ASSESSMENT OF THE POTENTIAL ENVIRONMENTAL IMPACTS OF A MAJOR AMMONIA SPILL FROM A POWER-TO-X PLANT AND FROM SHIPPING OF AMMONIA IN GREENLAND

Scientific Report from DCE – Danish Centre for Environment and Energy No. 487 2022

AARHUS UNIVERSITY
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Abstract:	Aarhus University, DCE - Danish Centre for Environment and Energy, has prepared an overall assessment of the potential environmental impacts from a major release or spill of ammonia in relation to production and transportation of ammonia in a PtX plant or by shipping in Greenland. Three sites were included in the assessment: Kangerlussuaq (Sdr. Strømfjord), Kangerlussuatsiaq (Evighedsfjorden) and Nuup Kangerlua (Godthåbsfjorden). The overall findings shows that a large, worst-case ammonia spill could cause severe toxic damage to organisms during the passage of the ammonia cloud from within a few km to possibly more than 10 km from the source. This could lead to local loss of animal and plant abundance for some years. However, the ammonia will be quickly diluted and degraded and will not be transferred in the food web, and the mortality will not seriously impact plant and animal populations at a regional scale. There could be a fertilising effect of ammonia on the nutrient-poor terrestrial environment lasting for some years.
Keywords:	Major ammonia spill impact, Large ammonia accident, Ammonia spill scenarios, Greenland, Ammonia Environmental impact, Greenland Power to X, Ammonia shipping accident.
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Supplementary notes:	The Danish Emergency Management Agency was invited to review the report due to their expertise in incidents involving chemicals, including ammonia. Special consultant Jan Steen Jensen reviewed the report and also tested our scenarios in their model.

Contents

Preface

The Government of Greenland is considering a tender process regarding development of hydropower potentials (> 100 MV).

The intention is to use the power generated from the potential hydropower plants to produce ammonia in a Power-to-X plant. Ammonia is considered as an alternative to fossil fuels in future shipping.

The Ministry for Agriculture, Self-Sufficiency, Energy and Environment has asked Aarhus University, DCE – Danish Centre for Environment and Energy, to prepare an overall assessment of the potential environmental impacts of a major worst-case accidental release or spill of ammonia in relation to production and shipping of ammonia in / from a Power-to-X plant in Greenland.

This report was funded by the Ministry for Agriculture, Self-Sufficiency, Energy and Environment.

Eqikkaaneq

Erngup nukissiorfiliarineqarsinnaasut (> 100 MV) suliariumannittussarsiorniarlugit Namminersorlutik Oqartussanit isumaliutigineqarpoq. Erngup nukissiorfiliarineqarsinnaasuni sarfap pilersinneqartup Power to X (PtX)-mi ammoniakkiliornermi atorneqarnissa siunertarineqarpoq. Tamatumunnga atatillugu tunisassiorfimmit PtX-mit umiarsuit ammoniakkimik assartuineranni piaaraluneernerunngitsumik aniasoornermi *pisut ajornersaanni* avatangiisitigut sunniutaasusssanik ataatsimut Aarhus Universitet, Danmarkimi Avatangiisinik Nukissiutinillu Misissuisoqarfik naliliisimavoq. Suliariumannittussarsiorneq pillugu paasissutissani sumiiffiit pingasut tunisassiorfissatut kiisalu umiarsuartigut angallassivissatut tikkuarneqarsimapput kiisalu annertuumik ajutoortoqassagaluarpat ammoniak maanngaannartinneqartussatut takorloorneqartoq nassuiarneqarsimalluni.

Sumiiffiit pingasut taakku tassaapput: Kangerlussuaq (Sdr. Strømfjord), Kangerlussuatsiaq (Evighedsfjorden) kiisalu Nuup Kangerlua (Godthåbsfjorden).

Ammoniak imerpalasoq, imertaqanngitsoq assorsuaq imermut akuleruteqqajaasuuvoq, avatangiisinullu aniaguni aalanngussaaq silaannarmullu akuliutissalluni. Taanna pujuusanngortarpoq qaqortoq, anorimit ingerlanneqarluni gassinik toqunaqisunik siammarterisarluni. Gassit uumassusilinnut aqqusaakkaminnut toqunartoqalersitsisarput, tamatuma kingorna ammoniak naasuni, issumi imermilu akuliutissaaq. Ammoniak toqunartuuvoq sakkortooq, kimitugunilu inunnut, uumasunut naasunullu toqunarsinnaalluni.

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Summary

The Government of Greenland is considering putting out to tender hydropower potentials (> 100 MV). The intension it to use the generated power from the potential hydropower plants to produce ammonia in a Power to X (PtX) plant. As part of this process, Aarhus University, DCE – Danish Centre for Environment and Energy, has prepared an overall assessment of the potential environmental impacts from a major worst-case accidental release or spill of ammonia in relation to production and transportation of ammonia in a PtX plant or by shipping in Greenland. The tender material designates three potential sites for production and shipping as well as the quantities of ammonia that can be spilled in the event of a major accident.

The three sites are: Kangerlussuaq (Sdr. Strømfjord), Kangerlussuatsiaq (Evighedsfjorden) and Nuup Kangerlua (Godthåbsfjorden)

Liquid anhydrous ammonia (LNH_3) is highly soluble in water and when released into the environment, it will also evaporate and react with water in the air. It will form a white cloud that will drift with the wind and spread highly toxic gasses. It will poison the organisms that it passes, and subsequently some of the ammonia will be deposited on vegetation, soil and water. Ammonia is highly toxic and exposure to elevated concentrations can be fatal to humans, animals and plants. Ultimately, it can cause disappearance of some species in the affected area for a period of time. However, ammonia is neither persistent nor does it bioaccumulate, and it is readily diluted and degraded in the environment. Thus, an accident will have some acute lethal effects where local population sizes may be reduced, followed by a recovery period whose length is dependent on the population status and reproductive potential. No toxic compounds will be left in the area after the acute phase.

For each of the three areas, this report presents maps with densities and highlights species of concern, vulnerable species and other relevant biological elements and human uses of the area. For the assessment of the potential environmental impacts of a major ammonia spill, modelled values and estimates of ammonia concentrations in the environment and thresholds values for toxicity are included and used to estimate potential risk zones of environmental impacts. The overall conclusions from the assessments are that a major, worst-case accidental ammonia spill would likely cause severe toxic damages up to several kilometres from the spill site, and some scenarios show that organisms might be affected more than 10 km from the spill sites. The actual impact of a spill will, to a large extent, depend on the weather conditions, the size of the spill as well as the recovery time of the affected populations.

A part of the project was also to conduct a literature search on historical spills. The ammonia industry is large and global and has accumulated experience from more than 100 years of production. From the literature it is evident that focus in the ammonia industry and the regulating authorities is on safety and prevention and on the implementation of Best Available Techniques (BATs) to avoid a large accident. It is very important that the highest safety standards are implemented to avoid an accident, also to save human lives. A large accident, with ammonia releases in the same order of magnitude as our spill scenarios, has been estimated to happen once in 10,000 years for a modern ammonia factory (DSB 2019).

Sammenfatning

Grønlands Selvstyre overvejer at sende vandkraftpotentialer (> 100 MV) i udbud. Hensigten er at bruge den genererede strøm fra de potentielle vandkraftværker til at producere ammoniak i et Power to X (PtX) anlæg. Som led i denne proces har Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, udarbejdet en samlet vurdering af de potentielle miljøpåvirkninger fra et større worst-case utilsigtet udslip eller spild af ammoniak i relation til produktion og transport af ammoniak i et PtX-anlæg eller ved skibstransport i Grønland. I udbudsmaterialet er angivet tre områder til produktion og skibstransport samt mængder af ammoniak, som kan spildes ved et større uheld.

De tre områder er: Kangerlussuaq (Sdr. Strømfjord), Kangerlussuatsiaq (Evighedsfjorden) og Nuup Kangerlua (Godthåbsfjorden)

Flydende, vandfri ammoniak (LNH_3) er let opløseligt i vand, og når det frigives til miljøet, vil det også fordampe og reagere med vand i luften. Dette danner en meget giftig hvid sky, der vil drive med vinden og forgifte de organismer, den passerer undervejs, og efterfølgende vil noget af ammoniakken blive afsat på vegetation, jord og vand. Ammoniak er meget giftig, og forhøjede koncentrationer kan være dødelig for mennesker, dyr og planter.

For hvert af de tre potentielle områder til produktion og skibstransport af ammoniak præsenteres kort med tætheder og fokus på arter, der giver anledning til bekymring, sårbare arter og anden relevant biologi og menneskelig anvendelse af området. Til vurdering af de potentielle miljøpåvirkninger af et større ammoniakudslip er modellerede værdier og estimater af ammoniakkoncentrationer i miljøet og tærskelværdier for toksicitet medtaget og brugt til at estimere potentielle risikozoner for miljøpåvirkninger. De overordnede konklusioner fra vurderingerne er, at et større, *worst-case* ammoniakudslip sandsynligvis vil forårsage alvorlige toksiske skader op til adskillige kilometer fra spildstedet, og nogle scenarier viser, at organismer sandsynligvis kan blive påvirket mere end 10 km fra spildstedet. Den faktiske påvirkning af et spild vil i høj grad afhænge af vejrforholdene, udslippets størrelse samt genopretningstiden for de berørte organismer.

En del af projektet var tillige at udføre en litteratursøgning om historiske spild. Ammoniakindustrien er stor og global og har oparbejdet erfaring fra mere end 100 års produktion. Det er tydeligt at fokus i ammoniakindustrien og hos de regulerende myndigheder er på sikkerhed og forebyggelse samt på implementering af de bedst tilgængelige teknikker (BAT'er) for at forebygge en stor ulykke. Det er meget vigtigt, at de højeste sikkerhedsstandarder implementeres for at undgå en ulykke, også for at redde menneskeliv. En stor ulykke med ammoniakudslip, i samme størrelsesorden som spildscenarierne i denne rapport, er blevet estimeret til at ske én gang per 10.000 år for en moderne ammoniakfabrik (DSB 2019).

1 Background

One of the main goals in the green transition and combat against climate changes is the substitution of fossil fuels to reduce greenhouse gas emissions. One option is to produce new fuels by the use of green electricity to drive electrolysis of water into H_2 and other hydrogen-based fuels. These fuels are named e-fuels and the production process is called Power-to-X (PtX).

By adding nitrogen in the process, e-ammonia is produced, which can directly substitute fossil ammonia for use both in agriculture and, with time (adaption of engines etc.), as fuels in ships, thereby decarbonising the agricultural as well as the shipping industry.

The Government of Greenland is considering putting out to tender two hydropower potentials (> 100 MV). The intention is to use the power generated from the potential hydropower plants to produce ammonia in a PtX plant. The Ministry for Agriculture, Self-Sufficiency, Energy and Environment has asked Aarhus University, DCE - Danish Centre for Environment and Energy, to prepare an overall assessment of the potential environmental impacts from a major release or spill of ammonia in relation to production and transportation of ammonia in a PtX plant or by shipping in Greenland. The tender material states three scenarios with sites for production and shipping as well as the quantities of ammonia that may be spilled in the event of an accident.

This report is comprised of 9 chapters:

Chapter 2 summarises the literature search of historical ammonia spills from production and transport as well as information on the probability of accident scenarios.

Chapter 3 gives an introduction to the basic physio-chemical properties and transformation of ammonia once it is released into the environment.

Chapter 4 presents the ecotoxicological threshold values determined for ammonia for aquatic and terrestrial organisms.

Chapter 5 presents the available data on terrestrial and aquatic organisms and known use of the three areas of interest.

Chapter 6 provides descriptions of the OML model (Operationelle Meteorologiske Luftkvalitetsmodeller) for modelling ammonia releases to air and the modelling results compared to the ecotoxicological threshold values.

Chapter 7 presents estimates of the extent of the impact of ammonia spills on marine and freshwater organisms.

Chapter 8 gives an overall assessment of the potential environmental impacts of an ammonia spill from a Power-to-X plant and from shipping of ammonia in Greenland based on input from the previous chapters and the scenarios.

Chapter 9 is the discussion and conclusion on the results.

2 Ammonia spills from production and transport: Some information on historical spills and probability of accident scenarios

2.1 Background on production and use of ammonia

2.1.1 Global scale of ammonia production

The global annual ammonia production is estimated to 180 million tonnes in 2020, an increase from 140 million tonnes in 2014. The production is quickly increasing as ammonia is expected to be used as an important green fuel, and by 2050 the hydrogen, and by extension, ammonia, market could be 20 times larger than it is today. The current transport of ammonia by ship, truck and train is estimated to 17.5 million tonnes yearly, and 120 ports are equipped with ammonia trading facilities worldwide (Valera-Medina et al. 2021; Anon. 2020).

So far, ammonia has mainly been used in the fertiliser industry, either sold as ammonia for direct application as fertiliser (especially in the US) or as a key ingredient in the production of N-fertiliser pellets. Ammonia is also extensively utilised globally in large cooling systems because of its ability to absorb large amounts of heat when changing from its liquid to its gaseous state. (Valera-Medina et al. 2021; Anon. 2020; Fecke et al. 2016).

2.1.2 Ammonia hazards

Ammonia (anhydrous ammonia), at standard temperature and pressure, is a colourless gas that is lighter than air. At -33 °C, ammonia is a liquid and is often kept as a liquid in pressurised and cooled tanks. Release of liquid ammonia results in formations of aerosols with the moisture contained in the atmosphere, creating a visible and dense white cloud. The ammonia vapour cloud, typically denser than the atmosphere in contrast to the gas itself, tends to travel along the ground and thus poses a hazard to humans as well as the environment in the vicinity of the liquid release location. Ammonia can be fatal to humans, animals and plants upon exposure to elevated concentrations. Additionally, ammonia poses a risk of explosion (deflagration) if the ammonia concentration in the vapour cloud is within the flammable regime (~15% to 28%). More details about ammonia in the environment (fate and effects) are given in Chapter 3 and 4.

2.2 The risk of accidental spills/loss of containment in the industrial ammonia production

Industrial ammonia production started more than a century ago. Though ammonia has been widely produced, accidents with large releases from ammonia production, storage and shipping have been rare in recent decades. Accidents with moderate ammonia releases, especially from cooling systems, have been more frequent. To minimise the risk of ammonia spills, as a release of ammonia presents a serious hazard, most countries have strict national regulations addressing the need for a formal risk assessment as well as specifying procedures for incident investigation, reporting and general training in minimising the risks. In the EU, the regulation of ammonia production facilities includes the

Seveso-III directive. This directive was developed to deal with the hazards of chemical industry because of large industrial gas accidents like the Bhopal in 1984 (methyl isocyanate) and Seveso in 1976 (dioxin). In Denmark, the Seveso III-directive (directive 2012/18/EU) is implemented in ”Risikobekendtgørelsen” (https://risikohaandbogen.mst.dk/media/191269/risikohaandbog-v-2-endelig.pdf). The EU Commission has developed a reference document on best available techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers (EU Commission 2007, https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/lvic_aaf.pdf).

For more details, the following references can be consulted: Fecke et al. (2016) review the global regulations for anhydrous ammonia production, use and storage, and Crolius et al. (2021) and Valera-Medina et al. (2021) describe safety and regulatory challenges of the increased production and use of “green” ammonia.

For a modern ammonia plant, a large accident, with ammonia releases in the same order of magnitude as our spill scenarios (Chapter 6 and 7), has been estimated to happen once in 10,000 years (DSB 2019). See further below, Section 2.4.1.

2.3 Examples of large accidental spills

In the following, we give examples of large accidental spills of ammonia and examples from risk assessments and regulatory work related to risk of spills from ammonia plants. Griffiths and Kayser (1982) compiled a list of ammonia releases from production and transport between 1952 and 1979 (Figure 2.1).

Since 1956, the American Institute of Chemical Engineers (AJChE) has conducted a yearly ammonia plant safety symposium, involving sharing of safety incidents and lessons learned. Major reviews of lessons learned from incidents (combination of technicalities and safety issues) were made in conference papers in 2005 and 2015 (Pattabathulla et al. 2005; Pattabathulla and Richarson 2015).

Fecke et al. (2016) give the following examples of severe incidents of loss of ammonia containment: “*In 2013 in China, leaks in ammonia refrigeration systems were blamed for fires at two food processing facilities, resulting in 135 fatalities. Also in 2013, an ammonia leak at a Ukrainian chemical plant caused the death of at least five people. In 2007 in the US, an ammonia release resulted in the temporary evacuation of three towns. In 1997, a fire broke out in a refrigerated warehouse in Le Havre, France, leading to an explosion in the refrigeration unit and the release of 2 tonnes of ammonia gas. In 1992, an ammonia tank violently ruptured in Senegal, resulting in 129 deaths and 1,150 injuries, mostly due to toxic exposure*”(quotation from Fecke et al. 2016, with minor edits).

List of ammonia releases

Year	Place	Quantity (tonnes)	Source	Injured	Dead
1952	?	15	ST	20	15
1959	Ube, Japan	—	R(Ex)	40	11
1961	Creve Coeur, Illinois	350	Barge	—	—
1962	Brandenburg, Kentucky	—	R(Ex)	19	0
1965	Pasadena, Texas	—	R(Ex)	3	2
1968	Lievin, France	19	RdT	15	6
1969	Crete, Nebraska	90	RlyT	53	9
1969	Cumming, Iowa	—	—	—	0
1970	Belle, West Virginia	75	RlyT	30	0
1970	Blair, Nebraska	160	ST	3	0
1971	Floral, Arkansas	600	PL	0	0
1971	Texas City, Texas	—	PW	2	—
1973	Potchefstroom, South Africa	38	ST	65	18
1973	Conway/McPherson, Kansas	280	PL	2	0
1974	Hutchinson, Kansas	350	PL	4	0
1975	Texas City, Texas	50	PL	—	0
1976	Glen Ellyn, Illinois	52	RlyT	15	0
1976	Landskrona, Sweden	180	Ship to ST	—	2
1976	Enid, Oklahoma	500	PL	—	0
1976	Houston, Texas	19	RdT	200	6
1977	Mexico	—	—	102	2
1977	Cartagena, Columbia	—	—	22	30
1977	Pensacola, Florida	40	RlyT	46	2
1979	Vilvorde, Belgium	8	Rly or RdT	—	—

Key
ST — Storage Tank
R — Reactor
Ex — Explosion
RdT — Road Tanker
RlyT — Railway Tankcar
PL — Pipeline
Cyl — Cylinder
PW — Pipework, including loading lines.
? — Information uncertain
— — Indicates lack of information

Figure 2.1. Ammonia releases from production and transport between 1952 and 1979 (from Griffiths and Kayser (1982)).

2.3.1 Environmental effects from accidental releases of ammonia

Few ammonia incident reports include information on environmental effects or concentrations beyond the acute toxic zone. Here, we provide two examples: 1) a release from a railway accident in the US where groundwater was at risk and 2) a large accident in Lithuania with long-range transboundary air pollution.

Release from a railway accident in the US

The National Transportation Safety Boards report (2004) on the derailment of a railway freight train and subsequent release of anhydrous ammonia near Minot, North Dakota, 18 January 2002 (Figure 2.2).

Five tank railway cars carrying anhydrous ammonia, as liquefied compressed gas, ruptured, and a vapour plume covered the derailment site and surrounding area. About 555 m^3 of liquefied anhydrous ammonia were released from the five cars, and a cloud of hydrolysed ammonia formed almost immediately. This cloud rose to an estimated height of 100 m and gradually expanded 8 km downwind of the accident site and over a population of about 11,600 people (injured people: 1 fatal, 11 serious and 322 minor injuries). Over the following six days, an additional 250 m^3 of liquefied compressed gas was released. To protect primarily the groundwater resources from the toxic anhydrous ammonia release, the following environmental remediation activities were initiated and finalised two years later:

- Development of a site-wide groundwater monitoring program.
- Completion of a track bed soil/groundwater assessment and excavation program.
- Removal of approximately 98,700 tonnes of soil exhibiting ammonia concentrations greater than 500 mg/kg from the general site and track bed area.
- Removal of approximately 25,000 ft^2 of ice from the Souris River.
- Installation of groundwater collection sumps in topographic low areas located south and north of the mainline track.
- Installation and continued operation of a groundwater extraction system.

Figure 2.2. Photograph of the derailment of the railway freight train near Minot, North Dakota, 18 January 2002 (The National Transportation Safety Boards, 2004).

Large accidental release of ammonia from a plant in Lithuania

Kukkonen et al. (1993) analysed the possible long-range effects of a large ammonia accident at a chemical plant near the town of Ionava, Lithuania, on 20 March 1989. Seven people died, 57 were injured and about 32,000 were evacuated as a result of the accident. A 10,000 tonnes capacity tank containing 7,000 tonnes of refrigerated ammonia at its boiling point (- 33 °C) were accidentally spilled. The rupture was caused by an erroneous filling of the tank with relatively warm (+ 10 °C) liquid ammonia. The warm ammonia formed a layer at the base of the tank and then suddenly rose to the surface and evaporated, whereby the increased pressure overwhelmed the relief valves. The released liquid ammonia formed a pool, with a thickness of up to 70 cm in several places. About 1,400 tonnes of the spilled liquid ammonia were estimated to evaporate. The pool caught fire, and the fire spread to a fertiliser store containing 15,000 tonnes of NPK. The intensive evaporation of the liquid pool lasted for about eight hours, and the fire continued for three days. The accident was unusual in several respects. First, the releases into the atmosphere were very large – with about 1,400 tonnes from pool evaporation and about 700 tonnes from the resulting fire. Second, atmospheric conditions were unfavourable for rapid mixing of contaminants with neutral or stable atmospheric conditions (neither resisting nor assisting vertical motion), mainly moderate or low wind speeds and no significant rainfall. Some ammonia measurements were performed locally, and the largest measured concentration on the day of the accident was 200 mg/m^3 about 5 km downwind of the accident site. Concentrations of about 20-25 mg/m^3 were measured at distances from 5 to 12 km from the source. Simulations of the spreading indicated that detectable levels of ammonia could have reached the south coast of Finland 500 km away. These simulated concentrations were not recorded at measurement stations in Finland, probably due to low resolution in measurements. However, the day after the accident and before the accident was known in the public, a number of phone calls to the authorities in Finland from individual citizens in a localised area at the coast of Finland reported eye irritation. The least detectable odour level of ammonia vapour varies from 1 to 50 ppm. Kukkonen et al. (1993) concludes that based on the simulations, the reported observations of eye irritation may have been caused by the Lithuanian accident.

2.4 Examples of how the hazard of ammonia spills from ammonia plants is assessed

The details of formal quantitative risk assessments for ammonia plants are generally not made publicly available. However, some conclusions can be made from EIAs and public risk information. In the following, examples are given of: 1) The Porsgrunn ammonia plant, Norway, 2) The Burrup Ammonia Plant, Western Australia and 3) a small-scale ammonia plant in Denmark.

2.4.1 The Porsgrunn ammonia plant, Norway

Herøya industrial park in Porsgrunn, Norway, has several factory units producing different kinds of fertilisers, including an ammonia factory with a capacity of 530,000 tonnes per year (http://www.yara.com/). In 2019, the Norwegian Directorate for Civil Protection and Emergency Planning (DSB) published an assessment report of different major risks, including a scenario for a major accident at the ammonia factory (DSB 2019). The conclusions are summarised here (translated and edited from DSB 2019):

A rupture occurs in Yara's ammonia tank, and the fracture includes both the inner tank and the outer tank. The rupture causes 34,000 tonnes of ammonia to leak out into the catch pond, which fills. This is a “worst-case scenario” as the probability is very low that a system failure can result in a larger discharge than outlined in this scenario. The scenario is estimated to have an annual probability of 1:10,000, that is that the probability of the event occurring during 100 years is 1 percent. In contact with air, the ammonia evaporates and a gas cloud is formed. A lot of gas is developed during the first 1-2 hours, while the gas evaporation decreases over time due to the cooling of the surrounding areas because of the energy needed for the evaporation. There is clear weather and wind speed of 3 m/s with a wind direction from northwest to southeast. The gas reaches residential areas 1-2 km southeast of the plant in concentrations that are fatal or very harmful to human health. The population is being asked to stay indoors and close doors and windows. Just under 100 people is estimated to die as a result of the gas leak. The number of seriously injured or sick is close to 500 people. It is estimated that the ammonium gas will have some immediate environmental effects but that it will not cause long-term or permanent damage to the nature.

2.4.2 Burrup ammonia plant, Western Australia

In 2001, Burrup Fertilisers applied the local EPA to construct and operate a 2,200 tonnes per day ammonia plant on the Burrup Peninsula. The EPA reported and advised on the project in a public document and concluded the following regarding risks: (edited quotes from EPA document: https://www.epa.wa.gov.au/proposals/ammonia-plant-burrup-peninsula):

The event with the potential to have the largest fatality risk is the release of toxic ammonia as a result of a catastrophic failure of one of the two 40,000 tonnes refrigerated ammonia storage tanks. However, the Preliminary Risk Assessment considered the risk to be low as the tanks will be designed as double-walled and double-integrity. The provision of water curtains will be a further mitigating measure. The potential release of ammonia from other vessels and pipework within the plant was considered to be minimal, given the design and redundancy of the control and shutdown systems. A Preliminary Risk Analysis indicated that the plant complies with EPA Criteria for individual risk but did not present the estimated ammonia concentrations encountered during spill scenarios. It was estimated that the "50 in a million year" individual risk contour from the Burrup Ammonia Plant does not extend beyond the plant site boundary, and the "1 in a million year" individual risk contour is about one km from the plant boundary (Figure 2.3). (https://www.epa.wa.gov.au/proposals/ammonia-plant-burrup-peninsula).

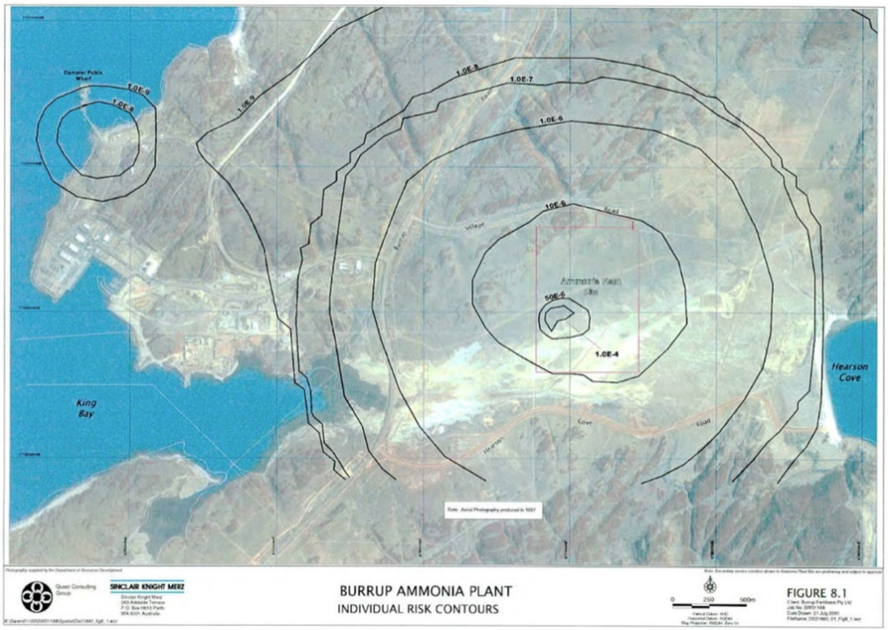


Figure 2.3. Individual risk contour from the Burrup Ammonia Plant. (from https://www.epa.wa.gov.au/proposals/ammonia-plant-burrup-peninsula).

2.4.3 Small-scale ammonia plant in Denmark

Denmark has no industrial ammonia production yet, but green ammonia plants are initially planned for Esbjerg and Hanstholm. However, a small-scale green ammonia plant has been permitted (https://mst.dk/media/227667/20211001-skovgaard-invest-aps-udkast-mgk.pdf). It has an ammonia pressure storage tank for 40 m^3 for liquefied ammonia. The risk for a large or total spill of the 40 m^3 liquid ammonia is roughly estimated to $1*10^{-6}$ (once per million years).

