QUANTITATIVE RISK ANALYSIS REPORT

BULK STORAGE FACILITIES, LYTTELTON PORT

PREPARED FOR: **QRA Steering Group**

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ABBREVIATIONS

AEGL	Acute Exposure Guideline Level
ALARP	As Low As Reasonably Practicable
BP	BP Oil NZ Ltd
CCC	Christchurch City Council
CFD	Computational Fluid Dynamics
ESD	Emergency Shutdown
GNS	GNS Science Consul
HIPAP	Hazardous Industry Planning Advisory Paper
HSNO	Hazardous Substances and New Organisms
IFR	Internal Floating Roof
IHLA	Independent High Level Alarm
LFL	Lower Flammability Limit
LPC	Lyttelton Port Company
LPRP	Lyttelton Port Recovery Plan
MLA	Marine Loading Arm
Mobil	Mobil Oil NZ Ltd
NZOSL	New Zealand Oil Services Ltd
OGP	Oil & Gas Producers
PGA	Peak Ground Acceleration
QRA	Quantitative Risk Analysis
Sherpa	Sherpa Consulting Pty Ltd
Z Energy	Z Energy Ltd

TERMINOLOGY

Term	Definition
Annual Individual Fatality Risk (natural hazards)	The term "annual individual fatality risk (AIFR)" is used in various natural hazards risk assessments. This is the risk of fatality to a person at a location including factors for probability of presence / exposure. NOTE: The natural hazards AIFR has a different basis to the individual fatality risk definition used in land use safety planning in the vicinity of hazardous facilities (as defined below) as the natural hazards AIFR calculation includes factors for probability of exposure / probability of presence.
Combustible liquid	Any liquid, other than a flammable liquid, that has a flash point, and has a fire point that is less than its boiling point (AS 1940–2004). Automotive diesel is an example of a combustible liquid considered in this study.
Consequence	Outcome or impact of a hazardous incident, including the potential for escalation.
Flammable liquid	Liquids [...] which give off a flammable vapour at temperatures of not more than 60.5°C, closed cup test, or not more than 65.6°C, open cup test, normally referred to as the flash point (AS 1940–2004). Gasoline is an example of a flammable liquid considered in this study.
Flash fire	The combustion of a flammable vapour and air mixture in which flame passes through that mixture at low velocity, such that negligible damaging overpressure is generated.
Flash point	The lowest temperature, corrected to a barometric pressure of 101.3 kPa, at which application of a test flame causes the vapour of the test portion to ignite under the specified conditions of test (AS 1940–2004).
Gasoline	Synonymous with petrol, gasoline is the common term used in the refining industry.
Heat radiation	The propagation of energy in the infra-red region of the radiation electromagnetic spectrum, commonly 'heat'.
Individual fatality risk	For land use safety planning this is the annual risk of fatality to a notional person at a particular point assuming exposure to the risk 24 hours a day and 365 days per year. NOTE this is a different basis to the AIFR used in natural hazards risk assessment which includes factors for probability of exposure / probability of presence. To avoid confusion with the natural hazards work, the term AIFR is not used in this QRA.
Individual risk	The frequency at which an individual may be expected to sustain a given level of harm from the realization of specified hazards. In this study the level of harm assessed is fatality.
Jet/spray fire	The combustion of material emerging with significant momentum from an orifice.
Lower flammability limit (LFL)	That concentration in air of a flammable material below which combustion will not propagate.
Offsite	Areas outside the bulk storage sites boundaries. This includes both public and private holdings, roadways, recreational facilities.
Onsite	Within any bulk storage facility site boundary.

Term	Definition
Pool fire	The combustion of material evaporating from a layer of liquid at the base of the fire.
Risk	The likelihood of a specified undesired event occurring within a specified period or in specified circumstances. It may be either a frequency (the number of specified events occurring in unit time) or a probability (the probability of a specified event following a prior event), depending on the circumstances. In this case, the risk under analysis is the likelihood of fatality per year due to loss of containment of hazardous materials resulting in fire or toxic exposure in the Lyttelton Port area.
Societal risk	The relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards. In this study societal risk is shown as FN curves which are obtained by plotting the cumulative frequency (F) at which hazardous events might kill N or more people, against N.
Vapour Cloud Explosion (VCE)	The combustion of a flammable vapour and air mixture in an environment where factors exist (for example equipment causing congestion or confinement of the cloud) that result in a high flame speed, consequently causing damaging pressure due to the inertia of the unburnt mixture in front of the flame.

1. SUMMARY

1.1. Background

The Port of Lyttelton in New Zealand includes a number of bulk liquids storage and handling facilities which are operated by different companies including BP Oil NZ Ltd, Fulton Hogan Ltd, Hexion (NZ) Ltd, Liquigas Ltd, Mobil Oil NZ Ltd, Z Energy Ltd, and Downer Group Ltd.

Hazardous materials including fuels (such as gasoline and diesel), bitumen, methanol and LPG are imported at the hazardous substances berth. Liquid hydrocarbon fuels are stored and then exported via road tanker or pipeline. LPG is exported continuously from the ship via a pumping station located at Lyttelton which feeds the export pipeline to the LPG storage at Woolston. There is no LPG storage in the Port area.

To meet agreed supporting commitments in the Lyttelton Port Recovery Plan (LPRP), a cumulative quantitative risk assessment report for the area covering the existing potentially hazardous developments and land uses, as well as a future growth case for the bulk liquids facilities and surrounding land uses is required.

A Steering Group was formed to ensure that the relevant commitments of the parties as set out in the LPRP are met. The Steering Group comprises the following stakeholders:

- Burton Consulting, representing Bulk Liquids Storage Facility lessees Z Energy Ltd, Mobil Oil NZ Ltd and BP Oil NZ Ltd.
- Lyttelton Port Company (LPC)
- Christchurch City Council (CCC)
- Environment Canterbury (ECAN).

Sherpa Consulting Pty Ltd (Sherpa) was retained as an independent consultant to prepare the quantitative risk assessment of the bulk liquids storage and handling facilities, including pipelines, within the Port area.

1.2. Context

The LPRP calls for a quantitative risk assessment for the area. A risk assessment includes calculation of risk levels (risk analysis phase), followed by comparison with risk acceptance criteria to draw conclusions regarding the acceptability of the risk levels (risk evaluation phase) and the need for risk reduction.

There are no defined land use safety planning risk criteria for planning in the vicinity of hazardous facilities in use in New Zealand, and no specific risk criteria have been adopted in Christchurch. Therefore only the quantitative risk analysis phase of the overall risk assessment process is covered in this report. The report presents generally accepted land use safety planning risk criteria for a range of jurisdictions to provide a framework for the analysis and context for the risk results. However, the report does not include an evaluation of risk acceptability against criteria, and does not propose or assess risk reduction or treatment plans.

1.3. Objectives

The main objectives of the quantitative risk analysis (QRA) study were:

- To determine the current offsite cumulative risk levels from all the bulk liquids storage and handling facilities operated by a number of different companies in the Port of Lyttelton area.
- To determine the potential future offsite cumulative risk levels from all the bulk liquids storage and handling facilities for a 10 year future case.
- To provide QRA results that can be used as an input to land use safety planning (by the CCC and LPC) in the Lyttelton Port area for both existing and potential future land uses.

1.4. Scope

Two cases are presented in the cumulative QRA report:

- a QRA baseline reflecting the cumulative risk from the current approved operations for all sites. This is referred to as the Current Case.
- a QRA future growth case reflecting the cumulative risk for a future operations case for all sites (up to around 2026). This is referred to as the Future Case.

Estimates of current populations for the existing land uses, and future population growth reflecting potential land uses in the Port area have also been provided by CCC and LPC for use in the societal risk component of the QRA.

The QRA focused on the effects of potential major accident scenarios which may have fatality impacts outside the facility boundaries. It does not cover consequential losses such as asset damage or fuel supply interruption, or other risks such as long-term or chronic impacts, continuous small emissions or environmental impacts.

1.5. Methodology

In broad terms, risk was estimated quantitatively for each site by:

- identifying hazardous incidents and developing these into representative release scenarios with physical parameters and effects on people that can be modelled.
- estimating the physical consequences, ie extent of fire, explosion or toxic release, and the associated impact on people in terms of the probability of fatality for the defined release scenarios due to heat radiation or engulfment from fire events, explosion overpressure or acute toxic exposure.

- estimating the frequency of each release scenario based on industry data and event tree analysis to calculate the likelihood of each outcome (ignited event or safe dispersal).
- combining the consequence and impact results with the incident frequency information, plant grid information and population data to quantitatively determine the risk for the Current and Future Cases.

After review and confirmation by each facility, the site specific QRA models were combined into one cumulative QRA model to provide the cumulative QRA results for the Lyttelton Port area contained in this report.

Due to the high seismicity in the area, the QRA also included consideration of the potential for earthquakes or cliff collapse to significantly elevate the likelihood or consequence of an incident compared to the statistical failure frequency data or operational failure rates typically used in QRA to quantify the frequency of scenarios resulting in loss of containment.

The QRA model was set up in the commercially available risk software TNO Riskcurves. The results of the risk calculations have been presented in two forms:

- **Individual Fatality Risk:** the likelihood of fatality to notional individuals at locations around the sites, as a result of the defined fire/explosion and toxic release scenarios. The units for individual risk are probability of fatality per year. By convention it is assumed that people are located outdoors, are always present and take no evasive action if an incident occurs. The results are presented as cumulative contours (ie representing the sum of all risk contributors) of equal risk level on a map of the area.
- **Societal Risk:** takes into account the number of people exposed to risk. Whereas individual risk is concerned with the risk of fatality to a (notional) person at a particular location 24 hours per day (person 'most at risk'), societal risk considers the likelihood of actual fatalities among people exposed to the hazard and allows mitigating effects such as probability of presence, whether people are located inside or outside to be accounted for, hence requires population data and probability of presence as an input. Societal risk is presented as an FN curve which relates the cumulative frequency (F) and Number (N) of fatalities.

1.6. Results

Hazardous incident scenarios

The main hazard at these sites is large quantities of flammable and combustible liquids. These materials may be involved in fires, or in the case of an extended duration release such as a gasoline tank overfill, large flammable clouds may develop resulting in flashfire or explosion events. Some materials (e.g. methanol) also have toxic properties in the immediate exposure area.

Individual fatality risk

The individual fatality risk contours are shown in Figure 1.1 (Current Case) and Figure 1.2 (Future Case).

The risk contours are presented as order of magnitude (i.e. each contour decreasing by a factor of 10) levels from 1×10^{-4} to 1×10^{-7} per year which covers the range of accepted land use safety planning risk criteria in other jurisdictions.

There is a relatively small change in the extent of the risk contours between the two cases.

Societal risk

Comparative societal risk results are shown in Figure 1.3 for the Current Case with current surrounding land use populations, and Future Case with estimated future populations covering potential land use changes in the Port area.

An FN curve is generally assessed against three broad bands: acceptable, intolerable and a region in between known as the 'as low as reasonably practicable' or ALARP area where the risk may be acceptable depending on the benefits gained. The Lyttelton QRA results. Indicative societal risk criteria are established in some jurisdictions however these are more variable than individual fatality risk criteria.

