AMMONIA DISPERSION STUDY

Initial Dispersion Analysis

Haifa Muncipality

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Objective:

This document sets out the results of a number of dispersion scenarios for Ammonia.

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1 EXECUTIVE SUMMARY

1.1 Basis

The Municipality of Haifa have requested analysis of the hazards associated with ammonia supply, specifically related to comparing the safety aspects of liquid tanker / carrier or ISO tank options for ammonia transport.

This document describes Initial Dispersion Analysis to determine the hazard ranges associated with a series of representative scenarios. The scenarios modelled are described in Section 4, and cover a range of scenarios from a single ISO tank (based on the present size of 25 metric tons, or tonnes, te) release to a liquid tanker / carrier failure (2500 te), with discharge to the sea and to the port (concrete) both considered.

1.2 Results

A full set of results, showing the pool formation and vaporisation as well as the dispersion hazard ranges in terms of both concentration and lethality effects, is given in Section 5.

A brief summary is given in Table 1-1 based around the dispersion distance to the PAC-3 concentration (1100 ppm) and to a 10% lethality level. This shows the progression of the hazard ranges from the smallest catastrophic release for a single ISO tank, through multiple ISO tanks, to various liquid carrier events. Note that the hazard ranges for a large leak (750 mm) from a carrier can be more significant than for catastrophic failure.

- The PAC-3 concentration is a widely used indicator of the threshold for life-threatening health effects, while 10% lethality is an example fatality probability, based on the combination of concentration and exposure duration. Both these measures are discussed further in Section 4.3.
- Each scenario is modelled as a simple liquid leak scenario and does not consider any associated explosion energy. Hence, this analysis is based on simple worst-case release scenarios, as an Initial Dispersion Analysis, without considering the specific release mechanisms. For example, if ignition occurs the fire / explosion outcomes will be significant but will not extend as far as the potential dispersion of an unignited release.

Further to the results in the table, a lower lethality level of 0.1% is taken as the threshold level (below which fatality is still possible, but unlikely). These results are shown for an example wind direction, from the West, in Figure 1-1 and Figure 1-2, showing the area covered (footprint) for that specific wind direction. Circular contours are also given to represent the effect zone, i.e. the areas potentially in range when considering all possible wind directions. The significant difference between the area covered by the 25 te (single ISO tank) and 2500 te (liquid carrier) cases is shown here by Figure 1-1 and Figure 1-2, respectively, while a full set of example plots is given in Section 5.5.

It should be emphasised that all of the results presented in this study are based on 'free air', 'flat earth' modelling and do not account for topography (and for an example wind direction). The dispersion in all cases is neutral or dense gas dispersion, such that the cloud height is generally a small fraction of the length. Where shallow slopes occur, the dispersion will tend to follow the ground and will not be sensitive to the topography. However, for significant changes in elevation, the dispersion ranges given in these results will tend to be over-predicted with respect to any locations where there are uphill slopes and, conversely, under-predicted for downhill.

Dense gas dispersion is sensitive to a wide range of parameters / assumptions, including the ambient temperature and surface roughness. However, the results presented in Section 5 show that the key aspects influencing the results are:

- The total mass spilt (for instantaneous releases) or the hole size / release rate.
- The weather conditions, where stable low wind speed (e.g. F2) conditions give the most significant hazards ranges.
- The surface, where the pool size and duration are generally greater for concrete, compared to spills to sea, leading to a greater range in results (i.e. shorter hazard range for D10 and longer hazard range for the maximum F2, case).

Note also that the concentration of interest is important, given a significant difference between the huge hazard ranges predicted for PAC-1 (30 ppm) and the relatively localised hazard ranges over which fatality potential is predicted.

Table 1-1 Summary of Key Hazard Ranges for Main Scenarios

Case	Summary Hazard Range – Maximum Downwind Distance		Notes
	1100 ppm (PAC-3)	10% Lethality	
Single ISO tank (25 te) – release to sea or port	1-2 km	150-350 m	Largest hazard ranges are for F2 conditions and spill to port (concrete surface)
Multiple (5-10) ISO tanks – release to port	1-5 km	0.3-1.2 km	Peak distances are lower for release to sea
Catastrophic liquid carrier failure – release to sea	5-10 km	1-2 km	Peak distances are greater for releases to port (due to longer duration pool and vaporisation)
Major (750 mm) liquid carrier leak – to sea	2-8 km	0.6-3.5 km	
Moderate (250 mm) liquid carrier leak – to sea	0.5-2 km	300-600	

Figure 1-1 0.1% Lethality Footprint and Effect Zone for Single ISO Tank (25 te) Catastrophic Release (to the Port / Concrete)

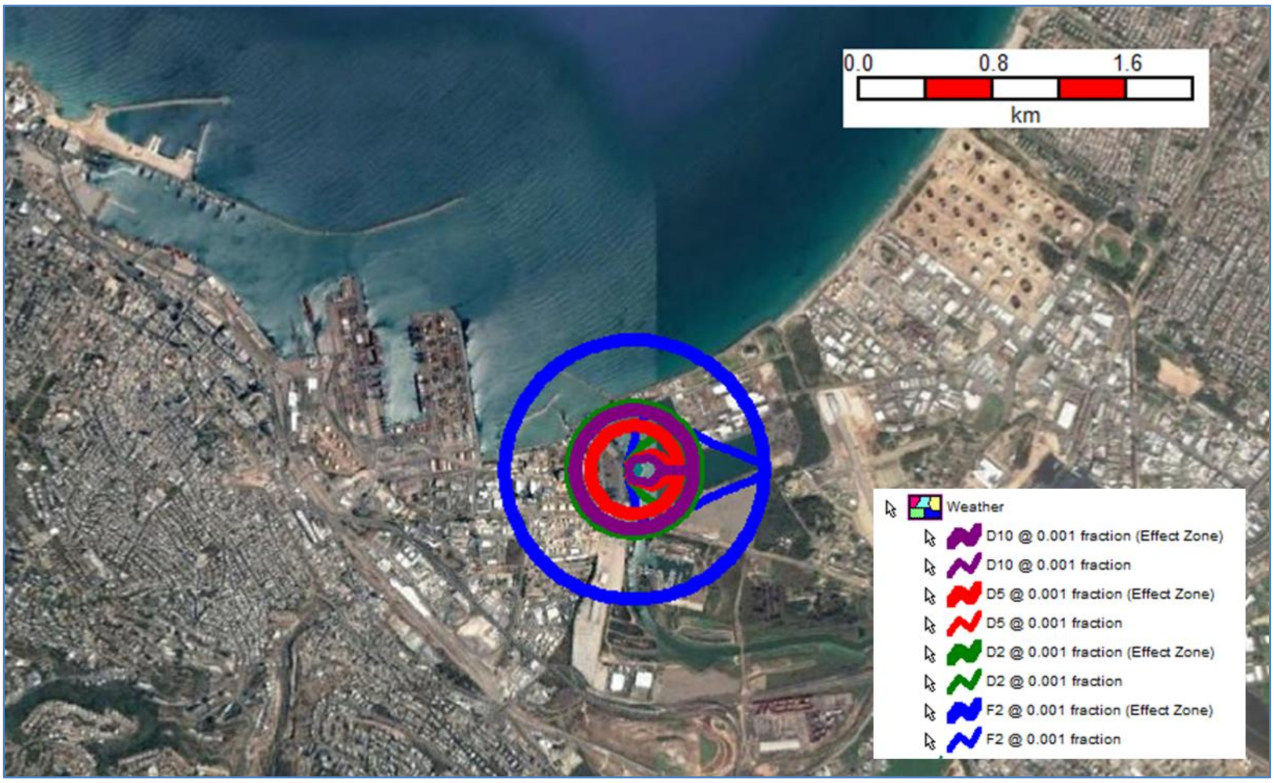


Figure 1-2 0.1% Lethality Footprint and Effect Zone for Liquid Carrier (2500 te) Catastrophic Release (to the Sea)

1.3 Conclusions

The focus of this study is on the dispersion only, rather than on the credibility of the scenarios. However, it can be summarised that:

- The worst-case hazard range for the liquid carrier events is huge in terms of dispersion to PAC-1 and PAC-3 levels and has fatality potential for distances between 2 and 5 km, depending on the weather and the specific failure modes.
- For a single ISO tank rupture / failure scenario the hazard range is not insignificant but is substantially shorter than for the above, with a maximum distance over which fatality potential applies of less than 800 m.
- For incidents involving multiple ISO tanks the hazard ranges predicted are somewhere between the above cases, depending on the number of tanks involved (as well as the surface assumed and the weather conditions). It should be emphasised, however, that modelling multiple tanks as a single instantaneous release is relatively conservative and in practice such an event is likely to be accompanied by ignition and/or to entail several different releases rather than one single outcome.

2 INTRODUCTION

2.1 Background

The Municipality of Haifa have requested analysis of the hazards associated with ammonia supply, specifically related to comparing the safety and risk aspects of liquid tanker / carrier or ISO tank options for ammonia transport.

DNV GL have submitted a proposal to undertake such work and this document describes one of the proposed tasks, which is to perform Initial Dispersion Analysis, to determine the hazard ranges associated with a series of representative scenarios.

2.2 Objectives and Scope

The overall objective of the investigations is to compare the safety aspects of ammonia supply options for Haifa Municipality, namely liquid carrier ship or ISO tank alternatives.

The primary basis for comparison, and selection of the preferred option, will be the maximum consequences in terms of the hazard ranges and worst-case impacts (i.e. potential fatalities).