3 Physio-chemical properties and transformation of ammonia in the environment

Knowledge of a few definitions and physio-chemical reaction pathways is needed in order to fully understand the fate and potential environmental implications of ammonia spilled on either land or on water.

At normal temperatures and pressures, ammonia (NH_3) is in the form of a colourless gas with a characteristic pungent odour. Due to its low density and low boiling point, liquid ammonia is very volatile. Storage and transport of ammonia (i.e. without water) typically occur following wither compression or cooling of the gas. Below the boiling point temperature at -33°C (Table 3.1) or at high pressure, gaseous ammonia will shift into its liquid phase. For the storage and transport of large quantities of liquid ammonia (often called 'liquid anhydrous ammonia' (LNH_3)), cooling is often the preferred method as large quantities of -33°C liquid ammonia can be transported at or near atmospheric pressure (https://www.irc.wisc.edu/export.php?ID=17). Uncooled storage of ammonia under high pressure is also a common practise for smaller tanks, where accidental release will lead to rapid decompression and cooling where the spilled liquid ammonia will be at or below its boiling point temperature (-33°C) until it is fully evaporated (IIAR, 2008).

From an environmental perspective, the term 'ammonia' is commonly used to describe the sum of the two chemical species of ammonia that are in equilibrium in water (Australian Government Initiative 2000): the un-ionised ammonia (NH_3) and the ionised ammonium ion (NH_4^+).

Ammonia is highly soluble in water (~900 g/L at 0 °C, Table 3.1) and reacts rapidly with both liquid water and humidity in the air. Once dissolved, the proportion of the two chemical species (NH_3 and NH_4^+) varies with the physio-chemical properties of the water. Anhydrous ammonia is generally not considered to be a flammable hazardous product, having a flash point of 132 °C and an auto ignition temperature of 651 °C[1]. However, if ammonia gas is heated by a strong external source it may ignite and burn within the flammable range of 16% - 25% ammonia/air mixture (https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia).

Table 3.1. Physical and chemical properties of ammonia

Properties		Unit	Reference
Density	0.77 (0 °C / 1 atm.)	g/L	PubChem (2021)
Relative vapour density	0.6	Ratio (air = 1)	PubChem (2021)
Molar mass	17.03	g/mol	PubChem (2021)
Boiling point (1 atm.)	-33.3	C	Cedre (2006)
Water solubility	895 (0 °C) 529 (20 °C)	g/L	Cedre (2006)
Lower explosive limit (LEL)	16	%	IIAR (2008)
Upper explosive limit (UEL)	25	%	IIAR (2008)

[1] Flash point is the lowest temperature at which a liquid can form an ignitable mixture in air near the surface of the liquid. The auto ignition temperature is the lowest temperature at which it will spontaneously ignite in normal atmosphere without an external source of ignition.

3.1 Chemical reactions in the environment

When liquid anhydrous ammonia (LNH_3) is released into the environment, it will react with different water sources such as humidity in the air, soil water, freshwater or seawater, producing ammonium hydroxide (NH_4OH), while at the same time boiling into the atmosphere as gaseous ammonia (NH_3) (Renard et al. 2004; IIAR, 2008). During solution of ammonia gas into the water source, considerable heat may be evolved (Pitt undated).

The physical processes governing atmospheric dispersion when large quantities (over 1,000 tons) of liquid anhydrous ammonia (LNH_3) are spilled instantaneously on, or under, water are not well understood (Pitt undated). In the case of accidental release of LNH_3, the ammonia concentrations will be several orders of magnitude higher than normal ambient concentrations, and the drivers of deposition and dissolution will be drastically different from those of normal atmospheric conditions (Renard et al. 2004). Computer models used to describe the dispersion of a plume of chemicals generally lack an accurate description of chemical transformations that the released chemicals will undergo in the atmosphere (Renard et al. 2004). However, the important parameters needed for analysis of instantaneous ammonia spills are typically considered to be the following (Pitt undated):

- The amount of LNH_3 released.
- The ratio of LNH_3 that evaporates into the atmosphere when the accident happens on either land surface or the ocean.
- The estimated rate of rise of the NH_3 vapour cloud.

3.2 Dispersion of NH_3 following release

Common for LNH_3 spills on both land and water is that liquid ammonia released will rapidly aerosolise, producing a mixture of liquid NH_3 and NH_3 vapour at a temperature of approximately -33 °C. The released ammonia rapidly absorbs moisture in the air and forms a visible white cloud of ammonium hydroxide (NH_4OH) aerosols (US-EPA 2001). In spite of its low molecular weight relative to that of air, the released NH3 can under certain conditions form denser-than-air mixtures (Kaiser and Griffith 1982). Especially during sudden releases of NH_3 from pressurised or cooled containers, the initial liquid fraction of NH_3 in relation to the total airborne mass of NH_3 may be greater than 15-20%, producing a denser-than-air mixture that tends to travel at ground level rather than rapidly rising into the atmosphere (Griffith and Kaiser 1982).

If released to a water surface, anhydrous ammonia will spread out and float on top of the surface and rapidly dissolve within the water body as ammonium hydroxide (NH_4OH). The relative amount of ammonia that dissolves into the receiving water is normally between 50%-80% for surface spills and somewhat higher for underwater spills (Pitt undated). The reaction between NH_3 and water will produce heat, which may influence how the plume is transported and mixed with ambient air in the atmosphere (Bouet et al. 2004), creating complex dispersion patterns. However, since a NH_4OH molecule is about twice as heavy as a water molecule, it is expected that the NH_4OH will be deposited from the atmosphere in closer proximity to the scene of the accident (Pitt undated). Certain chemical gas-phase reactions in the atmosphere with e.g. sulphur oxides may potentially produce ammonium salts that can be transported in dilute concentrations over longer distances (Behera et al. 2013; Renard et al. 2004).

3.3 Drivers of NH_3 dissolution in freshwater and seawater

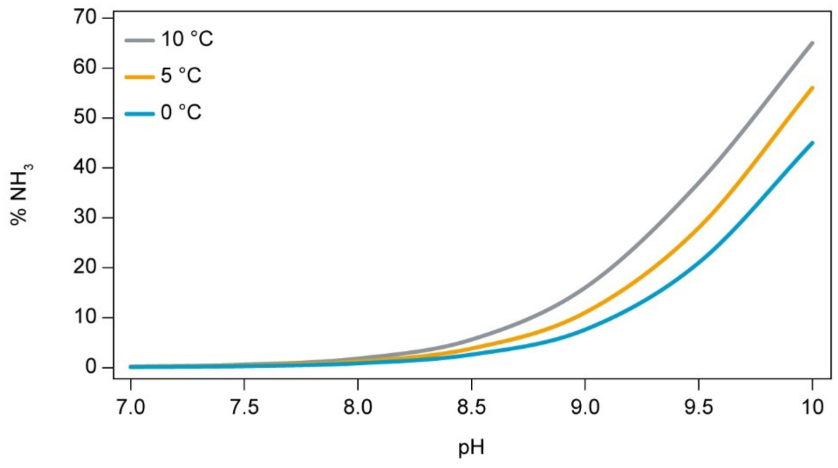
The dissolution ratio and chemical speciation between ammonia (NH_3) and ammonium (NH_4^+) once anhydrous ammonia dissolves in freshwater and seawater is greatly influenced by the pH, temperature and ionic strength of the water. This can have important environmental implications as the toxicity for aquatic organisms is dependent on the relative amount of unionised NH_3 to ionised NH_4^+. For further details about the toxicity of total ammonia consult Chapter 4.

The chemical equation describing the relationship between ammonia and ammonium is:

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$

The typical pH value of well-mixed seawater is 8.2, whereas the pH of freshwater lakes, ponds and rivers is typically between 6-8 depending on the surrounding soil and bedrock (Fondriest Environmental 2013). At pH levels typical of natural freshwater and seawater ecosystems, the amount of NH_3 only occupies a minor fraction of the total ammonia concentration (NH_3 + NH_4^+), with NH_4^+ being the dominant chemical species (Figure 3.1).

Figure 3.1. Percentage of NH_3 in relation to total ammonia (NH_3 + NH_4^+) in freshwater as a function of pH and temperature. Modified from SweMin (2012).



As seen in Figure 3.1, the temperature of the water plays only a minor role with respect to the fraction of total ammonia present as NH_3. The salinity (32-40‰) of the water reduces the dissolution of un-ionized NH_3 up-to one fifth compared to fresh water at the same temperature and pH (Bower and Bidwell, 1978).

3.4 Nitrification of NH_4^+ in the environment

In the case of a large LNH_3 spill, the concentration of NH_3 will be orders of magnitude higher than what is reported in most environmental studies of N transformation in natural ecosystems, and different mass transfer conditions may be present within the zone of impact (Renard et al. 2004). However, at typical natural concentrations and pH values, NH_4^+ is the dominant chemical species of total ammonia (NH_3 + NH_4^+) present in the environment.

In soils and surface waters, both nitrification and volatilisation are important processes regulating the total concentration of NH4+ and intermediate species present during the biogeochemical conversion. Nitrification is the biological process in which NH_4^+ is oxidised to nitrate (NO_3^-) via nitrite (NO_2^-).

In marine ecosystems, biologically available nitrogen is often a limiting nutrient. Addition of excess amounts of NO_3^- can lead to various environmental issues, such as acute toxicity in different species of wildlife, and contribute to eutrophication of coastal waters.

4 Ecotoxicological data on ammonia impact on aquatic and terrestrial organisms

Most data on the effects of ammonia exposure originate from organisms living in temperate regions. Hence, the effect values presented in this report should be used as indicative values for Arctic and sub-Arctic organisms. It is well known that temperature and pH can affect the toxicity of ammonia to the environment and thus, data on Arctic and sub-Arctic species should be prioritised in future investigations for more realistic effect levels.

A thorough literature review has been completed to identify relevant ecotoxicological values of ammonia exposure to different categories of terrestrial and aquatic organisms. The majority of the studies are controlled laboratory tests, where organisms have been exposed to known concentrations of ammonia. Toxicological data selected by United States Environmental Protection Agency (U.S. EPA) (2021) (ECOTOX database) and World Health Organization (WHO) (1986) have been used to define the ecotoxicological values used in this assessment. Data on different species within different organism groups have been included. The suggested threshold values for toxicity are conservative as they are chosen based on the most sensitive species in the dataset, i.e. the species where the lowest exposure level of ammonia results in a negative effect. The full list of organisms included in the data set can be seen in Appendix 1.

Below, the effect of high levels of ammonia to terrestrial and aquatic organisms, including humans, are summarised, and the suggested threshold values for toxicity are presented in Tables 4.2-4.6. These effect concentrations can be used to assess an estimated effect on Arctic and sub-Arctic ecosystems should an accidental release of ammonia occur. General definitions of the endpoints reported in Tables 4.2-4.6 are given in Table 4.1.

Table 4.1. Definitions of endpoints (effect level/concentration) reported in Tables 4.2-4.6 for aquatic and terrestrial organisms.

Endpoint	Definition
LC_{50} (Lethal concentration)	Exposure concentration of a toxic substance lethal to 50% of organisms tested
EC_{50} (Effective concentration)	Exposure concentration of a toxic substance where a given effect was observed for 50% of organisms tested. For animals, EC50 is for sublethal effects. For plants and algae, lethal effects can typically not be determined in short-term tests. Effect concentrations where, for example, the growth of plants/algae is inhibited by 50% (EC50) can be critical for the long-term survival of plants/algae
NOEL (No Observed Effect Level)	The highest tested exposure level of a toxic substance where no given effect in the organism was observed
LOEL (Lowest Observed Effect Level)	Lowest toxic substance level where a given effect in the organism was observed

4.1 Effects of ammonia gas in air

4.1.1 Humans

In humans, acute exposure to high levels of ammonia gas can cause airway obstruction, and ammonia levels of 5,000-10,000 ppm (3,480– 6,960 mg/m^3 (at 1 atm. and 25 °C air)) have been reported as rapidly fatal and 2,500-4,500 ppm (1,740– 3,132 mg/m^3) as fatal in about 30 min (ATSDR 2004 and references therein). Other effects when exposed to lethal concentrations of ammonia are chemical burns of the respiratory tract, eyes and exposed skin (ATSDR 2004 and references therein). For humans working in the industry, an exposure level of 50 ppm (35 mg/m^3) during an 8-hour working day (8-hour total weight average (TWA)) should not be exceeded (OSHA 2017), and the Immediately Dangerous to Life or Health concentration (IDLH) for ammonia is 300 ppm (208 mg/m^3) (NIOSH 1994).

4.1.2 Birds and mammals

The acute lethal exposure concentration of ammonia in land-based mammals (mice and rats) has been found to be within the range of that in humans (Back et al. 1972; National Research Council 2008; NIOSH 1994) and to depend on the duration of exposure (ATSDR 2004 and references therein; Michaels 1999 and references therein; National Research Council 2008) (Table 4.2). However, as birds have been reported to be more sensitive to ammonia exposure than mammals, their acute exposure concentrations of ammonia are lower (Table 4.2).

Table 4.2. Acute lethal concentrations (mg/m^3) of ammonia gas during acute (5-120 min) exposure for birds and mammals. Numbers in parenthesis indicate number (n) of studies included. See references in World Health Organization (WHO) (1986). See Table 3.1 for definitions of effect level.

Organism group	Acute lethal concentration (mg/m^3)
Wild birds*	1,600 (1)
Smaller mammals**	2,960 (13)

*Acute lethal concentration found for starlings, sparrows and pigeons from treating a barn with ammonia gas at 1,600 mg/m^3 for 7 min to exterminate the wild birds occupying the barn, **Acute lethal concentrations (LC50) in mice and rats found in laboratory studies

Sub-lethal effect concentrations of ammonia gas differ between organism groups and have been found to be lower for birds (poultry) than mammals (Table 4.3). Experiments with mammals (e.g. dogs, monkeys, rabbits, rats and pigs) have demonstrated sub-lethal effects such as lung damage during acute and longer-term exposure to ammonia (review by Brautbar et al. 2003). For birds and chickens in poultry houses, high ammonia levels have been shown to reduce their survival ability, food intake and immune system (Kristensen and Wathes 2000; Table 4 in Naseem and King 2018; Swelum et al. 2021) (Table 4.3). Similar effects of exposure to high levels of ammonia as those listed are expected for wild animals, including birds and mammals.

Table 4.3. Sub-lethal effect concentrations mg/m^3) of ammonia gas in birds and mammals during acute (<72 hrs) inhalation exposure. Numbers in parenthesis indicate number (n) of observations. See references in World Health Organization (WHO) (1986). See Table 3.1 for definitions of effect level.

Organism group	Sub-lethal effect concentration (mg/m^3)
Birds (poultry)*	14 (3)
Smaller mammals**	85 (7)
Larger mammals***	196 (1)

*Adults and chickens, **Mice, rats, rabbits and cats, ***Pigs

4.2 Effects of ammonia on plants and vegetation

Unfortunately, no examples of short-term exposure lethal ammonia concentrations have been found for vegetation or plants. Thus, we have no experimental data to support the impact assessment of a large ammonia spill on the vegation. However, the following information on Lowest observed effect level (LOEL) and No observed effect level (NOEL) may give an indication of plant sensitivity (Table 4.4). In general, there are more data on toxic effects of long-term ammonia exposure, and data on the effects of short-term exposure are only available for crops. According to Krupa (2003), the most to least sensitive plant species to NH_3 are: native vegetation > forests > agricultural crops. Thus, studies on the short-term effects on Artic vegetation should be prioritised in future studies.

Table 4.4. Effect levels (LOEL and NOEL; mg/m^3) in plants during short-term (< 7 days - note: small sample size n=2)) and long-term (7-91 days) exposure to ammonia gas. For effect levels for each species included in the dataset see Appendix 1. Numbers in parenthesis indicate number (n) of observations. Data from ECOTOX database (United States Environmental Protection Agency (U.S. EPA) 2021). See Table 4.1 for definitions of effect levels.

Terrestrial plants	Lowest observed effect level (LOEL; mg/m^3)	No observed effect level (NOEL; mg/m^3)
Plants (short-term)*		0.6 (2)
Plants (long-term)**	0.064 (29)	0.064 (67)

* Short-term exposure (<7 days) of tomato plants, growth impacts, ** Long-term exposure (7-91 days) of flowers, trees and shrubs, injuries.

High concentrations of ammonia have been observed to cause acute damage to vegetation (Fangmeier et al. 1994). Damage to foliage (i.e. leaves) will occur when the foliar uptake of NH_3 is greater than the ability of the foliage to detoxify (Krupa 2003). Other adverse effects on higher plants exposed to increased ammonia levels are changes in productivity and growth and reduced resistance to stress, such as drought and frost (Krupa 2003 and references therein). Wild vegetation, especially lichens and bryophytes, is thought to be more sensitive to high levels of ammonia compared to trees and agricultural crops (Cape et al. 2009; Fangmeier et al. 1994; Krupa 2003).

4.3 Effects of ammonia on aquatic (marine and freshwater) organisms

Ammonia is produced naturally from degradation of organic matter; it is furthermore a by-product of fish metabolism and occurs in the aquatic environment at low levels (ATSDR 2004). However, if present at high enough levels, e.g. due to runoff / waste from land or a major spill, ammonia can be very harmful to aquatic life as aquatic organisms will have difficulties in excreting or detoxifying the ammonia (United States Environmental Protection Agency (U.S. EPA) 2009, 2013). Exposure to high ammonia concentrations can affect reproduction, growth and survival due to toxic build-up in blood and internal tissues and can directly lead to mortality (United States Environmental Protection Agency (U.S. EPA) 2009, 2013). The acute or chronic effects of ammonia exposure on aquatic life depend on the organism type and stage (United States Environmental Protection Agency (U.S. EPA) 2009). For example, ATSDR (2004) reports that, in general, invertebrates are more tolerant to ammonia than fish. Salmonid fish are reported to be particularly sensitive and aquatic vascular plants to be the most tolerant (ATSDR 2004 and references therein).

There are two forms of ammonia in natural surface waters: ionised (NH_4^+ (ammonium)) and un-ionised (NH_3 (ammonia)), and the toxicity of "total ammonia" (here used as a term for $NH_4^+ + NH_3$ existing in a dynamic equilibrium) highly depends on pH and temperature (see Chapter 3.3). Increased pH levels and increased temperature lead to a higher proportion of un-ionised ammonia, NH_3 (e.g. Emerson et al. 1975 and references therein; United States Environmental Protection Agency (U.S. EPA) 2009), which can cross epithelial membranes of aquatic organisms more readily than ionised ammonia, NH_4^+ (ARMCANZ 2000). Thus, NH_3 is believed to be the most toxic form for aquatic organisms (e.g. Ward et al. 2013), but under certain conditions NH_4^+ can also contribute significantly to ammonia toxicity (ARMCANZ 2000).

Threshold values for toxicity of ammonia to marine and freshwater organism are listed in Table 4.5 and 4.6, respectively.

Table 4.5. Threshold values for toxicity (EC_{50} and LC_{50}; mg/l) in marine organisms during short-term exposure (i.e. < 5 days) to total ammonia ($NH_3 + NH_4^+$). Numbers in parenthesis indicate number (n) of studies included. Data from ECOTOX database (United States Environmental Protection Agency (U.S. EPA) 2021). For threshold values for each species included in the dataset see Appendix 1.

Marine organisms	**Effect concentration (EC50; mg/L)**	**Lethal concentration (LC50; mg/L)**
Algae	29.2 (1)	
Crustaceans		4.98 (84)
Molluscs		2.55 (16)
Fish		2 (24)

Table 4.6. Threshold values for toxicity (EC_{50} and LC_{50}; mg/l) in freshwater organisms when exposed to total ammonia ($NH_3 + NH_4^+$). Data are from short-term exposure (i.e. < 5 days). Numbers in parenthesis indicate number (n) of studies from where data were extracted. Data from ECOTOX database (United States Environmental Protection Agency (U.S. EPA) 2021). For average reported values see Appendix 1.

Freshwater organisms	**Effect concentration (EC50; mg/L)**	**Lethal concentration (LC50; mg/L)**
Crustaceans	2.1 (3)	0.53 (9)
Molluscs	0.8 (37)	3.97 (4)
Fish		0.17 (30)

5 Biology and vulnerable species in the focus areas

Three areas were selected by The Ministry for Agriculture, Self-Sufficiency, Energy and Environment to be used for the scenarios in this assessment:

- Kangerlussuaq (Sdr. Strømfjord)
- Kangerlussuatsiaq (Evighedsfjorden)
- Nuup Kangerlua (Godthåbsfjorden).

Maps for each of the three areas showing densities and highlighting occurrence of species of concern, vulnerable species and other relevant biology and human uses of the area are given below (Figure 5.1-5.6). The data are from the DCE and GINR data centre and oil spill sensitivity atlas databases.

On each map, selected points for scenarios of spill releases are given: 1) an accidental spill in the fjord during shipping d 2) accidental spill by tank collapse on land at the ammonia plant, 3) accidental spill when loading a ship at the pier. Scenarios 2) and 3) are assumed to occur at the same location. The coordinates for the spill sites are given in Table 5.1.

Table 5.1. Coordinates for the selected points for simulating ammonia spills in the three areas.

Location	Spill type	Longitude	Latitude
Kangerlussuaq	Ammonia plant/pier	-52.12	66.47
Kangerlussuatsiaq	Ammonia plant/pier	-51.70	66.09
Nuup Kangerlua	Ammonia plant/pier	-50.17	64.81
Kangerlussuaq	Spill in fjord	-53.55	66.01
Kangerlussuatsiaq	Spill in fjord	-52.22	65.95
Nuup Kangerlua	Spill in fjord	-51.95	64.09

5.1 Kangerlussuaq/Søndre Strømfjord

5.1.1 Short description of the biology

There are very few breeding colonies of seabirds in this fjord and those that occur are generally small and insignificant without species of conservation concern (i.e. no species listed on the national red list of threatened species) (Figure 5.1). The species occurring include Iceland gull, black guillemot and great cormorant. The seabird winter surveys in 1999 and 2017 found only few common eiders in the fjord and only in the mouth. There are spawning and fishing areas for capelin and lumpsucker in the mouth of the fjord.

Several of the rivers in the area hold Arctic char, and one of the most important rivers in this respect is the Sarfartoq river in Paradisdalen. A protected area lies in the central part of the valley app. 17 km from the proposed plant site to the east. The protection is justified by its natural beauty and its cultural and scientific significance (Hjemmestyrets bekendtgørelse nr. 31 af 20. oktober 1989 om fredning af Arnangarnup Qoorua, Maniitsoq kommune, Vestgrønland) Archaeological remains and a large willow thicket (*Salix* *glauca*) are among the important features of the protected area. The Sarfartoq River holds a very large and important population of Arctic char that winters in the river and pass the proposed plant site in spring and autumn.

Important species (including nationally red-listed species) in the terrestrial environment include great northern diver, Greenland white-fronted goose (at the proposed plant site there is an important spring staging area for this species), gyr falcon, white-tailed eagle and several rare and endemic plants. Moreover, the area is important to large populations of caribou and muskoxen. Wildlife also occurring in the area includes Arctic hare, Arctic fox, ptarmigan, Canada goose and harlequin duck.

The proposed plant site is located along the access route for humans from Kangerlussuaq to Paradisdalen.

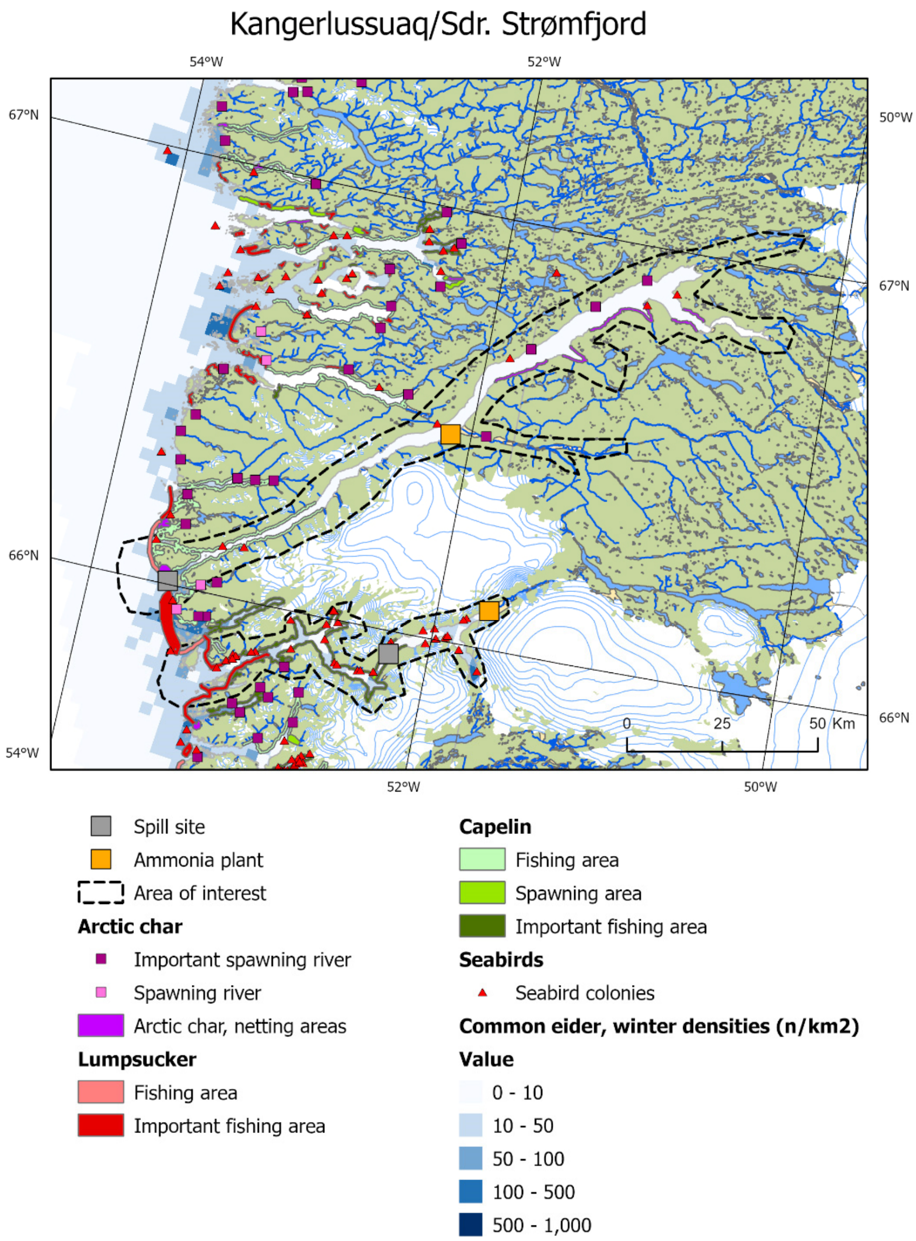


Figure 5.1. Kangerlussuaq area – Densities and highlights of species of concern, vulnerable species and other relevant biology and human uses of the area. The data are from the DCE and GINR data centre and oil spill sensitivity atlas databases.

5.1.2 Short description of the vegetation

The extent, degree of coverage and health of the vegetation are often approximated by mapping the "Normalized Difference Vegetation Index" (NDVI). NDVI is an indicator of photosynthetically active biomass by comparison of the amount of reflected visible red and near-infrared light by the vegetation (Fritt-Rasmussen et al. 2022).

The NDVI index map shows that relatively lush vegetation is found in the inner half of the fjord region where the topography is dominated by a relatively low altitude undulating surface, while the outer half of the region is dominated by high altitude alpine areas and glacier ice to the south (Figure 5.2).

The proposed plant is located on the south side of the fjord very close to the outlet of the Sarfartoq River. The 'Lumina Sustainable Materials' anorthosite mine (formerly known as Hudson Resources Inc.) is located right on the opposite side of the fjord. The region is characterised by dwarf shrub heaths and steppe grasslands, but there are also vast areas with very sparse vegetation. The rare plant species *Gentiana detonsa* has been found in the vicinity of the proposed plant site.

