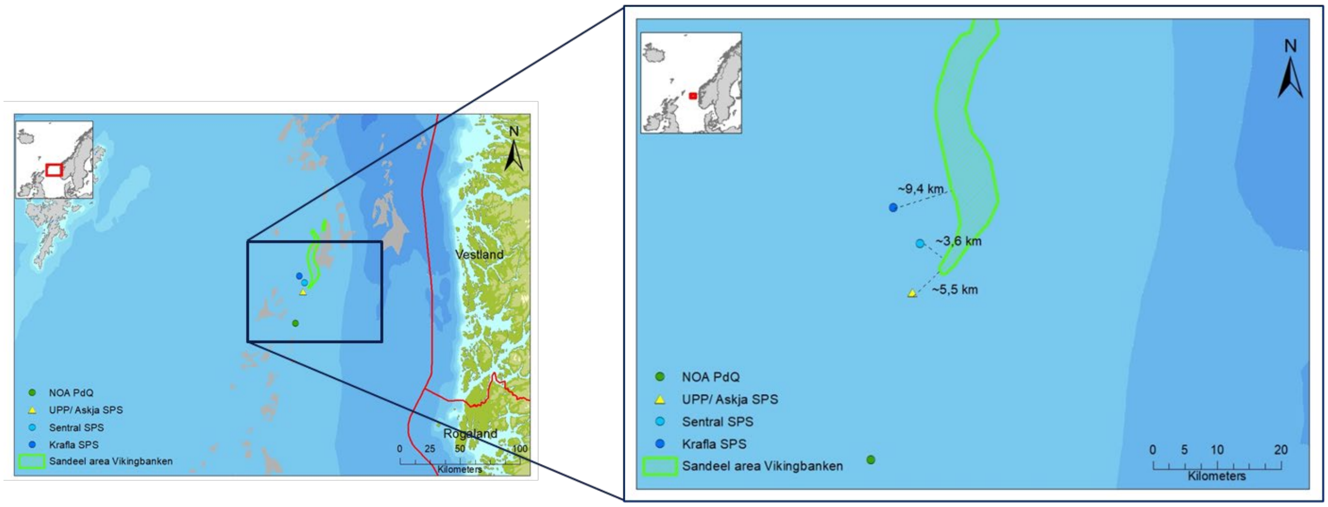


Figure 0-1 *Location of the Krafla SPS, Central SPS, Askja SPS, UPP and NOA PdQ and the defined sandeel area at Vikingbanken.*

The project has looked at how various subsea leaks of hydrocarbons from hole sizes ≤ 120 mm will behave in the water column, and to what extent they will reach the surface and whether they can have effects on the sea surface above effect limits for seabirds or in the water column for fish eggs and larvae. The possibility of detection on the sea surface from SAR satellite and / or radar has also been considered, and weather windows for detection throughout all months of the year have been mapped. The results for the various scenarios are summarized in Equinor's risk matrix (RM100), where both environmental impact and leakage frequency are plotted. Based on the results in the risk matrix, a maximum allowed leak detection time (functional requirements) for the leak detection system for the Krafla field have been suggested. Finally, a screening and BAT evaluation of suitable leak detection techniques (in addition to the base-case techniques) including a ALARP evaluation for the Krafla field has been done.

Based on the scenario's placement in the risk matrix, functional requirements are suggested in Table 0-1. The functional requirements are based on the results in the environmental analysis, and they are set before implementing any leak detection techniques.

Equinor also have two risk tolerability criteria for subsea leakages. The criteria are used to set risk-based requirements for leak detection:

- The frequency of volumes (before detection) above 50 m^3 - shall be limited to 10^{-2} per year.
- All leaks with lower frequencies shall in any case be detected before leak volumes have reached 5000 m^3.

Table 0-1 *Suggested functional requirements and Equinor's risk tolerance criteria for modelled leaks. The modelled scenarios have leak rates lower than what a mass balance system will be able to detect.*

Location/ scenario	Hole size (mm)	Env. risk-based functional requirement (time)	5000 m³ (days)
16'' Krafla production line between Krafla SPS and UPP, KP 0.1	**2.5**	< 1 year	262
	5	months	66
	10	weeks	17
	20	days	4
	30	1 day	3
	40	1 day	2
	50	hours	1
16'' Krafla production line between Krafla SPS and UPP, UPP seabed (inside 500 m zone)	**2.5**	year(s)	1224
	5	< 1 year	306
	10	months	77
	20	weeks	19
	30	week	9
	40	days	5
	50	1 day	3
	60	1 day	2
	70	1 day	2
	80	hours	1
	90	hours	1
16'' Askja production line between Askja SPS and UPP, KP 0.375	**2.5**	year(s)	2189
	5	year	547
	10	months	137
	20	weeks (month)	34
	30	week	15
	40	week	9
	50	days	6
	60	days	4
	70	1 day	3
	80	1 day	2
	90	1 day	2
	100	hours	1
	120	hours	1
Krafla Liquid export line (Midway UPP - PdQ)	**2.5**	< 1 year	173
	5	weeks (month)	43
	10	week	11

The total leak frequency for Krafla is above 10^{-2} for the smallest leak sizes (< 10 mm) and the requirement is therefore assessed qualitatively when recommending possible additional leak detection techniques for Krafla in addition to the base case before these leaks exceeds 50 m³. The base case with methane sniffers and passive acoustic sensors at each template will significantly increase early detection of the smaller leaks before reaching 50 m³.

Krafla is located close to a defined sensitive sandeel habitat at *Vikingbanken* and it is important that subsea leaks with potential to give environmental consequences will be detected within short time. Equinor consider local subsea leak detection at templates as BAT and will install subsea leak detection on Krafla. Different leak detection techniques are available for Krafla. The base case for the development is to have satellite (SAR) surveillance, mass balance for the multi-phase Krafla Liquid Export Line (KLE), ISPAS radar on UPP, Franatech sniffer sensors and Naxys passive acoustic leak detection sensors at templates and visual observations. In addition, increased frequency on satellite images and evaluation of ROV required frequency is relevant for Krafla. Subsea inspection drones, active acoustic sensors and fiber optic are not considered BAT today (because of low TRL) but are relevant for further exploration as part of technology qualification for leak detection.

Table 0-2 give an overview of relevant leak detection techniques available for Krafla in addition to the base-case and whether these techniques are required or recommended for implementation by Krafla. The recommendations are given based on the suggested functional requirements (from the environmental risk assessment) and Equinor's risk tolerance criteria.

Table 0-2 *Relevant leak detection technologies, either required or recommended for implementation by Krafla, in addition to the "Base case" technologies. The table also include technologies for further exploration (not considered BAT today because of low TRL). (NA = Not applicable, e.g., due to not technically feasible).*

Leak detection technique	Location	Krafla Liquid Export Line (KLE)	16" Krafla production line between Krafla SPS and UPP, KP 0.1	16" Askja production line between Askja SPS and UPP, UPP side within 500 m zone	16" Askja production line between Askja SPS and UPP, KP 0.375	Comments
Mass balance	Internal	Base case	Required	Required	Required	Multi-phase mass balance is base case for KLE (from UPP to NOA PdQ, 27 km).
Methane sniffer	Subsea	NA	Base case	Base case	Base case	Base case on subsea templates. The export line between Krafla UPP and NOA PdQ (KLE) is 27 km and too long to be covered by sufficient number of local sensors.
Passive acoustic	Subsea	NA	Base case	Base case	Base case	Base case on subsea templates. The export line between Krafla UPP and NOA PdQ (KLE) is 27 km and too long to be covered by sufficient number of local sensors.
Satellite (SAR)	Surface (AOI)	Base case	Base case	Base case	Base case	
ISAPAS radar (on IPP)	Surface	Base case	Base case	Base case	Base case	Based on functional requirements Krafla UPP side, Askja SPS. Much shorter response time than SAR.
ROV inspection	Subsea	Required	Recommended	Recommended	Recommended	Evaluate ROV required frequency based on tolerance criteria 5000 m^3.
Increased satellite radar images (SAR)	Surface (AOI)	NA	Recommended	Recommended	Recommended	Based on functional requirements with detection within hours to one day in order to cover total pipelines (outside OSD radar area). For KLE none of the modelled leaks is expected to reach surface, and

						increased satellite radar images will not be applicable for small leaks from this pipeline.
Pressure/ temperature monitoring in carrier pipe	Internal	NA	Recommended	Recommended	Recommended	Based on functional requirements hours - 1 day. Only applicable for Bundle concept.
Active acoustic	Subsea	Explore further	Explore further	Explore further	Explore further	Not BAT
Fiber optic	Internal/ subsea	Explore further	Explore further	Explore further	Explore further	Not BAT
Underwater drones	Subsea	Explore further	Explore further	Explore further	Explore further	Not BAT

DEFINITIONS AND ABBREVIATIONS

Abbreviation	Definition
ALARP	As low as reasonably practicable
AOI	Area of interest
AUV	Autonomous underwater vehicle
BAT	Best Available Techniques
DAS	Distributed Acoustic Sensing. Fiber optic
Detection	The action or process of identifying the presence of something concealed. The act or process of discovering, finding, or noticing something.
ENVID	Environmental HAZID
FEED	Front End Engineering Development
GOMO	Guidelines for Offshore Marine Operations
HAZID	HAZard IDentification. Systematic method to evaluate and identify risk for a system or activity.
HC	Hydrocarbon
HP	High pressure
HSE	Health, Safety and Environment
LD	Leak detection
LDS	Leak Detection System. A leak detection system consists of different leak detection technologies for surface and seabed detection.
LDT	Leak Detection Technology. Different technologies for surface or seabed leak detection. Different leak detection technologies will together form a leak detection system for the field/installation.
LE	Liquid Exportline
LP	Low pressure
Leakage	accidentally loss or admittance of contents, (especially liquid or gas), through a hole or crack in a hydrocarbon production system content. In this context: Discharge of hydrocarbons from subsea production systems. The leak relevant for detection may be a small leak for monitoring or repair or a large leak that will necessitates immediate action to stop the discharge.
MBS	Mass Balance System
NEA	Norwegian Environmental Agency (Miljødirektoratet)
NCS	Norwegian Continental Shelf
NOFO	Norsk oljevernforening for operatørselskap
OLGA	Dynamic Multiphase Flow Simulator, The industry-standard tool for dynamic multiphase flow simulation.
OSCAR	Oil Spill Contingency and Response. OSCAR is a state-of-the-art model and simulation tool for predicting the fates and effects of oil released during an accidental release of oil.
OSD	Oil Spill Detection
OSPAR	Oslo-Paris Convention (For the Protection of the Marine Environment of the North-East Atlantic)
PdQ	Processing platform with skid over drilling and living quarter located in North of Alvheim (NOA) area
PiP	Pipe in Pipe
PLEM	Pipeline end manifold
PLET	Pipeline end termination
PSA	Petroleum Safety Authority (Petroleumstilsynet)
PTIL	Petroleumstilsynet
RP	Recommended Practice

Abbreviation	Definition
ROV	Remotely Operated Vehicle
SAR	Synthetic-aperture radar
SBV	Stand by vessel
SPS	Subsea Production System
SSIV	Subsea isolation valve
SURF	Subsea, Umbilicals, Risers and Flowlines
SUTU	Subsea Umbilical Termination Units
THC	Total Hydrocarbon Concentration
TRA	Total Risk Assessment
UID	Underwater Inspection Drone
UPP	Unmanned Processing Platform
UTA	Umbilical Termination Assembly
UTH	Umbilical Termination Head
XT	X-mas Tree (production/injection tree)

1 INTRODUCTION

1.1 Background

Equinor is planning for the first major unmanned remote operated field development on NCS. Krafla is located in the North Sea south of Oseberg about 132 km from the coastline of Øygarden municipal in Vestland county, and the water depth in the area varies between 105 and 121 meters. The field is planned with subsea templates at Krafla, Central and Askja, all connected to an unmanned production platform (UPP). The field internal pipelines will be either a reeling concept or a bundle concept. The installations are located close to a defined Sandeel (tobis) area at Vikingbanken (Figure 1-1).

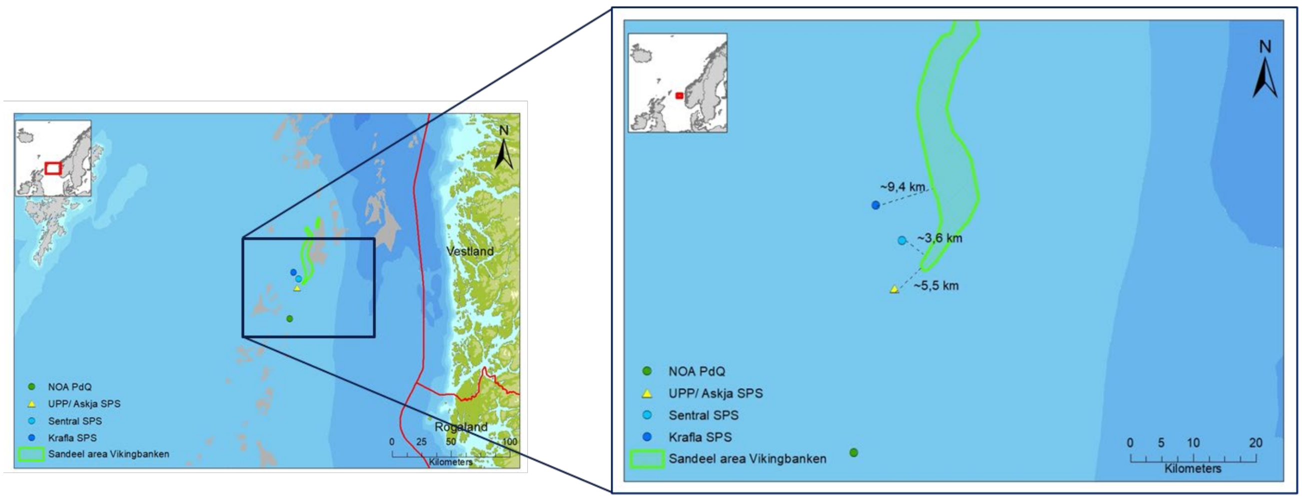


Figure 1-1 *Location of the Krafla SPS, Central SPS, Askja SPS, UPP and NOA PdQ and the defined sandeel area at Vikingbanken in the North Sea. Existing fields are shown in grey.*

The regulations for leaks and acute discharges have been updated, and there are new requirements for establishing a leak detection philosophy and strategy based on risk assessments for installations and fields. DNV has on behalf of Equinor prepared a leak detection philosophy for the Krafla development project.

The project has looked at how various subsea leaks of hydrocarbons will behave in the water column and to what extent they will reach the surface and whether they can have effects on the sea surface above effect limits for seabirds or in the water column for fish eggs and larvae. The possibility of detection on the sea surface from SAR satellite and / or radar has also been considered, and weather windows for detection throughout all months of the year have been mapped. The results for the various locations are collected and summarized in Equinor’s risk matrix (RM100), where both environmental impact and leakage frequency are plotted. Based on the results in the risk matrix, functional requirements for the leak detection system for the Krafla field have been suggested. Finally, a screening and BAT evaluation of suitable leak detection techniques including a ALARP evaluation for the Krafla field has been done.

1.2 The Krafla development

Krafla is located south of the Oseberg Field Centre. UPP™ will establish a significant gas export capacity with gas exported directly to Statpipe (Gassled Area A). Partly stabilized oil and produced water are exported to NOA PdQ for further processing. NOA PdQ will provide needed utilities and services. The field will have low CO_2 emissions with onshore power.

Krafla field development consists of three drilling locations. Both Krafla and Askja will be developed with 2x 6-slots SPS at each location. Sentral will be developed with one 6 -slots SPS. Illustration of field layout is shown in Figure 1-3. The first license award in PL035 was in 1969, and Krafla Main discovery was in 2011. The license is part of an area development consisting of seven licenses in the NOAKA area between Oseberg and Alvheim FPSO (Figure 1-2).

The Krafla reservoirs are complex, with small and segmented structures and large fluid variations. Krafla licenses is mainly a gas/condensate field, with above 65 % of total expected oil equivalents being gas. Equinor is operator for the Krafla area (licenses 272 and 035), and the ownership is split 50 % / 50 % between Equinor and Aker BP.

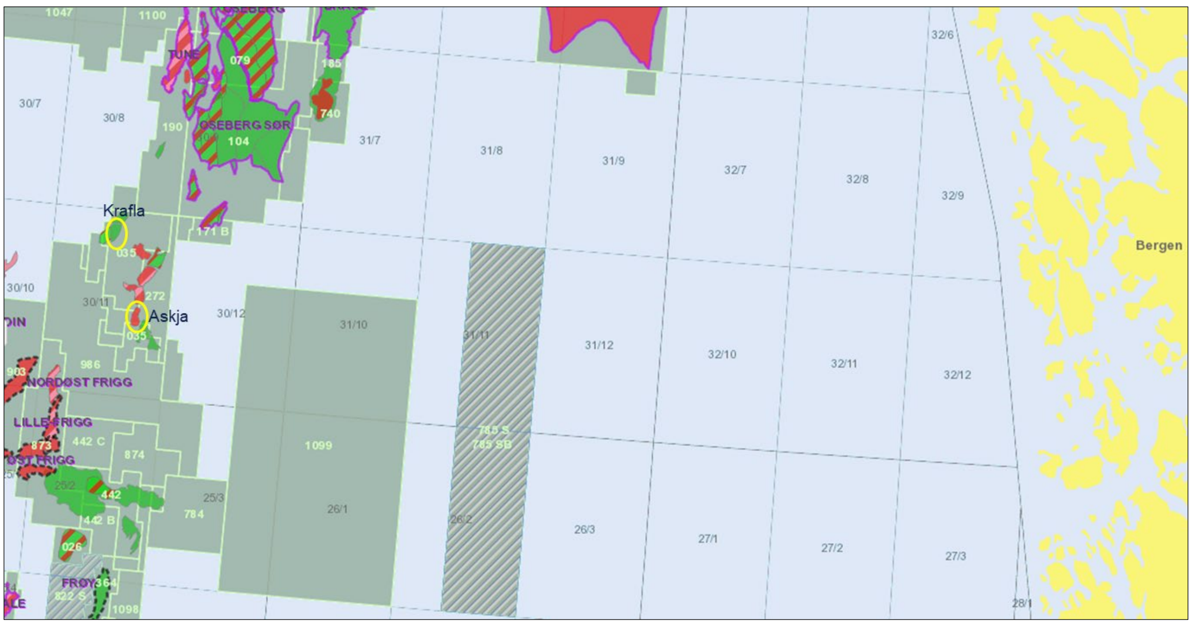


Figure 1-2 *Location of the Krafla and Askja developments in the North Sea.*

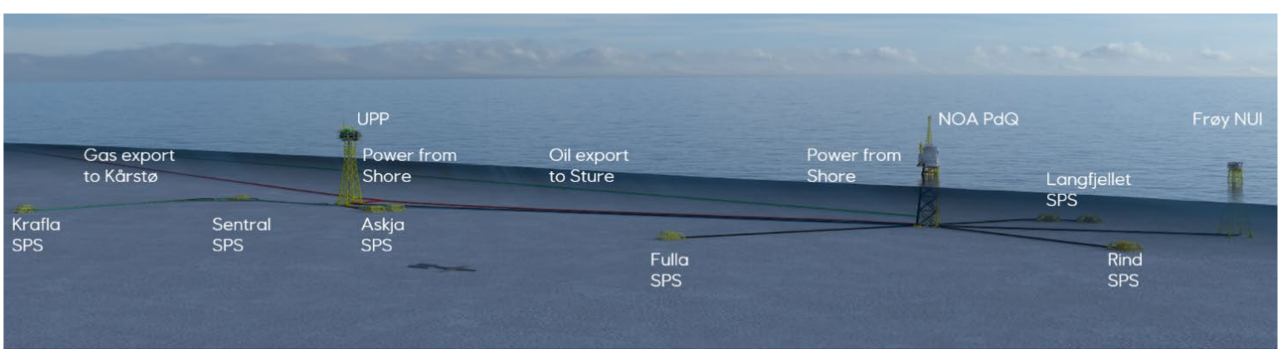


Figure 1-3 *Schematic overview of the area development with Krafla, Askja, Sentral and UPP to the left in the picture.*

Figure 1-4 shows an illustration of the area field layout. The Krafla development project is marked in pink/red. Distances from UPP to installations is shown in Table 1-1.

Table 1-1 *Distances from UPP to installations on Krafla (Equinor, 2021b).*

From UPP to:	Distance (km)
NOA PdQ	27
Krafla SPS	13
Sentral SPS	7
Askja SPS	0.55

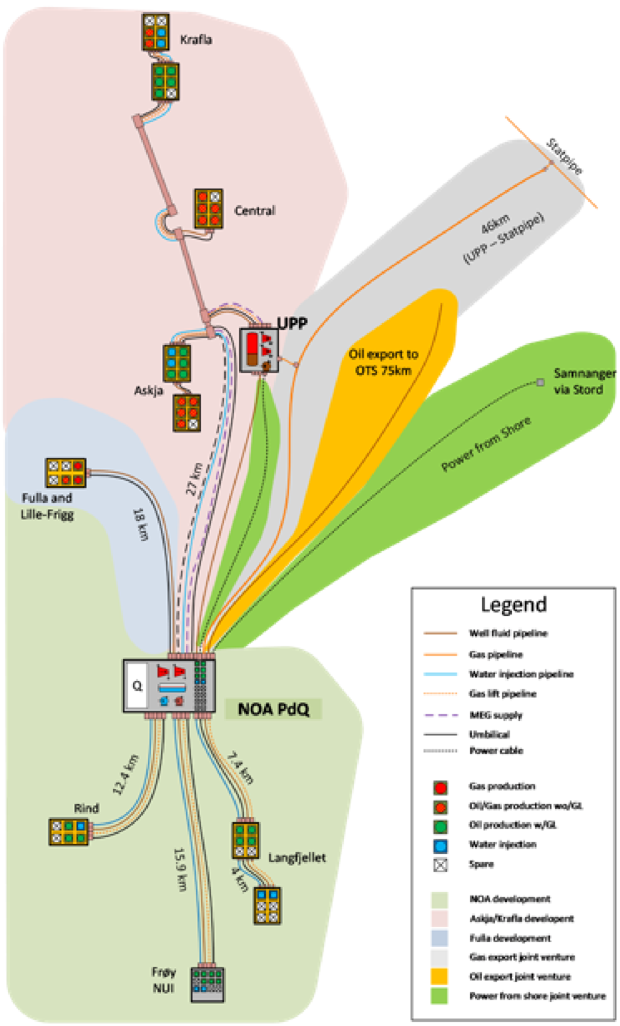


Figure 1-4 *Area field layout (illustration) with the Krafla project marked with pink/red (Equinor, 2021b).*

Two different subsea concepts are under evaluation in the project (for pipelines from UPP to the subsea templates) and will be covered in this study:

- Bundle concept with 2 production pipelines, overview is shown in Figure 1-5.

- Pipeline (Reeling) concept with 2 production pipelines, overview provided in Figure 1-6

Note that pipelines between NOA PdQ and UPP will be the same for both the concepts.

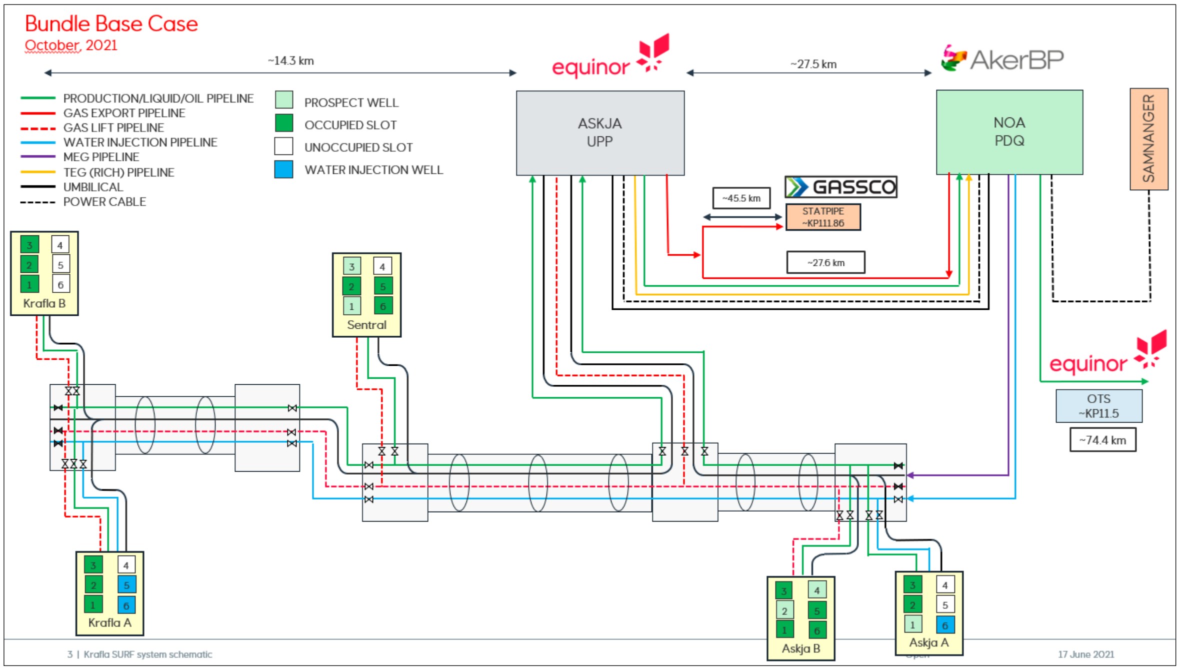


Figure 1-5 *Overview bundle concept.*

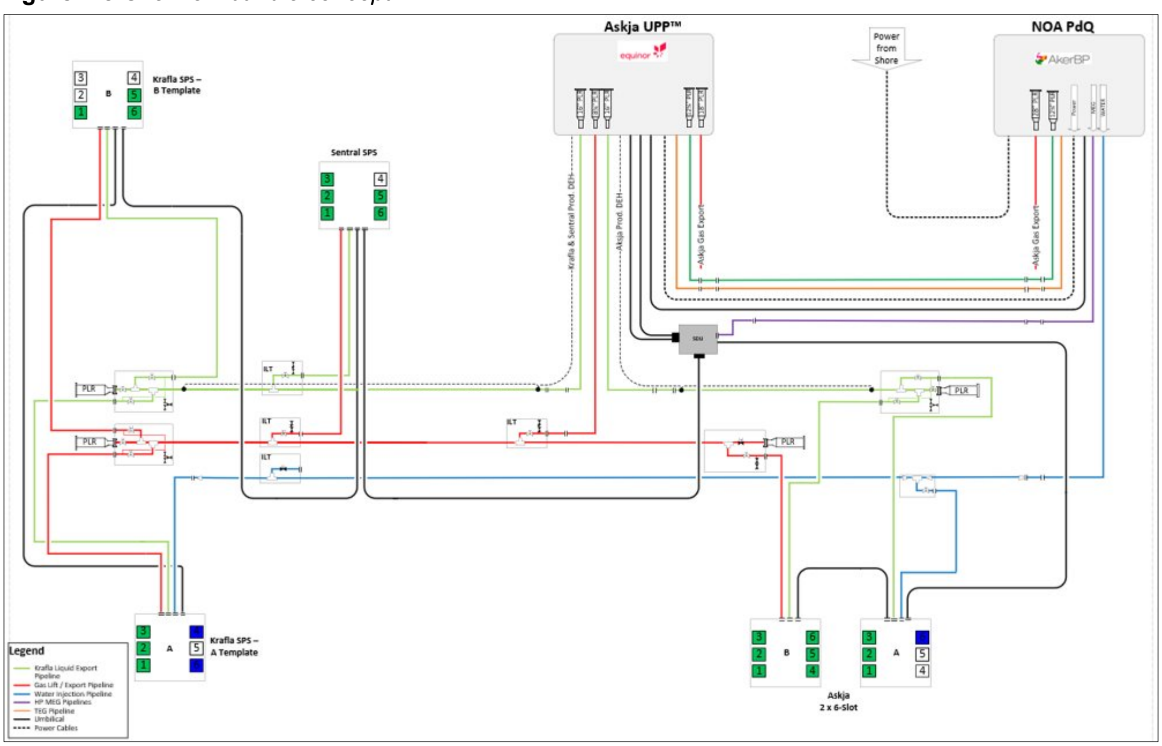


Figure 1-6 *Overview pipeline/reeling concept.*

Based on input data from Equinor the following part of the development is selected for further modelling in OSCAR:

- 16" Krafla production line between Krafla SPS and UPP, Krafla SPS seabed KP 0.1
- 16" Krafla production line between Krafla SPS and UPP, UPP seabed (inside 500 m zone)
- 16" Askja production line between Askja SPS and UPP, Midway SPS and UPP KP 0.375
- Krafla Liquid export line, Midway UPP and NOA PdQ

1.3 Framework

The analysis has been carried out based on government requirements and Equinor Energy's own company requirements and procedures. Figure 1-7 shows the regulatory hierarchy for petroleum activity on the Norwegian shelf. Laws and regulations are required to follow, while guidelines and norms are recommended to follow.

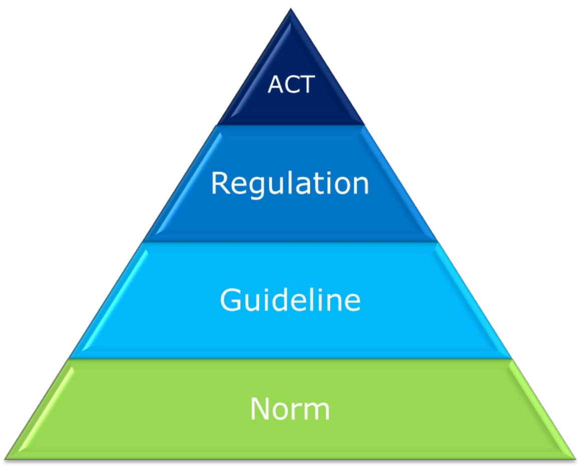


Figure 1-7 *The regulatory hierarchy for petroleum activity on the NCS.*

1.3.1 Regulatory requirements

A brief summary of current regulatory requirements for leaks / leak detection is given below, with reference to relevant sections of the Pollution Control Act and regulations.

The Pollution Control Act

§1, Purpose of the law; the purpose of the law is to protect the external environment from pollution and to reduce existing pollution, to reduce the amount of waste and to promote better treatment of waste. The law shall ensure a reasonable environmental quality, so that pollution and waste do not lead to health damage, harm well-being or damage nature's ability to produce and self-renew.

§7, Duty to avoid pollution; When there is a risk of pollution in violation of the law, or decisions pursuant to the law, the person responsible for pollution must provide measures to prevent it from occurring.

Framework regulation

§45, Development solutions; subsea facilities and pipeline systems shall in addition be designed and installed so that the facilities can withstand mechanical damage due to other activity, and so that they do not cause fishing gear damage or hinder fishing activity to an unreasonable degree.

§48, Duty to monitor the external environment; To ensure that the decision basis and knowledge of the marine environment is sufficient to maintain an acceptable environmental condition, the operator shall carry out monitoring of the external environment. Sufficient information must be provided so that pollution caused by own activities is discovered, mapped and assessed, and that necessary measures are implemented as soon as possible.

Management regulation

§29, Notification and notification to the supervisory authorities of danger and accident situations; The operator shall ensure coordinated and immediate notification by telephone to the Petroleum Safety Authority Norway in the event of danger and accident situations that have led to, or in insignificantly changed circumstances could have led to e) acute pollution.

Facility regulation

§7 Security functions; Facilities shall be equipped with the necessary safety functions that can at any time a) detect abnormal conditions, b) prevent abnormal conditions from developing into hazardous and accident situations, c) limit the damage in the event of accidents. Requirements shall be set for the performance of safety functions. The status of security functions must be available in the central control room.

Activity regulation

§57, Detection and mapping of acute pollution; The operator shall as soon as possible detect acute pollution, cf. the framework regulations § 48 and the management regulations § 29 first paragraph letter e. The operator shall have a system for detecting acute pollution. The system shall be as independent as possible of visibility, light and weather conditions and shall consist of various methods that together are suitable for detecting relevant types and amounts of acute pollution that may occur from the facilities. The system must also provide sufficient information about minor leaks that over time can constitute significant pollution.

1.3.2 Guidelines and norms

The analysis is aligned with guideline R-100 from NOROG, and recommended practice for offshore leak detection RP-F302 from DNV.

- **NOROG R-100**, Anbefalte retningslinjer for deteksjon av akutte utslipp (ny revisjon 2021)
- **DNV GL RP-F302,** Recommended practice - Offshore leak detection

1.3.3 Equinor Energy- company requirements

Equinor has several internal company requirements for describing technical requirements, work process requirements, guidelines and operating procedures for the development and operation of their fields and installations. Requirements for implementation and operation of leak detection systems are given in the following documents:

- Arbeidsprosesskrav WR1151, Miljøvurderinger, utslippsbegrensninger og driftsoppfølging. Final ver. 4. published 2019-03-08
- Operasjonsprosedyre, System 18 - Lekkasjedeteksjon – Driftsrutiner og alarmhåndtering. Rev 1, 19/09/2019.
- TR1055 (Technical Requirement), Performance standards for safety systems and barriers – offshore. Version 9.0.
- TR1011, Environmental requirements for offshore installation Section 2.10 Oil spill detection.
- TR1244, Technical requirements for facilities scope and cost estimate classes – offshore projects
- TR2076, DPN risk analyses and risk tolerance criteria, section 2.2.1 etc.
- GL0139 (Guideline), ALARP Principles Final ver. 5.0, published 2019-03-11
- GL0282 Risk and emergency preparedness analysis
- GL0393 Pipeline and subsea systems leak detection
- Krafla Safety Barrier Specification (PM786-PMS-052-017), chapter 2.6 and 6.3.4.

1.4 Audit on subsea installations from Norwegian Environmental Agency (NEA) and Petroleum Safety Authorities (PSA)

Equinor has been audited by the Norwegian Environment Agency and the Petroleum Safety Authority to assess the system for leak detection for subsea installations, as required by the HSE regulations. The audit theme touches on both the parts of the leak detection system that will contribute to stop acute pollution, and the parts of the system that will contribute to reduce environmental risk by detecting, mapping and limit discharges to sea that are or may develop into acute pollution.

Five non-conformities and one comment were given based on the audit (Ptil and Mdir, 2021). The non-conformities are:

1. The company does not have a sufficient system for detecting small leaks.
2. Establishment of performance requirements for leak detection is not in accordance with the regulatory requirements.
3. The facility does not have an overview of when detection on the sea surface is not available.
4. The company does not handle non-conformance of leak detection systems.
5. The Trestakk field is not operated in accordance with the terms in the PDO and the preconditions used for consent to use the facility.

The comment is:

A. The company does not have a uniform practice for registration, assessing and archiving of OBS reports after ROV inspections.

1.5 Assumptions and limitations in the analysis

DNV has based the evaluations and report on documentation made available from Equinor during the project.

The following limitations apply to the analysis:

- Only scenarios that can cause subsea oil / condensate leaks have been modelled further in the OSCAR model in the analysis.
- Umbilicals (chemical pipelines) and water injection pipeline (with chemicals) normally contain limited volumes of chemicals (usually less than 10 m^3 per chemical for the whole pipeline) except for MEG and TEG. MEG is a classified green chemical and is water soluble, TEG is a classified yellow chemical but is not toxic and is water soluble and will not accumulate (see Appendix A). Chemical supplier for the Krafla field is not decided yet, and hence the chemical composition and classification of the different chemicals to be used is not known. Chemical pipelines are still evaluated in the analysis.
- Topside leaks/discharges from risers are not included in this study but will be included in the environmental risk analysis for the Krafla field.
- The hole sizes (2.5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120 mm) were chosen to cover the span of leaks that potentially not will come to the sea surface or be detected by satellite or other detection measures. Based on an evaluation of results from Equinor's OLGA modellings for leak rates, the rates for 2.5 mm hole sizes are representative for all hole sizes <2.5 mm.
- The modeling has been performed for leaks with a duration of 7 days (no follow time), and for 2 seasons; summer and winter.
- The analysis is based on defined leak locations on the Krafla field, described in chapter 2.
- The modelling and risk-based leak detection analysis in chapter 2-4 is based on leak rates for the separate pipeline concept.
- The base-case techniques for Krafla leak detection are:
    - Satellite (SAR) – daily image through NOFO agreement
    - Mass balance (multi-phase Krafla Liquid Export Line (KLE))
    - ISPAS radar (UPP)
    - Franatech methane sniffer sensor at each template
    - Naxys passive acoustic leak detection at each template
    - Visual observations from UPP (during maintenance) and from vessels, helicopter, and surveillance plane

1.6 Uncertainties

According to the PSA's definition of risk, it is emphasized that the uncertainty element in a risk analysis, and how the uncertainty is handled, should be addressed. Risk analyses are based on assumptions and assessments that to a varying degree will be supported by experience, knowledge, scientific methods and expectations for the future. It is therefore crucial to have insight into what a risk analysis is based on and the limitations of the analyzes.

During the project it has been a focus on limiting the uncertainty as far as possible by using field-specific input data and state of the art models. Model set up and limit values are discussed with SINTEF and KSAT during the project.

Behind the figures in the analysis are a number of parameters that contain a greater or lesser degree of uncertainty, including:

1.6.1 Modelling

Modeling of seabed leaks in the OSCAR model. The results from modeling are critical in relation to further assessments both in terms of possible consequences for seabirds and fish and for detection possibilities on the surface. Following the Deepwater Horizon accident in 2010 in the Gulf of Mexico, a lot of research has been done on seabed discharges and the OSCAR model has been significantly upgraded in recent years on this issue. In addition, in the prevailing analysis, in consultation with SINTEF, adjustment of droplet size for leaks with an exit velocity above 10 m/s has been used. The adjustment of droplet size in the OSCAR model increases in uncertainty with increasing discharge velocity. In addition to the behavior of oil in the water column, there is also uncertainty associated with modeling of the film thickness of oil on the surface. High resolution data have been used in OSCAR and set up of parameters follow best practice for ERA Acute modeling (including "refinement" which divides model grid cells into smaller grid cells for better estimation of film thickness and oil coverage in the model).

1.6.2 Weather limitations and interpretation

Uncertainty related to limit values for detection under different weather conditions from both radar and satellite. There are many variables that are relevant for detection capability, such as meteorological and oceanographic conditions, satellite sensor, satellite mode, resolution, and angle. In addition, in many cases there is a lack of knowledge on what is detected; for example, whether attenuation of the intensity of the electromagnetic wave is due to oil spills or other sources of wave dampening (e.g. algae blooms, tank washing from vessels, wind shadows, etc.). Chapter 5 provides an overview of the monthly weather window for good surface detection from satellite.

1.6.3 Frequencies

In calculating risk, both consequence estimates (what will be the consequence if a leak occurs) and frequency estimates (how likely is it that a leak occurs) are used. The frequency estimates are based on a number of figures that have emerged through historical events and collected in databases. This is a common approach for assessing frequencies, but there is however a great uncertainty about how suitable experience material is for describing / predicting future events. Leakage frequency used for valves and flanges is estimated based on experience data from surface installations and adjusted by a factor to take into account that fault mode associated with manual intervention in the system is not relevant for underwater control. This is a rough approach and there is therefore uncertainty associated with both the use of the experience base and the choice of the factor. See chapter 4.2.2 for frequency evaluations for bundle concept.

1.6.4 Scenario duration

The risk assessment is performed based on an assessment of the consequences for seabirds and fish from modeling of discharges with a duration of 7 days (plus some sensitivity on longer durations, see chapter 4.1.1). 7 days were selected in order to properly address the fate of a subsea leakage in the oil spill model.

The actual presence of the environmental resources has been assessed to a lesser extent, but the Krafla area is generally characterized by a lot of seabirds both on the open sea and close to the coast, and this is the basis when possible consequences has been evaluated. Furthermore, a qualitative assessment has been made of more long-term leaks by expecting an increased level of consequences, one category up for leaks lasting 1 month and 2 consequence categories up for leaks that exceed duration of 1 year. However, there is great uncertainty and limited experience for assessing possible consequences for the environment and environmental resources in the event of very long-term leaks.

2 LEAK SCENARIOS AND LEAK RATES FOR KRAFLA

An overview of leak scenarios included in the analysis for the Krafla field are shown in Figure 2-1 and in Table 2-1 (Equinor, 2021; Equinor, 2021b). For the export line the midway between UPP and PdQ was chosen as the difference between the leak scenarios at pipeline ends were small, while for the oil production line from Krafla SPS to the UPP, both ends (KP 0.1 and within 500-meter zone UPP) were chosen. The production line from Askja SPS to UPP is short, and KP 0.375 (midway between SPS and UPP) were chosen. The export pipeline between UPP and NOA PdQ will have mass balance installed, and the detection limit for this system is set to 960 m^3/d (Equinor, 2021). The other field internal production pipelines have three alternatives for mass balance on the flowlines, and for this study the most conservative alternative of 46 % of the total flow is used (Equinor, 2021b).

The leak scenario for the liquid export line is based on the maximum rate from UPP, 10 000 Sm^3/d in oil rate and 2000 Sm^3/d in water rate (total 12 000 m^3/d liquid rate). This case has been chosen because it gives the highest export pressure from UPP and thus also the highest leakage rate.

The water cut is zero for the production lines between Krafla, Central, Askja and the UPP due to the initial reservoir pressure and before water production occurs. This is regarded as the worst case for leaks from the production lines from the wells.

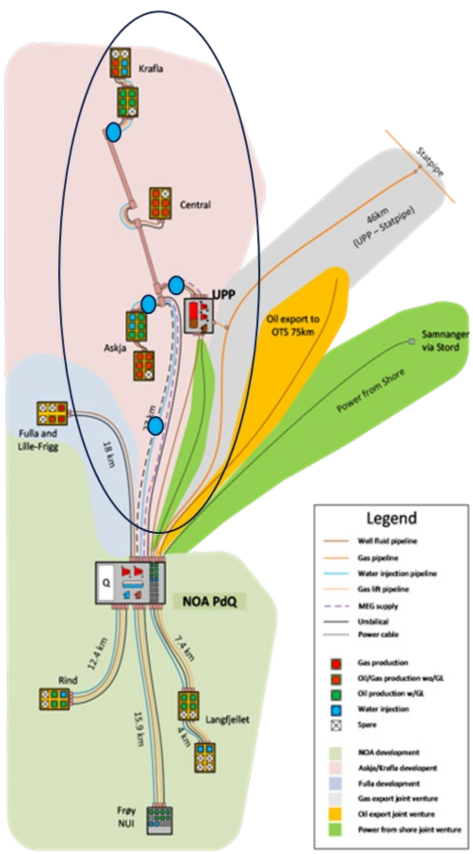


Figure 2-1 *Selected subsea leak hot spots (blue dots) for the Krafla field development (Equinor, 2021b).*

Table 2-1 *Overview of leak detection scenarios modelled for Krafla. Scenarios not expected to be detected by the mass balance system are selected for modelling in OSCAR and further assessment (Equinor, 2021; Equinor, 2021b). d50 and d95 is the 50 and 95 percentiles in the oil droplet size distribution, and exit velocity is velocity of leakage out of the leak hole. WC = Water cut, GOR = gas to oil ratio.*

Functional Location	Leak location	Depth (m)	Oil type	Density (t/m3)	Hole size (mm)	kg/s	Oil m3/d	WC (vol %)	Exit vel (m/s)	d50 (um)	d95 (um)	Tot m3/d	GOR	Coordinates (geographical) E	Coordinates (geographical) N	Detection limit MBS
Krafla Liquid export line UPP-NOA PdQ	Midway UPP - PdQ	115	Oseberg Sør	0,839	2,5	0,3	29	17,0 %	191,8	14	31	**35**	50	02° 34' 50,8''	59° 59' 21,4''	960 (m3/d)
					5	1,1	115		190,5	17	39	**139**				
					10	4,6	458		189,2	22	49	**552**				
16'' Krafla production line between Krafla SPS and UPP	Krafla SPS seabed KP 0.1	106	Oseberg Sør	0,839	2,5	0,2	19	0,0 %	233,8	12	26	**19**	351	02° 29' 51,7''	60° 13' 20,1''	46 % of flow
					5	0,8	76		233,9	14	32	**76**	351			
					10	3,0	299		230,2	18	41	**299**	350			
					20	11,3	1117		215,1	24	54	**1117**	349			
					30	19,6	1957		210,1	28	63	**1957**	348			
					40	32,5	3238		197,0	33	74	**3238**	352			
					50	45,7	4564		182,5	38	86	**4564**	367			
	UPP seabed (inside 500m zone)	106			2,5	0,0	4	0,0 %	117,1	22	50	**4**	926	02° 35' 44,2''	60° 06' 39,3''	
					5	0,2	16		117,1	28	62	**16**	926			
					10	0,7	65		119,0	34	77	**65**	926			
					20	2,7	259		118,7	44	98	**259**	924			
					30	6,1	575		117,2	51	114	**575**	922			
					40	10,6	1004		115,2	57	128	**1004**	920			
					50	16,8	1599		118,4	60	135	**1599**	918			
					60	23,5	2238		115,0	66	148	**2238**	917			
					70	30,9	2947		111,5	72	161	**2947**	919			
					80	38,9	3706		108,0	78	175	**3706**	925			
					90	47,1	4488		104,6	84	188	**4488**	939			
16'' Askja production line between Askja SPS and UPP	Midway SPS and UPP, KP 0.375	106	Oseberg Sør	0,839	2,5	0,02	2	0,0 %	89,9	29	65	**2**	1595	02° 35' 31,42''	60° 06' 37,94''	46 % of flow
					5	0,1	9		101,2	32	72	**9**	1595			
					10	0,4	37		104,0	39	89	**37**	1594			
					20	1,5	146		102,6	51	114	**146**	1591			
					30	3,5	328		102,3	58	131	**328**	1586			
					40	6,1	581		101,7	65	146	**581**	1580			
					50	9,5	904		100,9	71	159	**904**	1572			
					60	13,6	1295		100,1	76	171	**1295**	1564			
					70	18,5	1753		99,1	81	182	**1753**	1555			
					80	24,0	2274		98,1	86	193	**2274**	1546			
					90	30,1	2855		97,0	91	204	**2855**	1539			
					100	36,7	3486		95,9	95	214	**3486**	1538			
					120	50,8	4819		93,7	104	235	**4819**	1568			

3 LEAKAGE MODELLING IN OSCAR

Input data and results from the OSCAR modelling for the different leak scenarios for Krafla are given in chapter 3.2 to chapter 3.5.

3.1 Modelling information

Modelling of the leaks has been performed with the oil operation model OSCAR 11.0.1 (SINTEF, 2020). In OSCAR, a near-zone model Plume3D has been implemented which calculates the course of the discharge / plume from the seabed to the surface. A plume can here be defined as a "package" consisting of oil, water and gas. Depending on the leakage rate, leakage area, oil type, depth, GOR and the vertical density layer for the area in question, either the plume will reach the surface or be trapped in the water column at a certain depth because it has lost its buoyancy. If the plume is trapped in the water column, then oil droplets will rise individually to the surface over time if the droplets are large enough and have sufficient buoyancy. If not, they remain in the water masses and dissolve over time.

The oil leak simulations are run in a 200 × 200 m grid. Subsequently, the results have been exported to a 500 × 500 m grid for use in the analysis. For each scenario, a transect is plotted from a single simulation for the summer period and one for the winter period. The transect is shown in 2D with particles and concentrations of THC in the water column, as well as any particles that reach the surface during the first 24 hours. The transect is taken along the dominant operating direction for oil (see Figure 3-1).

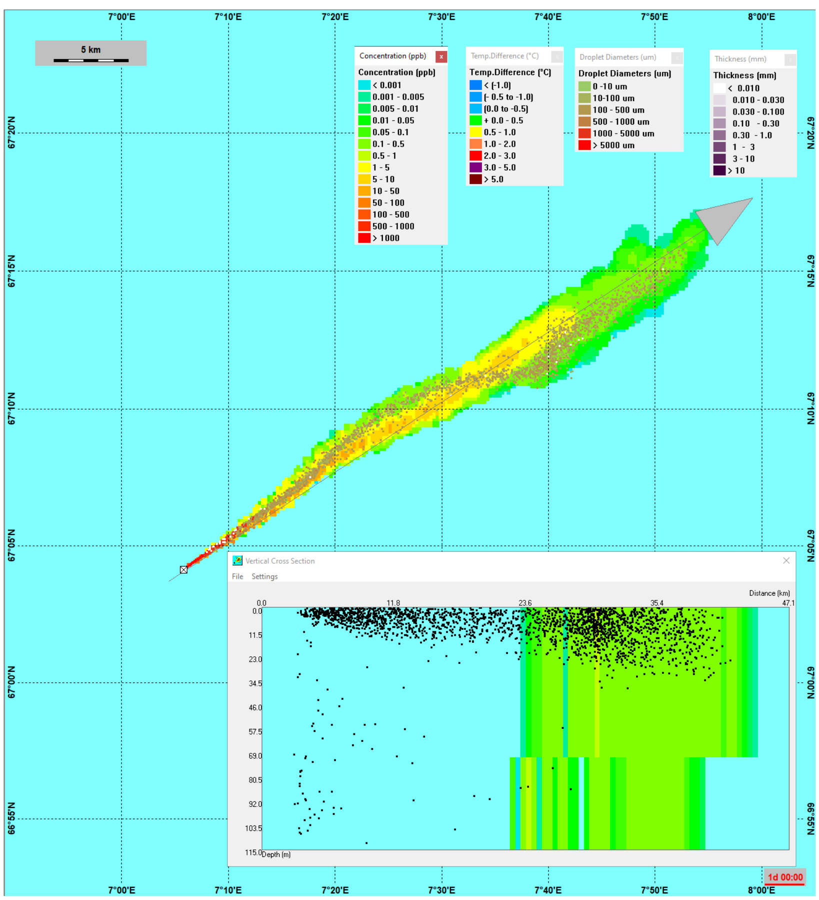


Figure 3-1 *Example of a transect along the main drift direction of oil in the water column showing oil particles and THC concentrations in the water column.*

Maps are also shown based on the stochastic simulations modelled with a duration of 7 days. First, the probability that oil will exceed 2 µm film thickness on the sea surface (current threshold for acute effects on seabirds, see https://www.norskoljeoggass.no/miljo/mer-om-miljo/miljorisiko-og-miljorisikoanalyser2 /era-acute/) is shown. The probability of exceeding 58 ppb oil concentration (THC) in the water column is also shown, and the upper 50 meters of the water column have been used for this assessment based on the expected occurrence of eggs and larvae in the upper water layer.

A threshold value has also been set for the detection of oil from SAR satellite. The Norne study (SINTEF, 2020b) set a limit at 0.3 km^2 with a film thickness of more than 0.5 µm (corresponding to an oil volume of 150 litres). In the present study, there is used a model grid of 500x500 meters (0.25 km^2) and DNV have used 0.1 tonnes within 0.25 km^2 as the limit value for detection from SAR satellite.

3.2 Krafla Liquid export line (Midway UPP - PdQ)

3.2.1 Input data for the OSCAR modelling

Leak rates for the different hole sizes and other key input for Krafla liquid export line (midway UPP-PdQ) is shown in Table 3-1.

Table 3-1 *Hole sizes and leak rates for Krafla liquid export line (midway UPP-PdQ) for OSCAR modelling.*

Functional Location	Lekkasje-lokasjon	Depth (m)	Oil type	Hole size (mm)	Exit vel (m/s)	Oil leak rate (m3/d)	GOR
Krafla Liquid export line	Midway UPP - PdQ	115	Oseberg Sør	2,5	191,8	28,9	50
				5	190,5	115,3	
				10	189,2	458,0	

3.2.2 Plume

A subsea leakage from Krafla Liquid export line midway between UPP and PdQ was modelled with leak size from 2.5 mm to 10 mm with oil leakage rates from 29 m^3/d to 458 m^3/d at 115 meters depth. The GOR is 50 and the oil and gas exit velocity from a leakage is very high (> 100 m/s) and very small oil droplets are formed (d50 from 14 to 22 µm).

The plume will be trapped in the water column (due to the low GOR, leak rates, droplet size, viscosity (oil type), stratification of water column) and individual droplets may rise to the sea surface. For a 2.5 mm leak the droplets will stay in the lower part of water column, while 10 mm leak size will to a larger degree rise to the surface (Figure 3-2).

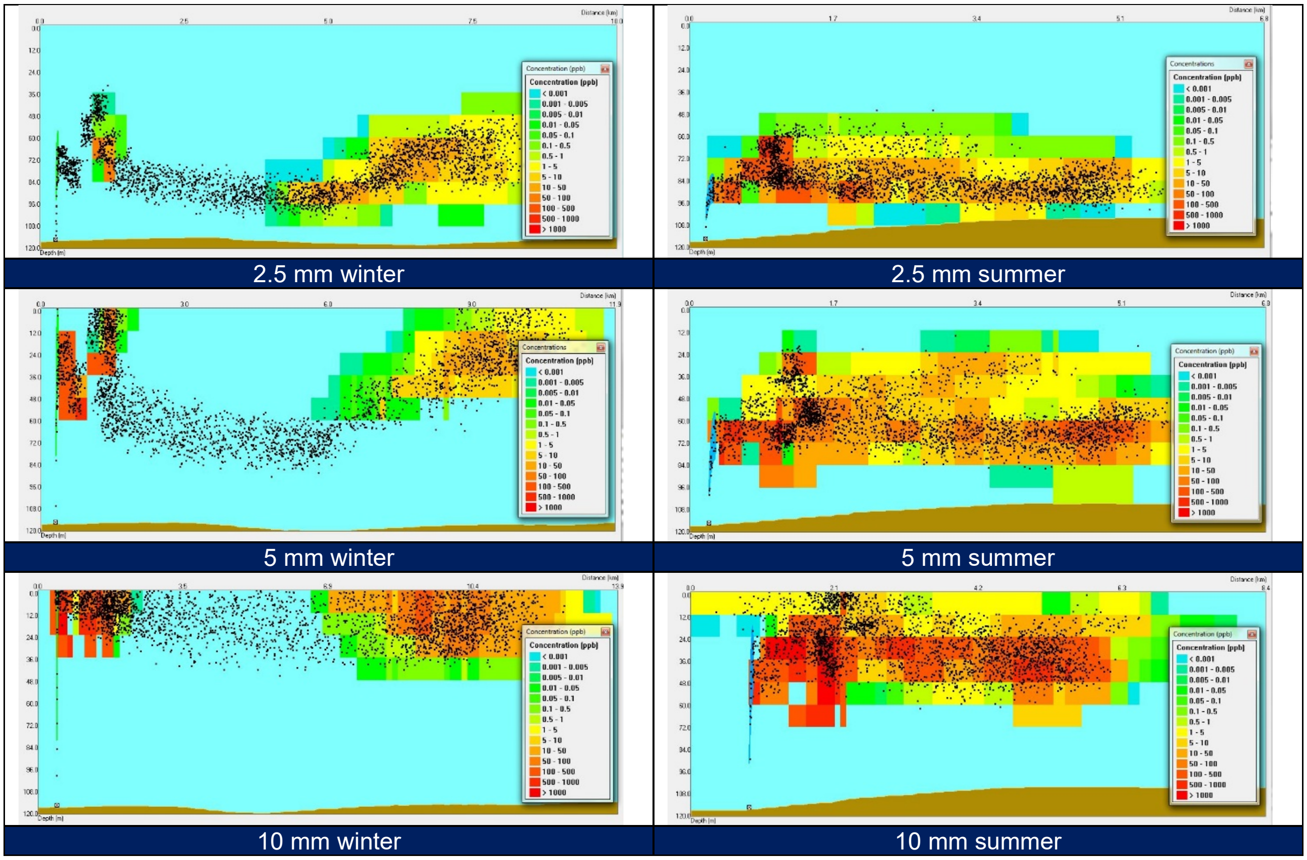


Figure 3-2 *Leakage behaviour from subsea leakages at Krafla LE (midway UPP and PdQ) with different leak sizes. Transects along main drift direction after 1-day leak duration.*

3.2.3 Surface impact

Probability for a leakage from Krafla LE reaching the surface with a film thickness above 2 µm is shown in Figure 3-3. 2 µm is used as the effect threshold for seabirds (see chapter 4.1). The smallest leak size (2.5 mm) will not form oil slicks above 2 µm at the sea surface and will not give any impact to seabirds. 5 mm leak size will give a small probability for impact in winter, while the probable impact area increases for a 10 mm leak size although small.