The different options under consideration are:

- The liquid carrier option is an Ammonia carrier ship with two containers, each with capacity of 1250 metric ton (te), which would anchor at Haifa's sea port and offload to pipelines and/or road tankers.
- The ISO tank option relates to transport via up to 100 ISO tank containers, which would arrive by sea and be transferred to a parking lot in the port. These are currently 25 metric ton (te), which will be taken as the basis for this study.

3 APPROACH

3.1 Overview

The following describes briefly the overall scope of work that has been proposed, noting that this specific study is only a part of the following (see Section 3.2).

Dispersion modelling can be undertaken using the Phast consequence tool, which will show the hazard ranges to concentrations of interest. This can be used to determine approximate numbers of fatalities per scenario or can be readily applied to the Safeti risk tool to determine a more direct measure of the number of fatalities predicted, *but neither assessment has been conducted in this study*. This can include associated risk estimates as necessary.

This dispersion (and risk) modelling can be undertaken for a series of worst-case outcomes associated with both the liquid carrier and ISO container options, as well as comparing against 'typical' ammonia transfer hazards.

However, before undertaking the above dispersion modelling it is critical to define realistic scenarios in terms of the initiating event and the subsequent ammonia discharge parameters. This will be the key step, which will determine the extent to which other tasks are needed.

The main tasks proposed *for the overall scope* were therefore:

- Hazard analysis workshop, to determine source terms
- Workshop preparation, including initial dispersion modelling
- Workshop follow-up, each of which can be considered to be options (and will depend to some extent on the workshop findings):
    - Further investigation into the source terms, i.e. review of standards and literature to support the selected scenarios (and to potentially screen out some scenarios as non-credible)
    - Detailed dispersion (and impact) analysis / modelling
    - Risk modelling

Of the above tasks it is only the initial dispersion modelling covered by this document, as discussed further below.

3.2 Initial Dispersion Modelling

The following describes briefly the scope and approach for the analysis undertaken for this study.

The modelling approach is based around using the very latest version of Phast (version 8) to superimpose the effect zone / dispersion footprint for a key concentration onto an area map for each of the scenarios considered, for a set of representative weather conditions.

The Phast software is a semi-empirical consequence model, similar in nature to ALOHA but with generally more advanced features, widely used throughout the oil, gas and chemical industries. Details are available from: https://www.dnvgl.com/services/process-hazard-analysis-software-phast-1675

The scenarios considered for this initial assessment will cover ammonia dispersion for:

- Catastrophic (instantaneous) release of maximum liquid carrier inventory (e.g. 1250 te)

- Major leak from liquid carrier (e.g. 750 mm diameter hole)
- Moderate leak from liquid carrier or other ammonia containment (e.g. 250 mm diameter hole)
- Catastrophic (instantaneous release of ISO container inventory (e.g. 25 te)

These are discussed further in Section 4.1, including some additional sensitivity cases.

Each will be modelled as a liquid spill, with the pool formation, vaporisation and subsequent dispersion modelled by the Phast software. Releases from the vapour side of the containment will tend to have significantly shorter hazard ranges and will not be considered at this stage.

Each will be modelled for four weather categories, but with the results focussed on presenting the worst-case only (which will tend to be low wind speed stable conditions). The results will be presented in terms of the distances to the Protective Action Criteria (PAC) concentration levels and the distances to 10 and 90% lethality limits (for the purposes of estimating the potential fatalities), as discussed further in Section 4.3.

For the purposes of this initial input there will be limited sensitivity analysis, but key assumptions such as the surface conditions and the influence of the key discharge assumptions will be discussed.

4 BASIS

4.1 Scenarios

The scenarios modelled in this initial analysis are listed in Table 4-1 and Table 4-2 for cases relevant to the liquid carrier and the ISO tanks, respectively. The tables describe the basic scenario and include notes on each, discussing the relevance to the key ammonia transport scenarios - and associated hazards – under consideration. The key scenarios are considered to be:

- A catastrophic failure of the liquid carrier leading to 2500 te spill of liquid ammonia to the sea surface in the port. This should represent the worst possible outcome in terms of spilled inventory, noting that any scenario that causes catastrophic failure of both ship containers without an associated ignition source is considered to be an extreme outcome.
- A major leak from the liquid carrier leading to a spill to the sea. This is represented by a 750 mm hole size, which leads to a release rate of just over 1000 kg/s and a spill duration of around 40 minutes. This is considered to be the most credible worst-case outcome consistent with ship collision or a similar major event (potentially including missile attack if ignition does not occur).
    - For both of these cases the influence of a spill to the port side (i.e. concrete surface rather than the sea) is also considered, as is a 250 mm leak scenario, although the above sea spill cases are considered the most meaningful scenarios.
- A catastrophic failure of a single ISO tank, leading to a 25 te spill of liquid ammonia to the port (i.e. concrete surface). This is considered to be the most relevant scenario for a major ISO tank event.
    - Additional cases are modelled to apply the above to the sea surface, and to also consider larger inventories associated with multiple (5 or 10) ISO tank failures, although these are each for sensitivity analysis only.

Each scenario is modelled as a simple liquid *leak* scenario aimed at the worst-case outcome, based on a direct leak / release only, without any ignition. If a fire or explosion occurs, much (or all) of the ammonia will be burned and the subsequent dispersion will be much smaller (if any occurs). If the explosion energy increases the rate of discharge of some unignited ammonia it will vaporise rapidly and be accompanied with greater turbulence and, hence, it would be highly likely that the hazard ranges would reduce. Hence, it is important to be clear that the scenarios modelled are only representative outcomes for this initial dispersion modelling and not necessarily the most likely outcomes for missile attack, for example. The scenarios modelled should be the most conservative outcomes, but this would need to be confirmed by considering the top level events (e.g. how a missile would cause the release) in more detail.

The parameters used in modelling each release and the criteria for reporting the results are considered in the following sections.

Table 4-1 Scenarios Considered for Liquid Carrier Leak Scenarios

Source	Type	Size	Description	Notes / discussion
Liquid Carrier	Catast-rophic Failure	2500 te	2500 te of anhydrous liquid ammonia released instantaneously to the sea surface forming a pool, with subsequent vaporisation and dispersion	Simultaneous failure of both storage tanks from a liquid carrier would represent an extreme incident (and would be likely to be accompanied by ignition in practice). Instantaneous formation of a large pool is relatively theoretical, although rapid formation of a very significant pool is the key feature – and is considered reasonable.
		2500 te	As above, but release to a concrete surface, such as the port	This is for reference only and not representative for this scenario
		1250 te	1250 te releases to the sea, as above	To show sensitivity to the more credible case where catastrophic failure covers one tank only
	Major leak	750 mm leak	750 mm hole leading to 1105 kg/s release (which last for around 40 minutes)	Represents a major leak occurring at a high rate, forming a major pool – to the sea surface. This is typical of a ship collision or loading arm rupture, but also potentially representative of terrorist action.
		750 mm leak	As above, but release to a concrete surface, such as the port	This is potentially representative of a loading arm / line event to the port side, although would be conservative since the duration would be expected to be short in practice
	Moderate leak	250 mm leak	250 mm hole leading to 123 kg/s release (which last for >1 hour)	Represents a significant leak forming a major pool – to the sea surface. This is typical of a loading arm leak, but also potentially representative of terrorist action.
		250 mm leak	As above, but release to a concrete surface, such as the port	This is representative of a loading arm / line event to the port side.

Table 4-2 Scenarios Considered for ISO Tank Leak Scenarios

Source	Type	Size	Description	Notes / discussion
ISO Tank	Catast-rophic Failure	25 te	25 te of anhydrous liquid ammonia from one ISO tank - released instantaneously to the port (concrete) surface forming a pool, with subsequent vaporisation and dispersion	This is considered the most likely ISO tank outcome - either associated with a general accident or terrorist activity.
		25 te	As above, but release to the sea surface	This is for reference and considered less likely than for the port side (i.e. any such event at sea would be spilled to ship deck, or the ISO tank may be submerged if coming off the ship)
		125 te	125 te releases to the port (concrete), representing simultaneous failure of 5 ISO tanks	This is a reference case, noting that simultaneous catastrophic failure of multiple tanks is unlikely to be credible without an ignition source, noting also that in practice the full inventory would be released as 5 sets of 25 te instantaneous release rather than one 125 te event
		250 te	250 te releases to the port (concrete), representing simultaneous failure of 10 ISO tanks	As above, but for 10 ISO tanks
	Moderate leak	250 mm leak	250 mm hole leading to 123 kg/s release (which lasts for a few minutes for a single ISO tank)	Represents a significant leak forming a major pool – to the port – noting that this will have moderate duration for a single tank.
		250 mm leak	As above, but release to the sea	This is representative of a leak from an ISO tank spilling from a ship to the sea

4.2 Parameters

In all cases, four representative weather conditions are considered:

- F2 – this represents low wind speed and stable atmospheric conditions. This combination of conditions represents the minimum atmospheric turbulence option, which is the worst-case for dense gas dispersion.
- D2 – this uses the same wind speed as above, but for neutral stability, for reference.
- D5 – this is the most typical weather, representing neutral stability and a moderate wind speed of 5 m/s.
- D10 – as above, but showing the influence of higher wind speed (i.e. 10 m/s).

A representative ambient temperature of 30^{o}C is assumed in all cases. The surface temperature for concrete is taken as 30^{o}C also, while the sea surface temperature is taken as 20^{o}C.