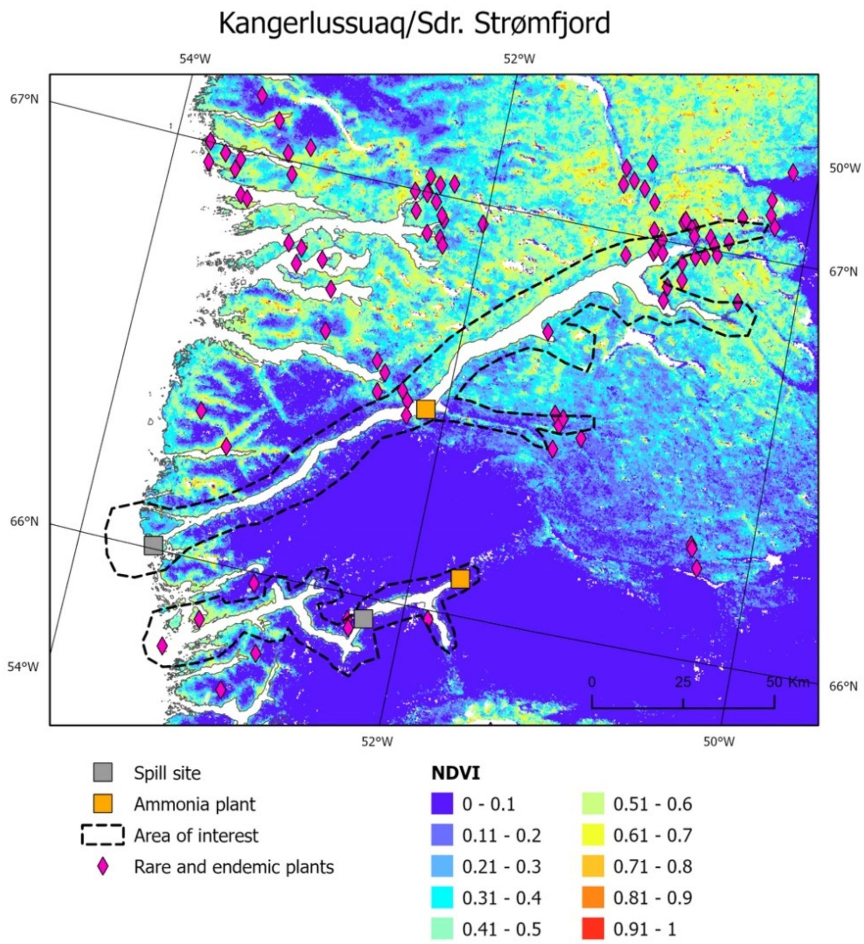


Figure 5.2. Kangerlussuaq area – NDVI map and sites with rare and endemic plants.

5.2 Kangerlussuatsiaq/Evighedsfjorden

The site is located between the Sukkertoppen ice cap to the north and another ice cap to the south.

5.2.1 Short description of the biology in the area

There are several breeding colonies of seabirds along the shores of the fjord. Among the species of conservation concern (including nationally red-listed species) in these colonies are thick-billed murre (one colony), kittiwake (several colonies) and cormorant. Along the shores, both capelin and lumpsucker spawn in spring, and important fishery for these take place. The winter seabird surveys found only few common eiders within the fjord, most in and off the mouth. See Figure 5.3.

Species of conservation concern in the terrestrial parts include great northern diver, white-tailed eagle and gyr falcon. Other important species are harlequin duck and caribou.

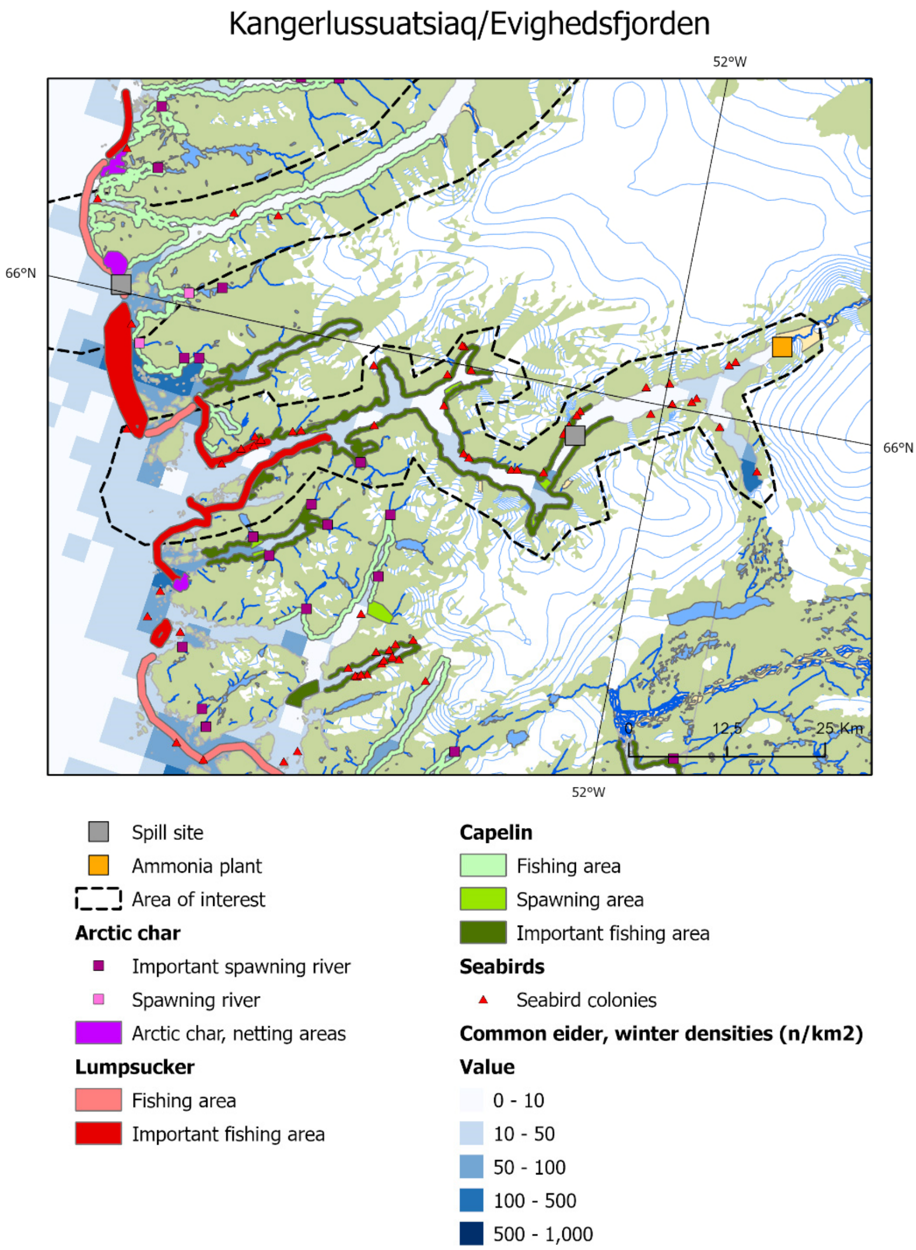


Figure 5.3. Kangerlussuatsiaq – Densities and highlights of species of concern, vulnerable species and other relevant biology and human uses of the area. The data are from the DCE and GINR data centre and oil spill sensitivity atlas databases.

Knowledge of terrestrial wildlife in the area is sparse and due to the size of the area, the proposed plant locality hardly plays any significant role for muskoxen and caribou populations for foraging or for the size of these populations. On the other hand, the locality is probably important for the exchange of animals between Angujaartorfiup Nunaat to the north, which houses a large population of muskoxen, and the land area east of Maniitsoq. The connection between caribou populations north and south of the ice caps probably also relies on the passage of the valley where the proposed plant at the head of 'Evighedsfjorden' is located.

5.2.2 Short description of the vegetation

The NDVI-index map shows that relatively lush vegetation is found in narrow strips along the shores of the fjord. These become wider towards the west as the general topography of the region becomes less alpine and more extended lowlands occur (Figure 5.4). The large areas with very low NDVI are either covered with glacial ice or are high-altitude alpine areas.

The vegetation in the region is low Arctic with a clear difference between the oceanic coastal areas and the continental areas towards the inland ice. The most continental areas are found at the head of Kangerlussuaq, but also the areas at the head of Nuup Kangerlua have distinct continental characteristics.

Rare, endemic plants have been found at a few sites. The rare fern species Northern Moonwort (*Botrychium boreale*) and yellow thimbleweed (*Anemone richardsonii*) occur in the area around the head of Evighedsfjord and may also be found at the proposed plant site.

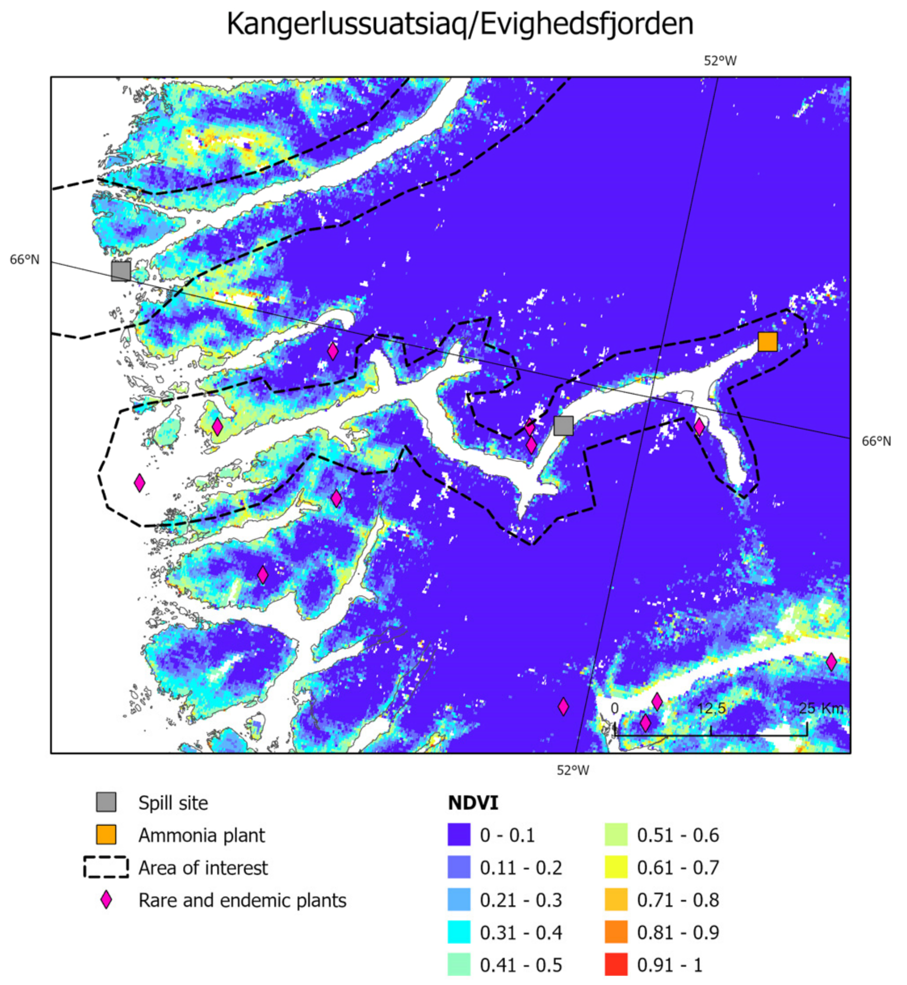


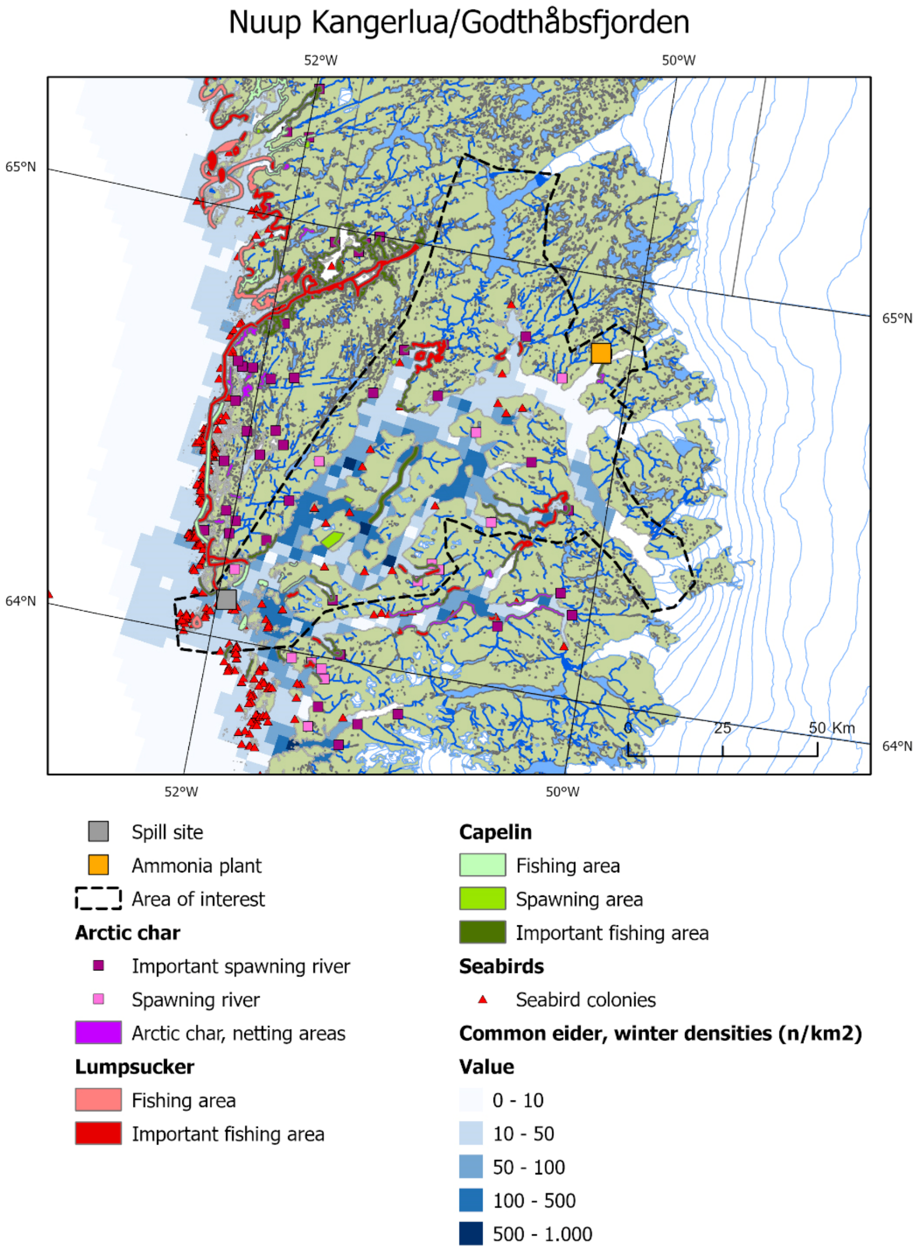
Figure 5.4. Kangerlussuatsiaq – NDVI map and sites with rare and endemic plants.

5.3 Nuup Kangerlua/Godthåbsfjord

5.3.1 Short description of the biology in the area

There are many breeding colonies of seabirds in this fjord region (Figure 5.5). These include the nationally red-listed species kittiwake (a few colonies), Atlantic puffin (some in the mouth), Arctic tern (also in the mouth) and gulls (Iceland, glaucous, great black-backed and lesser black-backed), black guillemots, great cormorant (one) and common eider. Other red-listed species include white-tailed eagle (a relatively dense breeding population), gyr falcon (very few) and great northern diver.

Figure 5.5. Nuup Kangerlua – Densities and highlights of species of concern, vulnerable species and other relevant biology and human uses of the area. The data are from the DCE and GINR data centre and oil spill sensitivity atlas databases.



In winter, the western parts are a very important habitat for common eiders, and harlequin ducks in high numbers winter among the westernmost archipelagos. There are several important fishing and spawning areas for capelin.

The only river in Greenland with spawning Atlantic salmon is located in this fjord region, and there are several rivers with Arctic char. Thus, fishing areas for Arctic char are found at the location of the proposed plant site.

In the terrestrial environment, important species include caribou, which occurs in the entire region and the population is extensively hunted. There are also several rare and endemic (and red-listed) plants. The valley at the proposed plant site provides access to caribou hunting grounds. Also, muskoxen are found in the area north of the fjord and widespread are Arctic hare, Arctic fox, ptarmigan, Canada goose, and harlequin duck.

5.3.1 Short description of the vegetation

The topography of most of the Nuup Kangerlua fjord region is characterised by low altitude with relatively lush vegetation, and only in the high altitude alpine areas in the central and southern parts the NDVI is low (Figure 5.6). The large blue areas to the east are the Greenland ice sheet.

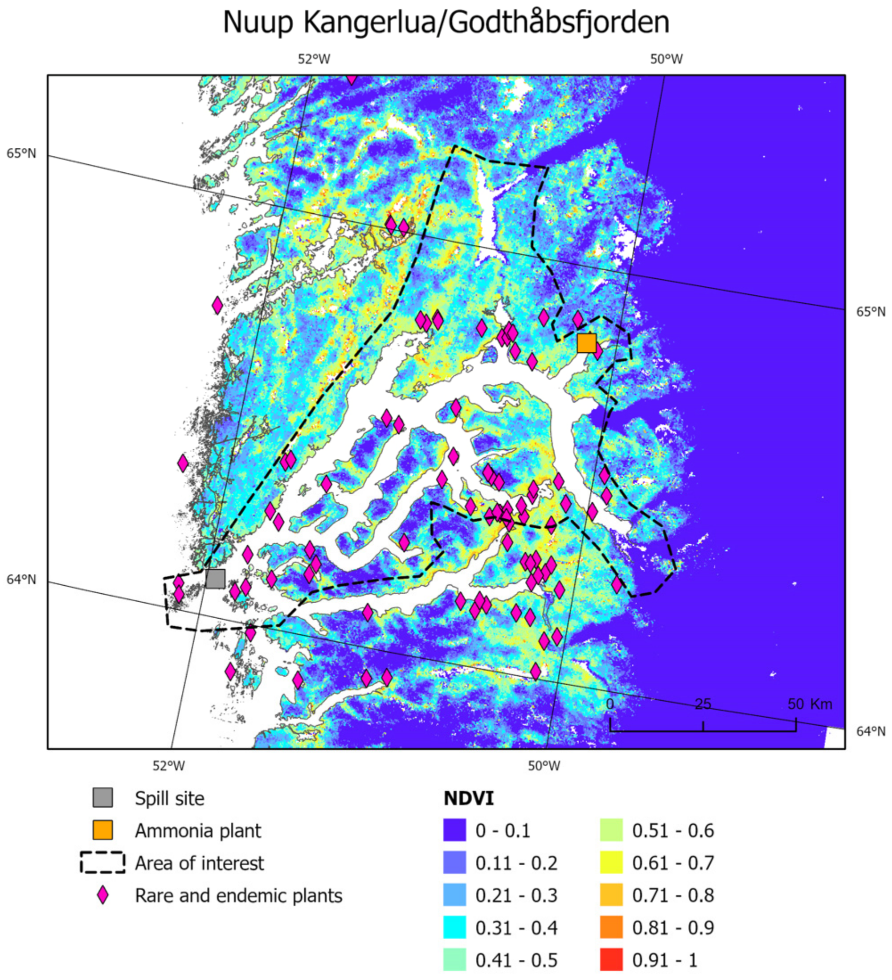


Figure 5.6. Nuup Kangerlua – NDVI and sites with rare and endemic plants.

6 Modelling of ammonia spill – Air

6.1 Background simulation details

Worst-case simulations of acute ammonia spills were computed using the OML model ("Operationelle Meteorologiske Luftkvalitetsmodeller"). There were three spill simulation scenarios. A) Spill from the ammonia plant where the estimated maximum tank capacity of 50,000 tonnes is immediately released and contained in the catch pond. B) Spill of ammonia during transfer from the plant to a transport tanker, where it is assumed that 50% will reach the water and the remaining 50% will be spilled on the ground. C) Spill of a complete tank of ammonia in the fjord during shipment.

The amounts and sizes of the spill pool are given in Table. 6.1. For B) and C) scenarios, it was assumed that the ammonia would rapidly spread out to a thin pool.

Table 6.1. Simulated ammonia spills and sizes for worst-case-scenarios

NH_3 spill type	Amount tons	Amount m^3	Pool thickness m	Pool area m^2	Pool width m	Pool radius m	NH_3 in water tons	NH_3 in water %
A) Accidental spillage by tank collapse on land at the ammonia plant	50,000	73,314	3	24,438	156	88		0
B) Accidental spillage when loading ship at pier	10,000	14,663	0.01	1,466,276	1,211	683	7,331	50
C) Accidental spillage in fjord during shipping	40,000	58,651	0.01	5,865,103	2,422	1,367	41,056	70

Regarding the ambient weather conditions, summer and winter scenarios (i.e. high and low air temperature respectively) were simulated.

The emission rate of ammonia from the pool depends on the wind speed. To estimate worst-case situations, low wind speed simulations were prioritised.

Low wind results in both slower evaporation of NH_3 sustaining the source for a longer time period, and lower mixing thereby increase ammonia concentrations in the air. One high wind speed simulation was included, though. See Table 6.2 for overview and details of the model input specifications.

Note that the model is not including the very strong initial evaporation that results from the release of superheated ammonia. Further, in the modelling as well as the following assessment we are not considering the possibility of ignition of ammonia.

A total of seven spill simulations were completed. Air concentrations were simulated for four different heights (1.5 m, 50 m, 100 m and 200 m). For the simulation period, also the maximum hourly NH_3 concentrations in the air was calculated in one scenario.

With respect to the deposition of NH_3, this was calculated only for the simulations at 1.5 m height. Dry depositions were calculated as follows:

$$\text{Dry-dep.} = c \cdot \langle V_d \rangle \cdot \Delta t\ (s) \quad \text{(eq. 1)}$$

Where, c is NH_3 concentrations at the surface. For simplicity the average deposition velocities of $\langle V_d \rangle = 0.0071$ m / s (summer) and $\langle V_d \rangle = 0.0054$ m / s (winter) are used. The difference between the two seasons is due to the differences in surface type, i.e. grass vs snow. Δt denotes the time step, which in our case is $\Delta t = 3600$ s . Thus, the calculated dry deposition is mass per hour.

Table 6.2. Specifications for the OML simulations.

Simulation name	Spill type	Wind	Evaporation time	Emission rate (g/s)	Air temperature (°C)
Tank_sum_lvs	Tank	Low	7 d 20 h	73578	10
Tank_sum_hvs	Tank	High	3 d 9 h	171020	10
Tank_win_lvs	Tank	Low	20 d 19 h	27840	-17.8
fship_sum_lvs	Transfer	Low	1133 s	4414707	10
Fship_win_lvs	Transfer	Low	2993 s	1670429	-17.8
Fjord_sum_lvs	Fjord	Low	680 s	17658829	10
Fjord_win_lvs	Fjord	Low	1795 s	6681719	-17.8

6.1.1 The OML-Multi model

The dispersion of NH_3 was calculated by the OML-Multi model. The OML-Multi model is a local-scale atmospheric model simulating the mixing of air pollutants from point and area sources in the atmospheric boundary layer (Olesen et al. 2007). The theoretical framework of OML-Multi is based on a Gaussian plume model with more elaborate schemes for horizontal and vertical dispersion coefficients, which are continuous functions of physical and meteorological parameters such as friction velocity, heat flux, atmospheric stability and mixing height. OML is therefore driven by meteorological data on transport and turbulence in addition to surface roughness and emission source data (including the emissions themselves, emission release height, temperature, vertical velocity etc.).

The OML-Multi model has been applied to different regulatory aspects in Denmark, including environmental impact assessment of industrial air pollution, regulation of odour and of ammonia deposition. OML-Multi was originally developed and validated for Danish meteorological conditions and the relatively flat Danish landscapes. It has consequently not been well tested for topographical complex conditions such as those found along the Greenlandic west coast. Therefore, we chose a simulation set-up with a flat terrain but conducted simulations at several heights representing different possible bird cliff heights.

Meteorology

The meteorology used to drive OML-Multi was extracted from the Danish Eulerian Hemispheric Model (DEHM) driven by meteorological data from the WRF model (Skamarock et al. 2008). The data from the DEHM model were derived from a regional simulation for Greenland with a 25 km spatial resolution and extracted from the Qianngua Avannarleq area. Therefore, it should be representative for the meteorological conditions in the coastal area where the construction of an ammonia plant is considered. Several years of data were analysed, and 2020 was found to represent a typical meteorological year at the location and hence used in the OML-Multi model simulations.

6.2 Accidental spill in the fjord during shipping

A spill of 40,000 tonnes of ammonia to the fjord, as a simulation of the worst-case scenario, is presented for a summer and a winter scenario in Figure 6.1 and 6.2.

It is assumed that the spill is spreading very fast and come to cover a very large surface area with a thickness of 1 cm and a pool radius of 1367 m, and that 30% is boiled off or evaporated. The remaining 70% is dissolved in the water. The large film area results in rapid evaporation of the ammonia (less than one hour), and consequently only high NH_3 atmospheric concentrations occur within one hour of the spill in the model domain. After one hour, the NH_3 concentrations have been transported out of the model domain. If the fast spreading is overestimated, the expected concentrations in the air would be lower but would be found for a longer period of time. The concentrations are higest closest to the spill site, both with respect to the horisontal and the vertical dispersion, and overall decrease with increasing distance from the spill site. Higher concentrations are found during winter, which is a result of the weather conditions, decreasing the vertical mixing in the boundary layer.

Both acute lethal and sub-lethal concentrations for birds and mammals are exceeded, as indicated in Figures 6.1 and 6.2.

No short-term lethal concentration values are found for vegetation or plants. The threshold values given in Table 4.4 for plants and vegetation are no-effect concentrations of 0.6 mg / m^3 on the growth of cultivated crops. Most to least sensitive plant species to NH_3 are native vegetation > forests > agricultural crops (Krupa 2003). The data in Appendix 1 indicate long-term foliage injuries at ammonia concentrations above 150 µg / m^3.

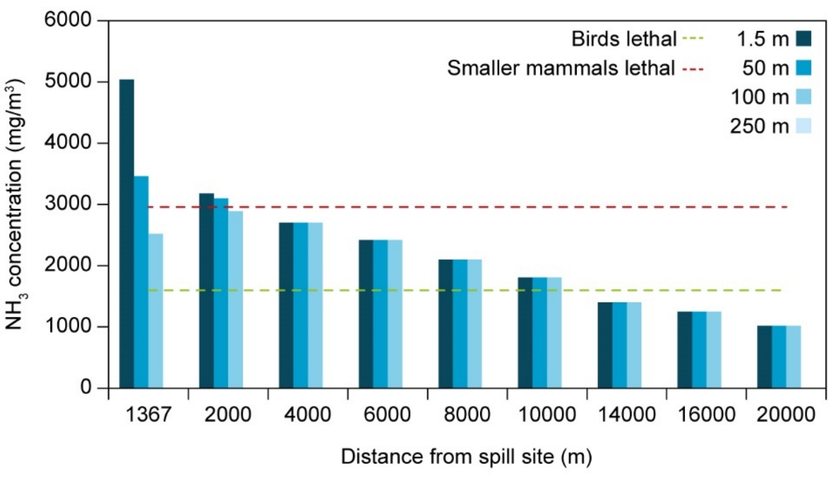


Figure 6.1. Accidental spill in the fjord during shipping – summer, low wind. Bars indicate the concentration of ammonia at different heights above ground level. Dotted lines indicate threshold values for toxic effects for birds and mammals..