NA	NA
2.5 mm winter	2.5 mm summer

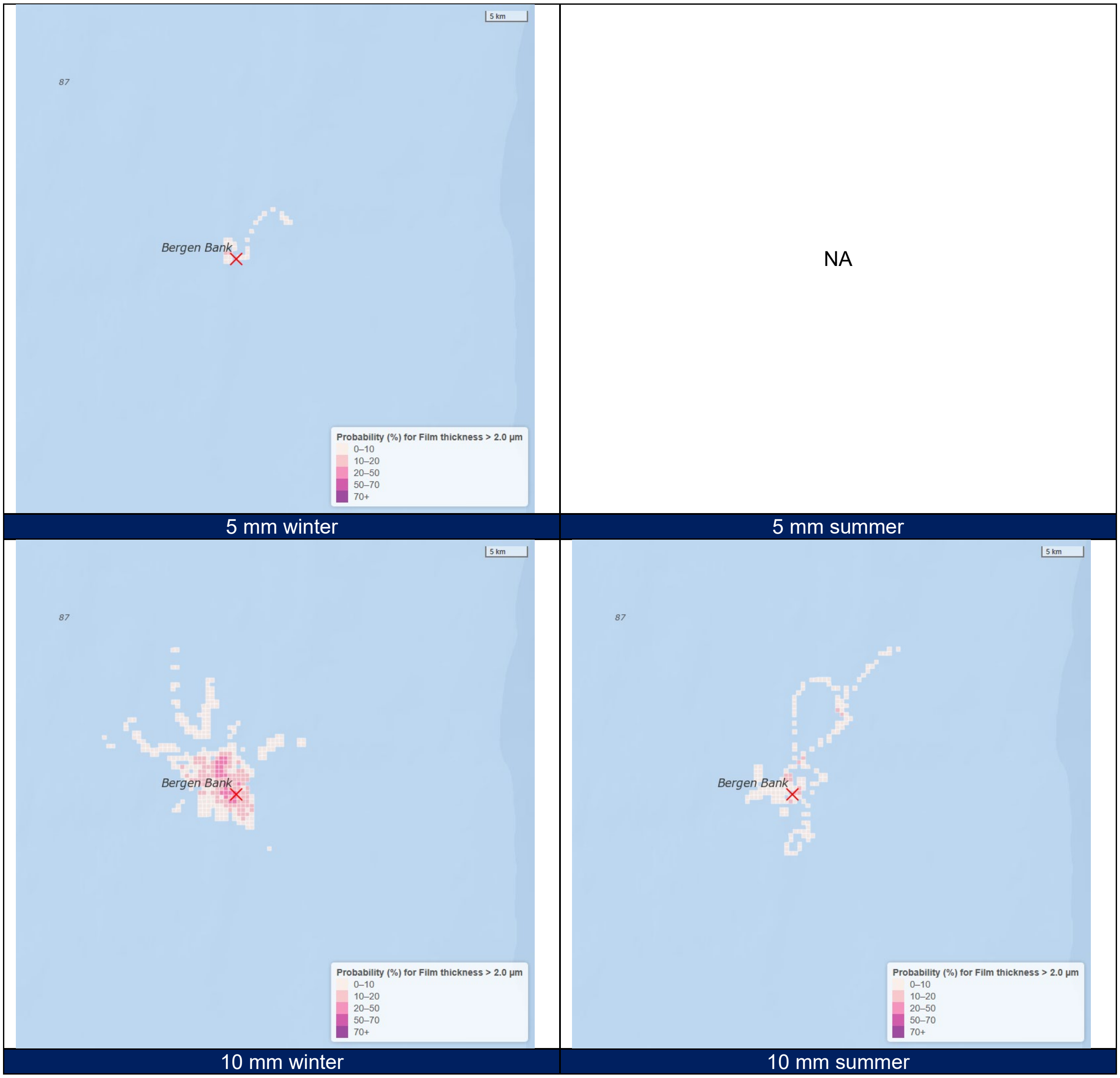


Figure 3-3 *Probability for film thickness above 2 µm from leak scenarios at Krafla LE (midway UPP and PdQ) with different leak sizes. Spill duration 7 days.*

3.2.4 Surface detection

Probability for surface detection from satellite is related to the minimum detection threshold defined as 0.1 tons per 500x500 meter grid cell (0.25 km^2). The smallest leak sizes (2.5 and 5 mm in winter) will not reach the surface detection threshold of 0.1 t/0.25 km^2 and will not be detected by satellite, while the 5 mm leak in summer and 10 mm leak could possibly be detected on the surface at least over some time (days or weeks) (Figure 3-4). The detection threshold of 0.1 t/0.25 km^2 adjusted from SINTEF (2020b) detection threshold of 150 L/ 0.3 km^2.

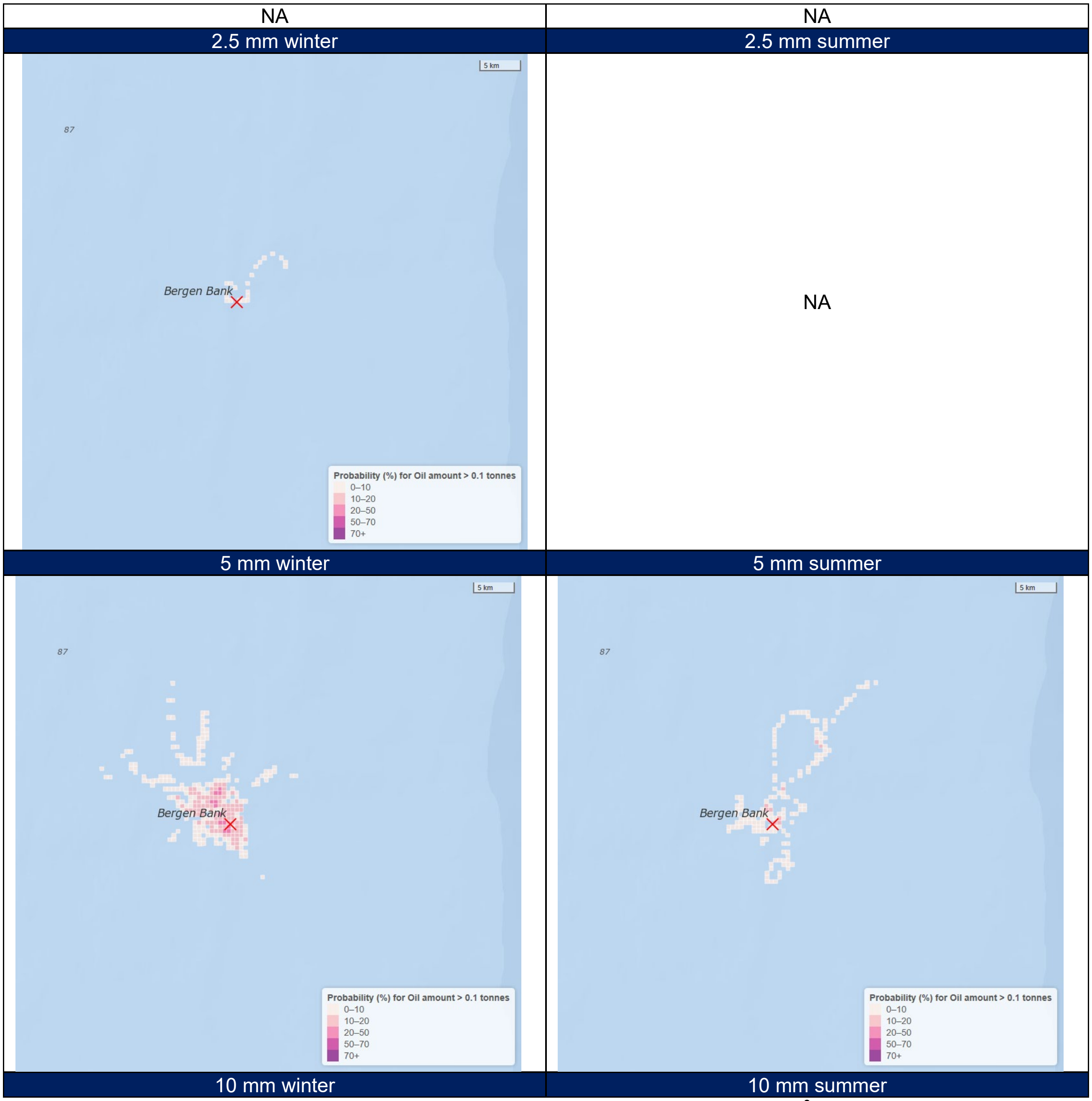
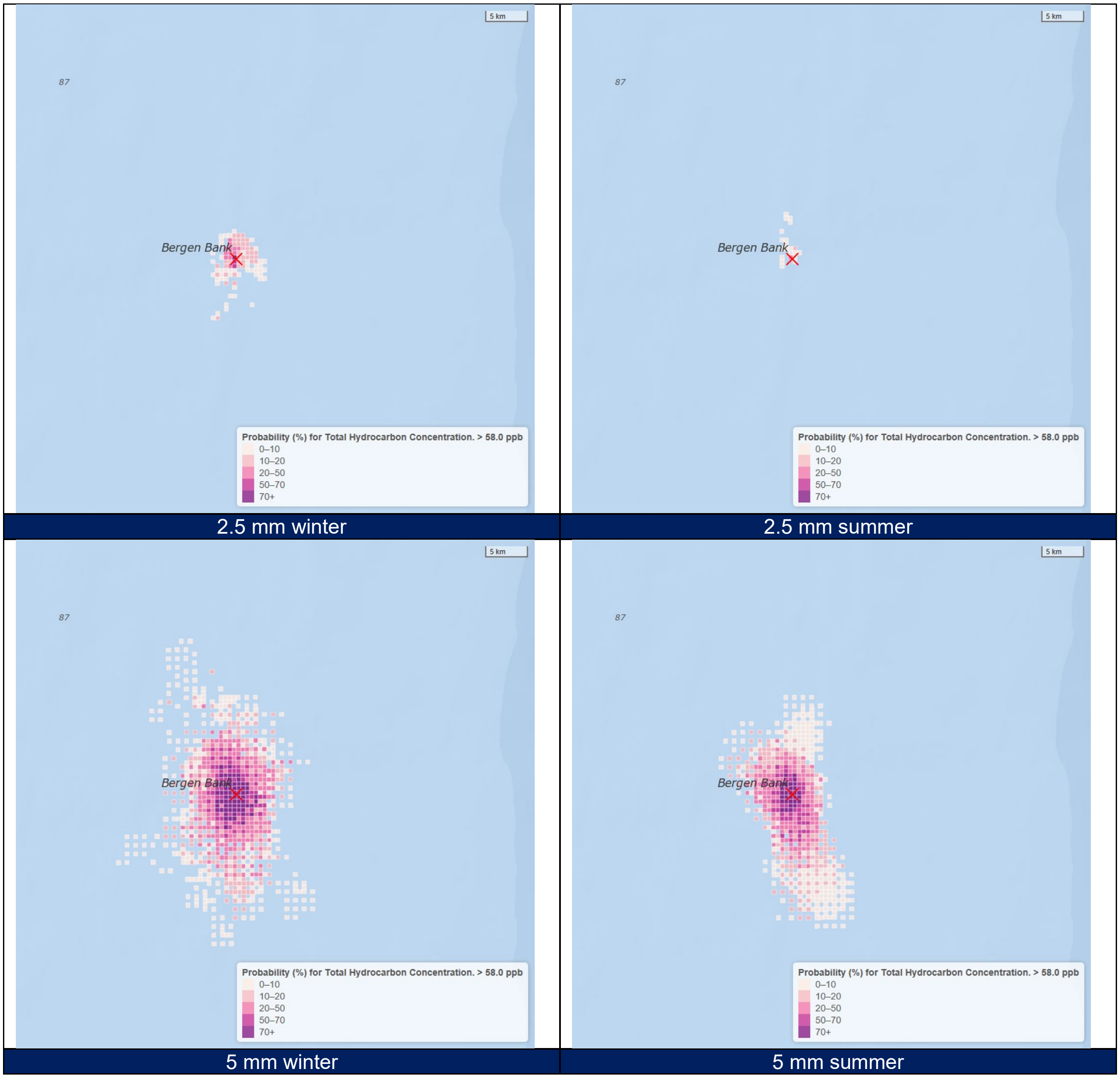


Figure 3-4 *Probability for surface oil volumes above SAR detection limit (0,1 t per 0.25 km^2) from leak scenarios at Krafla LE (midway UPP and PdQ) with different leak sizes. Spill duration 7 days.*

3.2.5 Water column impact

Probability for THC above the effect threshold of 58 ppb in the upper 50 meter of the water column is shown in Figure 3-5. 58 ppb is used as the effect threshold for the most sensitive stages of water column organisms like fish eggs and larvae (see chapter 4.1) There is a steady increase in the size of the effect area with leak size and even the 2.5 mm leak size will have some probability for exceeding 58 ppb. The 10 mm leak size will have the biggest effect area stretching 10-15 km away from the location and further in winter than in summer.


5 km
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
2.5 mm winter
5 km
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
2.5 mm summer
5 km
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
5 mm winter
5 km
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
5 mm summer

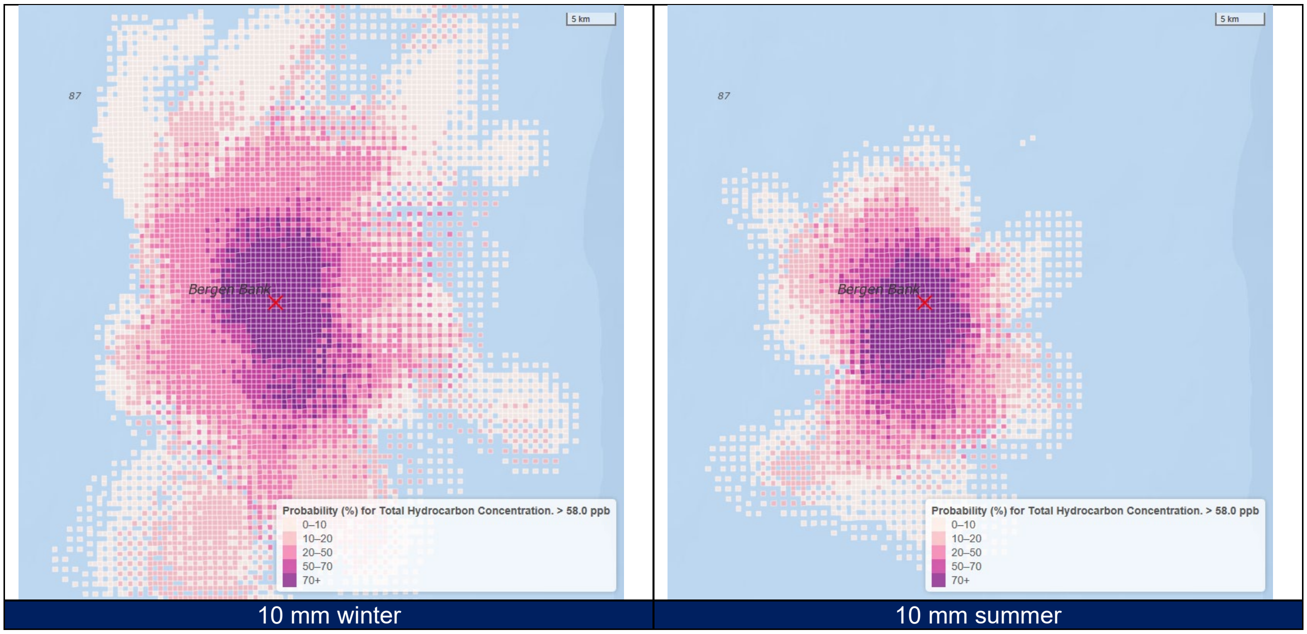


Figure 3-5 *Probability for THC above 58 ppb in upper 50 meters of water column from leak scenarios at Krafla LE (midway UPP and PdQ) with different leak sizes. Spill duration 7 days.*

3.3 16'' Krafla production line Krafla SPS – UPP (SPS seabed KP 0.1)

3.3.1 Input data for the OSCAR modelling

Leak rates for the different hole sizes and other key input for 16'' Krafla production line Krafla SPS – UPP (SPS seabed KP 0.1) is shown in Table 3-2.

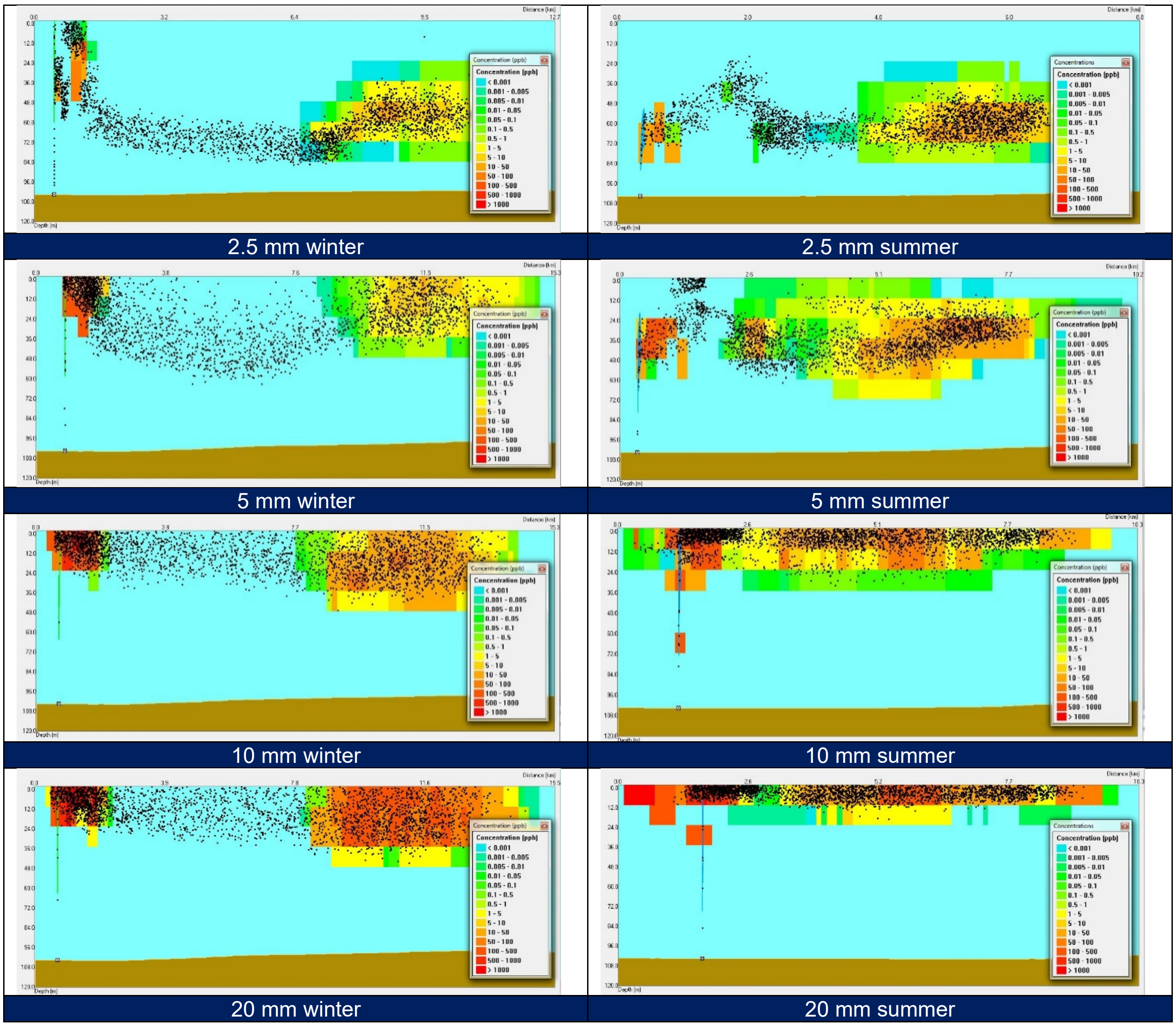
Table 3-2 *Hole sizes and leak rates for 16'' Krafla production line Krafla SPS – UPP (SPS seabed KP 0.1) for OSCAR modelling.*

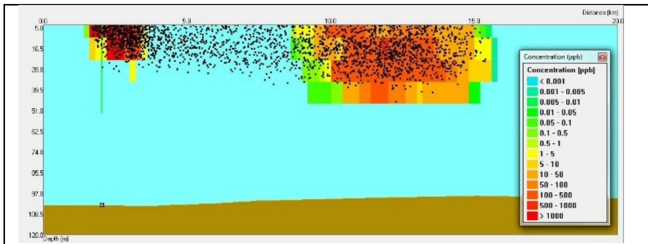
Functional Location	Lekkasje-lokasjon	Depth (m)	Oil type	Hole size (mm)	Exit vel (m/s)	Oil leak rate (m3/d)	GOR
16'' Krafla production line Krafla SPS – UPP	SPS seabed KP 0,1	106	Oseberg Sør	2,5	233,8	19,1	253
				5	233,9	76,0	
				10	230,2	299,1	
				20	215,1	1117,1	
				30	210,1	1956,6	
				40	197	3238,4	
				50	182,5	4563,5	

3.3.2 Plume

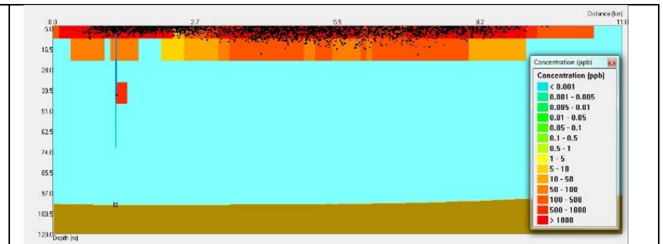
A subsea leakage from the 16'' Krafla production line (Krafla SPS – UPP) at the SPS seabed (KP 0,1) was modelled with leak size from 2.5 mm to 50 mm with oil leakage rate from 19 m^3/d to 4564 m^3/d at 106 meters depth. The GOR is 253 and the oil and gas exit velocity from a leakage is very high (mostly > 200 m/s) and very small oil droplets are formed (d50 from 12 to 38 µm).

The plume will rise to the surface, except from the smallest leak sizes (Figure 3-6). The small droplets from the smallest leak sizes (2.5 and 5 mm) will cause oil to easily be dispersed deeper into the water column. Larger leak sizes (10 and 20 mm) will have more oil on the surface and in the upper part of the water column, especially in a summer situation.

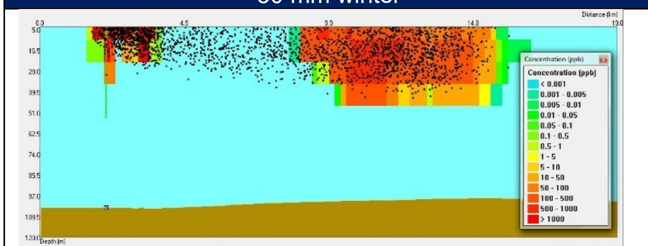




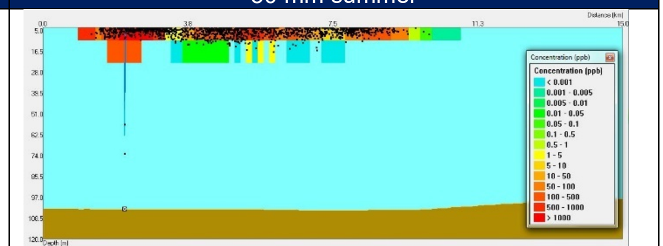
30 mm winter



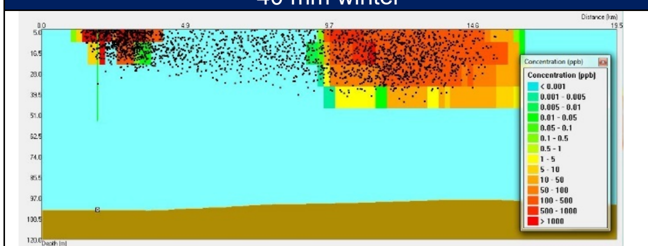
30 mm summer



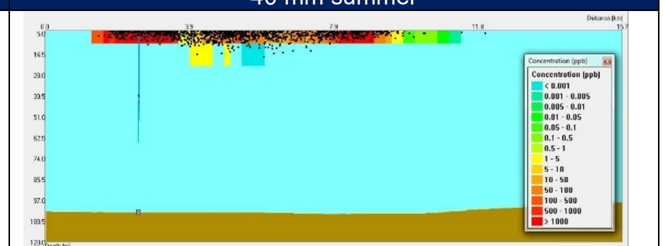
40 mm winter



40 mm summer



50 mm winter



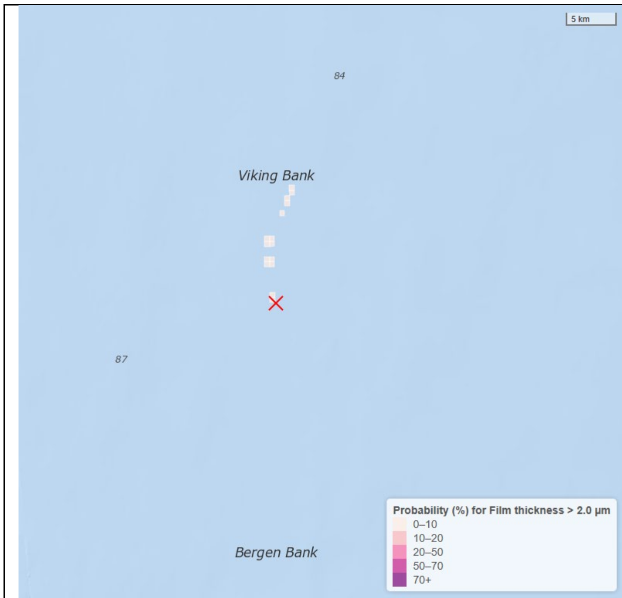
50 mm summer

Figure 3-6 *Leakage behaviour from subsea leakages at 16'' Krafla PL (Krafla SPS seabed) with different leak sizes. Transects along main drift direction after 1-day leak duration.*

3.3.3 Surface impact

Probability for a leakage from 16'' Krafla PL (Krafla SPS seabed) for reaching the surface with a film thickness above 2 µm is shown in Figure 3-7. The smallest leak sizes (2.5 mm and 5 mm summer) will not form oil slicks above 2 µm at the sea surface and will not give any impact to seabirds, but a 5 mm leak size (winter) and a 10 mm leak size will have some probability for such impact scattered around the leak location. The biggest leak size (50 mm) will have a high probability for surface slicks above 2 µm in an area up to 10 km away from the location, especially in summer. Note change in scale from 20 mm figures to 30 mm.

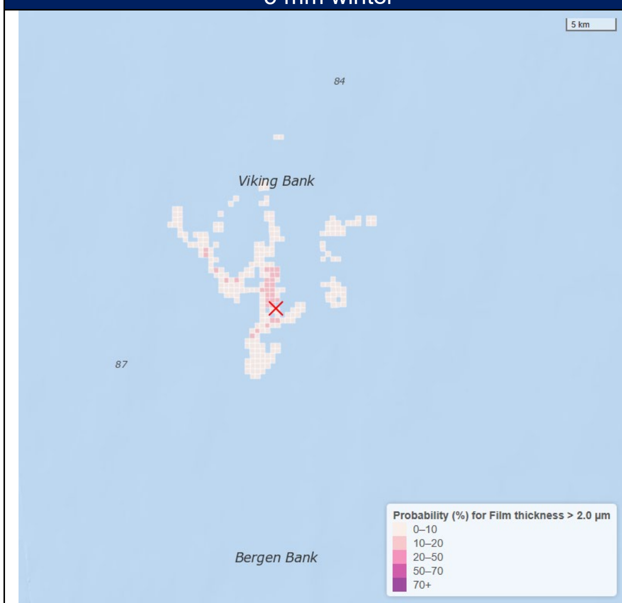
NA	NA
2.5 mm winter	2.5 mm summer



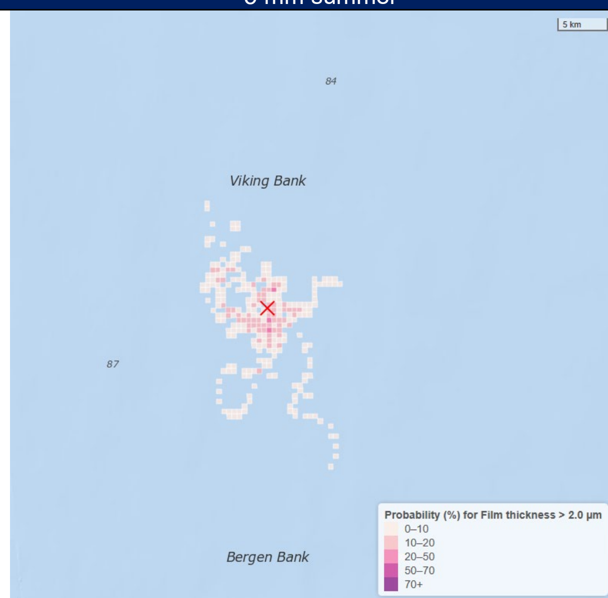
5 mm winter

NA

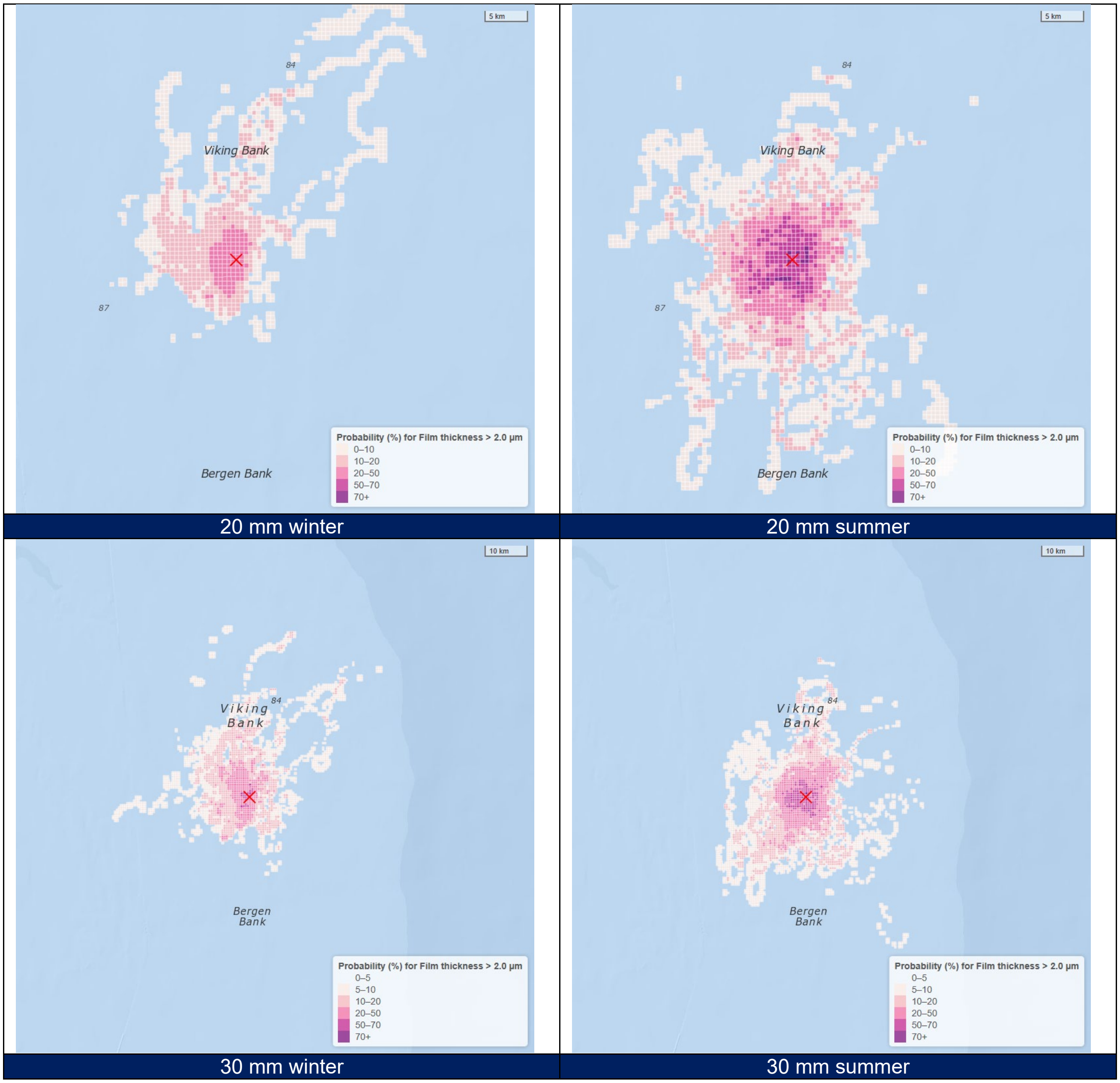
5 mm summer



10 mm winter



10 mm summer



5 km
84
Viking Bank
87
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–10
10–20
20–50
50–70
70+
20 mm winter
5 km
84
Viking Bank
87
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–10
10–20
20–50
50–70
70+
20 mm summer
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
30 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
30 mm summer

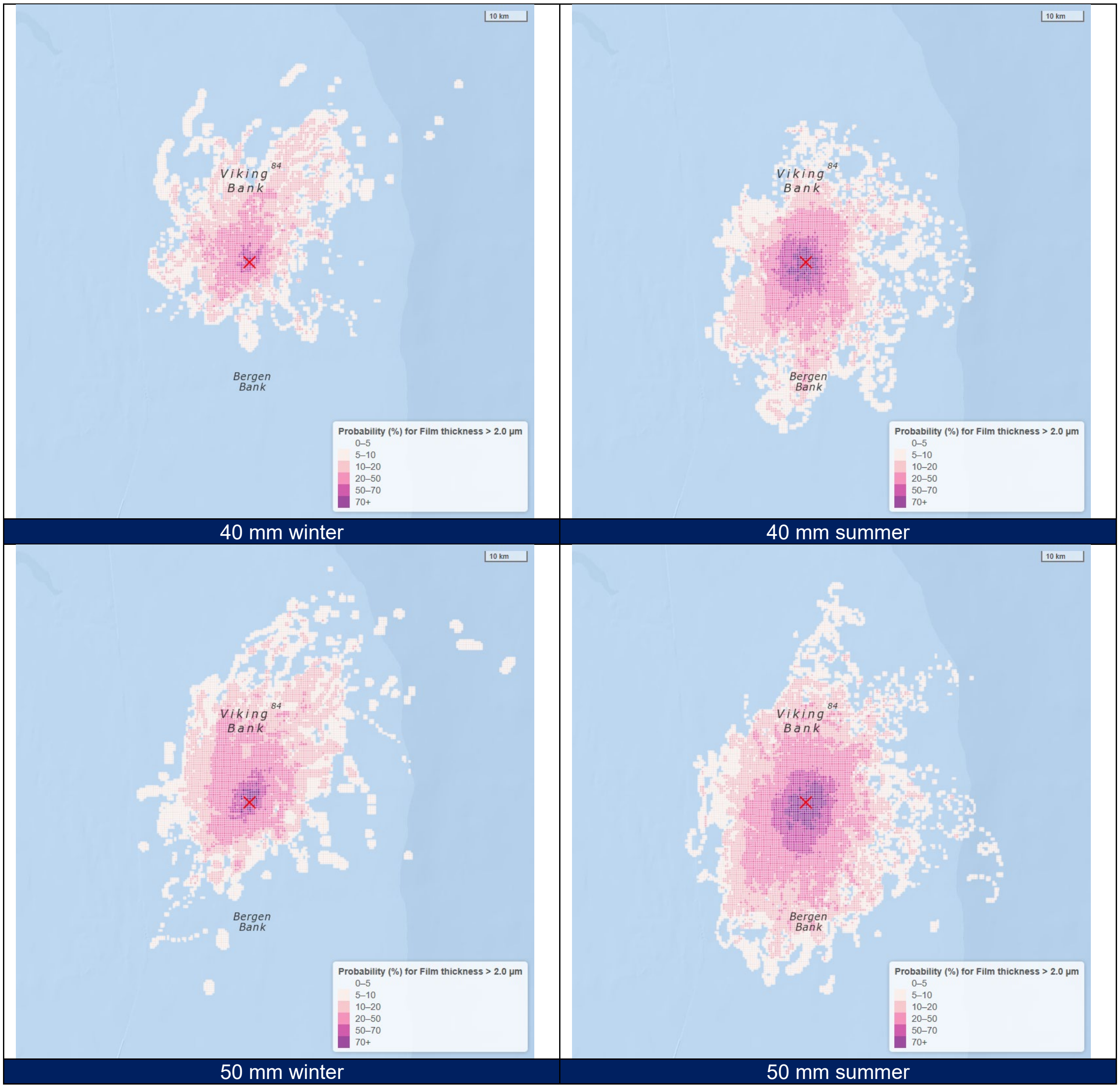


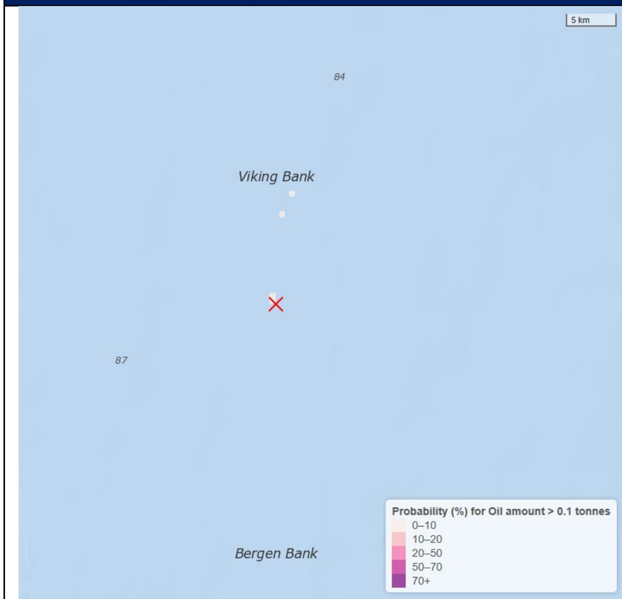
Figure 3-7 *Probability for film thickness above 2 µm from leak scenarios at 16'' Krafla PL (Krafla SPS seabed) with different leak sizes. Spill duration 7 days.*

3.3.4 Surface detection

Probability for surface detection from satellite is related to the minimum detection threshold defined as 0.1 tons per 500x500 meter grid cell (0.25 km^2). The smallest leak sizes will not reach this threshold and will not be detected by satellite, while the 10 mm leak size have some small probabilities for surface detection scattered around the leak location. Larger leak sizes (20 to 50 mm) are likely to be detected by SAR (Figure 3-8).

NA	NA

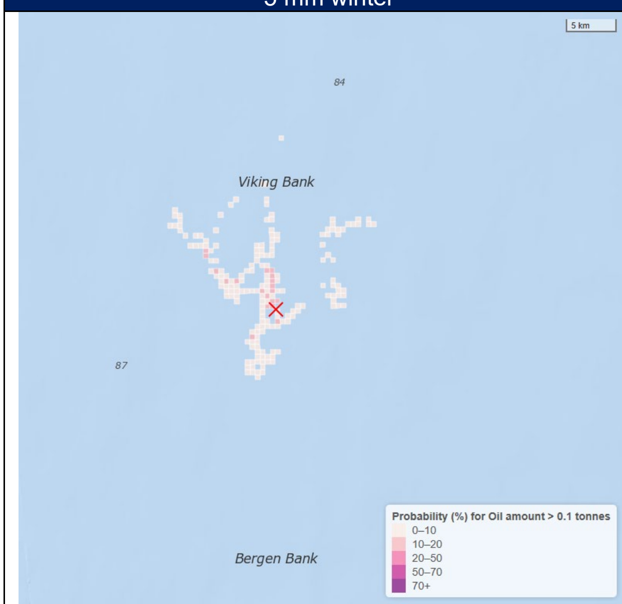
2.5 mm winter



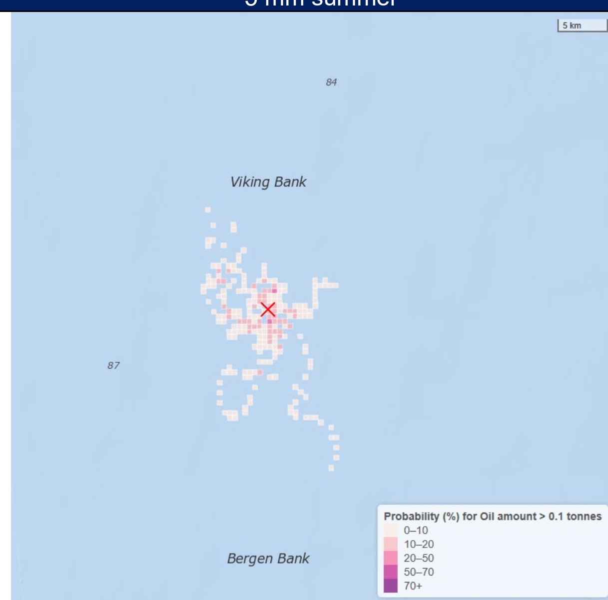
2.5 mm summer

NA

5 mm winter

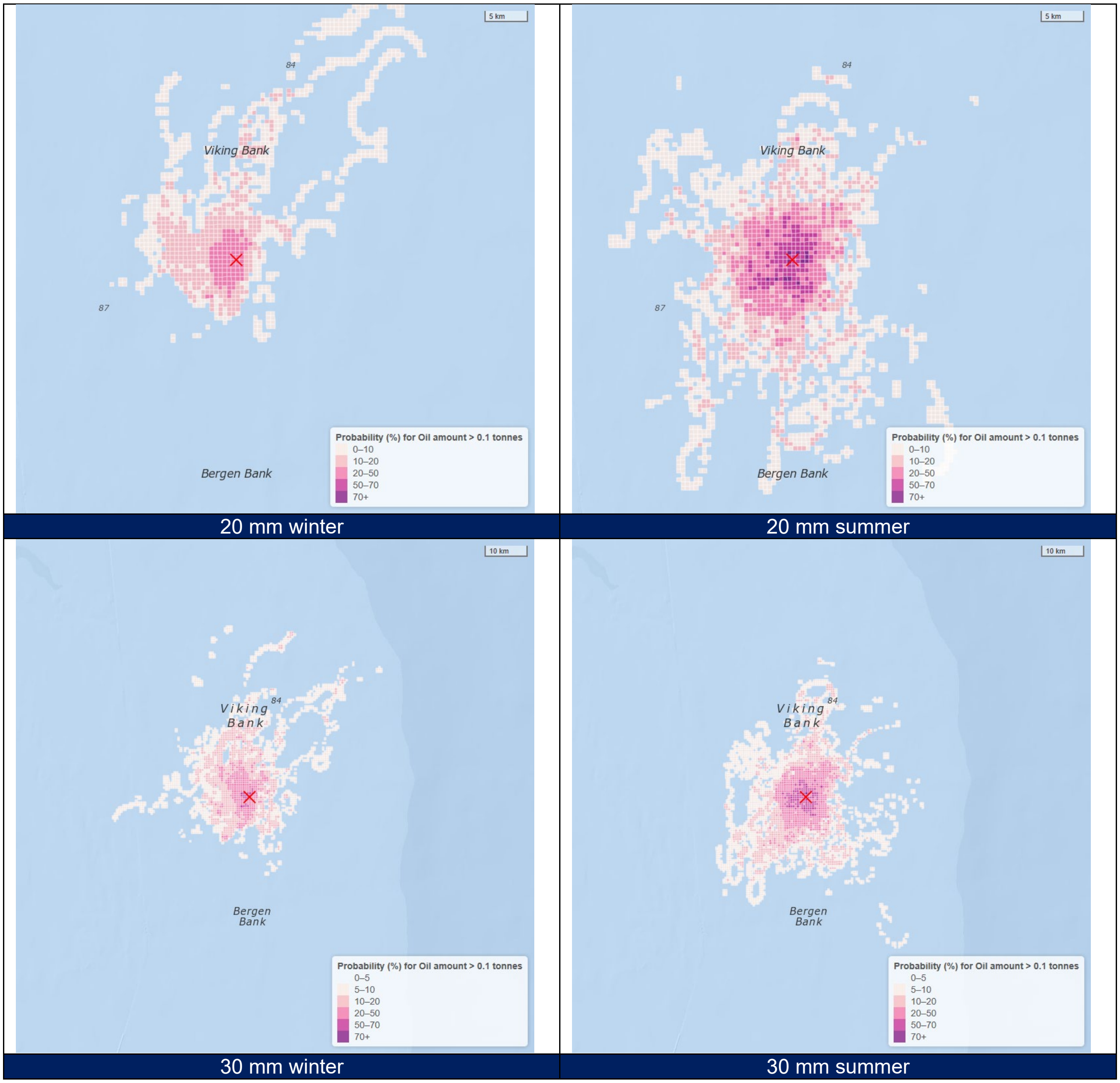


5 mm summer



10 mm winter

10 mm summer


5 km
84
Viking Bank
87
Bergen Bank
Probability (%) for Oil amount > 0.1 tonnes
0–10
10–20
20–50
50–70
70+
20 mm winter
5 km
84
Viking Bank
87
Bergen Bank
Probability (%) for Oil amount > 0.1 tonnes
0–10
10–20
20–50
50–70
70+
20 mm summer
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Oil amount > 0.1 tonnes
0–5
5–10
10–20
20–50
50–70
70+
30 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Oil amount > 0.1 tonnes
0–5
5–10
10–20
20–50
50–70
70+
30 mm summer

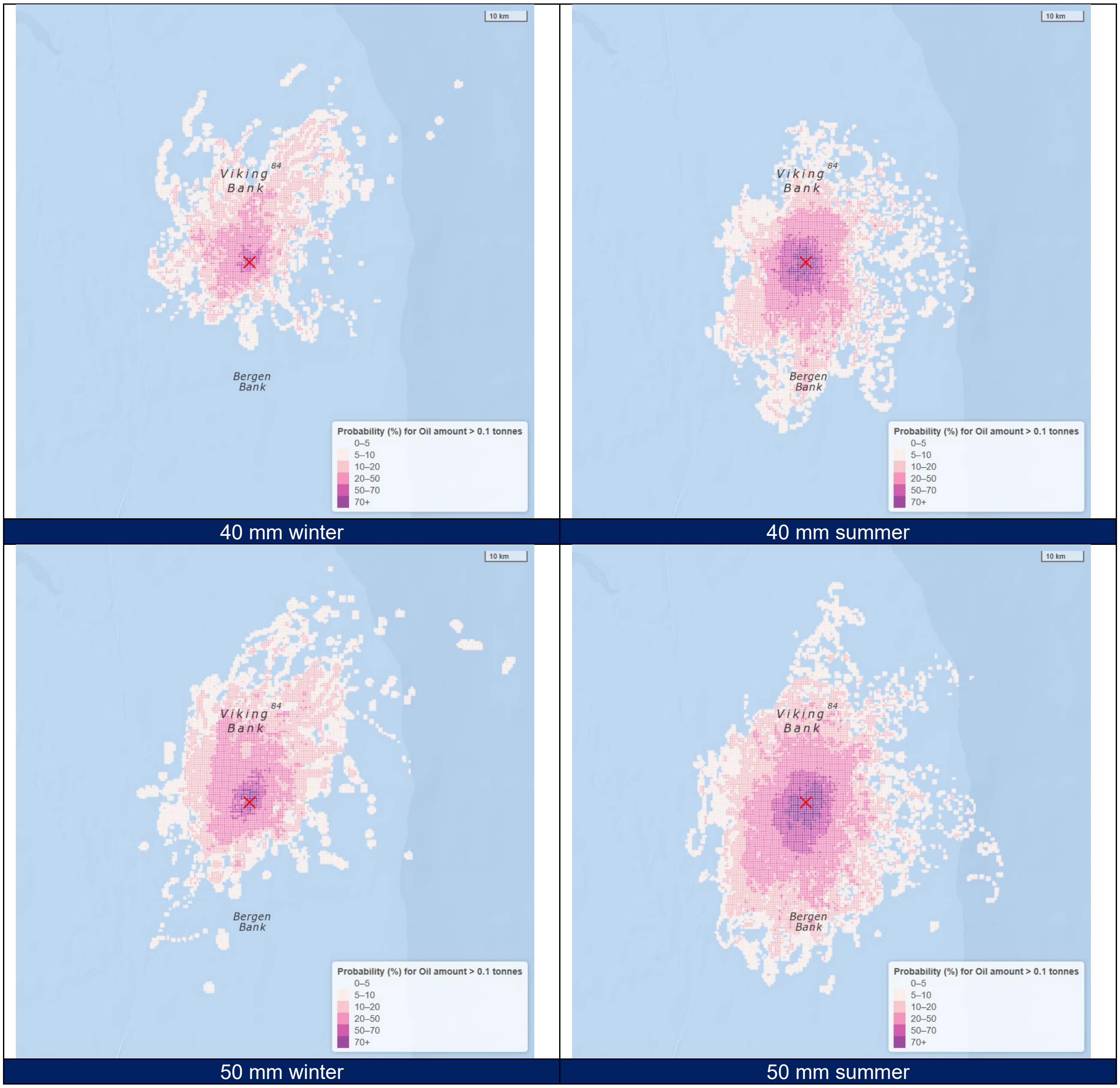
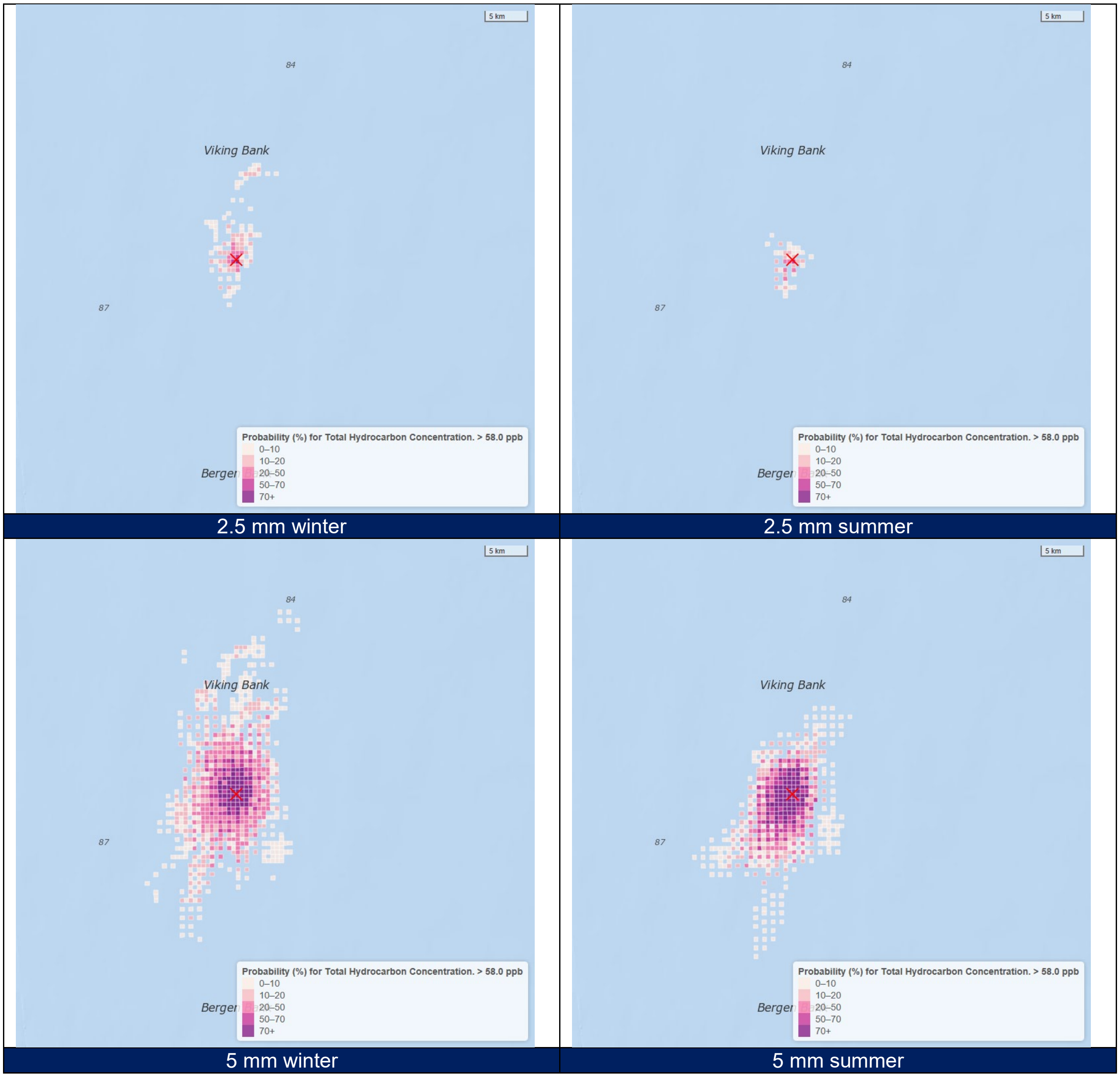
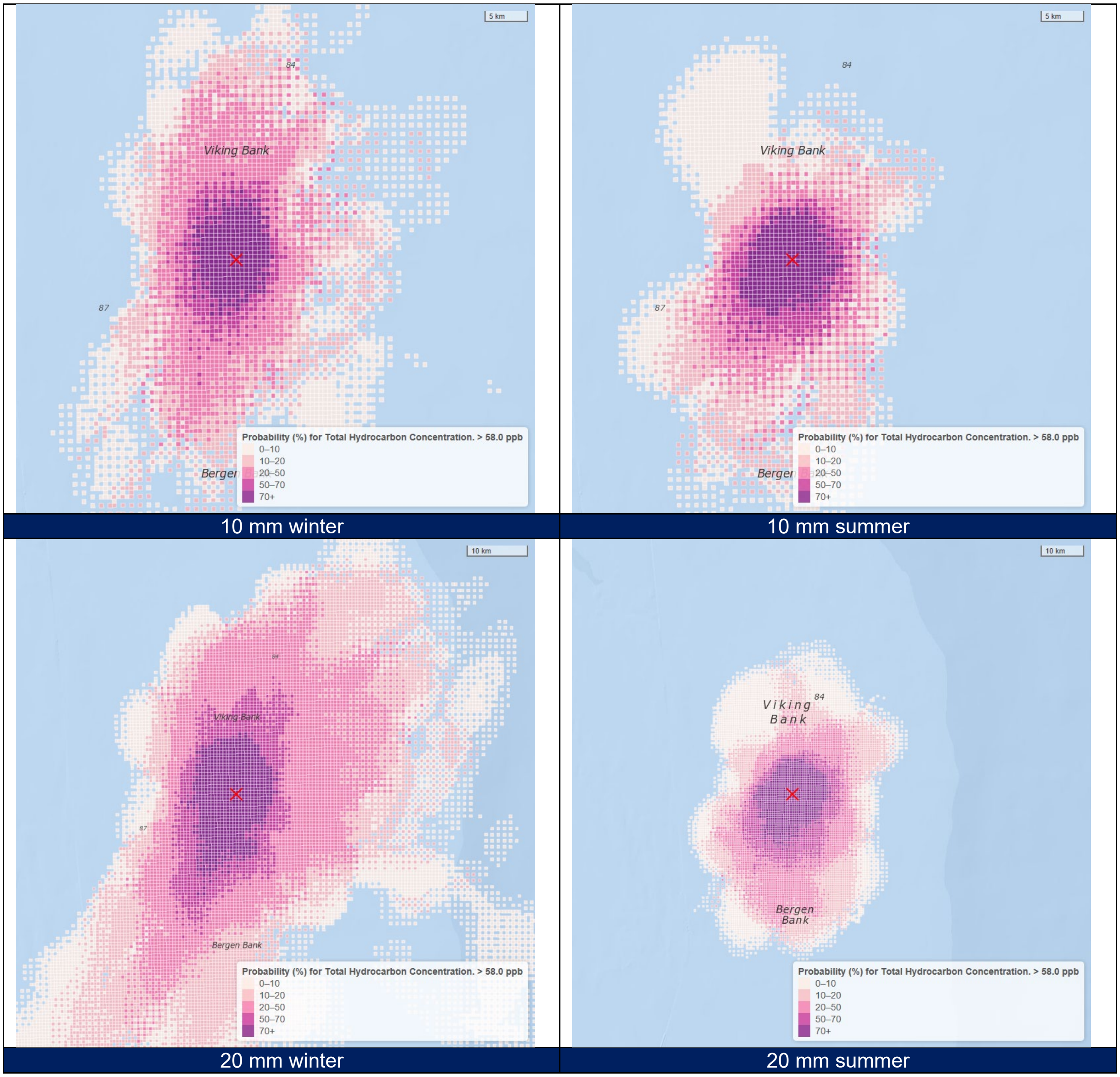


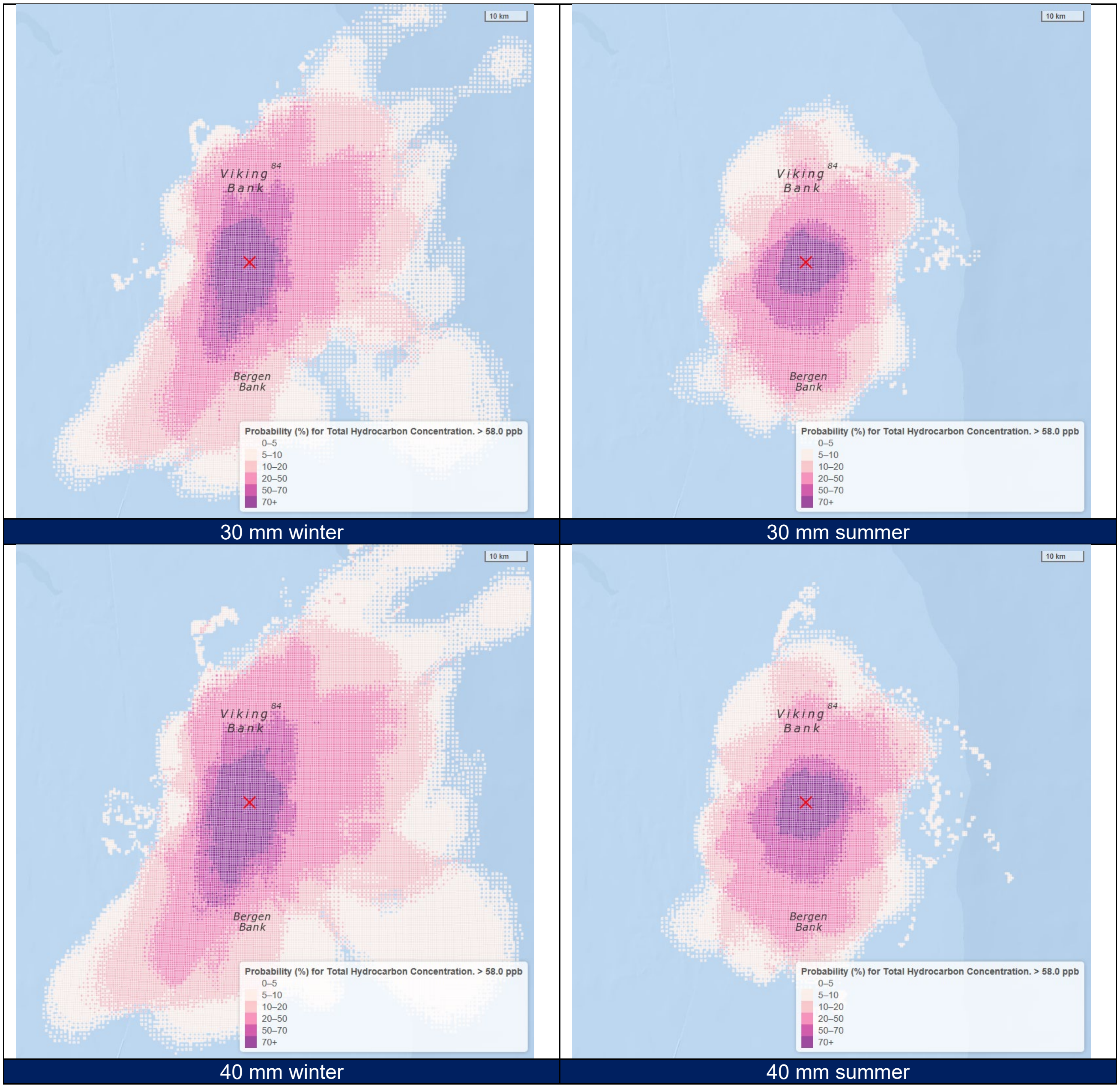
Figure 3-8 *Probability for surface oil volumes above SAR detection limit (0,1 t per 0.25 km2) from leak scenarios at 16'' Krafla PL (Krafla SPS seabed) with different leak sizes. Spill duration 7 days.*

3.3.5 Water column impact

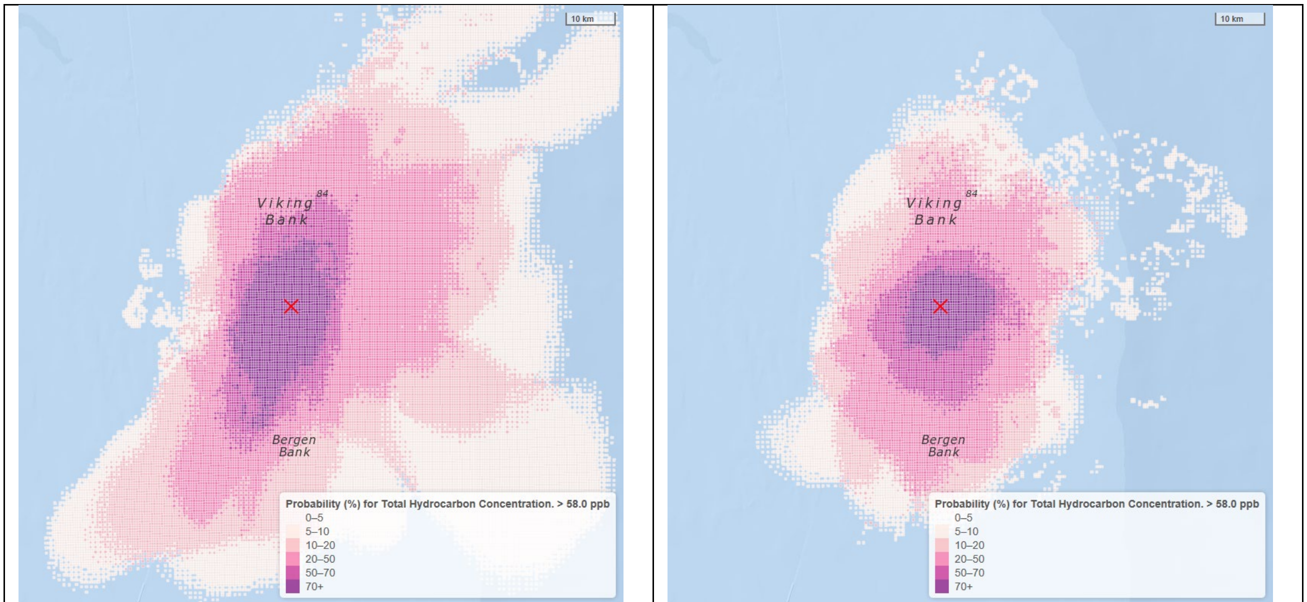
Probability for THC above the effect threshold of 58 ppb in the upper 50 meter of the water column is shown in Figure 3-9. There is a steady increase in the size of the effect area with leak size, and even the smallest leak size (2.5 mm) has some probability for exceeding 58 ppb in a small area. The biggest leak size of 50 mm will have the biggest effect area stretching 20-40 km away from the location, with the area being larger in winter- than in summertime. Note the change in scale from 10 mm to 20 mm maps.