The Phast software uses different parameters according to the surface for heat transfer to pools, where the port is defined as "concrete" and the sea as "shallow open water".

The default surface roughness within Phast is 183 mm, which is broadly representative of medium crops and moderate obstacles. This is intended to replicate the potential dispersion conditions for the cloud when over land, with moderate turbulence generated by the surface.

4.3 Impact Criteria

The Protective Action Criteria (PAC) levels defined by the US DOE for ammonia will be reported, noting that the PAC-1 PAC-2 and PAC-3 levels for ammonia are 30, 160 and 1100 ppm, respectively.

Note that these are the same as the widely used AEGL (Acute Exposure Guideline Levels) for 60 minutes exposure, noting that:

- Level 1 corresponds to "notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure".
- Level 2 corresponds to "irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape".
- Level 3 corresponds to "life-threatening health effects or death".

These are well established levels used in land use planning where toxic impacts are anticipated and will provide a clear basis for comparing the different scenarios.

It should, however, be emphasised that these levels are based on thresholds for impacts, i.e. representing the limits of potential impacts. Fatality and significant harm for exposure to toxic effects requires a combination of concentration and exposure duration, which is typically measured as a dose. For potential fatality even for 1 hour exposure the PAC-3 / AEGL-3 concentration tends to result in limited fatality potential.

The lethality level accounting for dose is calculated in Phast using a probit function, as shown by Figure 4-1, for which the A, B and N values are -16.21, 1 and 2, respectively.

This function can be used to determine the distances to any fatality probability, or lethality, with 90%, 10% and 0.1% used as representative examples, in order to put the fatality potential into perspective. 90% is used to represent 'almost certain' fatality, 10% is broadly indicative of 'significant' fatality potential, while 0.1% is considered the lower threshold, below which the potential for fatality is low.

Figure 4-1 Toxic Probit Function

The toxic parameters are used in the Probit equation as follows:

$$Pr = A + B\,ln\left(C^{N}t\right)$$

Where:

Pr = *Related to the probability of death for an "average" person*

A = *PROBIT Parameter A*

B = *PROBIT Parameter B*

C = *Concentration of the **pure** toxic chemical*

N = *PROBIT Parameter N*

t = *Duration of exposure*

5 RESULTS

5.1 Introduction

The results for a catastrophic failure of a 25 te ISO tanker are discussed in Section 5.2 in order to illustrate the progression of a release.

The corresponding results for a 2500 te release from a liquid carrier are presented in the same way in Section 5.3.

Tables of the same results for each of the scenarios modelled are then presented in Section 5.4, which includes additional discussion and illustrations. The key scenarios are illustrated further in Section 5.5 by way of a summary.

5.2 ISO Tank 25 te Release

Figure 5-1 to Figure 5-6 show example outputs of the discharge and dispersion results for a 25 te ISO tank failure scenario, noting that these give the results for a spill to the sea surface (the corresponding results for a spill to land are shown in Section 5.4).

The liquid spill forms a pool, which is illustrated by Figure 5-1 and Figure 5-2, showing how the pool vaporisation rate and pool radius, respectively, vary with time. The rate of vaporisation is greater for higher wind speeds, which then limits the pool radius, such that:

- For the higher wind speed cases (D5 and D10) the pool vaporisation increases rapidly to a peak of just over 300 kg/s and is depleted in around 60 s, with the maximum pool size reached being a radius of around 35 m.
- For the lower wind speed cases (F2 and D2) the pool vaporisation profile is similar but slightly slower with a peak of around 225 kg/s and a duration of around 100s. The pool radius is around 43 m in this case.
- Note that in both cases the total duration of the cloud formation is less than 2 minutes, which is relevant in the context of the PAC criteria being based on 1 hour exposure limits.

Figure 5-3 shows a plan view or footprint of the ‘maximum’ dispersion to 30 ppm. It is important to note that this shows all areas exposed to 30 ppm or greater at any time in the dispersion, so ‘traces’ the path covered by the cloud. The snapshot at any given time will show a rather shorter hazard envelope, as illustrated by Figure 5-4, which shows the footprint after 100 s:

- Figure 5-3 shows that the dispersion is generally more onerous in F2 conditions, due to the limited turbulence and hence limited dilution, with the cloud near the source being almost circular with a radius of around 2 km, while the subsequent downwind dispersion has a thinner profile but reaches as much as 11.5 km downwind. The hazard ranges in other conditions are still significant, reaching up to 7 km downwind for this (30 ppm) concentration.
- Figure 5-4 shows that the dispersion is not a continuous release but a cloud that has detached from the initial source and drifts downwind. During the initial stages the higher wind speeds (i.e. D10 in this case) cause more rapid dispersion downwind, although this is accompanied by greater dilution, such that the ultimate hazard ranges (as per Figure 5-3) are greater for F2 conditions.

Figure 5-5 shows the maximum footprint for the dispersion to 1100 ppm (PAC-3), which reaches between 1.4 and 1.8 km downwind. For this concentration level there is a less marked difference according to the weather conditions, although the dispersion remains most onerous for the F2 case.

Given that the cloud duration is short the probability of fatality is limited for these concentration levels, as illustrated by Figure 5-6. This shows the envelope within which the lethality (probability of fatality) exceeds 0.1%. This can be seen to have a similar shape to the 1100 ppm dispersion, but where the distances are shorter, the maximum reached being between 400 m for D5 conditions and around 630 m for F2 conditions.

These results are discussed further in Section 5.4, with the key outcomes / results superimposed on a map in Section 5.5.

Figure 5-1 Pool Vaporisation Profile, by Weather, for 25 te Catastrophic Release (to Sea)

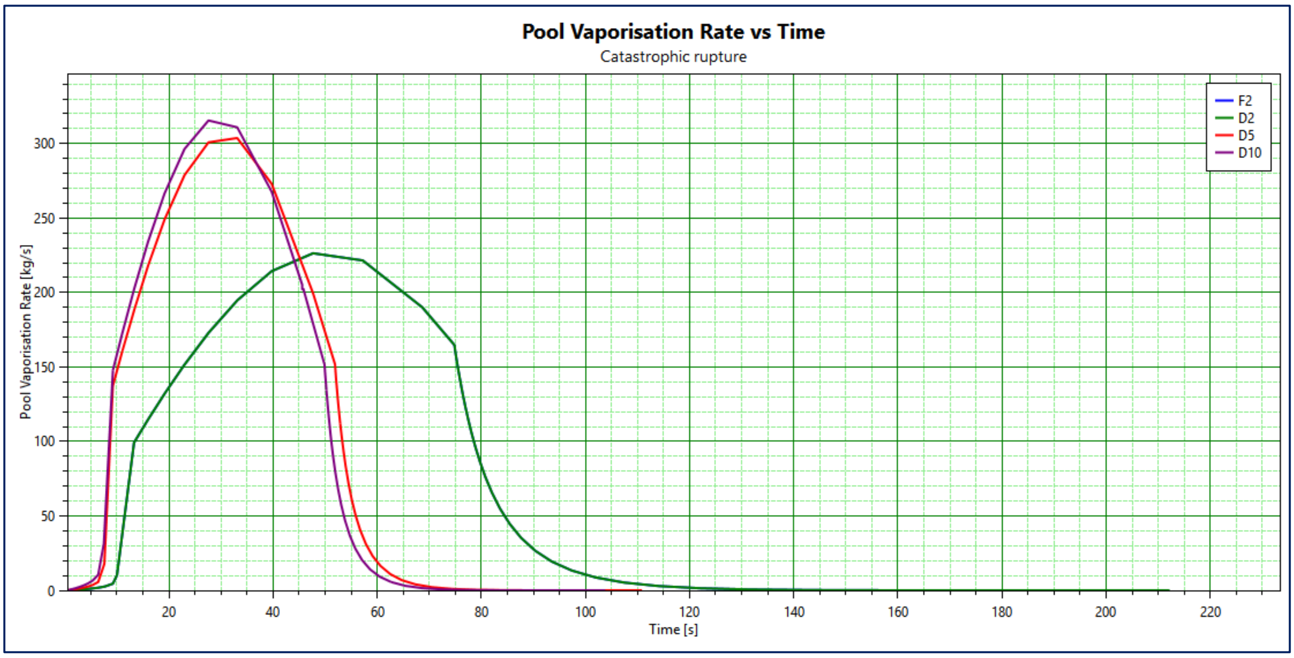


Figure 5-2 Pool Radius, by Weather, for 25 te Catastrophic Release (to Sea)