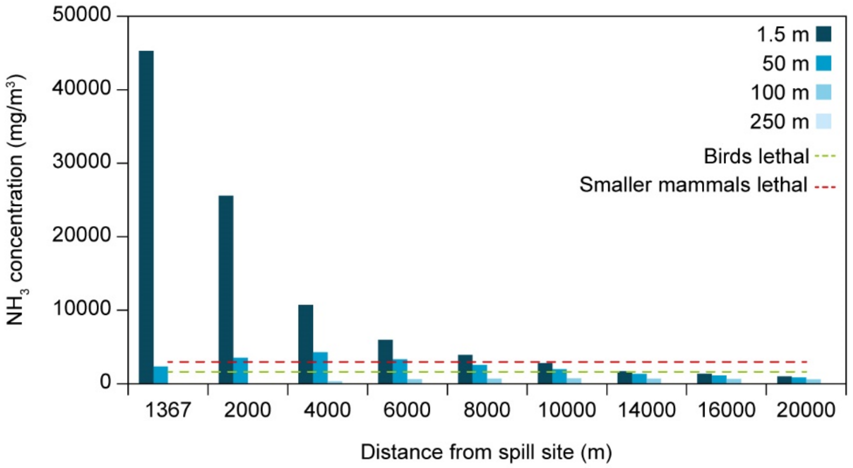


Figure 6.2. Accidental spill in the fjord during shipping – winter, low wind. Bars indicate the concentration of ammonia at different heights above ground level. Dotted lines indicate threshold values for toxic effects for birds and mammals.

Effects of ammonia on the growth of plants and vegetation may be seen at concentrations above 0.6 mg / m^3. The aerial exposure to and deposition from the vapour plume from an ammonia spill will exceed these concentrations (see Appendix 2 for data on deposition). Hence, it is likely that effects on plants and vegetation (sub-lethal and lethal) will occurat sites up to several kilometres away from the spill site in the direction that the ammonia is being transported to.

6.3 Accidental spill when loading ship at pier

A spill of 10,000 tonnes of ammonia to the fjord / land during loading of a ship is considered and simulated as a worst-case scenario for such type of spill and is presented for a summer and a winter scenario in Figure 6.3 and 6.4.

Again, as for the tanker spill, the ammonia is expected to spread rapidly and form a thin pool covering a large area. The evaporation / dissolution is fast and the pool disappears within one hour. If the fast spreading is overestimated, the expected concentrations in the air would be lower but would be seen for a longer period of time.

Small variations appear between the two seasons. Acute lethal concentrations for birds are recorded up to a height of 100 m at a horisontal distance of 4,000 m for the summer scenario. For the winter scenario, the ammonia is dispersed at a larger horisontal distance in acute lethal concentrations for birds (8,000 m), but only up to 50 m. For mammals, the area with lethal concentrations are smaller (Figure 6.3 and 6.4).

No short-term lethal concentration values are found for vegetation or plants. The threshold values given in Table 4.4 for plants and vegetation are no-effect concentrations of 0.6 mg / m^3 on the growth of cultivated crops. Most to least sensitive plant species to NH_3 are native vegetation > forests > agricultural crops (Krupa 2003). The data in Appendix 1 indicate long-term foliage injuries at ammonia concentrations above 150 µg /

Figure 6.3. Accidental spill when loading ship at pier – summer, low wind. Bars indicate the concentration of ammonia at different heights above ground level. Dotted lines indicate threshold values for toxic effects for birds and mammals.

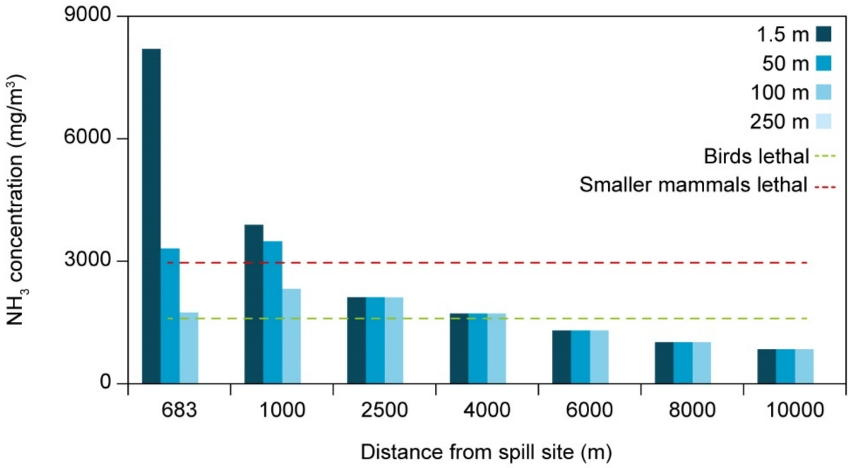
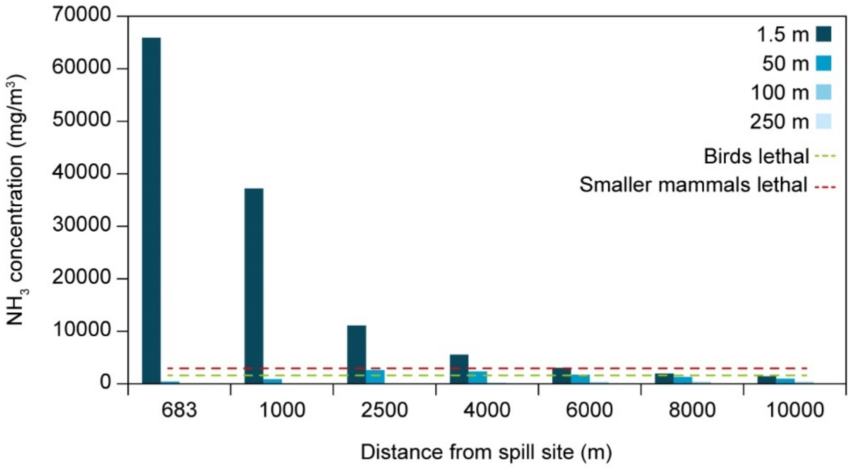


Figure 6.4. Accidental spill when loading ship at pier – winter, low wind. Bars indicate the concentration of ammonia at different heights above ground level. Dotted lines indicate threshold values for toxic effects for birds and mammals.



No short-term lethal concentration values are found for vegetation or plants. The threshold values given in Table 4.4 for plants and vegetation are no-effect concentrations of 0.6 mg / m^3 on the growth of cultivated crops. Most to least sensitive plant species to NH_3 are native vegetation > forests > agricultural crops (Krupa 2003). The data in Appendix 1 indicate long-term foliage injuries at ammonia concentrations above 150 µg / m^3.

Effects of ammonia on the growth of plants and vegetation may be seen at concentrations above 0.6 mg / m^3. The aerial exposure and deposition from the vapour plume from an ammonia spill exceed these concentrations (see Appendix 2 for data on deposition). Hence, it is likely that effects on plants and vegetation (sub-lethal and lethal) will occur up to several kilometres away from the spill site in the direction that the ammonia is being trasnported to.

6.4 Ammonia plant, total tank collapse (onshore)

A spill of 50,000 tonnes of ammonia to the cath pond of the ammonia plant, as a simulation of the worst-case scenario for a spill at the plant, is presented for two summer scenarios (low and high wind conditions) and a winter scenario (low wind) (Figure 6.5, 6.6 and 6.7). In contrast to the other scenarios, where the ammonia is considered to have an infinite area of spreading, the ammonia is here contained in the cath pond and is assumed to have an initial thickness of 3 m. Therefore, the evaporation simulation period is much longer (see Table 6.2). The highest simulated concentrations are found at 1.5 m height and clostest to the spill site (Figure 6.5-6.7). Up to 500 m from the site, the ammonia concentrations are exceeding the treshold lethal concentrations for birds, and up to 250 m from the site the lethal concentrations are exceeded for small mammals. The variations in concentrations with time are mainly due to changes in the meterological conditions, in particular wind direction. For the two summer scenarios, the higher wind result in a very short period of evaporation. All other results can be found in Appendix 2.

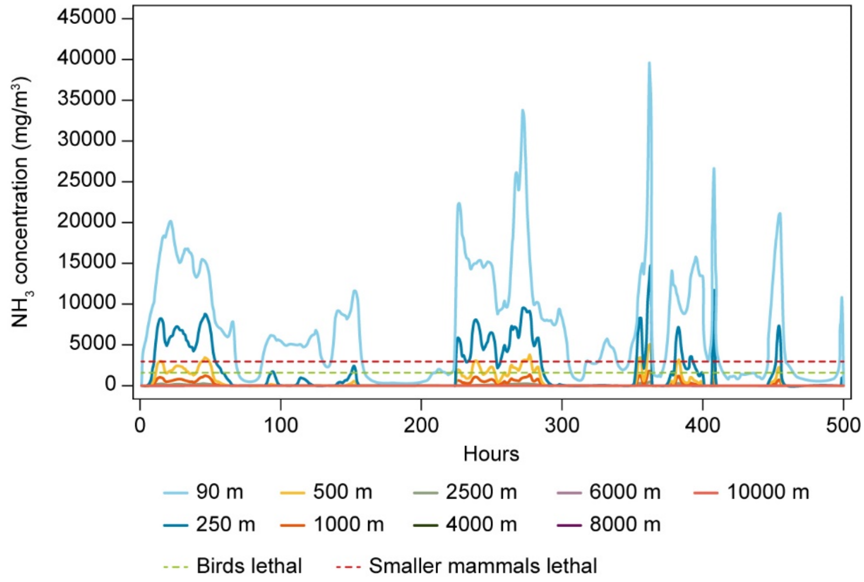


Figure 6.5. Accidental spill by tank collapse on land at the ammonia plant – winter, low wind. Lines indicate concentration of ammonia 1.5 meters about ground level at different distances from the spill. Dotted lines indicate threshold values for toxic effects for birds and mammals.

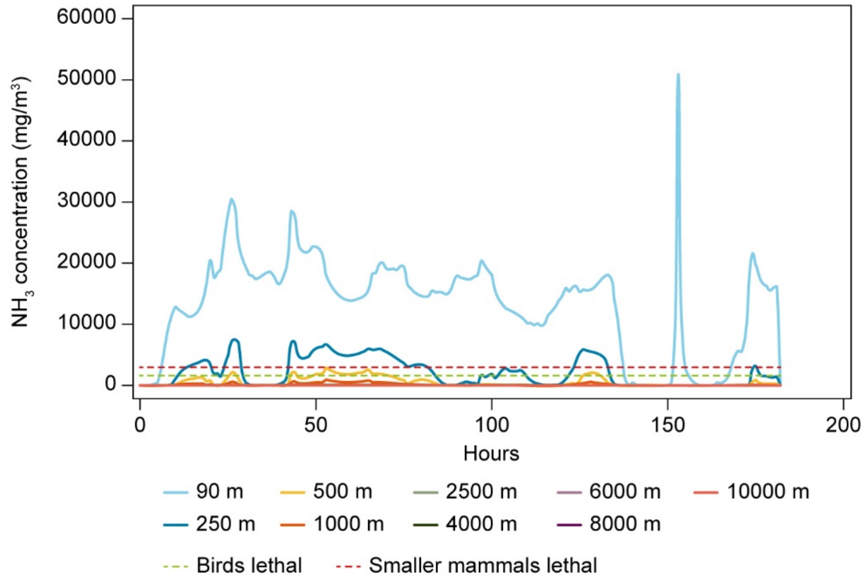
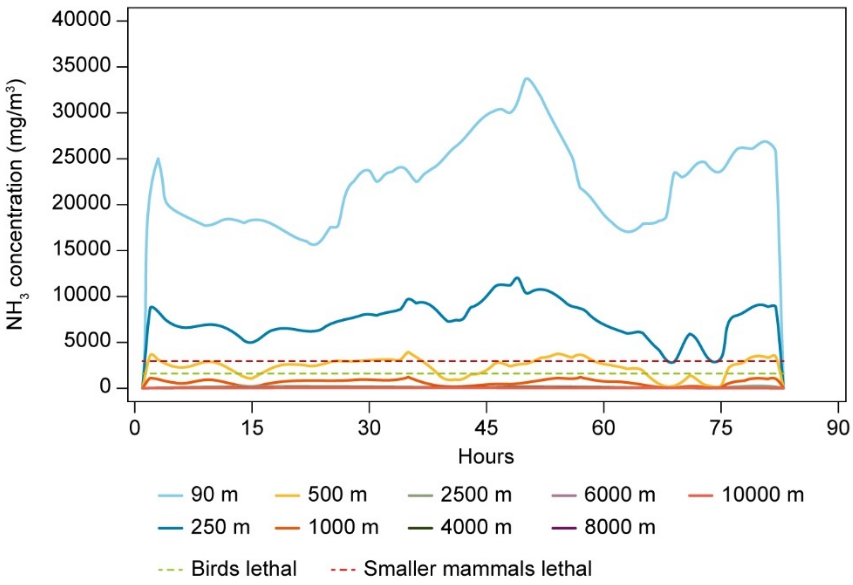


Figure 6.6. Accidental spill by tank collapse on land at the ammonia plant – summer, low wind. Lines indicate concentration of ammonia 1.5 meters about ground level at different distances from the spill. Dotted lines indicate threshold values for toxic effects for birds and mammals.

Figure 6.7. Accidental spill by tank collapse on land at the ammonia plant – summer, high wind. Lines indicate concentration of ammonia 1.5 meters about ground level at different distances from the spill. Dotted lines indicate threshold values for toxic effects for birds and mammals.



No short-term lethal concentration values are found for vegetation or plants. The threshold values given in Table 4.4 for plants and vegetation are no-effect concentrations of 0.6 mg / m^3 on the growth of cultivated crops. Most to least sensitive plant species to NH_3 are native vegetation > forests > agricultural crops (Krupa 2003). Data in Appendix 1 indicate long-term foliage injuries at ammonia concentrations above 150 µg / m^3.

Effects of ammonia on growth on plants and vegetation may be seen at concentrations above 0.6 mg / m^3. The aerial exposure and deposition from the vapour plume from an ammonia spill exceed these concentrations (see Appendix 2 for data on deposition). Hence, it is likely that effects on plants and vegetation (sub-lethal and lethal) will occur up to several kilometres away from the spill site in the direction that the ammonia is being transported to.

6.5 Overall findings from the modelling of ammonia release to the air

Generally, for winter vs summer spills, winter spills tend to show higher concentrations closer (both vertical and horizontal) to the spill site than the summer spills, whereas the dispersion of high concentrations of ammonia is more severe for the summer scenarios.

Where the ammonia is allowed to spread out into a thin slick with a large area, the evaporation occurs very fast, resulting in a short period with high concentrations of ammonia in the air. For a spill in a confined area, the evaporation period is prolonged, especially in winter and at low wind conditions. A confined spill will, however, expectedly be mitigated by the available response equipment on site; thus, it is likely that the scenarios will not be prolonged for as long as our simulations.

The longest period of simulated evaporation was 20 days (winter, ammonia plant spill), which would likely produce lethal as well as sub-lethal concentrations in the vicinity of the spill site. However, for the shorter scenarios, only lethal concentrations would be expected.

Dharmavaram et al. (1994) modelled the fate and transportation of ammonia spilled from a barge. They simulated a spill of 2,500 ton of ammonia, assuming that 30% would evaporate and the remaining would be dissolved in the water. The authors used the TRACE™ model to simulate the gas dispersion and found that distances to three concentration levels of concern (5,000, 2,000, and 250 ppm) were 1.8, 3.8 and 14.4 miles, respectively. This is in the same order of magnitude as in our modelling.

7 Risk for toxic effects of ammonia in sea and freshwater

The following evaluation of effects from an ammonia spill on marine and freshwater organisms is based on the established threshold values for toxicity (Chapter 4) and estimates for the possible amount of ammonia entering the water environment for the three different spill scenarios:

A) Accidental spill by tank collapse on land at the ammonia plant

B) Accidental spill when loading ship at pier

C) Accidental spill in fjord during shipping.

7.1 Threshold values for toxicity

Threshold values for toxicity are defined on the basis on data from ecotoxicological tests where different aquatic species are exposed to ammonia under controlled conditions (se Chapter 4).

7.1.1 Marine organisms

Threshold values for toxicity in marine organisms during short-term exposure to total ammonia (NH_3 + NH_4^+) are given in Table 7.1. The underlying data are presented in Chapter 4 and Appendix 1.

Table 7.1. Threshold values for toxicity in marine organisms during short-term exposure to total ammonia (NH3 + NH4+). Underlying data are presented in Chapter 4 and Appendix 1

Marine organisms	Threshold level (mg/L)
Algae	29.2
Crustaceans	4.9
Molluscs	2.6
Fish	2.0

7.1.2 Freshwater organisms

Threshold values for toxicity in freshwater organism during short-term exposure to total ammonia (NH_3 + NH_4^+) are given in Table 7.2. The underlying data are presented in Chapter 4 and Appendix 1.

Table 7.2. Threshold values for toxicity in freshwater organism during short-term exposure to total ammonia (NH_3 + NH_4^+). The underlying data are presented in Chapter 4 and Appendix 1.

Freshwater organisms	Threshold level (mg/L)
Crustaceans	0.5
Molluscs	0.8
Fish	0.2

7.2 Spill scenarios for seawater and freshwater

7.2.1 Seawater

In the event of an accidental spill of ammonia during shipping or during loading of a ship at pier, ammonia could be released directly onto the water. Ammonia is highly soluble in water and spill of liquid ammonia will dissolve in the water within minutes. Literature values indicate that between 60 and 80% of an ammonia spill at sea will be dissolved in the seawater (Raj and Read 1978) and will be more soluble at low temperatures, the remaining will evaporate to the air. If a large quantity of ammonia is spilled, evaporated ammonia may form a vapour cloud that may act like a heavy gas and move around just above the water surface.

In the scenario for "Accidental spill in fjord during shipping", it is assumed that 70% of the spill is dissolved in the seawater. In the scenario "Accidental spill when loading ship at pier", it is assumed that 50% of the spill is dissolved in the seawater (Table 7.3).

Table 7.3. Simulated ammonia spills and sizes for worst-case-scenarios.

Spill scenario – Seawater/fjord				
Spill type	**Spill amounts (tonnes)**	**Spill amount (m^3)**	**Percent of spill dissolved in seawater (%)**	**Amount of spill in seawater (tonnes)**
A) Accidental spill by tank collapse on land at the ammonia plant	50,000	73,314	0	0
B) Accidental spill when loading ship at pier	10,000	14,663	50	5,000
C) Accidental spill in fjord during shipping	40,000	58,651	70	28,000

7.2.2 Freshwater

For freshwater ammonia exposure (lakes and rivers), it is assumed that the load / exposure of the lakes / rivers is caused by the deposition of ammonia that has evaporated from accidental spills. The deposition of ammonia at different distances from the spill sites for the two scenarios A) and B) (Table 7.4) is estimated by the OML model (se Chapter 6 and Appendix 2).

The deposition of ammonia is estimated for accidental spills on land by tank collapse and accident spill when loading ship at pier. The two scenarios are presented in Table 7.4.

Table 7.4. Spill scenarios where ammonia deposition is estimated by the OML model (Chapter 6).

Spill scenario – Seawater/fjord				
Spill type	**Spill amount (tonnes)**	**Spill amount (m^3)**	**Percent of spill evaporated to atmosphere (%)**	**Amount evaporated to atmosphere (tonnes)**
A) Accidental spill by tank collapse on land at the ammonia plant	50,000	73,314	100	50,000
B) Accidental spill when loading ship at pier	10,000	14,663	50	5,000

Model estimates for ammonia deposition at different distances from the spill site for the two scenarios A) and B) are found in Table 7.5 and 7.6.

Table 7.5. Deposition at different distances from the 'Accidental spill by tank collapse on land at the ammonia plant' – spill site. The deposition estimates are the total amount of ammonia deposited until all ammonia has evaporated (188 hours).

Distance from spill site (m)	90 m	250 m	500 m	1000 m	2500 m	4000 m	6000 m	8000 m	10000 m
Deposition (g/m^2)	2411	387.3	100.7	27.2	7.5	4.6	3.1	2.3	1.9

Table 7.6. Deposition at different distances from the 'Accidental spill when loading ship at pier'. The deposition estimates are the total amount of ammonia deposited in the period until all ammonia has evaporated (2 hours).

Distance from spill site (m)	683 m	1000 m	2500 m	4000 m	6000 m	8000 m	10000 m
Deposition (g/m^2)	8.2	3.9	2.1	1.7	1.3	1.0	0.8

7.3 Impact of ammonia spills in seawater

The volume of seawater in which the ammonia spill must be diluted until the concentrations of ammonia are below threshold values for toxic effects is calculated. These potential impact volumes of the fjord are calculated by dividing the amount of ammonia spilled in the fjord by the threshold value for toxicity on marine organisms. Similar calculations are used in the assessment of discharges / spills from oil / gas offshore installations (Johnsen et al. 2000). The potential risk zones are estimated assuming that the ammonia is mixed down to a depth of 30 m, which is in accordance with results from previous modelling of ammonia spills by Cedre (2006).

The potential impact volumes and risk zones for toxic effects on marine algae, crustacean, and fish from a spill of ammonia in the fjord are given in Table 7.7 and 7.8 and shown on maps in Chapter 8.

Cedre (2006) completed a number of simulations of different types of ammonia spills by use of the CHENMAP software model. The scenario included ammonia spills in different spill rates and for open sea, port, and instant wreck and river scenarios. The movement and fate of the ammonia spills were modelled for fresh and seawater. The Cedre (2006) modelling indicated that ammonia released in open sea may spread over an area up to 30 x 18 km and be dissolved down to about 27 m depth. The spreading depends on the wind speed and the sea currents. Hence, the highest concentrations were found in the port scenario. The Cedre (2006) modelling for sea spills are in the same order of magnitude as our findings. For the river scenario, ammonia was modelled to spread up to 3.6 km downstream of the spill location.

Table 7.7. Impact volume and size of risk zone of the accidental spill of ammonia from ship in seawater. The potential impact area is estimated assuming that ammonia is mixed up to a depth of 30 m.

Organism group	Threshold values for toxicity (mg/L)	Impact volume (m^3)	Impact areal (km^2)	Radius of impact area (km)
Algae	29.2	9.59E+08	32	3,191
Crustaceans	4.9	5.62E+09	187	7,726
Molluscs	2.6	1.10E+10	366	10,797
Fish	2.0	1.40E+10	467	12,191

Table 7.8. Impact volume and risk zone in fjord of the accidental spill of ammonia at loading of ship at pier. The potential risk zone is estimated assuming that ammonia is mixed up to a depth of 30 m.

Organism group	Threshold values for toxicity (mg/L)	Impact volume (m^3)	Risk zone (km^2)	Radius of risk zone (m)
Algae	29.2	1.71E+08	5.7	1,348
Crustaceans	4.9	1.00E+09	33.5	3,265
Molluscs	2.6	1.96E+09	65.4	4,562
Fish	2.0	2.50E+09	83.3	5,152

7.4 Impact of ammonia spill in freshwater

The ammonia concentrations in fresh water were estimated based on the deposited amount of ammonia and an assumed mean depth of the potential freshwater recipient of 5 m (Table 7.9). The estimated ammonia concentrations in freshwater were compared with threshold values for the toxicity of freshwater organisms. Risk quotients (the ratio between the ammonia concentration in water and the thresholds values for toxicity) were calculated as well. There is a risk of toxic effects for risk quotients greater than 1. There is a risk of effects on freshwater organisms up to 6 km from the spill site.

The risk of toxic effects on freshwater organisms for different distances from 'Accidental spill by tank collapse on land at the ammonia plant' spill site is shown in Table 7.9. The deposition estimates are the total amount of ammonia deposited until all ammonia has evaporated (188 hours).

The results (Table 7.9) show that there is a risk of toxic effects on freshwater organisms at a considerable distance from the spill site, 6 km and > 10 km for crustaceans and fish, respectively.

For the estimated risk of toxic effects from 'Accidental spillage when loading ship at pier', the impact area is 1 km and 8 km for crustaceans and fish, respectively (Table 7.10).

Table 7.9. Risk quotient (RQ)* for toxic effects on freshwater organisms at different distances from the spill site ('Accidental spill by tank collapse on land at the ammonia plant'). Bold numbers indicate the maximum distance where RQ values are above 1.

Distance from spill site (m)	90 m	250 m	500 m	1000 m	2500 m	4000 m	6000 m	8000 m	10000 m
Deposition (g/m2)	2411.6	387.3	100.7	27.2	7.5	4.6	3.1	2.3	1.9
Estimated concentration in freshwater (mg/L)	482.3	77.5	20.1	5.4	1.5	0.9	0.6	0.5	0.4
RQ-Crustaceans	964.6	154.9	40.3	10.9	3.0	1.9	**1.2**	0.9	0.7
RQ-Molluscs	602.9	96.8	25.2	6.8	1.9	**1.2**	0.8	0.6	0.5
RQ-Fish	2411.6	387.3	100.7	27.2	7.5	4.6	3.1	2.3	**1.9**

*(RQ: ratio between ammonia concentration in water and thresholds values for toxicity).

Table 7.10. Risk quotient (RQ) for toxic effects on freshwater organism at different distances from the accident spills on land by tank collapse. Model estimates are the total amount deposited in the period until all ammonia at the spill site has evaporated (2 hours). Bold numbers indicate distance where RQ values are above 1.

Distance from spill site (m)	683 m	1000 m	2500 m	4000 m	6000 m	8000 m	10000 m
Deposition (g/m2)	8.2	3.9	2.1	1.7	1.3	1.0	0.8
Estimated concentration in freshwater (mg/L)	1.6	0.8	0.4	0.3	0.3	0.2	0.2
RQ-Crustaceans	3.3	**1.6**	0.8	0.7	0.5	0.4	0.3
RQ-Molluscs	2.1	**1.0**	0.5	0.4	0.3	0.3	0.2
RQ-Fish	8.2	3.9	2.1	1.7	1.3	**1.0**	0.8

7.5 Summary

The assessment of the impact from an ammonia spill in the fjord indicates that a direct spill from shipping or loading of ammonia may cause toxic effects on marine organisms in the fjords in a significant area of up to 10 km from the spill site. The finding is consistent with results of the modelling performed by Cedre (2006) of a spill of 500 tonnes ammonia in open sea that becomes distributed over an area of up to 30 km x 18 km and dissolved down to about 27 m depth.

However, the impact on pelagic organisms will probably be of short-term duration as the dilution is expected to be significant in the fjords and because the recovery of organisms would be fast due to an inflow of organisms from the adjacent water areas. The risk of long-term effects will be greatest if the spill occurs in shallow waters where the recovery of benthic organisms in general is slow. A possible long-term result of an ammonia spill could be increased eutrophication of the receiving waters, which could stimulate blooms of algae, creating higher productivity but potentially also water quality degradation.

Modelling of the atmospheric deposition of ammonia evaporated from the spill site indicates that freshwater recipients (lakes and rivers) may be affected at a distance of more than 10 km from the spill site.

8 Assessment of the consequences of a major release of ammonia

Ammonia can be fatal to humans, animals and plants upon exposure to elevated concentrations. Accidental releases of ammonia (NH_3), resulting in high ammonia levels in the environment, can lead to poisoning of the organisms present and ultimately cause disappearance of some species in a local area for some years. In addition, ammonia release to the environment can lead to eutrophication of ecosystems (terrestrial as well as aquatic).

The potential acute environmental effects of an ammonia spill from a Power-to-X plant and shipping in Greenland are assessed and evaluated for three types of spill scenarios for three localities (three production sites and three spill sites in connection with shipping). Based on estimates of ammonia concentrations in the environment (Chapter 6 and 7) and thresholds value for toxicity (Chapter 4), potential risk zones for seabirds, mammals, plants and vegetation, marine organisms (algae, crustaceans and fish) and freshwater organisms (crustaceans and fish) have been estimated (Table 8.1.) The potential risk zones are defined by use of the estimated distances for each scenario and for the different organism types for which the threshold values for lethal acute toxic effects can be exceeded (Table 8.1). The threshold values for toxicity ammonia exposure have been selected on the basis of a thorough literature review (Chapter 4). The estimated risk zones are plotted on the important biology maps and vegetation / NDVI maps (Figures 8.2-8.10) for assessment of the results.

In the following, each of the Figures 8.2-8.10 will be discussed based on the modelled and estimated ammonia exposure together with the known information on the specific ecological values of each area. The same legend applies to each map (Figure 8.1). The abbreviations used in Figures 8.2-8.10 are explained in Table 8.1 (grey shaded row).