5 km
84
Viking Bank
87
Berger
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
2.5 mm winter
5 km
84
Viking Bank
87
Berger
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
2.5 mm summer
5 km
84
Viking Bank
87
Berger
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
5 mm winter
5 km
84
Viking Bank
87
Berger
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
5 mm summer


5 km
84
Viking Bank
87
Bergen
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
10 mm winter
10 mm summer
10 km
Bergen Bank
20 mm winter
Viking Bank
20 mm summer



30 mm winter | 30 mm summer
40 mm winter | 40 mm summer



50 mm winter | 50 mm summer

Figure 3-9 *Probability for THC above 58 ppb in upper 50 meters of water column from leak scenarios at 16'' Krafla PL (Krafla SPS seabed) with different leak sizes. Spill duration 7 days.*

3.4 16'' Krafla production line Krafla SPS – UPP (UPP seabed, inside 500m zone)

3.4.1 Input data for the OSCAR modelling

Leak rates for the different hole sizes and other key input for 16'' Krafla production line Krafla SPS – UPP (UPP seabed, inside 500m zone) is shown in Table 3-3.

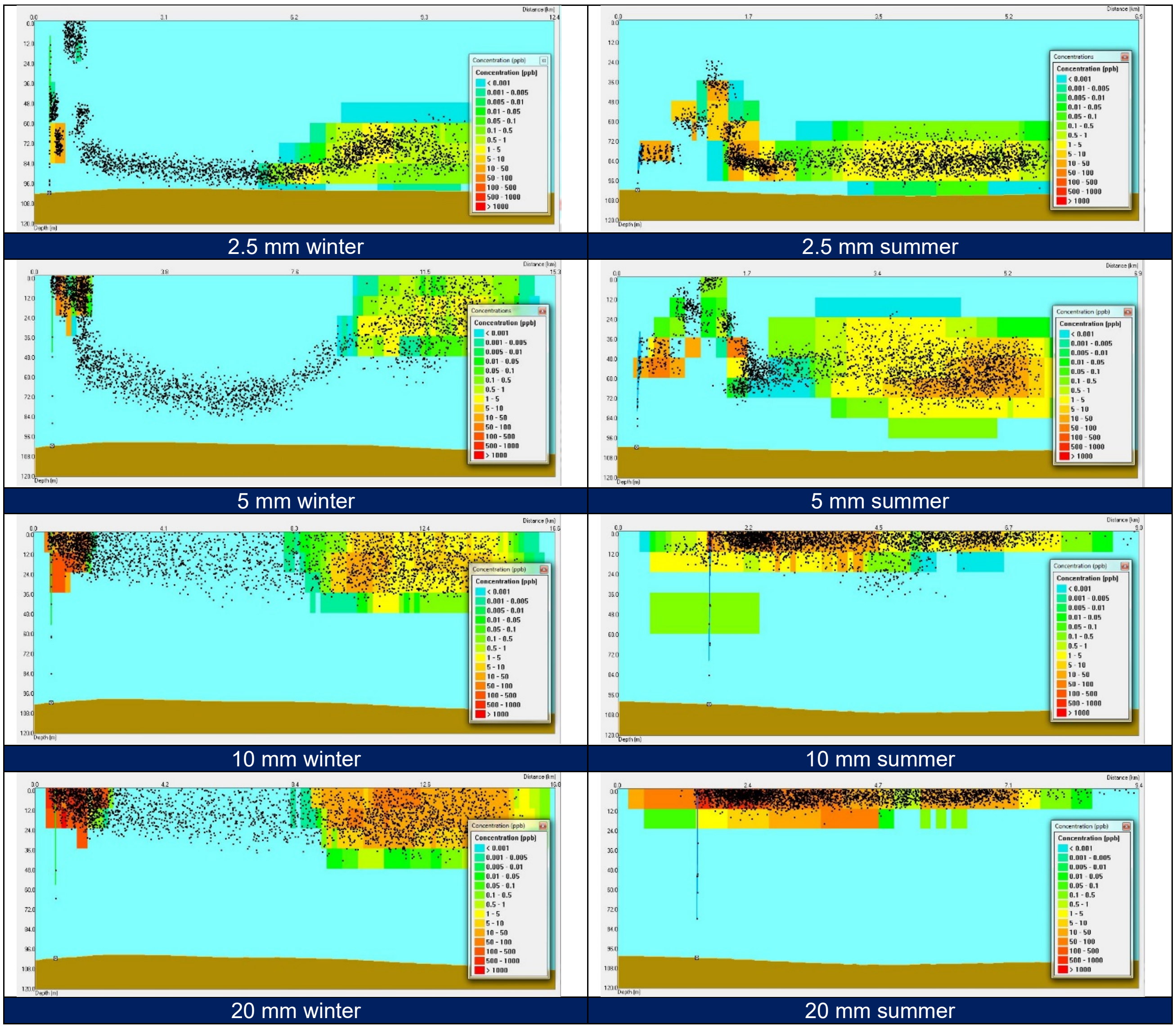
Table 3-3 *Hole sizes and leak rates for 16'' Krafla production line Krafla SPS – UPP (UPP seabed, inside 500m zone) for OSCAR modelling.*

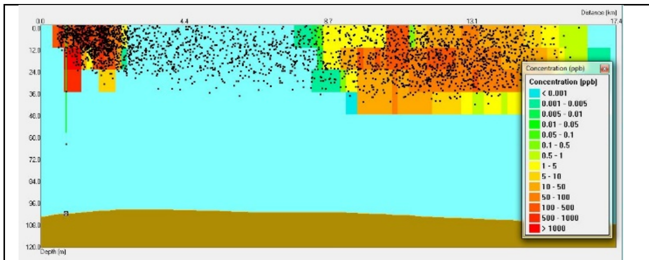
Functional Location	Lekkasje-lokasjon	Depth (m)	Oil type	Hole size (mm)	Exit vel (m/s)	Oil leak rate (m3/d)	GOR
16'' Krafla production line Krafla SPS – UPP	UPP seabed (inside 500m zone)	106	Oseberg Sør	2,5	117,1	4,1	924
				5	117,1	16,3	
				10	119	65,2	
				20	118,7	258,8	
				30	117,2	575,0	
				40	115,2	1004,0	
				50	118,4	1598,8	
				60	115,0	2237,8	
				70	111,5	2947,1	
				80	108,0	3706,5	
				90	104,6	4487,6	

3.4.2 Plume

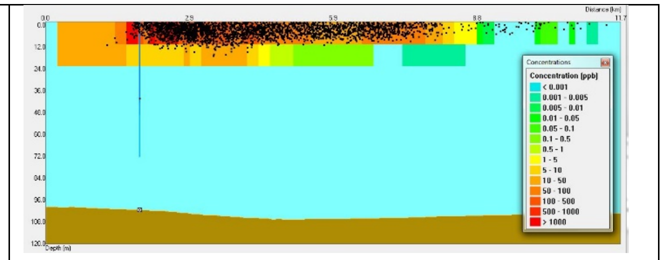
A subsea leakage from the 16'' Krafla production line (Krafla SPS – UPP) at UPP seabed (inside 500m zone) was modelled with leak size from 2.5 mm to 90 mm with oil leakage rate from 4 m^3/d to 4488 m^3/d at 106 meters depth. The GOR is 924 and the oil and gas exit velocity from a leakage is very high (> 100 m/s) and very small oil droplets are formed (d50 from 22 to 84 µm).

The plume will rise to the surface, except from the smallest leak sizes (Figure 3-10). The small droplets from the smallest leak sizes (2.5 and 5 mm) will cause oil to easily be dispersed deeper into the water column. Larger leak sizes will have more oil on the surface and in the upper part of the water column, especially in a summer situation.

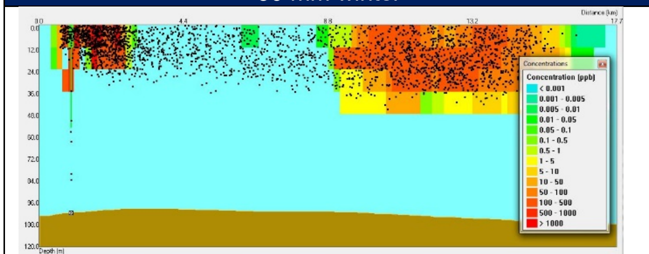




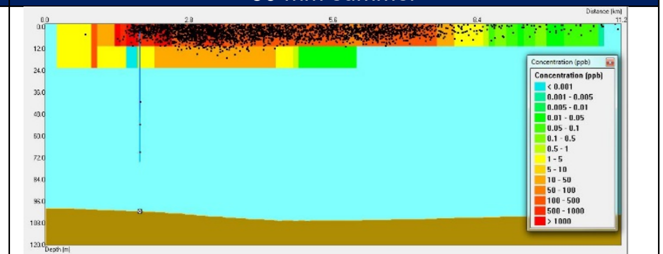
30 mm winter



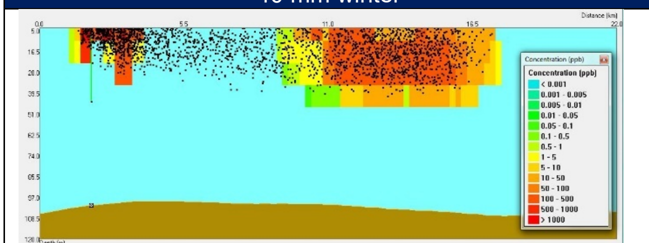
30 mm summer



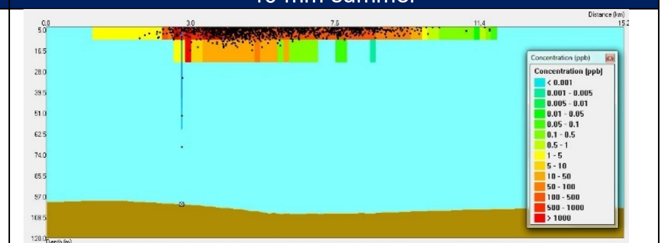
40 mm winter



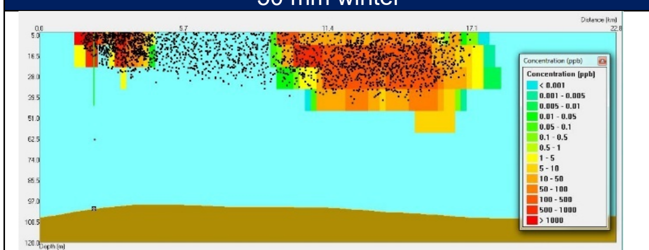
40 mm summer



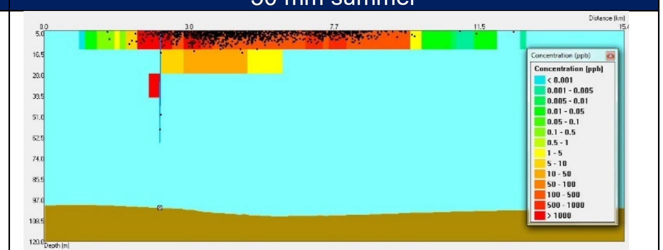
50 mm winter



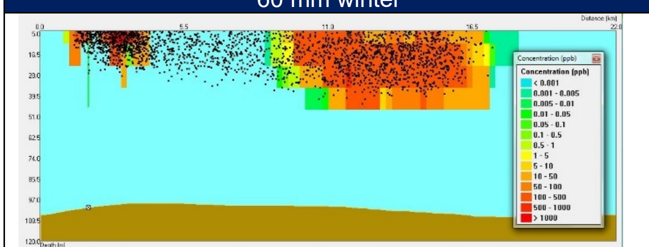
50 mm summer



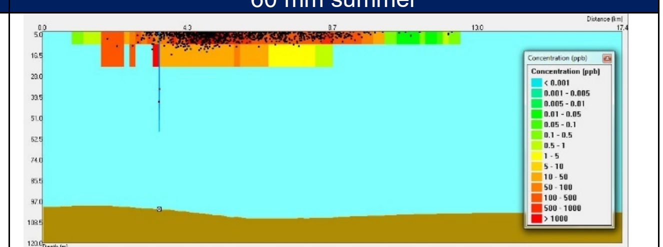
60 mm winter



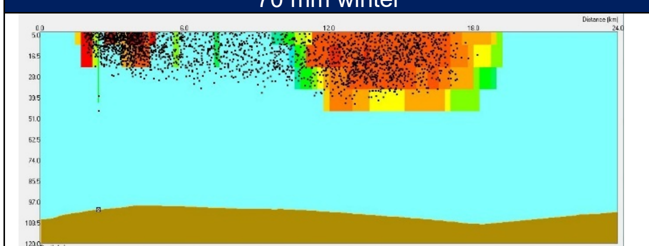
60 mm summer



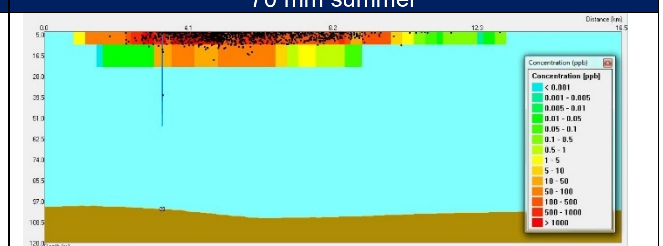
70 mm winter



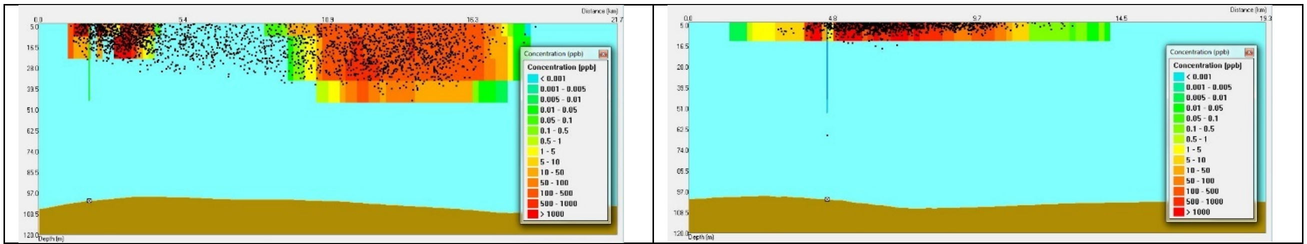
70 mm summer



80 mm winter



80 mm summer



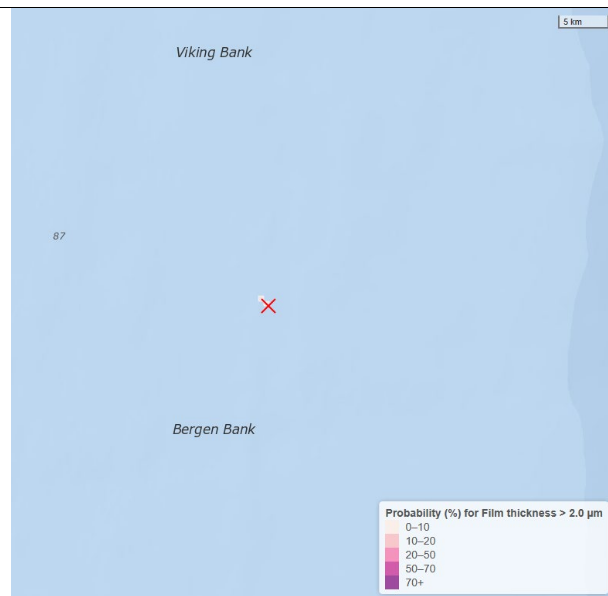
90 mm winter | 90 mm summer

Figure 3-10 *Leakage behaviour from subsea leakages at 16'' Krafla PL (UPP seabed) with different leak sizes. Transects along main drift direction after 1-day leak duration.*

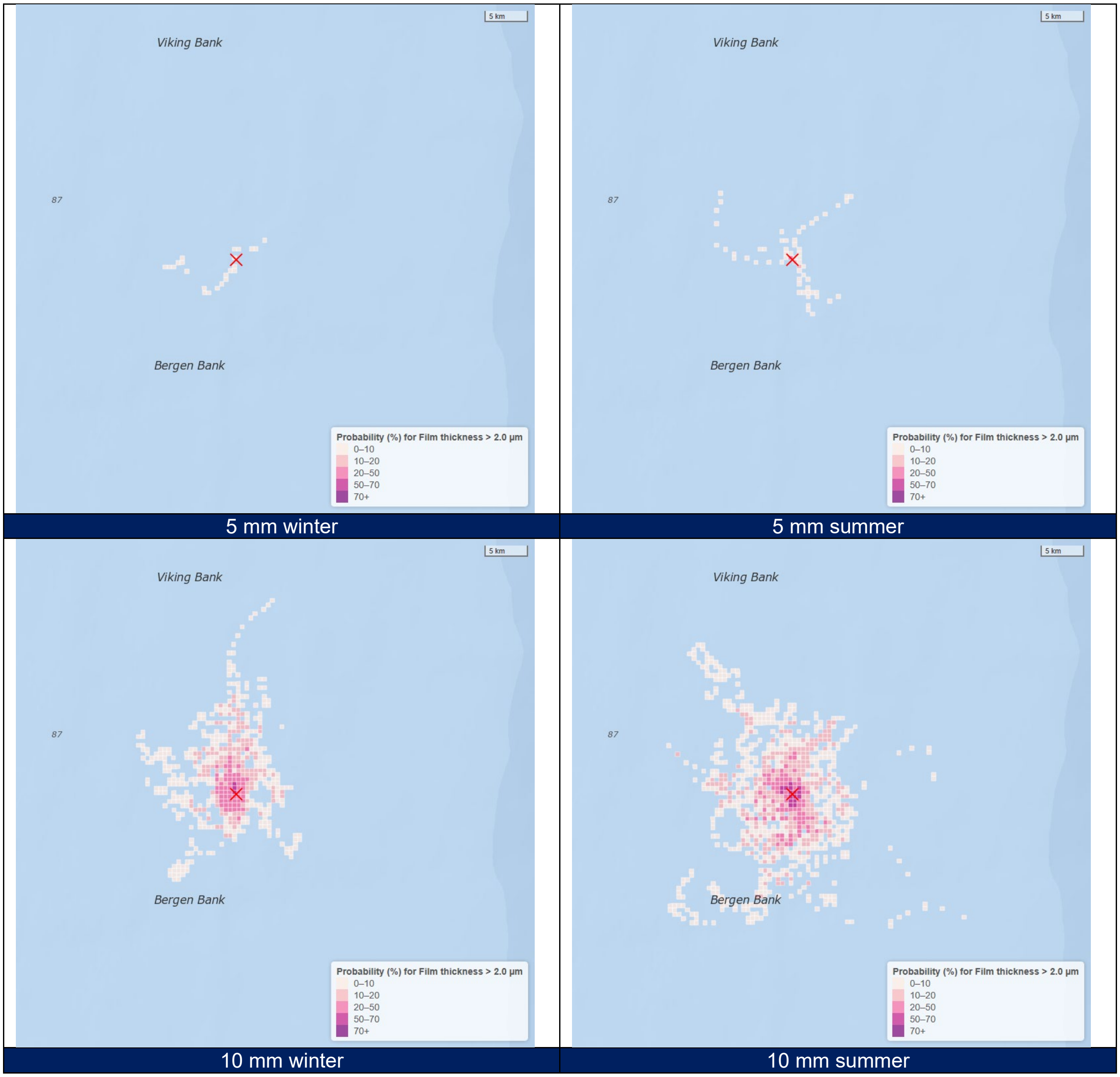
3.4.3 Surface impact

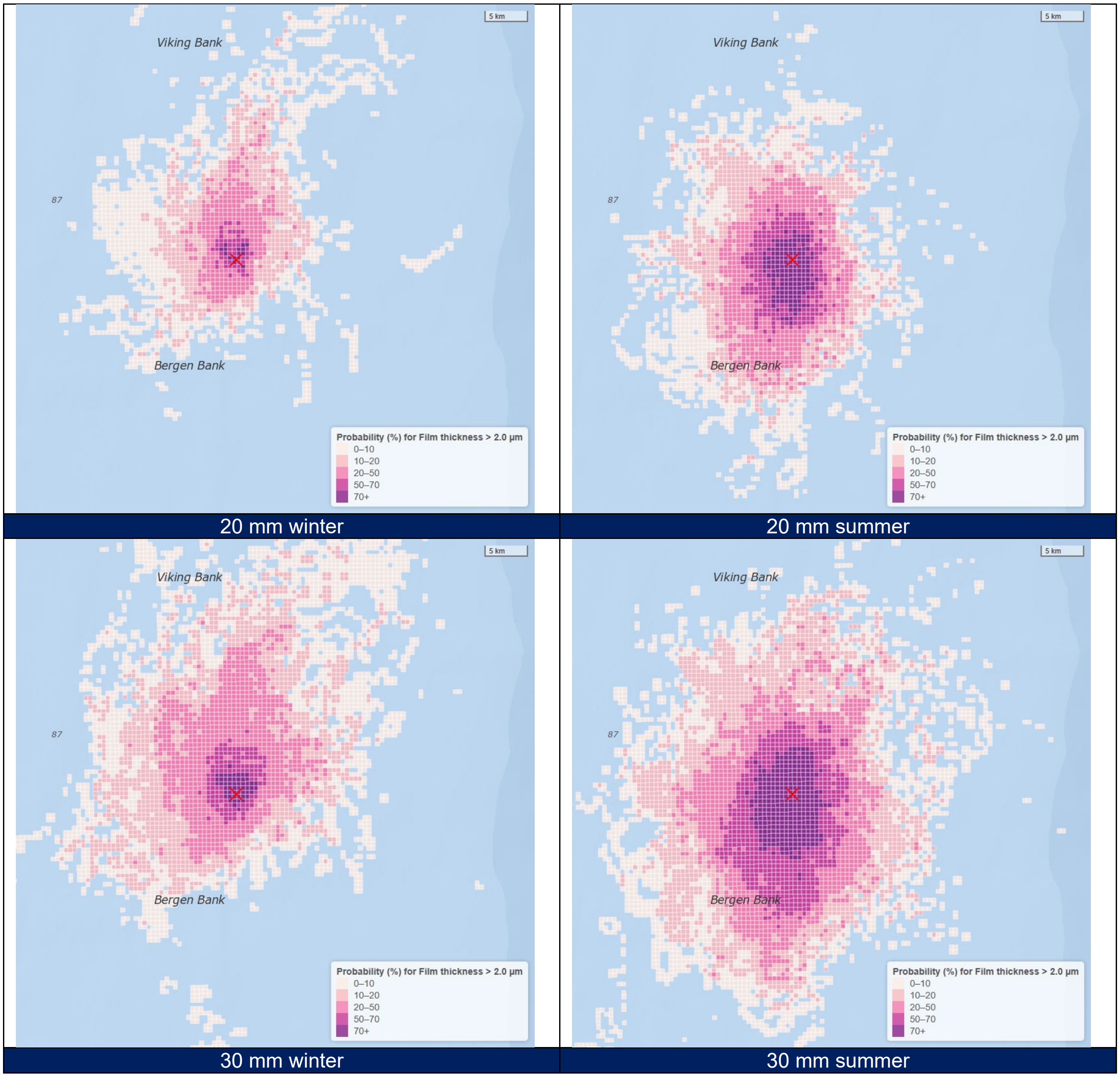
Probability for a leakage from the 16'' Krafla PL (UPP seabed) for reaching the surface with a film thickness above 2 µm is shown in Figure 3-11. The smallest leak sizes (2.5 and 5 mm) will have very little probability for surface slicks above 2 µm and will not give any or very limited impact to seabirds. From there, the size of the effect area increases with leak size, and the 90 mm leak size results in a high probability for surface slicks above 2 µm in an area stretching 10-30 km away from the location. Note the change in scale from 40 to 50 mm figures.

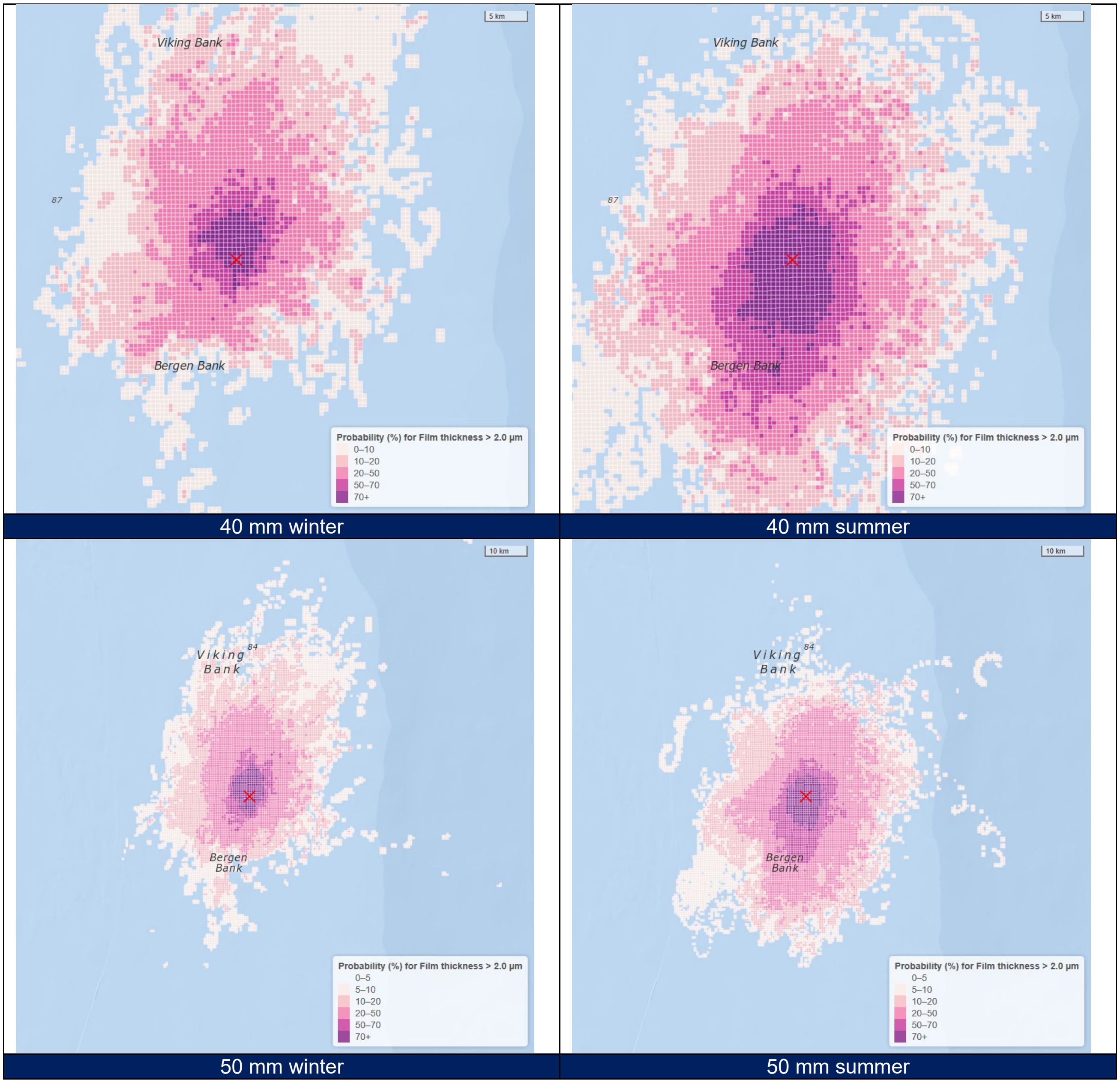
NA

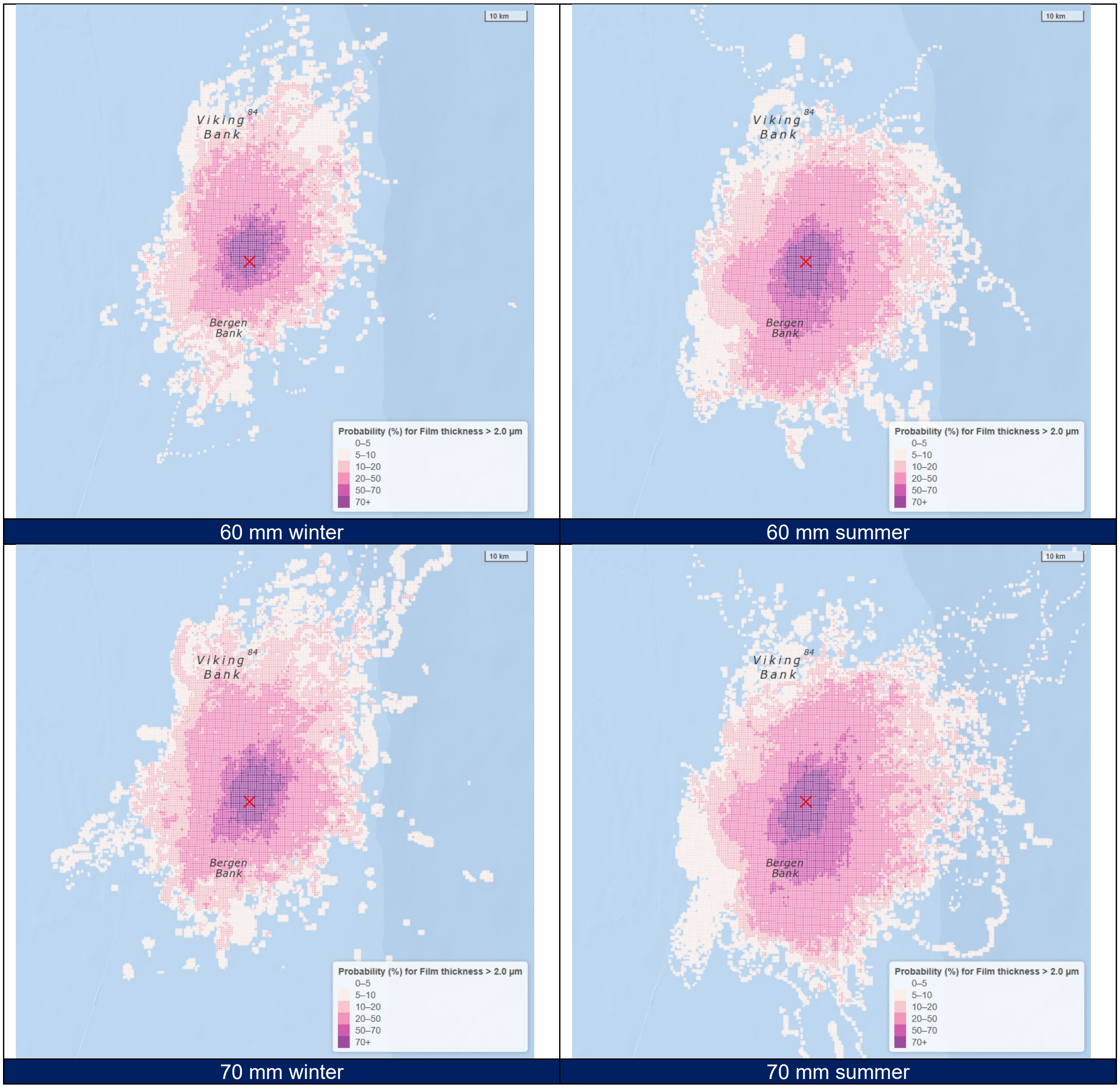


2.5 mm winter | 2.5 mm summer


Viking Bank
87
Bergen Bank
5 km
Probability (%) for Film thickness > 2.0 µm
0–10
10–20
20–50
50–70
70+
5 mm winter
5 mm summer
10 mm winter
10 mm summer


Viking Bank
87
Bergen Bank
5 km
Probability (%) for Film thickness > 2.0 µm
0–10
10–20
20–50
50–70
70+
20 mm winter
20 mm summer
30 mm winter
30 mm summer


5 km
Viking Bank
87
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–10
10–20
20–50
50–70
70+
40 mm winter
5 km
Viking Bank
87
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–10
10–20
20–50
50–70
70+
40 mm summer
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
50 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
50 mm summer


10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
60 mm winter
60 mm summer
70 mm winter
70 mm summer

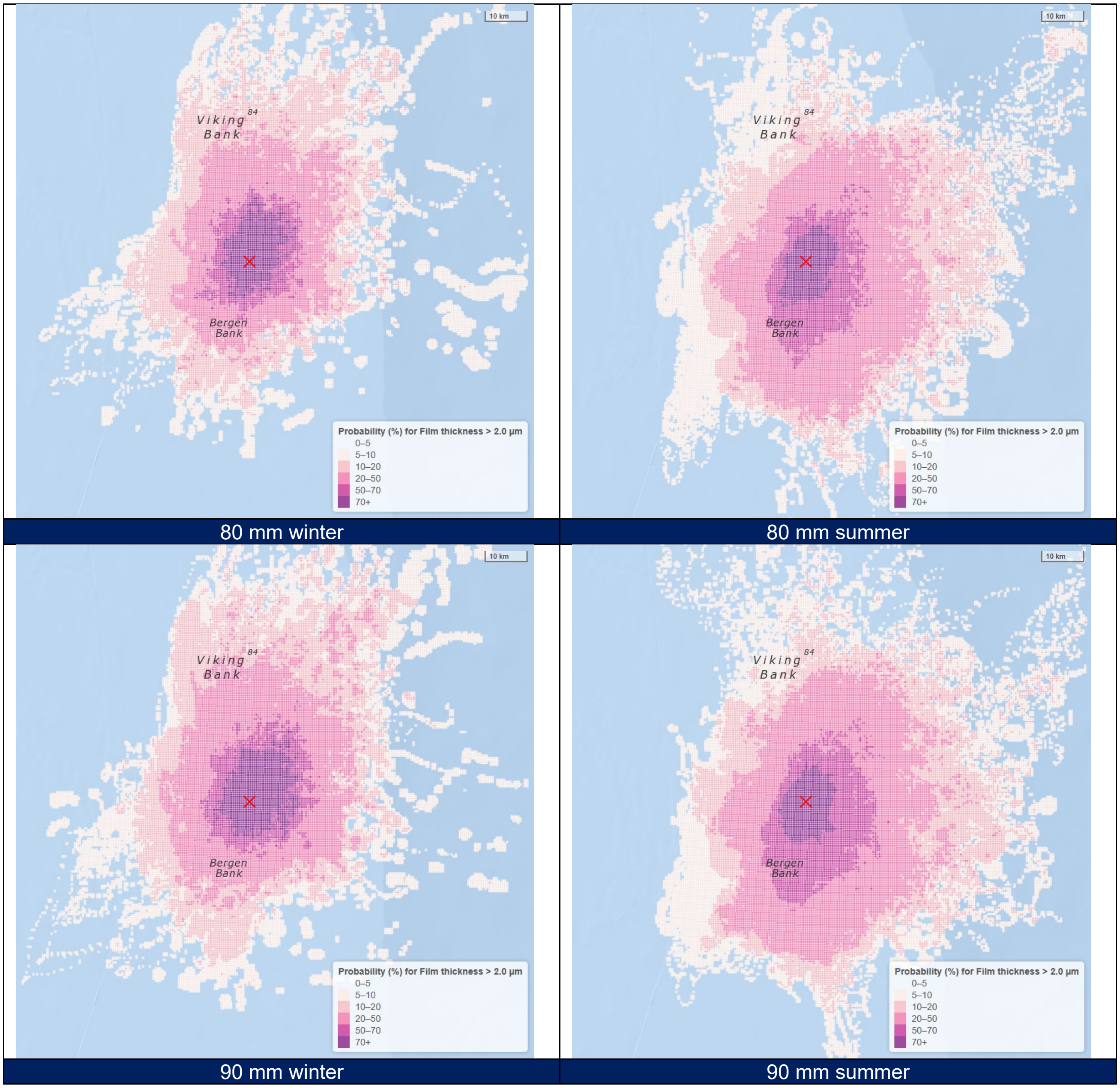
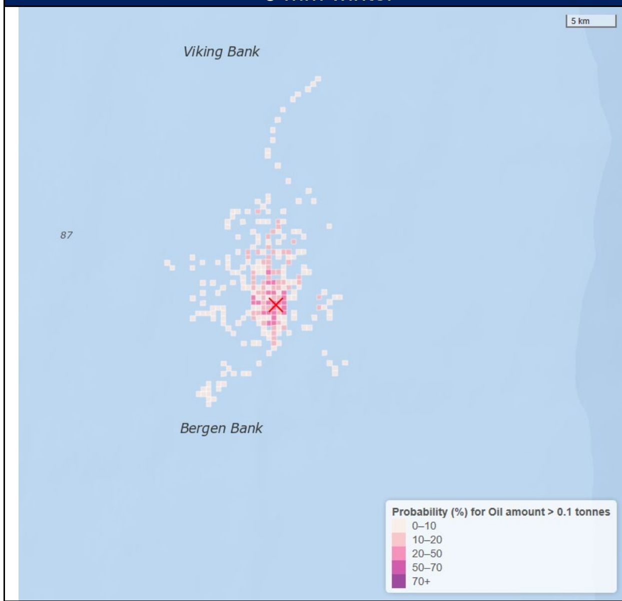
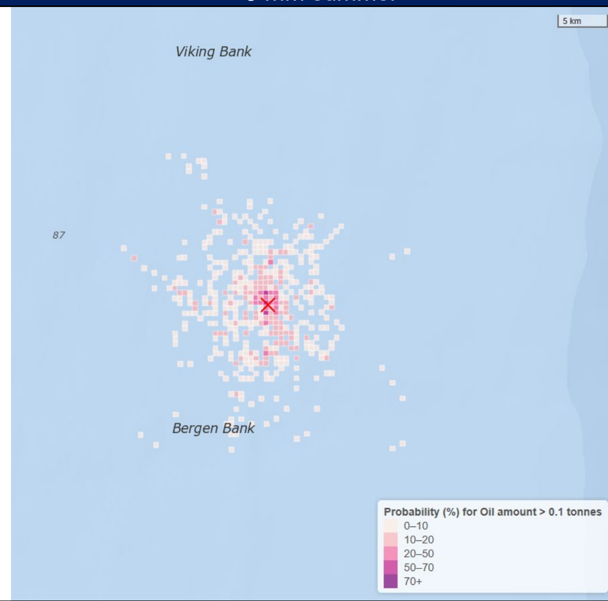


Figure 3-11 *Probability for film thickness above 2 µm from leak scenarios at 16'' Krafla PL (UPP seabed) with different leak sizes. Spill duration 7 days.*

3.4.4 Surface detection

Probability for surface detection from satellite is related to the minimum detection threshold defined as 0.1 tons per 500x500 meter grid cell (0.25 km^2). As for the surface impact area for seabirds, the smallest leak sizes (2.5 and 5 mm) will not reach this threshold and will not be detected by satellite, while the larger leak sizes (>10 mm) have a high surface detection probability (Figure 3-12). Note the change in scale from 40 to 50 mm figures.

<table>
<tr><td>NA</td><td>NA</td></tr>
<tr><td>2.5 mm winter</td><td>2.5 mm summer</td></tr>
<tr><td>NA</td><td>NA</td></tr>
<tr><td>5 mm winter</td><td>5 mm summer</td></tr>
<tr><td>
</td><td>
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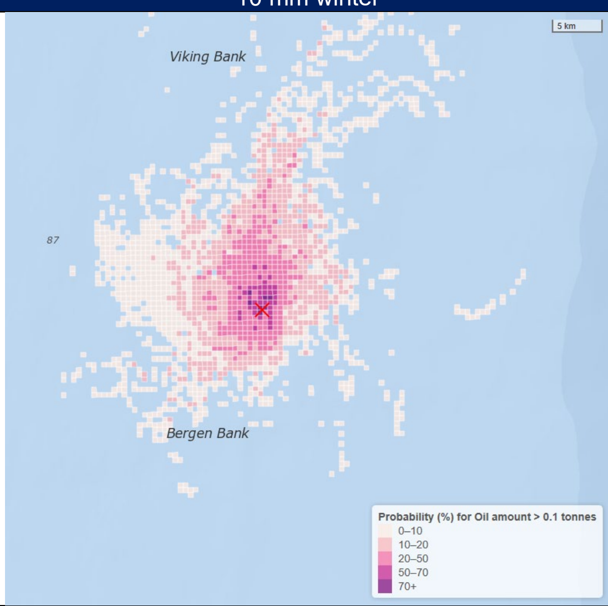
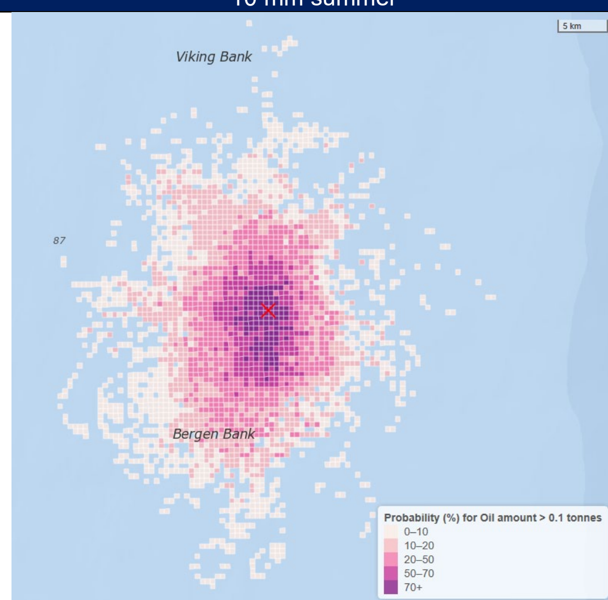
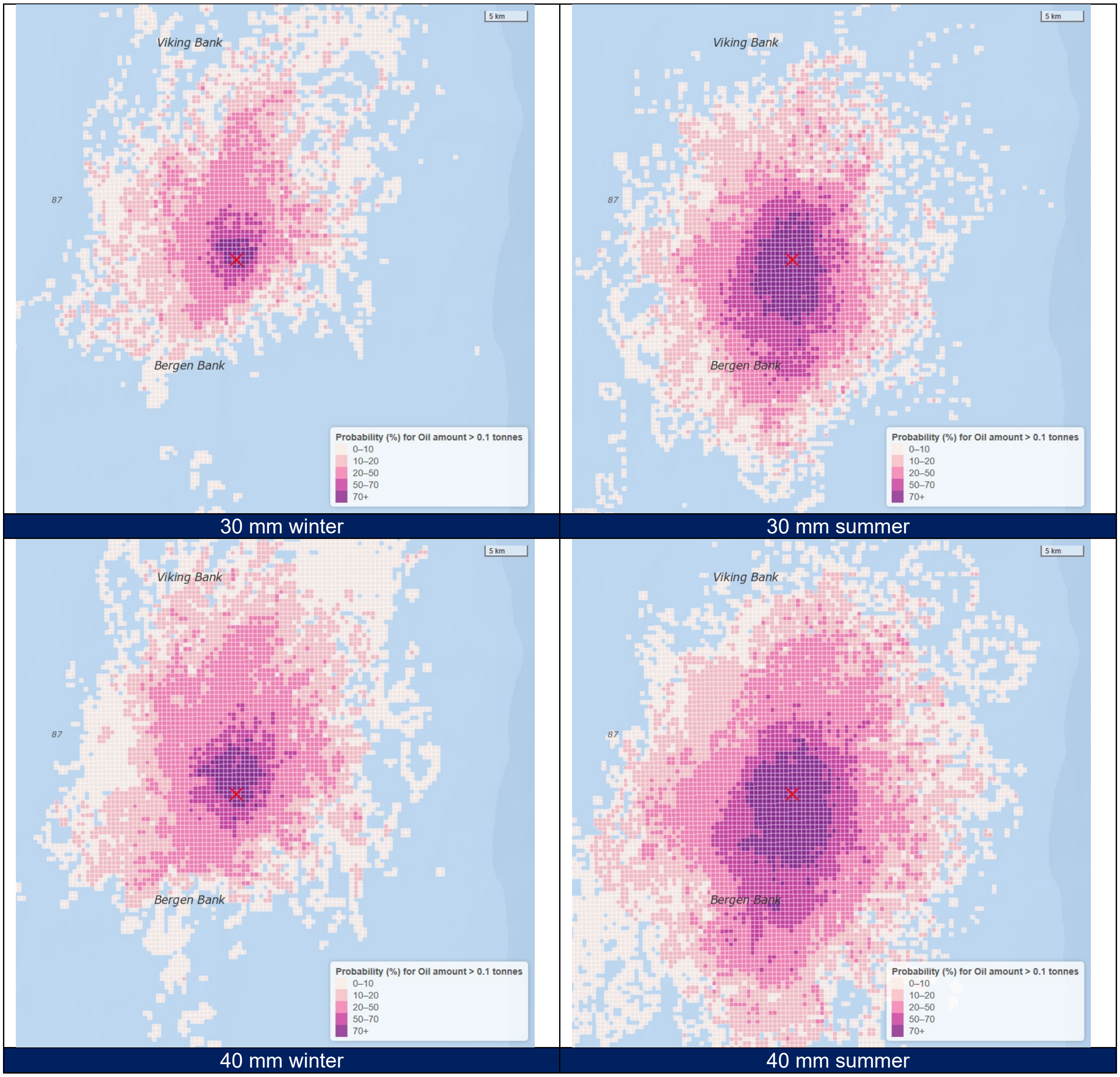
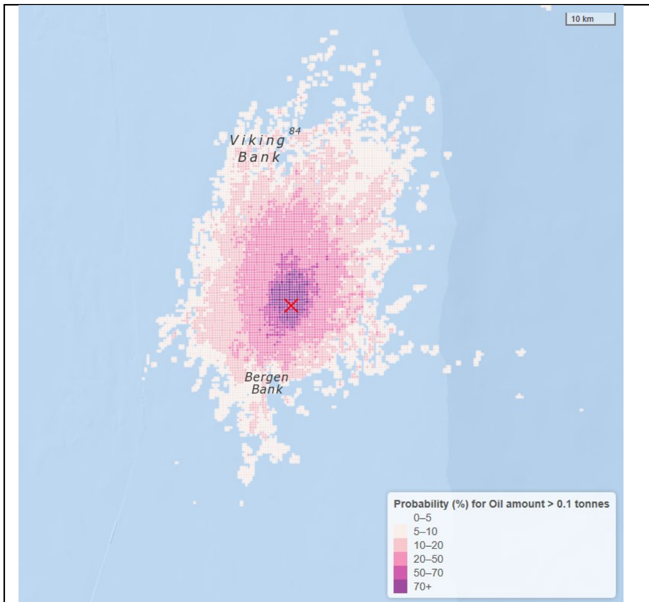
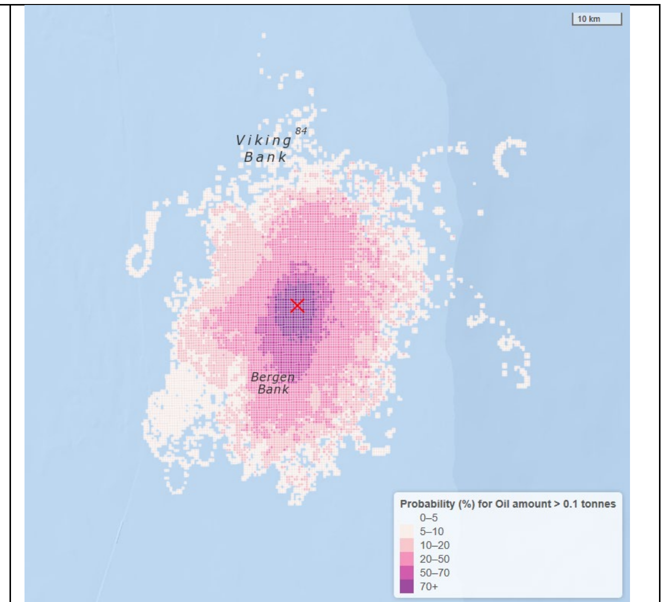
<tr><td>10 mm winter</td><td>10 mm summer</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>20 mm winter</td><td>20 mm summer</td></tr>
</table>

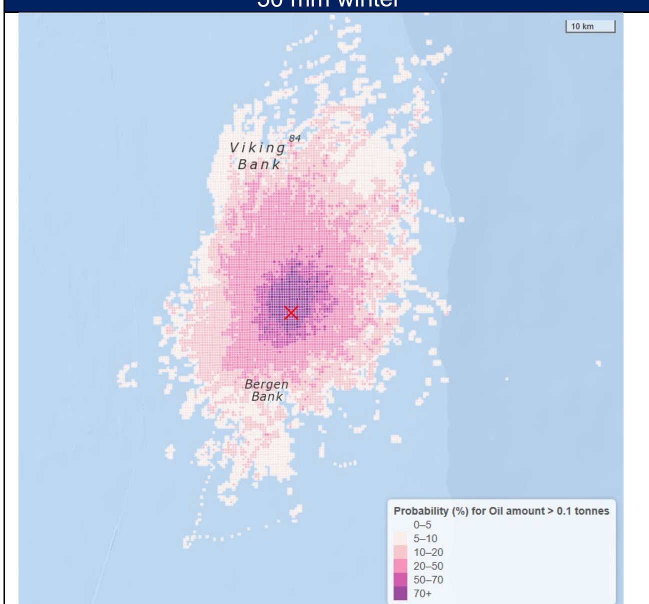

Viking Bank
Bergen Bank
87
5 km
Probability (%) for Oil amount > 0.1 tonnes
0–10
10–20
20–50
50–70
70+
30 mm winter
30 mm summer
40 mm winter
40 mm summer