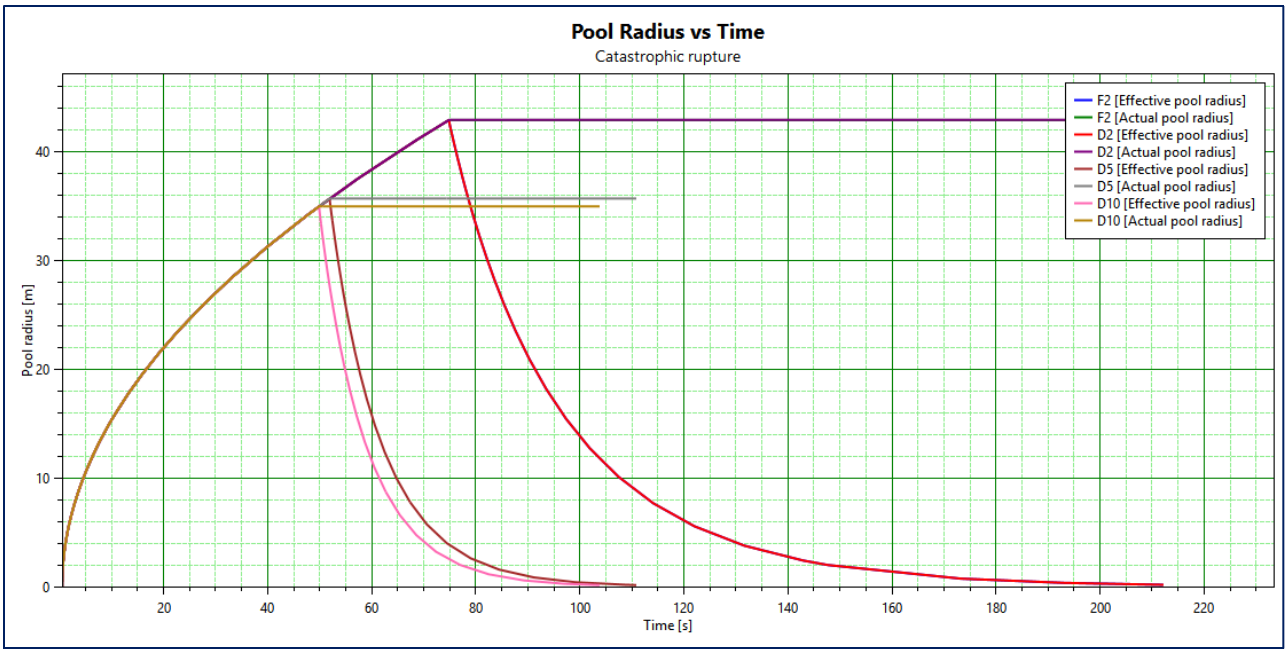


Figure 5-3 Maximum Footprint of Dispersion to 30 ppm (PAC-1), by Weather, for 25 te Catastrophic Release (to Sea)

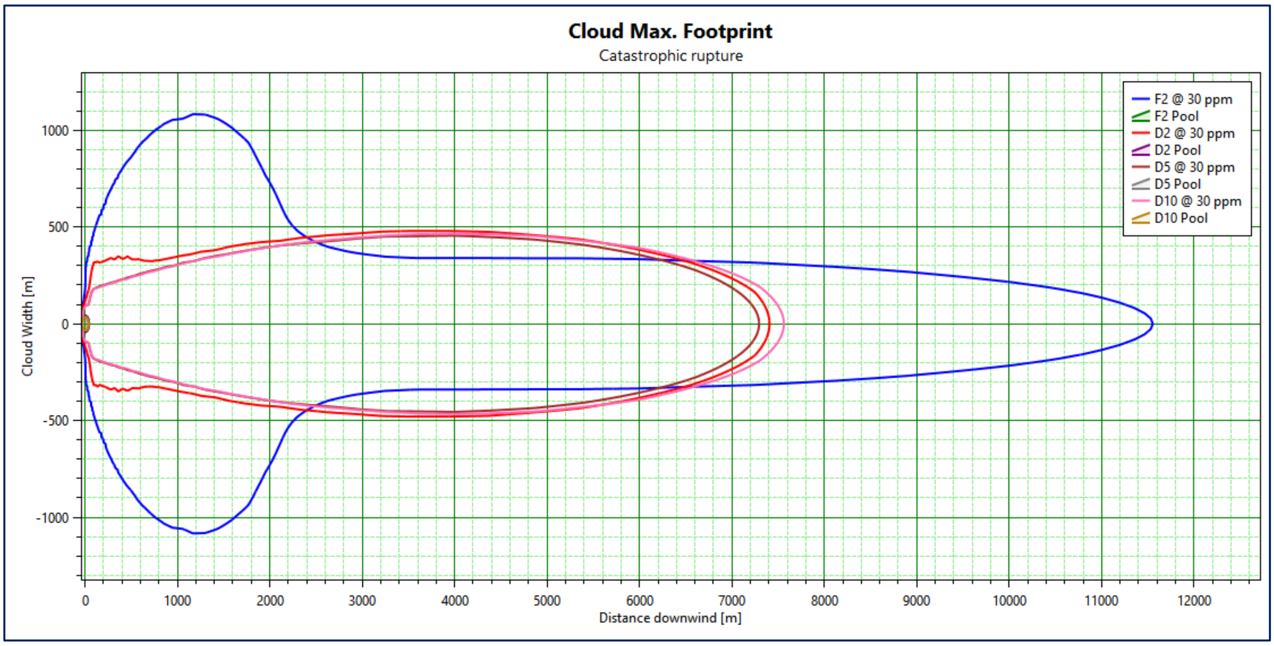


Figure 5-4 Footprint After 100s for Dispersion to 30 ppm (PAC-1), by Weather, for 25 te Catastrophic Release (to Sea)

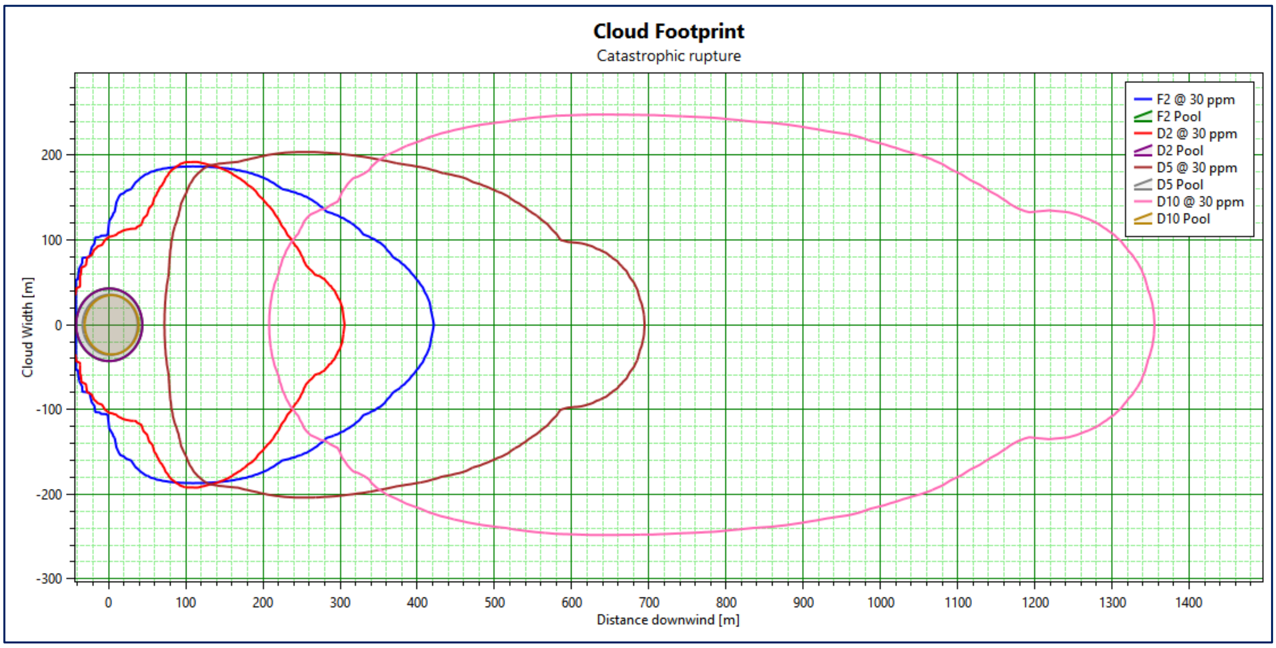


Figure 5-5 Maximum Footprint of Dispersion to 1100 ppm (PAC-3), by Weather, for 25 te Catastrophic Release (to Sea)