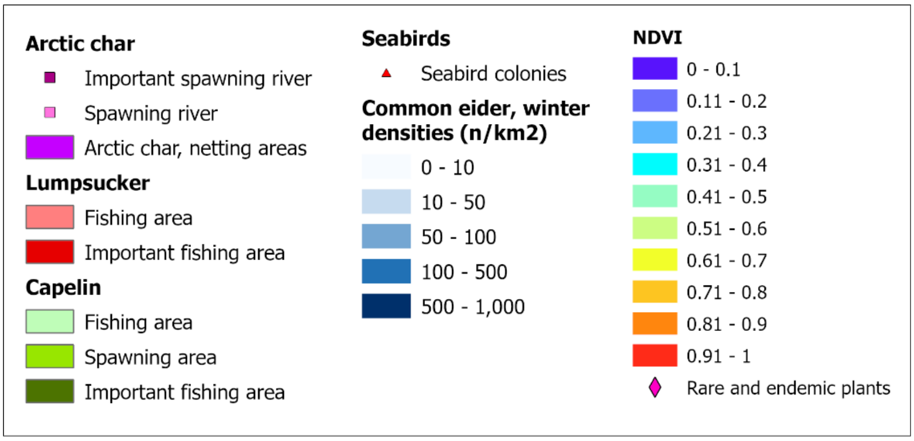


Figure 8.1. Explanatory legend for Figures 8.2-8.10.

Table 8.1. Estimated sizes of risk zone around spill sites (m) where threshold values for ammonia toxicity can be exceeded for different organism types. The uppercase letter is the abbreviation used in Figures 8.2-8.10

	Season	Exposure of birds to ammonia through the air	Exposure of small mammals to ammonia through the air	Exposure of plants and vegetation to ammonia through the air	Exposure of marine organisms to ammonia dissolved in water at spill site	Exposure of freshwater organisms through aerial deposition of ammonia to lakes and rivers
Abbreviations used in Figures 8.2-8.10		**B (Birds)**	**M (Land mammals)**		**SW-a, SW-c, SW-f (Seawater – algae, crustaceans and fish)**	**FW-c, FW-f (freshwater crustaceans and fish)**
Accidental spill in fjord during shipping	Summer	10,000	2,000	Several kilometres	Algae: 3,000 Crustaceans: 7,500 Fish: 12,000	-
	Winter	14,000	8,000			-
Accidental spill by tank collapse on land at the ammonia plant	Summer – low wind	500	250	Several kilometres		Crustaceans: 6,000 Fish: >10,000
	Summer – high wind	500	250	Several kilometres		
	Winter	500	250			-
Accidental spill when loading ship at pier	Summer	4,000	1,000	Several kilometres	Algae:1,300 Crustaceans: 3,000 Fish: 5,000	Crustaceans:1,000 Fish: 8,000
	Winter	8,000	6,000			-

8.1 Kangerlussuaq (Sdr. Strømfjord)

See Figures 8.2-8.4, the same legend applies to each map (Figure 8.1).

8.1.1 Assessment of the consequences of a major release of ammonia from the proposed plant and pier

Birds

The risk zone for birds resulting from both a tank collapse and a loading spill is very small and restricted to the immediate surroundings of the plant and in case of loading also to the opposite shore of the fjord. Bird populations in these land areas including freshwater habitats are mainly passerines, ptarmigans, ducks (mallard) and shorebirds (phalaropes) are small in summer and absent in winter; thus, very few land birds are at risk of impact (acute mortality). Chicks in nests and in company with parent birds are probably the most vulnerable as they cannot avoid airborne ammonia. Long-term population effects on land birds from such spills are, however, not expected.

The most important species occurring in the area is the Greenland white-fronted goose, which has an important spring staging habitat in the valley where the plant is located. However, these geese are sensitive to disturbance and will probably abandon the habitat if a plant is established; consequently, impacts from plant establishment are more relevant to consider in relation to this species.

Mammals

The risk zone for mammals is also very small and restricted to the immediate surroundings of the plant. A few mammals residing in the area (foxes, hares) may be killed by an ammonia spill, but this will most likely have no effect at population level. The affected areas are not heavily used by caribou, and a spill of ammonia will have no effects on the population level.

Vegetation

The effects of deposition of ammonia on vegetation depend on the distance from the source and will be temporary at a time scale ranging from a few weeks to a few years, or perhaps decades at vegetation die-off. The effects will range from being detrimental to the vegetation to a fertilizing effect, causing increased growth rates of plants and probably changes in the composition of the plant communities. Overall, these effects are expected to be small and temporary.

In Kangerlussuaq, vegetation in the immediate risk zone is sparse and not considered as a significant food resource for wildlife – particularly caribou.

No impacts on vegetation are expected in the protected area "Arnangarnup Qoorua".

Seawater

The risk zones for flora and fauna in the sea at the spill site (loading) cover the fjord to a distance of 6 km (for fish) from the spill site. Within this distance, acute mortality can be expected (at different distances for the specific species) depending on the spread of the spill. Due to the relatively small area, no long-term effects on most of the populations in the area are expected. However, the Arctic char population that spawns and winters in the Sarfartoq River will be vulnerable to a spill when the population moves into the area before migrating up in the river. Yet, as the duration of a spill will be short, only a small fraction of the Arctic char stock may be affected. No long-term effects on the population are therefore expected.

A risk of long-term effects exists if shallow waters are affected by the spill. Here, toxic concentrations of ammonia may reach the seabed and affect benthic communities that usually recover slowly.

Finally, ammonia can contribute to the eutrophication of the receiving waters, and this can stimulate algae blooms. These will most likely be of short-term duration and of limited extent, due to the large, tidal water exchange.

Freshwater

The risk zone of freshwater habitats is also restricted. The habitats are small lakes, ponds and a number of rivers, of which the Sarfartoq River holds a strong and very important stock of Arctic char. Fauna and flora may be killed in small stationary water bodies, and a fertilizing effect must be expected in areas that are less impacted by ammonia. The most vulnerable elements in the freshwaters are eggs, larvae and fry of Arctic char in the Sarfartoq River, and acute mortality of these in affected areas is likely. However, as only a small part of the river will be affected by toxic ammonia concentrations, long-term impacts on the Arctic char population are not likely.

8.1.2 Assessment of the impact of ammonia spill from shipping in the fjord

Birds

A spill in the mouth of the fjord in winter may affect (acute mortality) some staging common eiders. However, the number wintering in the area is relatively low and no population effects are therefore expected. On land and along the coasts in summer, breeding bird populations may be affected, but again breeding bird densities are low and no long-term population effects are consequently expected.

Mammals

The risk zone for land mammals is very small and as mammal (mainly foxes and a few caribou) populations in this area are small as well, only a few individuals will be affected by a fjord spill.

Several marine mammal species occur in the fjord mouth, but if the same risk zone as for land mammals is applied, very few marine mammals will be affected – mainly seals – and no population effects are likely.

Vegetation

The nearby vegetation covers mainly alpine areas with little vegetation. Coastal areas with more lush vegetation may be affected, primarily by the fertilizing effect of the ammonia. Locally die-off of plants may occur.

Seawater

The risk zones for flora and fauna in the sea cover waters up to ca. 12 km from the spill site. Within this distance, acute mortality of some fish, plankton and benthic organisms can be expected (at different distances for the specific species) depending on the spread of the spill. Due to the relatively small area and the replacement effect from adjacent waters, no long-term effects on the populations in the area are expected.

A risk of long-term effects is present if shallow waters are affected. Here, toxic concentrations of ammonia can reach the seabed and affect benthic communities that usually recover slowly.

There are important spawning and fishing areas for lumpsucker and capelin within the risk zone for fish. An ammonia spill will temporarily affect eggs, larvae and adult fish (acute mortality). The spawning season for lumpsucker is several months in the spring, and an ammonia spill (which is of short duration) will only affect a very small part of the spawning population and the produced eggs. The spawning season of capelin is shorter (some weeks), but still much longer than the impact time of an ammonia spill, and no effects on the population are therefore expected. Impacts on the fisheries on these fish will most likely be only a few days closure.

There are also fishing areas for Arctic char within the fish risk zone. If these are affected in the fishing season, short-term effects on fishery are highly likely to occur.

Finally, ammonia can contribute to the eutrophication of the receiving waters, and this can stimulate algae blooms. These will most likely be of short-term duration and of limited distribution, due to the large, tidal water exchange.

Freshwater

The freshwaters affected by a spill in the mouth of the fjord are very limited at spatial scale. There are no rivers with spawning and wintering Arctic char near to the spill site.

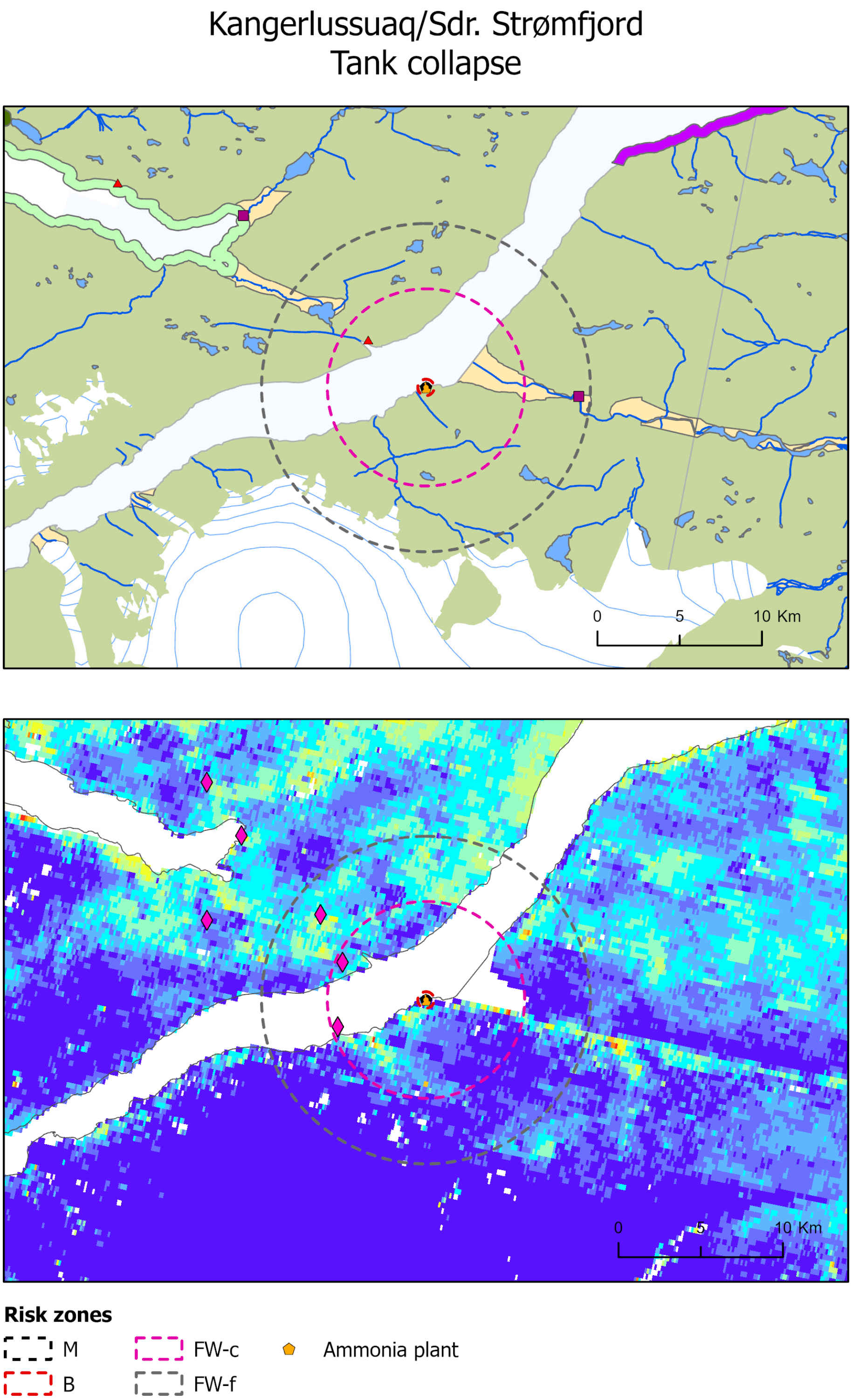


Figure 8.2. Risk zones in case of spill from tank collapse on land at the ammonia plant in Kangerlussuaq. B: Birds; M: Land mammals, FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.

Figure 8.3. Risk zones in case of ship loading spill at pier in Kangerlussuaq. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater - fish; FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.

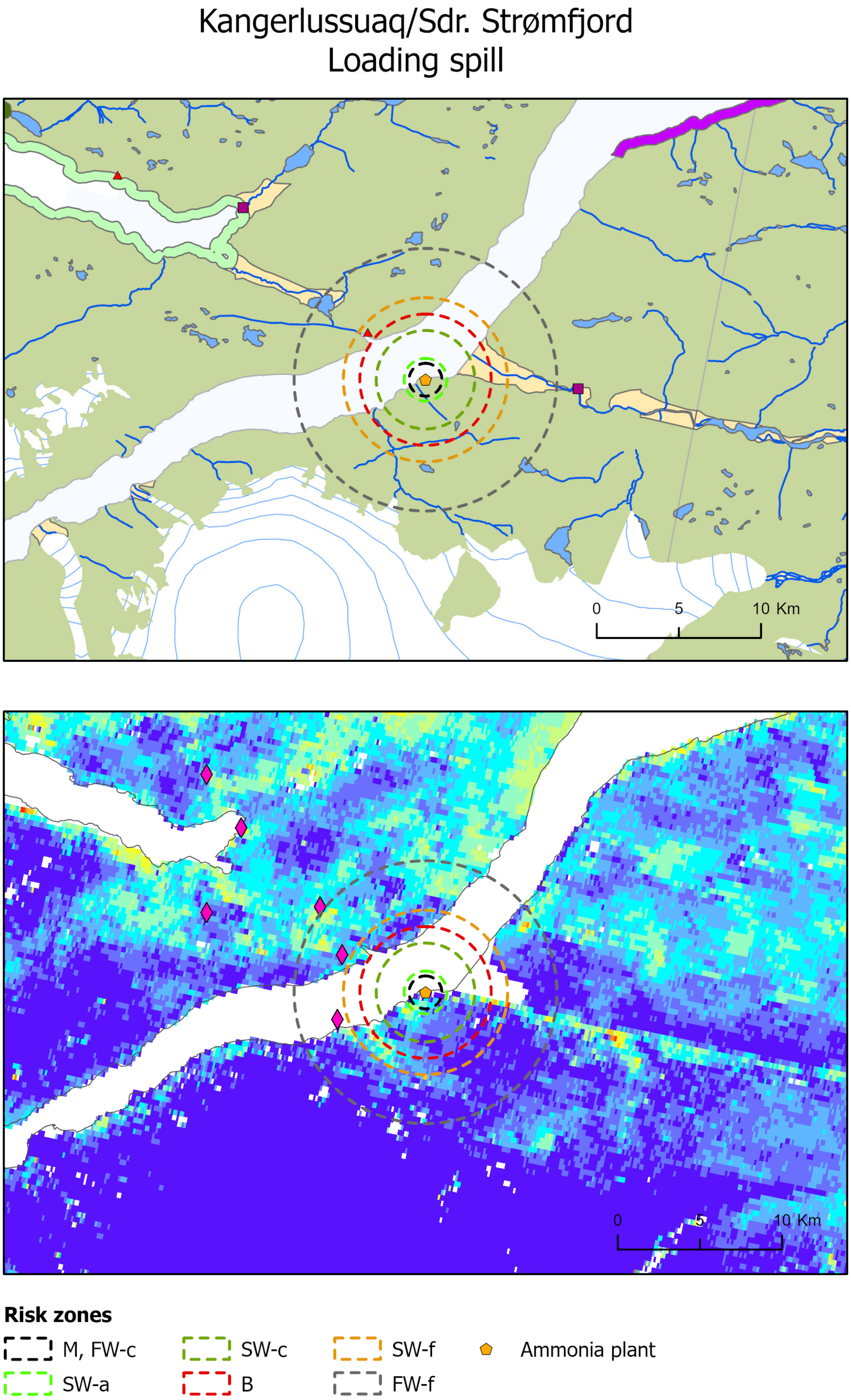
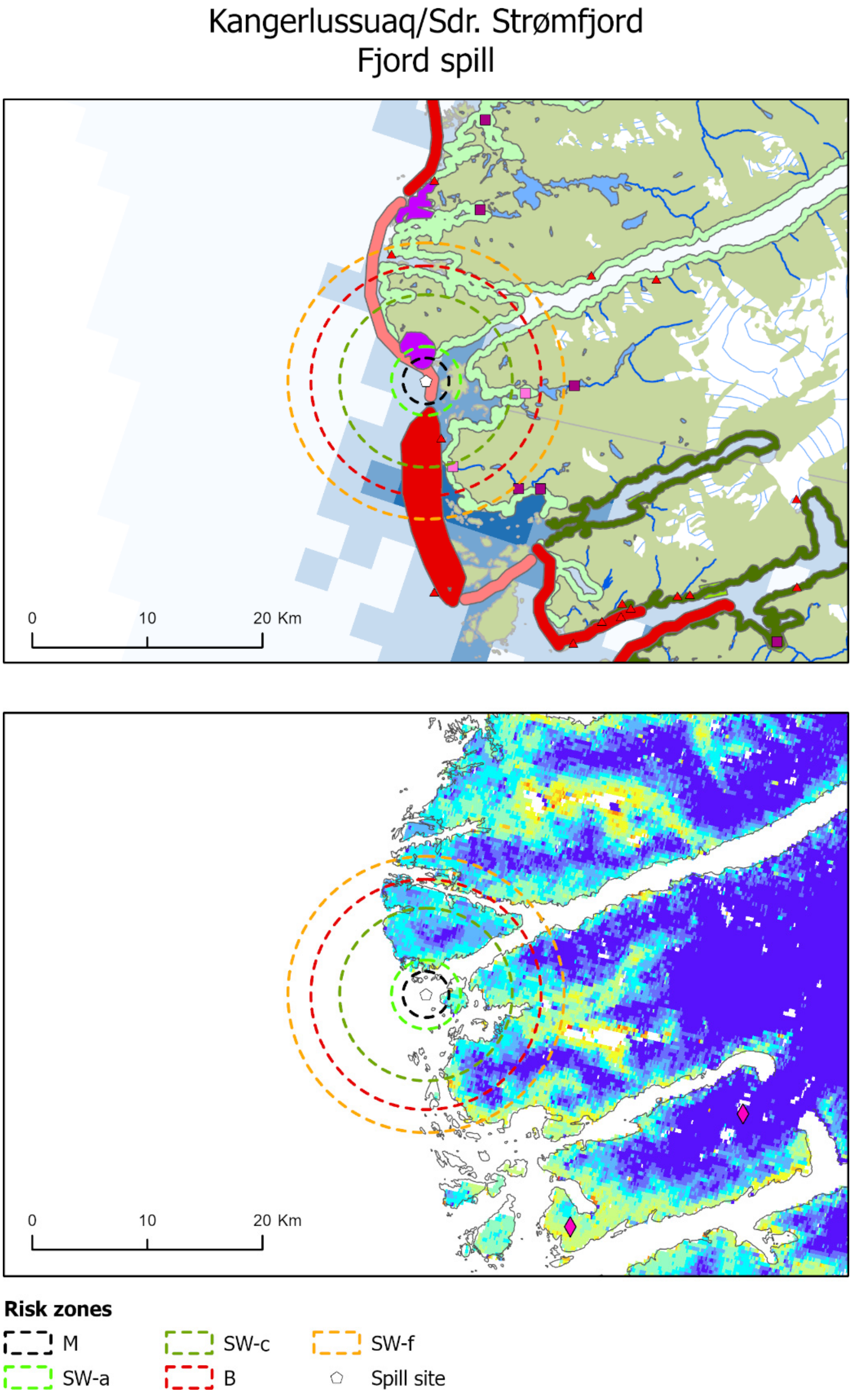


Figure 8.4. Risk zones in case of fjord spill from shipping in Kangerlussuaq. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater – fish.



8.2 Kangerlussuatsiaq (Evighedsfjorden)

See Figures 8.5-8.7, and the same legend applies to each map (Figure 8.1).

8.2.1 Assessment of the consequences of a major release of ammonia from the proposed plant and pier

Birds

In summer, no seabird breeding colonies are found within the bird risk zone from a tank collapse or from a spill during loading. In winter, there are very few, if any, seabirds present, and no significant effects on seabirds are therefore expected in either summer or winter.

The risk zone for birds covers very restricted land areas with small bird populations. Consequently, only few landbirds will be affected (acute mortality) by a spill, and no population effects are expected.

Mammals

The risk zone for land mammals covers very restricted land areas where only few mammals (mainly foxes) are expected to occur in case of an accident; accordingly, no population effects are expected.

Vegetation

As most of the surroundings consist of ice caps, steep mountains and a valley with only sparse vegetation in the river bed, the vegetated area affected by a spill will be very small. The recovery of damaged vegetation will probably be slow and may last for decades

Seawater

The risk zones for flora and fauna in the sea from a loading spill is ca. 8 km and cover the innermost part of the fjord. Within this distance, acute mortality of some fish, plankton and benthic organisms can be expected (at different distances for the specific species) depending on the spread of the spill. Due to the relatively small area and the replacement effect from the fjord to the west, no long-term effects on the planktonic populations in the area are expected. However, as benthic communities have a very slow recovery rate, the effects on these may be of longer duration.

Freshwater

The risk zone for freshwater organisms is ca. 10 km, but freshwaters are restricted to the main river (very turbid water) and a few ponds within that zone. There are apparently no Arctic char in the river. No effects on freshwater organisms are likely from an ammonia spill during loading.

8.2.2 Assessment of the consequences of a major release of ammonia from shipping in the fjord

Birds

The risk zone for birds from a fjord spill includes several seabird breeding colonies that may be affected by an ammonia release in the breeding season (summer). Especially chicks in the nests will be vulnerable as they cannot avoid ammonia in the air, and a high acute mortality among these is likely in case of a spill. The adults may also suffer from acute mortality, and the number of birds in the affected colonies may decrease in the following years. However, it is not known to what degree birds are able to detect and avoid ammonia in the air.

The most important seabird colony in the fjord is Taateraat with thick-billed murres, which is situated further west and outside the risk zone as shown in Figure 8.7. If a spill occurs near that colony, it would cause risk of high mortality among both chicks and adult birds. The recovery potential of the Taateraat colony is low due to its almost isolated position – the nearest neighbouring colony is located 95 km (over the sea) away – and moreover its population is declining. Additional mortality from an ammonia spill could thus be fatal for this vulnerable colony.

Mammals
The risk zone for mammals is very small. Due to the extremely alpine topography of the area, very few mammals occur, and the effects from an ammonia spill will thus be negligible.

Marine mammals occur in the fjord, but when applying the same risk zone as for land mammals to these, only very few will be affected – mainly seals, and no population effects are likely.

Vegetation
The topography of the region is extremely alpine, and the distribution of lush vegetation is limited; accordingly, the effects of an ammonia spill will be very local.

Seawater
The risk zones for flora and fauna in the sea cover an area ca. 15 km away from the spill site. Within this distance, acute mortality of some fish, plankton and benthic organisms can be expected (at different distances for the specific species) depending on the spread of the spill. Due to the relatively small size of the area and the replacement effect from adjacent waters, no long-term effects on the planktonic populations are expected. However, as benthic communities have a very slow recovery rate, the effects on these may be of longer duration.

Within the risk zone for fish, there are spawning and fishing areas for capelin whose eggs, larvae and adult fish may be temporarily affected by an ammonia spill. The spawning season for capelin lasts several weeks and much longer than the impact time of an ammonia spill, and no effects on the population are therefore expected. Impacts on the fisheries on these fish will most likely be a few days closure.

Finally, ammonia can contribute to the eutrophication of the receiving waters, and this can stimulate algae blooms that most likely will be of short-term duration and with limited distribution, due to the large, tidal water exchange.

Freshwater
The spatial extent of the freshwaters affected by a spill is very limited. There are no rivers with spawning and wintering Arctic char near to the spill site.

Figure 8.5. Risk zones in case of spill from tank collapse on land at the ammonia plant in Kangerlus-suatsiaq.
B: Birds; M: Land mammals, FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.