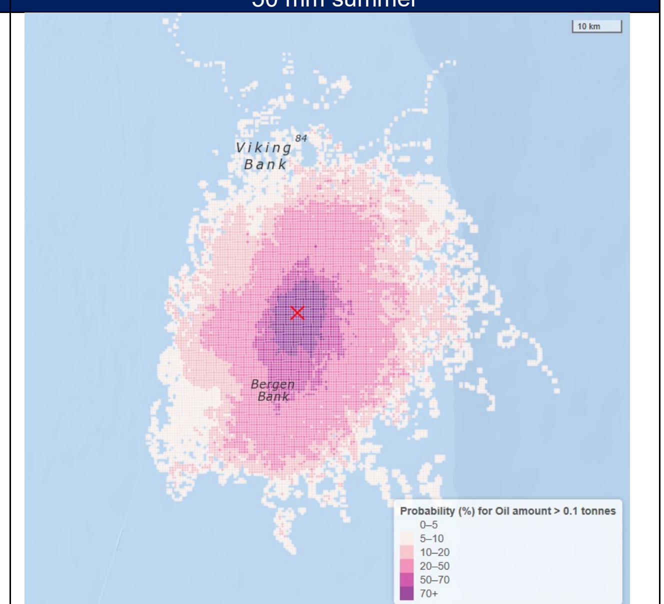
50 mm winter



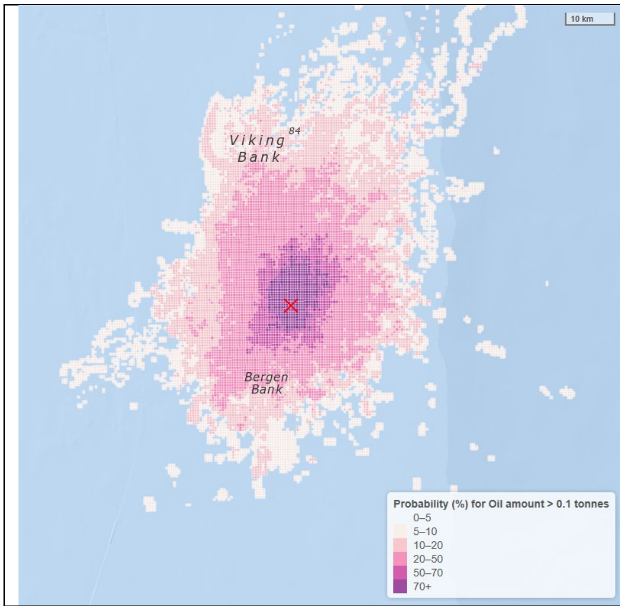
50 mm summer



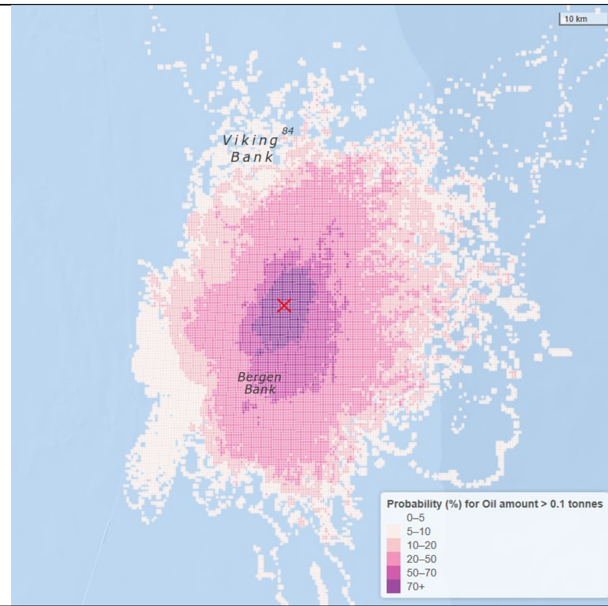
60 mm winter



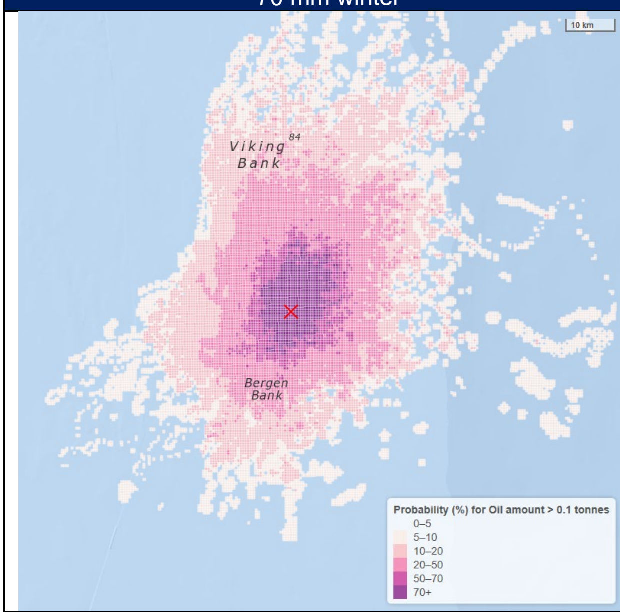
60 mm summer



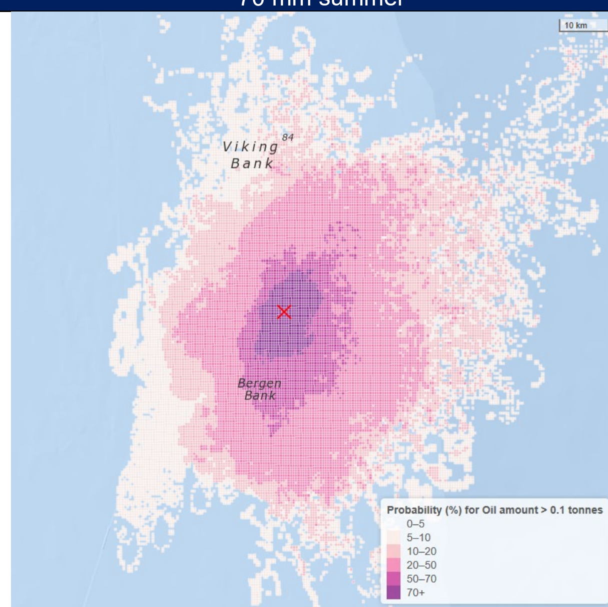
70 mm winter



70 mm summer



80 mm winter



80 mm summer

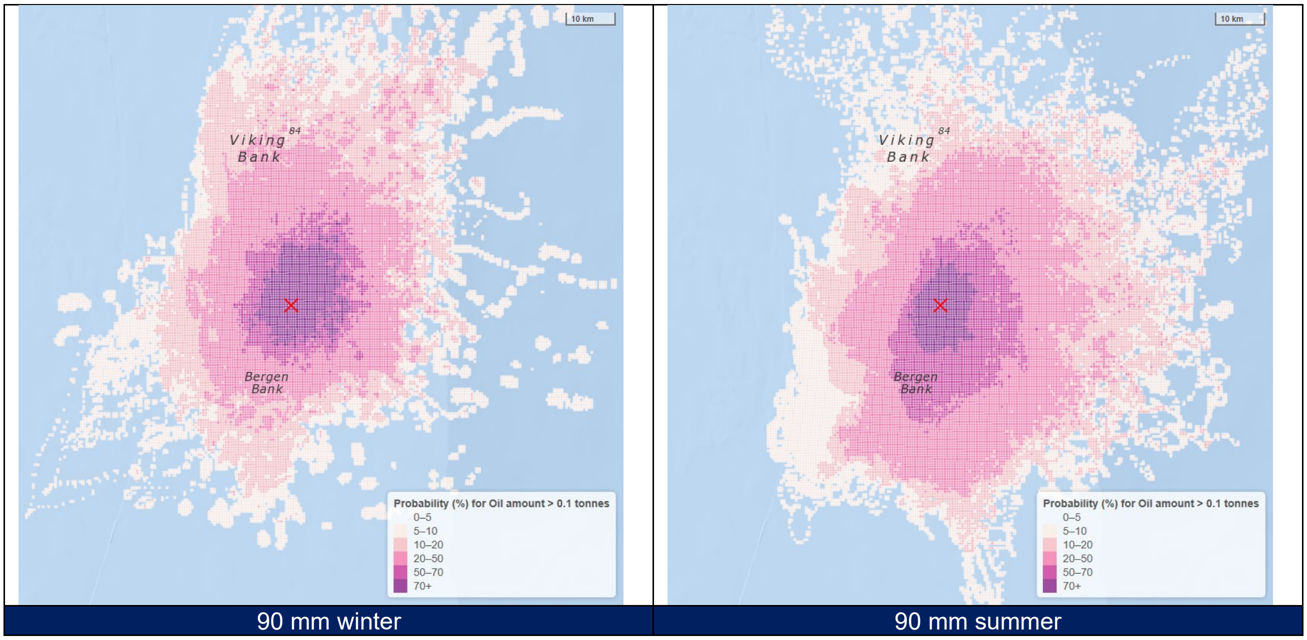
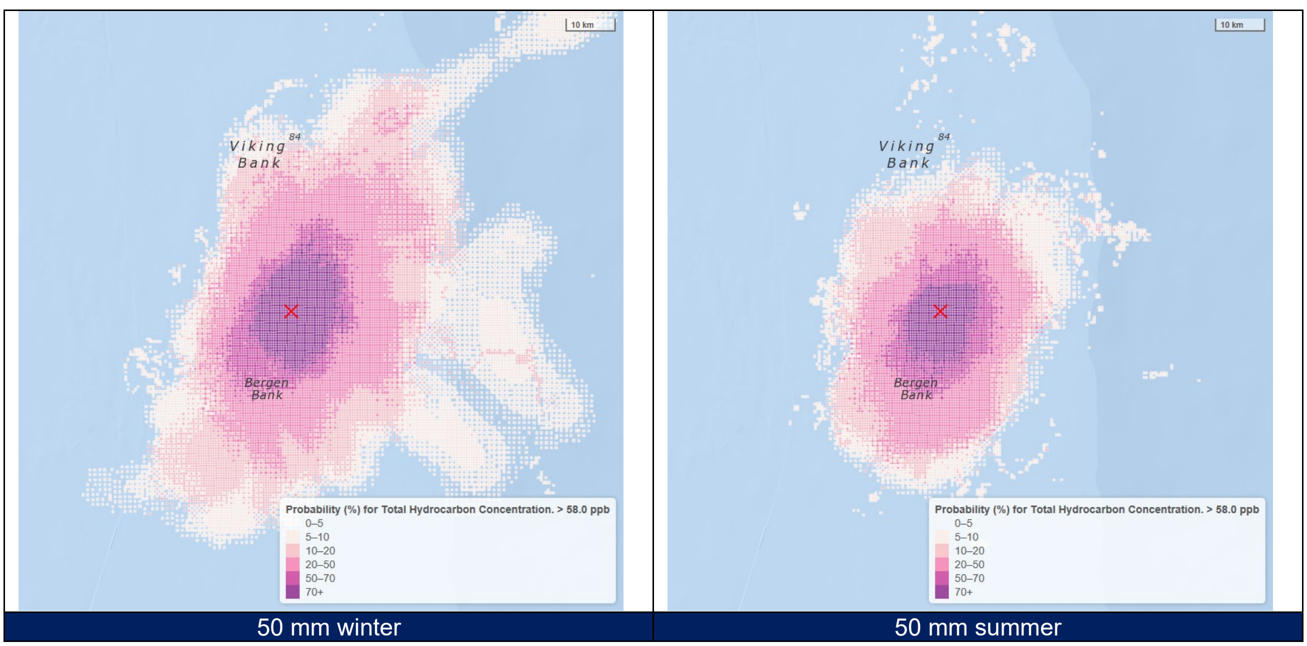
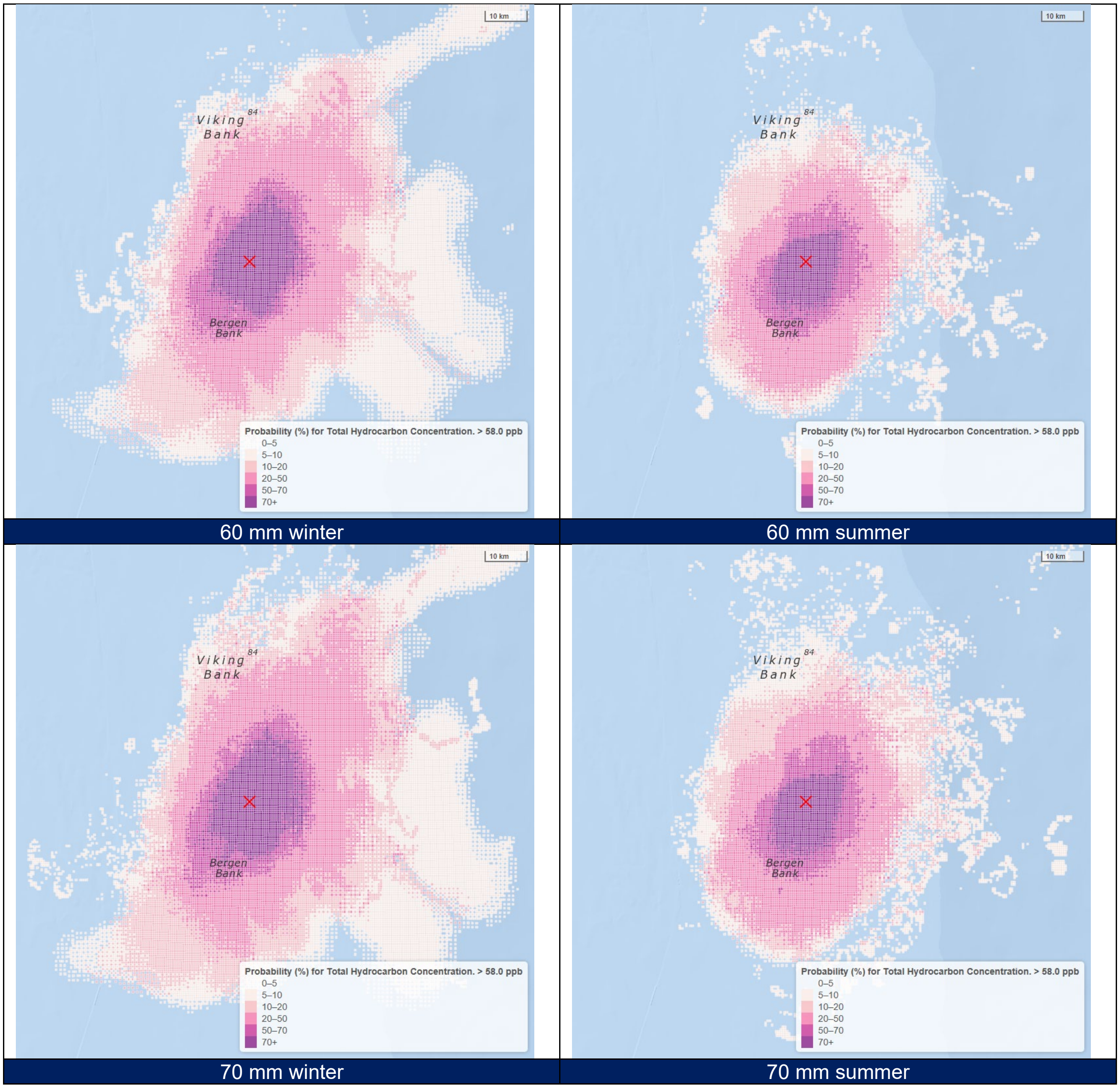


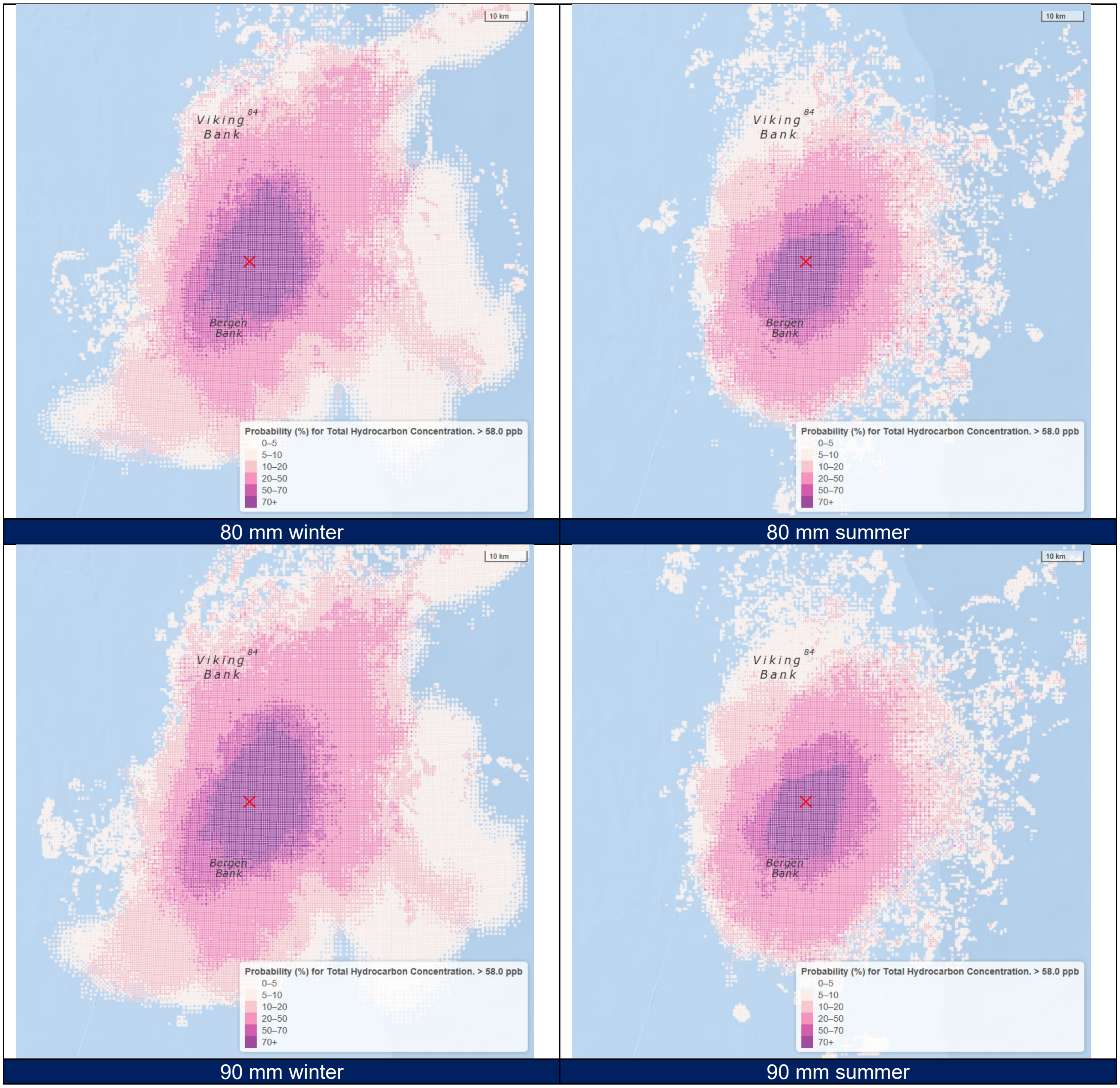
Figure 3-12 *Probability for surface oil volumes above SAR detection limit (0,1 t per 0.25 km2) from leak scenarios at 16" Krafla PL (UPP seabed) with different leak sizes. Spill duration 7 days.*

3.4.5 Water column impact

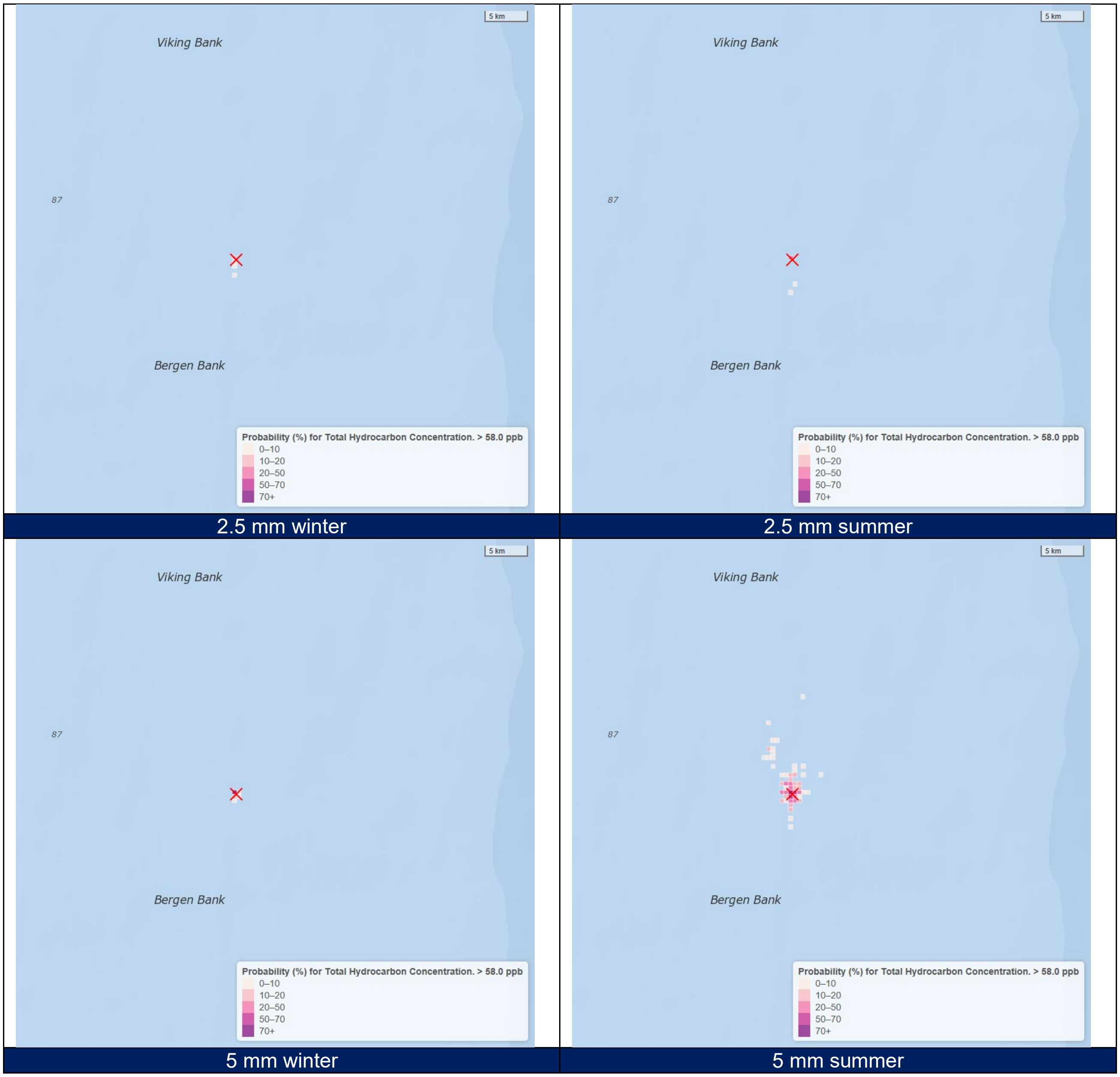
Probability for THC above the effect threshold of 58 ppb in the upper 50 meter of the water column is shown in Figure 3-13

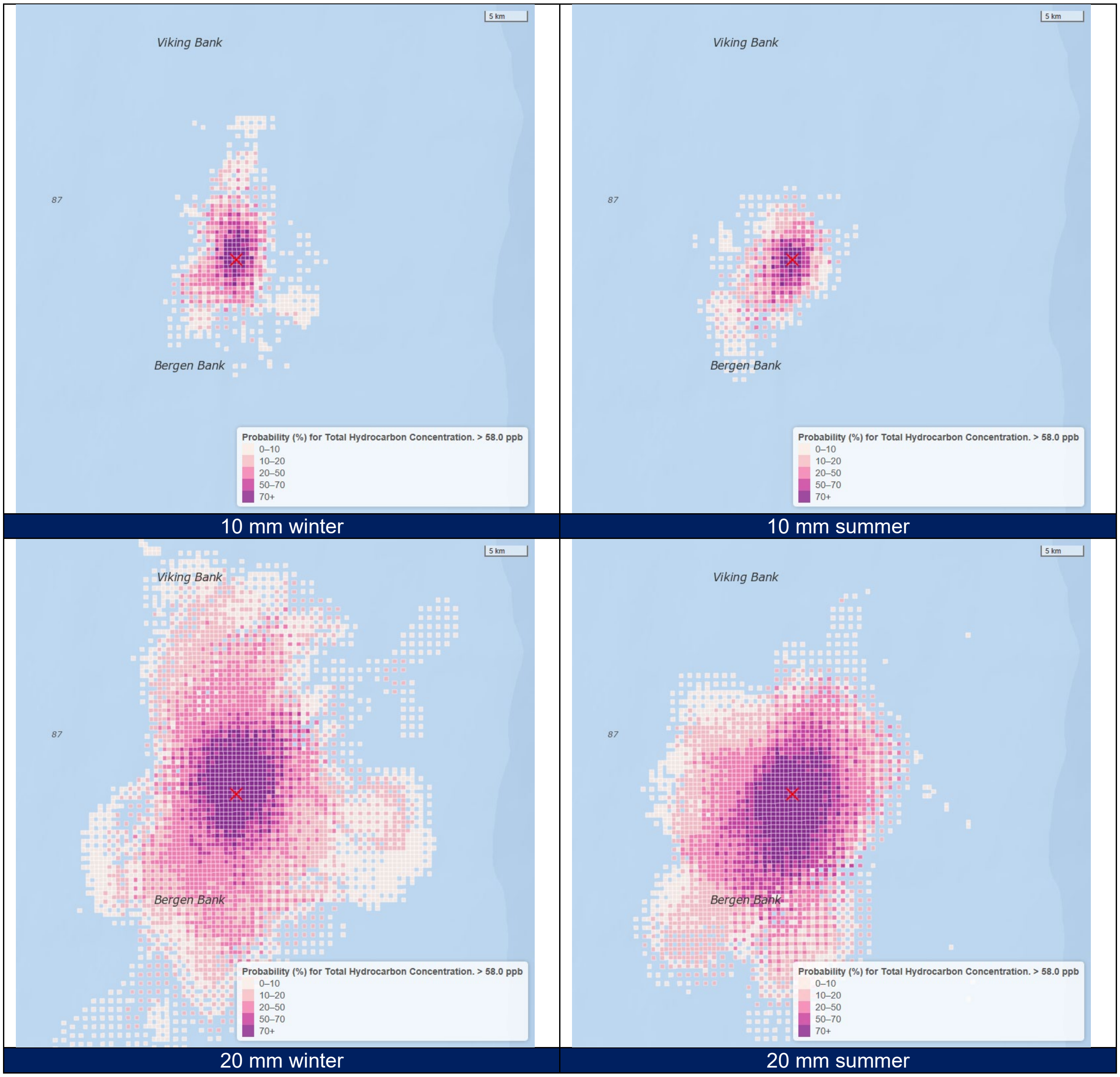


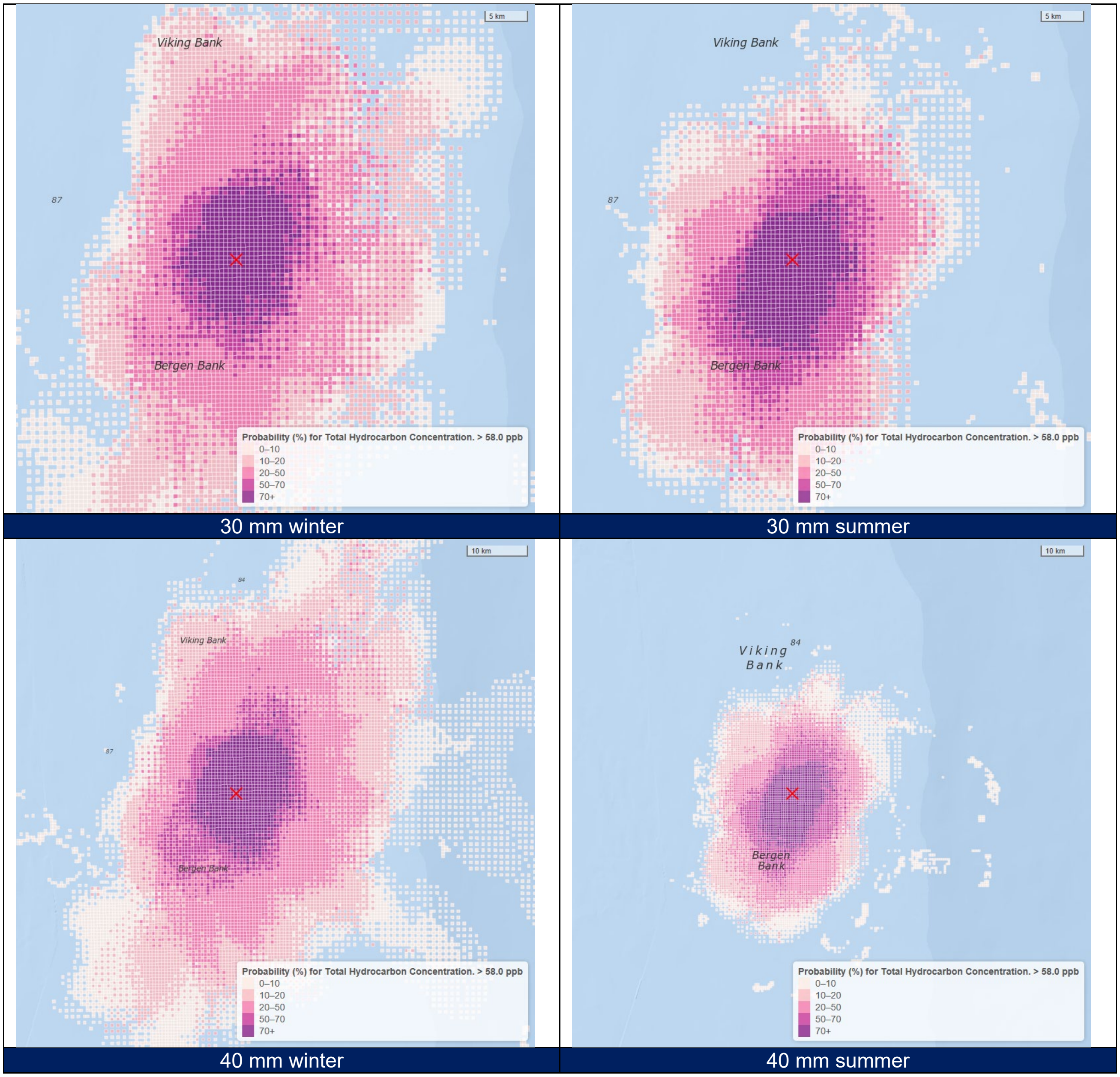

10 km
Viking Bank
84
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–5
5–10
10–20
20–50
50–70
70+
60 mm winter
60 mm summer
70 mm winter
70 mm summer

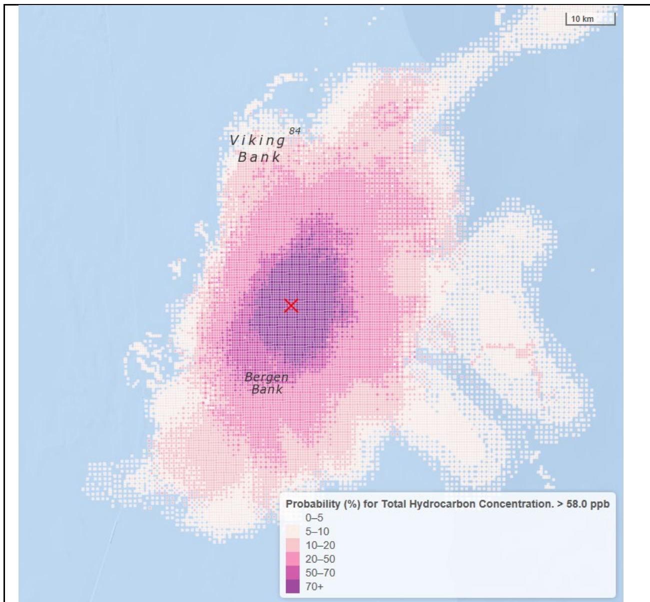


. The smallest leak sizes (2.5 and 5 mm) have small probabilities for reaching the effect threshold of 58 ppb, but for the remaining leak sizes (10 mm to 90 mm) there is a steady increase in the size of the effect area with leak size, ending with an effect area up to 30 km away from the location.

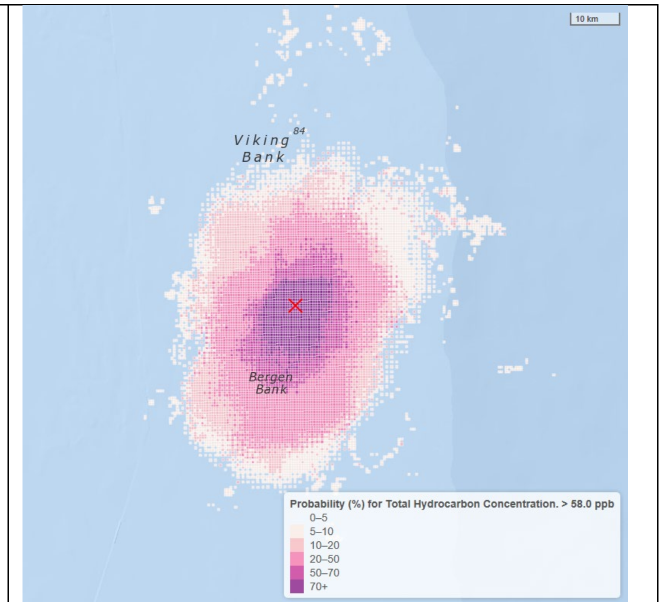

5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
2.5 mm winter
5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
2.5 mm summer
5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
5 mm winter
5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
5 mm summer


5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
10 mm winter
10 mm summer
20 mm winter
20 mm summer

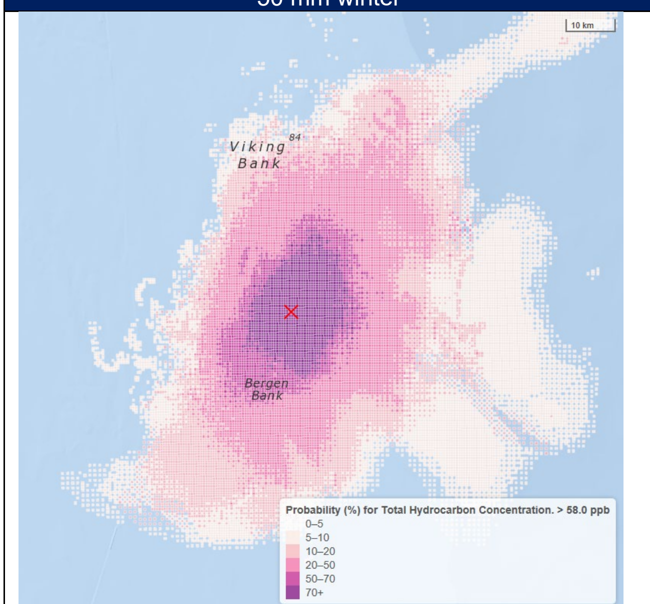

5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
30 mm winter
5 km
Viking Bank
87
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
30 mm summer
10 km
Viking Bank
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
40 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–10
10–20
20–50
50–70
70+
40 mm summer



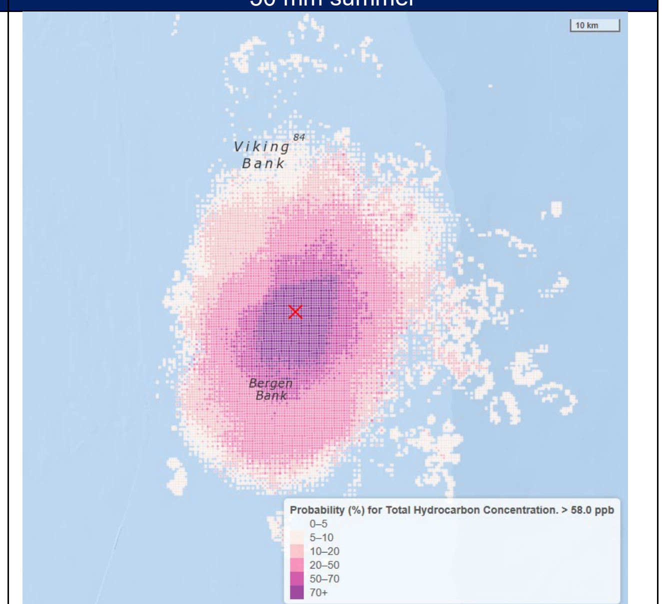
50 mm winter



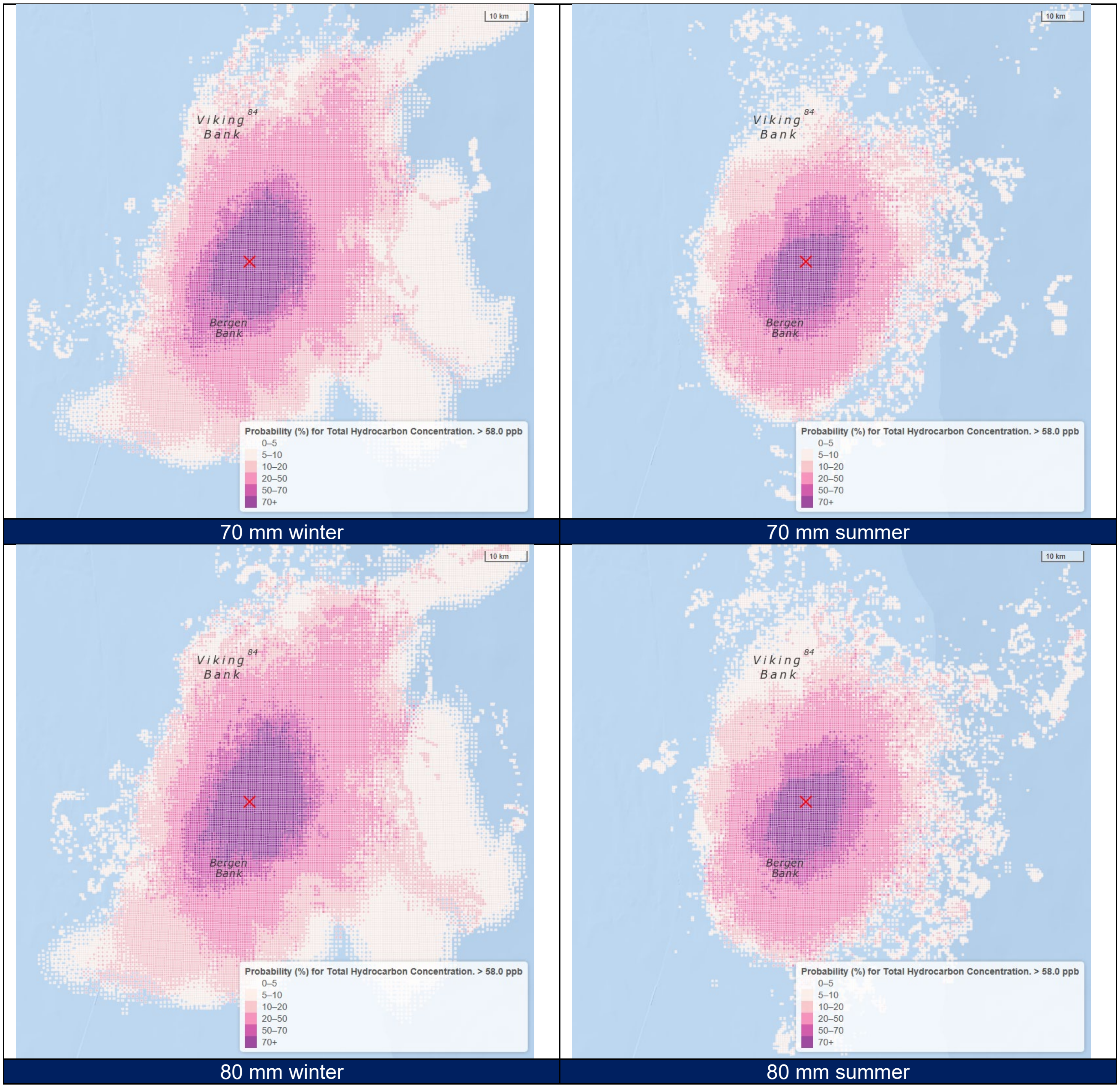
50 mm summer

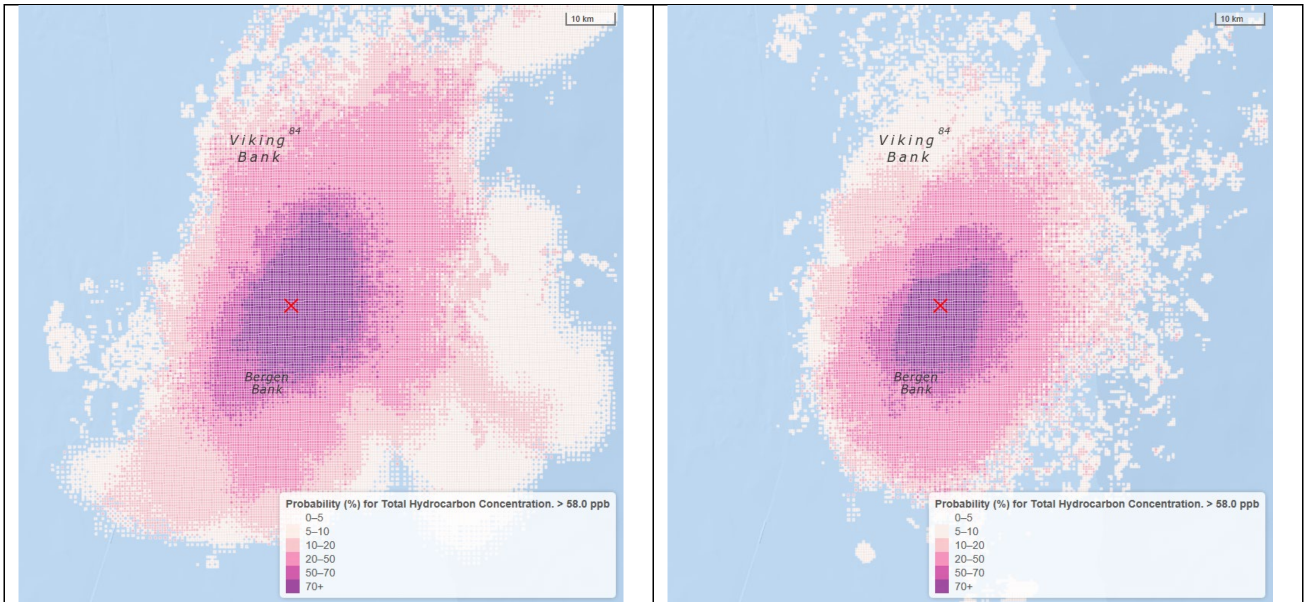


60 mm winter



60 mm summer


10 km
Viking Bank
84
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–5
5–10
10–20
20–50
50–70
70+
70 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–5
5–10
10–20
20–50
50–70
70+
70 mm summer
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–5
5–10
10–20
20–50
50–70
70+
80 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Total Hydrocarbon Concentration. > 58.0 ppb
0–5
5–10
10–20
20–50
50–70
70+
80 mm summer



90 mm winter	90 mm summer

Figure 3-13 *Probability for THC above 58 ppb in upper 50 meters of water column from leak scenarios at 16'' Krafla PL (UPP seabed) with different leak sizes. Spill duration 7 days.*

3.5 16´´ Askja production line Askja SPS – UPP (midway SPS – UPP, KP 0,375)

3.5.1 Input data for the OSCAR modelling

Leak rates for the different hole sizes and other key input for 16´´ Askja production line Askja SPS – UPP (midway SPS – UPP, KP 0,375) is shown in Table 3-4.

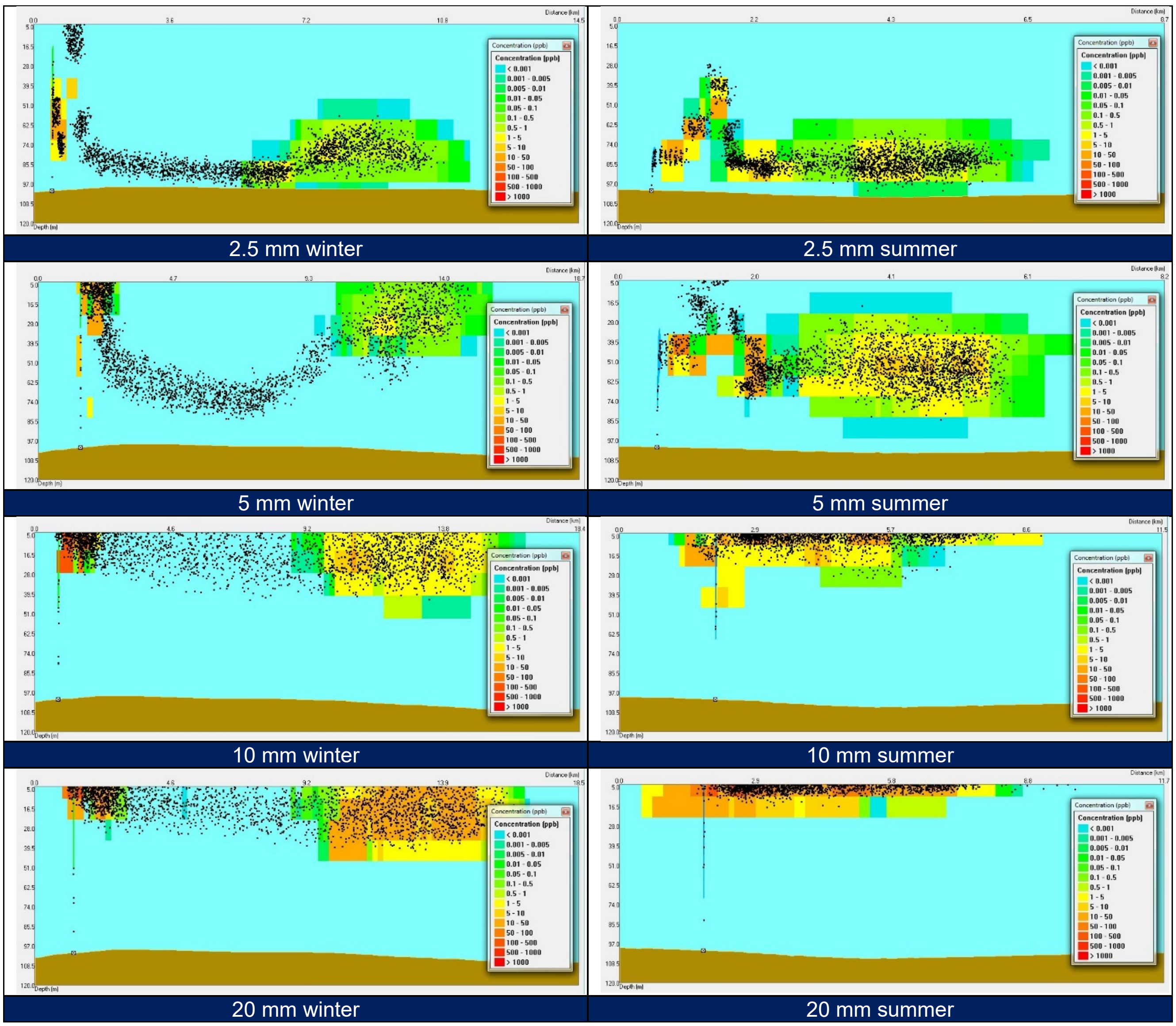
Table 3-4 *Hole sizes and leak rates for 16´´ Askja production line Askja SPS – UPP (midway SPS – UPP, KP 0,375) for OSCAR modelling.*

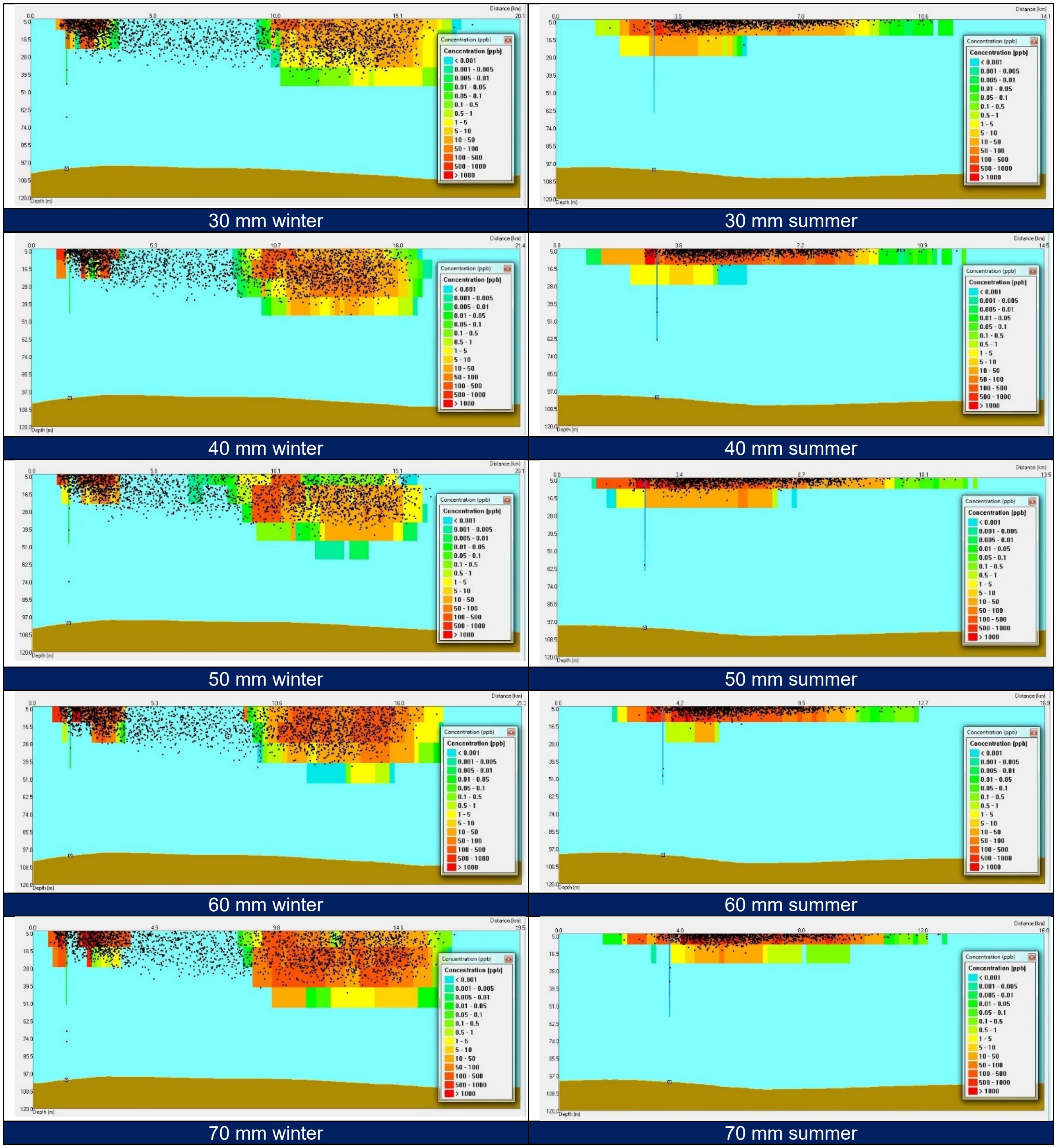
Functional Location	Lekkasje-lokasjon	Depth (m)	Oil type	Hole size (mm)	Exit vel (m/s)	Oil leak rate (m3/d)	GOR
16'' Askja production line Askja SPS - UPP	Midway SPS - UPP KP 0,375	106	Oseberg Sør	2,5	89,9	2,3	1571
				5	101,2	9,1	
				10	104	36,5	
				20	102,6	145,9	
				30	102,3	327,7	
				40	101,7	580,6	
				50	100,9	903,6	
				60	100,1	1294,9	
				70	99,1	1752,7	
				80	98,1	2274,3	
				90	97,0	2854,9	
				100	95,9	3485,8	
				120	93,7	4819,4	

3.5.2 Plume

A subsea leakage from the Askja production line midway between Askja SPS and UPP was modelled with leak size from 2,5 mm to 120 mm with oil leakage rates from 2 m^3/d to 4819 m^3/d at 106 meters depth. The GOR is 1571 and the oil and gas exit velocity from a leakage is very high (90-104 m/s) and small oil droplets are formed (d50 from 29 to 104 µm).

From the smallest leak sizes (2.5 and 5 mm), the plume will be trapped in the water column, and oil droplets may rise slowly to the surface, although easily dispersed into the water column again with wave action due to small droplets (Figure 3-14). From the 10 mm leak size and up to 120 mm, the plume will bring oil to the sea surface, and oil droplets remains in the upper water column or at the surface.




30 mm winter
30 mm summer
40 mm winter
40 mm summer
50 mm winter
50 mm summer
60 mm winter
60 mm summer
70 mm winter
70 mm summer

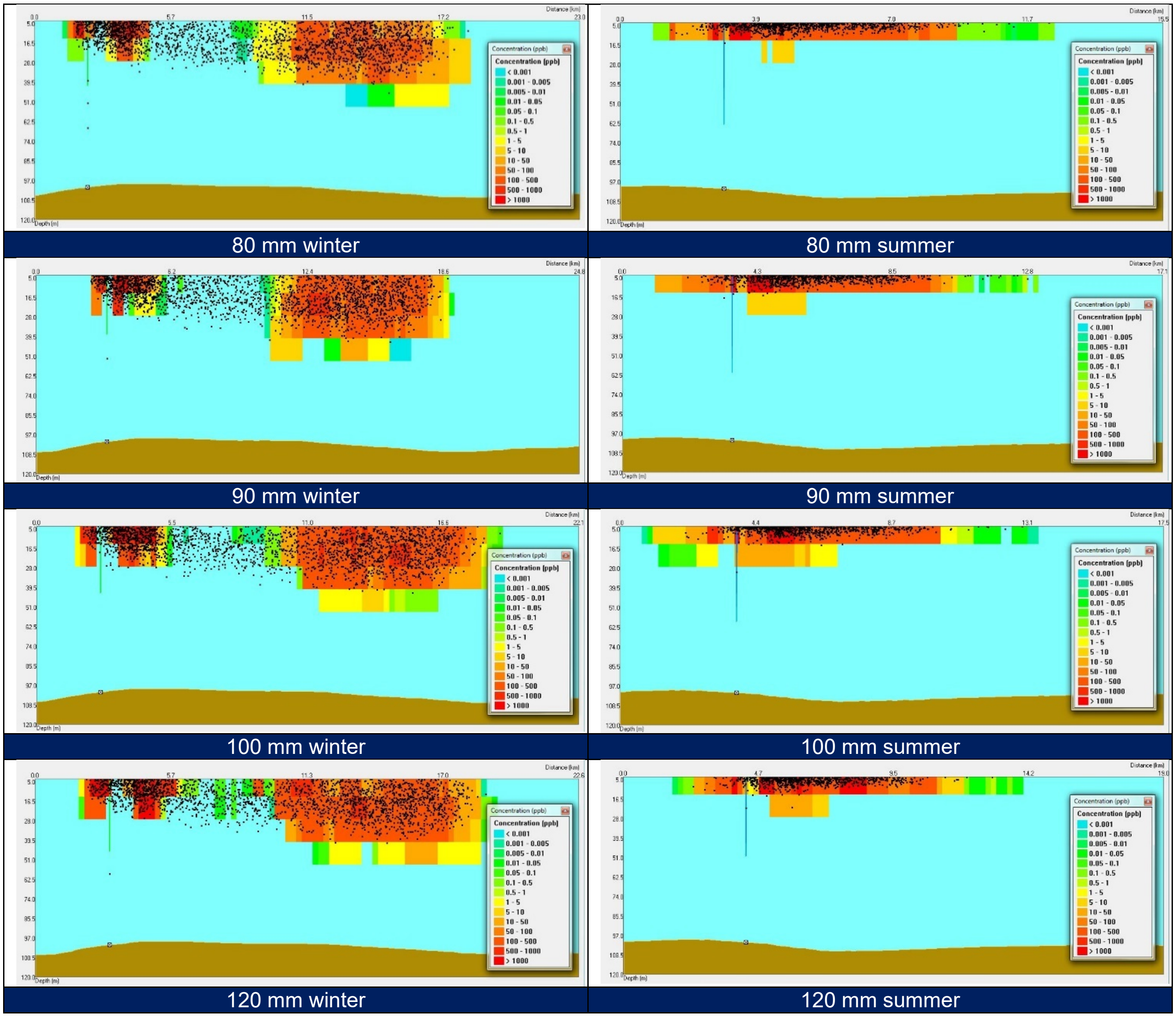
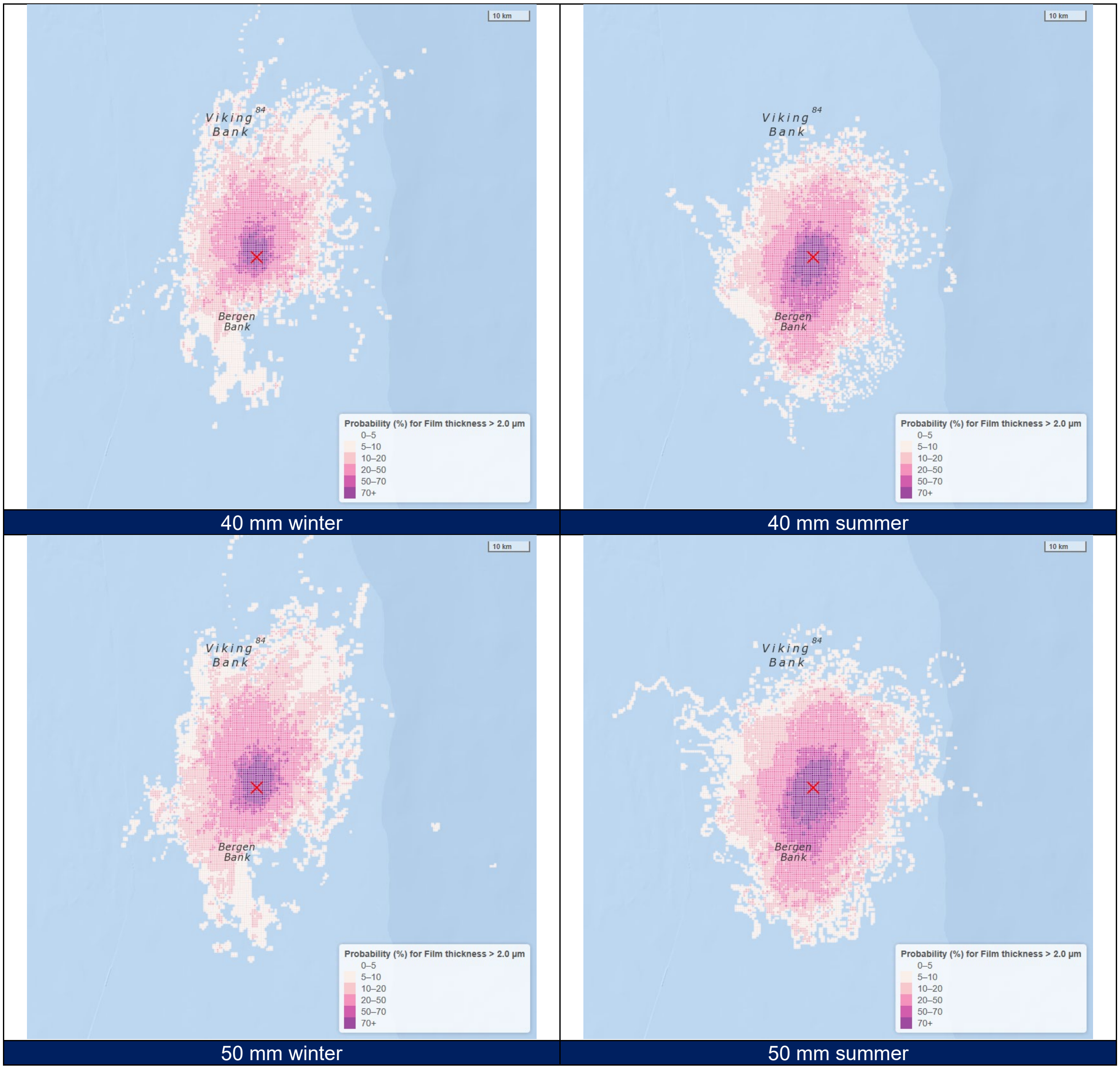
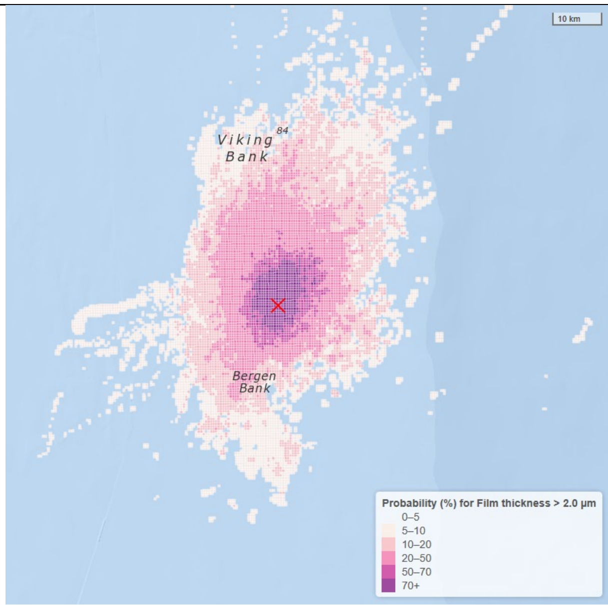


Figure 3-14 *Leakage behaviour from subsea leakages at Askja PL (midway SPS – UPP) with different leak sizes. Transects along main drift direction after 1-day leak duration.*

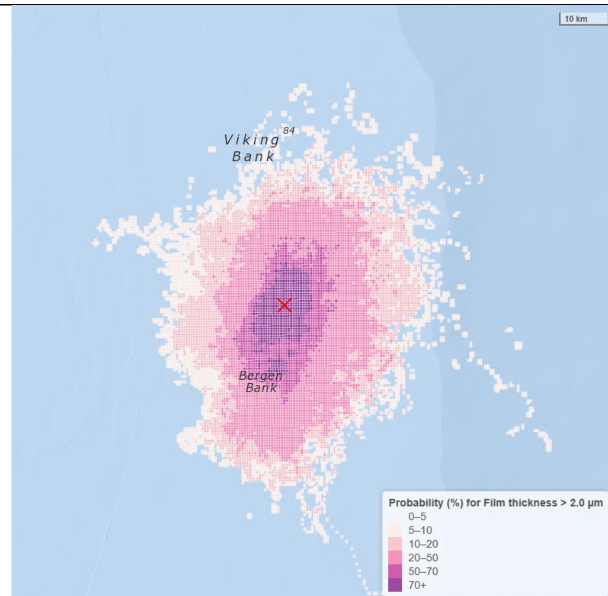
3.5.3 Surface impact (seabirds)