To provide context for the societal risk results for Lyttelton, Figure 1.3 shows the upper tolerability boundary for a range of tolerability criteria from different locations, together with the FN curve. Broadly the Current Case results are below the intolerable boundary for all criteria shown. However for the Future Case, the potential increases in population result in societal risk exceeding the intolerable criteria in use in some locations.

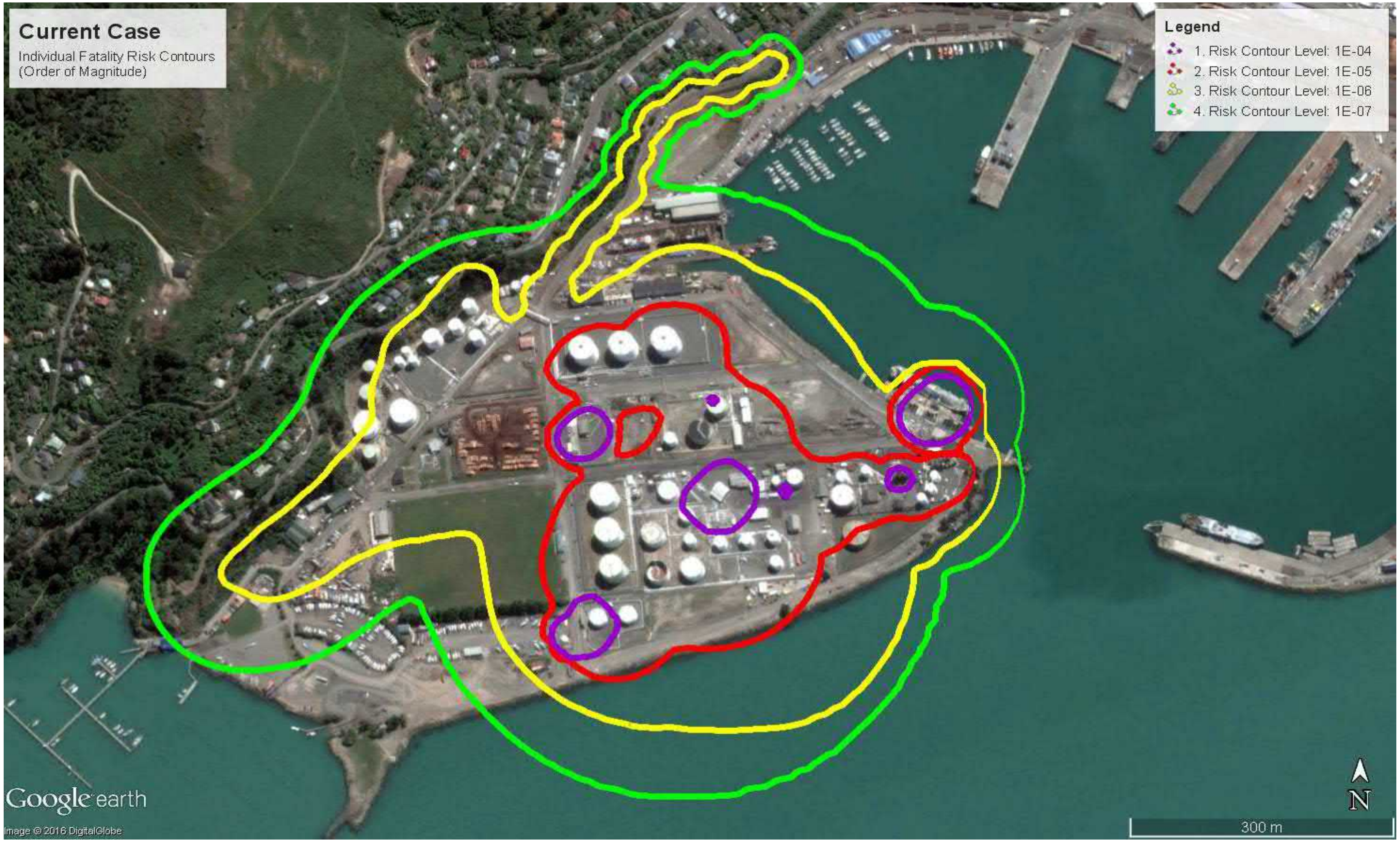
Results

The risk results show that:

- The risk to the existing residential area along Brittan Terrace in either the current or future growth case from incidents involving hazardous substances is approximately 1×10^{-6} per year. Only low hazard products are stored in this area and event frequencies hence risk levels are correspondingly low. Storage of higher hazard products (flammables) would increase the risk level in this area. It should also be noted that the fatality risk level due to hazardous substances incidents is below the existing natural hazards annual individual fatality risk identified in this area due to slope instability (which is around 10^{-4} to 10^{-5} per year based on the publicly available natural hazard risk reports for the area).
- The risk level in the recreational areas in the western Port area is generally below 1×10^{-6} per year however is well above 1×10^{-6} per year at the recreational sporting oval.

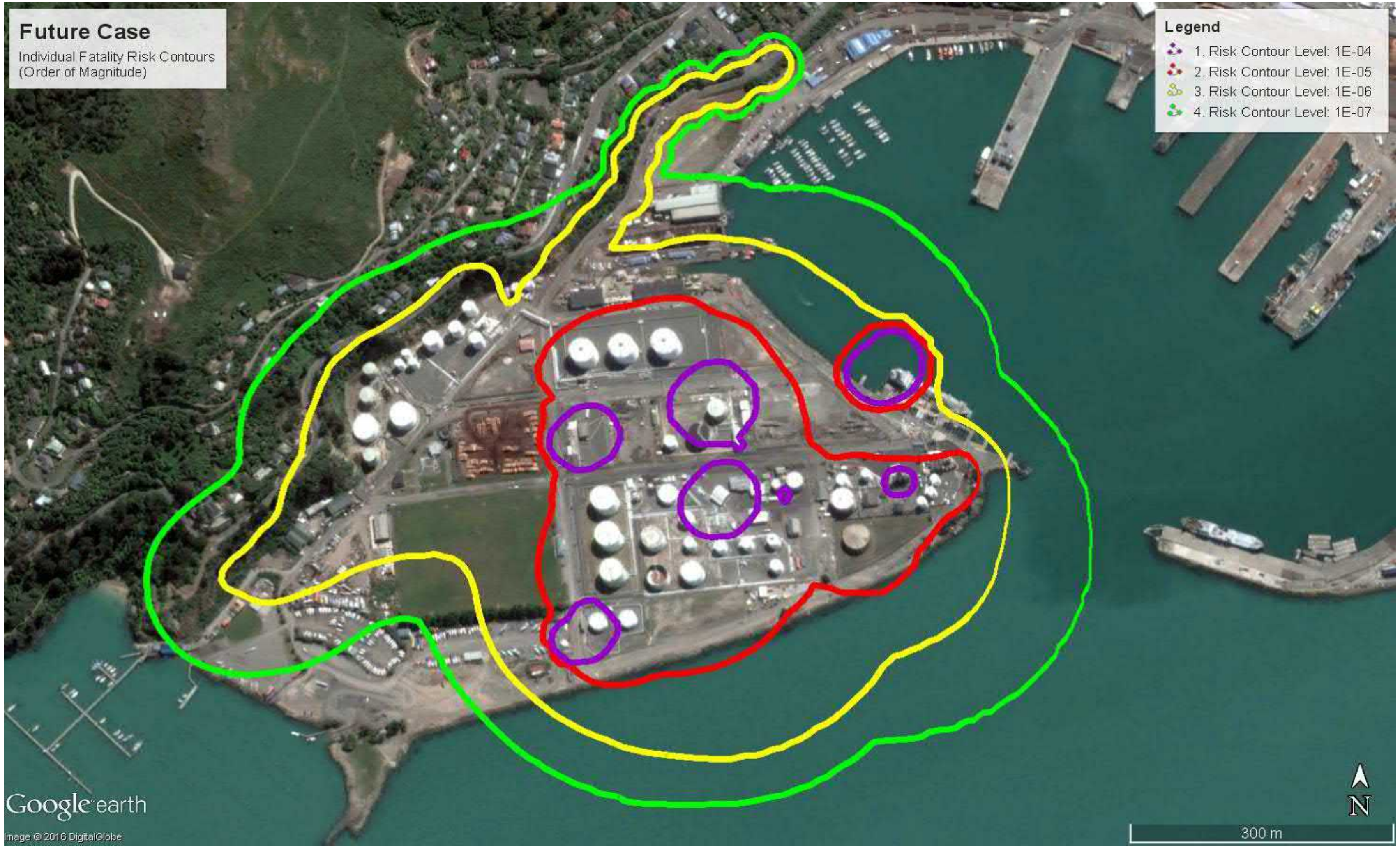
- The public roads running east – west between the different storage facilities (George Seymour Quay, Charlotte Jane Quay) are exposed to fatality risk levels significantly exceeding 1 x 10^{-5} per year. Pipelines are also located in publicly accessible areas alongside these roads which are used for parking during sporting events.
- Godley Quay (running north-south) along the western side of the bulk storage facilities is also exposed to fatality risk levels significantly exceeding 1 x 10^{-5} per year. Godley Quay is the only access route in and out of the Port area.
- The risk level at the proposed cruise ship mooring location is approximately 1 x 10^{-6} per year. Disembarkation would result in large numbers of people on the shore within the immediate vicinity of the risk affected areas at the southern part of the bulk storage facilities. This would result in exposure of high populations to risk levels exceeding 1 x 10^{-5} per year and a corresponding increase in societal risk. It may also introduce elevated probabilities of ignition sources compared to average ignition probabilities assumed in the QRA, further increasing the risk profile (although this effect has not been quantified).
- Sensitivity studies around the societal risk results indicate that increases in population, particularly in near vicinity to the bulk storage facilities such as the cruise ship disembarkation area, result in a significant societal risk increase. Increases in the bulk liquids facilities storage and operational throughputs (as defined in the Future Case), but with no change in surrounding population, have only a very small effect on societal risk. This means that the societal risk results are more sensitive to the potential population increases than they are to increases in source risk from the defined Future Case storage and throughput growth at the bulk liquids facilities.
- Godley Quay is the only entry/exit route to the Port Area. This runs directly north/south within the risk affected areas alongside of the bulk storage facilities. An incident may block this route, potentially compromising both access by emergency services or evacuation of populations in an emergency.
- Whilst outside the scope of land use safety planning, an incident at the bulk storage facilities could also affect other infrastructure in the Port area.