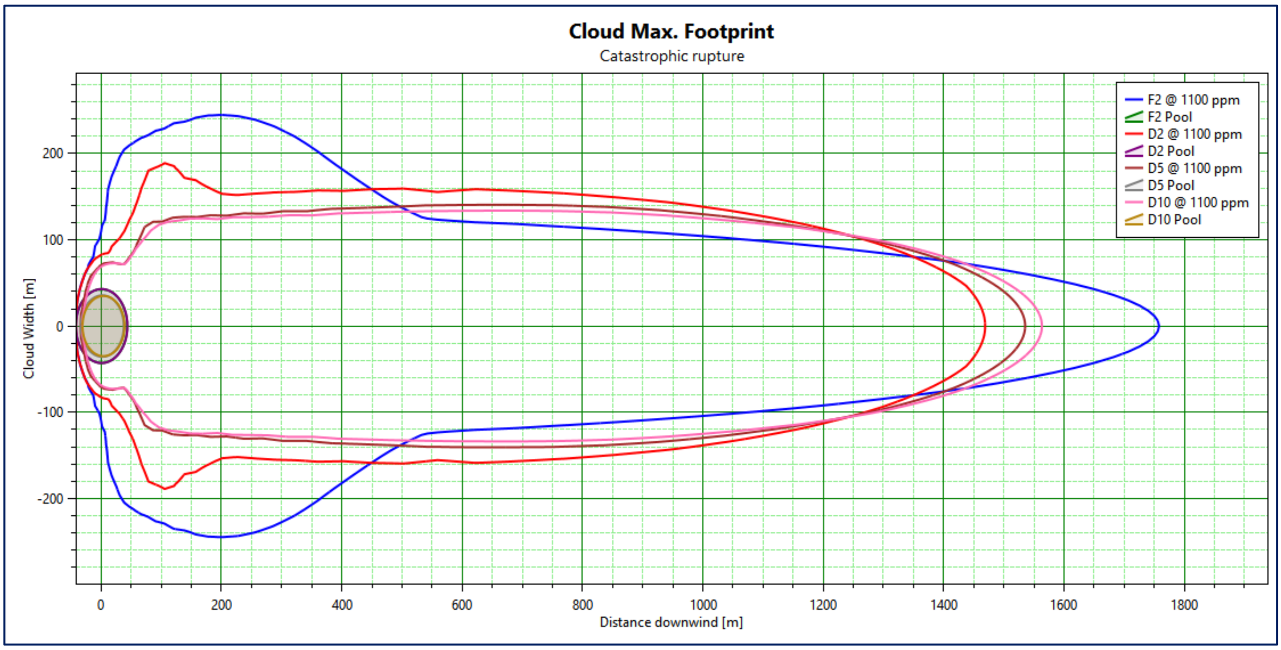
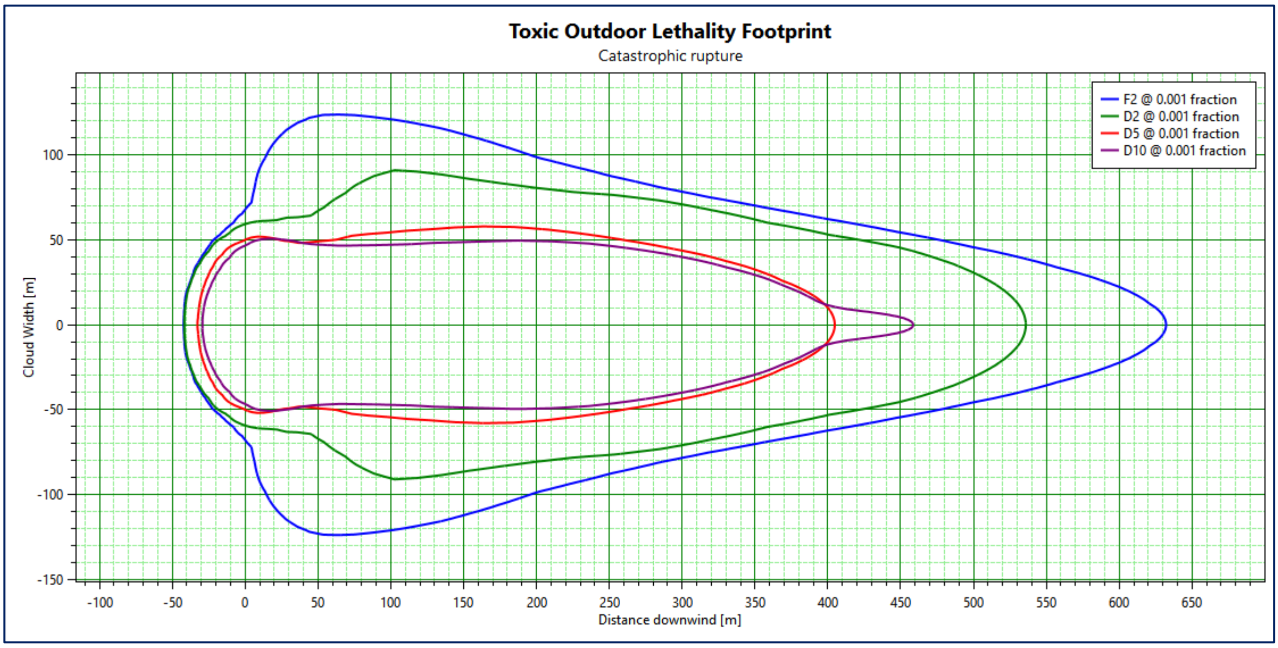


Figure 5-6 0.1% Lethality Footprint, by Weather, for 25 te Catastrophic Release (to Sea)



5.3 Liquid Carrier 2500 te Release

Figure 5-7 to Figure 5-10 show example outputs of the discharge and dispersion results for a 2500 te liquid carrier failure scenario, noting that these give the results for a spill to the sea surface, while the corresponding results for a spill to land are shown in Section 5.4.

Figure 5-7 and Figure 5-8 shows that the shape of the pool vaporisation profile is similar to that of the 25 te case, but in this case the duration is slightly longer and the vaporisation rate much more significant. The peak vaporisation rate is around 9000 kg/s (and 6000 kg/s for lower wind speed) with a total duration of around 180 s (and 300 s). The pool radius reaches just over 200 m for high wind speed and up to 260 m in lower wind speeds. Note that this pool spread is theoretical and will depend on the port / harbour dimensions.

Figure 5-9 shows the maximum footprint for the dispersion to 1100 ppm (PAC-3), which reaches just under 7 km downwind in D2 conditions and around 9.5 km in F2 conditions (with the D5 and D10 results between these limits).

The corresponding lethality profile is given as Figure 5-10 and shows shorter, but significant, distances to the 0.1% lethality level. This indicates a maximum downwind distance of between 2.8 km (D10) and 4.7 km (F2).

Comparison of these results with those for a single ISO tank case in the previous section shows clearly the important difference in potential exposure. This is, however, discussed further in the following sections in the context of all the cases considered, with these figures shown primarily to illustrate the progression of the dispersion from pool vaporisation to downwind concentrations and lethality.

Figure 5-7 Pool Vaporisation Profile, by Weather, for 2500 te Catastrophic Release (to Sea)

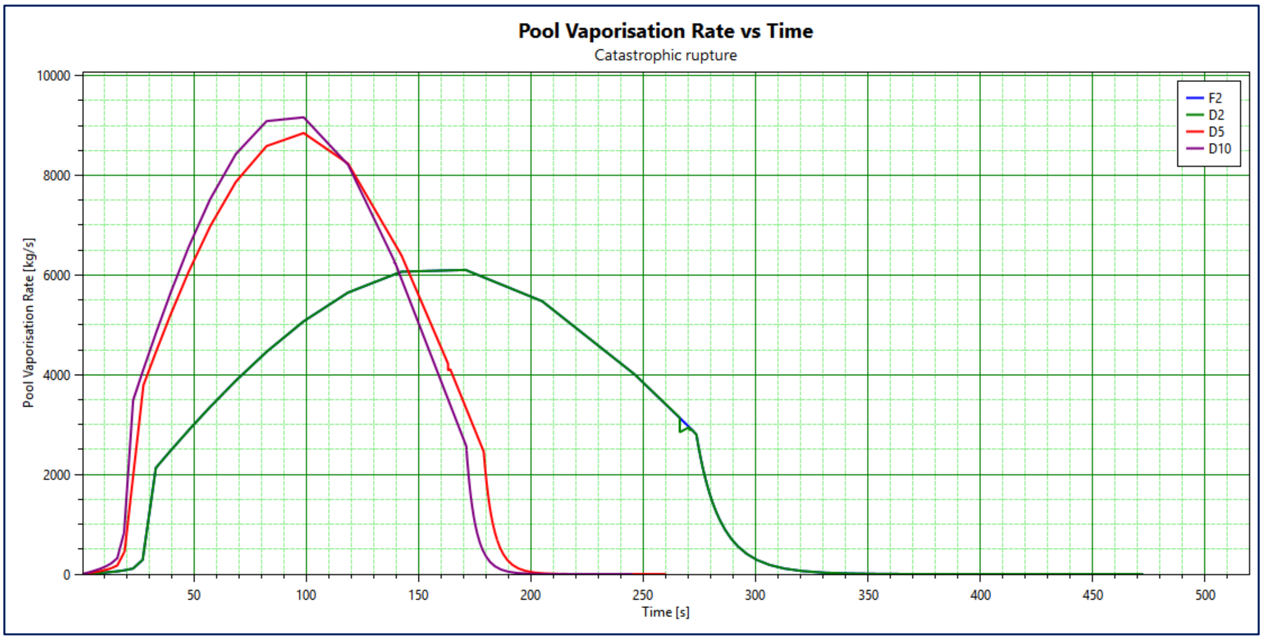


Figure 5-8 Pool Radius, by Weather, for 2500 te Catastrophic Release (to Sea)

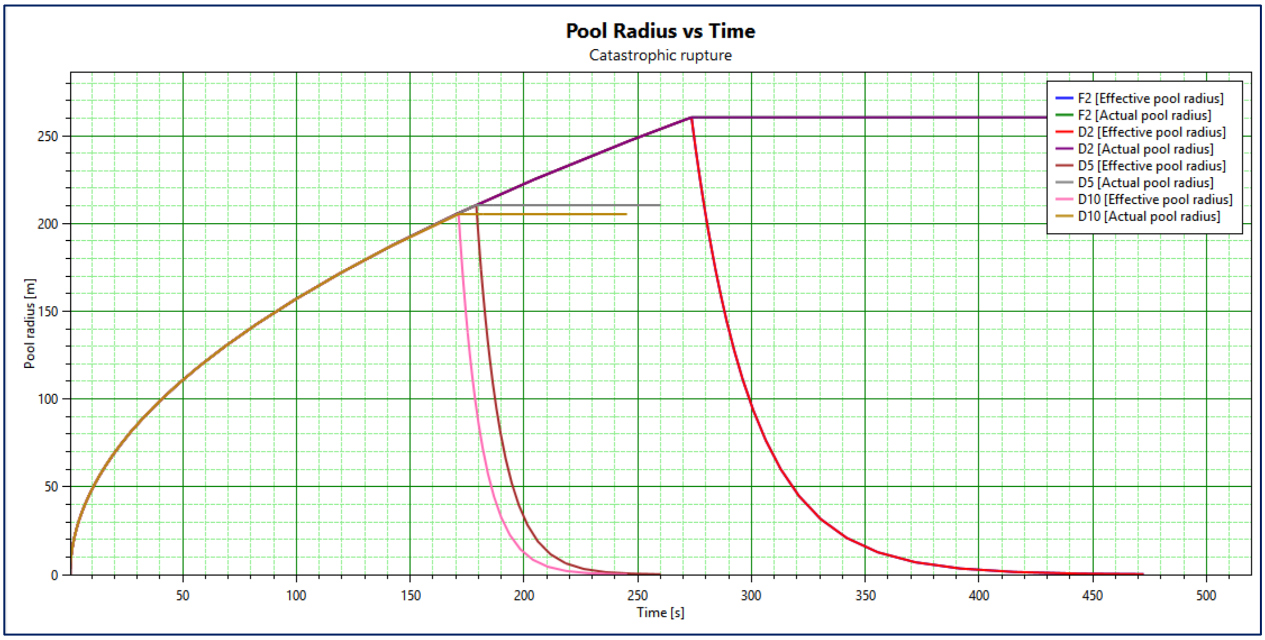


Figure 5-9 Maximum Footprint of Dispersion to 1100 ppm (PAC-3), by Weather, for 2500 te Catastrophic Release (to Sea)