Probability for a leakage from Askja PL (midway SPS – UPP) to reach the surface with a film thickness above 2 µm is shown in Figure 3-15

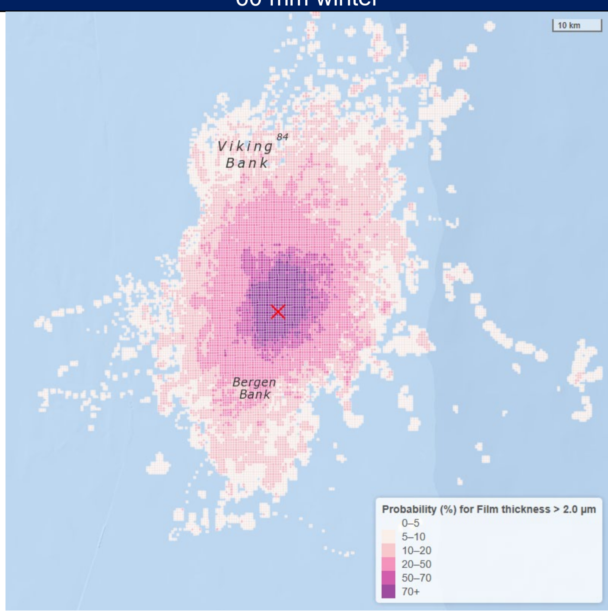

10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
40 mm winter
40 mm summer
50 mm winter
50 mm summer



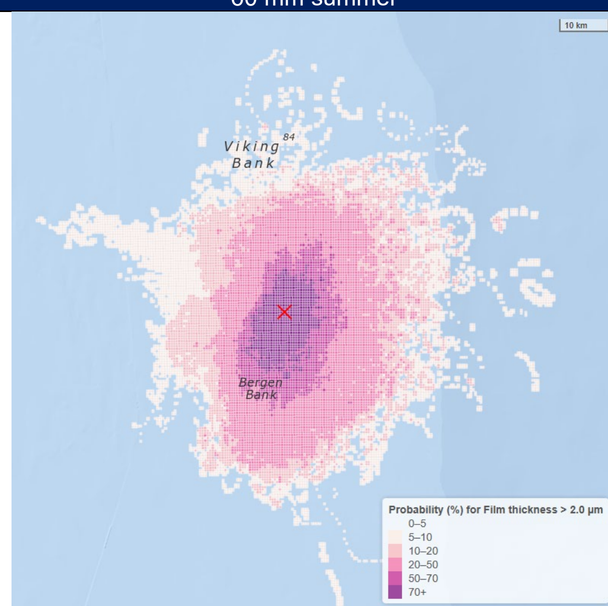
60 mm winter



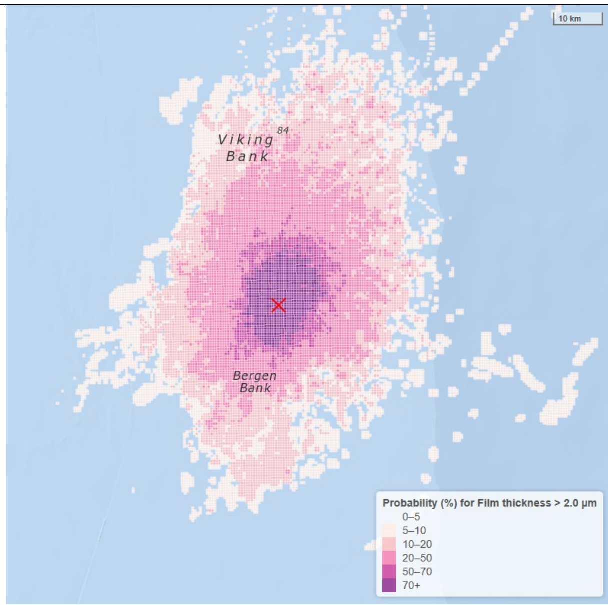
60 mm summer



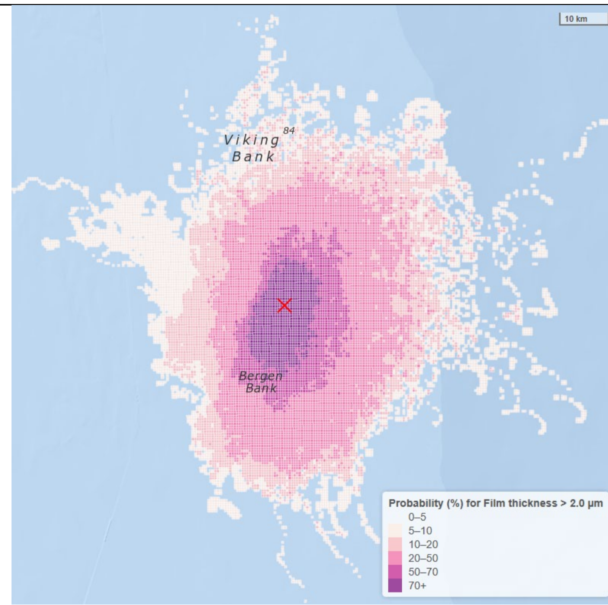
70 mm winter



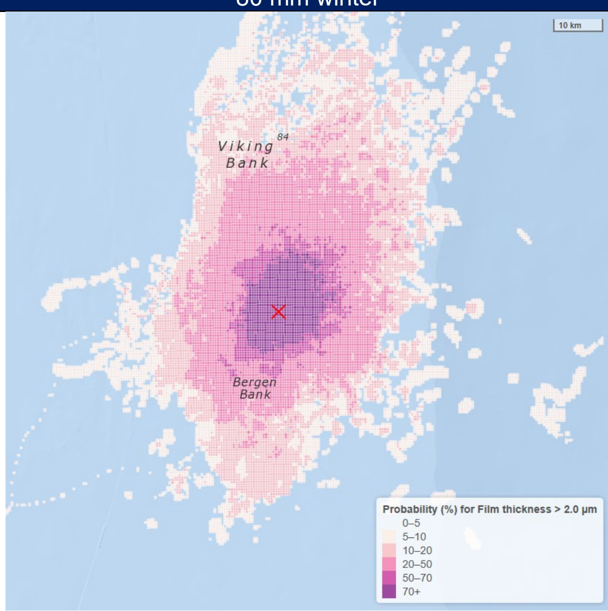
70 mm summer



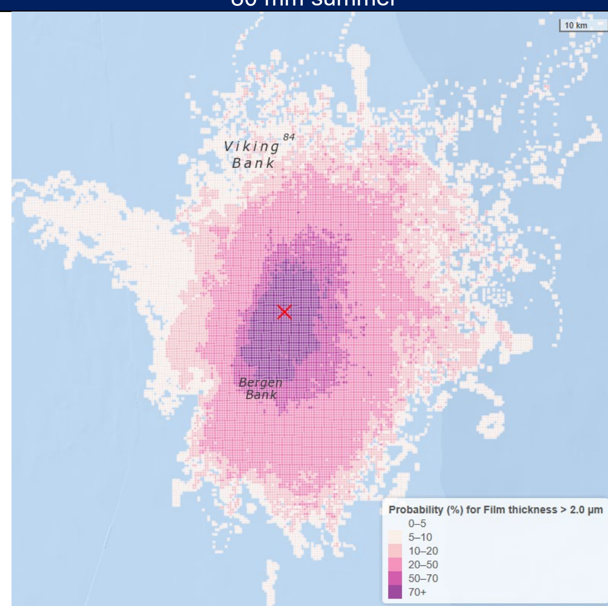
80 mm winter



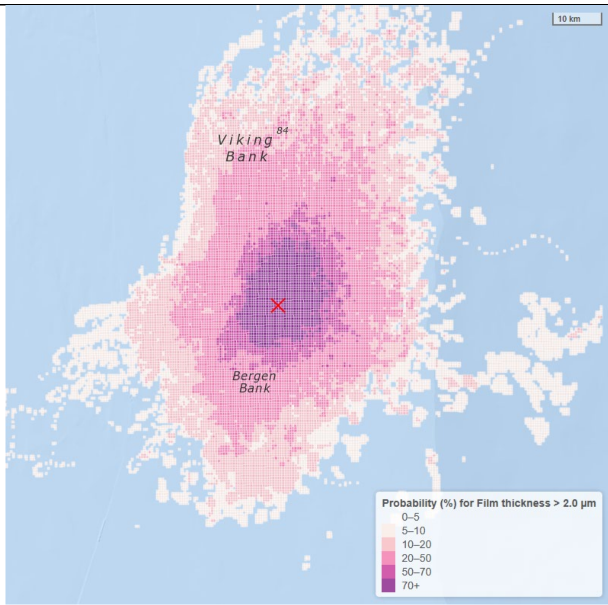
80 mm summer



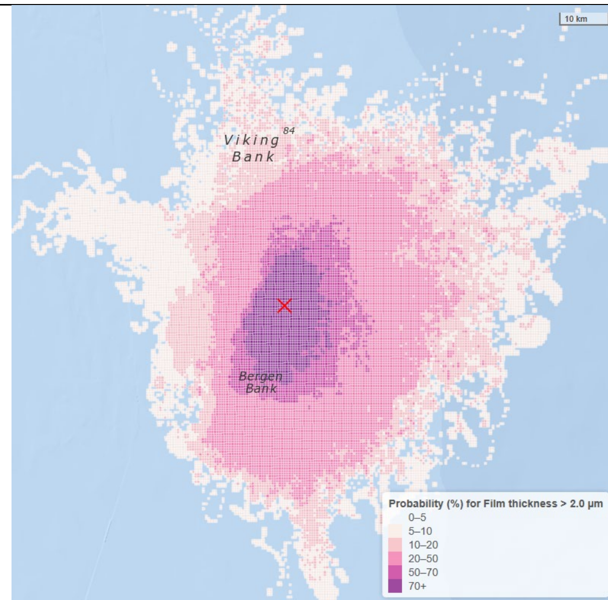
90 mm winter



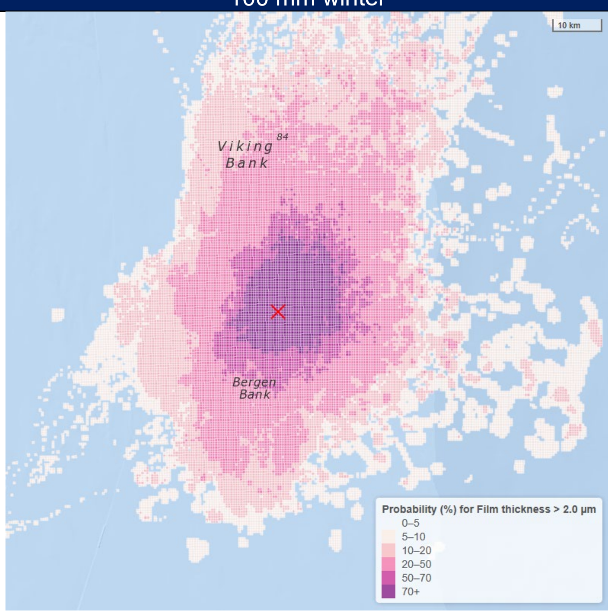
90 mm summer



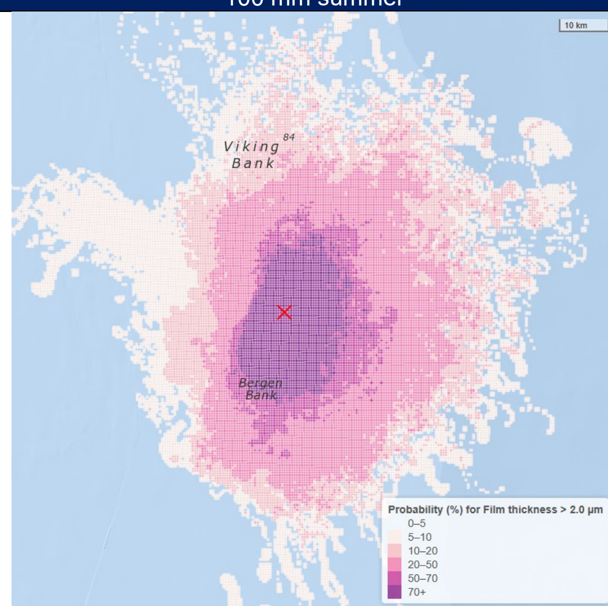
100 mm winter



100 mm summer



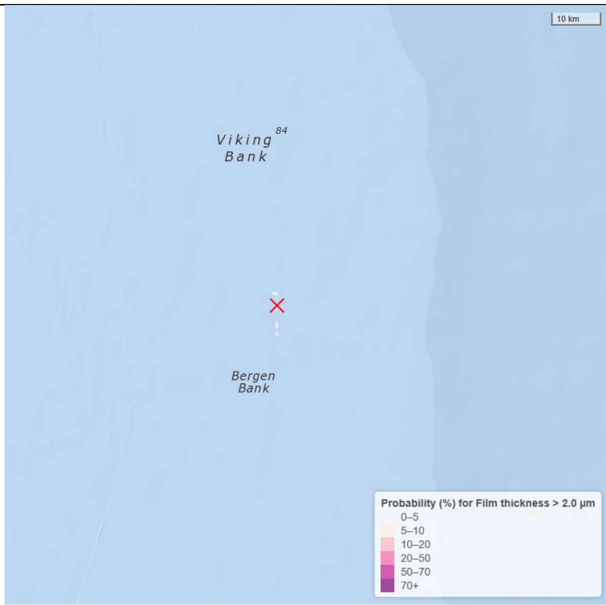
120 mm winter



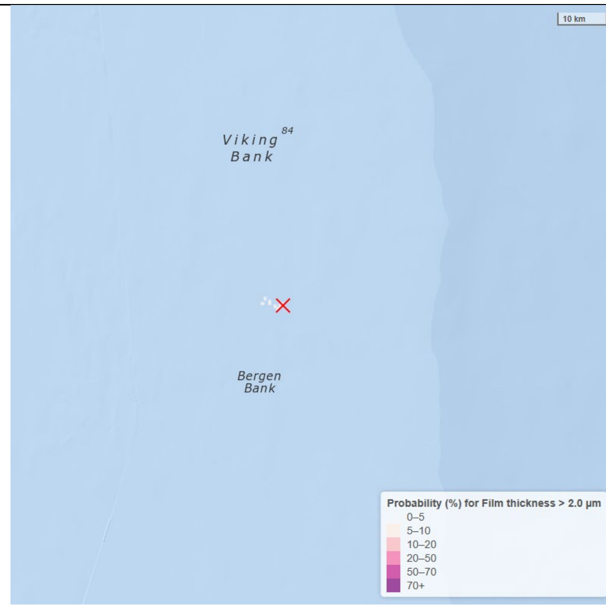
1200 mm summer

Figure 3-15. The 2.5 mm leak size will not form oil slicks above 2 µm at the sea surface and will not give any impact to seabirds. A 5 mm leak size will have a very small probability for such impact, while the remaining leak scenarios have a steady increase in the size of the effect area with leak size. The largest leak size (120 mm) will have an effect area stretching up to 20 km away from the leak location.

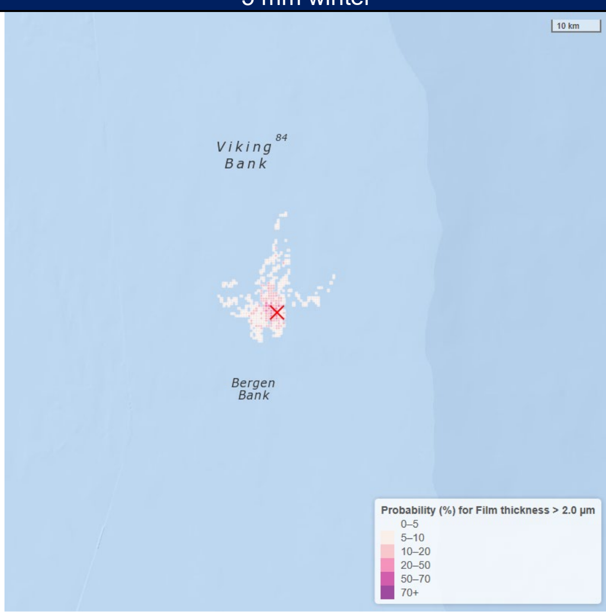
NA	NA
2.5 mm winter	2.5 mm summer



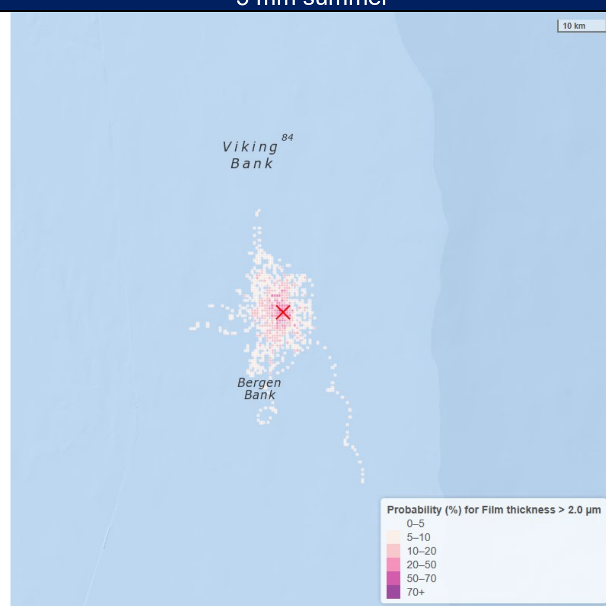
5 mm winter



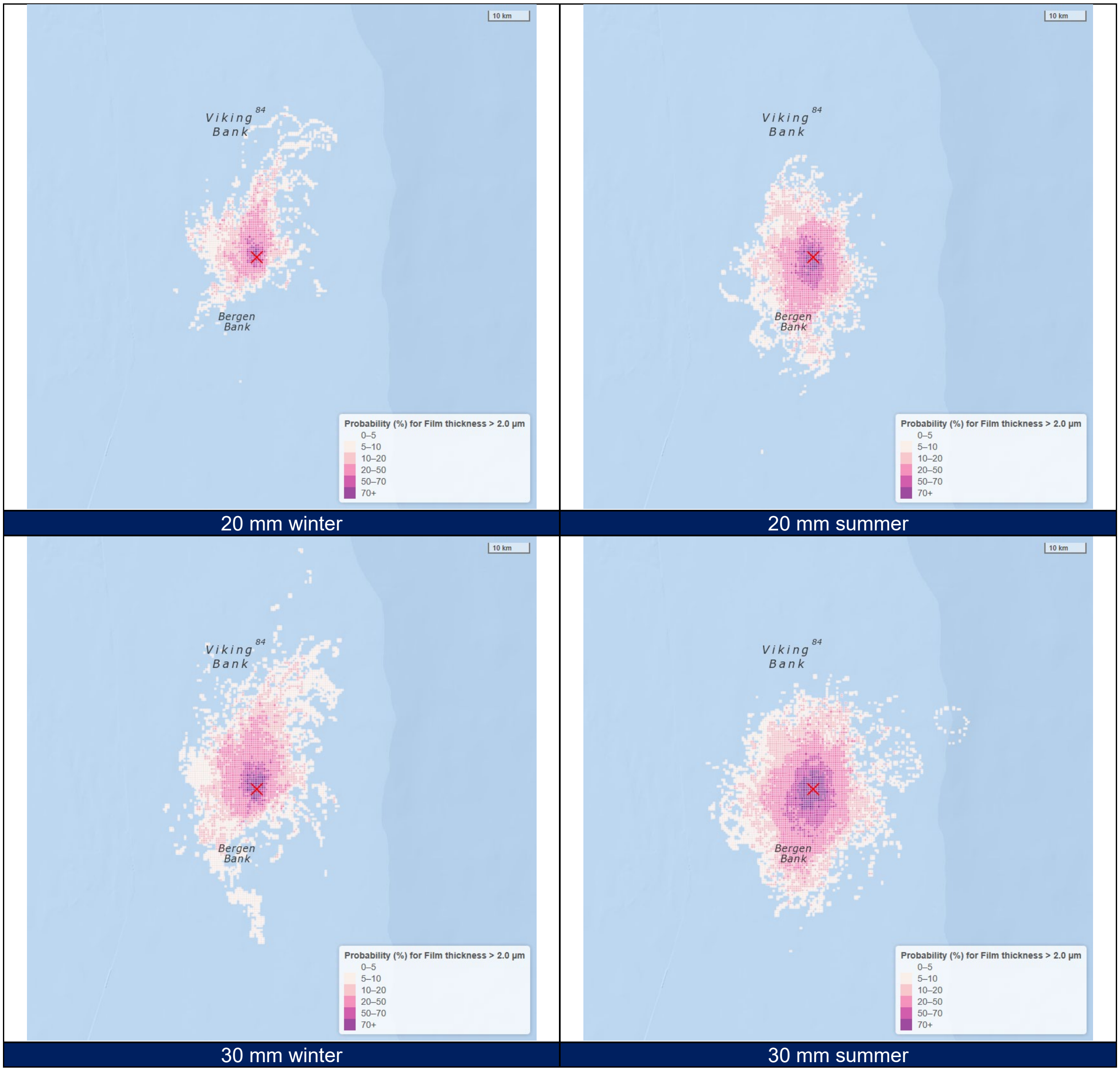
5 mm summer

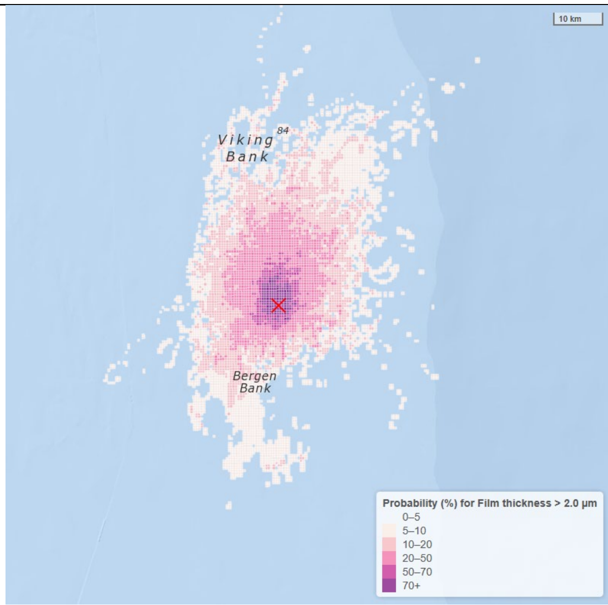


10 mm winter

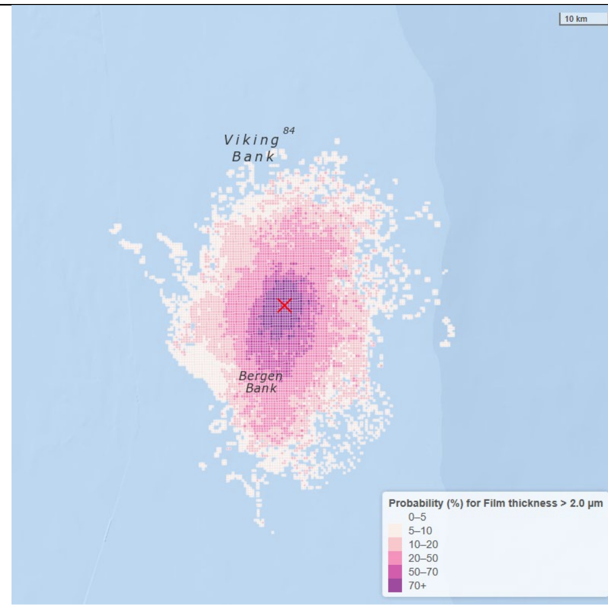


10 mm summer

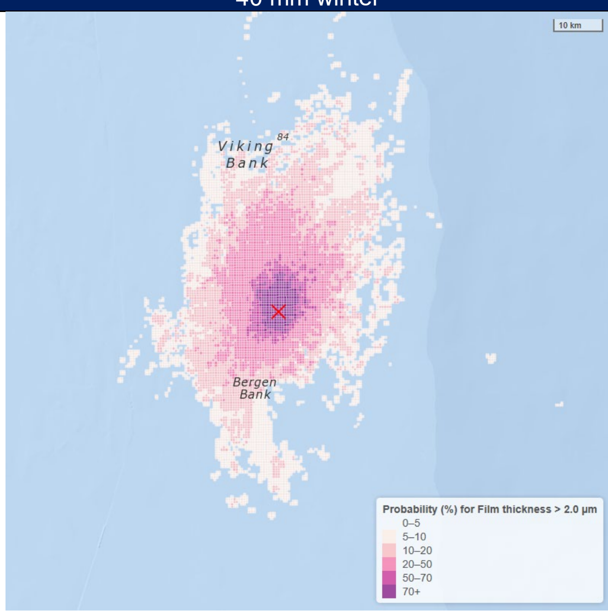

10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
20 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
20 mm summer
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
30 mm winter
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
30 mm summer



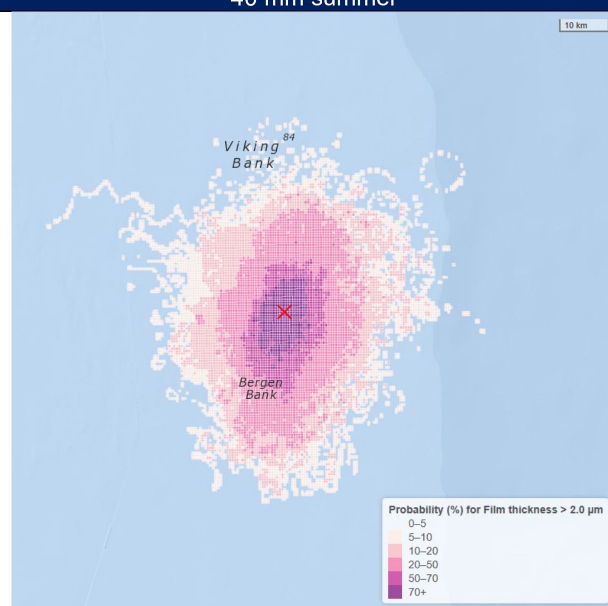
40 mm winter



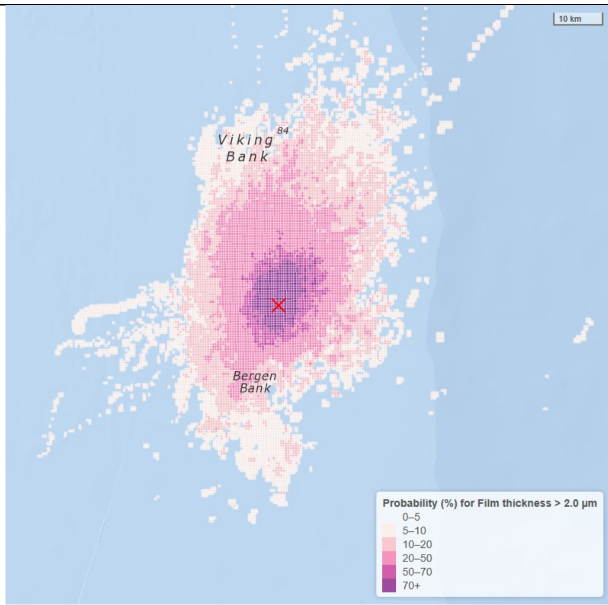
40 mm summer



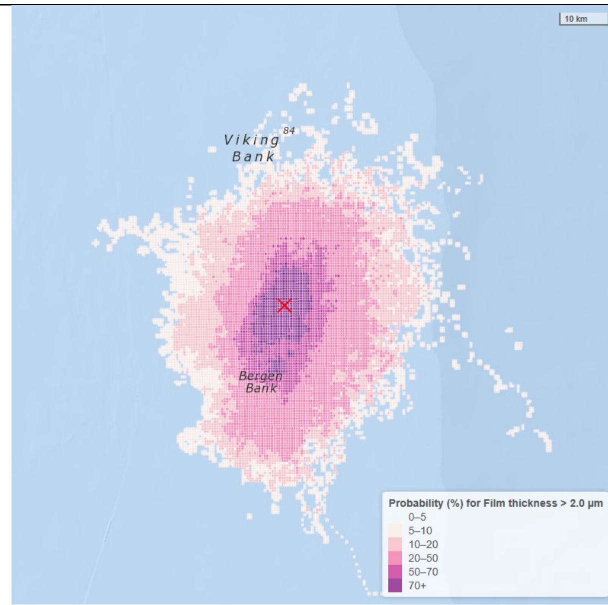
50 mm winter



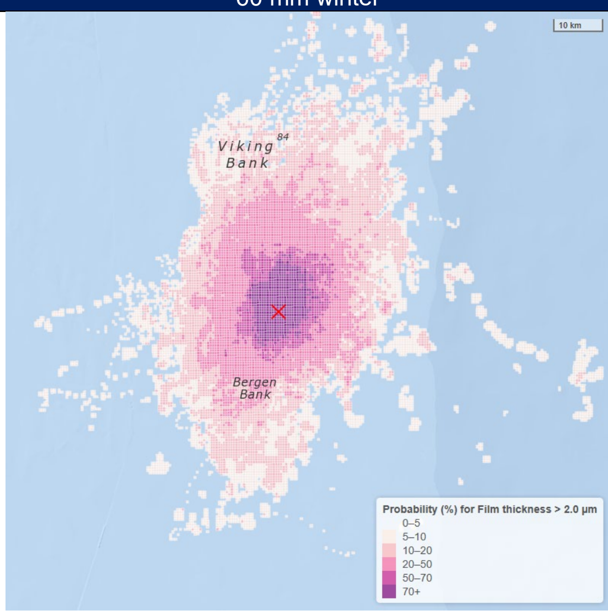
50 mm summer



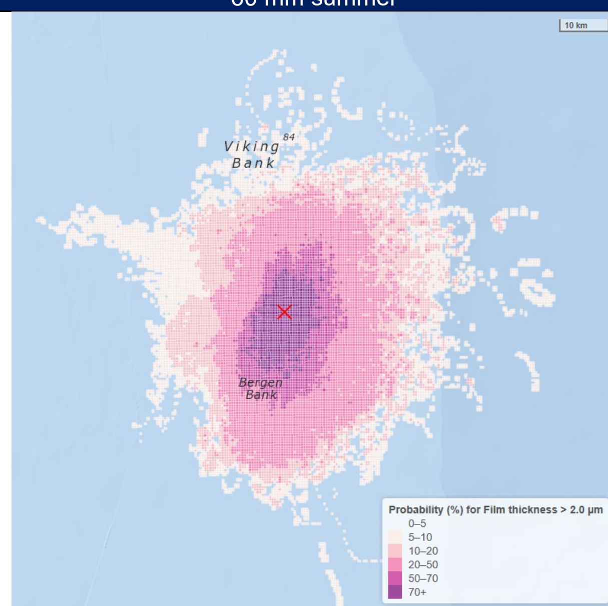
60 mm winter



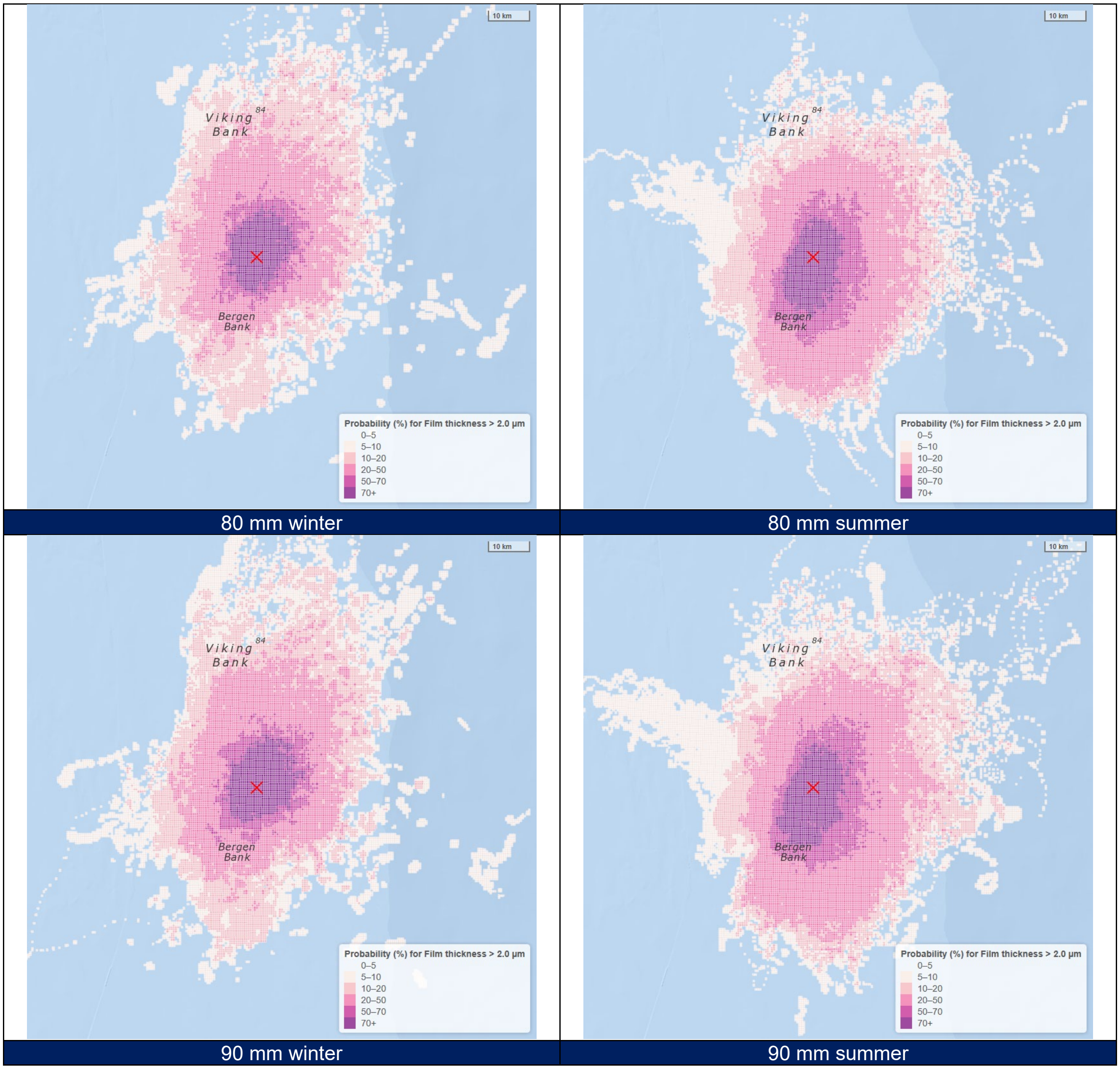
60 mm summer



70 mm winter



70 mm summer


Viking Bank
84
Bergen Bank
10 km
Probability (%) for Film thickness > 2.0 µm
0–5
5–10
10–20
20–50
50–70
70+
80 mm winter
80 mm summer
90 mm winter
90 mm summer

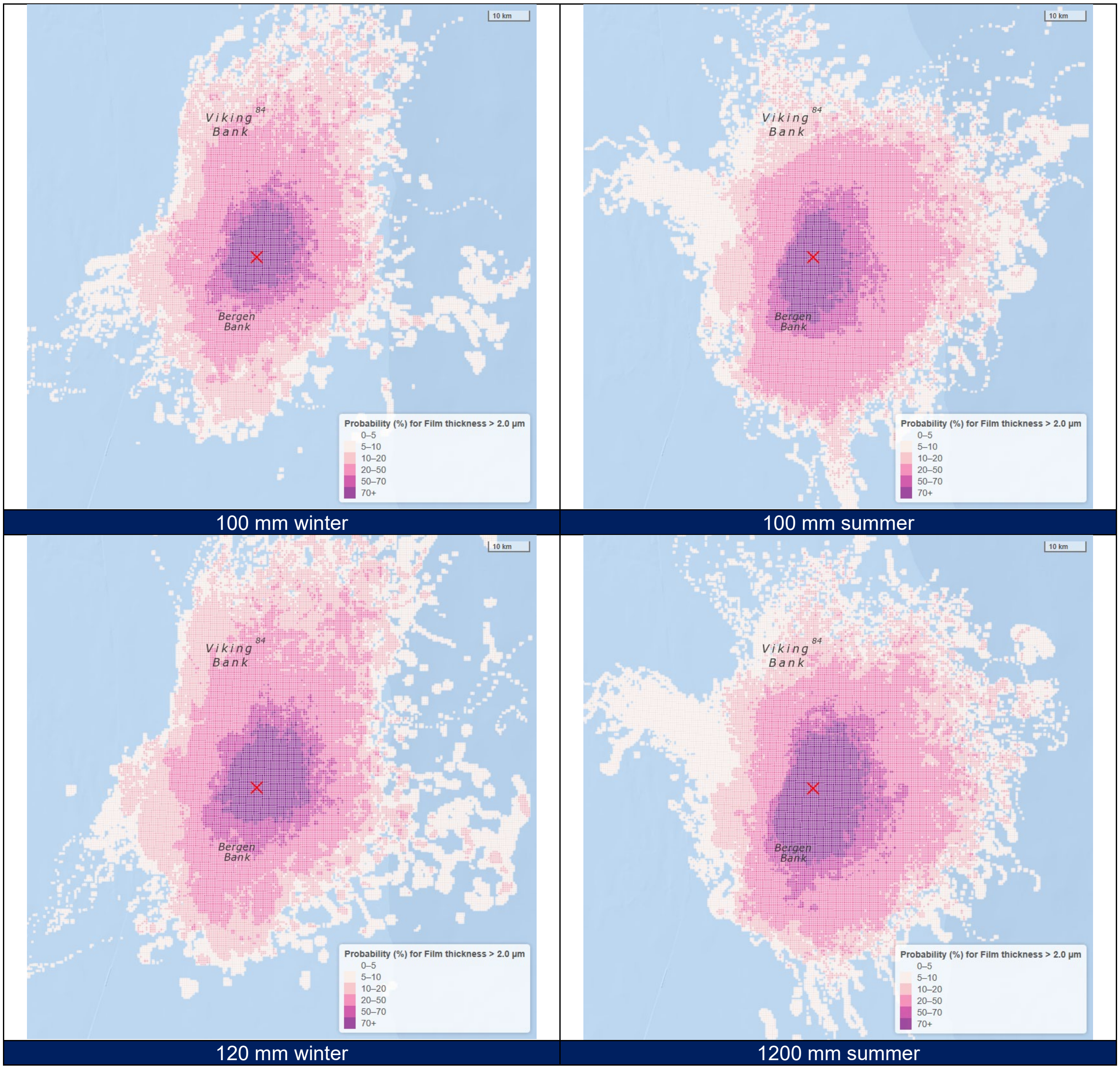
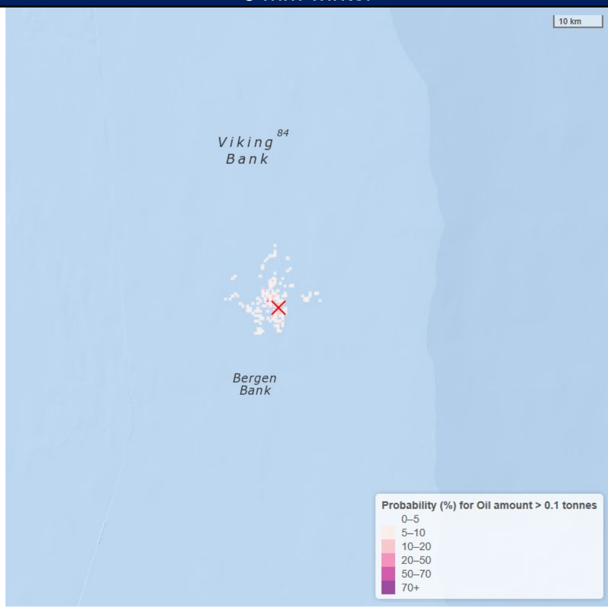
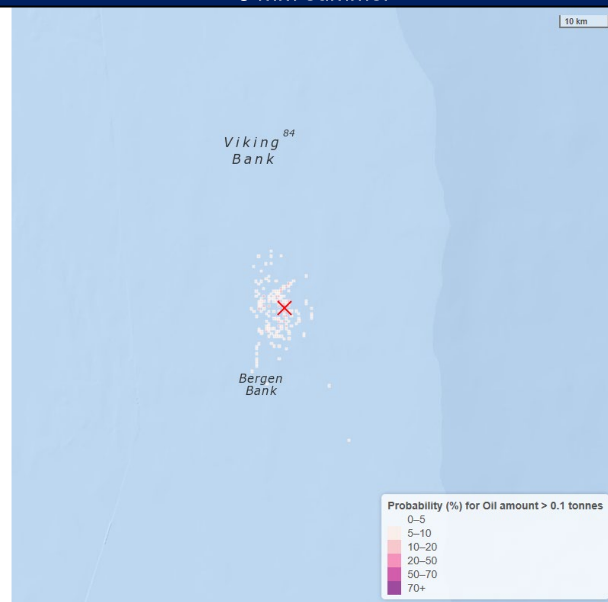
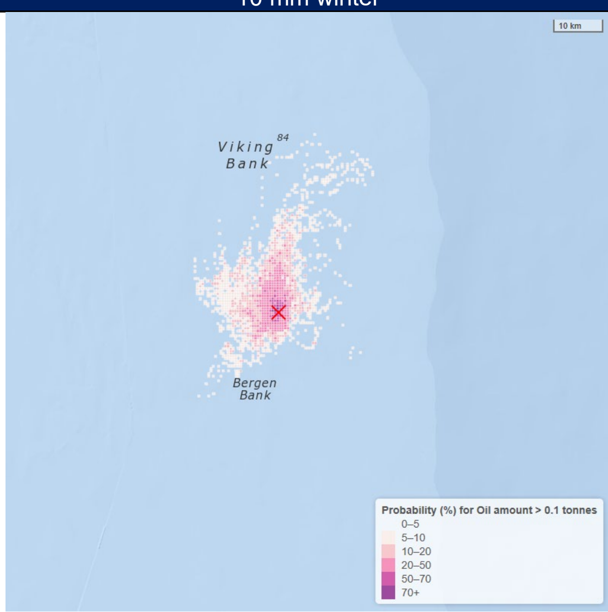
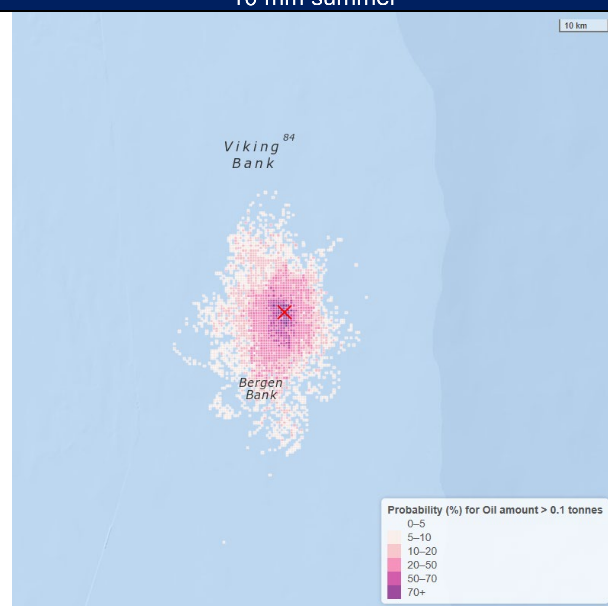
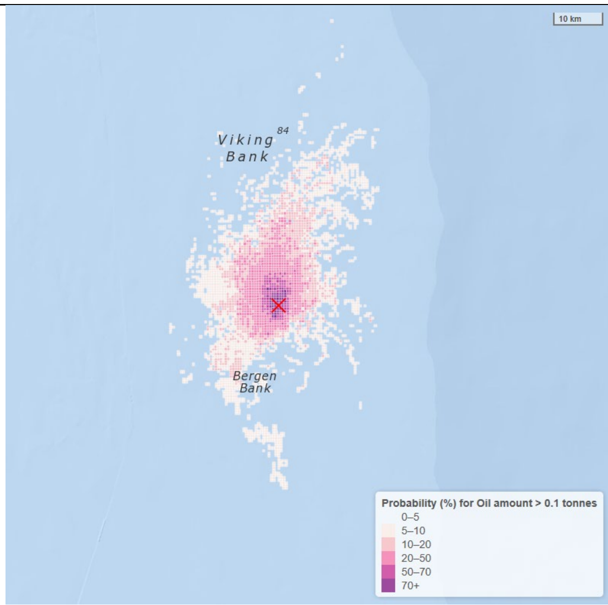


Figure 3-15 *Probability for film thickness above 2 µm from leak scenarios at Askja PL (midway SPS – UPP) with different leak sizes. Spill duration 7 days.*

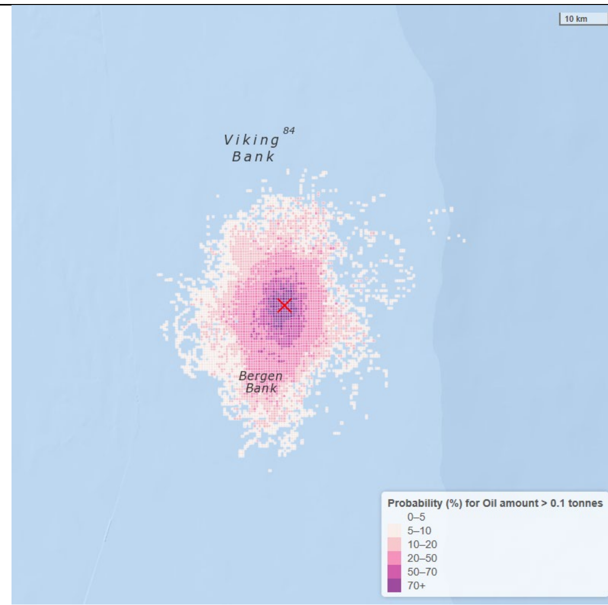
3.5.4 Surface detection

Probability for surface detection from satellite is related to the minimum detection threshold defined as 0.1 tons per 500x500 meter grid cell (0.25 km^2). The smallest leak sizes (2.5 and 5 mm) will not reach this threshold and will not be detected by satellite. Leaks from hole sizes 10 and 20 mm have a slightly higher detectability, while the remaining leak sizes (30 – 120 mm) are all likely to be detected by SAR (Figure 3-16).

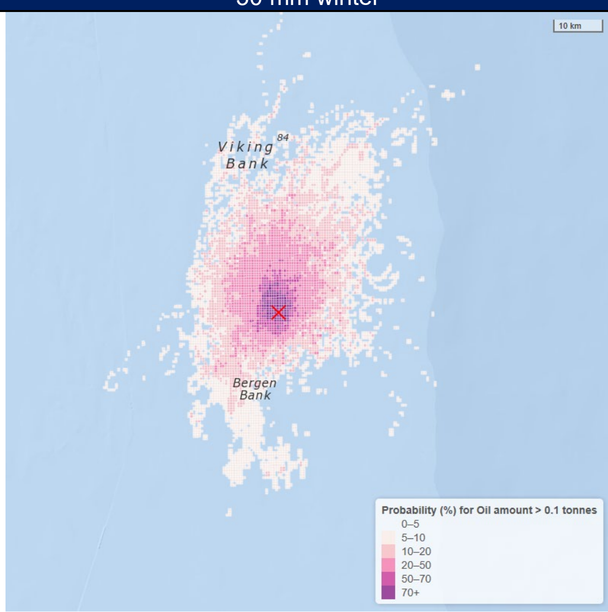
<table>
<tr><td>NA</td><td>NA</td></tr>
<tr><td>2.5 mm winter</td><td>2.5 mm summer</td></tr>
<tr><td>NA</td><td>NA</td></tr>
<tr><td>5 mm winter</td><td>5 mm summer</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>10 mm winter</td><td>10 mm summer</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>20 mm winter</td><td>20 mm summer</td></tr>
</table>



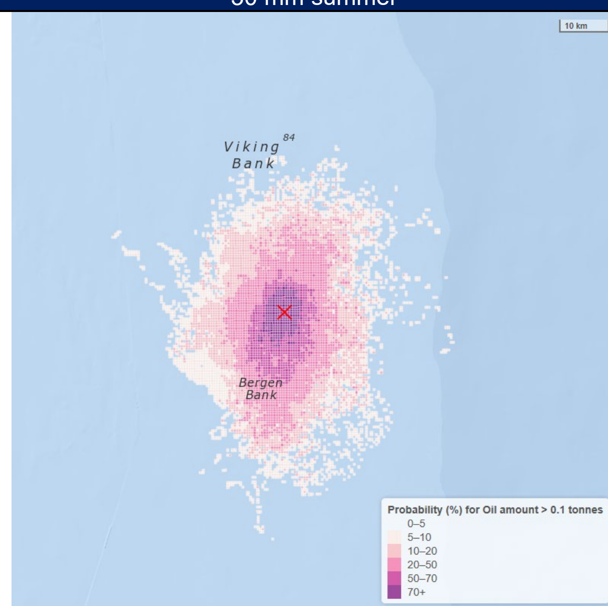
30 mm winter



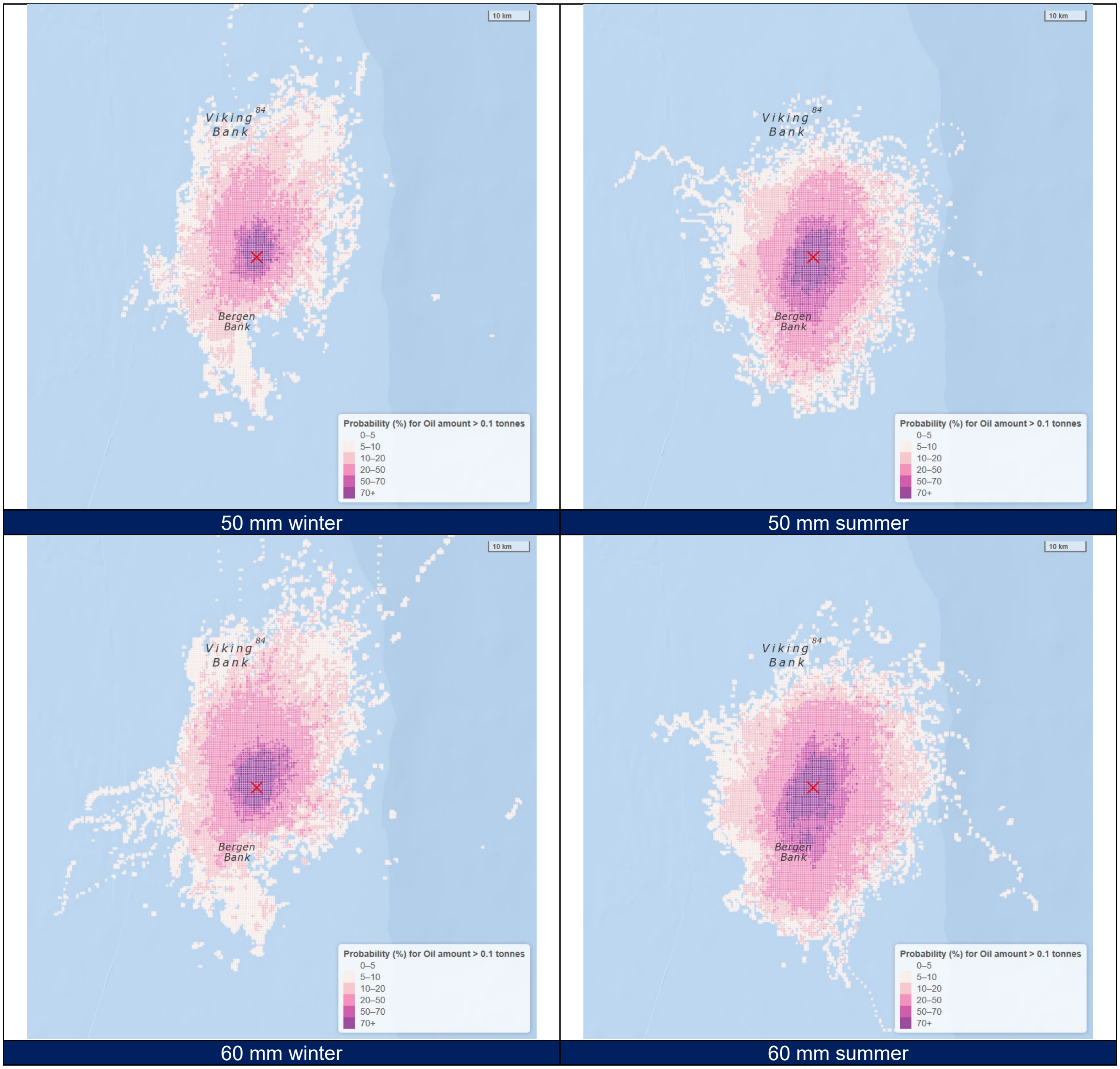
30 mm summer

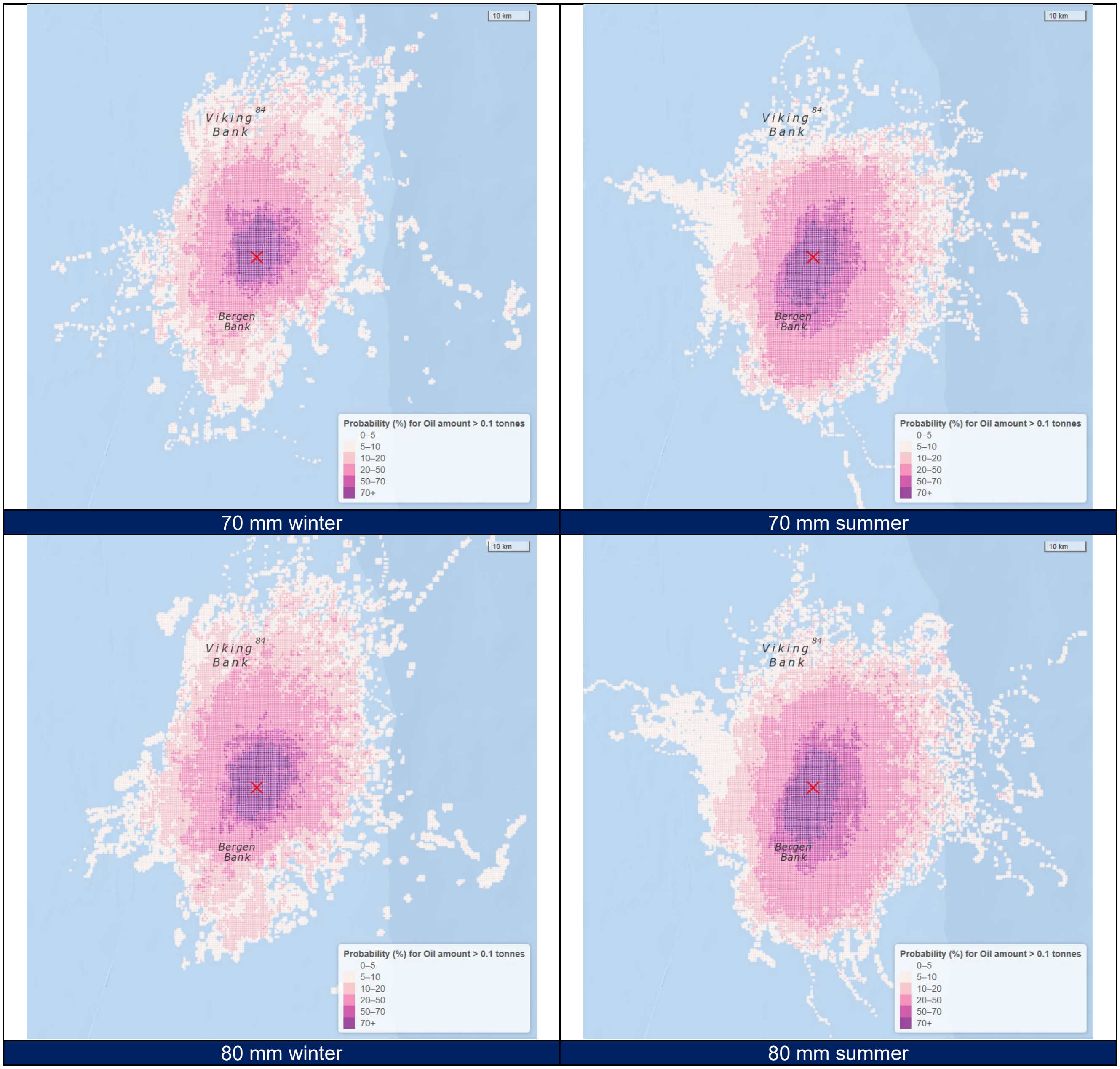


40 mm winter

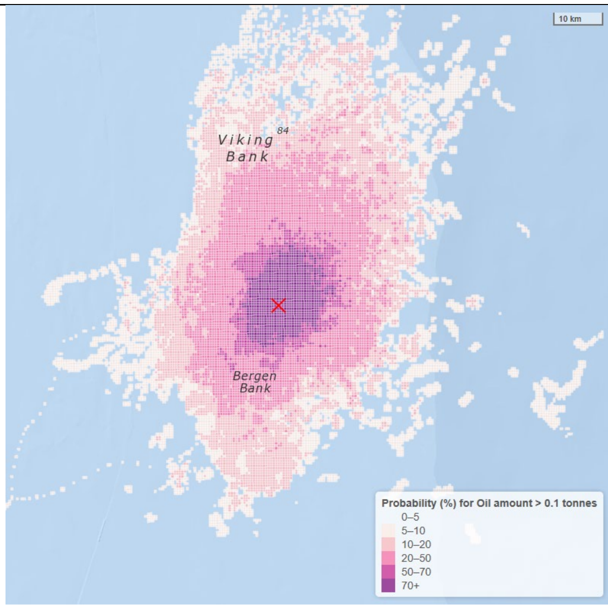


40 mm summer

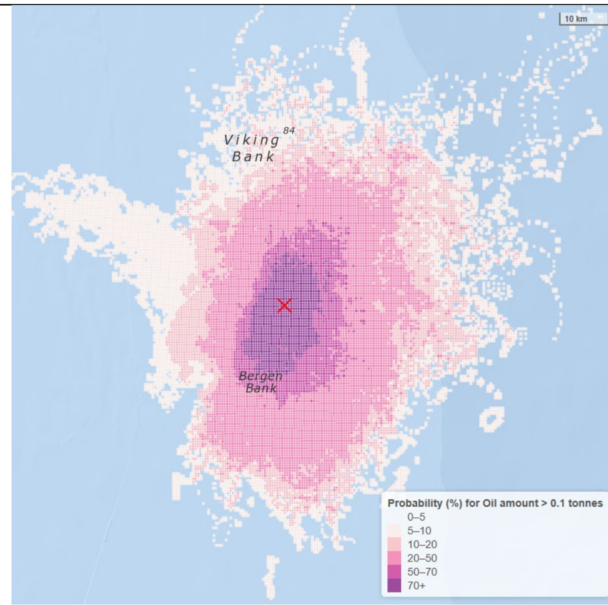

10 km
Viking Bank
84
Bergen Bank
Probability (%) for Oil amount > 0.1 tonnes
0–5
5–10
10–20
20–50
50–70
70+
50 mm winter
50 mm summer
60 mm winter
60 mm summer