Figure 1.1: Individual fatality risk, Current Case



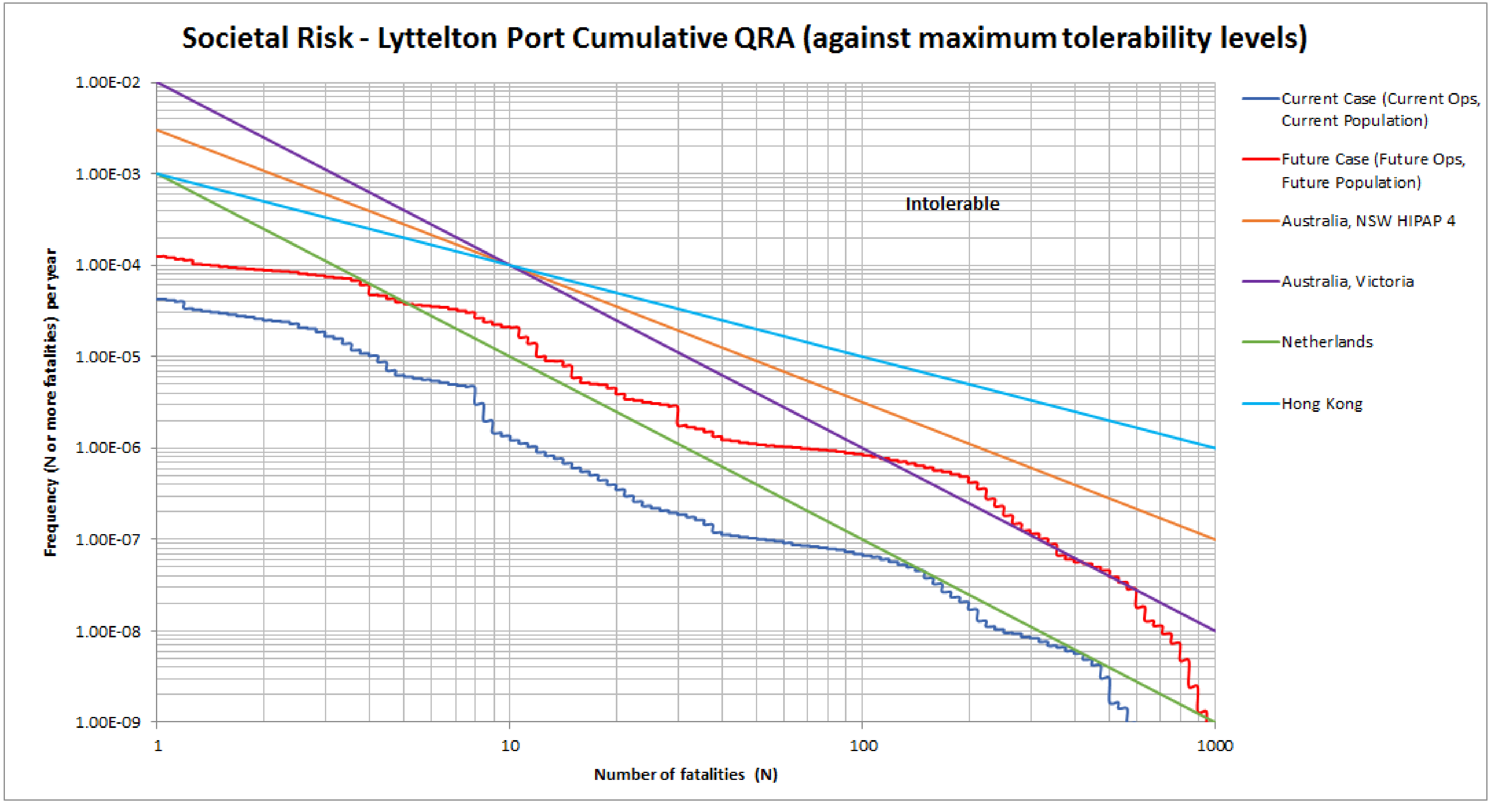
NOTE: 'Individual fatality risk' is defined for land use safety planning as the annual risk of fatality to a notional person at a particular point assuming exposure to the risk 24 hours a day and 365 days per year.

Figure 1.2: Individual fatality risk, Future Case



NOTE: 'Individual fatality risk' is defined for land use safety planning as the annual risk of fatality to a notional person at a particular point assuming exposure to the risk 24 hours a day and 365 days per year.

Figure 1.3: Societal risk results



2. INTRODUCTION

2.1. Background

Sherpa Consulting Pty Ltd (Sherpa) was retained by Burton Planning Consultants Ltd to provide independent risk consultancy services for a land use safety planning study for the bulk liquids storage and handling facilities which are operated by a number of different companies in the Port of Lyttelton area, New Zealand.

Operators of the facilities include BP Oil NZ Ltd, Fulton Hogan Ltd, Hexion (N.Z.) Ltd, Liquigas Ltd, Mobil Oil NZ Ltd, Z Energy Ltd, and Downer Group Ltd, collectively termed 'the Companies'. The term 'the Oil Companies' refers collectively to BP Oil NZ Ltd, Mobil Oil NZ Ltd and Z Energy Ltd.

The services require provision of a cumulative quantitative risk assessment for the area covering the existing potentially hazardous developments as well as a future growth case for the facilities and surrounding land uses.

2.2. Requirement for QRA

The QRA is required to address the following supporting commitments in the Lyttelton Port Recovery Plan (LPRP) which was gazetted on 19th November 2015:

> *5.7 Cruise Ship Berth*
>
> *The Christchurch City Council and Lyttelton Port Company Limited have committed to looking at options for short-term and long-term solutions to providing for a dedicated cruise ship berth facility at Lyttelton Port and funding for these options. They will consider the preferred location of the cruise ship berth facility, taking into account the landside and waterside requirements of the cruise ship industry and the needs of other users, and transport and servicing needs. This consideration will include assessment of risk in relation to hazardous facilities in the vicinity and the ability to meet future demands, including the results of a quantitative risk assessment of the bulk liquids storage facilities (discussed below).*
> *Christchurch City Council and Lyttelton Port Company Limited will agree on a collaborative approach to progress a fit-for-purpose cruise ship berth facility in Lyttelton to achieve a timely return as a cruise destination. The process may involve other interested parties.*
>
> *5.8 Bulk Liquids Storage Facilities*
>
> *Christchurch City Council with support from Lyttelton Port Company Limited and the lessees of the bulk liquids storage facilities has committed to developing a quantitative risk assessment of the bulk liquids storage facilities at Naval Point within nine months of Gazettal of the Recovery Plan.*

2.3. Steering Group

A QRA Steering Group was formed to ensure that the QRA meets relevant commitments in the LPRP. The QRA Steering group comprises the following stakeholders:

- Burton Consultants, representing Bulk Liquids Storage Facility lessees Z Energy Ltd, Mobil Oil NZ Ltd and BP Oil NZ Ltd
- Lyttelton Port Company (LPC)
- Christchurch City Council (CCC)
- Environment Canterbury (ECAN).

The Steering Group's role was to:

- Confirm the scope of the QRA
- Agree the cumulative baseline scenario for QRA
- Agree the cumulative future scenario the QRA should consider
- Arrange for peer review of the QRA.

There are no agreed land use safety planning risk criteria in use in New Zealand. The Steering Group's role also included agreeing on risk criteria to be used in evaluation of the risk results, however risk criteria have not yet been adopted for the Lyttelton Port area.

Therefore the QRA report outlines the risk, indicates the risk levels that might be generally acceptable elsewhere, but does not assess risk acceptability in the context of the LPRP.

2.4. Objectives of QRA

The main objectives of this study are to:

- Determine the current offsite cumulative risk levels from the bulk liquids storage and handling facilities operated by a number of different companies in the Port of Lyttelton area.
- Determine the potential future offsite cumulative risk levels from the bulk liquids storage and handling facilities for a 10 year future growth case
- Provide QRA results that can be used as an input to land use safety planning (by the CCC and LPC) in the Lyttelton Port area for both existing and potential future land uses.

2.5. Scope of report

This report provides:

- A summary of the QRA methodology.

- Cumulative individual fatality risk results for the current and future bulk liquids storage and handling facility operations.
- Societal risk results for the current and future bulk liquids storage and handling facility operations for current and future estimated population in the Lyttelton Port area.

This report does not provide facility specific risk profiles and does not address risk acceptability compared to relevant risk criteria, or the need for risk reduction options.

2.6. Limitations

As the final purpose of the QRA is to assess the suitability of various proposed land use changes, the focus is on potential accident events with the potential to cause offsite effects (i.e. to land uses outside operating site property boundaries). The study does not assess the following:

- Onsite risk to personnel/employees or occupational, health and safety issues that may arise from routine plant operations.
- Potential chronic (i.e. non-acute) or health impacts from long-term or continuous emissions, nuisance issues (e.g. odour) either on or offsite.
- Transport risk (i.e. offsite pipelines, road tanker movements, or ship movements) outside the immediate Port area.
- Environmental risks.
- Consequential loss, for example fuel supply interruption, security breaches or damage at the berth following an incident.
- For natural hazards, an average risk increase due to location specific natural hazards factors (based on existing earthquake and landslip frequency of occurrence information) that may elevate the frequency or scale of damage across the Lyttelton Port bulk storages area compared to a typical process and equipment based QRA has been included in the QRA as a sensitivity case. Specific risks to particular tanks or other infrastructure have not been analysed, i.e. detailed structural response reviews to natural hazards events have not been carried out.

2.7. QRA exclusions

The QRA scope specifically excludes:

- Demonstration that risks have been reduced to a level as low as reasonably practicable (ALARP or SFARP).
- Comparison of risk results against risk criteria as the QRA Steering Group has not yet confirmed the risk criteria to be used for evaluation of risk acceptability.

- Risk reduction recommendations are not made as part of this report. Depending on the agreed results of the QRA, these may be addressed by a separate study.
- Marine risk assessment of vessel movements to/from the port (i.e. activities on the water, shipping collisions, incidents involving the cargo on board the ship) is generally undertaken by marine specialists and port personnel and this is not included in the QRA which focuses only on risks associated with the land based activities.
- Shipboard incidents involving the hazardous cargo inventory on the ship regardless of whether it is moored or on the water are not covered in the QRA. Note that the transfer of hazardous cargo between a berthed ship and the onshore pipelines and loss of containment incidents involving marine loading arms (MLA) or hoses on the wharf are included in the QRA.
- Consideration of risks of any types of hazardous substances that are not hydrocarbon type fuels or alcohols. For example, the berth could theoretically in the future handle ammonium nitrate based fertilisers (explosion risks), grains (combustible dust risk), or cold storage with ammonia refrigerant packages as many other Port areas do. There are no specific plans for these activities hence they are not included as part of the future growth case. They have very different hazards to the existing hydrocarbon materials handled, a development consent would be required and the risk would require assessment at that time. They are not covered in the QRA.
- Construction of a new hazardous substances wharf is proposed to replace the existing berth that was damaged in the 2010/2011 earthquakes. This will require a temporary wharf and additional workforce for a period of more than a year. This is not included in the QRA as it is more logically assessed with the new wharf project.

2.8. Revision status of report

This is the final (Rev 0) revision of the QRA report for peer review and public release. It will form the basis of communications with the public.

2.9. Report structure

The QRA methodology report is organised into the following sections:

- Section 1: Summary which provides a simple explanation the QRA process and summary of results. This may form the basis of future public consultation.
- Section 2: Introduction which provides a background to the project, objectives, limitations, exclusions and scope of report.