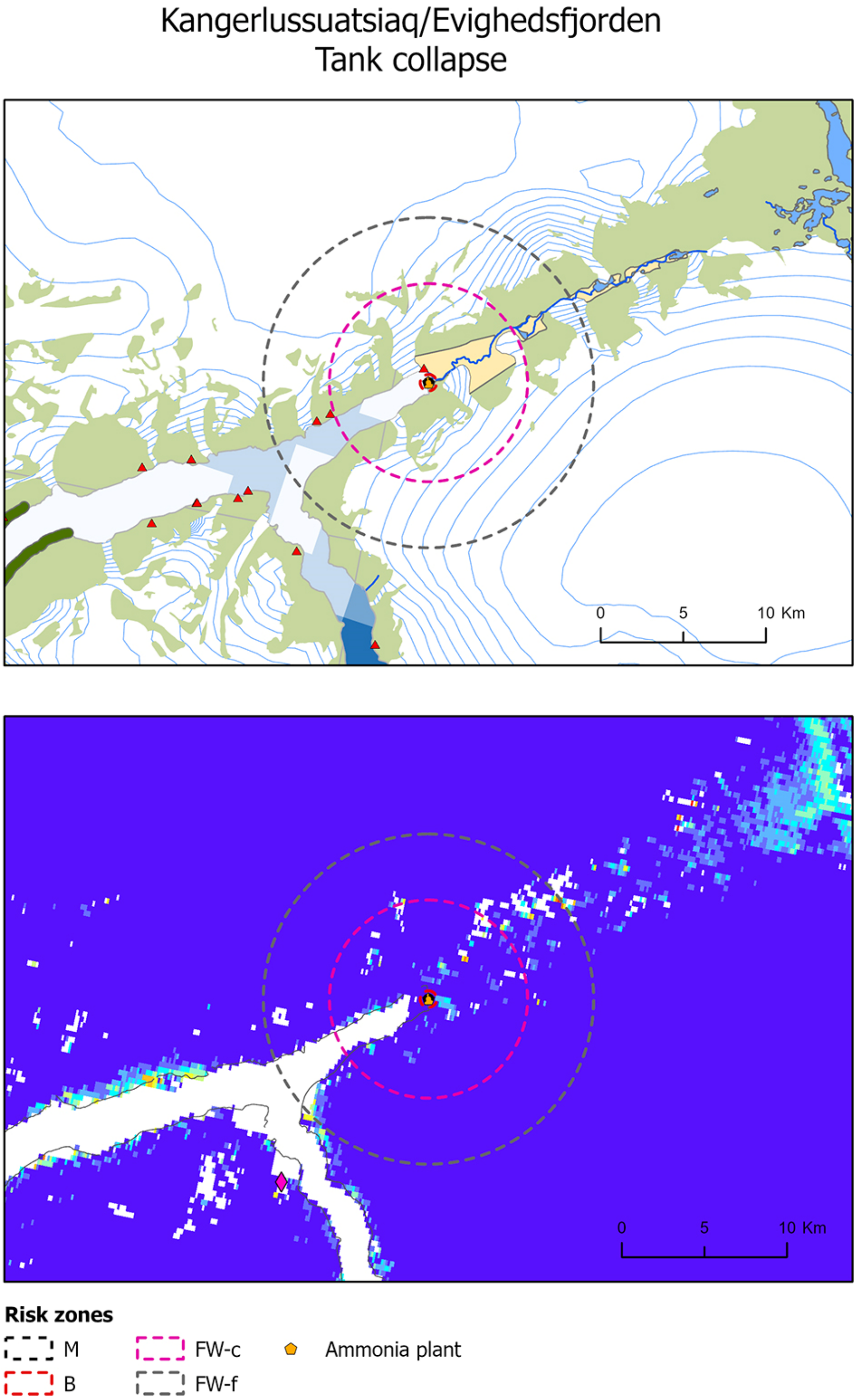
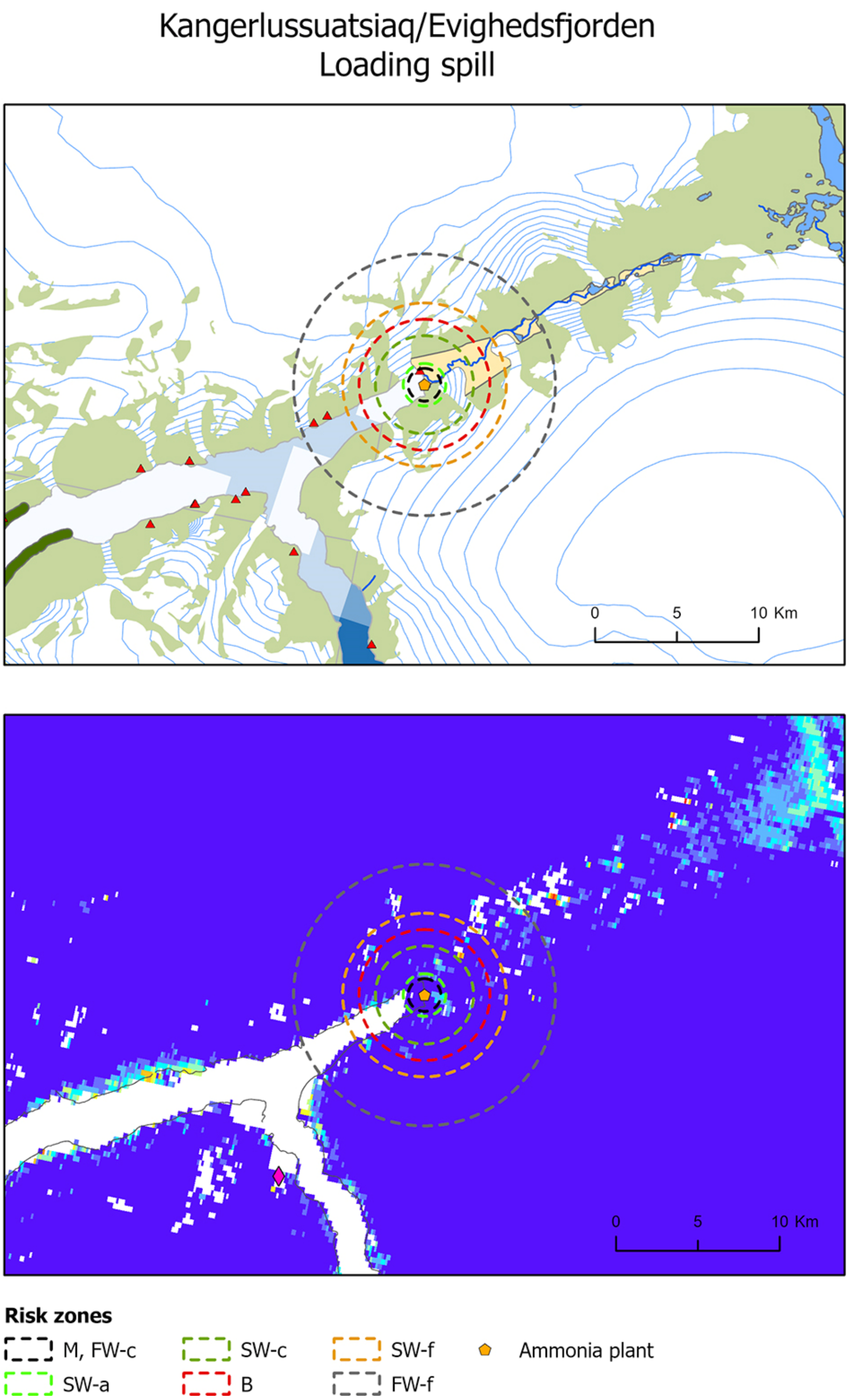


Figure 8.6. Risk zones in case of ship loading spill at pier in Kangerlussuatsiaq. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater – fish; FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.



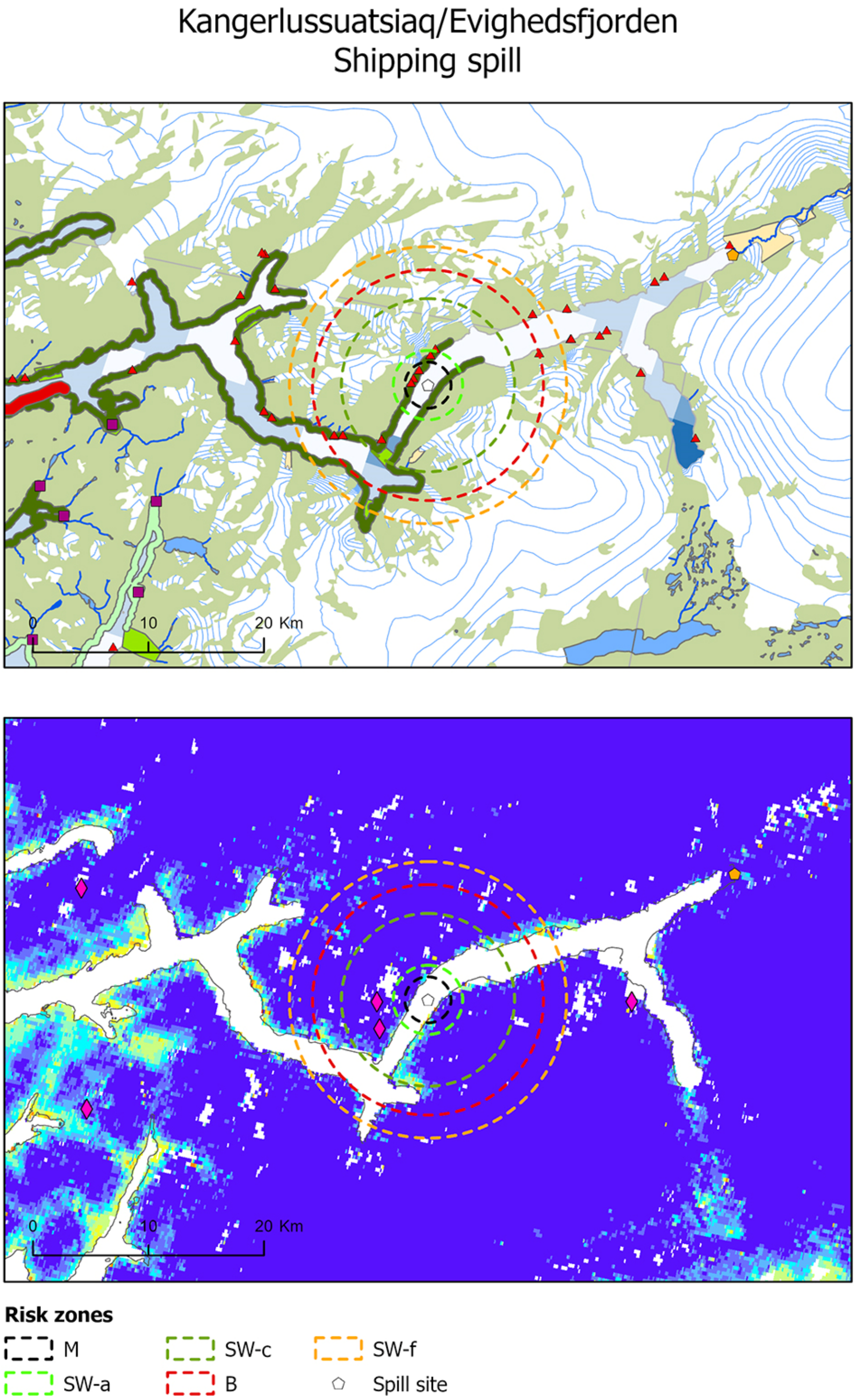


Figure 8.7. Risk zones in case of fjord spill during shipping in Kangerlussuatsiaq. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater – fish; FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.

8.3 Nuup Kangerlua (Godthåbsfjorden)

See Figures 8.8-8.10 and the same legend applies to each map (Figure 8.1).

8.3.1 Assessment of the consequences of a major release of ammonia from the proposed plant and pier

Birds

The risk zone for birds is very small without seabird breeding colonies. On land, common species like snow buntings and ravens may be present, but species vulnerable or of conservation concern, such as great northern diver, white-tailed eagle and harlequin duck etc., are shy and will have abandoned the risk zone during the establishment of the plant and pier facilities. Acute mortality of some of the common species must be expected, but no population effects on land birds are likely from an ammonia spill at this site.

Mammals

The risk zone for mammals is very small, and very few (foxes for example), if any, mammals will be affected (acute mortality) from an ammonia spill.

The occurrence of marine mammals in this shallow fjord is limited to seals. When applying the same risk zone as for land mammals, very few seals, if any, will be affected, and no population effects are likely.

Vegetation

Lush vegetation is found in the area and effects are likely to occur, ranging from damages due to eutrophication depending on the scale of exposure. Sensitive vegetation includes copses of *Salix* and *Alnus* and rich herb slopes and fens. Recovery of herb slopes and fens will probably take several years, while copses may have a faster recovery rate.

The fertilising effect of ammonia may also impact areas with poorer vegetation, thereby increasing their plant cover and making them more attractive to grazing mammals such as caribou and muskoxen.

Seawater

The risk zones for flora and fauna in the sea from a loading spill is ca. 6 km and cover the innermost part of the fjord. Within this distance, acute mortality of some fish, plankton and benthic organisms can be expected (at different distances for the specific species) depending on the spread of the spill. Due to the relatively small area and the replacement effect from the fjord to the west (high tide water amplitude and water exchange), no long-term effects on the planktonic populations in the area are expected. However, as benthic communities have a very slow recovery rate, the effects on these may be of longer duration.

Freshwater

The risk zone for freshwater organisms is ca. 8 km. Within this zone, there is a multitude of lakes, ponds and rivers, and at least two of the rivers hold Arctic char. Here, wintering adult fish, eggs in autumn and larvae and fry will be at risk of being affected. In winter, ice will protect the water column, but in summer and autumn eggs and larvae will be vulnerable and high acute mortality within the risk zone is expected. The risk zone covers the major part of the rivers, and a worst-case spill may kill a significant part of a season's production.

Fauna and flora may be killed in small stationary water bodies, and a fertilising effect changing the species composition must be expected in areas less impacted by ammonia. This may alter their quality as habitats for water birds.

8.3.2 Assessment of the consequences of a major release of ammonia from shipping in the fjord

Birds

There are several breeding colonies of seabirds within the bird risk zone of the spill site. Particularly chicks in the nests will be vulnerable as they cannot avoid the airborne ammonia, and high acute mortality of these must be expected. Among other species of conservation concern is the white-tailed eagle, which breeds with four or five pairs within the bird risk zone, and which may also be affected by mortality of chicks and perhaps also of adult birds.

Local populations within the risk zone may decline temporarily due to a spill, but will most likely recover after a few years.

In winter, high numbers of common eiders (and other seabirds) occur within the bird risk zone, and high acute mortality among these must be expected. Whether this mortality will have population effects will depend on the amount of dead birds, but it should be noted that eiders are extensively hunted in this area in winter, causing high mortality. Whether an ammonia spill mortality is additive or compensatory to the hunting mortality is unknown.

Mammals

Very few mammals on land will be affected by an ammonia spill, but as the vegetation within the risk zone can be impacted both negatively and positively (fertilising effect), indirect effects on caribou may occur in the form of both reduced and enhanced grazing.

Vegetation

The potential effects on the vegetation will depend on the distance from the shore. In most cases, the spill will occur at such a distance from the shore that no detrimental effects will occur. The most likely scenario is a temporary fertilising effect on the vegetation growth.

Seawater

The risk zones for flora and fauna in the sea cover area ca. 12 km from the spill site. Within this distance, acute mortality of some fish, plankton and benthic organisms can be expected (at different distances for the specific species) depending on the spread of the spill. Due to the relatively small area and the replacement effect from adjacent waters, no long-term effects on the planktonic populations in the area are expected. However, benthic communities have a very slow recovery rate and effects here may be of longer duration.

Within the risk zone for fish, there are important spawning and fishing areas for lumpsucker and capelin, and these may be temporarily affected by mortality of eggs, larvae and adult fish. The spawning season for lumpsucker is several months in the spring, and an ammonia spill (of short duration) will only affect a very small part of the spawning population and the produced eggs. The spawning season of capelin is shorter (weeks) but still much longer than the impact time of an ammonia spill, and no effects on the population are therefore expected. Impacts on the fisheries on these fish will most likely be a few days closure.

Finally, ammonia can contribute to the eutrophication of the receiving waters, and this can stimulate algae blooms that will most likely be of short-term duration and limited distribution, due to the large, tidal water exchange.

Freshwater

The risk zone for freshwater organisms is ca. 12 km. Within this zone, there are many ponds, especially to the north. Fauna and flora may be killed in such small stationary waterbodies, and a fertilising effect changing the species composition must be expected in areas less impacted by ammonia. This may alter their quality as habitats for water birds in both a negative way (less food) and a positive way (better foraging for some species). However, many of these ponds are temporary or freeze to the bottom during winter, and their fauna and flora are thus adapted to extreme environmental fluctuations.

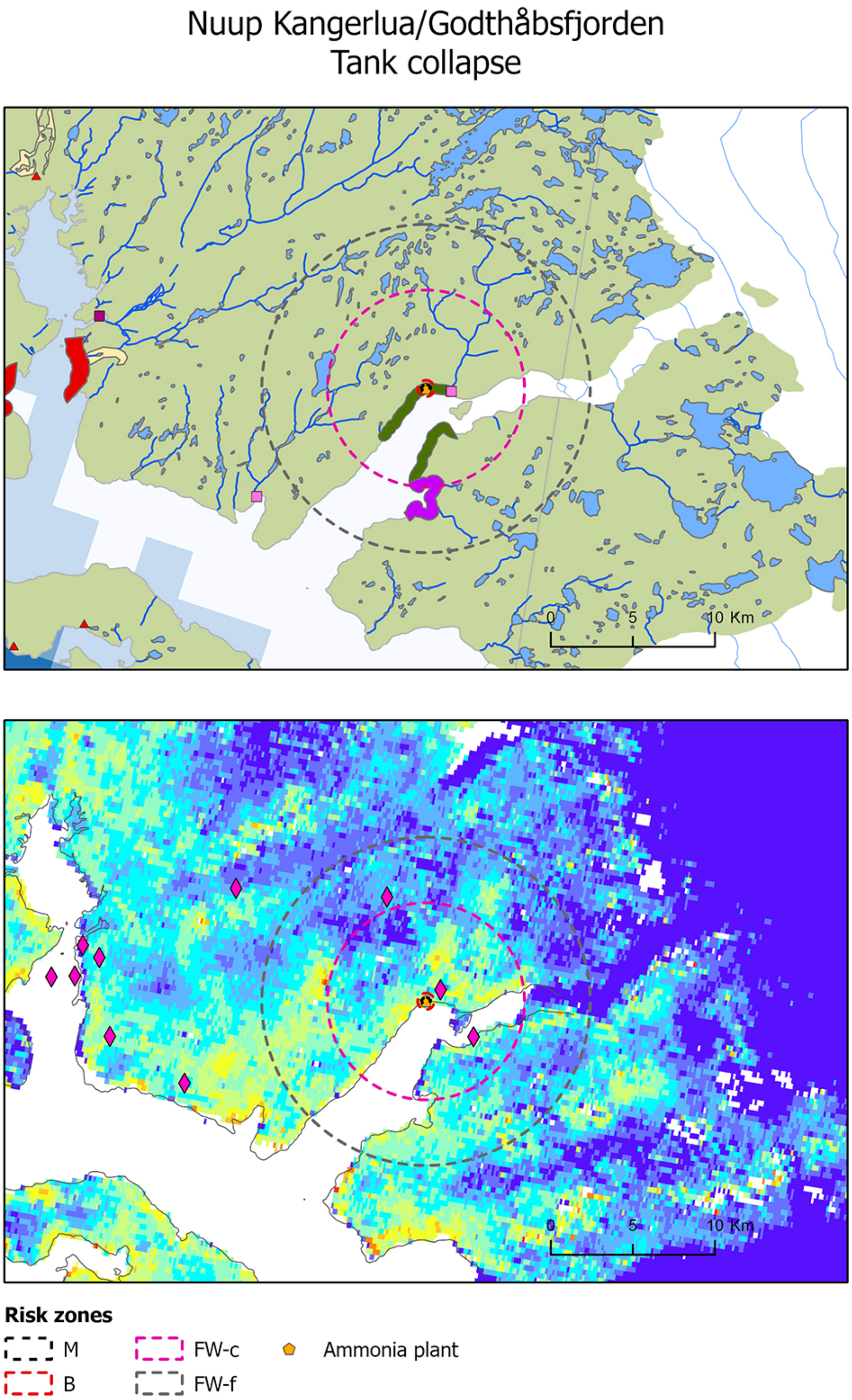


Figure 8.8. Risk zones in case of spill from tank collapse on land at the ammonia plant at Nuup Kangerlua. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater – fish; FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.

Figure 8.9. Risk zones in case of ship loading spill at pier in at Nuup Kangerlua. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater – fish; FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.

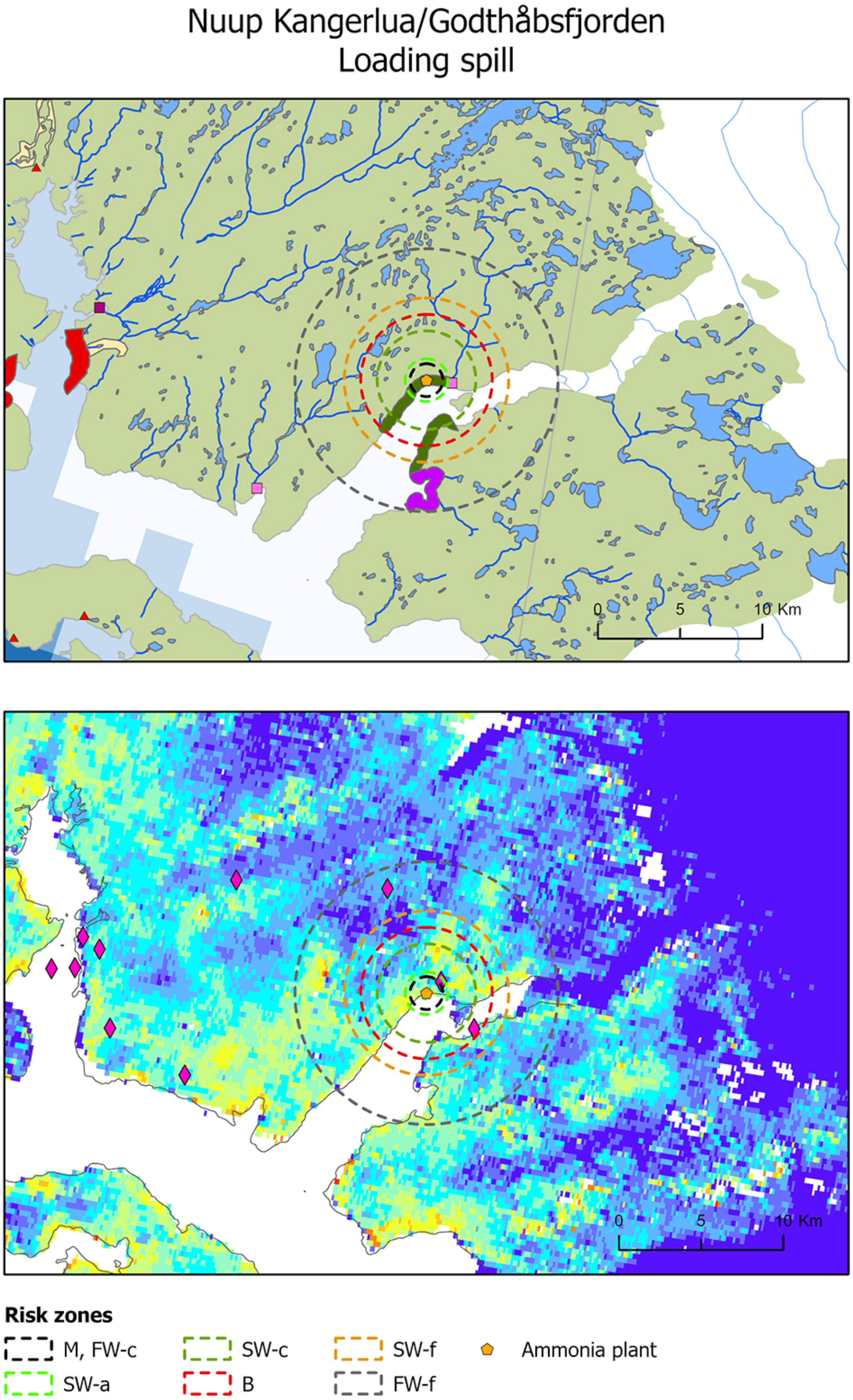
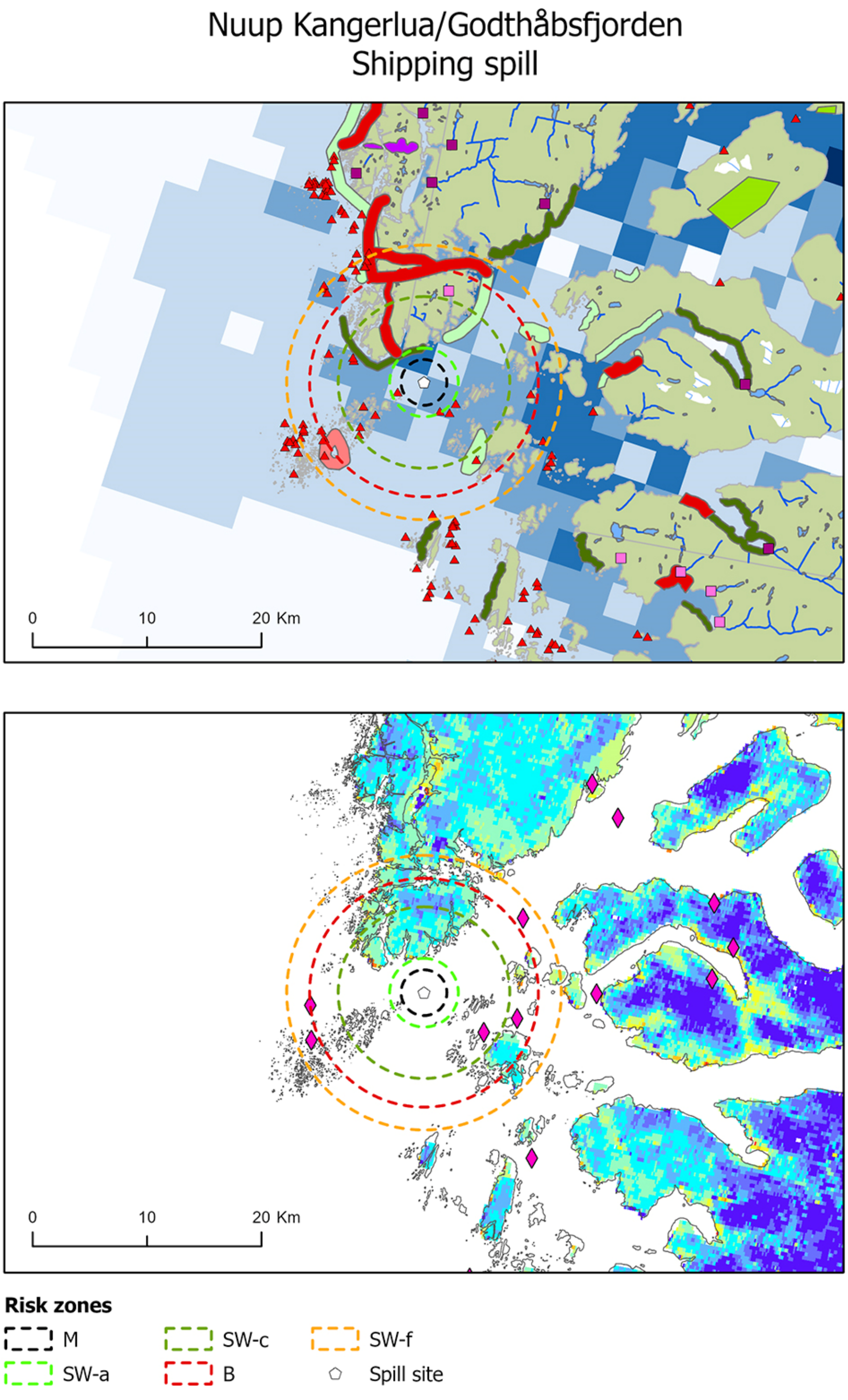


Figure 8.10. Risk zones in case of fjord spill during shipping in at Nuup Kangerlua. B: Birds; M: Land mammals, SW-a: Seawater – algae; SW-c: Seawater – crustaceans: SW-f: Seawater – fish; FW-c: Freshwater – crustaceans; FW-f: Freshwater – fish.



9 Discussions and conclusions

It is inherent in a scenario-based approach assessing the environmental impact of a “worst-case” accident that the results are examples of what could happen based on several assumptions. However, taken together, this report presents a rather robust picture showing that, despite significant mortality of animals and plants, the environmental impact would be relatively transient without long-term degradation of environmental quality and ecosystem services like hunting and fishing. The reason for this is the transient toxic impact of ammonia.

When released into the environment, liquid anhydrous ammonia (LNH_3) will evaporate and react with water in the air. It will form a white cloud that drifts with the wind and spreads the highly toxic gasses. It will poison the organisms it passes, and, subsequently, some of the ammonia will be deposited on vegetation, soil and water. Ammonia is highly toxic, and exposure to elevated concentrations can be fatal to humans, animals and plants. Ultimately, it may lead to the disappearance of some species in the affected area for a period of time. However, ammonia is neither persistent nor does it bioaccumulate, and it is readily diluted and degraded in the environment. Thus, an accident will have some acute lethal effects where local population sizes may be reduced, followed by a recovery period whose length is dependent on population status and the reproductive potential. No toxic compounds will remain in the area after the acute phase.

For the assessment of the potential environmental impacts of an ammonia spill from a Power-to-X plant and shipping in Greenland, three types of spill scenarios for three localities (three production sites and three spill sites in connection with shipping) were evaluated. Based on estimates for ammonia concentrations in the environment (Chapter 6 and 7) and thresholds values for toxicity (Chapter 4), the potential risk zones for seabirds, mammals, plants and vegetation, marine organisms (algae, crustaceans and fish) and freshwater organisms (crustaceans and fish) were estimated and assessed (Chapter 8). The threshold values for toxic effects of ammonia exposure were selected on the basis of a thorough literature review. Most data on the effects of ammonia exposure originated from organisms living in temperate regions, and relevant plant toxicity data were absent. To improve the assessment of the possible environmental effects of an ammonia spill in Greenland, Arctic species should be prioritised in future investigations to obtain more realistic effect levels of ammonia. The overall findings from the assessment of the scenarios are: A very large accidental ammonia spill (worst-case scenario) would likely cause severe toxic damage up several kilometres from the spill site, and in some scenarios organisms could probably be affected more than 10 km from the spill sites. The actual impact of a spill will, to a large extent, depend on the weather conditions. The toxic cloud will drift with the wind where it may follow the ground or rise and mix in the atmosphere.

The duration of effects and impacts will also depend on the size of the actual spill (i.e. extent of exposure) as well as the recovery time of the affected organisms. For the marine environment, it is assessed that the effects from a large spill would be of short-term duration as ammonia is not persistent and does not bioaccumulate. In the fjord systems, the dilution is expected to be significant and the recovery of organisms fast due to inflow of organisms from adjacent water areas. The recovery time for birds and mammals depends on the specific species. The regeneration of terrestrial habitats could last somewhat longer due to slower / lower recovery (the actual recovery time will vary between species). For species in decline due to other factors like climate change or hunting, the population size may not recover.

Ammonia is a fertiliser, and a large spill may fertilise many km^2 of terrestrial habitat. The impact of this may last for some years as the nutrient may be recycled. In this assessment of a worst-case accident, we did not find it relevant to include the fertiliser effect. However, chronic leakage of ammonia from a factory may cause changes in the surrounding vegetation.