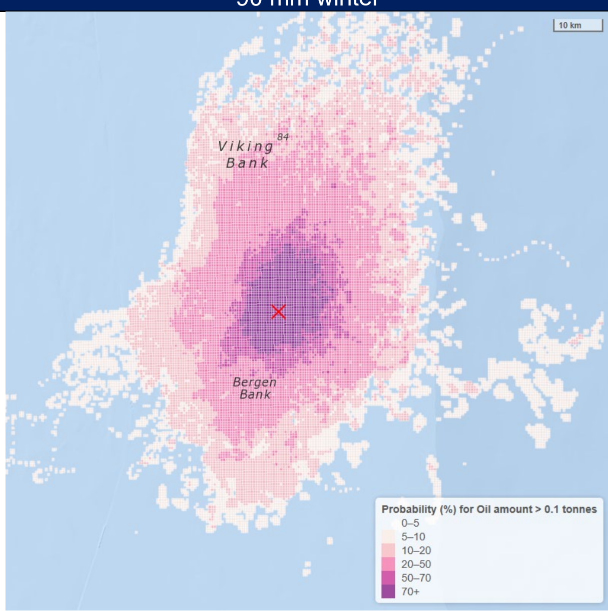
10 km
Viking Bank
84
Bergen Bank
Probability (%) for Oil amount > 0.1 tonnes
0–5
5–10
10–20
20–50
50–70
70+
70 mm winter
70 mm summer
80 mm winter
80 mm summer



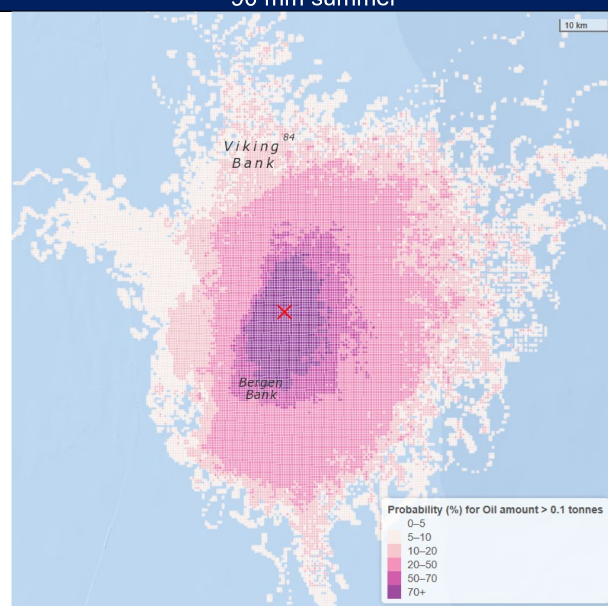
90 mm winter



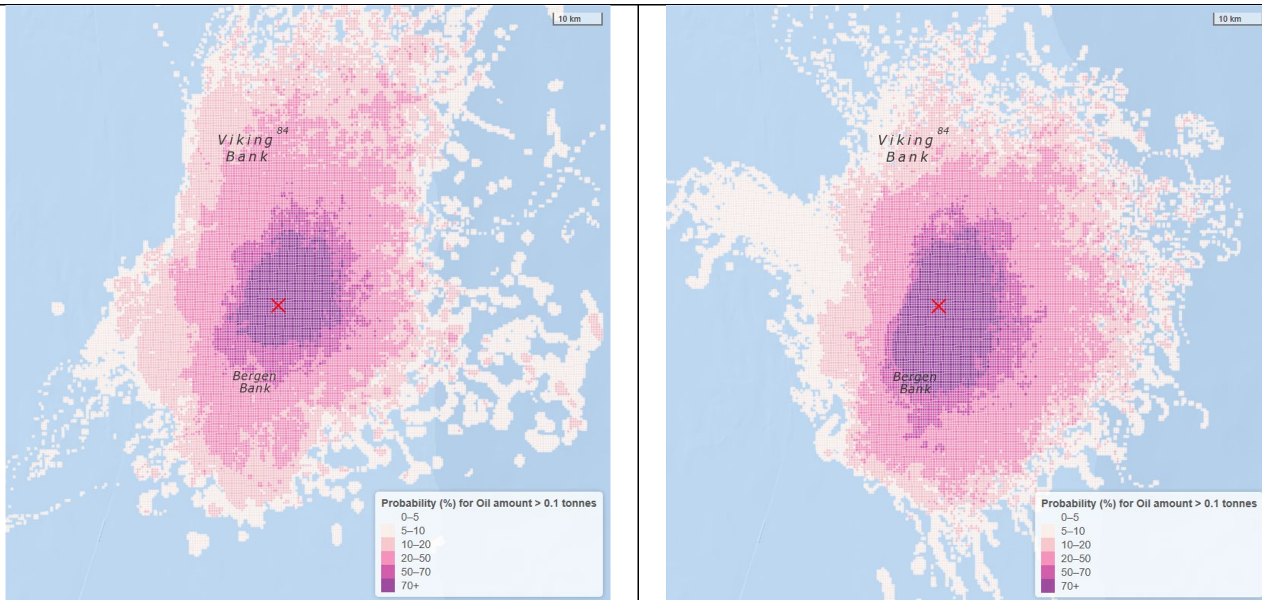
90 mm summer



100 mm winter



100 mm summer



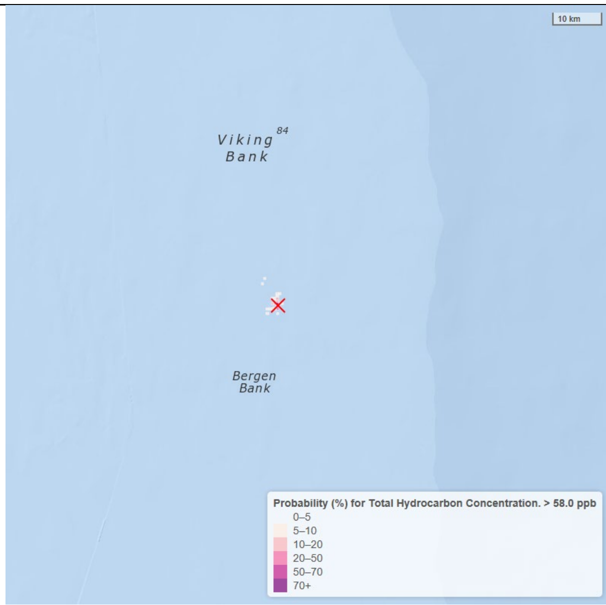
120 mm winter	1200 mm summer

Figure 3-16 *Probability for surface oil volumes above SAR detection limit (0,1 t per 0.25 km^2) from leak scenarios at Askja PL (midway SPS – UPP) with different leak sizes. Spill duration 7 days.*

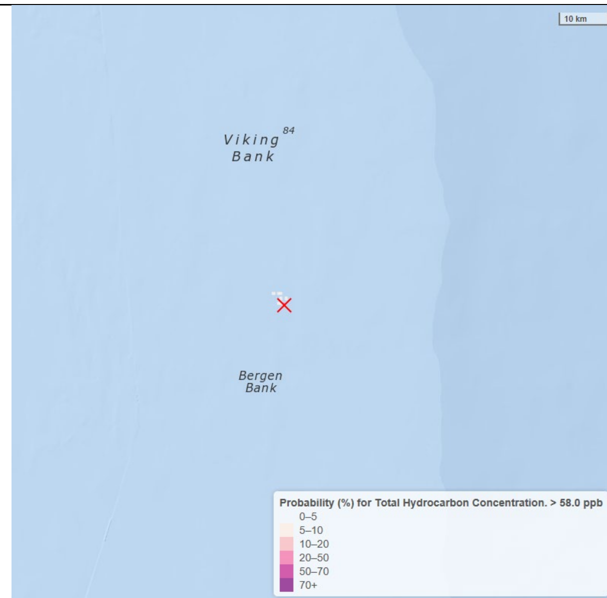
3.5.5 Water column impact

Probability for THC above the effect threshold of 58 ppb in the water column is shown in Figure 3-17 for leakages at Askja PL (midway SPS – UPP). The 2.5- and 5-mm leak size will most likely not reach the 58 ppb THC threshold, but for the remaining leakages there is a steady increase in the probability and size of the effect area with leak size. The 120 mm leak size will have an effect area stretching 10-30 km away from the leak location.

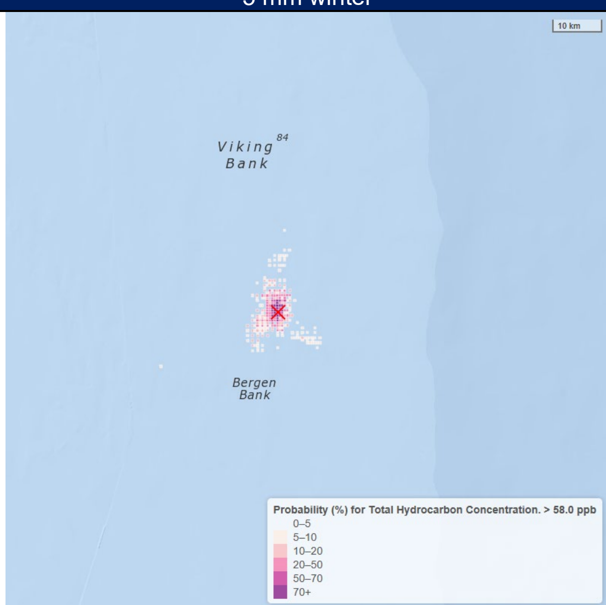
NA	NA
2.5 mm winter	2.5 mm summer



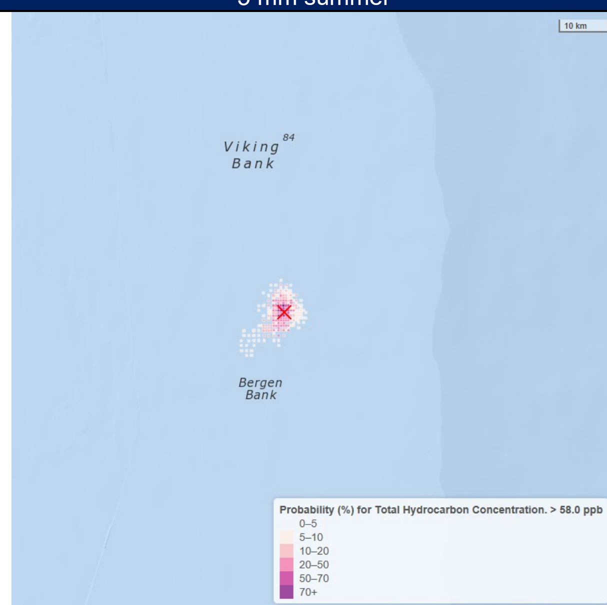
5 mm winter



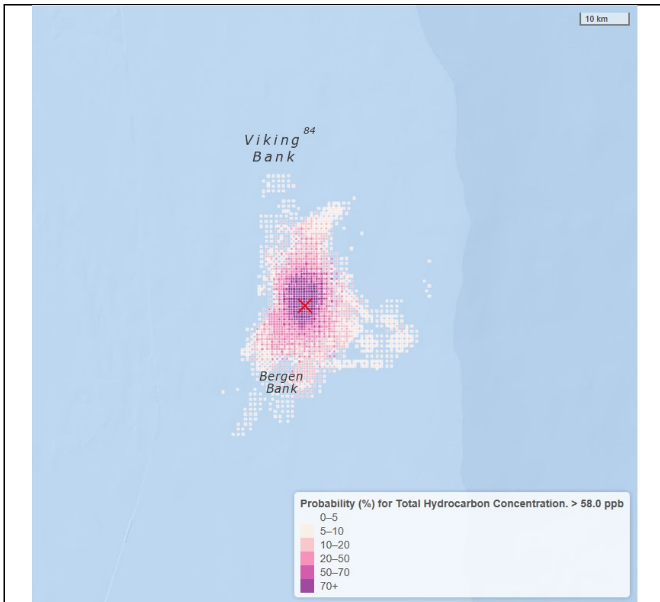
5 mm summer



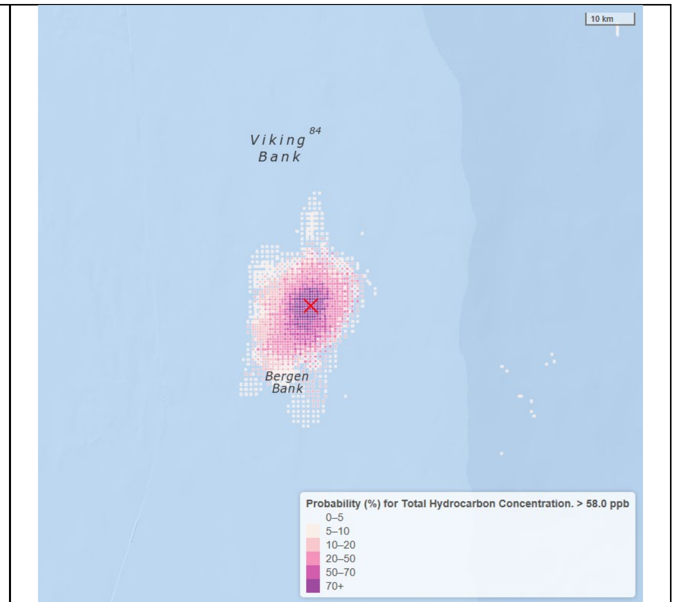
10 mm winter



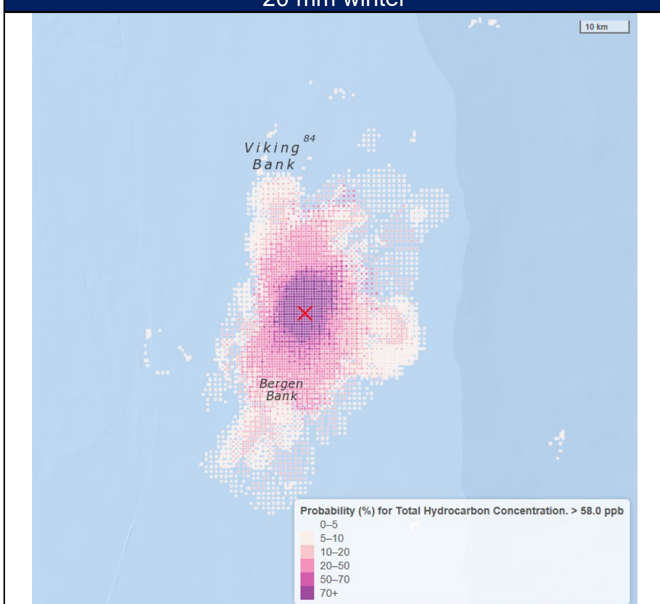
10 mm summer



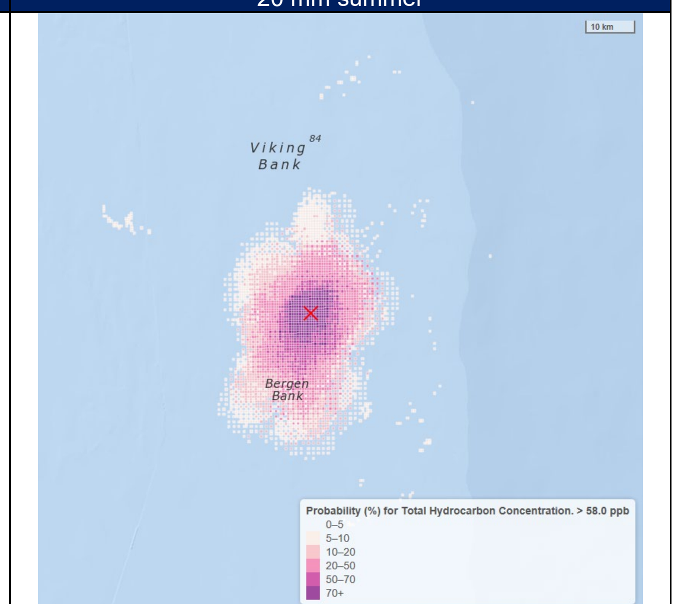
20 mm winter



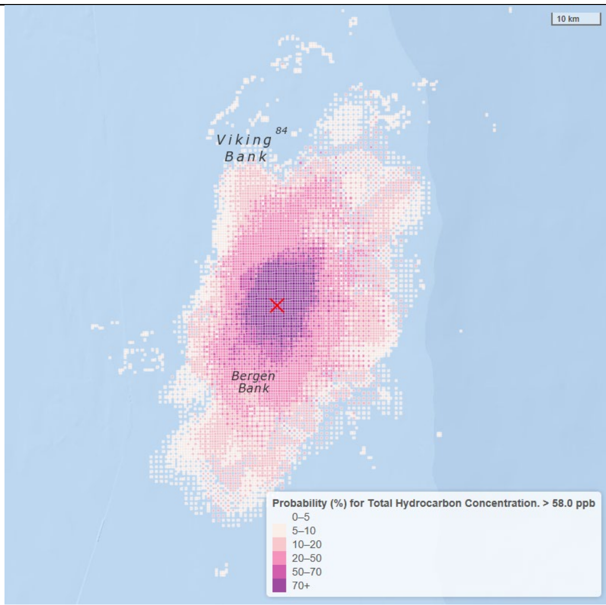
20 mm summer



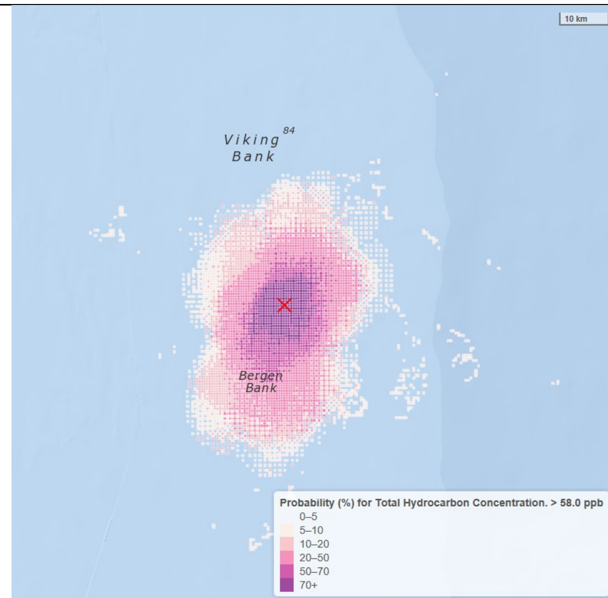
30 mm winter



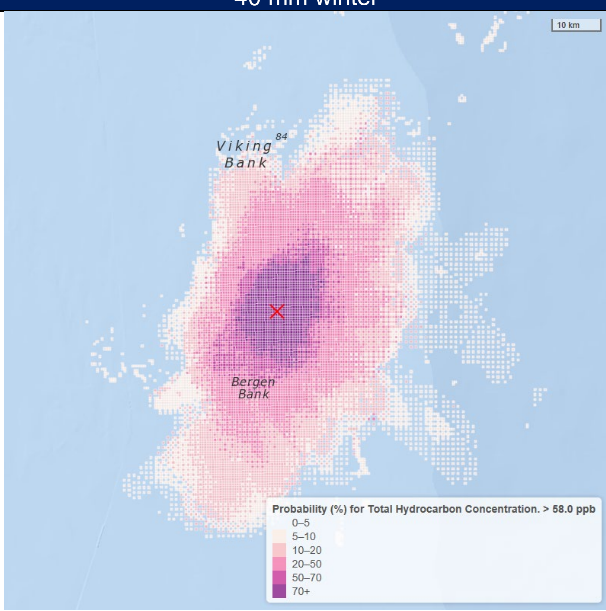
30 mm summer



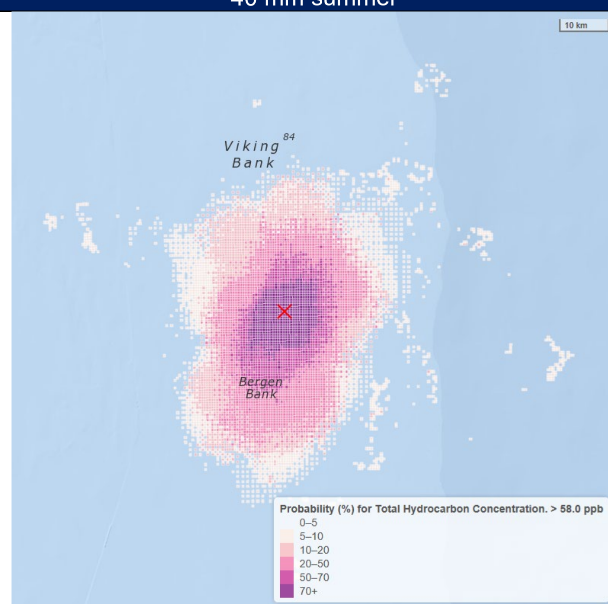
40 mm winter



40 mm summer

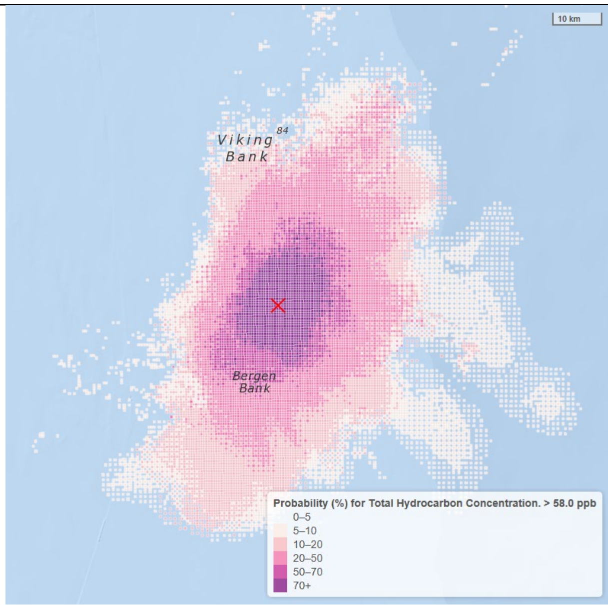


50 mm winter

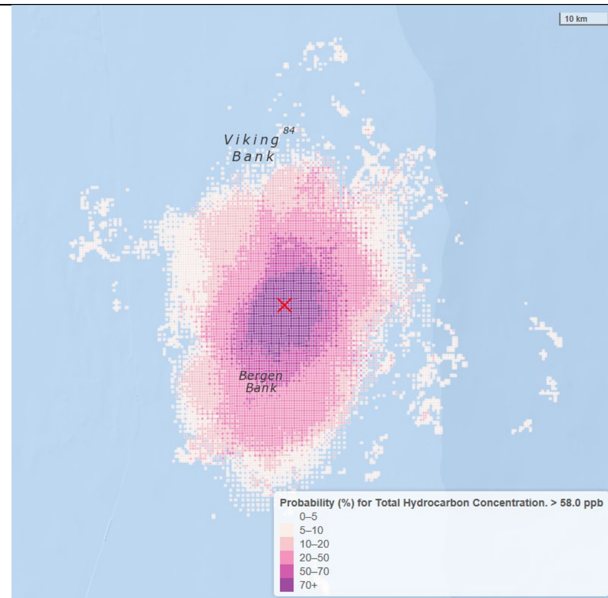


50 mm summer

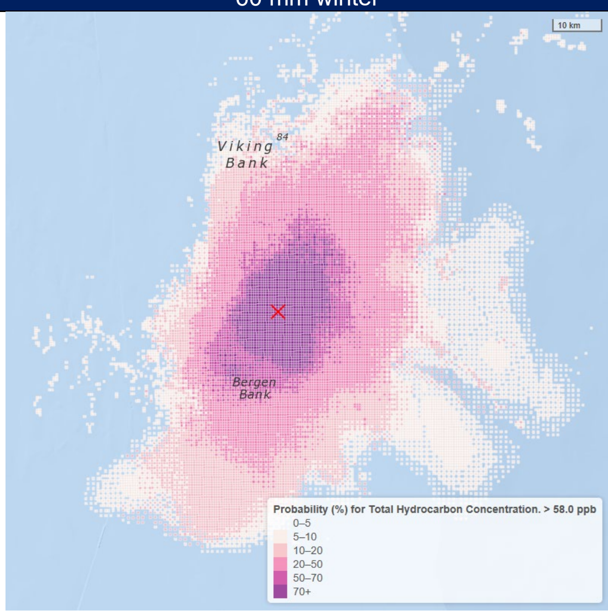
DNV



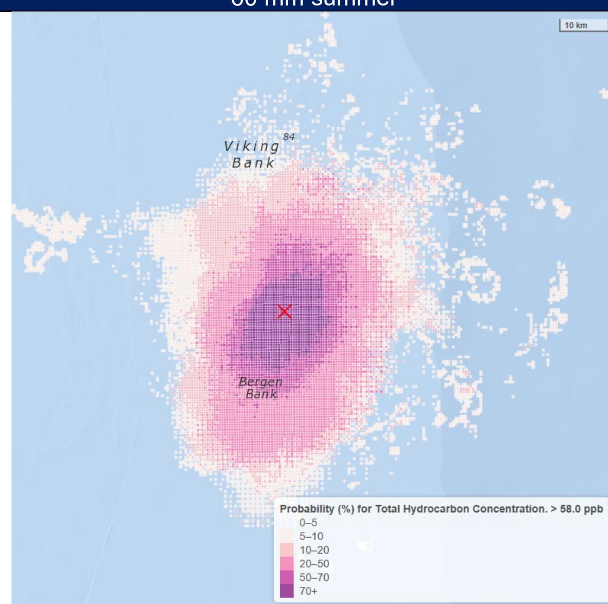
60 mm winter



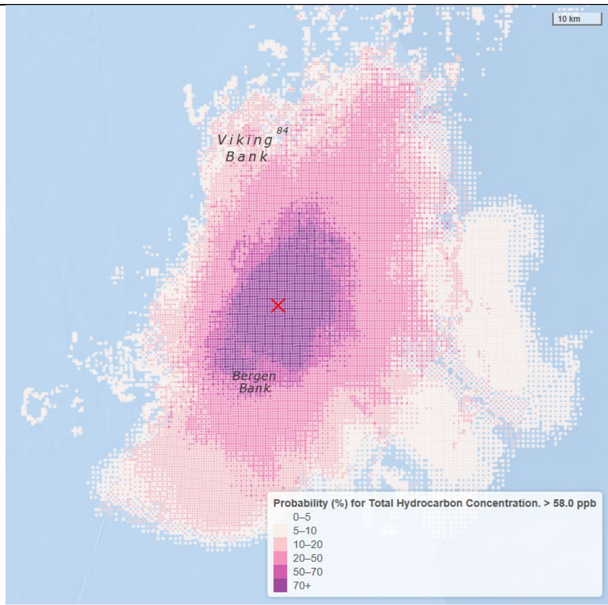
60 mm summer



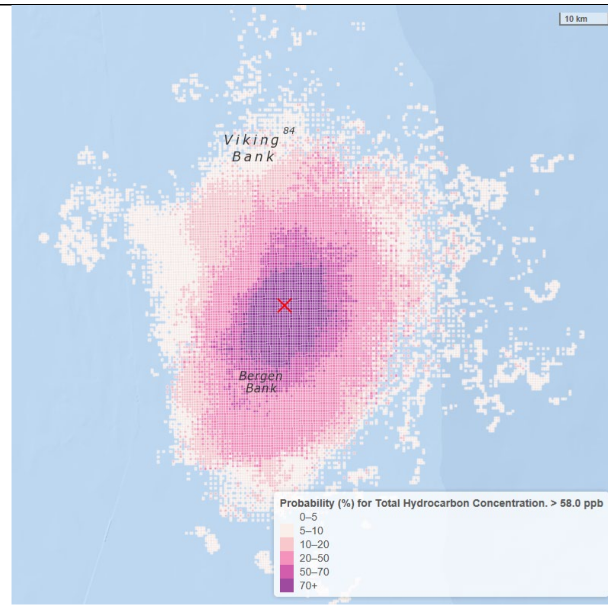
70 mm winter



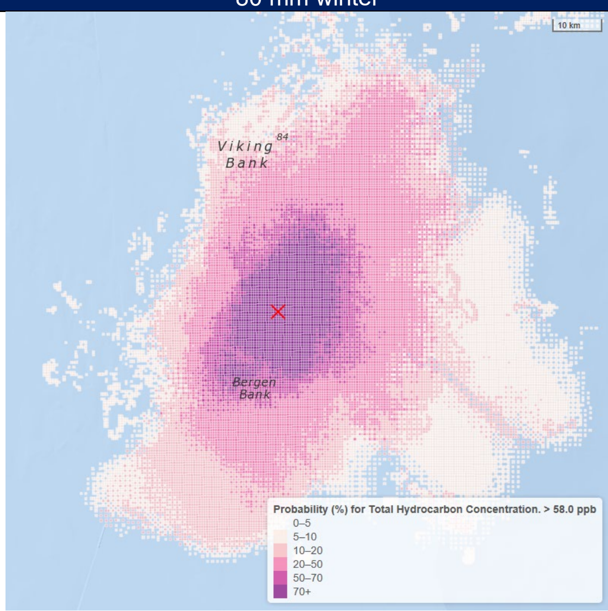
70 mm summer



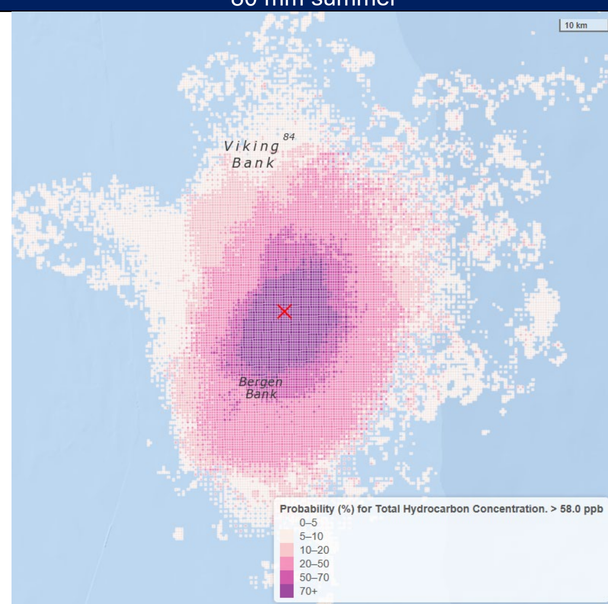
80 mm winter



80 mm summer



90 mm winter



90 mm summer

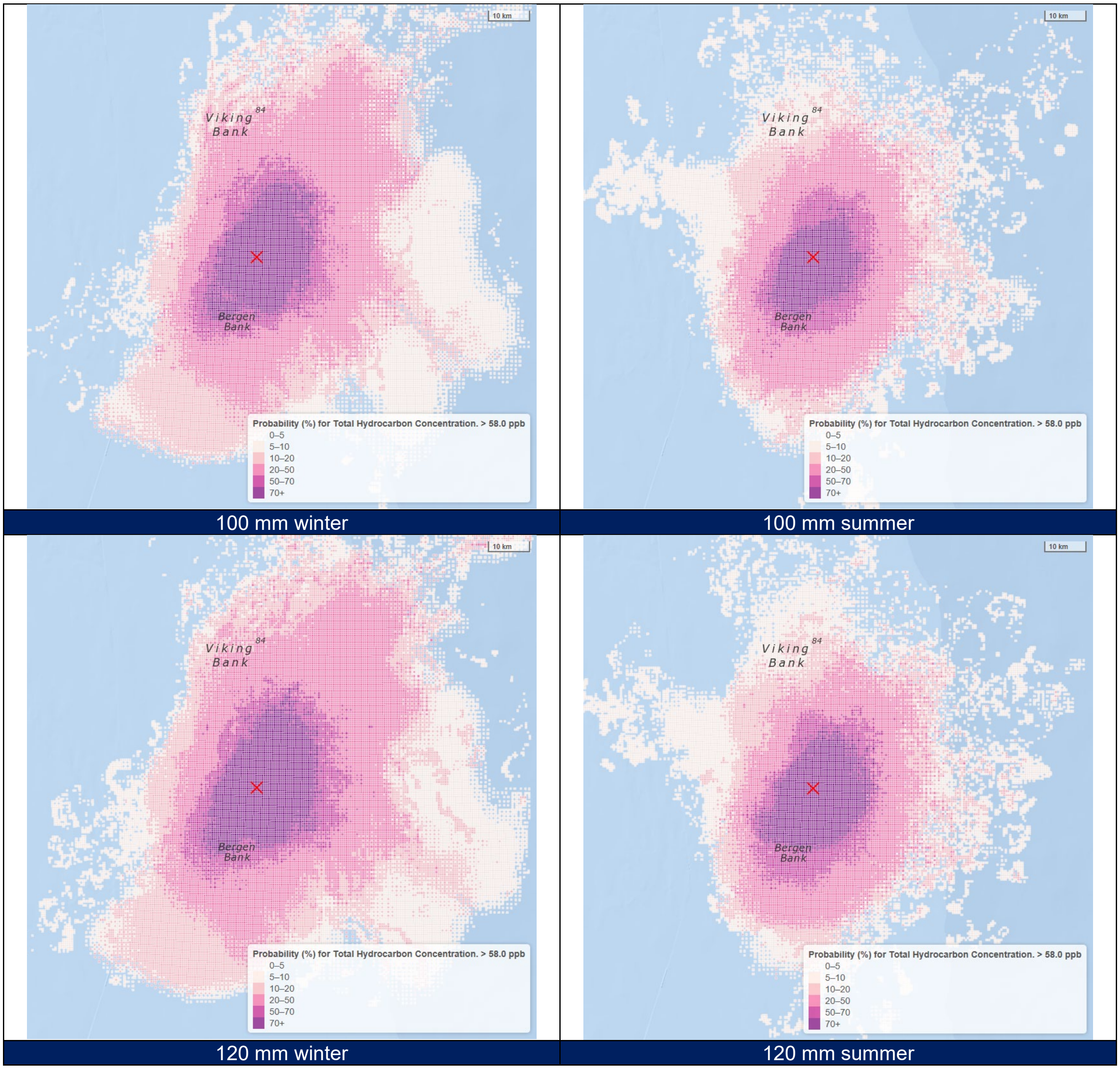


Figure 3-17 *Probability for THC above 58 ppb in upper 50 meters of water column from leak scenarios at Askja PL (midway SPS – UPP) with different leak sizes. Spill duration 7 days.*

4 RISK EVALUATION OF LEAK SCENARIOS

Based on the results presented in Chapter 3, a grouping of the results has been made to evaluate whether each leak scenario can have effects in the water column or on the sea surface and what possibilities there are for surface detection (SAR satellite or OSD radar).

The criteria in Table 4-1 have been used for categorizing consequence in the water column for fish and on the sea surface for seabirds and marine mammals based on the extent of the effect area. The categories and the effect area categorisation are defined by DNV in their suggested environmental risk-based leak detection approach.

Table 4-1 *Categorisation of environmental consequence based on extent of effect area.*

Consequence category	Area (km^2)
Insignificant (1)	0
Minor (2)	1-100
Moderate (3)	100-500
Considerable (4)	500-1500
Serious (5)	1500-3000
Very Serious (6)	3000-6000
Cathastrophic (7)	>6000

4.1 Effect areas and possibilities for surface detection

The effect area on the sea surface is calculated from the stochastic runs (over 7 days of leakage time) and shows the accumulated area which gives mortality to seabirds in the area (auks that have been chosen as the representative species group). Impact calculation (mortality) is based on the ERA Acute methodology (NOROG, 2020).

A 2.5 mm or 5 mm leak size will not give a surface impact in any of the leak scenarios. The 10 mm leak size will have effect areas stretching from 2 to 24 km^2, and from the 30 mm leak size and up, almost all scenarios will exceed an effect area of 100 km^2. For the 120 mm leak size at the Askja production line, the impact area is substantially high at a 1571km^2 during summer, where mortalities could be as high as 90% in limited areas (Figure 4-1). Consequence assignment according to Table 4-1 is included in the figure.

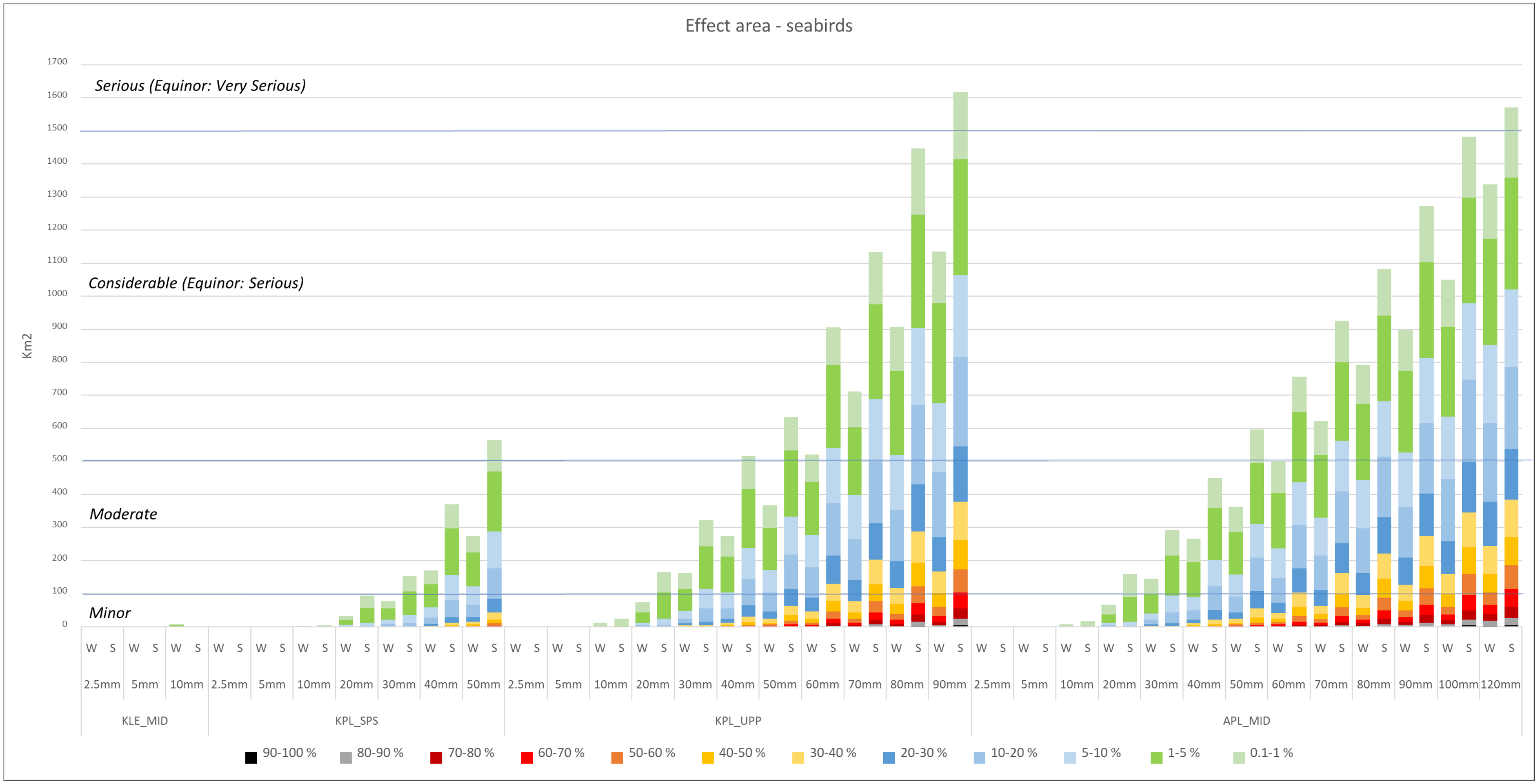


Figure 4-1 *Area on the sea surface (km²) with expected mortality for seabirds (auks) calculated for different leak scenarios based on 7 days leak duration. S = summer, W = winter. ERA Acute algorithms are used for mortality calculation. KLE_MID = Krafla Liquid Export line (midway UPP and PdQ), KPL_SPS = 16'' Krafla Production Line (Krafla SPS seabed), KPL_UPP = 16'' Krafla Production Line (UPP seabed), APL_MID = Askja Production Line (midway SPS – UPP).*

There is no probability for surface detection with SAR satellite or OSD radar on the smallest leak sizes (2.5 and 5 mm). A 10 mm leak has a very limited detection area (2-8 km^2), but probably sufficient to be detected over time from satellite (weeks more than days), and perhaps sooner with OSD radar with its continuous monitoring. The 20 mm leak size and above have a huge area available with surface oil above detection limit (from 29 to 1305 km^2) and could be rapidly detectable on the sea surface under normal conditions (Figure 4-2).

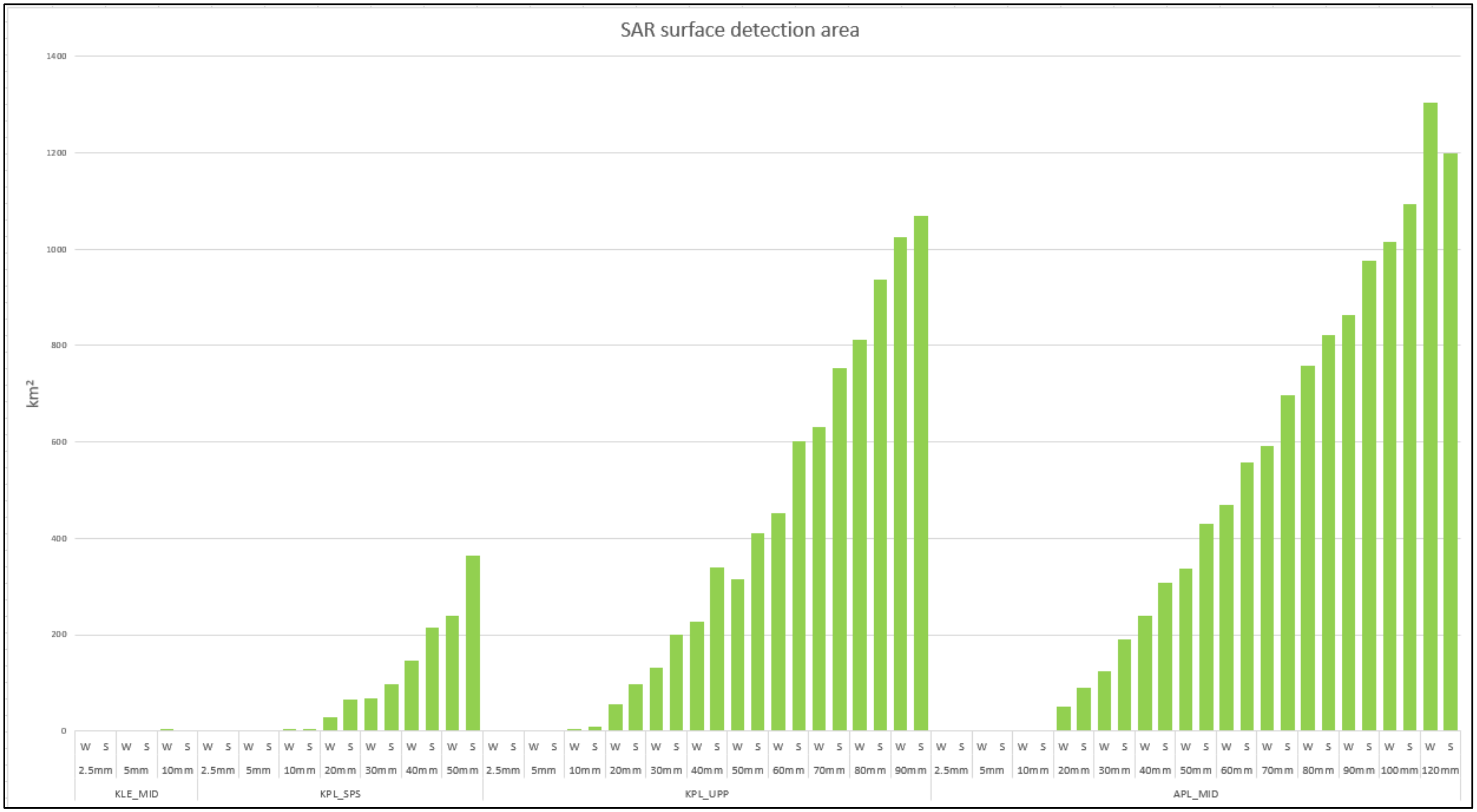


Figure 4-2 *Area on the sea surface (km^2) with potential for oil detection from SAR satellite (or OSD radar) calculated for different leak scenarios based on 7 days leak duration. S = summer, W = Winter. KLE_MID = Krafla Liquid Export line (midway UPP and PdQ), KPL_SPS = 16'' Krafla Production Line (Krafla SPS seabed), KPL_UPP = 16'' Krafla Production Line (UPP seabed), APL_MID = Askja Production Line (midway SPS – UPP)*

For water column, the effect area is summarized for concentrations in the upper 50 meters of the water column ranging from >58 ppb to >500 ppb (Figure 4-3). Concentrations exceeding the effect limit of 58 ppb THC can result in 5 % mortality of fish eggs and larvae (NOROG, 2020), while THC concentrations exceeding 300 and 500 ppb both represent high mortality (> 50%) of eggs and larvae. For all scenarios, the 30 mm leak size gives a substantial total effect area (from 129 to 1286 km^2).

A 2.5 mm leak size has a very limited effect area of maximum 3 km^2 across all scenarios, while a 5 mm leak has an effect area of up to 51 km^2 at the Krafla liquid export line (mid) (Figure 4-3). The 10 mm leak size has a moderate effect area at the Krafla liquid export line (mid) and the Krafla production line (SPS), but a smaller area for the two other scenarios (max 37km^2). For the larger leaks (20 mm-120 mm) the effect area increases significantly (max 1958 km^2), and there is also possibility for higher mortalities for fish eggs and larvae as the THC could exceed both 300 and 500 ppb. Consequence assignment according to Table 4-1 is included in Figure 4-3.

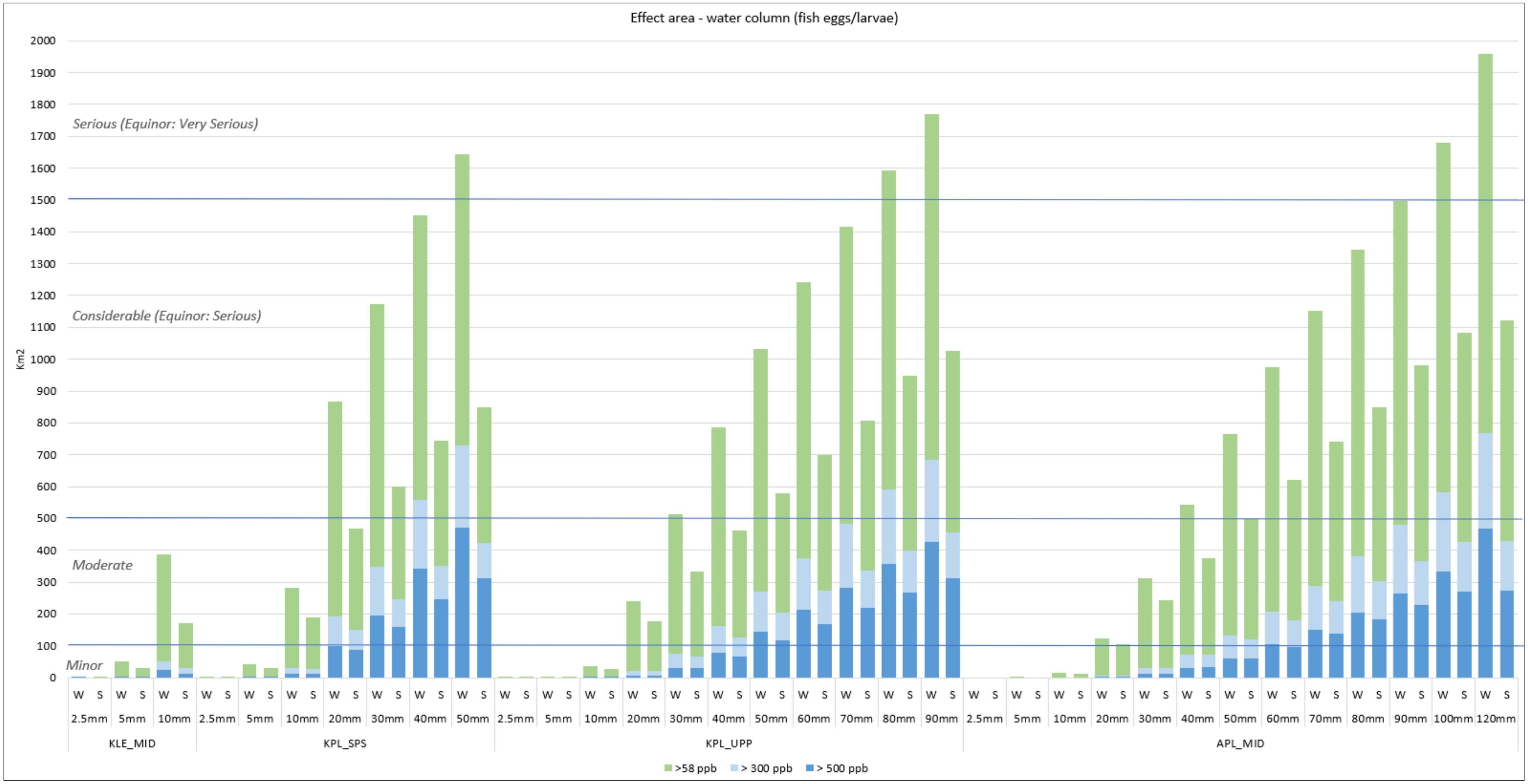


Figure 4-3 *Area (in km²) above effect threshold for acute effects on fish eggs and larvae in upper 50 meters of the water column calculated for different leak scenarios based on 7 days leak duration. S = summer, W = winter. KLE_MID = Krafla Liquid Export line (midway UPP and PdQ), KPL_SPS = 16'' Krafla Production Line (Krafla SPS seabed), KPL_UPP = 16'' Krafla Production Line (UPP seabed), APL_MID = Askja Production Line (midway SPS – UPP).*

4.1.1 Sensitivity scenarios

To see the effect of leakage duration on model results, some sensitivity cases were run on Krafla SPS. The 5-, 10- and 20-mm leak size were selected and run for 30 days to compare with the 7 days simulations. In addition, a sensitivity was run with 10 ppb THC as threshold level for effects on fish eggs/larvae.

The 5 mm scenario (7 days duration) had no impact area on the sea surface and no detection area for SAR satellite / OSD radar (Figure 4-1 and Figure 4-2). With 30 days leak duration, there is still no impact area or surface detection area (Figure 4-4). This indicates that a leakage that will not give any impact or be detected on the surface after one week also has a very little potential for such effects from a much longer leak duration. The 10 mm leak size has a small effect area based on 7 days leak duration and this area increases a bit for 30 days duration (Figure 4-4). This indicates a small escalation potential regarding possible seabird impacts and also increased detectability for a leakage with longer duration (Figure 4-5). Impacts will also increase due to longer exposure time in the area for a long-lasting leakage (see section 8.3). The increased consequence is best illustrated by the 20 mm leak where the impact area grows from 32 km^2 to 313 km^2 with the prolonged leak duration of 30 days.

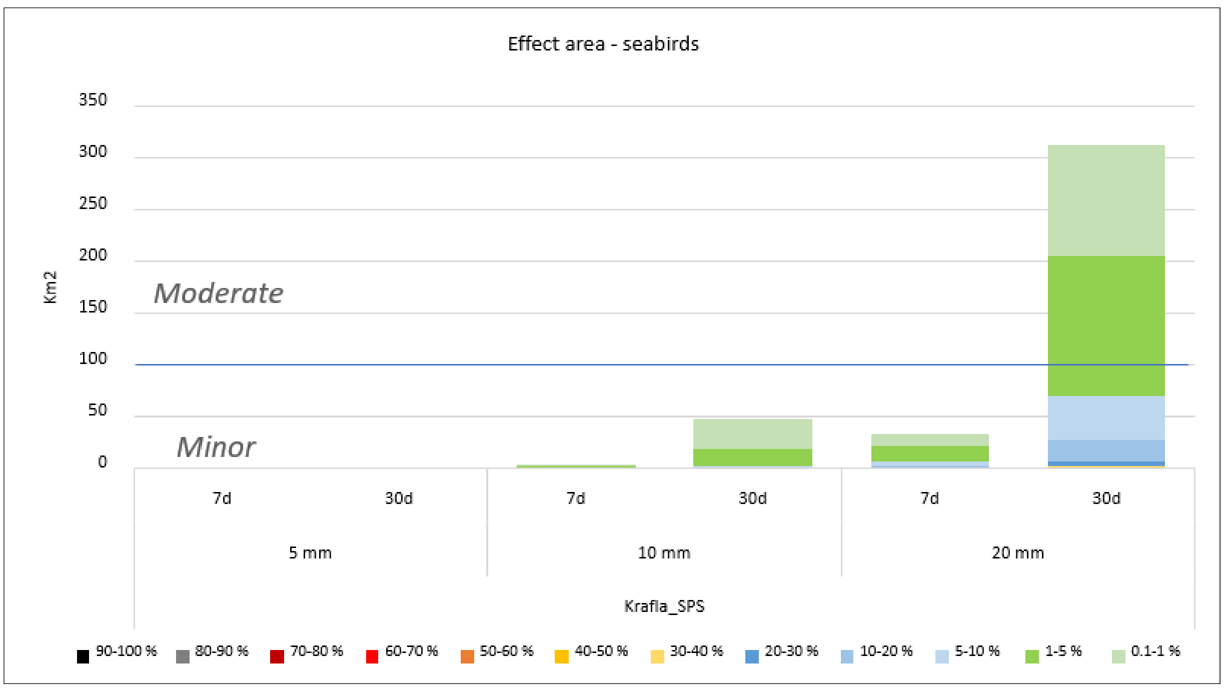


Figure 4-4 *Area on the sea surface (km^2) with expected mortality for seabirds (auks) calculated for different leak scenarios at Krafla SPS.*

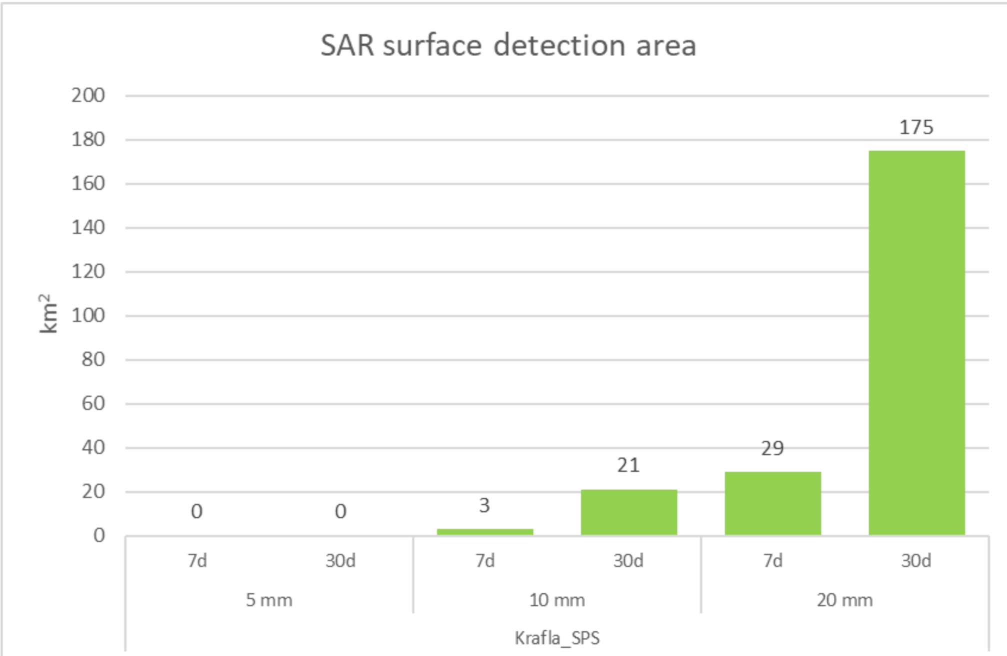


Figure 4-5 *Area on the sea surface (km²) with potential for oil detection from SAR satellite / OSD radar calculated for different leak scenarios at Krafla SPS.*

A summary of the water column impact area, comparable to Figure 4-3 but including the 10 ppb THC effect threshold, is given in Figure 4-6. The effect area will typically double when including the 10-58 ppb area as well.