- Section 3: Scope of QRA. This includes definition of the physical area and the baseline (current) and future growth cases from an operations and population perspective that are covered in the QRA.
- Section 4: QRA Methodology overview. This section includes a description of the overall QRA methodology and key assumptions.
- Section 5: Risk Analysis. This section provides details of the software used and discussion of typical land use planning risk criteria used in other locations.
- Sections 6 and 7: Risk Results. This section provides the risk results as individual fatality risk contours and societal risk FN curves.
- Section 8: Conclusions. This section provides a discussion of the estimated risk levels in the various land uses for current and future land uses.
- Technical Appendices which contain examples and supporting data.

3. SCOPE OF QRA

3.1. QRA basis

A number of simplifying assumptions need to be made to prepare a QRA and the results are dependent on the assumptions made in defining the input scenarios. This is particularly true of bulk terminal sites due to the potential variety of products and throughputs.

The main parameters that have a potentially significant effect on risk results are:

- Throughputs (i.e. number of imports/tank filling operations, number of road tanker exports).
- Product classes handled (in this case hydrocarbon liquid fuels, methanol, bitumen and LPG only).
- Storage tank and bund sizes, and location in relation to site boundaries.
- Safeguarding (primarily level instrumentation in tanks and degree of operator attendance during tank import).
- Population density in vicinity of the sites (societal risk only).

For this study two main cases are presented in the cumulative QRA report:

- A QRA baseline reflecting current approved operations and existing populations/land uses. This referred is to as the Current Case.
- A QRA Future Case reflecting future operations and changes in populations/land uses over the next 10 years (up to around 2026). This is referred to as the Future Case.

3.2. Physical area

The physical land based area being considered in the QRA is limited to the Lyttelton Port area as shown in Figure 3.1. To the north and west, the geographical features of area (i.e. the cliff bordering the Port area) make this a logical delineation and the LPRP also is applicable to this area only. Areas outside the port area are covered by other planning instruments.

The QRA includes consideration of potential effects due to or on:

- the potential cruise ship terminal
- future Dampier Bay marina development
- the proposed relocated hazardous substances wharf
- potential for impacts on water based users e.g. recreational boating
- the existing residential area along Brittan Terrace at the top of the cliff at Naval Point in the western port area
- the existing recreational areas in the western part of the port area.

3.3. Facilities

Broadly, all operators import hazardous materials including fuels (such as gasoline and diesel), bitumen, and methanol at the hazardous substances berth, store the materials and export them via road tanker or pipeline. LPG is imported and pumped directly to storage at Woolston several kilometres away via the Lyttelton LPG pumping station. There is no LPG storage in the Port area. There are no reactive processes, and, with the exception of the bitumen plants where blending activities occur, there is no processing of materials.

The operating sites (i.e. sources of risk) covered by the QRA are summarised in Table 3.1. The QRA covers only sites or activities where hazardous materials (i.e. classified under the NZ HSNO regulations) are stored or handled in bulk storages or pipelines. For non-hazardous materials, the likelihood and severity of any incident is much lower, so is not assessed.

Note that there may be small quantities of hazardous substances (e.g. diesel, welding gases, flammable liquids such as paints, glues, solvents) at other facilities in the Port area such as boat builders. These are not regarded as significant sources of risk (i.e. small quantities, well separated from bulk liquids storage sites) and are not included in the QRA.

Table 3.1: Facilities included in QRA

Site (Lessee)	Operator	Comments
BP Z Energy	NZOSL (operate both the BP and Z Energy site)	- Receive fuels from the wharf - Above ground storage in atmospheric bulk tanks - Distribution via Mobil's Lyttelton – Woolston fuel pipeline and road tanker gantries at both Z Energy and BP sites.
Mobil	Mobil	- Receive fuels from the wharf - Above ground storage in atmospheric bulk tanks - Distribution via Mobil's Lyttelton – Woolston fuel pipeline and road tanker.
Hexion	Hexion	- Receive methanol from the wharf - Above ground storage in atmospheric bulk tanks - Distribution of methanol by road tanker.
Liquigas	Liquigas	- Receive LPG from the wharf - Distribution via Lyttelton – Woolston LPG pipeline and pumping station in Lyttelton. NOTE: This site is a pumping station only, there is no storage of LPG on the site.
Fulton Hogan	Fulton Hogan	- Receive bitumen from the wharf - Bitumen and emulsion blending facility - Distribution and supply bitumen via road tanker.

Site (Lessee)	Operator	Comments
BP	Downer Group (operate site which is sub leased from BP to Emulco)	- Receive bitumen from the wharf - Bitumen and emulsion blending facility - Distribution and supply bitumen via road tanker.
Hazardous materials Berth (LPC's infrastructure)	NZOSL (fuels and bitumen) Liquigas (LPG, mercaptan) SGS (Logistics contractors for Hexion's methanol)	- Receive products from ship at berth - Mercaptan storage and handling - Export of products from site to wharf (very low frequency) - Ship refuelling (bunkering)
Pipelines	Various. (A variety of under ground and above ground pipelines).	- Transfer products from wharf to sites (some are left full of product) and between sites. - There are two pipe bridges crossing overhead of public roads. One crosses Godley Quay. There are a number of disused pipes on this pipebridge, however limited transfers of diesel or slops currently occur. Utilisation may increase in the Future Case. The other pipebridge crosses George Seymour Quay and this is in frequent use. Refer to Figure 3.2 and Figure 3.3 for Current and Future pipeline routes

3.4. QRA baseline

3.4.1. Operations

The current baseline operations for each site were developed via a QRA basis agreement with each operator based on all approved operations and equipment as follows:

- Licensed (HSNO) storage quantities and materials including any resource consents (even if consented equipment/inventory is not physically installed). It is noted that this situation applies to two tanks only (which are consented but have not yet been installed) at one of the facilities.
- If there is a specific reason for assuming a reduced basis such as decommissioned or unavailable equipment (for example storage that was damaged in the 2010 landslips and operator has advised will not be restored/re-commissioned) the basis may be less than the licence quantity.
- Typical annual throughputs for pipeline transfers as agreed with each operator.

- Typical annual throughputs for road tanker unloading/loading as agreed with each operator.
- Typical materials stored. This includes the highest throughput material or a sufficient range of materials to cover all types handled at the site, and also any high hazard materials (even if handled occasionally only) as agreed with operator.

This report does not provide facility specific information as this is commercial in confidence. However the cumulated data for all facilities for key parameters that affect the QRA is summarised in Table 3.2 to Table 3.5 inclusive for both the Current Case and Future Case.

3.4.2. Populations and land uses

The existing land uses around the bulk storage facilities in the Port area are industrial (largely industries associated with port activities) with low average populations, or recreational (fishing, boating and sporting facilities) in the western Port area with higher temporary populations. There are no existing commercial land uses (high density offices, shops, restaurants) in the general Port area.

Residential land uses are present along Brittan Terrace at the top of the cliff running along the western boundary of the Naval Point area in the Port. There are no sensitive[1] land uses (hospitals, child care facilities) in the vicinity.

Population data is required for societal risk assessment. LPC and CCC provided typical day and night population data for each lot of their land holdings for all sites within the Port area as defined in Figure 3.1 other than the risk source sites.

Populations within the Port area only are included in the societal risk assessment. There are no populations included in the societal risk calculations for areas outside the Port area as defined in the physical scope limits shown in Figure 3.1. Residential populations along Brittan Terrace are not included as this area is outside the scope. It is also at a higher elevation (top of a cliff more than 30 m high) than the bulk liquids operations, which would provide some exposure mitigation from hazardous events.

The population data used in the societal risk calculations for both the Current and Future Cases is provided in APPENDIX A.

3.5. QRA Future Case

3.5.1. Operations

The cumulated data for the Future Case for key parameters that affect the QRA is summarised in Table 3.2 (ship imports) and Table 3.3 (exports by road tanker and pipeline).

[1] 'sensitive' means vulnerable (e.g. the elderly, small children) or difficult to evacuate populations in land use safety planning.

The timeframe being considered is development over the next 10 years, i.e. up to around 2026. Future changes of the following type were agreed with the operators and LPC as the land holder for defining the Future Case:

- Increases in throughput (this means increased utilisation of wharf and pipelines or more road tanker export but this is not equipment change).
- Construction of a new hazardous substances wharf and associated pipework to replace existing wharf (location shown in Figure 3.3).
- Additional development (e.g. new products or new tanks, larger tanks etc) on existing sites leased by the Companies (this covers potential additional tank development that does not have a resource consent at the time of the QRA).
- Additional development on LPC sites not currently leased by the Companies i.e. potential development of new areas within the Port area (which are either vacant or used for something other than hazardous substances facilities), with new hazardous substance facilities such as tanks, pumps, loading bays etc.

Throughput increase

In conjunction with facility operators and LPC, it has been established that there are no specific plans in place to significantly increase the hydrocarbon fuel throughputs at the Port. No changes are anticipated in methanol throughputs. Bitumen throughputs are anticipated to increase.

Therefore to account for some growth in fuel throughputs as may occur due to economic growth, a representative throughput increase was estimated based on projected demand for hydrocarbon fuels in New Zealand. The assessment was based on data tables produced by the Ministry of Business, Innovation & Employment which records fuel demand in New Zealand each year (Ref 1).

No specific data for the Christchurch area was available, so the NZ wide data was assumed to apply. Based on the analysis of data since 2006, an average of a 2% growth rate per year for all liquid hydrocarbons fuels was assumed. This corresponds to a 22% increase in the throughput of fuel over a 10 year period, which was rounded up to a total 25% increase in fuel inputs over 10 years. LPG increases were estimated as higher corresponding to around 50% increase over 10 years.

This approach is consistent with LPC's overall Business Plan.

Highest hazard fuel product

The highest hazard liquid hydrocarbon fuel product handled and stored in significant quantities at Lyttelton is gasoline as this is the easiest to ignite and also has the potential to form large flammable vapour clouds in some circumstances, hence gasoline has the largest impact on risk results.

LPG is also high hazard however there is no storage except the inventory in the underground pipeline from the Lyttelton pumping station to Woolston.

The Current Case throughput data indicates that approximately 30% of the total liquid hydrocarbon fuel throughput at Lyttelton Port is gasoline. Out of the operators handling gasoline (not all do), the proportion is around 40% of total fuels. For the purposes of the QRA future growth case, it is assumed that 40% of the total fuels throughput for the Future Case will be gasoline. This is likely to be conservative as the data indicates that demand for gasoline is quite flat compared to other fuels such as diesel.

Exports

The majority of hydrocarbon fuel that is imported by ship at Lyttelton is exported from the individual terminals via road tanker or via the Mobil Lyttelton to Woolston pipeline. A very small proportion is either used to bunker (i.e. refuel) ships or is re-exported by ship.

There are a number of constraints that currently exist in exporting products:

- Road tankers carrying flammable products (gasoline and jet fuel) are only able to travel out of the Port area via the Lyttelton tunnel (infrastructure that is vulnerable if a vehicle accident and escalation flammable load occurs) with a vehicle escort at night time.
- The pipeline is virtually fully utilised and has minimal additional capacity.