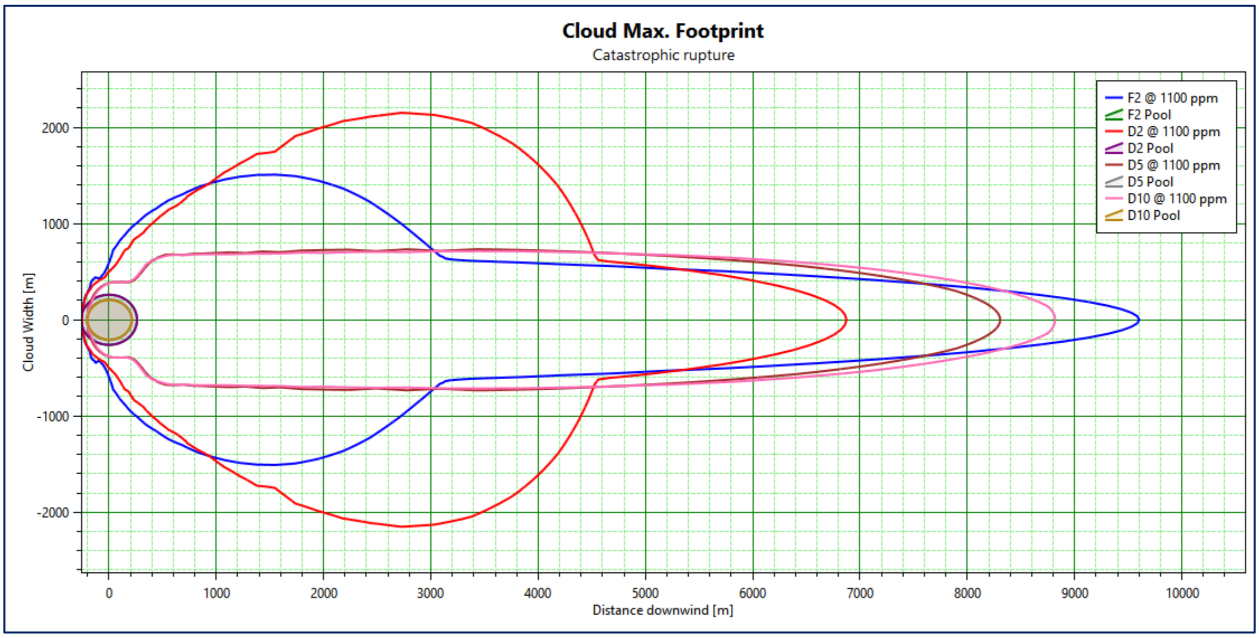
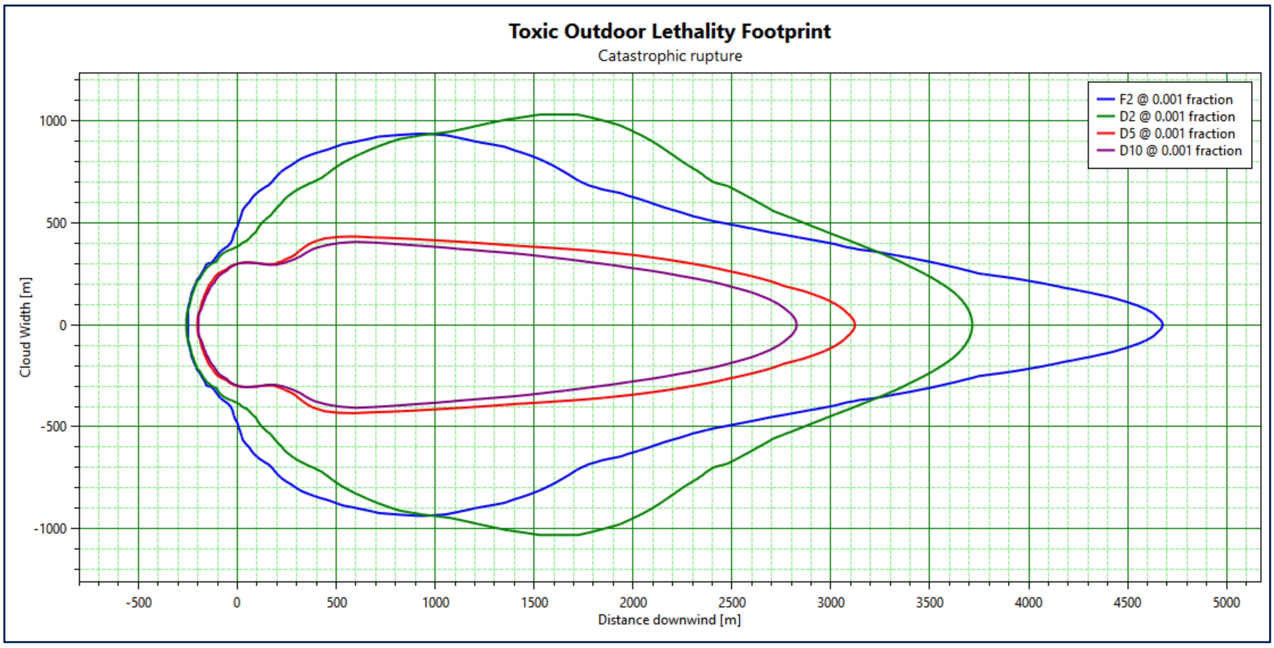


Figure 5-10 0.1% Lethality Footprint, by Weather, for 2500 te Catastrophic Release (to Sea)



5.4 All Results

The results for each of the scenarios defined in Section 4.1 are illustrated in Table 5-1 and Table 5-2 in terms of the pool dimensions, maximum downwind distance to key concentrations (30 and 1100 ppm, representing PAC-1 and PAC-3), as well as the distances to different levels of lethality (90%, 10% and 0.1%).

In all cases a range of results is given to cover the minimum and maximum values for the 4 weather conditions considered. Note that the maximum is always the F2 weather case for the dispersion / lethality distances.

The catastrophic liquid carrier failure scenario, based on a spill to sea, is shown in Table 5-1 for 2500 te and 1250 te cases, where:

- The pool vaporises rapidly and the cloud formation occurs in less than 5 minutes, with a vaporisation rate than exceeds 5000 kg/s and a pool diameter that approaches 500 m. (Note that this will be sensitive to the port dimensions in practice.)
- The corresponding distance to PAC-1 (30 ppm) is huge, potentially reaching 70 km and exceeding 30 km for all weather conditions. The distance to PAC-3 (1100 ppm) is between 6 and 10 km.
- The PAC concentrations are a relevant measure, although due to the limited duration the lethality potential is limited. Hence, in terms of the distances at which different likelihoods of fatality apply:
    - A High fatality potential (i.e. 90% lethality) will have a distance of less than 500 m from the spill.
    - A significant (i.e. 10% or more) lethality level will have a distance of between 1 and 2 km, depending on the spill size and the weather conditions.
    - The distance to a threshold for fatality (taken as 0.1% lethality) is between 2 and 5 km, with the F2 conditions being the most onerous.

If the same (2500 te) spill is assumed to occur to the port side, i.e. to concrete, the heat transfer is much lower and the vaporisation rate is reduced to around 2000 kg/s. After an initial peak the pool vaporisation continues at a lower rate for up to an hour (rather than being complete in a few minutes for the sea case). In this case:

- The hazard range to PAC-1 and PAC-3 are broadly similar to the sea spill case and very significant.
- Generally speaking the lethality hazard ranges are also similar, but the maximum hazard range, applying in F2 conditions, is increased due to the additional duration (being approximately double that of the sea spill case).

The results for the single ISO tank case (i.e. 25 te catastrophic rupture) are also shown in Table 5-1, where:

- The results vary between the sea and port cases, in the same way as discussed above, with a much higher release rate and shorter duration for the sea spill case and broadly similar hazard ranges, where the port / concrete spill case has a bigger range (i.e. the hazard range is shorter for high speed and longer for low wind speed relative to the sea spill case).
- In either case the distance to PAC-1 is between 6 and 13 km, while the PAC-3 distance is 1 to 2 km. These remain significant distances but can be seen to be substantially shorter than for the liquid carrier case.
- The lethality levels are generally within 100 m for 90%, 150-350 m for 10% and between 250 and 800 m for 1% lethality – again, significantly shorter than for the liquid carrier case.