To minimise the risk of ammonia spills, most countries have implemented strict national regulations addressing the need for a formal risk assessment as well as specified procedures for incident investigation, reporting and general training in minimising the risks. In the EU and Denmark, the regulation of ammonia production facilities includes the Seveso-III directive. In addition, the EU Commission has developed a reference document on Best Available Techniques (BAT) for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers. A large accident, with ammonia releases in the same order of magnitude as our spill scenarios, has been estimated to happen once in 10,000 years for a modern ammonia factory (Yara Porsgrunn, the Norwegian authorities, DSB 2019).

In this study, we found a striking lack of scientific literature on the environmental impact of large ammonia spills. Focus in the literature has been directed at chronic releases of ammonia in industrialised areas, where nutrient-poor habitats are damaged by the fertilising impact, and on human safety in case of large ammonia accidents because of the high toxicity of ammonia gas. However, attention to reducing the risk to humans to acceptable levels in the ammonia industry would also help to ensure low risk of large environmental accidents.

To sum up, a large, worst-case ammonia spill from an ammonia plant could cause severe toxic damage to organisms during the passage of the ammonia cloud from within a few km to possibly more than 10 km from the source. This could lead to local loss of animal and plant abundance for some years. However, the ammonia will be quickly diluted and degraded and will not be transferred in the food web, and the mortality will not seriously impact plant and animal populations at a regional scale. There could be a fertilising effect of ammonia on the nutrient-poor terrestrial environment lasting for some years.

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Appendix 1 Background ecotoxicology data on ammonia

Table A1.1. Detailed information on acute lethal concentrations (LC50; µg/m^3) of ammonia gas during acute (5-120 min) exposure in small mammals and birds. Numbers in parenthesis indicate number (n) of studies from where data were extracted. If more than one study is behind the data, a range of effect concentrations are reported. Numbers in bold are overall values for mice and rats, respectively. Red numbers indicate the acute lethal concentrations reported in Table 4.2 in the report. Data mainly from Table 17 in World Health Organization (WHO) (1986) and references can be found here.

	Effect concentration (LC_{50}; µg/m^3)	
	Range	Average
Mice	2,960,000-7,060,000	4,468,666.67 (3)
LC50 (10-min)		7,060,000 (1)
LC50 (1-hr)	2,960,000-3,386,000	3,173,000 (2)
Rats	5,137,000-31,612,000	13,602,300 (10)
LC50 (5-min)		18,693,000 (1)
LC50 (10-min)		31,612,000 (1)
LC50 (15-min)		12,160,000 (1)
LC50 (20-min)		20,017,000 (1)
LC50 (30-min)		7,035,000 (1)
LC50 (40-min)		14,210,000 (1)
LC50 (1-hr)	5,137,000-11,620,000	8,232,000 (3)
LC50 (2-hrs)		7,600,000 (1)
Wild birds*		
Effect level (7-min)		1,600,000 (1)

*Acute lethal concentration in starlings, sparrows and pigeons.

Table A1.2. Detailed information on sub-lethal concentrations (µg/m^3) of ammonia gas during acute (<72 hrs) exposure in poultry (adults and chickens) and small and large mammals. Numbers in parenthesis indicate number (n) of studies from where data were extracted. If more than one study is behind the data, a range of effect concentrations are reported. Red numbers indicate the minimum values reported in Table 4.3 in the report. References can be found in World Health Organization (WHO) (1986).

	Effect concentration (µg/m^3)	
	Range	**Average**
Birds (poultry)*		18,000 (1)
Chickens (poultry)	14,000-700,000	357,000 (2)
Mouse**		212,000 (1)
Rabbits		1,750,000 (1)
Rat	85,000-3,000,000	1,096,250 (4)
Cats		700,000 (1)
Pigs		196,000 (1)

*Recommended maximum exposure level in poultry houses (Kristensen and Wathes 2000), ** RD50 (concentration expected to elicit a 50% decrease in respiratory rate).

Table A1.3. Effect levels (µg/m³) on different effect parameters in plants during short-term (<7 days – NB: only for tomato plants) and long-term (7-91 days) exposure to ammonia gas by fumigation. Values reported are average values reported in the ECOTOX database (United States Environmental Protection Agency (U.S. EPA) 2021), i.e., range represents the minimum and maximum values of all average values reported. Numbers in parenthesis indicate number (n) of observations. Red numbers indicate the minimum effect levels reported in Table 4.4 in the report.

Species	**LOEL**		**NOEL**	
	Range	**Average**	**Range**	**Average**
Overall average effect level (µg/m³)*	64-105	103.24 (29)	64-1500	155.46 (67)
Azaleas				
Injury				1500 (1)
Canadian Poplar			64-1500	351.2 (5)
Injury				1500 (1)
Physiology		64 (1)		64 (4)
English Yew				
Injury				150 (1)
Heath Dog Violet				105 (8)
Biochemistry		105 (16)		105 (4)
Growth				105 (4)
Hemlock Spruce				
Injury				300 (1)
Leyland Cypress				
Injury				150 (1)
Mountain Arnica				105 (14)
Biochemistry		105 (10)		105 (10)
Growth				105 (4)
Mugo Pine				
Injury				300 (1)
Northern White Cedar				
Injury				300 (1)
Wavy Hairgrass				100 (32)
Biochemistry		100 (2)		100 (14)
Growth				100 (18)
Yellow Spruce				
Injury				150 (1)
Yew				
Injury				300 (1)
Tomato**				
Growth				600 (2)

*Only including long-term (7-91 days) exposure, **Short-term (<7 days) exposure

Table A1.4. Threshold values for toxicity (EC50 and LC50; mg/l) in marine organisms during short-term exposure (i.e. < 5 days) to total ammonia (NH_3 + NH_4^+). Numbers in parenthesis indicate number (n) of reported observations. Data from ECOTOX database (United States Environmental Protection Agency (U.S. EPA), 2021). Numbers in parenthesis indicate number (n) of observations. Red numbers indicate the minimum effect levels reported in Table 4.5 in the report.

Marine species	EC50		LC50	
	Range	Average	Range	Average
Algae				
Germination				
Sea Lettuce		29.2 (1)		
Crustaceans				
Mortality			4.98-1290.4	102.17 (77)
Brine Shrimp			399.1-1290.4	673.71 (8)
Fleshy Prawn			28.18-66.73	44.87 (9)
Greasyback Shrimp			26.63-93.97	62.61 (9)
Jumbo Tiger Prawn				73 (1)
Kuruma Shrimp			4.98-93.55	29.27 (18)
Redtail Prawn			5.21-60.81	28.83 (16)
San Paulo Shrimp			5.49-102.3	28.07 (16)
Crustaceans; Standard Test Species				
Mortality			49.8-154.7	107.67 (7)
Amphipod			49.8-126.7	95.18 (4)
Harpacticoid Copepod				70 (1)
Scud			148.3-154.7	151.5 (2)
Molluscs			2.55-320	36.49 (16)
Immobile				
Ark Shell			7.4-320	46.82 (12)
Mortality				
Bay Scallop			5.25-7.84	6.47 (3)
Taiwan Abalone				2.55 (1)
Fish				
Mortality			2-78.6	28.56 (13)
Red Sea Bream			2-5.0	3.65 (6)
Striped Bass			54-77-78.6	61.34 (4)
White Sea Bass			10-76.0	34.67 (3)
Fish; Standard Test Species				
Mortality			2.01-338.37	73.63 (11)
Inland Silverside			2.01-338.37	64.73 (8)
Sheepshead Minnow			80.67-121.19	97.37 (3)

Table A1.5. Threshold values for toxicity (EC50 and LC50; mg/l) in freshwater organisms during short-term exposure (i.e. < 5 days) to total ammonia (NH3 + NH4+). Numbers in parenthesis indicate number (n) of reported observations. Data from ECOTOX database (United States Environmental Protection Agency (U.S. EPA), 2021). Numbers in parenthesis indicate number (n) of observations. Red numbers indicate the minimum effect levels reported in Table 4.6 in the report.

Freshwater species	**EC50**		**LC50**	
	Range	**Average**	**Range**	**Average**
Crustaceans				
Immobile	8.24-14.45	11.35 (2)		
Aquatic Sowbug		14.45 (1)		
Water Flea		8.24 (1)		
Mortality			8.18-17.1	13.07 (3)
Aquatic Sowbug				13.92 (1)
Mysid				17.1 (1)
Water Flea				8.18 (1)
Crustaceans; Standard Test Species				
Immobile				
Water Flea		2.1 (1)		
Mortality			0.53-126	45.44 (6)
Scud			117-126	121.5 (2)
Water Flea			0.53-25.4	7.41 (4)
Molluscs				
Mortality				
Pheasantshell, Mussel				17.07 (1)
Survival	0.8-16	10.67 (37)		
Ellipse	3-16.0	8 (3)		
Lamp-Mussel	13-16	14.86 (7)		
Mucket	3-16.0	10.6 (10)		
Pink Papershell	7-16.0	13 (3)		
Rainbow Mussel	0.8-14	7.5 (9)		
Wavy-Rayed Lampmussel	6-16.0	10.88 (5)		
Molluscs; Standard Test Species				
Mortality				
Paper Pondshell			3.97-11.36	8.44 (3)
Fish				
Mortality			0.17-45.2	27.69 (7)
Guntea Loach			41.6-45.2	43.2 (4)
Milkfish, Salmon-Herring				20.65 (1)
Snake-Head Catfish				0.17 (1)
Walking Catfish				0.23 (1)
Fish; Standard Test Species				
Mortality			1.02-305.5	99.43 (23)
Channel Catfish			1.02-305.5	124.43 (9)
Fathead Minnow			5.9-8.2	7.05 (2)
Guppy			71.1-148	96.08 (12)

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Appendix 2 OML modelling results

Table A2.6. Specifications for the OML simulations.

Simulation name	Spill type	Wind	Evaporation time	Emission rate (g/s)	Air temperature (°C)
Tank_sum_lvs	Tank	Low	7 d 20 h	73578	10
Tank_sum_hvs	Tank	High	3 d 9 h	171020	10
fship_sum_lvs	Transfer	Low	1133 s	4414707	10
Fjord_sum_lvs	Fjord	Low	680 s	17658829	10
Tank_win_lvs	Tank	Low	20 d 19 h	27840	-17,8
Fship_win_lvs	Transfer	Low	2993 s	1670429	-17,8
Fjord_win_lvs	Fjord	Low	1795 s	6681719	-17,8

Table A2.7. Simulated ammonia spills and sizes for worst-case-scenarios.

NH_3 spill type	Amount	Amount	Pool thickness	Pool area	Pool width	Pool radius	NH_3 in water	
	Tonnes	m^3	m	m^2	m	m	tonnes	%
Tank collapse (onshore)	50000	73314	3	24438	156	88		0
Accident during discharge (sea/land)	10000	14663	0,01	1466276	1211	683	7331	50
Accident during shipping (fjord)	40000	58651	0,01	5865103	2422	1367	41056	70

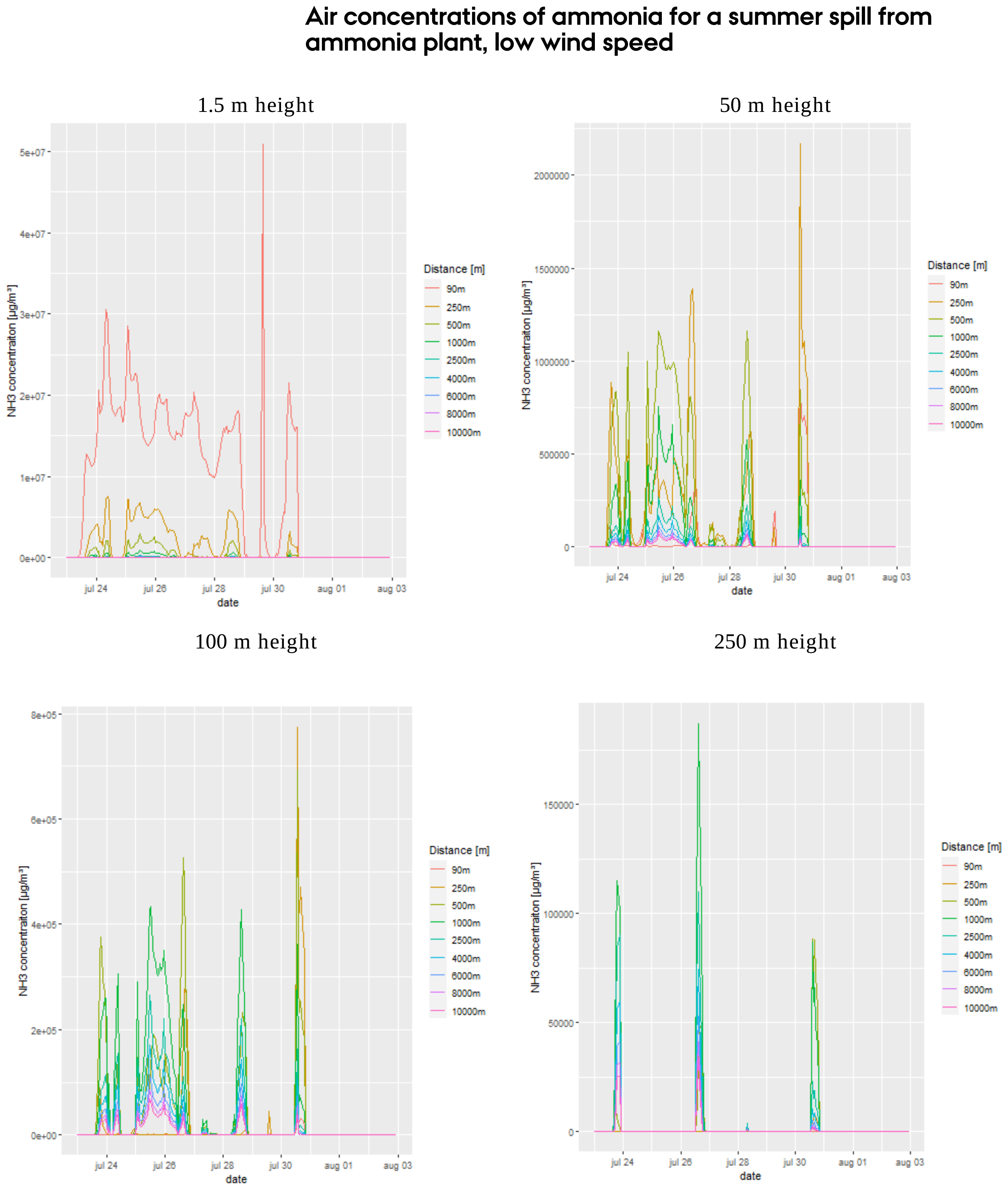

Figure A2.1. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Summer spill from ammonia plant, low wind speed.

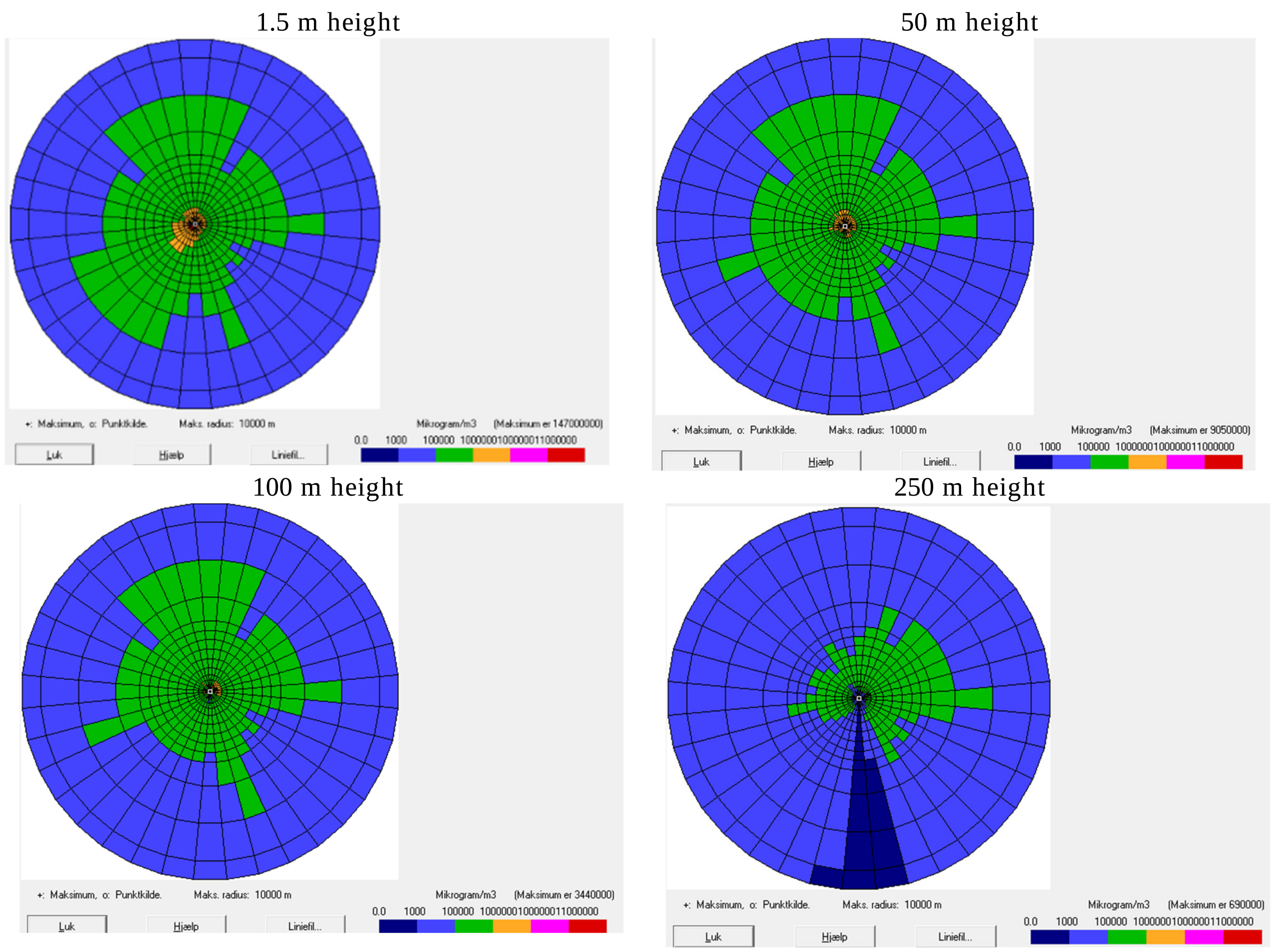

Figure A2.2. Maximum hourly concentrations of ammonia in air at different heights above ground and with different horizontal distances from the source. Summer spill from ammonia plant, low wind speed.

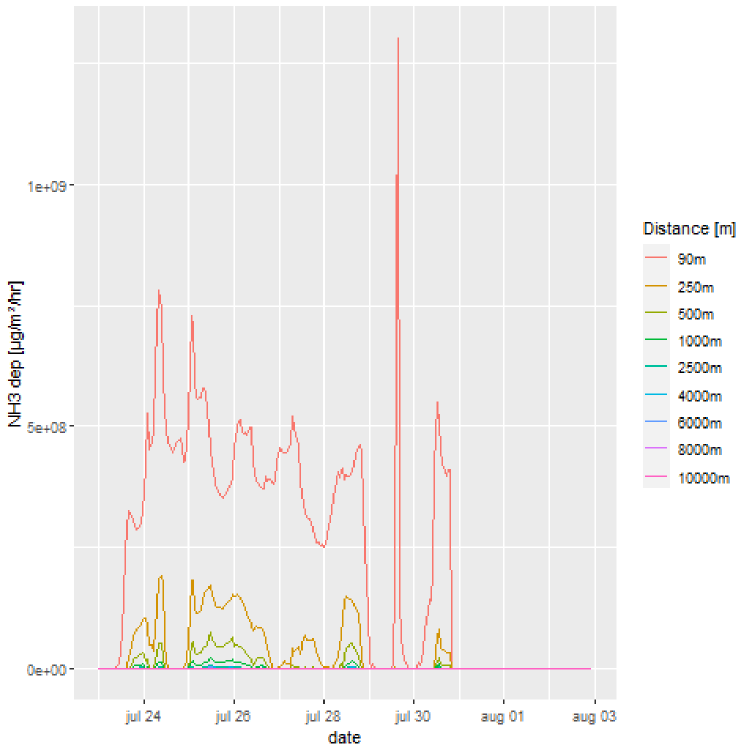

Figure A2.3. Dry deposition of ammonia from 1.5 m and at different distances from the source. Summer spill from ammonia plant, low wind speed.

Air concentrations of ammonia for a winter spill from the ammonia plant, low wind speed

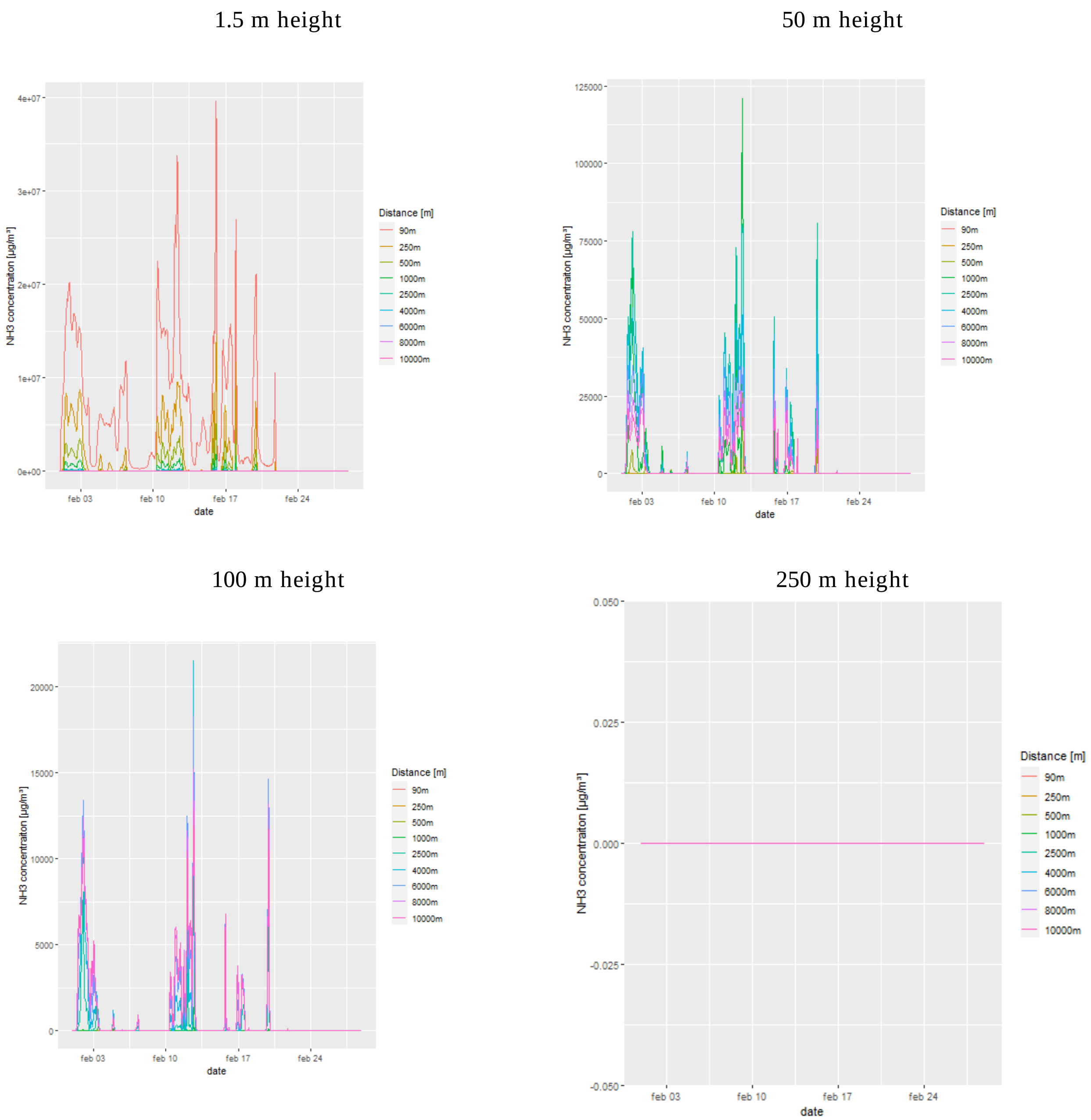

Figure A2.4. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Winter spill from ammonia plant, low wind speed.

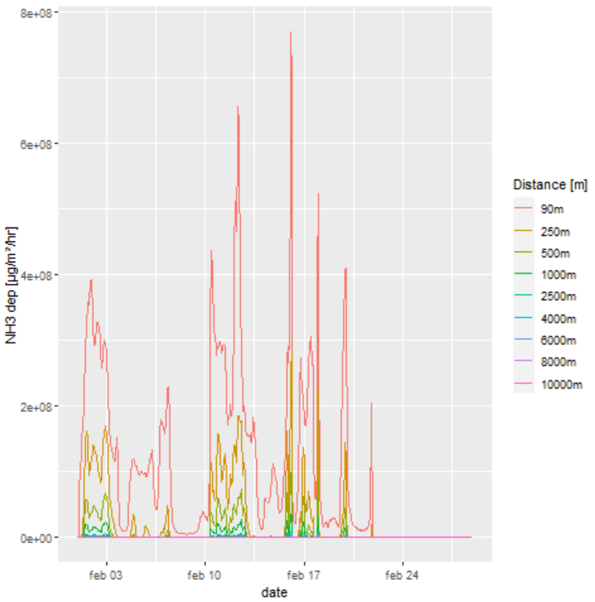

Figure A2.5. Dry deposition of ammonia from 1.5 m and at different distances from the source. Winter spill from ammonia plant, low wind speed.

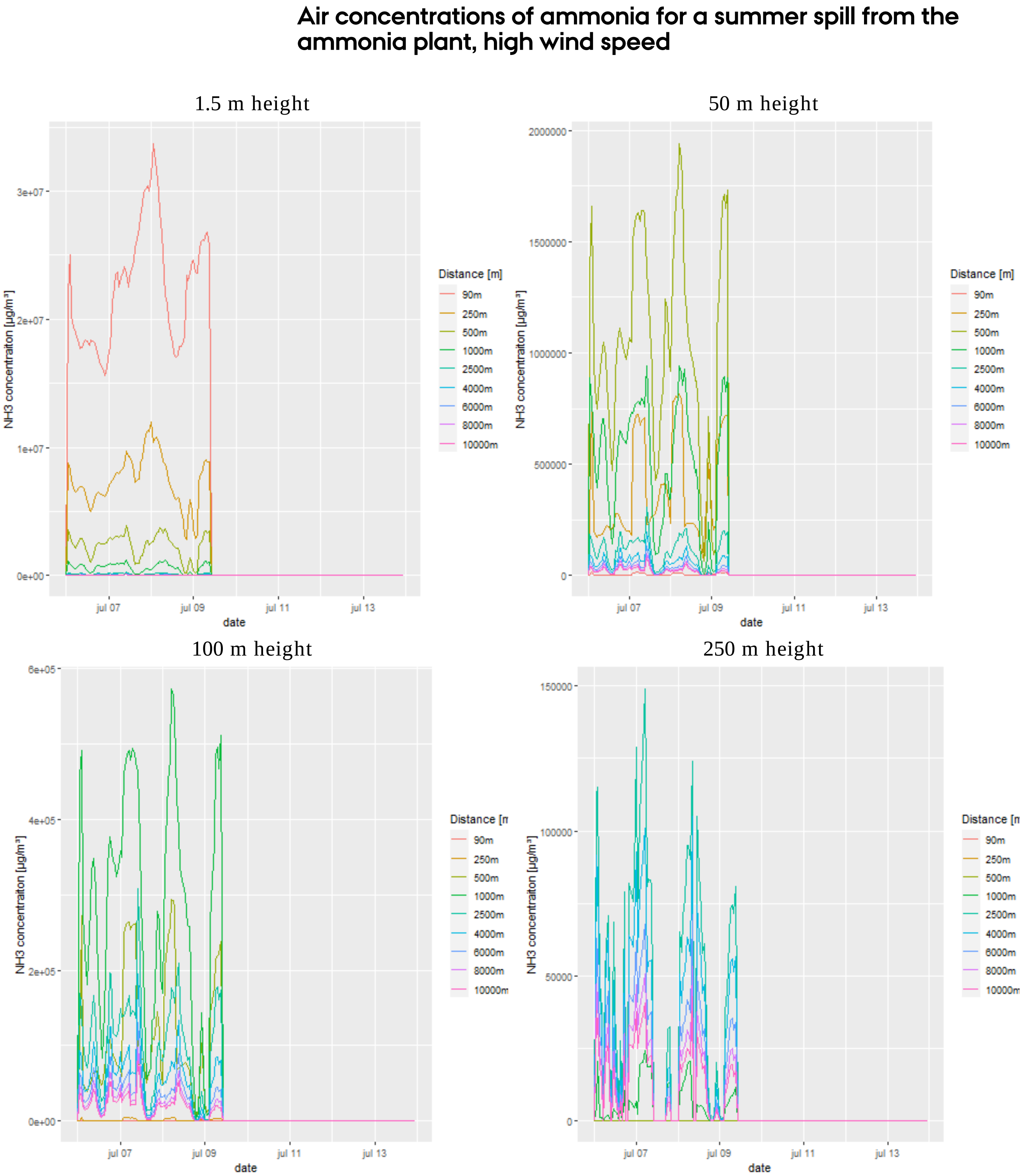

Figure A2.6. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Summer spill from ammonia plant, high wind speed.