Therefore two export cases have been defined which represent the possible extremes of operation representing the risk envelope for the Future Case. A case in between these two is most likely.

- Future Case 1. All additional liquid fuel throughput is exported via road tanker and pipeline operations remain at current capacity. This is the higher risk option as there are significantly more road tanker filling operations at each site and more road tankers on the roads within the Port area.
- Future Case 2. The pipeline is uprated or replaced to cater for all existing pipeline throughput plus the additional future growth throughput. All gasoline throughput is exported via pipeline and any residual in the uprated pipeline capacity will be for other products. The remainder would be exported via road tanker. This is the lowest risk option as there are no gasoline road tanker filling operations at each site and no gasoline road tankers on the roads within the Port area.

Note that there are no specific plans to uprate the pipeline but it is theoretically possible subject to engineering feasibility reviews, for example by increasing pipeline pressures and pumping capacity, a duplicate pipeline on the same route or a new pipeline through the hill.

3.5.2. Tankage

It is generally agreed that the Port area is under-tanked, due to degradation of assets over time and also damage to tanks sustained in the March 2014 landslide. The following approach was taken:

- Identify sites that may be developed for additional tankage that are not currently used for hazardous material storage. Potentially suitable sites have been agreed with LPC as the land holder.
- Include some minor additional tankage or changes of product use on existing operator sites as per operator advice regarding their specific plans for larger tanks or product reallocation in existing tanks.

The cumulative future QRA case takes this as an outer envelope of possible development. The additional sites are not assumed to be developed by any particular operator, they are theoretically available to a proponent for development (appropriate consents would need to be obtained) for future fuel storage if this arises.

Table 3.4 summarises potential changes in tankage included in the future growth case for the cumulative QRA. Table 3.5 summarises the locations of potential new tanks on currently undeveloped sites. This is also shown in Figure 3.4

The tank sizes have been based on the largest tanks that would physically fit. Note that there have been no engineering feasibility studies or checks of separation distances required under NZ HSNO regulations. This is a nominal case only.

3.5.3. Populations and land uses

Population change is associated with proposed changes in land use on LPC or CCC land (i.e. land uses not associated with the risk sources). The population changes for the Future Case relate to non-industrial development. These were provided by the LPC and CCC and include:

- Proposed cruise ship terminal
- Upgrades to general recreational area facilities including boat club and new clubhouse
- Dampier Bay marina development.

There are no proposed population changes included in the Future Case for the existing non-hazardous industrial land uses.

The population data used in the societal risk calculations for both the Current and Future Cases showing the populations that have been increased is provided in APPENDIX A.

There are no proposed changes in type of land use within the Port area, i.e. land use remains recreational or industrial.

LPC advised that the cruise ships are not anticipated to stay overnight except in exceptional circumstances such as very poor weather or breakdown hence can be regarded as a recreational type population. If this were to change to routine overnight stays, the population could be regarded as residential from a land use safety planning perspective (or possibly sensitive due to difficulties with dealing with an emergency or evacuation).

Other proposed changes relate to intensification of the recreational sporting and boating facilities in the south western Port area or the Dampier Bay marina development to east of the QRA study area.

The only other change is related to location rather than land use. A new hazardous substances wharf at a new location will be provided to replace the existing berth and all hazardous cargo transfer operations relocated accordingly.

3.6. Compilation of cumulative QRA

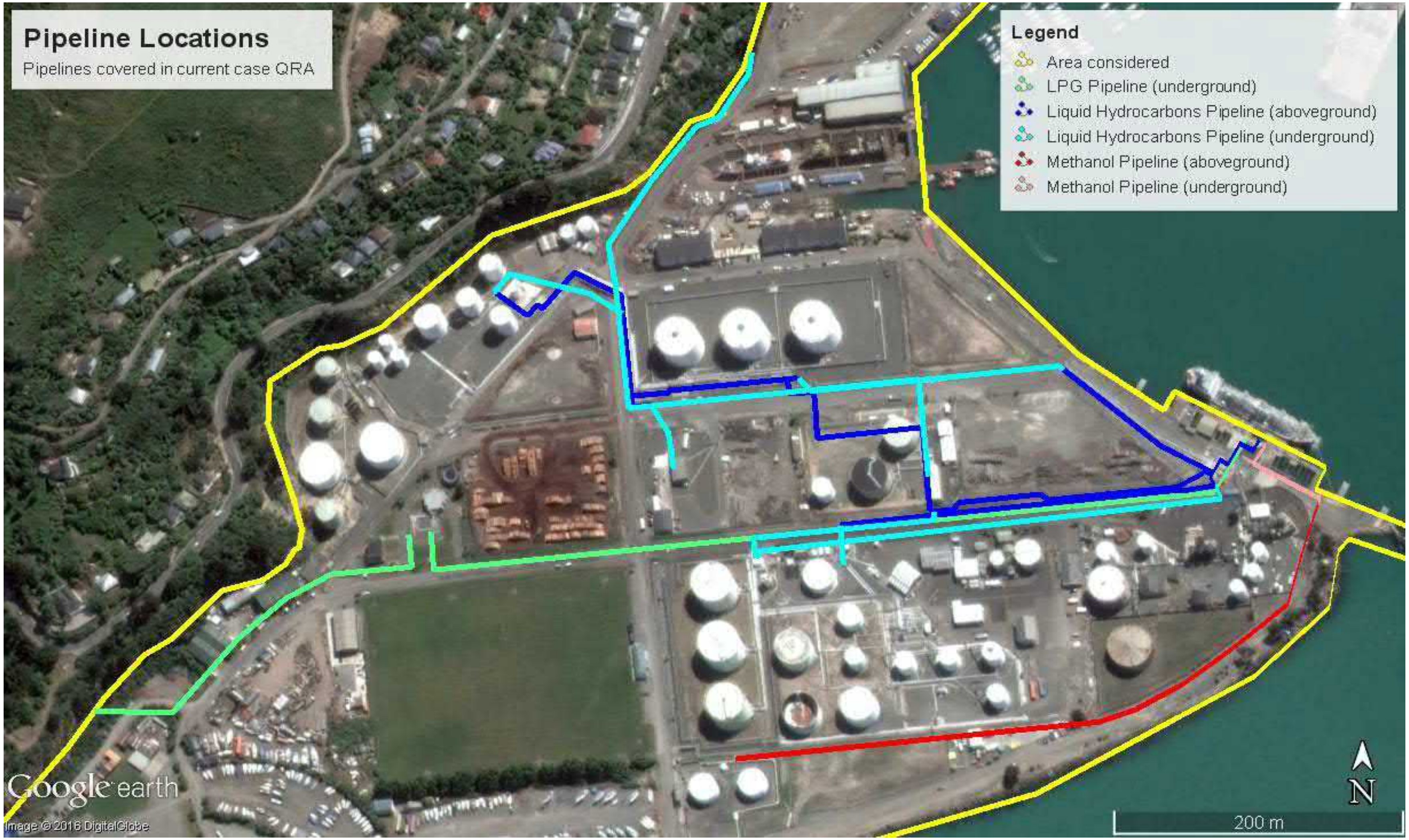
A standalone site specific QRA basis for the Current and Future Cases and associated QRA results report covering the hazard identification, scenarios modelled, consequence, frequency and risk results was prepared by Sherpa and reviewed and approved by each facility operator and/or lessee.

These were then combined into one cumulative QRA model to provide the cumulative QRA results contained in this report.

Figure 3.1: Lyttelton Port area covered by QRA

Note: All Google Earth background maps contained in this report are taken from satellite imagery taken on 04/11/2015 (most recent clear image available).

Figure 3.2: Pipeline routes covered by QRA (Current Case)



Note: pipelines routes are approximate only. Some routes have multiple individual pipes.

Table 3.2: Total future growth of imports (10 years to 2026)

Product	2016 throughput (Current Case in QRA) m^3/year	Estimated 2026 throughput (Future Growth Case in QRA) m^3/year	Comments
Bitumen	12,000	20,000	As advised by operators
Hydrocarbon liquid fuels	1,200,000	1,500,000	Based on 25% increase projected from historical fuel growth rates in NZ. Agreed by operators and LPC as reasonable basis
LPG	100,000	150,000	Based on 50% increase projected from historical LPG growth rates in NZ. Agreed by operator as reasonable basis
Methanol	18,000	18,000	As advised by operator - no change in business using methanol expected or planned.
Total	**1,300,000**	**1,700,000**	LPC advise that this is consistent with their Business Plan
Note: these figures have been rounded off, so are approximate.			

Table 3.3: Cumulative QRA basis - Exports (excludes bitumen)

Mode	Units	Current	Future growth case 1 – road tanker increase	Future growth case 2 – pipeline capacity increase	Comments
Road tanker exports:					
Total road tanker throughput	m^3/yr	330,000	660,000	330,000	These figures exclude bitumen and methanol
Total number of road tankers	Total tankers per year	9,500	19,000	9,500	Future growth tanker numbers based on average tanker volume of 35 m^3. Current case on actual tanker numbers (i.e. variable capacities)
Number of road tankers that are gasoline	Total gasoline tankers per year	1,300	7,000	0	For Case 1 the gasoline tankers numbers assume no change in product mix that is transferred by pipeline. Given the tunnel constraints it is likely more gasoline would need to be diverted to the pipeline.
Mobil Lyttelton to Woolston Pipeline exports:					
Total pipeline throughput	m^3/yr	810,000	810,000	1,100,000	No specific pipeline uprate is proposed – nominal case only
Gasoline pipeline throughput	m^3/yr	300,000	300,000	580,000	Future growth assumes all gasoline export is through pipeline

Table 3.4: Potential changes in total tank capacity (liquid hydrocarbon fuels)