Results are also shown for multiple ISO tank failures (i.e. 125 te and 250 te cases), in Table 5-1, noting that these are only modelled for the port spill case:

- These cases, as would be expected result in dispersion to the PAC-1 and PAC-3 concentrations that are somewhere between those for the single ISO tank and liquid carrier failure scenarios. The distance to PAC-3 is, for example, between 1 and 4 km depending on the inventory and the weather.
- The lethality levels are up to 375 m for 90%, up to 1.2 km for 10% and up to 2.5 km for the 1% lethality distance.

Further to the above cases, Table 5-2 shows the same results for the 750 mm and 250 mm leak scenarios, for both spills to sea and to the port. These cases are modelled for the liquid carrier case, with significant inventory such that:

- Although the initial peak vaporisation rate has moderate duration, the overall vaporisation continues for a long duration at a lower rate.
- The relatively long duration means that the lethality effects for the 750 mm case are more onerous than for the catastrophic liquid carrier release scenario. For this case the 0.1% lethality level is only marginally shorter than the 1100 ppm (PAC-3) distance, being between 1 and 7 km for the sea spill case and between 3 and 14 km for the port spill case. Note that the latter is relatively theoretical since the pool diameter may be up to 640 m, which is unlikely to occur in practice due to obstructions and topography.
- Note also that the 250 mm leak case gives hazard ranges that are more onerous than the multiple ISO tank failure scenarios, with the 0.1% lethality distance reaching up to 6 km for the port spill case (in F2 conditions), albeit being closer to 1 km in most of the other scenarios.

Table 5-1 Key Discharge and Dispersion Results for Leak Scenarios – Liquid Carrier and ISO Tank

Measure	Liquid Carrier			10 x ISO	5 x ISO	Single ISO	
	2500 te sea	**2500 te port**	**1250 te sea**	**250 te port**	**125 te port**	**25 te port**	**25 te sea**
Pool vaporisation peak	6000-9000 kg/s	1700-2100 kg/s	3700-5400 kg/s	28-380 kg/s	160-230 kg/s	50-70 kg/s	230-300 kg/s
Pool vaporisation duration	300-180 s	>1 hour*	250-150 s	>1 hour*	>1 hour*	>1 hour*	120-60 s
Pool radius	200-260 m	360-380 m	160-200 m	130 m	90 m	43-44 m	35-43 m
30 ppm distance	41-68 km	47-71 km	32-57 km	16.5-39 km	11.5-28 km	5.5-13.2 km	7.3-11.6 km
1100 ppm	6.8-9.6 km	3.2-11.6 km	5.5-7.5 km	1.5-4.2 km	1.3-3.0 km	0.8-1.5 km	1.4-1.8 km
90% lethality	350-450 m	400-1300 m	300-350 m	125-375 m	100-250 m	50-120 m	60-90 m
10% lethality	1.4-2.0 km	1.0-4.0 km	1.0-1.5 km	0.4-1.2 km	0.3-0.8 km	160-360 m	190-250 m
0.1% lethality	2.8-4.7 km	1.8-8.2 km	2.0-3.5 km	0.7-2.5 km	0.5-1.8 km	260-770 m	400-630 m

Note *: These cases have peak vaporisation rates that have a limited duration but then decay steadily but with some vaporisation, at a lower rate, for at least 1 hour (which is the maximum modelled by Phast).

Table 5-2 Key Discharge and Dispersion Results for Leak Scenarios – Leak Sizes

Measure	750 mm Leak		250 mm Leak	
	Sea	Port	Sea	Port
Pool vaporisation peak	550-600 kg/s	800-900 kg/s	60-80 kg/s	100 kg/s
Pool vaporisation duration	180-240 s**	>1 hour*	100 s**	>1 hour*
Pool radius	70-100 m	270-320 m	20-30 m	100-120 m
30 ppm distance	14-57 km	43-73 km	4-21 km	11-54 km
1100 ppm	1.6-8 km	3.5-16 km	0.6-2.1 km	1.0-7.1 km
90% lethality	200-900 m	800-1800 m	20-120 m	300-1300 m
10% lethality	0.6-3.5 km	1.4-6.8 km	0.3-0.55 km	0.5-3.2 km
0.1% lethality	1.0-6.6 km	2.6-13.8 km	0.5-1.7 km	1.0-6.1 km

Note *: These cases have peak vaporisation rates that have a limited duration but then decay steadily but with some vaporisation, at a lower rate, for at least 1 hour (which is the maximum modelled by Phast).

Note **: These cases have a very clear peak, as indicated, but then have some residual vaporisation for a significant duration, of close to 1 hour.

5.5 Key Results

To support the results presented in the previous section, the key scenarios are illustrated in the following figures by superimposing the 0.1% lethality contours on a map of the city. Note that:

- A representative location is used as the source of a release.
- The footprint of the lethality contours is shown for wind from the West, for each of the four weather conditions.
- Also shown are circles showing the 'effect zone', i.e. the radius around the representative location that is in range of the respective hazards, for any / all wind directions.
- Note that the 0.1% lethality level is selected as the threshold for fatality, i.e. these contours represent the potential for fatality, with fatality having an increasing likelihood towards the centre of the footprint / effect zone.

Figure 5-11 shows the footprint and effect zone for the single ISO tank rupture case for 0.1% lethality. This shows that the area exposed to some lethal potentially lethal effects is not insignificant but is relatively local to the port, even in the worst-case F2 conditions.

Figure 5-12 shows the corresponding results for simultaneous, instantaneous release of the contents of 10 ISO tanks, i.e. 250 te of ammonia. In this case the area potentially covered is relatively local (similar to the D2 results for the 25 te case) in D5 and D10 conditions, but is larger for the D2 conditions and has potential to impact a significant proportion of the city in F2 conditions.

Figure 5-13 and Figure 5-14 show the same results for two liquid carrier scenarios – the catastrophic release of 2500 te and a 750 mm leak case, respectively. The results are more onerous for the 750 mm leak case in terms of the maximum downwind distance and hence the effect zone radius. However, the area covered by the 0.1% lethality footprint, due to the width of the contour, is greater for the catastrophic failure case. In both cases, the area covered in the higher wind speed cases is similar to that for the F2 results for the above case, while the area potentially covered in F2 conditions by these releases is rather larger.

It should be emphasised that all of the results presented in this study are based on 'free air', 'flat earth' modelling and do not account for topography. The dispersion in all cases is dense gas dispersion, such that the cloud height is generally a small fraction of the length, as illustrated by Figure 5-15 (for the 750 mm leak case). Where shallow slopes occur, the dispersion will tend to follow the ground and will not be sensitive to the topography. However, for significant changes in elevation, the dispersion ranges given in these results will tend to be over-predicted with respect to any locations where there are uphill slopes and, conversely, under-predicted for downhill.

Dense gas dispersion is sensitive to a wide range of parameters / assumptions, including the ambient temperature and surface roughness. However, the results presented show that the key aspects influencing the results are:

- The total mass spilt (for instantaneous releases) or the hole size / release rate.
- The weather conditions, where stable low wind speed (e.g. F2) conditions give the most significant hazards ranges.
- The surface, where the pool size and duration are generally greater for concrete, compared to spills to sea, leading to a greater range in results (i.e. shorter hazard range for D10 and longer hazard range for the maximum F2, case).

Note also that the concentration of interest is also important, given a significant difference between the huge hazard ranges predicted for PAC-1 (30 ppm) and the relatively localised hazard ranges over which fatality potential is predicted.

Figure 5-11 0.1% Lethality Footprint and Effect Zone for Single ISO Tank (25 te) Catastrophic Release (to the Port / Concrete)

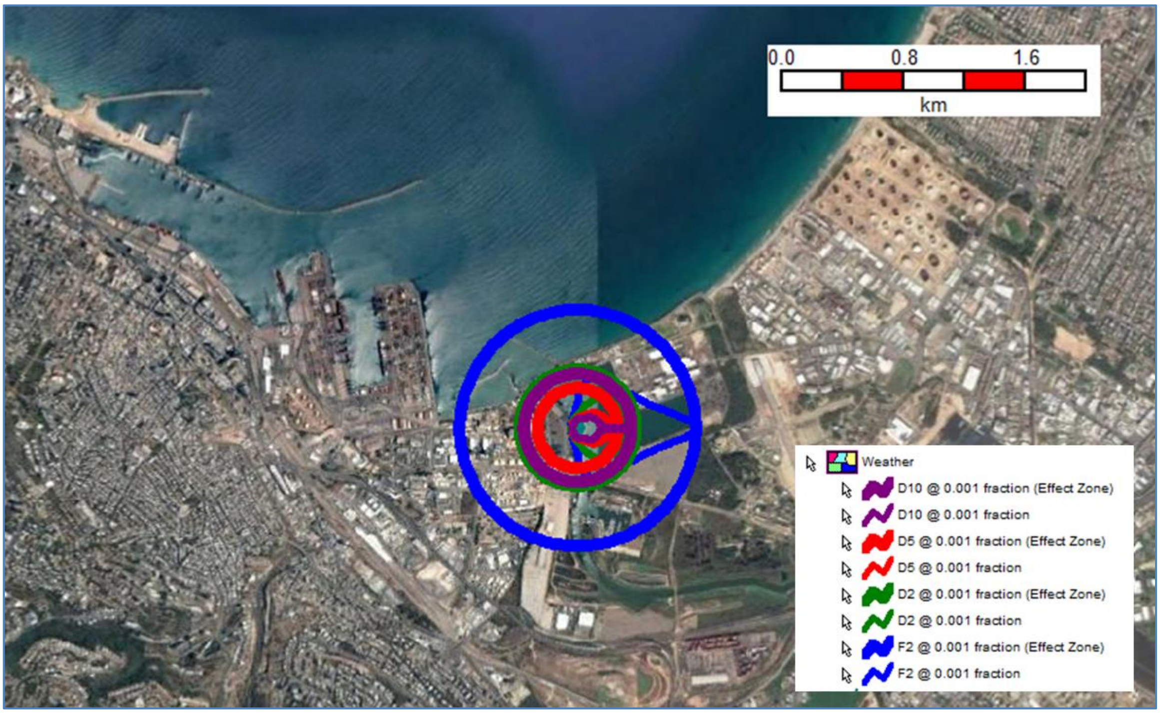


Figure 5-12 0.1% Lethality Footprint and Effect Zone for Multiple (10) ISO Tanks (250 te) Catastrophic Release (to the Port / Concrete)