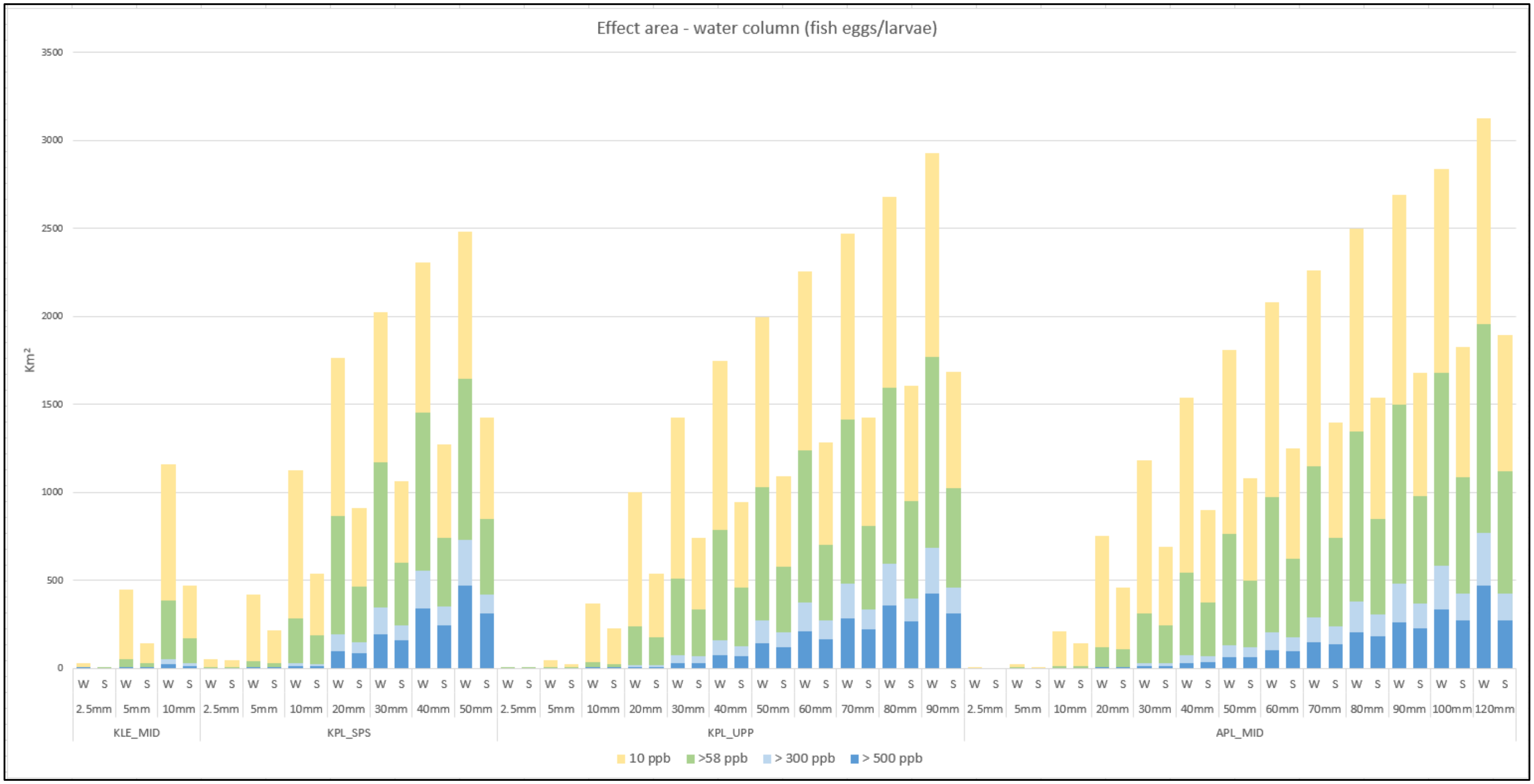


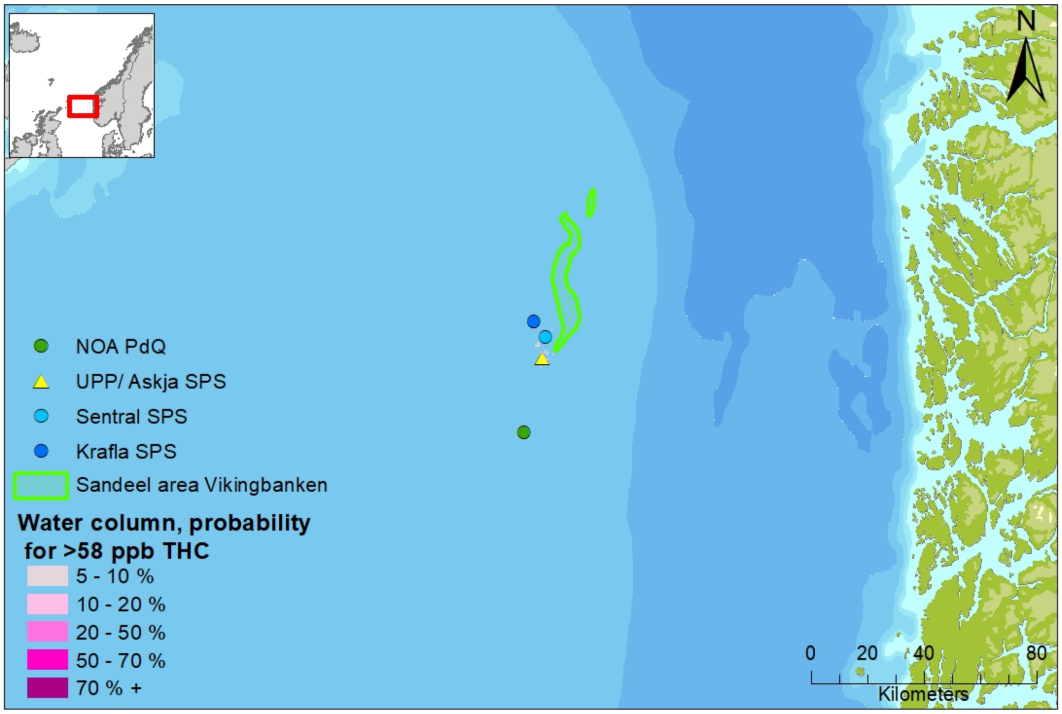
Figure 4-6 *Area (in km²) shown with threshold 10ppb in upper 50 meters of the water column calculated for different leak scenarios based on 7 days leak duration. S = summer, W = winter. KLE_MID = Krafla Liquid Export line (midway UPP and PdQ), KPL_SPS = 16'' Krafla Production Line (Krafla SPS seabed), KPL_UPP = 16'' Krafla Production Line (UPP seabed), APL_MID = Askja Production Line (midway SPS – UPP).*

4.1.2 Sandeel areas on Vikingbanken

Sandeel spawning areas at Vikingbanken are an area of concern for Equinor. The amount of sandeel at Vikingbanken is at historical low levels with an estimated biomass of less than 100 tons for 2021 (IMR, 2021). Overlap between the Vikingbanken spawning area and THC in the upper 50 meters of the water column is shown for 16'' Krafla production line (Krafla SPS – UPP) at the UPP side (inside 500m zone) for a 5 mm and 30 mm leak size in Figure 4-8. The 5 mm leak has a very limited effect area above 58 ppb in the water column and no overlap with Vikingbanken spawning area, while the 30 mm leak has a quite large effect area and will also overlap the southern part of Vikingbanken. The large 30 mm leakage has the highest concentrations in the upper 10 meters of the water column and will not have the potential to affect sandeel near the seabed or in the sediment (Figure 3-9).

The area above 10 ppb in the water column is also presented (Figure 4-9) as a conservative effect area to illustrate potential overlap with the sandeel spawning area at Vikingbanken and in order to account for possible sub-lethal effects of short-term exposure (IMR, 2021). The 5 mm leakage still has no overlap with Vikingbanken area, while the 30 mm leakage has high probabilities for overlap when using a conservative 10 ppb effect area.

Probability for THC concentrations >58 ppb, 5 mm (UPP)



Probability for THC concentrations >58 ppb, 30 mm (UPP)

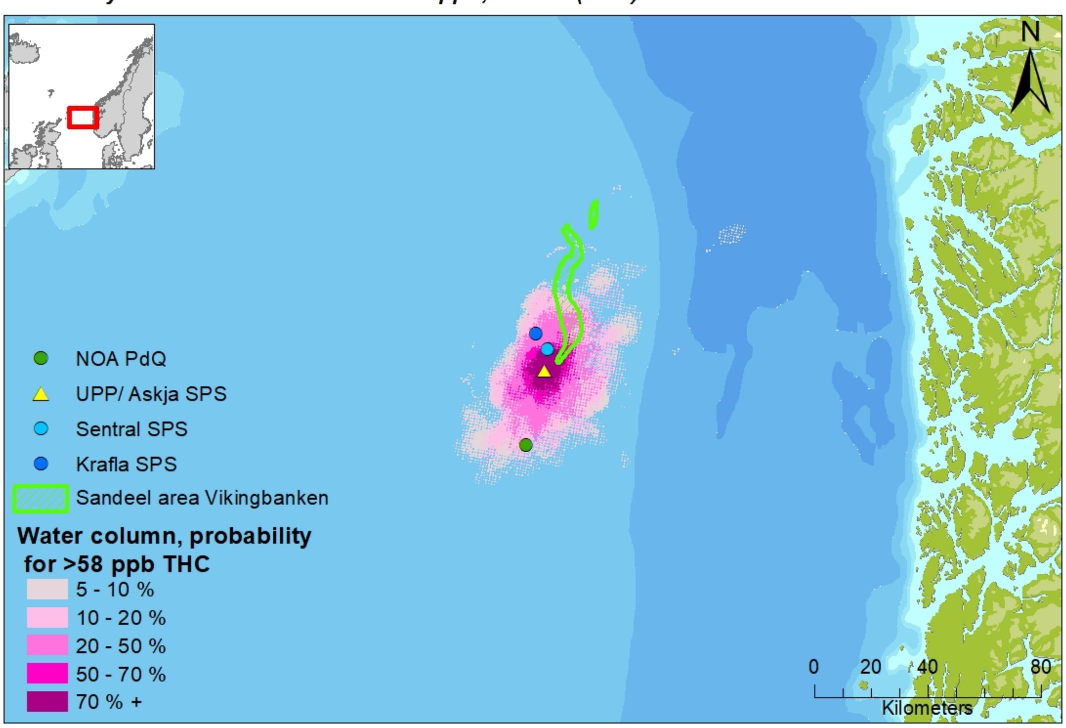
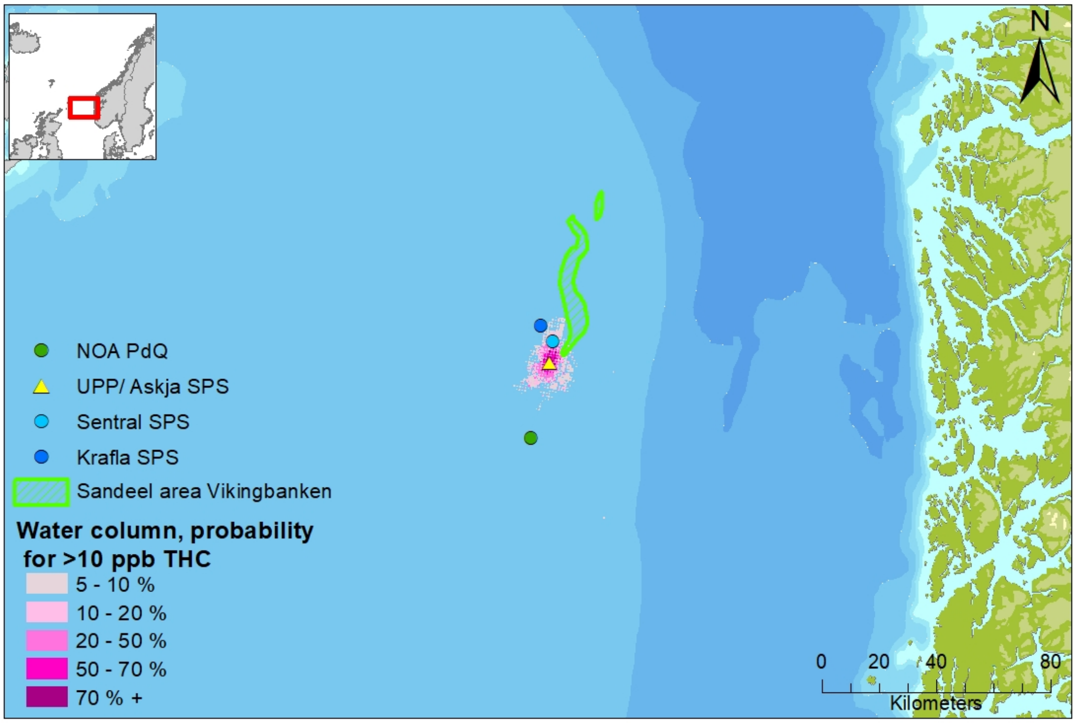


Figure 4-7 *Probability for THC above 58 ppb in upper 50 meters of water column from leak scenarios 5 mm and 30 mm at 16'' Krafla Production line on the UPP side.*

Probability for THC concentrations >10 ppb, 5 mm (UPP)



Probability for THC concentrations >10 ppb, 30 mm (UPP)

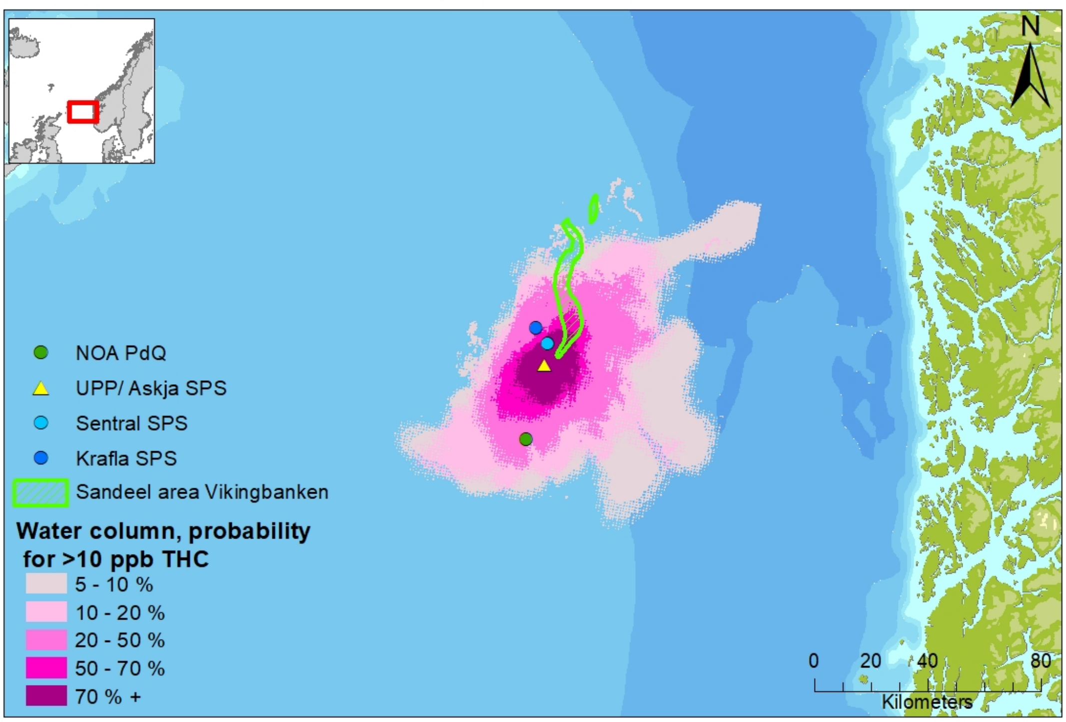


Figure 4-8 *Probability for THC above 10 ppb in upper 50 meters of water column from leak scenarios 5 mm and 30 mm at 16'' Krafla Production line on the UPP side.*

4.2 Environmental consequence and risk

4.2.1 SPS and Pipeline reeling concept

A summary of the modelled leak scenarios for Krafla together with results of the consequence assessment and possibility for SAR (satellite) surface detection is given in Figure 4-10. Leak frequencies are calculated by Equinor (Equinor, 2021c). Frequencies for 10 mm leak scenarios (smallest category) are applied to both 2.5, 5 and 10 mm in this study. The risk-based leak detection analysis is based on leaks from separate pipelines (pipeline concept).

Table 4-2 *Summary of consequence and surface detectability assessment for Krafla leak scenarios together with Leak frequencies for the different scenarios (Equinor, 2021c).*

Functional Location	Location	Leak size (mm)	Leak rate oil (m^3/d)	Seabirds	Fish	SAR detection	Leak frequency
Krafla Liquid export line	Midway UPP - PdQ	2,5	29	Insignificant	Minor	No	3,47E-03
		5	115	Insignificant	Minor	No	3,47E-03
		10	458	Minor	Moderate	Low	3,47E-03
16'' Krafla production line Krafla SPS – UPP	SPS seabed KP 0,1	2,5	19	Insignificant	Minor	No	4,27E-03
		5	76	Insignificant	Minor	No	4,27E-03
		10	299	Minor	Moderate	Low	4,27E-03
		20	1117	Minor	Considerable	Moderate	1,31E-04
		30	1957	Moderate	Considerable	Moderate	6,16E-05
		40	3238	Moderate	Considerable	High	4,06E-05
		50	4564	Considerable	Serious	High	2,06E-05
	UPP seabed (inside 500m zone)	2,5	4	Insignificant	Insignificant	No	4,24E-03
		5	16	Insignificant	Minor	No	4,24E-03
		10	65	Minor	Minor	Low	4,24E-03
		20	259	Moderate	Moderate	Moderate	7,17E-04
		30	575	Moderate	Considerable	High	1,96E-04
		40	1004	Considerable	Considerable	High	5,35E-05
		50	1599	Considerable	Considerable	High	3,35E-05
		60	2238	Considerable	Considerable	High	1,13E-05
		70	2947	Considerable	Considerable	High	1,01E-05
		80	3706	Considerable	Serious	High	4,28E-05
		90	4488	Serious	Serious	High	4,44E-05
16'' Askja production line Askja SPS - UPP	Midway SPS - UPP KP 0,375	2,5	2	Insignificant	Insignificant	No	4,85E-03
		5	9	Insignificant	Insignificant	No	4,85E-03
		10	37	Minor	Minor	No	4,85E-03
		20	146	Moderate	Moderate	Low	2,99E-04
		30	328	Moderate	Moderate	High	1,25E-04
		40	581	Moderate	Considerable	High	6,11E-05
		50	904	Considerable	Considerable	High	3,12E-05
		60	1295	Considerable	Considerable	High	1,76E-05
		70	1753	Considerable	Considerable	High	1,53E-05
		80	2274	Considerable	Considerable	High	2,39E-05
		90	2855	Considerable	Considerable	High	2,71E-05
		100	3486	Considerable	Serious	High	4,04E-04
		120	4819	Serious	Serious	High	4,04E-04

Results from the consequence and frequency assessment is plotted in Equinor's risk matrix (RM100) in Figure 4-9. Consequences are mapped towards Equinor's consequence categories according to Table 4-3.

Table 4-3 *DNVs seven consequence categories used in leak detection studies based on size of effect area and corresponding 8 consequence categories from Equinor's risk matrix RM100.*

Consequence category	Area (km^2)	Equinor consequence category
Insignificant (1)	0	Insignificant (1-2)
Minor (2)	1-100	Minor (3)
Moderate (3)	100-500	Moderate (4)
Considerable (4)	500-1500	Serious (5)
Serious (5)	1500-3000	Very serious (6)
Very Serious (6)	3000-6000	Major (7)
Cathastrophic (7)	>6000	Catastrophic (8)

Highest consequence (mainly in water column) is given for each scenario and consequence is assessed based on modelling of 7 days leak duration. Scenarios for the liquid export line are all in the green part of the risk matrix and at most a moderate consequence.

Scenarios for Krafla SPS-UPP are all in the green part of the risk matrix except for 20 mm leaks on the SPS, 30 mm on the UPP side and 50, 80 and 90 mm on UPP (80 and 90 mm represented by 90 mm in the figure). All leaks in the yellow part of the risk matrix detectable at the sea surface from SAR satellite or OSD radar.

Scenarios for Askja SPS-UPP are all in the green part of the risk matrix except for 100 mm leaks or above. Such leaks will be detectable at the sea surface from SAR satellite or OSD radar.

It is assumed that for a prolonged duration of the leak (1 month), the consequence for a given scenario will increase 1 consequence category. Likewise, for a very long duration leak (1 year), the consequence will increase 2 categories. The rationale is that for seabirds, exposure time is part of the impact algorithm and longer exposure time will give higher mortality in the affected area and possibility of new birds to be exposed. This is also the case for effects on fish eggs and larvae in the water column. For the smallest leaks with a very limited effect, the above assumption seems conservative as a small effect area not necessarily will escalate in the same way as a larger one.

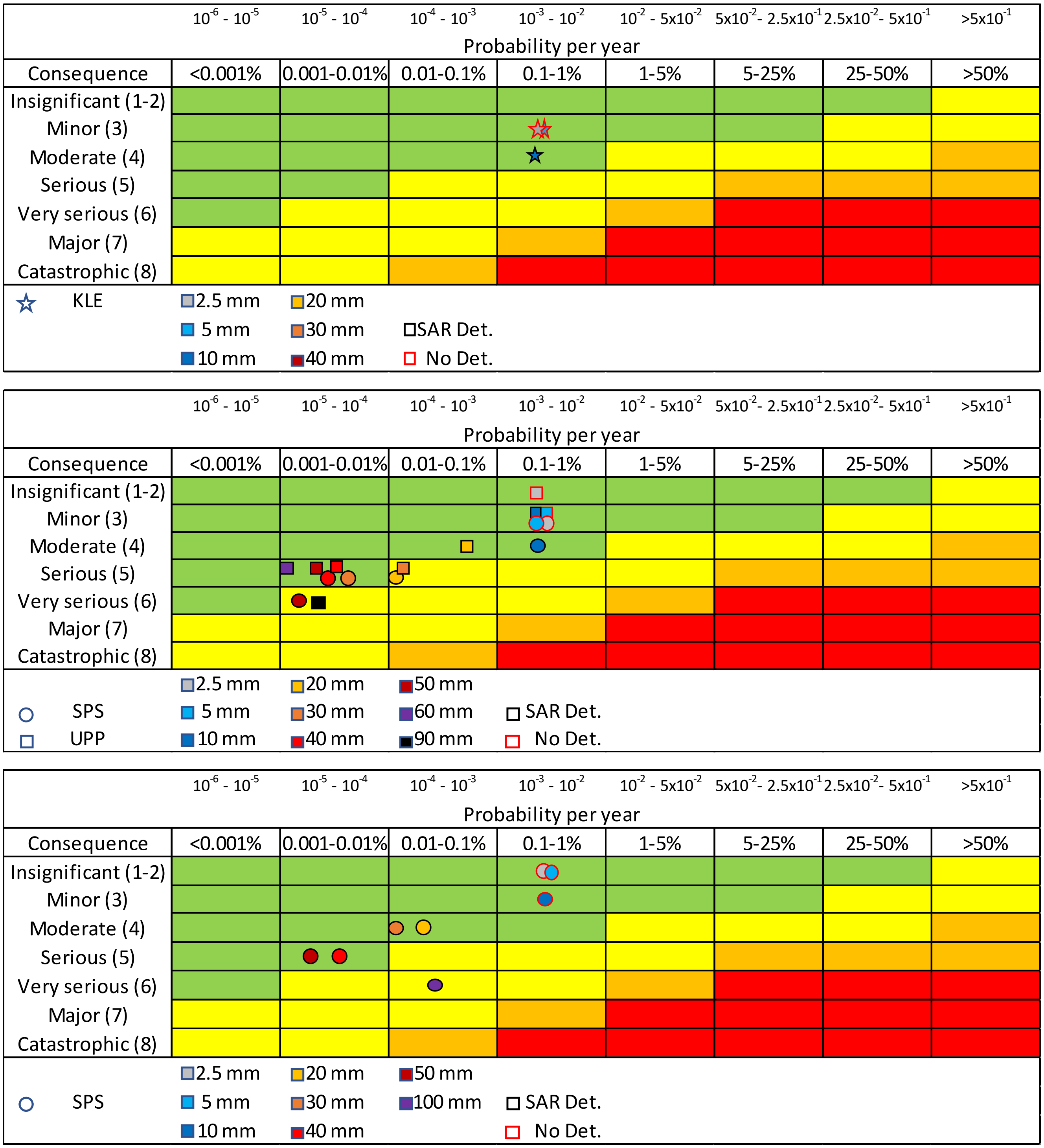


Figure 4-9 *Environmental risk plotted in Equinor's risk matrix with probability and consequence for each scenario. Black outline indicates very good potential for SAR detection of surface slicks, while red outline indicates limited or no surface detection. Krafla- Liquid export line (top), Krafla SPS-UPP (Middle) and Askja SPS-UPP (bottom).*

4.2.2 Pipeline – Bundle concept

Equinor is evaluating two different concepts for the production pipelines between Krafla SPS and the UPP and between Askja SPS and the UPP.

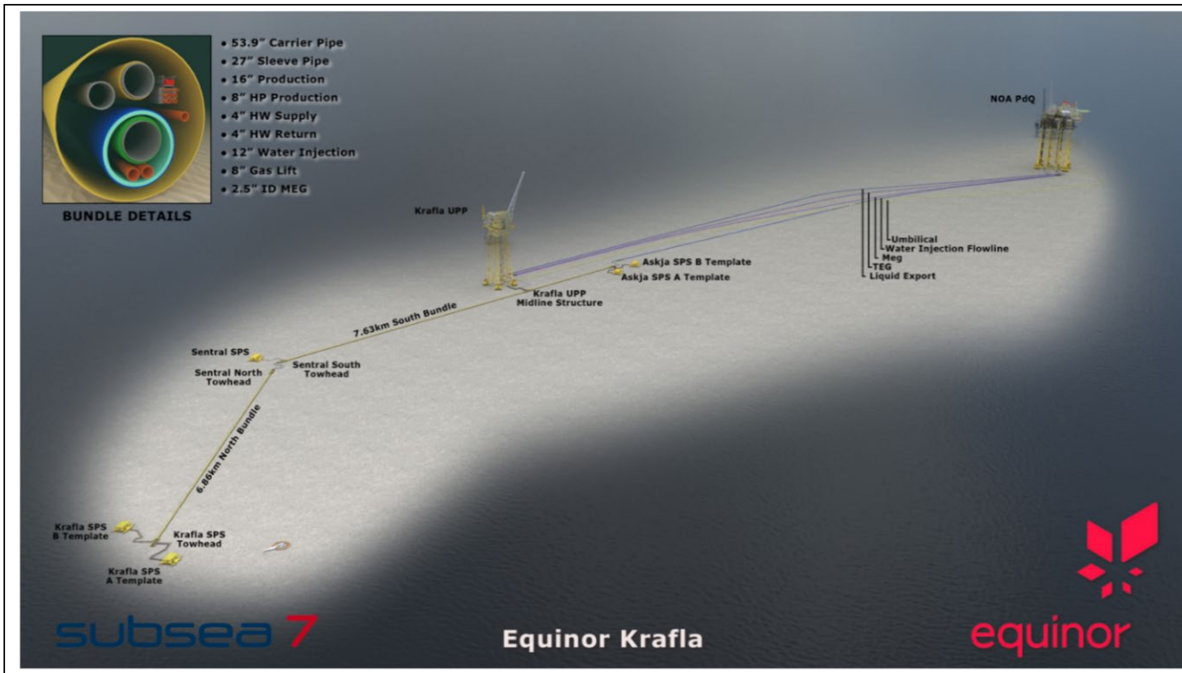
- Pipeline/reeling concept: Separate pipelines as shown in Figure 1-6.
- Bundle concept: all pipelines between Krafla SPS and UPP and Askja SPS and UPP in bundles as shown in Figure 4-10. Pipelines between UPP and NOA PdQ will be the same as in the pipeline concept.

The subsea system at Krafla will consist of two 6-slot subsea templates connected to the Krafla northern bundle towhead. Sentral will consist of a 6-slot subsea template connected to the Sentral southern bundle towhead. Askja will consist of two 6-slot subsea templates connected to the southern bundle Askja towhead. Askja UPP will be connected to a mid-line structure in the southern bundle. All wells will be operated from Krafla Onshore Operation Centre.

The bundle will consist of three sections connected with towheads to Krafla SPS, Central SPS and Askja SPS. Each section of the carrier pipe will have one bursting disc each, placed on the highest point of the pipeline route independent of the tow ends location (but outside of the 500-meter zone). The bursting discs will have a diameter of 2''.

The main purpose of the bursting discs is the ensure that over-pressure is avoided in the installation phase. The discs must be qualified if they are to be used as a safety device subsea, but it can however be anticipated that any leakage will appear through the bursting disc. Pipelines need to exceed design pressure and safety factors to cause discharge to sea. The bursting disc will however hold 40 bar delta pressure from the carrier annulus and the sea. The carrier annulus will be free flooded during installation.

The overall external carrier pipe is sized to provide the requisite buoyancy and protection to the bundle internals. The Carrier pipe annulus is initially nitrogen filled for CDTM (Controlled Depth Tow Method) purposes and is flooded offshore to set the Bundle on seabed and provide the necessary weight for stability purposes. The carrier pipe selected for North and South Bundles is within previous project experience.



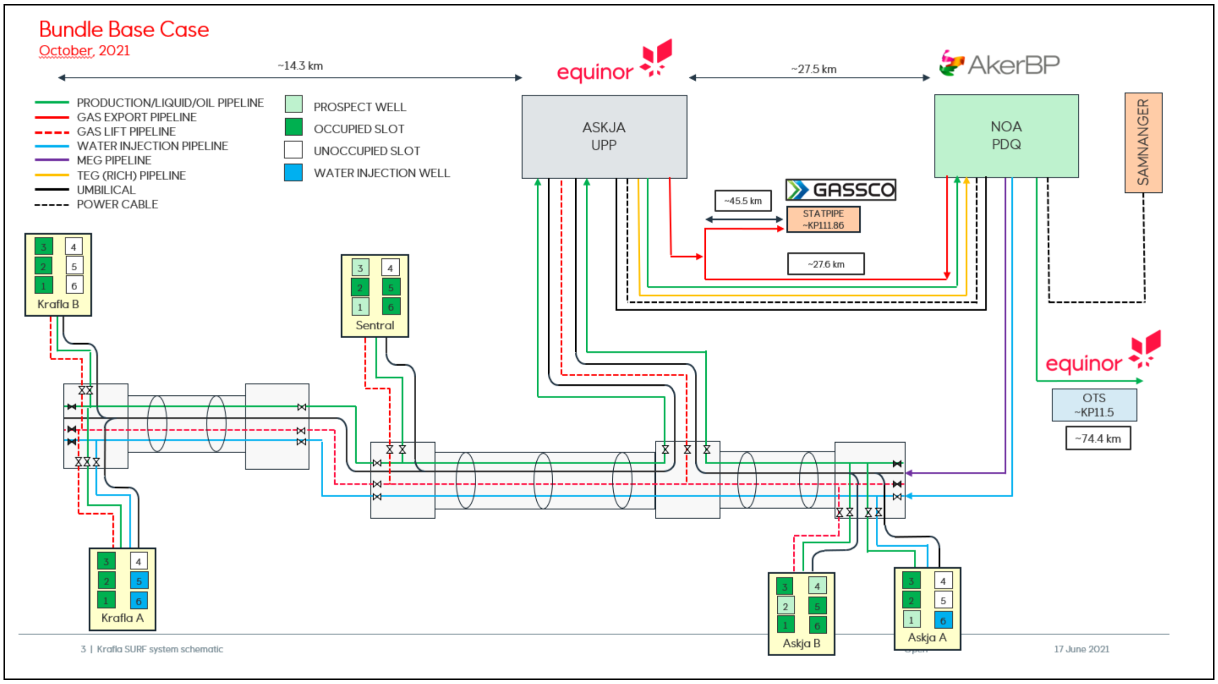
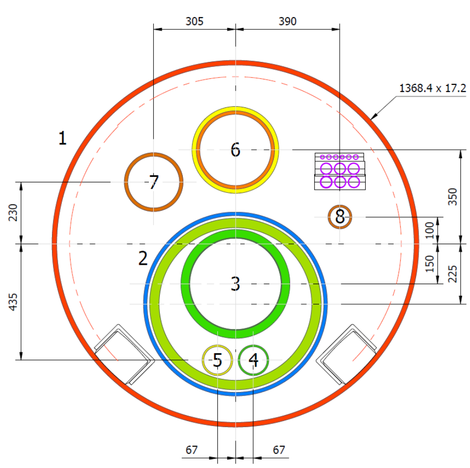


Figure 4-10 *Schematic overview of the area development with Krafla to the left in the picture for the bundle concept (top) and a more detailed overview of the three bundle sections (bottom).*

Details of the bundle is shown in Figure 4-13. A 53.9'' carrier pipe will include a 27.1'' sleeve with insulations, and inside the sleeve a 16 '' production pipeline will be placed together with two 4'' hot water supply and return pipes (circulation system) for heating the production flowline, if needed, before production start-up after a shutdown. There will also be a 12'' water injection pipe, an 8'' gas lift pipe, a 2.5'' MEG pipe and electric cables within the carrier pipe (Equinor, 2021b; Subsea 7 & Equinor, 2021). Perforated partition walls will be placed inside the carrier pipe to keep the different pipes stable and in the right locations.



Flowlines					
Item	Description	Nominal Size	OD (mm)	WT (mm)	Material
1	53.9" Carrier	53.9"	1368.4	17.2	API 5L L360/L415 MO (Mod) [Note 1]
2	27.1" Sleeve	27.1"	686.0	13.0	API 5L L360 MO (Mod)
	Insulation	-	-	35.0	35mm LDPUF Insulation
3	16" Production	16.0"	406.4	32.0 / 30.18 [Note 2]	DNV SMLS 485 L S
	CRA Liner 316L	-	-	2.5	with 2.5mm S31603 liner
4	4" HW Supply	4.0"	114.3	6.5 / 6.0 [Note 3]	DNV SMLS 450
5	4" HW Return				
6	12" Water Injection	12.0"	323.9	17.0 / 16.2 [Note 4]	DNV HFW 450
	HDPE Liner	-	291.5	12.5	with 12.5mm HDPE liner
7	8" Gas Lift	8"	219.1	14.3 / 12.7 [Note 5]	DNV SMLS 450
8	2.5" ID HP MEG	3"	88.9	8.5 / 7.6 / 6.35 / 5.49 [Note 6]	DNV SMLS 450 / DNV SMLS 25CR

Figure 4-11 *Bundle details (Subsea 7 and Equinor, 2021).*

Due to limited data, estimating leak frequencies for bundle pipe systems is more challenging than for single pipelines. The cause of a leak may typically be from internal/external corrosion, fatigue or from other damages to the pipe or from 3rd party damage (e.g., trawling, dropped objects etc.). In general terms frequencies for leaks from bundles is expected to be lower than leaks from a separate pipeline concept, since the leak must pass through both the production pipe, the sleeve, and the carrier pipe to be released to sea. However, having the gas lift pipe in the same bundle as the production line may constitute an additional threat since the gas lift pipe holds a lot of energy. In case of a rupture of the gas-lift line, potential escalation scenarios need to be considered.

The exit velocity of the leak out of the hole is an important parameter for how the hydrocarbon leak will behave in the sea water. A high exit velocity will crush the oil into small droplets that may be trapped in the water masses and use a long time to reach the surface and create an initially thin oil film on the surface. With lower velocity the oil droplets will be bigger and is expected to move faster to the sea surface and create an initially thicker oil film on the surface. It is also possible that a leak with high exit velocity that happens inside the carrier pipe will have small droplets initially, but that these droplets will stick to each other and coagulate to bigger droplets that will “burp” out when the bursting disc crack.

The bursting disc is 2’’ in diameter and this is about the same size as a 50 mm leak modelled in this study. For all modelled scenarios equal or above 50 mm leak size the leak is expected to reach the surface and can be detected on the sea surface. All these scenarios have a possibility for considerable and serious environmental effects and should be detected within hours to a week. The advantage of bursting discs is that the location of a possible leak is known, and leak detection sensors (area sensors like methane sniffers, passive acoustic or active acoustic) should be placed to cover these locations.

Since there are many uncertainties in both leak rates, velocity, and frequencies for a bundle, it is suggested to do a more detailed frequency analysis for the bundle, and model leak rates for the bundle concept in OLGA for a more robust comparison of the two pipeline concepts.

5 MAPPING OF WEATHER STATISTICS AND DETECTION WINDOWS

Wind speed and waves have a great influence on whether and when oil from a seabed leak can be detected on the sea surface by satellites and other radar equipment. KSAT (Ringjord, 2020) and Paplia et.al., 2018 have somewhat different limit ranges on wind speeds and wave heights in combination for when there is a good opportunity to detect the oil on the sea surface, see Table 5-1.

Table 5-1 *Limit intervals for wind speeds and significant wave height for a good opportunity for oil detection on the sea surface for KSAT and Paplia et.al., 2018.*

Company	Wind speed (m/s)	Significant wave height (m)
KSAT	2-12	0,2 – 3,5
Paplia et.al., 2018	3-10	0,3 - 3

DNV compiled statistics for wind and waves based on a time series of 10 years (2007-2016) in a project for the Norwegian Coastal Administration (DNV GL, 2018). In predefined grid routes of 10 x 10 km, which cover Norwegian waters, wind speed and significant wave height are registered every hour throughout the ten years. The percentage of time the two Metocean factors in combination (fulfilled simultaneously) are within the given limit interval values for detection of oil on the sea surface is shown in Figure 5-1. To study seasonal variations, the statistics are generated on monthly basis.

The results in Figure 5-1 show the proportion of time (in percent) it is possible for satellites/radar to detect oil on the sea surface in the grid route where Krafla is located, based on wind speed and significant wave height with both KSAT and Paplia et.al., 2018's approaches to limit intervals. X-band radar and ISPAS radar have the same limit intervals as KSAT (2-12 m/s) and is not shown separately in Figure 5-1.

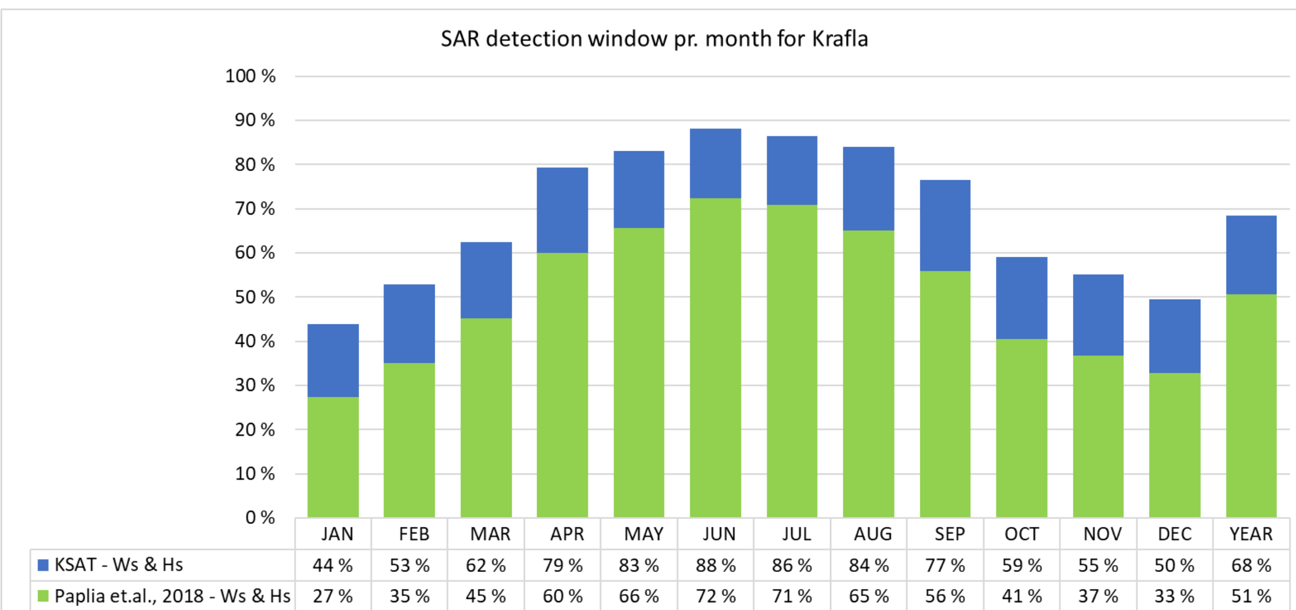


Figure 5-1 *Detection window, or percentage of the time per month where it is possible for satellites to detect oil on the sea surface on Krafla with KSAT and Paplia et.al., 2018's wind speed and wave limitations in combination. X-band radar and ISPAS radar have the same limit intervals as KSAT (2-12 m/s).*

The results show that the detection window for the satellites is largest in summer, over 80 % of the time in May-August, due to lower wind speeds and wave heights, while it is the other way around in the winter. The detection window is naturally larger for KSAT than for Paplia et.al., 2018 since the limit intervals at KSAT are larger. A percentage value of more than 50 % indicates that the satellite can detect leaked oil on the sea surface more frequently than every other day. For KSAT's intervals, this applies to all months except January, while for Paplia et.al., 2018’s intervals it applies from April to September (see Figure 5-1).

6 FUNCTIONAL REQUIREMENTS AND TOLERABILITY CRITERIA

6.1 Suggestion for functional requirements

Based on the scenario's placement in the risk matrix, a maximum allowed leak detection time is suggested below. The functional requirements are based on the results in the analysis and is without any leak detection techniques.

- Leaks with very serious consequences in yellow part of the risk matrix shall be detected as quickly as possible and **within hours**. The 50 mm leak on the Krafla SPS side, the 80 mm leaks or higher on the Krafla UPP side and 100 mm leaks or higher on the Askja SPS are in this category.
- Leakages in the yellow part of the risk matrix with serious consequences shall be detected as quickly as possible and minimum **within a day**. The 20 mm leak on Krafla SPS side and 30 mm leak from on the Krafla UPP side are in the yellow part of the risk matrix.
- Leaks in the green part of the risk matrix with serious consequences shall be detected as quickly as possible and minimum **within a week**. The 30-50 mm leaks on Krafla SPS and 40-60 mm leaks on Krafla UPP together with 40-50 mm leaks on Askja SPS are in this category.
- Leakages with moderate consequences in the green part of the matrix one consequence category below yellow would be supposed to reach yellow level in the risk matrix within a month and should be detected **within a month (weeks)**. This includes a 10 mm leak from Krafla SPS, a 20 mm leak from Krafla UPP, 20-30 mm leaks from Askja SPS and 10 mm leakages from Krafla export line (KLE).
- Leakages with minor consequences in the green part of the matrix two consequence categories below yellow would be supposed to reach yellow level in the risk matrix within a year and should be detected **within a year**. This includes 2.5 and 5-mm leakages from Krafla SPS, 5-10 mm leaks from Krafla UPP, 10 mm leak from Askja SPS and 2.5 and 5-mm leaks from KLE.
- Leakages with insignificant consequence in the green part of the matrix three consequence categories below yellow would not be supposed to reach yellow level in the risk matrix and should be detected **with ROV inspection (within year(s))**. This includes 2.5 leakages from Krafla UPP and 2.5 and 5-mm leaks from Askja SPS oil production lines.

6.2 Tolerability criteria

Equinor have two risk tolerability criteria for subsea leakages. The criteria are used to set risk-based requirements for leak detection:

- The frequency of volumes (before detection) above 50 m^3 - shall be limited to 10^{-2} per year
- All leaks with lower frequencies shall in any case be detected before leak volumes have reached 5000 m^3.

Table 6-1 list the leak scenarios at Krafla and the suggested functional requirements based on environmental risk and the number of days to reach the 5000 m^3 requirement.

Table 6-1 *Leak scenarios, leak frequencies, suggested functional requirements based on environmental risk and number of days to reach 5000 m³.*

Functional Location	Scenario	Leak size (mm)	Leak rate oil (m^3/d)	Leak frequency	Functional requirements	5000 m3 (days)
Krafla Liquid export line	Midway UPP - PdQ	2,5	29	3,47E-03	< 1 year	173
		5	115	3,47E-03	weeks (month)	43
		10	458	3,47E-03	week	11
16'' Krafla production line Krafla SPS – UPP	SPS seabed KP 0,1	2,5	19	4,27E-03	< 1 year	262
		5	76	4,27E-03	months	66
		10	299	4,27E-03	weeks	17
		20	1117	1,31E-04	days	4
		30	1957	6,16E-05	1 day	3
		40	3238	4,06E-05	1 day	2
		50	4564	2,06E-05	hours	1
	UPP seabed (inside 500m zone)	2,5	4	4,24E-03	year(s)	1224
		5	16	4,24E-03	< 1 year	306
		10	65	4,24E-03	months	77
		20	259	7,17E-04	weeks	19
		30	575	1,96E-04	week	9
		40	1004	5,35E-05	days	5
		50	1599	3,35E-05	1 day	3
		60	2238	1,13E-05	1 day	2
		70	2947	1,01E-05	1 day	2
		80	3706	4,28E-05	hours	1
		90	4488	4,44E-05	hours	1
16'' Askja production line Askja SPS - UPP	Midway SPS - UPP KP 0,375	2,5	2	4,85E-03	year(s)	2500
		5	9	4,85E-03	year	556
		10	37	4,85E-03	months	135
		20	146	2,99E-04	weeks (month)	34
		30	328	1,25E-04	week	15
		40	581	6,11E-05	week	9
		50	904	3,12E-05	days	6
		60	1295	1,76E-05	days	4
		70	1753	1,53E-05	1 day	3
		80	2274	2,39E-05	1 day	2
		90	2855	2,71E-05	1 day	2
		100	3486	4,04E-04	hours	1
		120	4819	4,04E-04	hours	1

The total leak frequency for Krafla is above 10^{-2} for the smallest leak sizes (< 10 mm, see Figure 6-1) and the requirement is therefore assessed qualitatively when recommending possible additional leak detection techniques for Krafla in addition to the base case before these leaks exceeds 50 m^3. The base case with methane sniffers and passive acoustic sensors at each template will significantly increase early detection of the smaller leaks before reaching 50 m^3.

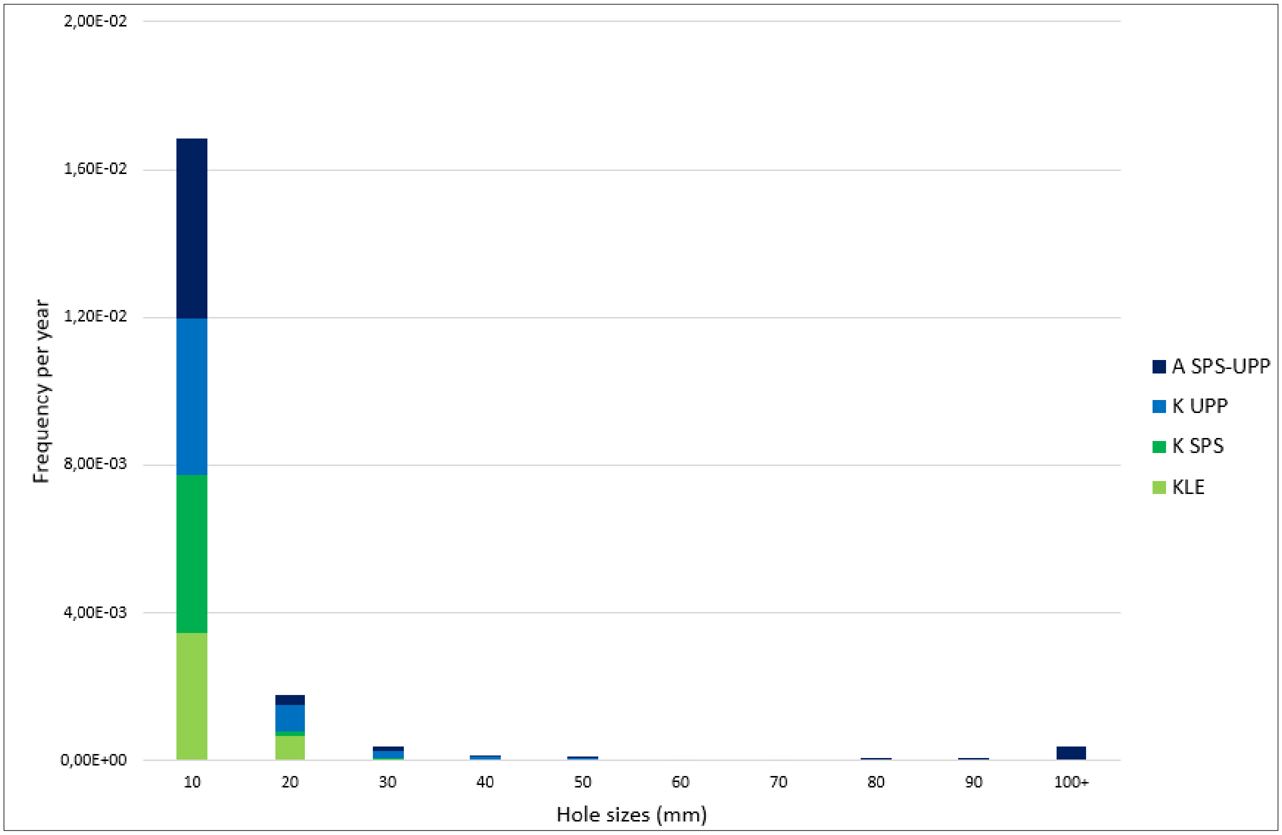


Figure 6-1 *The total leak frequency for Krafla for the different hole sizes, summarized for the defined scenarios (Equinor, 2021c).*

6.3 Risk reducing measures

The BAT/ALARP principle states that risk-reducing measures shall be identified and implemented, unless there is a large disproportion between the achieved risk reduction and the total cost (money, time, or other resources) associated with the implementation. Figure 6-2 shows the BAT/ALARP process for identifying risk-reducing measures for leak detection.

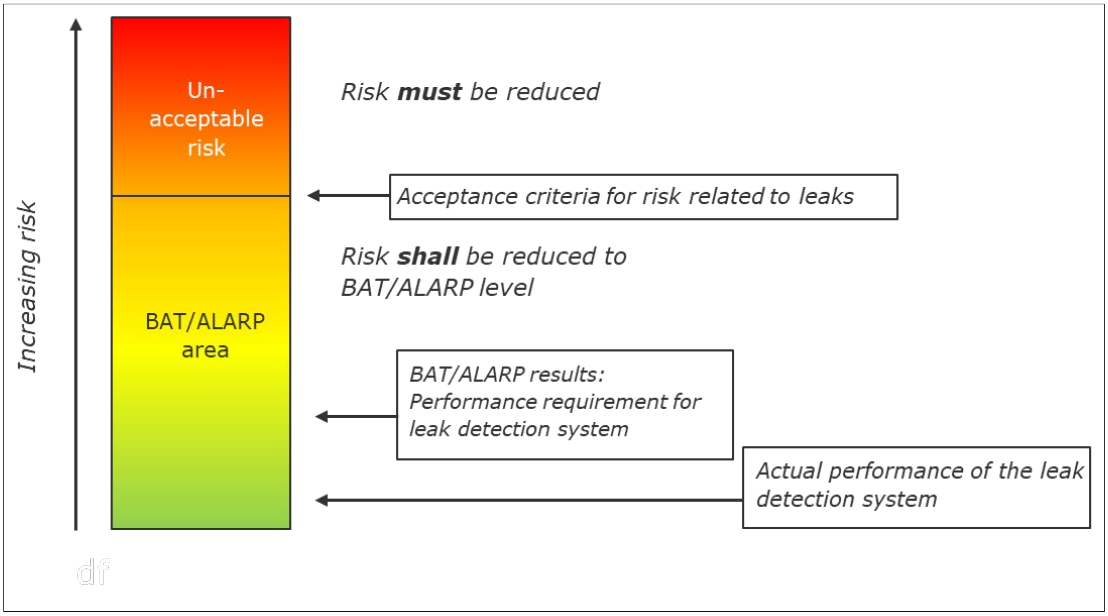


Figure 6-2 *BAT/ALARP process for identifying risk reducing measures for leak detection.*

To interpret the results from a risk matrix, there is a need-to-know which combinations of consequences and probabilities that gives acceptable or unacceptable risk. This is indicated by different colors in a risk matrix. If risk is unacceptable, risk reduction measures must be identified, and if risk is in the ALARP area, risk reduction measures should be considered. The functional requirements for leak detection should be in the area of the matrix that indicates acceptable risk based on the ALARP principle.

7 EVALUATION OF LEAK DETECTION TECHNIQUES FOR KRAFLA DEVELOPMENT

The challenge for operators is to successfully implement a leak detection system that is reliable and capable of detecting leaks with an acceptable level of certainty and at the same time meets regulatory requirements. This may require integrating sensors from various suppliers into one system and operating and maintaining the leak detection system over the lifetime of the field.

The different leak detection techniques available for Krafla is divided into:

- Base case techniques for Krafla
- Additional techniques available for Krafla

The different groups are presented in the chapters below, and the techniques are summarized in Table 7-1.

7.1 Base case techniques for Krafla

The base-case techniques for Krafla leak detection philosophy includes:

- Satellite (SAR)
- Mass balance (multi-phase Krafla Liquid Export Line (KLE))
- ISPAS radar (UPP)
- Franatech methane sniffer sensor at each template
- Naxys passive acoustic leak detection at each template
- Visual observations from UPP (during maintenance) and from vessels or helicopters/aircrafts

7.1.1 Satellite SAR (KSAT)

SAR (Synthetic-aperture radar) is a type of radar in which a relatively small antenna moves over a controlled path, whereupon the measurement data from the entire path is compiled to form a much larger synthetic aperture or synthetic antenna. Since the resolution is proportional to the dimension of the antenna, a much higher resolution can be achieved than with a conventional antenna. The radar is mounted on a satellite.

There are many variables that are relevant to the detection capability of SAR, such as meteorological and oceanographic conditions, satellite sensor, satellite mode, resolution, and angle. In addition, there are many cases where one does not know what is detected; for example, whether attenuation of the intensity of the electromagnetic wave is due to oil spills or other sources of wave dampening (e.g., algal blooms, tank washing from vessels, towing of whales, wind shadows, etc.) (Ringjord, 2020).

Radar indirectly detects oil film on the sea surface. To be able to use radar to detect leaks from subsea installations, one is dependent on the oil reaching the surface and create an oil film over a certain area on the sea surface (Brandvik et.al., 2020). Detection with SAR works best within given intervals for wind speeds and significant wave heights (Figure 5-1).

Kongsberg Satellite Services AS (KSAT) monitors the Norwegian continental shelf on behalf of the operators, and this is done through an agreement between NOFO and KSAT. Monitoring is based on predefined areas of interest (AOI). Through the NOFO agreement as it stands today, surface installations on the Norwegian shelf will be covered approx. once a day (on average 24-28 hours). In the event of a discharge, KSAT will be able to contribute with significantly more images than those available through the NOFO agreement. The number of pictures, quality and area coverage may vary per month and in general, temporal coverage is higher in the north than in the south.

7.1.2 Mass balance system (MBS)

Mass balance is an internal leak detection system that is based on pressure and volume monitoring and can detect potential leaks. Measured values for the monitored parameters are compared with simulated values that predict expected pressure and flow at normal flow and production. Deviations in measured and predicted values indicate a leak in the system and are notified with an alarm.

The mass balance system provides continuous monitoring and will alert in minutes or hours depending on the size and location of the leak. For example, large leaks can be detected within minutes with the correct system configuration, while smaller leaks can take longer to detect and may not be detected until scheduled ROV inspection detects it visually.

Advantages of using mass balance for leak detection are:

- Uses already installed process instrumentation (internal)
- Continuous
- Real-time
- It has no weather restrictions
- The technology is mature for single phase system

Mass balance works best when the production rate is high and the metering is representative (high accuracy and repeatability), and generally has good uptime when the system is set up accurately and when the staff has good experience in interpreting alerts and alarms. The method requires software for calculating changes in pipeline inventory and comparing actual and estimated changes in flow and pressure to identify abnormal deviations that indicates a leak.

7.1.3 ISPAS radar

ISPAS delivers an advanced Oil Spill Detection (OSD) radar with electronically scanned antennas that can map the sea surface and detect oil-spill on both quiet and coarse sea. Oil spills on the sea surface is either detected directly on quiet sea, i.e., sea state 0-1, using polarimetry or detected indirectly though observing the attenuation of wind generated capillary waves by the oil spill, sea state 2 – 5. Unlike X-band OSD radars with HH polarization, ISPAS uses dual polarization and VV polarization has delivered good oil spill detection results both on the NOFO Oil-on-water field trial (June 2018) and the Oil-on-water Qualification test at Edvard Grieg (September 2018).

The ISPAS OSD radar is using a higher frequency to optimize radar reflections from the sea and is using the polarization to detect the presence of oil on the surface by using the one polarization that is transparent to oil as a reference and the other polarization that is affected by the oil as a detector. By looking at the relationship between the two polarizations oil-spill can both be detected, and there is a potential that relative thickness might be estimated. The technology is minimal affected by waves, weather, and light conditions.

The IPSAS radar is expected to have an oil detection range of up to 5 km, but this is dependent of the height the radar is installed (typically between 50 and 100 meters). Advantages of using ISPAS radar is significantly reduced detection time (estimated at 1 hour for radar under Beauford sea condition 1-6 i.e., 2 to 12 m/s wind and waves up to 4-5 meters) compared to satellite SAR. It is expected that the ISPAS radar will have a better performance compared to a standard OSD solution and will be able to detect an oil spill at a longer distance from the installation, with fewer false alarms and at extended weather conditions, also on calm sea.

7.1.4 Methane sniffers (Franatech)

Methane sniffers do continuous direct measurement of methane dissolved in water. The point sensor technology assessed is a methane sensor (dissolved gas) from Franatech. The principle is that dissolved gas diffuses over a membrane into a chamber where the gas is measured by infrared absorption spectrometry or laser technology. The sensor is not dependent on bubbles or noise and is therefore not dependent on high operational pressures and therefore suitable for late life production. The sensors have a 25-year design life for permanent installation. The maintenance is limited to the eventual uploading (remote upload) of a new firmware onto the sniffer internal micro-processor. It requires no re-calibration. It is intrinsically anti-fouling and corrosion-free. No cleaning required, it is designed to prevent debris and mud particles accumulation on the sensitive surface. The funnel itself is designed for preventing debris accumulation as well. If necessary, the sniffer (including the sensitive surface) can be cleaned by water jet.