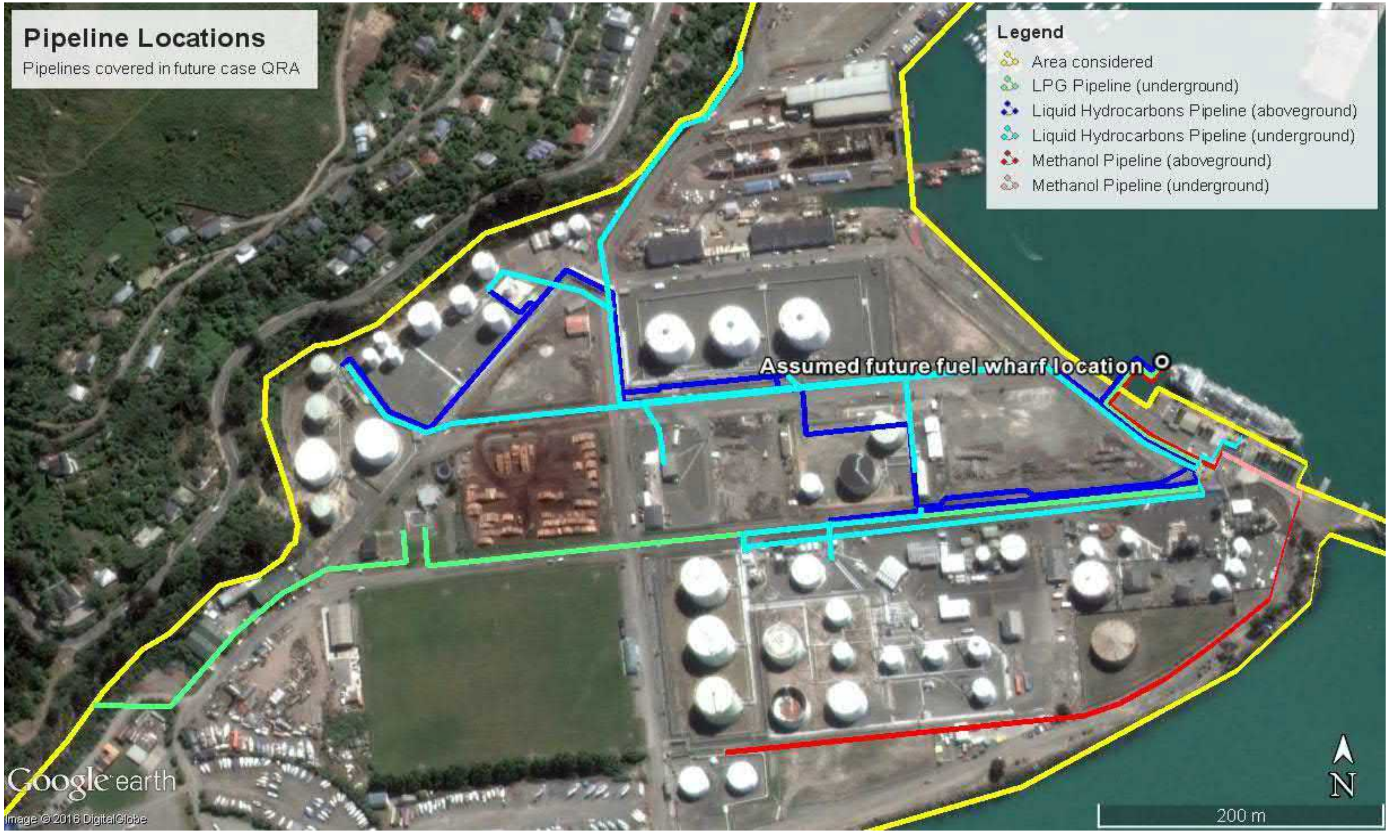
Parameter	Current	Future	Comments
Total number of tanks	18	29	Excludes small slops and additives tanks, non-hazardous tanks such as firewater The total number of tanks includes recommissioning Mobil facilities (5 currently out of commission tanks) at Naval Point. This is conservative as this capacity is more likely to be covered by additional capacity in other (new) location rather than recommissioning the Naval Point tanks
Total tank capacity (m^3)	100,000	150,000	This is a higher increase in capacity than 25% throughput increase as largest tank sizes that will fit on site are assumed. This also provides additional flexibility for activities such as tank inspection
Total number of gasoline tanks	6	10	This is a higher increase in capacity than 25% throughput increase as at least one tank in all the identified new areas is assumed to be in gasoline service as this is the highest hazard product
Total gasoline tank capacity (m^3)	26,000	65,000	

NOTE:
1. This table excludes the bitumen and methanol facilities as there are no changes proposed to these.
2. There is no storage of LPG.

Table 3.5: Additional tank locations

LPC lot no.	Current leasee	Current land use	Future land use assumed (next 10 years) – no specific operator	Potential products	Potential configuration of additional tankage
19	Vacant	Vacant	Potential development (Oil companies)	Diesel/gasoline	3 future fuel tanks (1 of these to be gasoline as worst case)
26b	Hexion (N.Z.) Ltd	Vacant	Potential development – subdivision of existing site. (Oil companies)	Diesel/gasoline	2 future tanks (assume 1 gasoline as worst case)
54	Z Energy Ltd	Not in commission	Potential development (Oil companies)	Diesel/gasoline	1 tank (assume 1 gasoline as worst case)

Figure 3.3: Pipeline routes covered by QRA (Future Case)



Note: pipelines routes are approximate only. Some routes have multiple individual pipes.

Figure 3.4: Future additional tankage (currently undeveloped sites)

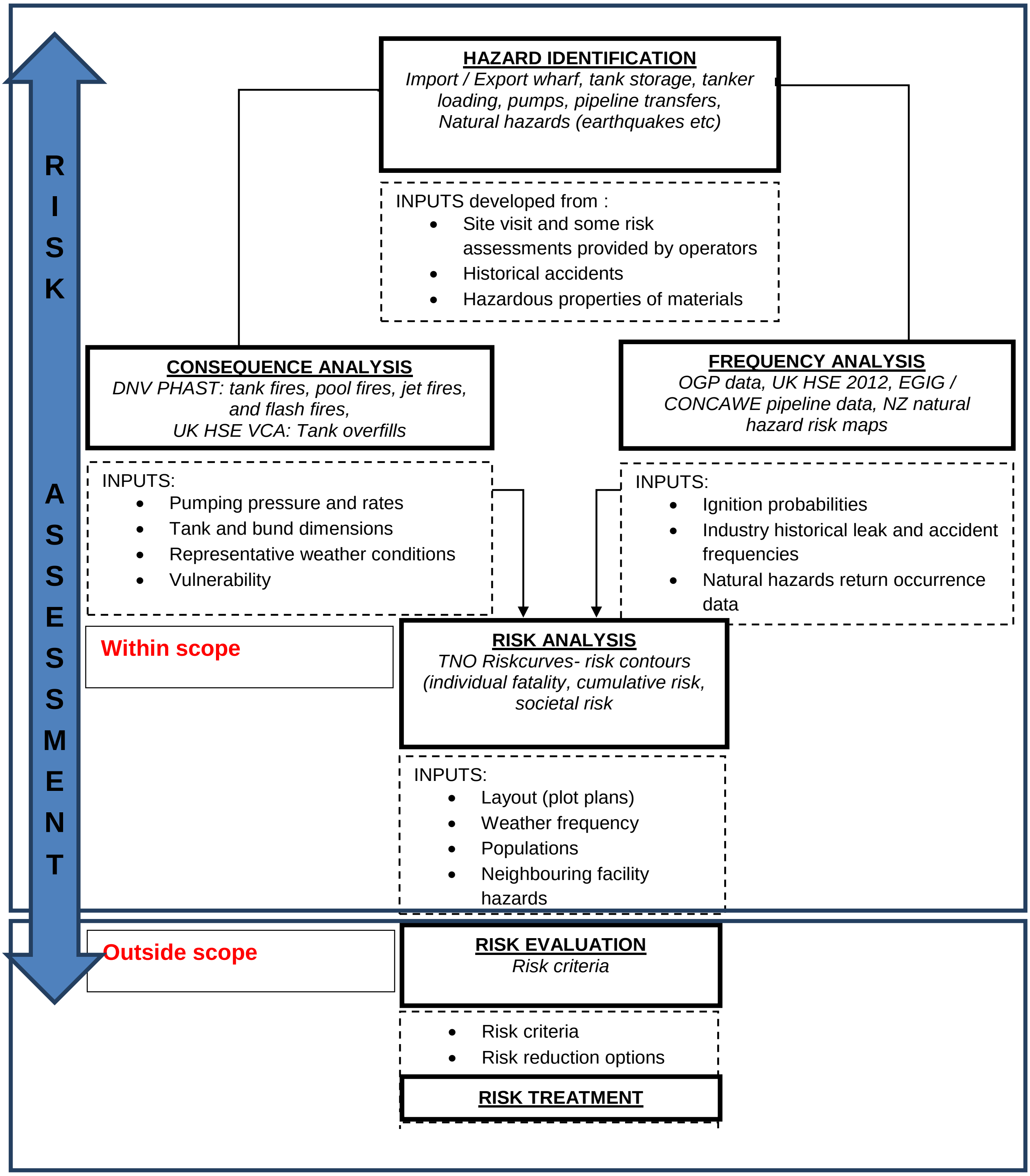
4. QRA METHODOLOGY OVERVIEW

4.1. Overview

An overview of the QRA process, including the steps and inputs for this study is shown in Figure 4.1. This is consistent with the risk management framework given in *AS/NZS ISO 31000:2009 Risk management - Principles and guidelines.*

The diagram also identifies the steps of the typical risk management approach that are addressed in this report and those that aren't. The subsequent sections provide further information of each step.

Figure 4.1: Overview of Risk Management Process



4.2. Hazard identification

Hazard identification is the process of establishing the scenarios that could result in an adverse impact offsite, together with their causes, consequences and existing safeguards.

Hazard identification for the sites was undertaken as a desktop activity based on the typical known hazards for bulk hydrocarbon liquids storage and distribution terminals, review of previous risk studies and with input from the site operators.

4.2.1. Hazardous materials

The properties of materials handled at the facilities are summarised in APPENDIX B.

The main hazard at these sites is the storage and handling of large quantities of flammable and combustible liquids as well as LPG. Flammable materials may be involved in fire or explosion events. Some of the materials (methanol, mercaptan) also have some acute toxicity properties.

4.2.2. Scenarios

The hazard identification is then developed into representative scenarios with physical parameters and effects that can be modelled to determine whether offsite effects (i.e. outside the site boundaries) are possible.

Scenarios applicable for specific equipment types or operations are summarised in the hazardous incident identification table in Table 4.1. As these are atmospheric fuel storage terminals there are relatively few types of process equipment.

A summary of the scenarios modelled in the QRA is given in Table 4.2.

- Flammable consequences due to a loss of containment of flammable and combustible materials are considered in the QRA.
- Toxic consequences (i.e. dispersion of unignited vapours) are also considered for methanol and mercaptan.

The main input parameters required for scenarios modelled explicitly in the QRA are also listed in Table 4.2.

4.2.3. Safeguards and control measures

Table 4.1 also summarises the typical safeguards that are in place for the facilities although these do vary between the sites. Some of the safeguards are accounted for quantitatively if they are present at a site as described in APPENDIX E.

In summary:

- Hardware safeguards (for examples automated trip such as on high tank level) are accounted for quantitatively as they generally reduce event frequencies.
- Automatic shutdowns based on fire or gas detection or lone worker systems are accounted for quantitatively as they generally reduce event severity by limiting the duration and quantity of a loss of containment.

- Operator initiated shutdown may be accounted for is some events provided there is sufficient response time and the operator is likely to be unaffected by the event or there are multiple personnel on attendance (such as ship unloading).
- Procedures and management systems (e.g. training, maintenance practices) are generally not accounted for quantitatively. Data used to estimate event frequencies in a QRA is largely based on generic historical information from a variety of plants and processes with different standards, designs and management systems, hence this will always lag the implementation of better engineering or procedural controls in particular industries. Therefore the use of statistical data is conservative in that it will overstate the risk from modern, well managed installations but may understate the risk from older or poorly managed facilities.
- Fire protection systems may be accounted for in some events to prevent escalation, for example escalation of a rim seal fire (localised consequence) to a full tank surface fire (larger consequence, potential offsite effects) may be prevented by application of foam, provided that there is adequate detection and remote activation of fire protection systems.
- Response by Emergency Services is not accounted for. This will generally take some time (of the order of 15 minutes or more) after an initial event. Attendance by the Emergency Services prevents further escalation and additional asset damage, as well as management of evacuations.