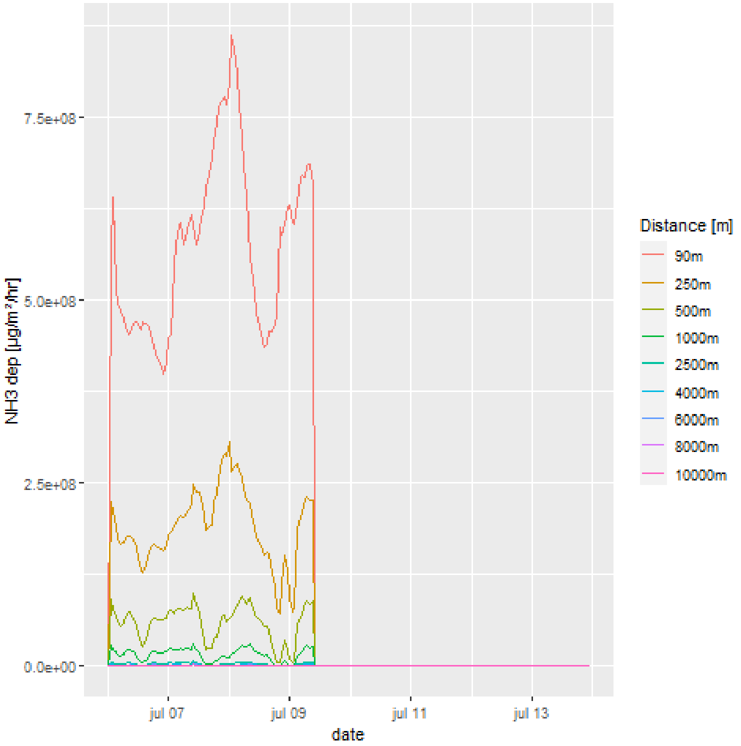

Figure A2.7. Dry deposition of ammonia from 1.5 m and at different distances from the source. Summer spill from ammonia plant, high wind speed.

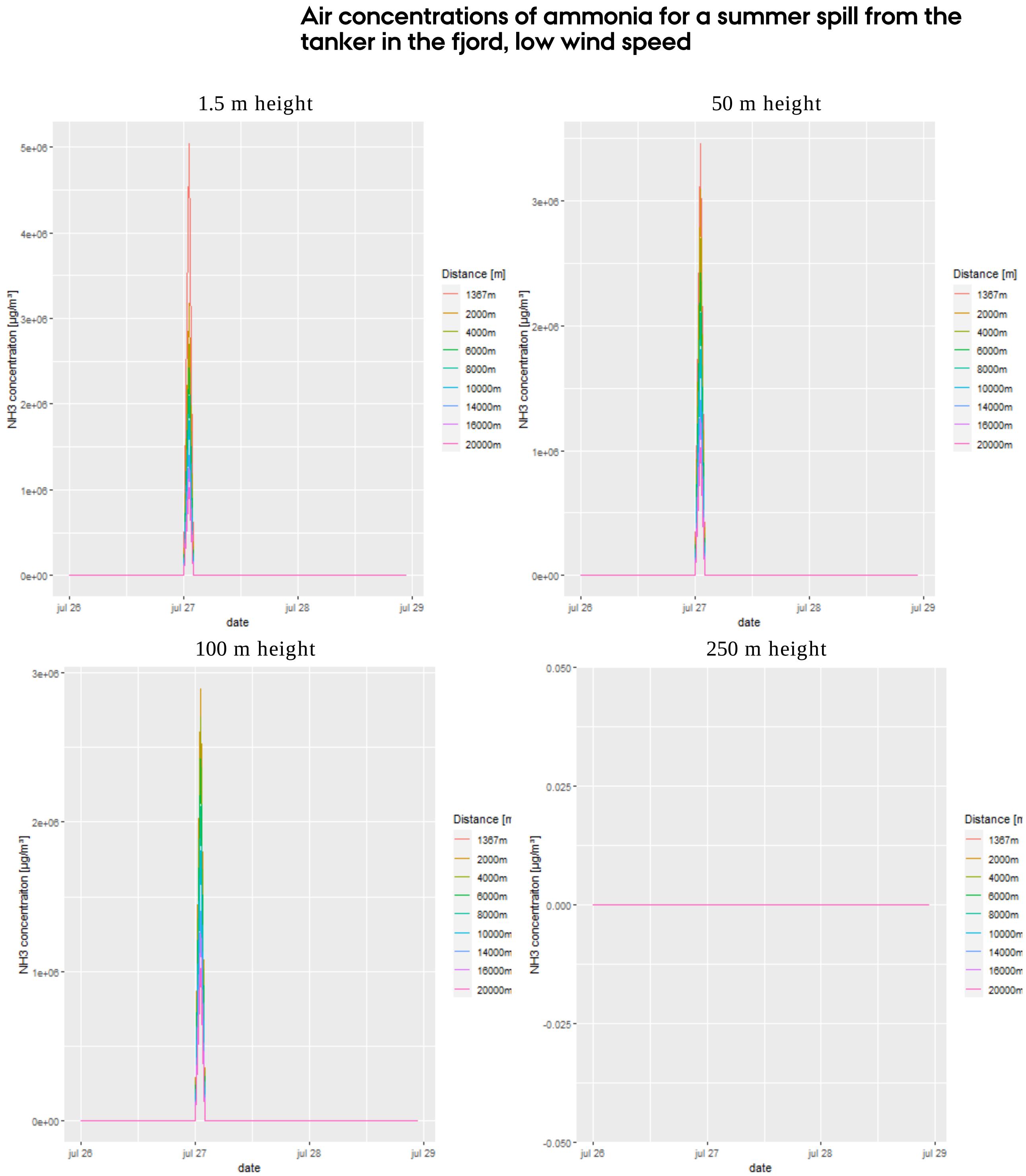

Figure A2.8. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Summer spill from tanker in the fjord, low wind speed.

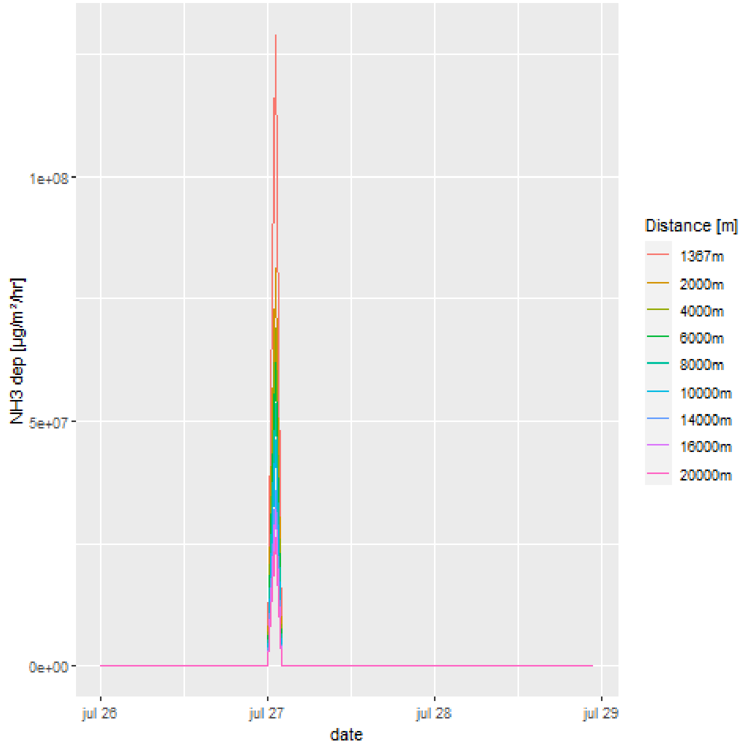

Figure A2.9. Dry deposition of ammonia from 1.5 m and at different distances from the source. Summer spill from tanker in the jord, low wind speed.

Air concentrations of ammonia for a winter spill from the tanker in the fjord, low wind speed.

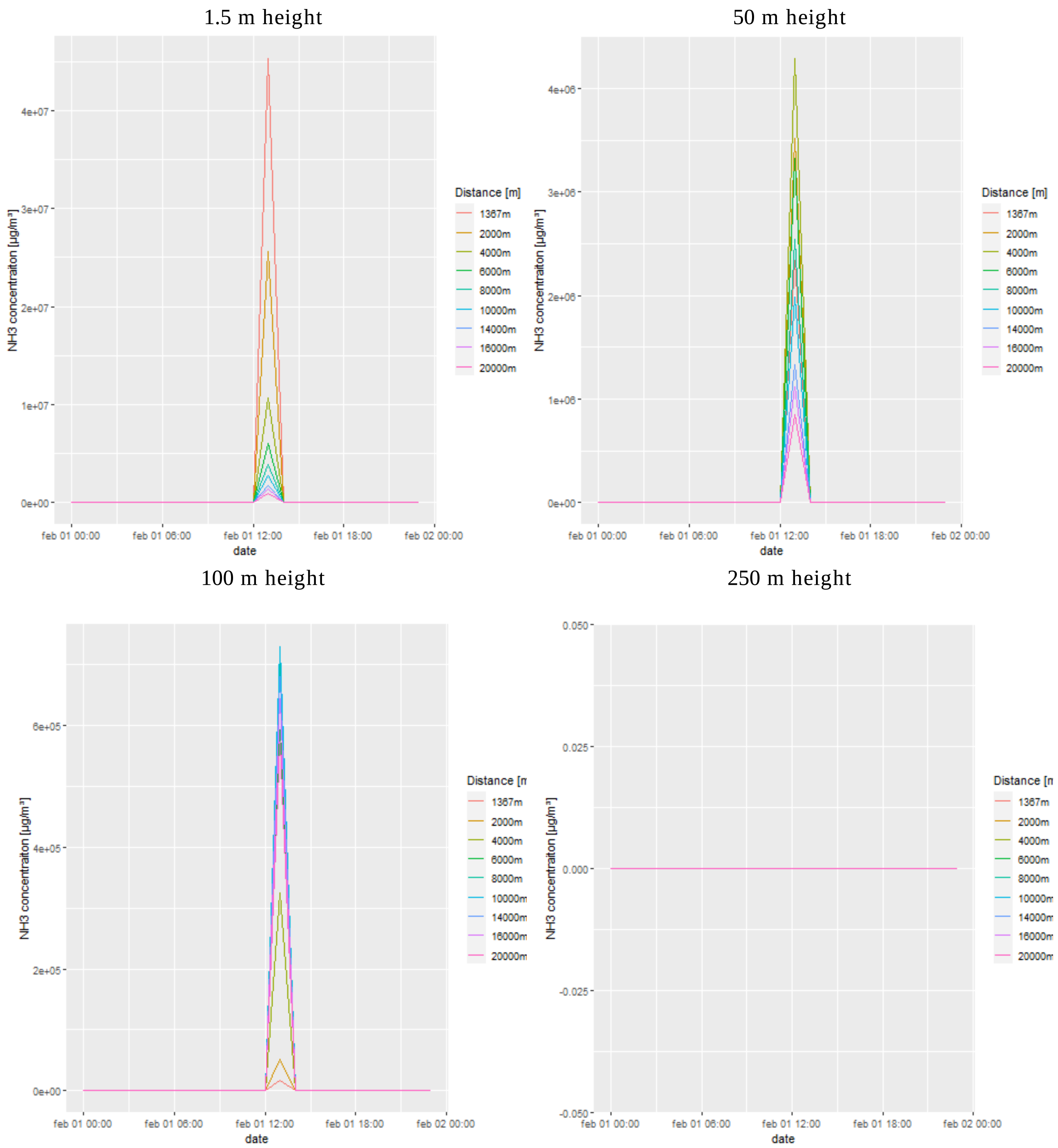

Figure A2.10. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Winter spill from tanker in the fjord, low wind speed.

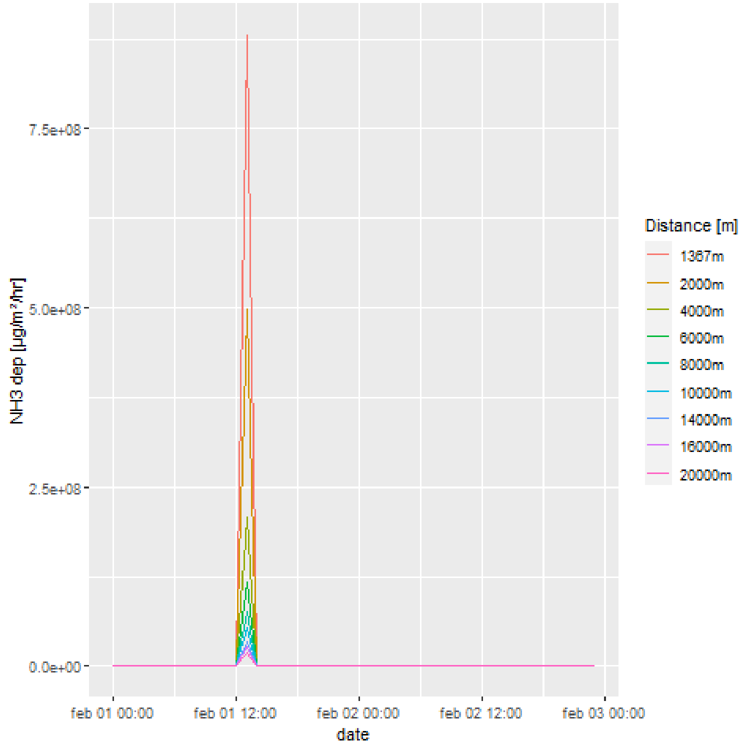

Figure A2.11. Dry deposition of ammonia from 1.5 m and at different distances from the source. Winter spill from tanker in the fjord, low wind speed.

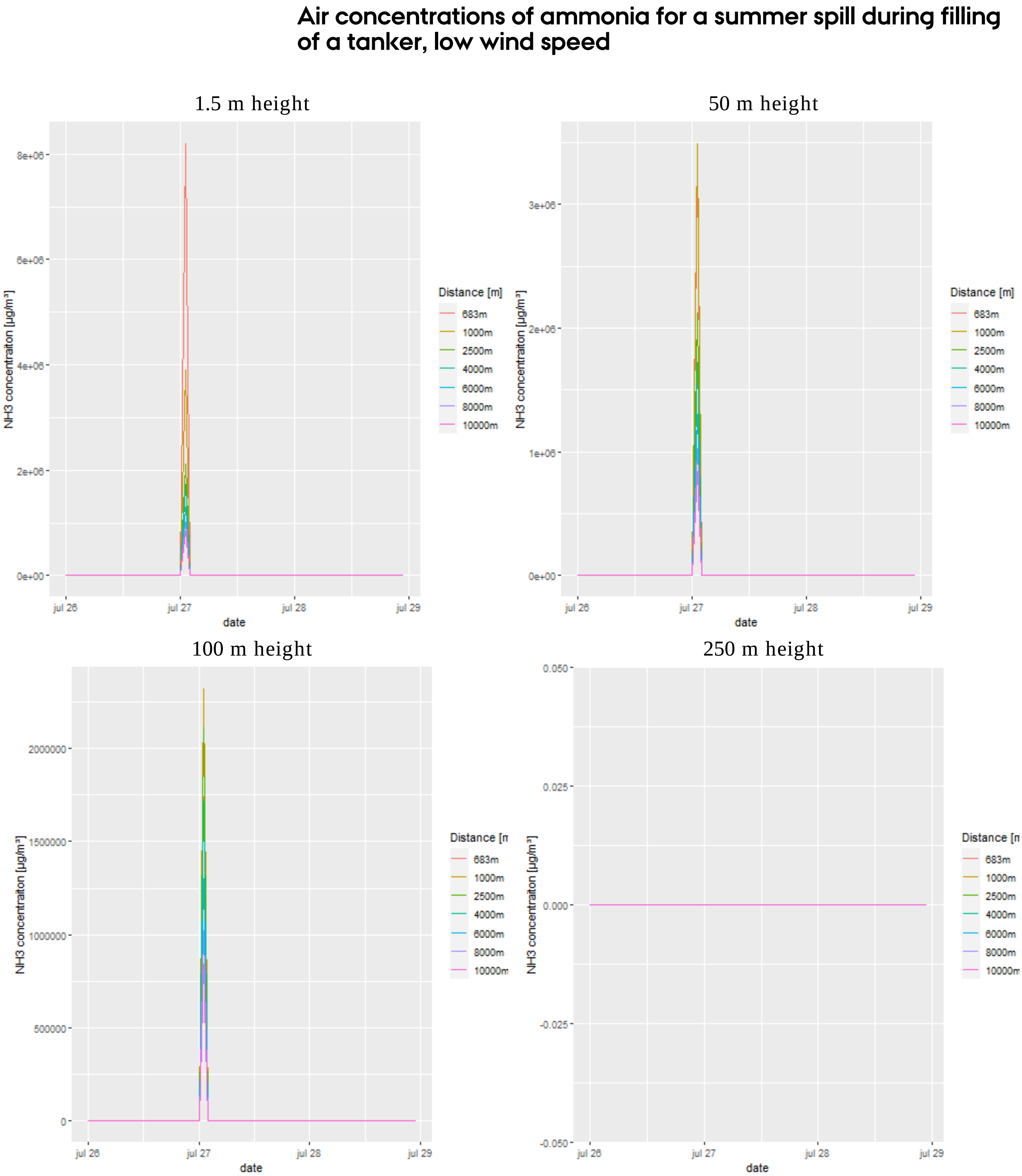

Figure A2.12. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Summer spill during filling of a tanker, low wind speed.

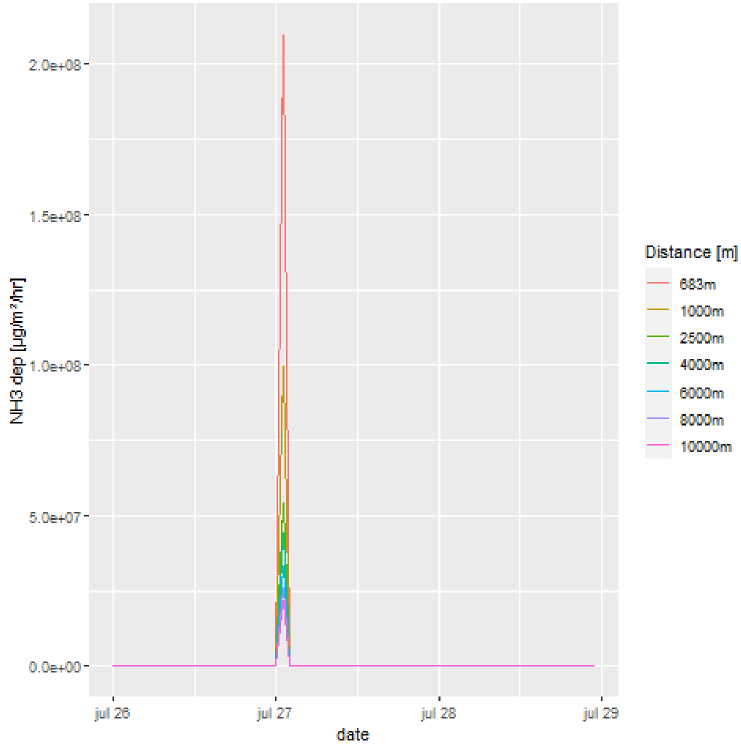

Figure A2.13. Dry deposition of ammonia from 1.5 m and at different distances from the source. Summer spill during filling of a tanker, low wind speed.

Air concentrations of ammonia for a winter spill during filling of a tanker, low wind speed

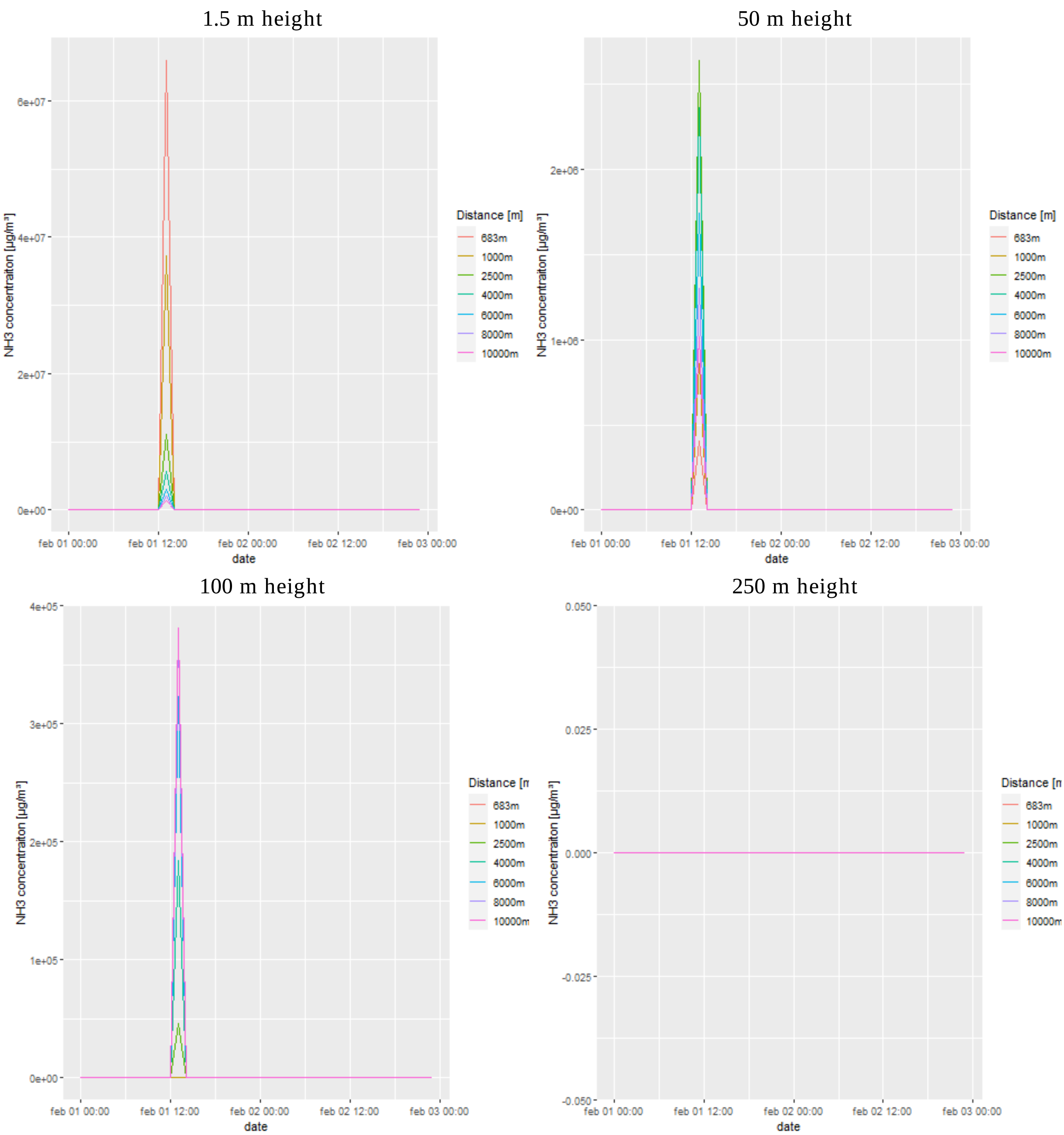

Figure A2.14. Ammonia concentrations in air at different heights above ground (1.5 m, 50 m, 100 m and 250 m) for different distances from the source (90, 250, 500, 1000, 2000, 4000, 6000, 8000, 10000 m). Winter spill during filling of a tanker, low wind speed.

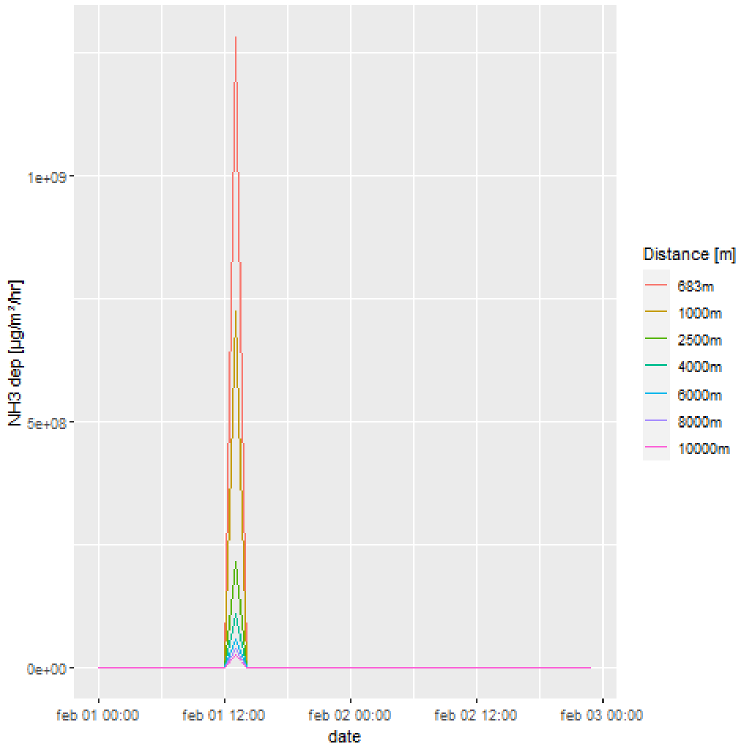

Figure A2.15. Dry deposition of ammonia from 1.5 m and at different distances from the source. Winter spill during filling of a tanker, low wind speed.

ASSESSMENT OF THE POTENTIAL ENVIRONMENTAL IMPACTS OF A MAJOR AMMONIA SPILL FROM A POWER-TO-X PLANT AND FROM SHIPPING OF AMMONIA IN GREENLAND

Aarhus University, DCE - Danish Centre for Environment and Energy, has prepared an overall assessment of the potential environmental impacts from a major release or spill of ammonia in relation to production and transportation of ammonia in a PtX plant or by shipping in Greenland. Three sites were included in the assessment: Kangerlussuaq (Sdr. Strømfjord), Kangerlussuatsiaq (Evighedsfjorden) and Nuup Kangerlua (Godthåbsfjorden). The overall findings shows that a large, worst-case ammonia spill could cause severe toxic damage to organisms during the passage of the ammonia cloud from within a few km to possibly more than 10 km from the source. This could lead to local loss of animal and plant abundance for some years. However, the ammonia will be quickly diluted and degraded and will not be transferred in the food web, and the mortality will not seriously impact plant and animal populations at a regional scale. There could be a fertilising effect of ammonia on the nutrient-poor terrestrial environment lasting for some years.

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