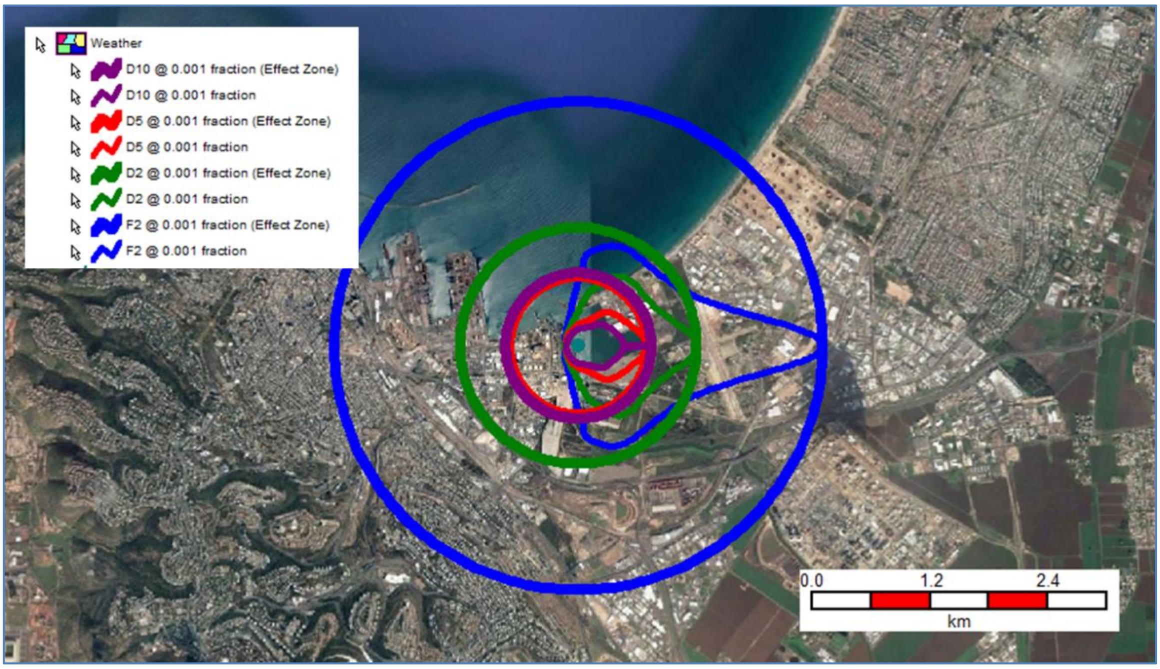


Figure 5-13 0.1% Lethality Footprint and Effect Zone for Liquid Carrier (2500 te) Catastrophic Release (to the Sea)

Figure 5-14 0.1% Lethality Footprint and Effect Zone for Liquid Carrier 750 mm Leak (to the Sea)

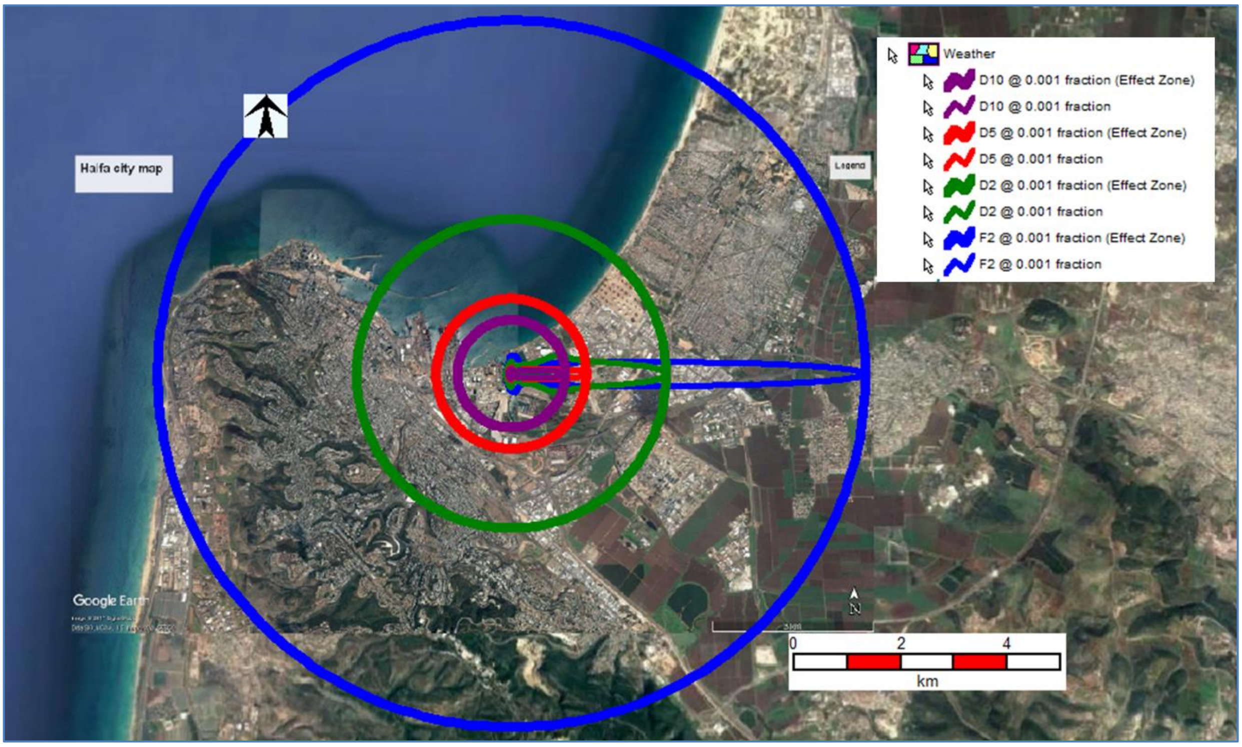
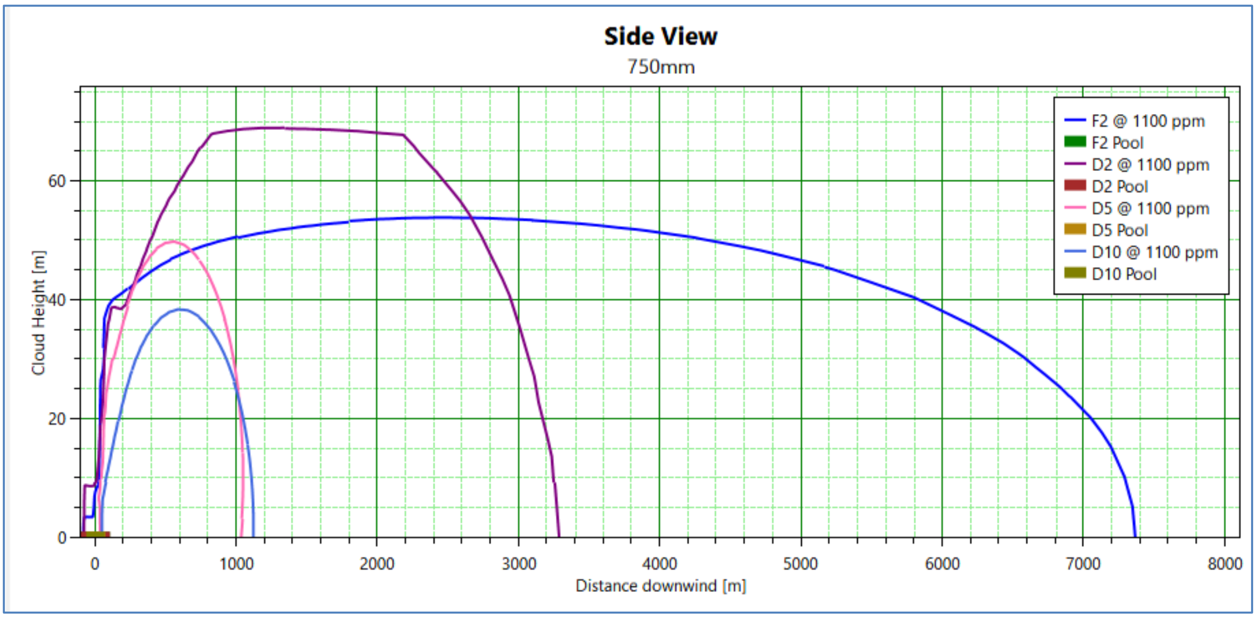


Figure 5-15 Side view of Dispersion to PAC-3 (1100 ppm) for Liquid Carrier 750 mm Leak (to the Sea)



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