Table 4.1: Hazardous incident scenarios

Area	Hazard scenario	Causes/threats	Typical consequences	Typical safeguards
Wharf	Loss of containment at wharf during ship to shore transfer	MLA failure (material corrosion/wear) Hose/fitting leak	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Pre-operation test of MLAs. Shore officer and wharf procedures (emergency response measures – activate ESD Wharf bunding Ignition control. Firefighting (Emergency Services).
		Ship movement (bad weather, poor mooring)	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Ship unloading procedures Shore officer and wharf procedures (emergency response measures – activate ESD). Wharf bunding. Ignition control. Firefighting (Emergency Services)
Pipelines	Leak from pipeline during ship to shore transfer	Pipeline rupture Pipeline leaks Hammer due to sudden valve closure	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Pipelines fully-welded Operator unloading procedures (walk the line to identify leaks) Surge analysis study for pipeline Firefighting (Emergency Services).
	Leak from pipeline - static (line left full and thermal expansion)	Pipeline leaks	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Pipelines fully-welded Aboveground line is water flushed, line left full is underground. Firefighting (Emergency Services).
	Leak from underground export pipelines (high pressure > 15barg)	Pipeline rupture Pipeline leaks	Jet or pool fire. Flammable gas dispersion and flash fire.	Pipelines fully-welded Cathodic protection and wrapping Depth of cover (1.5 m) Concrete covers at road crossings or other higher risk locations Firefighting (Emergency Services).

Area	Hazard scenario	Causes/threats	Typical consequences	Typical safeguards
Tank storage	Tank overfill	Human error (incorrect dip prior to start of fill or missed maximum safe fill level)	Pool fire and potential full-surface bund fire. Tank roof fire and escalation to adjacent tanks. Tank vent fire. Pool evaporation and flammable gas dispersion and flash fire. Flammable vapour cloud if tank rim overflowed (the Buncefield scenario)	Stock reconciliation and ordering practices Level gauges Independent High Level Alarm (IHLA) on tanks Remotely actuated shutdown Firefighting (Emergency Services).
		Level gauge error/failure	Pool fire and potential full-surface bund fire. Tank roof fire and escalation to adjacent tanks. Tank vent fire. Pool evaporation and flammable gas dispersion and flash fire. Flammable vapour cloud if tank rim overflowed (the Buncefield scenario)	Manual dip of tanks Independent High Level Alarm (IHLA) on tanks. Remotely actuated shutdown Firefighting (Emergency Services).
	Leak from tank	Tank rupture Fitting leak	Pool fire and potential full-surface bund fire. Pool evaporation and flammable gas dispersion and flash fire.	Tank farm operator patrols Firefighting (Emergency Services).
	Tank roof fire	Failure of rim seals (FR tanks) Sinking of roof Lightning	Tank roof fire and escalation to adjacent tanks.	Tank inspection procedures Tank filling procedures Water drains on FRs Spray cooling of surrounding tanks Firefighting (Emergency Services).
Product transfer pumps	Leak from pump during road tanker loading	Seal leak Flange leak Pump rupture	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Tank farm operator patrols. Drainage to closed interceptor. Automatic sprinkler system. Manually activated foam deluge. Firefighting (Emergency Services).

Area	Hazard scenario	Causes/threats	Typical consequences	Typical safeguards
Tanker loading gantry	Tanker leak during loading	Hose rupture Hose, tanker or piping fitting leak	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Operator in attendance (activates ESD) Drainage to closed interceptor. Firefighting (Emergency Services).
	Tanker overfill	Human error	Pool fire. Pool evaporation and flammable gas dispersion and flash fire.	Operator in attendance (checks ullage in tanker prior to loading and stops filling based on metered quantity - invalid barrier since it is not independent of initiating event/cause). Drainage to closed interceptor. Scully system (includes earthing and high level interlock) Driver in attendance (activates shutdown). Lone worker shutdown systems Ignition control. Foam activation or deluge Firefighting (Emergency Services).

Table 4.2: Scenario summary

Equipment type	Scenario	Main physical inputs	Quantitative assessment	Effect assessed (offsite or escalation to neighbouring facilities)
Floating Roof tank (internal cover, external roof)	Rim seal fire	Seal area	No – effect area is limited to immediate area of tank A proportion of rim seal fires assumed to escalate to full surface fires as per frequency data	n/a
	Tank top full surface fire	Tank diameter Tank height:	Yes	Heat radiation
	Overfill - large flammable cloud or pool fire	Rate of tank overfill Surface area	Yes	Extent of LFL for flame engulfment (i.e. impact area of flashfire - only for tanks in gasoline service) Heat radiation
Fixed Roof tank (Note : No fixed roof tanks in gasoline service)	Fire at tank vent fire	Vent diameter	No – effect area is limited to immediate area of tank vent. Escalation covered in full surface fire	n/a
	Tank top full surface fire	Tank diameter Tank height:	Yes	Heat radiation
	Overfill - pool fire		Yes	Heat radiation

Equipment type	Scenario	Main physical inputs	Quantitative assessment	Effect assessed (offsite or escalation to neighbouring facilities)
Bunded areas (e.g. tank storage, tanker bay)	Pool fire - intermediate bund	Rate of fill into pump (depends on leak size or overfill rate) Surface area and evaporation rate from pool	Yes	Heat radiation Extent of LFL for flame engulfment (i.e. impact area of flashfire - only for tanks in gasoline service)
	Pool fire - full bund	Rate of fill into pump (depends on leak size or overfill rate) Surface area and evaporation rate from pool	Yes	Heat radiation
Pumps	Spray fire Pool fire	Operating pressure Leak/hole size/seal size	Yes	Heat radiation
Pipelines	Spray fire Pool fire Flammable vapour cloud	Operating pressure Leak/hole size / seal size	Yes	Heat radiation Extent of LFL for flame engulfment (i.e. impact area of flashfire – gasoline/LPG)
Process piping and associated fittings, flanges etc	Spray fire Pool fire	Operating pressure Leak/hole size/seal size	Yes	Heat radiation

4.3. Consequence analysis

Consequence analysis involves qualitative and/or quantitative review of the identified hazardous incidents to estimate the potential to cause injury or fatalities, damage to property or damage to the environment.

4.3.1. Software and models

Quantitative consequence modelling for identified scenarios (except gasoline tank overfill) was undertaken using DNV PHAST v7.11 to determine the impact area (as heat radiation, area within a flammable cloud) and the resulting extent of fatality effects.

For gasoline tank overfill scenarios, the extent of the flammable cloud envelope is modelled following the UK HSE's Vapour Cloud Assessment (VCA) method (Ref 2), which provides a means of calculating the rate at which the volume of a vapour cloud increases during an overfilling incident, hence predicting the distance to the LFL of the cloud. The distance to LFL is then used as the extent of the flashfire and overpressure impact area if an ignition occurs.

This is an empirical model that can be set up in a spreadsheet and was developed after significant research as part of the incident investigation into the Buncefield incident that occurred in 2005. It is regarded as best practice for estimating the effect areas for this type of event without undertaking detailed site specific Computational Fluid Dynamics (CFD) modelling.

4.3.2. Site conditions

Meteorological data was obtained for Lyttelton for use in the consequence modelling. Overall parameters adopted for consequence modelling are also required. This data is contained in APPENDIX C.

4.3.3. Modelling methodology and assumptions

The materials are generally flammable with minimal acute toxicity issues. Hence, fire scenarios are modeled as follows:

- Pool/bund fires. Ignited vapours on the surface of a liquid pool.
- Tank roof fires. Ignited vapours on the surface of a liquid at liquid surface in tank.
- Jet/spray fires. This is an intense directional fire resulting from ignition of a vapour or two phase release with significant momentum (i.e. pressurized release).
- Flashfire. An ignited flammable vapour cloud with no overpressure effects. Dimensions typically taken to be the extent of the Lower Flammability Limit (LFL).

Note that after a flashfire event a residual pool or jet fire may remain. This is not explicitly modeled as the effect distances are smaller than the initial flammable cloud resulting in flashfires.

Overpressure due to a vapour cloud explosion was not specifically modelled in this study. Overpressure is a function of congestion and confinement. The Port area is relatively open with minimal congested areas and overpressures would be anticipated to be extremely low and within the LFL effect area of the flammable clouds. For this study all delayed ignition events have been modelled as flash fires (i.e. no overpressure effects, flame engulfment only accounted for).

Toxicity effects are modelled for mercaptan and methanol only as unignited vapour cloud dispersion from evaporating pool or spray release.

Methodology and input assumptions for each event type are explained in APPENDIX D.

4.3.4. Vulnerability

For each scenario, the consequence models predict a physical effect (e.g. heat radiation) versus distance relationship. The probability of fatality is then estimated using a threshold value for relevant effects.

The consequence effect criteria and threshold values used in this QRA are summarized in the following tables. These have been compiled from sources used in Australia and the US as there was no specific guidance that could be found available in NZ.

For fire scenarios, people are vulnerable to fire through:

- engulfment by fire
- thermal radiation from a fire
- inside buildings exposed to fire.

Threshold levels are given in Table 4.3.

For toxic effects (injury due to methanol or mercaptan exposures) the US EPA Acute Emergency Guideline Level (AEGL3) value as defined in Table 4.4 has been used the onset of fatality effects. AEGLs are based on extensive review of toxicological data, and are also set for a range of times (from 10 mins to 8 hours).

Table 4.3: Consequence assessment rule sets, fire events

Event	Level	Probability of Fatality Assumed in QRA		Other effects	References
		Indoor	Outdoor		
Jet, spray or pool fire	Within fire envelope	20%	100%	Escalation due to direct impingement	OGP Risk Assessment Data Directory (Ref 3)
	12.5 kW/m^2	0 %	90%	Possible fatality indoors if line of sight exposure occurs. Not included in	TNO probit (Ref 4) and assumes 60 second exposure

Event	Level	Probability of Fatality Assumed in QRA		Other effects	References
		Indoor	Outdoor		
				QRA	
	6 kW/m^2	0 %	10%		TNO probit (Ref 4)
	4.7 kW/m^2	-	Injury	Injury only	HIPAP 4 (Ref 5)
	23 kW/m^2	-	-	Escalation due to heat radiation	HIPAP 4 (Ref 5)
Flashfire	Within LFL (assumed to be flashfire envelope)	20%	100 %	No escalation – very short duration event	UK HSE Research Report 084 (Ref 6)

Table 4.4: Consequence assessment rule sets, toxicity effects

Impact	AEGL
Fatality onset (1% probability)	AEGL3 is the airborne concentration (expressed as ppm or mg/m^3) of a substance **above** which it is predicted that **the general population, including susceptible individuals**, could experience life-threatening health effects or death. (Refer to APPENDIX B for relevant values)

4.3.5. Consequence results

To provide a sense of scale of the effect area for the scenarios, APPENDIX D provides typical impact distances to the vulnerability levels defined in Section 4.3.4. Note that these are not specific to a particular site or facility however given there is a lot of similarity between the facility operations, these can be regarded as representative.