The sniffer itself features a ROV-grip, and a jumper cable connection with an oil-filled hose. The jumper cable comprises power and data lines. When in operation the sniffer is connected to the SCS on the template. The system is working permanently, and supplies data online and in real-time. The sniffer is typically installed on the template on-shore, in a parking position, off-power and cable coiled. It will stay there during all the time of template mobilization and installation. Once the template is completely installed, connected and ready for operation, a ROV will move the sniffer from its parking position to the final operation position. At both parking and operation positions, the sniffer is mounted in a funnel, oriented horizontally (Figure 7-1). The funnel is welded or bolted to the template structure. The sniffer is held in place by a lock-in mechanism.

Figure 7-1 *The sniffer with a ROV grip and a jumper cable with an oil-filled hose (left) and sniffer in the funnel (right).*

All point sensors have the weakness that they require direct contact with the leakage, giving limited spatial coverage. This means that the placement of the sensor relative to the leak and predominant current direction becomes critical. The leak detection sensitivity for one sensor, given exposure to hydrocarbons, is by vendor defined as 0.05 l/min after 2 minutes. This is a theoretical sensitivity under optimal conditions. For area coverage, a triangulation of sensors is used. Field specific performance is highly dependent on template structure, number and location of sensors, number and location of leak points and local conditions (current, water depth, waves, natural seeps). One should also note that in areas with natural gas seeps (shallow gas) these sensors could give false alarms and result in a lower detection ability due to the need to set higher alarm limits. Troll is a known pockmark area where natural gas seeps from the seafloor could cause false alarms, and the leak alarm limits needs to be evaluated carefully to find the optimal balance between sensitivity and reliability. The installation specific performance of the point sensor leak detection at template area will be dependent on the base line methane level and the resulting leak alarm limit.

The Franatech subsea hydrocarbon leakage sensor is considered as fully qualified (TRL 7). This includes measurement principle and robustness. The methane sensors have generally performed as expected, but further follow up is needed with respect to software updates and further investigation if any of the detected failures are related to the sensor design and demand hardware improvements. Per today a subsea leak detection system containing Franatech sensors is not considered as fully qualified (TRL 3). To enable improved integration to SAS, further work is ongoing to establish a software for defining leak alarm levels based on measured methane concentrations and other relevant parameters. An indicative timeline shows completion within Q3/2022.

The Troll Phase 3 templates are prepared for implementation of 2 Franatech sensors per template. An evaluation of sensor location and performance of methane sensors for the Snorre Expansion Project (SEP) has been performed by Franatech. The environmental conditions, layout and fluid data (GOR, density) are comparable to the Troll area. The SEP leak sensor analysis combines 4 sensors, however a coarse evaluation of results for 2 sensors gives an indication of performance. Leak detection results for a leak rate of 0.02 kg/s (oil and gas) and 2 sensors with the most optimal location covering the template area could give an average detection rate of about 60-70% and an average time to detect around 1 -2 hrs. The maximum detection time could reach 24 hours, however the fraction of leaks detected within 12 hours would be expected around 80 %. The detection rate illustrates the sum of periods when the methane concentration is above detector limit during the simulated period. The detector limit used in the analysis was conservatively set to 10 times the theoretic sensor limit. In the ALARP study, the sensors are assumed to detect all leaks ≥ 1 kg/s (10 mm hole size), with detection time of 1 hour. This is a general assumption, and the actual performance in operation is highly dependent on local conditions, such as natural seeps, environmental data, detector location and template design.

7.1.5 Passive acoustic (Naxys)

Passive acoustics is the action of listening for sounds and can be used for detection of noise generated by an expanding fluid (acoustic emission from leakage). The sensors contain hydrophones (under water microphones) picking up the pressure wave, or sound, generated by a rupture or leak. Passive acoustic sensors depend only on a sufficiently strong pressure wave and are not dependent on the chemical compound of the leaking medium.

Naxys A5 is a subsea passive acoustic leak detector using acoustic sensors (hydrophones) for detection of acoustic energy emitted by subsea leaks (sound propagating through water). The sound received by the sensors is digitized and processed by the electronics and software of the Naxys A5. Complex software algorithms are used to filter and analyse the data to detect possible leaks of gas and/or fluid. The analysed data is compared against a set of threshold values, and warnings and/or alarms are sounded if limits are violated. A summary of the processing result made available to the control system via various Modbus registers, as well as the topside service computer for storage, visualization and in-depth analysis.

Passive acoustic leak detection is based on detection of sound generated by a subsea leakage. Sound propagates from the leak and is picked up by the acoustic leak detector (Figure 7-2). Since other sources of acoustic noise exist, detection capability of the subsea leakage (source) is determined by the strength of the received leakage sound relative to the background noise sounds. This ratio is referred to as the detection threshold (DT). The characteristics of leakage sounds, and background noise have been studied empirically (deep water testing and data from offshore installations). Despite the extensive amount of empirical data, the DT for a specific installation must be evaluated since parameters and factors might not be exactly as those tested for. Basically, the Passive Sonar Equation considers the acoustic propagation of leakage sound and background noise.

Naxys Acoustic Leak Detector System Detection Threshold is 6 dB above background noise level with 95 % probability of detection.

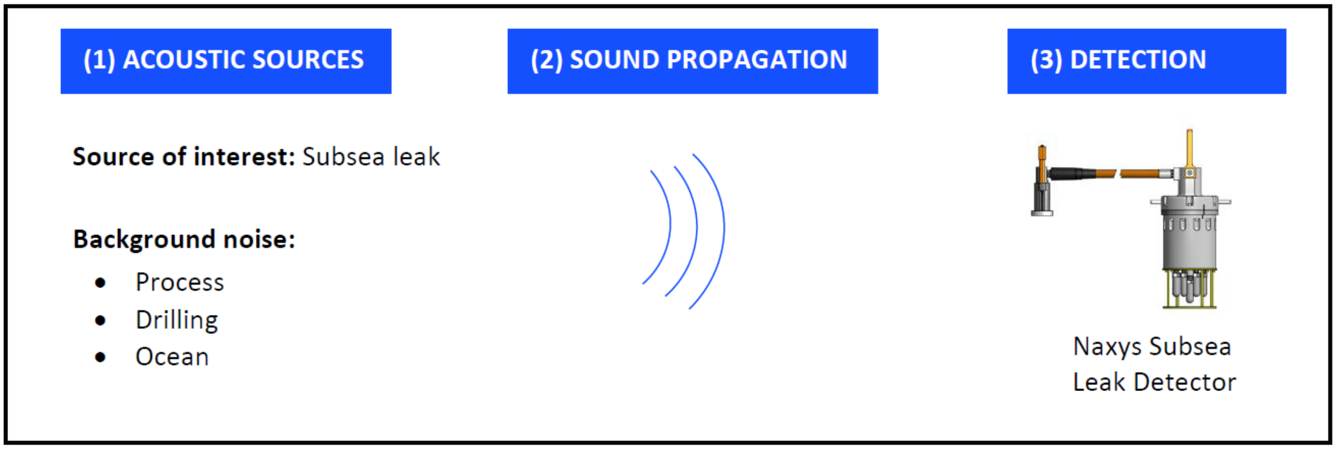


Figure 7-2 *Passive acoustic leak detection.*

Passive acoustic detectors come in variants designed for spatial coverage as well as variants for monitoring of specific critical components. Passive acoustic sensor allows area detection. The detection range will depend on type of sensor, differential pressure and size of the required minimum detectable leak. A detection-range up to 500 m is demonstrated but the detectable leak size will increase with increased distance from the leak source (Figure 7-3). Positioning is possible by using an array of sensing elements that provides 3D resolution. Arrival time of a sound at each sensor can be used to locate the origin of the sound. The noise level can be used to trend the leakage. Passive acoustic detectors may provide leak detection in combination with vibration monitoring, event detection and monitoring of subsea machinery. Systems are qualified for operation to 3000 meters' water depth and with design life up to 30 years. The data is communicated to the surface by either a dedicated fibre-optic cable or via a cable to the subsea control system (SCS). Various types of communication are available, depending on supplier and sensor type.

A limitation to this technology is that a sufficient pressure-drop over the leak path is a requirement for detection. Background noise may disturb the measurements and shadowing of the acoustic waves may be a problem. However, advanced systems utilize automatic adaption of alarm threshold relative to background noise level. The sensors are little affected by seawater currents and turbidity.

The advanced sensor versions require more space on the subsea structure than simpler local area detectors. The larger version may also be installed on the seabed using mud-mat. Smaller versions of passive acoustic detectors are designed to be installed close to critical points (valves, flanges, joints, etc). These versions do not provide system redundancy or location estimation and are more sensitive to background noise.

Passive acoustic sensors are qualified and available in the market. Naxys subsea leak detectors were developed in the early 2000s and since then more than 100 systems have been permanently deployed on the Norwegian Continental Shelf, Gulf of Mexico and Africa.

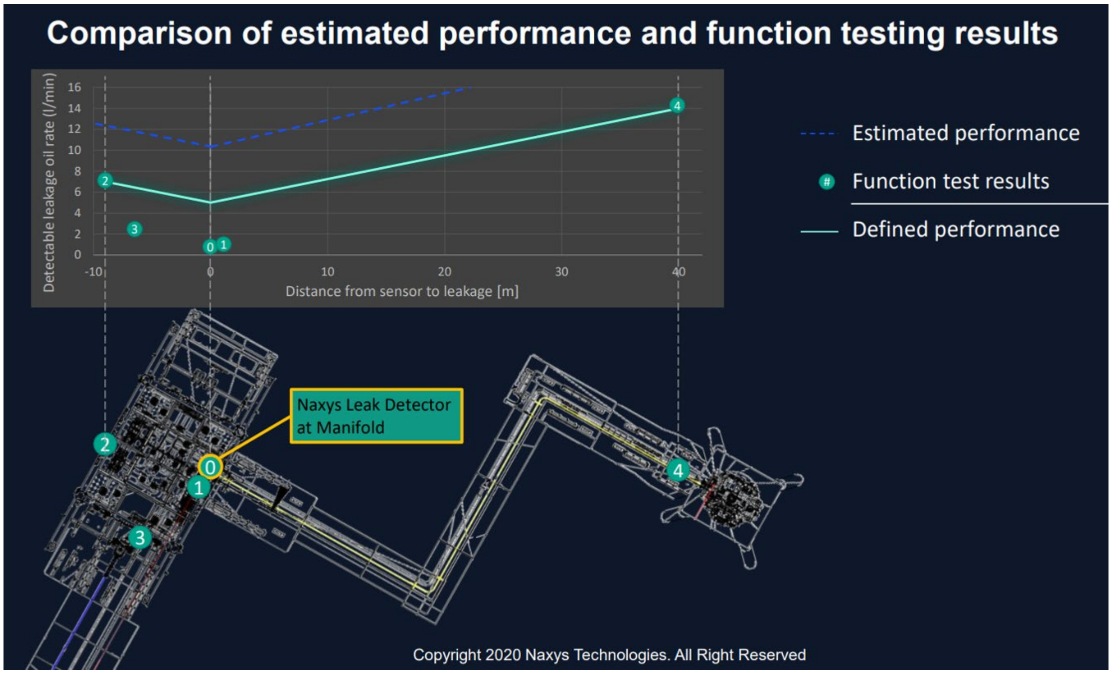


Figure 7-3 *For the passive acoustic leak detector the detectable leak size will increase with increased distance to the leak source (Equinor, 2021e).*

7.1.6 Visual observations from UPP (during maintenance)

Krafla will be unmanned and only manned during maintenance. UPP is planned with 2-3 campaigns per year, duration about 14 days.

7.1.7 Visual observations from vessels or helicopters/aircrafts

Oil on the sea surface can be detected by means of visual observations from passing vessels or from aircraft / helicopters. All offshore service vessels that are in the vicinity of installations or routes for pipelines carrying oil or gas are required to report if they observe oil or gas that is likely to come from a leak (in accordance with GOMO and operations manual for offshore service vessels Norwegian Shelf, Chapter 2 HSE). Other passing traffic that observes oil on the sea surface has obligation to notify (unless it is clearly unnecessary) according to the *Forskrift om varsling av akutt forurensning eller fare for akutt forurensning* (Forskrift om varsling av akutt forurensning eller fare for akutt forurensning - Lovdata).

7.2 Additional techniques relevant for Krafla

7.2.1 Satellite SAR (KSAT) – Enhanced frequency

NOFO agreement for satellite monitoring as it stands today, surface installations on the Norwegian shelf will be covered approx. once a day (on average 24-28 hours). Increased satellite images to twice a day can be included for an additional cost. The average cover for the field will then be every 12-14 hours.

7.2.2 Pressure or temperature monitoring

Pressure or temperature monitoring is an internal leak detection system. As for a MBS measured values for the monitored parameter are compared with simulated values that predict expected pressure/temperature at normal flow and production. Deviations in measured and predicted values indicate a leak in the system and are notified with an alarm.

7.2.3 Fiber optic

Leak detection using distributed fiber optic sensors can be a comprehensive solution for continuous, in-line, real-time monitoring of various pipelines. The monitoring of temperature profiles over long distance by means of optical fibers represents a highly efficient way to perform leak detection along pipelines. It works over long distances and large areas, without any disruption, and sends responses in real-time. An alternative to measuring temperature can be to use fibre optical cables as microphones. Distributed Acoustic Sensing (DAS) is undergoing testing on Johan Sverdrup and is still a technology under development.

7.2.4 Active acoustic leak detection (METAS)

Active acoustic leak sensors are based on the same principle as sonars and emit pulses of sound that are reflected from boundaries between different media (boundaries of impedance change[1]). Fluids of different density will have different acoustic impedance. This means that as the sound pulse travels through water and hits a bubble of gas or droplet of oil, sound will be reflected. This technology does not depend on the leaking medium being of a specific composition; however, the acoustic impedance must be different to that of water.

Active acoustic methods can be applied either for area coverage or local coverage as a point sensor. Leak positioning, quantification and trend monitoring is possible when using active acoustic methods. Both oil and gas can be detected using this technique. The sensitivity for gas is high, due to the high impedance contrast to water (assumed lower sensitivity for oil). Larger droplets or plumes of a leaking medium will give a stronger backscattered acoustic signal and are easier to detect. Experience has shown that the performance will depend on water depth, as gas bubble size will change with water depth. When used for area coverage the detection range will depend on type of sensor, quantity released and minimum detection threshold. Due to the active function and high processing demands, active acoustic sonar detectors require more bandwidth and power than passive acoustic detectors. Depending on type of sensor and application, alarms generated can be either manual or automatic.

METAS has commercially available a Wide Area Active Monitoring (WAAM) System designed for subsea installation. The WAAM system measures up to 1,000 meters out, 360 degrees around and from 0 to 90 degrees in the vertical plane, resulting in one-unit monitoring 3.14 km2 of the subsea field. For analysing detected leakages, an in house developed software system is used. To maximize performance and minimize operational interruptions, the WAAM System software incorporates machine learning. This allows tracking of all acoustic responses, classification and analysis to determine if an alarm should be reported or merely an interesting data point recorded for future analysis. If leakage is identified, the system will alarm and begin reporting approximate leakage rates. Additional information is available on demand, so as not to distract the operator. This information includes location of leak, plume size, distribution, direction of travel, and much more. METAS WAAM has been installed on Troll B since November 2019 and have validated detection on gas leak rate <8 l/min at a distance of 350 meters from sensor and <15 l/m 850 meters from sensor.

[1] The impedance is a material characteristic and depends on sound velocity, density, salinity and temperature of the medium

METAS has also available a Specified Area Active Monitoring (SAAM) System with fixed sonar with multiple transducers. Range will be 10 to 4000 meters depending on transducer selection.

Sonardyne also delivers an active acoustic leak detection system called Sentry. The Sentry integrity monitoring sonar system has been developed to automatically warn of integrity breaches around subsea oil and gas assets. The system is capable of monitoring seawater, with 360° of coverage from one sonar sensor location.

7.2.5 ROV inspections

Leaks from seabed installations can also be detected by visual inspections with ROV (remote operating vehicle). One limitation of offshore visual inspections is the low frequency of inspection intervals. Range and ability for leak detection is also dependent on size of ROV and equipment on the ROV.

7.2.6 Underwater Inspection Drones (UID)

Underwater drone with camera, sensors for detection and other equipment for inspection of subsea installations and structures. The drone will send real time data to a server for further processing. Advantage of underwater drones is that they can operate almost continuously and cover large areas over a short period of time. They will need some time off to re-charging and for maintenance.

Table 7-1 *Summary of relevant leak detection techniques for Krafla development. Base case for Krafla is shown in bold and blue.*

Technique	Surface / Subsea	Valid for oil or gas	Coverage	Range/ distance from leak source (m)	Performance requirements			TRL level for LD	BAT	Comments
					Time	Volume	Unit			
Satellite radar	Surface	Oil	Surface area	AOI	24 h - 5 days	0.1 ton in 0.25 km2	na	7	Yes	Covers pre-defined areas of interest (AOI). Most of the modelled scenarios in the analysis will reach the surface and create an oil film that will be detectable by satellite. Under normal conditions the satellite have an average frequency of 24-28 hours for AOI on NCS, but weather conditions and other use of the satellite may cause a longer detection time. See Table 5-1 for weather limitations for the Krafla area.
Increased frequency for Satellite radar images	Surface	Oil	Surface area	AOI	12 h – days	0.1 ton in 0.25 km2	na	7	Yes	Increased frequency of 12-14 hours for AOI on NCS, but weather conditions and other use of the satellite may cause a longer detection time.
X-band OSD radar	Surface	Oil	Surface area	3-5 km*	min-hours	Sheen (Thickness of oil slick)	na	7	Yes	Detection range is dependent on installed angel of the OSD and weather situation. The OSD radar can help determine position, area and drift direction, but cannot calculate amount of oil at sea. *E.g., Miros OSD radar has a range of 2-4 km in short pulse mode, and 4-7 km in medium pulse mode. See Table 5-1 for weather limitations for the Krafla area.
ISPAS radar	Surface	Oil	Surface area	4 km	1 h	>4	m3	7	Yes	The TRL level 7 is for oil detection and not as a marine radar. 360-degree detection. Needs to be installed high (50-100 meter). Detection volume is for Beaufort Sea conditions 0-6 (test conditions from Lundin Norway and Equinor, 2018).
				3 km	1 h	>1	m3			
Mass balance single phase system	Internal	Oil and gas	Pipeline/ riser	na	10 min - 1 hour	1-5 % of nominal flow	%	7	Yes	The TRL level is for one phase flow. Performance dependent on available metering and quality of measurements.
Mass balance multi-phase system	Internal	Oil and gas	Pipeline/ riser	na	1-2 h	10-15 % of nominal flow	%	1	No	Aim to detect leaks >30 % of plateau rates within 1-2 hours. Performance is mainly dependent on available metering and quality of measurements and level of transients in the system.

Technique	Surface / Subsea	Valid for oil or gas	Coverage	Range/ distance from leak source (m)	Performance requirements			TRL level for LD	BAT	Comments
					Time	Volume	Unit			
Pressure/ temperature monitoring	Internal	Oil and gas	Pipeline/ riser	Along pipeline	min-hours	na			No	For pipeline and risers.
Fiber optic	Subsea	Oil and gas	Pipeline	Along pipeline	min-hours	na		0	No	A potential continuous and steady detection for pipelines. A feasibility for DAS for leak detection has to be evaluated.
Active acoustic (Metas)	Subsea	Oil and gas	Subsea area (1-4 km)	500	min-hours	<5**	l/m	4	No	TRL 4 is the target by end 2021. Active acoustic sensors have a relatively high power-demand. The sensors can either use battery packs or electricity from the field. If the sensor is on 10 min every hour and battery module have 4 batteries, they need to be changed every 90 months. Replacement of battery module can be done with ROV. ** The performance numbers are only valid for gas.
				1000		<90**	l/m			
Passive acoustic (Naxys)	Subsea	Oil and gas	Subsea area (500 m)	9	min-hours	7	l/m	7	Yes	One sensor will give direction for leak, but two sensors will give position for leak. Lifetime up to 30 years.
				0		5	l/m			
				40		14	l/m			
Methane sniffers (Franatech)	Subsea	Oil and gas	Point /area (0-50 m)	0	1 h	0.05 (close to leak)	l/m	7	No	TRL level given for methane sniffing sensor, not for complete LD system (TRL 3 for LD system). Based on numbers and locations, the sniffers can have area coverage. 25 years lifetime.
ROV	Subsea	Oil and gas	Subsea area	Field/ pipeline	years			***	Yes	ROV inspections have a frequency of ~1-4 years. Range and leak detection ability is dependent on size and equipment of ROV. ***TRL for leak detection is dependent on what type of techniques the ROV is equipped with.
UID (Underwater Inspection Drone)	Subsea	Oil and gas	Subsea area	1 km	24 h			3	No	Assumed that all leak sizes will be detected (optimistic). Needs to be validated for use with regards to e.g., battery time and sending and processing of real time data. Continuous inspection of all subsea installations (battery time etc.) and sending and processing of real time data. Advantage: can be used for more than leak detection.
				5 km	7 days					
				>5 km	30 days					

8 LEAK DETECTION PHILOSOPHY FOR KRAFLA DEVELOPMENT

8.1 Summing up

The results from the modelling of the different scenarios shows that most of the leaks from hole sizes ≥10 mm will reach surface and can be detected by surface techniques like radar, satellite, and observations. However, the smaller leaks can be trapped in the water column and will not reach the surface. The smaller leaks are placed in the green and acceptable part of the environmental risk matrix, but some of them may reach yellow if the leaks last long and the environmental resources is exposed for a longer time. For the scenarios and leak sizes that is not expected to reach the surface, subsea leak detection techniques must be available.

It is important to keep in mind the uncertainties in the analysis when looking at the results. All the modelled scenarios have an exit velocity above 80 m/s. According to SINTEF the adjustment of oil droplet sizes with exit velocity above 10 m/s increases in uncertainty with increasing velocity. High velocity crushes the oil droplets into smaller droplets and smaller droplets will stay in the water column without reaching the surface. This means that some of the scenarios reported as trapped in the water column could have resulted in an increased/higher surface detection ability.

Satellite (radar) has a 24–28-hour detection time. This detection frequency is given good weather conditions and full availability of the satellite. The availability of the satellite is about 95 % according to KSAT. The weather conditions for optimal satellite detection in the Krafla area is above 80 % during the summer months (May-August) and between 44 % and 79 % in September to April. A percentage value of more than 50 % indicates that the satellite can detect leaked oil on the sea surface more frequently than every other day. Taken the limitations for satellite into account a more realistic detection time may vary between one day and five days with a lower maximum detection time during the summer months.

The scenarios are run with a 7-day duration, and with sensitivity for a longer duration of 30 days for some scenarios on Krafla SPS. The results from the sensitivity modelling shows a small escalation potential regarding possible seabird impacts for the 10 mm leak and a larger escalation for the larger 20 mm leak. This also implies increased detectability for a leakage with longer duration but not for the 5 mm leak that had neither impact nor detectability on the 7-day simulation. Impacts will also increase due to longer exposure time in the area for a long-lasting leakage.

The upper 50 meters of the water column is basis when looking at THC concentrations in the water column, but a sensitivity looking at the total water depth (110 meter) is included for one scenario. A larger impact area is recorded when comparing the upper 50 meters vs. the whole water column. This may partly be due to averaging over larger water column blocks for the 110-meter scenario, but nevertheless indicates that the highest concentrations are in the uppermost layers.

The effect limit for fish egg and larvae is set to 58 ppb in the environmental risk method (ERA Acute). Recently there has been discussions in the research community that 58 ppb is a too high effect limit for some species like sandeel, and there are research going on to find effect limits for these species. A sensitivity is done with a very conservative limit of 10 ppb for scenarios at Krafla LP (UPP) for 5 mm and 30 mm. The influence areas in the water column from the 5 mm leak is not overlapping with the defined sandeel areas neither for the 58-ppb limit or for the 10-ppb limit. The influence areas in the water column from the 30 mm leak will overlap with the defined sandeel areas both for the 58-ppb limit and for the 10-ppb limit, but this leak will reach the surface and can be detected by satellite or other surface detection techniques within days. The potential effects on sandeel will be further addressed in the environmental risk analysis for Krafla.

8.1.1 Krafla Liquid Export line (KLE) between UPP and NOA PdQ

For Krafla liquid export line (KLE) the leaks from 2.5 mm and 5 mm hole size will not reach the surface, while the bigger leaks (≥ 10 mm) are expected to reach the surface and create an oil film on the surface that can be detected by radar on platform or vessel or by satellite. The small leaks are placed in the green part of the risk matrix with potential for consequences in minor category. The leaks are modelled with 7 days duration and it is expected that after a longer time and a longer exposure time the consequences will go up a category and into the yellow part of the risk matrix. 10 mm leaks are placed in the yellow part of the risk matrix with potential for moderate consequences.

8.1.2 16’’ Krafla production line Krafla SPS – UPP, KP 0.1

For Krafla production line (at SPS side) the leaks from 2.5 mm and 5 mm hole size will not reach the surface, while the bigger leaks (≥ 10 mm) are expected to reach the surface and create an oil film on the surface that can be detected by vessel or by satellite. The small leaks are placed in the green part of the risk matrix with potential for consequences in minor category. The leaks are modelled with 7 days duration and it is expected that after a longer time and a longer exposure time the consequences will go up a category and into the yellow part of the risk matrix. ≥ 10 mm leaks are placed in the green and yellow part of the risk matrix with potential for moderate – serious consequences.

8.1.3 16’’ Krafla production line Krafla SPS – UPP, UPP seabed (inside 500-meter zone)

For Krafla production line (at UPP side) the leaks from 2.5 mm and 5 mm hole size will not reach the surface, while the bigger leaks (≥ 10 mm) are expected to reach the surface and create an oil film on the surface that can be detected by radar on platform or vessel or by satellite. The small leaks are placed in the green part of the risk matrix with potential for consequences in minor category. The leaks are modelled with 7 days duration and it is expected that after a longer time and a longer exposure time the consequences will go up a category and into the yellow part of the risk matrix. 10 mm -90 mm leaks are placed in the green and yellow part of the risk matrix with potential for minor – very serious consequences.

8.1.4 16’’ Askja production line Askja SPS – UPP, KP 0.375

For Askja production line (at KP 0.375) the leaks from 2.5 mm, 5 mm and 10 mm hole size will not reach the surface, while the bigger leaks (≥ 20 mm) are expected to reach the surface and create an oil film on the surface that can be detected by radar on platform or vessel or by satellite. The small leaks are placed in the green part of the risk matrix with potential for consequences in minor category. The leaks are modelled with 7 days duration and it is expected that after a longer time and a longer exposure time the consequences will go up a category and into the yellow part of the risk matrix. 20 mm -100 mm leaks are placed in the green and yellow part of the risk matrix with potential for moderate – very serious consequences.

8.1.5 Pipeline Bundle concept

The bursting discs on the bundle is 2’’ in diameter and this is about the same size as a 50 mm leak modelled in this study. For all modelled scenarios equal or above 50 mm leak size the leak is expected to reach the surface and can be detected on the sea surface. All these scenarios have a possibility for considerable and serious environmental effects and should be detected within hours to a week.

8.1.6 Umbilicals

The umbilicals contain production chemicals and helping chemicals (see list in Appendix A). The volumes of the different chemicals in the umbilical are small. There is not decided on chemical supplier for Krafla, so the list of chemicals is only given with application area. MEG and TEG will have the largest volume in the umbilicals. MEG is classified as green and is water-soluble. TEG is classified as yellow but are non-toxic, water-soluble and will not accumulate. Two main principles for monitoring of fluids in the umbilicals can be applied for Krafla (Equinor, 2021d):

- Rate measurement. Equinor measure consumption and NOA measures what is sent out. May be inaccurate because there are many consumers. The MEG system is primarily measured at PdQ.
- Pressure measurement at shut in. Measures both at PdQ and UPP / SPS. Can for example be done in connection with shut in or revision shutdown.

There may also be a need to develop a software application that estimates consumption, but in the early planning phase it is difficult to give any accuracy for this (Equinor, 2021d).

8.2 Suggested environmental risk-based leak detection philosophy for Krafla

Krafla is located close to a defined sensitive sandeel habitat at *Vikingbanken* and it is important that subsea leaks with potential to give environmental consequences will be detected within short time. Equinor consider local subsea leak detection at template as BAT and will install subsea leak detection on Krafla. Different leak detection techniques are available for Krafla. The base case for the development is to have satellite (SAR) surveillance, mass balance for the multi-phase Krafla Liquid Export Line (KLE), Franatech sniffer sensors and Naxys passive acoustic leak detection sensors at templates. In addition, enhanced satellite surveillance, OSD radar, active acoustic sensors, ROV inspections, Subsea drones and fiber optic are suitable for leak detection at Krafla. Number and location of the sensors must be discussed and agreed by Equinor and suppliers when the final concept is selected for Krafla and appropriate costs / benefit assessments are available.

Scenarios with consequence potential in the yellow part of the risk matrix (serious and very serious) should be detected quickly and within hours to a day (suggested functional requirements). These scenarios have a potential to reach the surface but taking the limitations for satellite into account a more realistic detection time will be a few days. A OSD radar is continuously swiping the surface around installations with a range and coverage depending on the installed height of the radar and other equipment on the installation. Enhanced satellite coverage will increase the picture frequency from one picture every 24-28 hours to one picture every 12-14 hours, and with the detection limitations (weather etc.) the detection time can be around 1 day (lower maximum detection time during summer). Regarding OSD radar both x-band radar and ISPAS radar can be chosen, but in addition to what the x-band radar can determine, the ISPAS radar can potentially say something about amount of oil and is also minimal affected by waves, weather, and light conditions. The range for ISPAS radar is up to 5 km with an installation height between 50-100 meters.

The operators are encouraged to contribute to development and innovation of technologies. Underwater inspection drones (UID) are an important part of "a new generation ROV's". Equinor should consider testing UID on Krafla with regards to inspection of subsea installations, reliability, and calibration. For the pipeline concept, fiber optic or other pressure/temperature monitoring should be considered for leak detection.

Table 8-1 lists relevant techniques for the Krafla leak detection system based on the suggested functional requirements and Equinor's tolerance criteria for smaller leaks not expected to be detected by mass balance. Leaks in the yellow part of the risk matrix should be detected within hours to a day. This applies to the larger leaks that quickly can be detected by local sensors or reach the surface and be detected by radar and/or satellite. The different techniques are complementary and will together provide a robust overall philosophy, given appropriate operational procedures for alarm handling and operation included personnel training.

Table 8-1 *Relevant techniques for the Krafla leak detection system based on the suggested functional requirements and Equinor's tolerance criteria for small leaks. The modelled scenarios have leak rates lower than what a mass balance system will be able to detect. Techniques in brackets indicate reduced detection possibilities based on rate (passive acoustic) or reduced probability for surface detection (Satellite and radar).*

Location/ scenario	Hole size (mm)	Leak rate (kg/s)	Leak rate (m³/d)	Leak rate (l/min)	Leak frequency	Probability for surface detection	Consequences surface (seabirds)	Consequences water column (fish egg/larvae)	Env. risk-based functional requirement (time)	5000 m³ (days)	Relevant techniques for leak detection
Krafla Liquid export line (Midway UPP - PdQ)	**2.5**	0,3	29	20	3,47E-03	No	Insignificant	Insignificant	< 1 year	173	Subsea drone, ROV, Fiber optic
	5	1,1	115	80	3,47E-03	No	Insignificant	Minor	weeks (month)	43	Subsea drone, ROV, Fiber optic
	10	4,6	458	318	3,47E-03	Low	Minor	Moderate	week	11	(Satellite), (radar), Fiber optic
16'' Krafla production line between Krafla SPS and UPP, KP 0.1	**2.5**	0,2	19	13	4,27E-03	No	Insignificant	Insignificant	< 1 year	262	Subsea drone, ROV, Active, or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	5	0,8	76	53	4,27E-03	No	Insignificant	Minor	months	66	Subsea drone, ROV, Active, or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	10	3,0	299	208	4,27E-03	Low	Insignificant	Moderate	weeks	17	Subsea drone, ROV, Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	20	11,3	1117	776	1,31E-04	Moderate	Minor	Considerable	1 day	4	Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	30	19,6	1957	1359	6,16E-05	Moderate	Moderate	Considerable	1 day	3	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	40	32,5	3238	2249	4,06E-05	High	Moderate	Considerable	1 day	2	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	50	45,7	4564	3169	2,06E-05	High	Considerable	Serious	hours	1	(Satellite), (radar), Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
16'' Krafla production line	**2.5**	0,0	4	3	4,24E-03	No	Insignificant	Insignificant	year(s)	1224	Subsea drone, ROV, (passive acoustic), sniffers, Fiber optic, pressure/temperature monitoring

Location/ scenario	Hole size (mm)	Leak rate (kg/s)	Leak rate (m³/d)	Leak rate (l/min)	Leak frequency	Probability for surface detection	Consequences surface (seabirds)	Consequences water column (fish egg/larvae)	Env. risk-based functional requirement (time)	5000 m³ (days)	Relevant techniques for leak detection
between Krafla SPS and UPP, UPP seabed (inside 500 m zone)	**5**	0,2	16	11	4,24E-03	No	Insignificant	Insignificant	< 1 year	306	Subsea drone, ROV, Active, or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	10	0,7	65	45	4,24E-03	Low	Minor	Minor	months	77	Subsea drone, ROV, (Satellite), (radar), Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	20	2,7	259	180	7,17E-04	Moderate	Moderate	Moderate	weeks	19	Subsea drone, ROV, Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	30	6,1	575	399	1,96E-04	High	Moderate	Considerable	days	9	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	40	10,6	1004	697	5,35E-05	High	Considerable	Considerable	days	5	Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	50	16,8	1599	1110	3,35E-05	High	Considerable	Considerable	1 day	3	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	60	23,5	2238	1554	1,13E-05	High	Considerable	Considerable	1 day	2	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	70	30,9	2947	2047	1,01E-05	High	Considerable	Considerable	1 day	2	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	80	38,9	3706	2574	4,28E-05	High	Considerable	Serious	hours	1	(Satellite), (radar), Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	90	47,1	4488	3116	4,44E-05	High	Serious	Serious	hours	1	(Satellite), (radar), Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
16'' Askja production line between Askja	**2.5**	0,02	2	2	4,85E-03	No	Insignificant	Insignificant	year(s)	2189	Subsea drone, ROV, (passive acoustic), sniffers, Fiber optic, pressure/temperature monitoring
	5	0,1	9	6	4,85E-03	No	Insignificant	Insignificant	year	547	Subsea drone, ROV, (passive acoustic), sniffers, Fiber optic, pressure/temperature monitoring

Location/ scenario	Hole size (mm)	Leak rate (kg/s)	Leak rate (m^3/d)	Leak rate (l/min)	Leak frequency	Probability for surface detection	Consequences surface (seabirds)	Consequences water column (fish egg/larvae)	Env. risk-based functional requirement (time)	5000 m^3 (days)	Relevant techniques for leak detection
SPS and UPP, KP 0.375	**10**	0,4	37	25	4,85E-03	No	Minor	Minor	months	137	Subsea drone, ROV, Active, or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	20	1,5	146	101	2,99E-04	Moderate	Moderate	Moderate	weeks (month)	34	Satellite, radar, Subsea drone, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	30	3,5	328	228	1,25E-04	Moderate	Moderate	Moderate	week	15	Satellite, radar, Subsea drone, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	40	6,1	581	403	6,11E-05	High	Moderate	Considerable	week	9	Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	50	9,5	904	627	3,12E-05	High	Considerable	Considerable	days	6	Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	60	13,6	1295	899	1,76E-05	High	Considerable	Considerable	days	4	Satellite, radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	70	18,5	1753	1217	1,53E-05	High	Considerable	Considerable	1 day	3	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	80	24,0	2274	1579	2,39E-05	High	Considerable	Considerable	1 day	2	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	90	30,1	2855	1983	2,71E-05	High	Considerable	Considerable	1 day	2	(Satellite), radar, Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	100	36,7	3486	2421	4,04E-04	High	Considerable	Serious	hours	1	(Satellite), (radar), Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring
	120	50,8	4819	3347	4,04E-04	High	Serious	Serious	hours	1	(Satellite), (radar), Active or passive acoustic, sniffers, Fiber optic, pressure/temperature monitoring

8.3 Cost / Benefit evaluations

Equinor's cost for different environmental consequences in accordance with internal guideline for ALARP principles (Guideline, GL0139, Final Ver. 5.0, 2019) is shown in Table 8-2.

Table 8-2 *Cost for the different environmental consequences from Equinor for use in the ALARP evaluations.*

Consequence category	Value/Cost
1 – 3 Low / Minor	0 USD
4 – Moderate	20 000 000 USD
5 – Serious	100 000 000 USD
6 – Very Serious	500 000 000 USD
7 – Major	3 000 000 000 USD
8 – Catastrophic	10 000 000 000 USD

Leak frequencies and consequence categories for the different leak scenarios modelled in this study is given a cost in Table 8-3. Cost given by Equinor for enhanced Satellite coverage per day (one extra image per day), ISPAS radar, Active and passive acoustic sensors and subsea drones are included in the cost-benefit evaluations. The costs are given for consequence category Moderate and above. The scenarios selected for this analysis is smaller leaks not expected to be detected by mass balance or other process monitoring, hence mass balance and Pal/PALL are not included.

Negative numbers in green indicate a benefit. Note that the cost is estimated based on 1 or more detection technique/sensor and that the number of sensors must be discussed with the suppliers to agree on sufficient coverage for the field. CAPEX costs are distributed on 10 years. An Excel sheet is delivered together with this report, so Equinor can change the number of sensors/techniques to evaluate the costs and benefit by adding additional number of sensors/techniques. Satellite, x-band radar and acoustic sensors are the most cost-beneficial techniques. Note that ISPAS radar have a higher CAPEX cost than x-band radar, and that same assumptions on detection has been made for these two techniques. METAS sensors have limited range and are therefore more limited in detection than subsea drone along a pipeline and cost savings on the pipeline are limited to pipeline ends. These two techniques are the only ones to detect leaks that will not reach the surface and in combination with surface detection techniques (satellite radar and radar) would form the best leak detection system for the Krafla field.

Environmental consequences as indicated in Table 8-3 are based on modeling of leaks lasting one week. It seems obvious that the level of consequence can increase in the event of longer-lasting leaks (weeks, months). In the ERA Acute method for calculating mortality on seabirds and marine mammals, exposure time is a parameter in the damage calculation, and mortality increases with increasing exposure time of oil at sea. Exposure time follows an exponential curve and mortality increases, for example, from 10 % at 1 day oil exposure to 19 % at 2 days oil exposure and further to 52 % at one week exposure time for a vulnerable Auke (ERA Acute methodology). There will also be a continuous replacement of birds in the exposed area and hence the level of impact will increase for a long-term leak. Based on this, a sensitivity has been made to the cost calculations by assuming surface detection techniques will be in place to detect all surface detectable spills and allowing consequences for non-detectable surface spills to increase due to prolonged leak duration (one month). In such a case one subsea drone and possibly 2 drones will be cost-beneficial assuming they could cover the entire pipelines within a month. In case of need of 3 subsea drones to cover the entire pipeline, that would not be cost-beneficial.

Table 8-3 *Cost for each leak scenario based on environmental consequences (after 7 days modelling) and leak frequencies, and cost for the different leak detection techniques: additional Satellite images per day, ISPAS radar, Metas active acoustic and subsea drones. Negative numbers (in green) indicate a benefit.*

Functional Location	Location	Leak size (mm)	Leak rate oil (m^3/d)	Seabirds	Fish	SAR detection	Leak frequency	Cost (USD)	Cost (USD) pr. year	Cost (NOK) pr. year					
										Satellite (enhanced)	ISPAS	X-band radar	Metas	Subsea drone	
Krafla Liquid export line	Midway UPP - PdQ	2.5	29	Insignificant	Minor	No									
		5	115	Insignificant	Minor	No									
		10	458	Minor	Moderate	Low	3.47E-03	20 000 000	69 491	kr 599 012	kr 88 743	kr 88 743	kr 22 186	kr 110 928	
16" Krafla production line Krafla SPS – UPP	SPS seabed	2.5	19	Insignificant	Minor	No									
		5	76	Insignificant	Minor	No									
		10	299	Minor	Moderate	Low	4.27E-03	20 000 000	85 472	kr 736 769			kr 109 965	kr 736 769	
		20	1117	Minor	Considerable	Moderate	1.31E-04	100 000 000	13 080	kr 90 200			kr 16 828	kr 112 750	
		30	1957	Moderate	Considerable	Moderate	6.16E-05	100 000 000	6 156	kr 53 065			kr 7 920	kr 53 065	
		40	3238	Moderate	Considerable	High	4.06E-05	100 000 000	4 064	kr 35 032			kr 5 229	kr 35 032	
		50	4564	Considerable	Serious	High	2.06E-05	500 000 000	10 320	kr 85 400			kr 13 277	kr 88 958	
	UPP seabed	2.5	4	Insignificant	Insignificant	No									
		5	16	Insignificant	Minor	No									
		10	65	Minor	Minor	Low	4.24E-03								
		20	259	Moderate	Moderate	Moderate	7.17E-04	20 000 000	14 339	kr 123 604	kr 53 163	kr 53 163	kr 13 291	kr 123 604	
		30	575	Moderate	Considerable	High	1.96E-04	100 000 000	19 579	kr 168 770	kr 72 589	kr 72 589	kr 18 147	kr 168 770	
		40	1004	Considerable	Considerable	High	5.35E-05	100 000 000	5 349	kr 46 104	kr 19 830	kr 19 830	kr 4 957	kr 46 104	
		50	1599	Considerable	Considerable	High	3.35E-05	100 000 000	3 352	kr 28 893	kr 12 427	kr 12 427	kr 3 107	kr 28 893	
		60	2238	Considerable	Considerable	High	1.13E-05	100 000 000	1 130	kr 9 737	kr 4 188	kr 4 188	kr 1 047	kr 9 737	
		70	2947	Considerable	Considerable	High	1.01E-05	100 000 000	1 013	kr 8 735	kr 3 757	kr 3 757	kr 939	kr 8 735	
		80	3706	Considerable	Serious	High	4.28E-05	500 000 000	21 391	kr 184 394	kr 79 309	kr 79 309	kr 19 827	kr 184 394	
		90	4488	Serious	Serious	High	4.44E-05	500 000 000	22 194	kr 191 317	kr 82 287	kr 82 287	kr 20 572	kr 191 317	
16" Askja production line Askja SPS - UPP	Midway SPS - UPP	2.5	2	Insignificant	Insignificant	No									
		5	9	Insignificant	Insignificant	No									
		10	37	Minor	Minor	No	4.85E-03								
		20	146	Moderate	Moderate	Low	2.99E-04	20 000 000	5 983	kr 51 577	kr 51 577	kr 51 577	kr 51 577	kr 51 577	
		30	328	Moderate	Moderate	High	1.25E-04	20 000 000	2 506	kr 21 601	kr 21 601	kr 21 601	kr 21 601	kr 21 601	
		40	581	Moderate	Considerable	High	6.11E-05	100 000 000	6 113	kr 52 694	kr 52 694	kr 52 694	kr 52 694	kr 52 694	
		50	904	Considerable	Considerable	High	3.12E-05	100 000 000	3 116	kr 26 863	kr 26 863	kr 26 863	kr 26 863	kr 26 863	
		60	1295	Considerable	Considerable	High	1.76E-05	100 000 000	1 756	kr 15 133	kr 15 133	kr 15 133	kr 15 133	kr 15 133	
		70	1753	Considerable	Considerable	High	1.53E-05	100 000 000	1 525	kr 13 148	kr 13 148	kr 13 148	kr 13 148	kr 13 148	
		80	2274	Considerable	Considerable	High	2.39E-05	100 000 000	2 391	kr 20 612	kr 20 612	kr 20 612	kr 20 612	kr 20 612	
		90	2855	Considerable	Considerable	High	2.71E-05	100 000 000	2 713	kr 23 390	kr 23 390	kr 23 390	kr 23 390	kr 23 390	
		100	3486	Considerable	Serious	High									
		120	4819	Serious	Serious	High	4.04E-04	500 000 000	201 807	kr 1 739 580	kr 748 206	kr 748 206	kr 1 739 580	kr 1 739 580	
										kr 4 325 627	kr 1 389 516	kr 1 389 516	kr 2 221 890	kr 3 863 651	*saving per year*
								Unit cost		kr 1 825 000	kr 1 800 000	kr 30 000	kr 500 000	kr 1 800 000	*cost per year*
								Number of units		1	1	1	2	3	
								Sum		-kr 2 500 627	kr 410 484	-kr 1 359 516	-kr 1 221 890	kr 1 536 349	*sum per year*

8.4 Recommendations

The base-case techniques for Krafla leak detection philosophy includes:

- Satellite (SAR)
- Mass balance (multi-phase for Krafla Liquid Export Line (KLE))
- ISPAS radar (UPP)
- Franatech methane sniffer sensor at each template
- Naxys passive acoustic leak detection at each template
- Visual observations from UPP (during maintenance) and from vessels, helicopter, and surveillance plane

Table 8-4 give an overview of relevant leak detection techniques available for Krafla and whether these techniques are required or recommended for implementation by Krafla in addition to the base case technologies. The recommendations are given based on the suggested functional requirements (from the environmental risk assessment) and Equinor's tolerance criteria. If the bundle concept is chosen, Naxys passive acoustic sensors should be placed at the towheads/templates and close to the location of the three bursting discs (the highest point on the pipeline route).

Table 8-4 *Relevant leak detection technologies, either required or recommended for implementation by Krafla, in addition to the "Base case" technologies (in bold). The table also include technologies for further exploration (not considered BAT today because of low TRL). (NA = Not applicable, e.g., due to not technically feasible).*

Leak detection technique	Location	Krafla Liquid Export Line (KLE)	16" Krafla production line, Krafla SPS - UPP, KP 0.1	16" Askja production line, Askja SPS - UPP, UPP side	16" Askja production line, Askja SPS - UPP, KP 0.375	Comments
Mass balance	Internal	Base case	Required	Required	Required	Multi-phase mass balance is base case for KLE (from UPP to NOA PdQ, 27 km).
Methane sniffer	Subsea	NA	Base case	Base case	Base case	Base case on subsea templates. The export line between Krafla UPP and NOA PdQ (KLE) is 27 km and too long to be covered by sufficient number of local sensors.
Passive acoustic	Subsea	NA	Base case	Base case	Base case	Base case on subsea templates. The export line between Krafla UPP and NOA PdQ (KLE) is 27 km and too long to be covered by sufficient number of local sensors.
Satellite (SAR)	Surface (AOI)	Base case	Base case	Base case	Base case	
ISAPAS radar (on IPP)	Surface	Base case	Base case	Base case	Base case	Based on functional requirements Krafla UPP side, Askja SPS. Much shorter response time than SAR.
ROV inspection	Subsea	Required	Recommended	Recommended	Recommended	Evaluate ROV required frequency based on tolerance criteria 5000 m^3.
Increased satellite radar images (SAR)	Surface (AOI)	NA	Recommended	Recommended	Recommended	Based on functional requirements with detection

						within hours to one day in order to cover total pipelines (outside OSD radar area). For KLE none of the modelled leaks is expected to reach surface, and increased satellite radar images will not be applicable for small leaks from this pipeline.
Pressure/ temperature monitoring in carrier pipe	Internal	NA	Recommended	Recommended	Recommended	Based on functional requirements hours - 1 day. Only applicable for Bundle concept.
Active acoustic	Subsea	Explore further	Explore further	Explore further	Explore further	Not BAT
Fiber optic	Internal/ subsea	Explore further	Explore further	Explore further	Explore further	Not BAT
Underwater drones	Subsea	Explore further	Explore further	Explore further	Explore further	Not BAT

9 SUGGESTION FOR FURTHER STUDIES/DOCUMENTATION

Suggestions for further studies and documentation are:

- Work with suppliers to decide and plan for location and number of sensors for the different techniques on the Krafla field.
- Since there are many uncertainties in both leak rates and frequencies for a bundle, it is suggested to do a more detailed frequency analysis for the bundle, and model leak rates for the bundle concept in OLGA for a more robust comparison of the two pipeline concepts.
- Get information about the chemicals to be used on Krafla and get information on the environmental classification of each chemical when the chemical supplier is selected.
- Check possibilities for testing (technology qualification) of UID, fiber optic and/or active acoustic in the leak detection system for Krafla.

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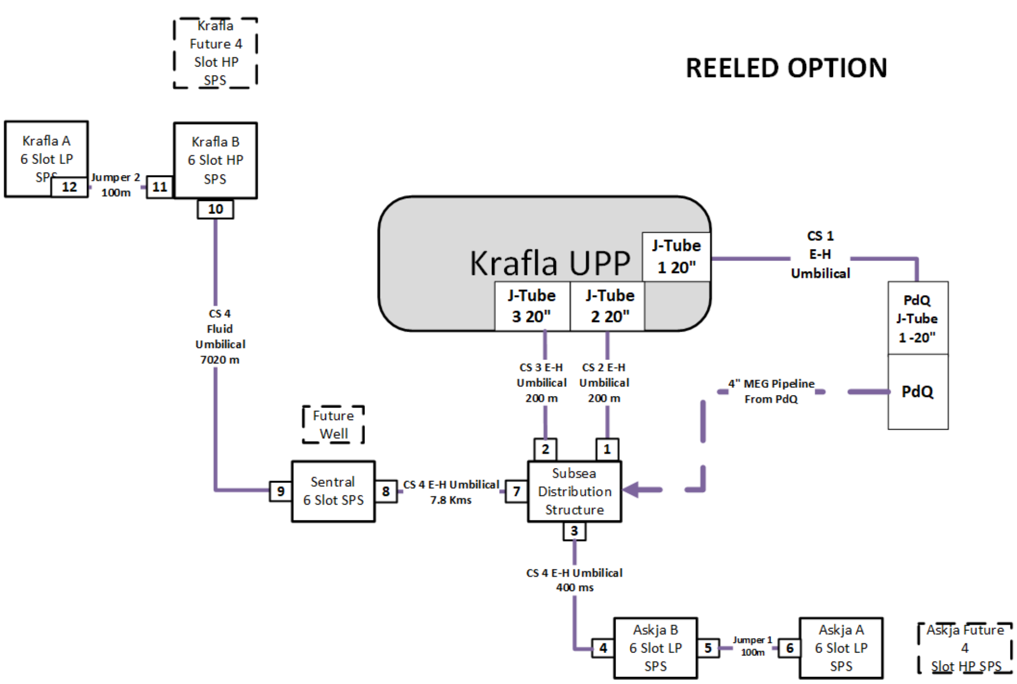
APPENDIX A
Chemicals on Krafla

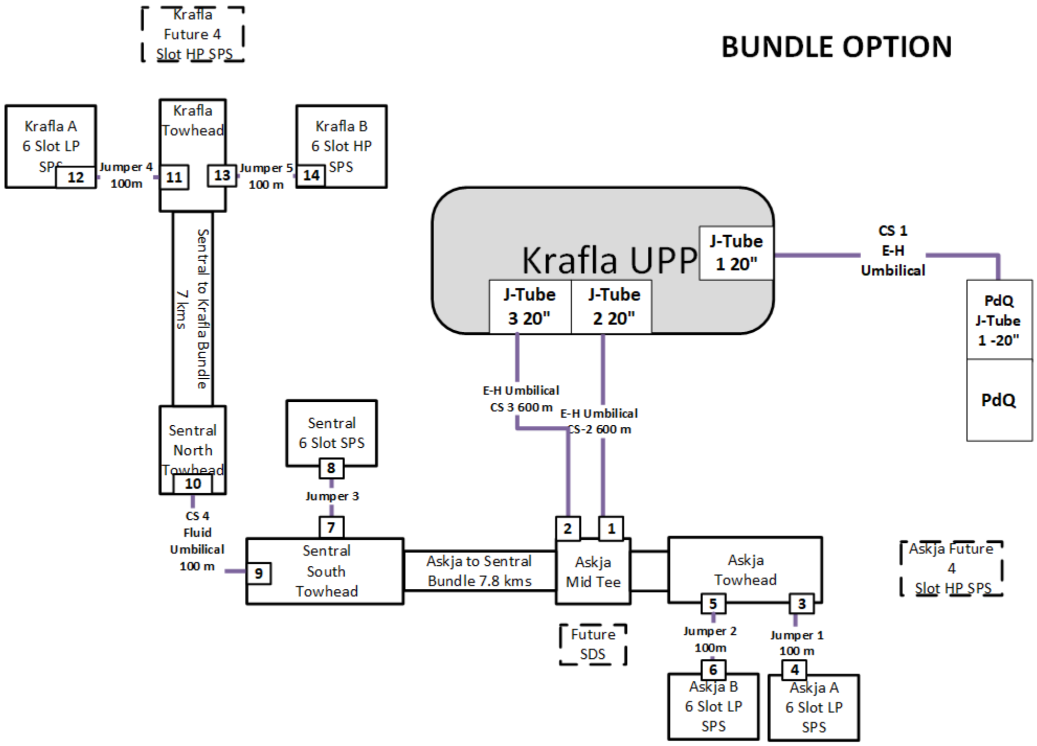
Chemical overview Updated Oct.21

		Size ID		Rating	Area	Length	Volume
		[inch]	[mm]	[bar]	[m²]	[m]	[m³]
MEG pipeline from NOA PdQ to Mid Line Towhead	1	3,62	92,00	628	0,006648	27482	182,7
Umbilical NOA PdQ - Askja UPP							
Lean TEG 1	1	1,5	38,10	517	0,00114	28271	32,2
Lean TEG 2	1	1,5	38,10	517	0,00114	28271	32,2
Lean TEG 3	1	1,5	38,10	517	0,00114	28271	32,2
Lean TEG 4	1	1,5	38,10	517	0,00114	28271	32,2
Nitrogen	1	1	25,40	517	0,000507	28271	14,3
HPU supply / fill up line	1	0,625	15,88	517	0,000198	28271	5,6
Pump seal barrier fluid	1	0,625	15,88	517	0,000198	28271	5,6
Antifoam Fluid	1	0,625	15,88	517	0,000198	28271	5,6
HP MEG Service LIne	1	0,625	15,88	690	0,000198	28271	5,6
Asphaltene inhibitor	1	1,5	38,10	517	0,00114	28271	32,2
Scale Inhibitor	1	1,5	38,10	517	0,00114	28271	32,2
Scale Inhibitor HP	1	0,625	15,88	690	0,000198	28271	5,6
Spare Chemical 1	1	0,625	15,88	690	0,000198	28271	5,6
Spare Chemical 2	1	1,5	38,10	517	0,00114	28271	32,2
Spare Chemical 3	1	0,625	15,88	690	0,000198	28271	5,6
Krafla UPP Riser Umbilical A							
UPP MEG service line	1	1,5	38,10	517	0,00114	600	0,7
Scale inhibitor LP	1	1,5	38,10	517	0,00114	600	0,7
Scale inhibitor HP	1	0,625	15,88	690	0,000198	600	0,1
HP1 Hydraulic Line	1	0,5	12,70	690	0,000127	600	0,1
LP1 Hydraulic Line	1	0,625	15,88	517	0,000198	600	0,1
Spare Chemical 1	1	1,5	38,10	690	0,00114	600	0,7
Krafla UPP Riser Umbilical B							
Spare MEG service line	1	1,5	38,10	517	0,00114	600	0,7
Asphaltene Inhibitor	1	1,5	38,10	517	0,00114	600	0,7
WI MEG Service Line	1	0,625	15,88	690	0,000198	600	0,1
HP2 Hydraulic Line	1	0,5	12,70	690	0,000127	600	0,1
LP2 Hydraulic Line	1	0,625	15,88	517	0,000198	600	0,1
Spare Chemical 2	1	1,5	38,10	690	0,00114	600	0,7

Bundle or Umbilical Askja UPP - Sentral Template & Askja Template A & B							
MEG service line	1	2,5	63,50	517	0,003167	7865	24,9
WI MEG service line	1	0,625	15,88	517	0,000198	7865	1,6
Scale Inhibitor	1	1,5	38,10	517	0,00114	7865	9,0
HP Scale Inhibitor	1	0,625	15,88	517	0,000198	7865	1,6
HP 1 Hydraulic line	1	0,5	12,70	690	0,000127	7865	1,0
HP 2 Hydraulic line	1	0,5	12,70	690	0,000127	7865	1,0
LP 1 Hydraulic line	1	0,625	15,88	517	0,000198	7865	1,6
LP 2 Hydraulic line	1	0,625	15,88	517	0,000198	7865	1,6
Asphaltene inhibitor	1	1,5	38,10	517	0,00114	7865	9,0
Chemical Spare 1	1	1,5	38,10	517	0,00114	7865	9,0
Chemical Spare 2	1	1,5	38,10	517	0,00114	7865	9,0
Bundle or Umbilical from Sentral to Krafla Templates A & B							
MEG service line	1	2,5	63,50	517	0,003167	6852	21,7
WI MEG service line	1	0,625	15,88	517	0,000198	6852	1,4
Scale inhibitor	1	1,5	38,10	517	0,00114	6852	7,8
HP Scale Inhibitor	1	0,625	15,88	517	0,000198	6852	1,4
HP 1 Hydraulic line	1	0,5	12,70	690	0,000127	6852	0,9
HP 2 Hydraulic line	1	0,5	12,70	690	0,000127	6852	0,9
LP 1 Hydraulic line	1	0,625	15,88	517	0,000198	6852	1,4
LP 2 Hydraulic line	1	0,625	15,88	517	0,000198	6852	1,4
Asphaltene inhibitor	1	1,5	38,10	517	0,00114	6852	7,8
Chemical Spare 1	1	1,5	38,10	517	0,00114	6852	7,8
Chemical Spare 2	1	1,5	38,10	517	0,00114	6852	7,8



BUNDLE OPTION



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