The maximum extent of any scenario is from the flammable vapour cloud scenario from gasoline tank overfills (the Buncefield scenario). For the filling rates and tank sizes present at the Port this could extend over distances of approximately 400 m (as per examples of results in Section D10).

4.4. Frequency analysis

Scenarios for these sites generally involve loss of containment of hydrocarbon fuels and subsequent ignition.

Loss of containment incidents are uncommon and the individual sites do not have sufficient statistical data to use in a QRA. The likelihood of these scenarios was estimated using historical industry frequency data for loss of containment and ignition probability.

OGP and LASTFIRE data was selected as it is specific to the oil and gas industry and is updated relatively frequently based on industry incident reporting.

The base data and sources used for all items are included in APPENDIX E.

4.4.1. Base leak frequencies for process equipment

Loss of containment frequencies were estimated by counting equipment items ('parts count') and combining with historical leak frequency data for each equipment type. The main source of historical leak frequencies from process equipment such as pumps, piping, loading hoses was OGP's Risk Assessment Data Directory *Process release frequencies* (Ref 7). This is supplemented by other sources where required.

4.4.2. Storage tank incident frequencies

Full surface tank roof fire frequencies were estimated from the most recent LASTFIRE project (Ref 8) based on the historical fire frequencies for each storage tank type.

The frequency of tank overfill was estimated using event tree analysis since this is dependent on instrument failures and safeguards specific to each site.

4.4.3. Pipeline incident frequencies

There is no statistically significant NZ pipeline failure data available so pipeline incident frequencies have been estimated from industry data sources CONCAWE for pipelines operating at less than 20 barg (Ref 29) and EGIG for pipelines about 20 barg (Ref 30).

As per Figure 3.2 there are two pipebridges over public roads and a number of aboveground pipelines running alongside George Seymour Quay and Charlotte Jane which are public roads and are used for parking during sporting events.

There is no specific data suggesting damage to pipelines occurs due to public interference or vehicle impact and no adjustment was made in the QRA to the industry wide pipeline failure frequency data to account for potential risk of vehicle impacts on these pipelines. However it is noted qualitatively that this risk may be greater than the statistical data indicates. The majority of aboveground industrial pipelines carrying hazardous materials are within secure port areas or within defined pipeline corridors which is not the case in the Lyttelton Port area.

4.4.4. Road transport incidents

Traffic accident rates for road transport were not available within the Port area. Anecdotal evidence and operator incident tracking suggests that there have been few vehicle related incidents or accidents in the immediate Port area as defined in Figure 3.1 and none that have resulted in a loss of containment of a hazardous material.

Therefore to provide an indication of the likely effect on risk, OGP accident rate and loss of containment data for dangerous good vehicles (Ref 36) was used as per APPENDIX E. This was applied to the proportion of road tanker traffic carrying flammable liquids (i.e. gasoline, jet fuel, methanol, cutback bitumen) only due to the higher likelihood of ignition in the event of a loss of containment due to an accident.

The OGP data is likely to be conservative as the speed of vehicles is low in the Port area and the amount of traffic generally low (with the exception of sporting activities on the weekends). Flammable liquids tankers also travel at night only due to restrictions on use of the Lyttelton tunnel.

4.4.5. Probability of ignition

All sites have safe work practices covering hazardous area classification and hot work permit systems to control ignition sources within their boundaries. There is very little access control up to the site boundaries which coincide with bund walls, process equipment such as loading bays is very close to public roads and live aboveground pipelines are in public areas hence ignition sources are considered to be potentially in closer proximity to these sites that would be the case in a secure port site.

The ignition probability values used in this study were based on the assessment by Cox, Lees and Ang (Ref 9). The probabilities are based on the release rate and the phase of the fluid assessed. This reference generally sets higher ignition probability for scenarios up to around 10 kg/s than other industry ignition source models such as Energy Institute models (Ref 10) and are considered appropriate for an area of this nature.

The ignition probability values used in the QRA are provided in APPENDIX E.

Releases for combustible liquids such as diesel are more difficult to ignite due to their high flash point. Frequencies were reduced for combustible only storages as per APPENDIX E.

4.4.6. Effect of safeguards

There are a number of hardware safeguards (instrumentation, automatic trip systems) that can be factored into the event frequencies, such as high level shutdowns in tanks. As per APPENDIX E Section E7, these have been included in frequency estimations where relevant on each site taking into account trip design and functional testing frequencies.

Manually initiated emergency shutdown (ESD) is also allowed in the situation where:

- there are personnel present and ESD functionality is available
- the event can be readily detected and isolated, particularly if continuous monitoring occurs.

Safeguards relating to fire protection are accounted for only in estimating the likelihood of escalation (as they do not prevent the initial event, but limit the consequences).

4.4.7. Escalation between sites

If the consequence assessment indicates that there is potential for escalation due to an incident on one site affecting hazardous materials on a neighbouring sites this has been included in the cumulative QRA. From the consequence assessment, an assessment was made to check if there is the potential for consequence propagation to tanks both at the Terminal and on other sites based on the heat radiation levels of:

- 8-12 kW/m^2 – the thermal radiation above which cooling of a tank may be necessary, based on the Energy Institute's Model Code of Safe Practice Part 19 for Fire Precautions at Petroleum refineries and Bulk Storage Installations (Ref 11). The average value of 10 kW/m^2 was chosen.
- 23 kW/m^2 – radiation at which escalation to equipment in the vicinity of a fire could occur, or rapid escalation to a tank inventory as per Table 4.3.

An escalation frequency is defined from the original event frequency (combined with a failure probability for safeguards such as activation of fire protection systems such as tank cooling sprays if they are present).

4.5. Natural hazards

If natural hazards (for example earthquakes, tsunamis, bushfires) interact with industrial facilities, large scale releases of hazardous material can occur that may be larger in scale than the equipment specific mechanical failure or operational upset events typically considered in a QRA.

Therefore the QRA included a review of external factors to determine whether there are factors specific to the location of the site that could:

- Significantly elevate the likelihood of an incident compared to the statistical failure frequency data or operational failure rates used to quantify the frequency of mechanical failure or operational upset incidents that result in loss of containment.
- Significantly increase the consequence (i.e. severity) of a loss of containment event and resultant fire, explosion or toxic exposure effects.

The following approach was taken:

- Identify the natural hazards applicable to the Lyttelton Port area using existing information relating to frequency and severity of natural hazards such as earthquakes that has previously been assembled by New Zealand authorities including the CCC.
- Relate the intensity of the natural hazard to the degree of damage (with the potential to result in loss of containment) to the bulk storage facilities using publicly available information correlating event intensity to degree of damage to equipment such as atmospheric storage tanks.
- Develop a consequence model and estimated impact area associated with the damage scenarios identified.
- Include the additional scenarios in the base QRA model, and also present the risk results without the natural hazards effects included as a sensitivity study. This shows the difference in risk when location specific natural hazards are factored in and allows an assessment to be made of whether location specific factors significantly increase the risk compared to the base risk from the

mechanical failure or operational upset events causing loss of containment typically considered in a QRA.

4.5.1. Equipment covered

The focus for natural hazards is on events where there is potential for a large scale consequence due a large loss of containment of a hazardous material. Bulk storage tanks are clearly the largest inventory items for these types of facilities hence only storage tanks are considered as having the potential to significantly increase the consequence from a natural hazards initiated event.

Pipeline damage or damage to other process equipment such as pumps, road tanker bays and process piping is not included in the natural hazards risk assessment as the inventories involved are far smaller than for bulk storages.

4.5.2. Natural hazards at Lyttelton

Natural hazards potentially relevant to the Lyttelton Port area are summarised in Table 4.5. The table also summarises the approach taken to incorporate the effects into the QRA.

The information used to develop the approach is summarised in APPENDIX F.

Table 4.5: Natural hazards considerations for QRA

Natural hazard	Damage/outcome	Comments on inclusion in QRA
Earthquake	Cliff collapse and boulders/debris impacting tanks	Potential for cliff collapse and rockfall has been assessed using the Institute of Geological and Nuclear Sciences Limited (GNS) slope instability risk studies prepared for CCC after the 2010/2011 Christchurch earthquakes (Refs 12 13, 14). Note that these studies provide data for the total risk of cliff collapse and rockfall due to either earthquakes or non-seismic events such as rainfall. Slope instability risks affect the area immediately at the base of the cliff at Naval Point. Only low hazard products (e.g. diesel) are stored in this area. An additional frequency of loss of containment from tanks due to impact of debris avalanche material from cliff collapse in Naval Point area and resulting fire has been included in QRA.
	Ground movement damaging/ collapsing tanks	Damage to tanks resulting in loss of containment did not occur in the 2010 and 2011 earthquakes, hence a higher strength earthquake would be required to occur to result in significant loss of containment. Strength of earthquake and the frequency / return period (from Ref 14) and probability of major damage to tanks resulting in significant loss of containment has been assessed based on fragility curves (Ref 15). Extra scenarios have been included in the QRA that account for multiple tank failures simultaneously, or damage to the bunds as well as tanks with larger scale release that is not contained in the bunded areas.

Natural hazard	Damage/outcome	Comments on inclusion in QRA
	Liquefaction of ground damaging/ collapsing tanks	Liquefaction in the Lyttelton Port area occurred in some localised areas of reclaimed land close to the wharf but damage to tanks resulting in loss of containment did not occur in the 2010 and 2011 earthquakes. No adjustment has been made to the QRA to account for specific liquefaction effects. Any damage due to liquefaction effects is assumed to occur only in the same scale of earthquake as damage due to ground movement / shaking and is assumed to be covered by the additional scenarios included in the QRA as part of the earthquake ground movement effects assessment noted above.
Tsunami	Inundation and tank movement/damage	Major damage to tanks has a high probability of occurring at maximum inundation depths of 5 m or greater (Ref 16). This inundation depth is not predicted at Lyttelton which shows maximum inundation depth of less than 2m in areas where bulk storages are located (Ref 17). In any case the risk of fatality from a tsunami due directly to inundation is substantially higher than any incremental fatality risk due to secondary effects from a loss of containment of hazardous materials and resulting fire. No adjustment to QRA
Storm event	Inundation due to storm surge	Inundation due to storm surge is of a lesser scale than tsunami inundation (Ref 18). No adjustment to QRA
	High rainfall initiating landslip and boulders/debris impacting tanks	Potential for landslip and rockfall has been assessed using the GNS slope instability risk studies as per earthquake comments. (Note that these studies provide data for the total risk of landslip due to earthquakes and non-seismic factors such as high rainfall events).
Cyclone	High wind speeds	Not relevant - not a cyclone area No adjustment to QRA
Lightning	Ignition resulting in tank top full surface fire	Lyttelton is not identified as a high lightning strike area. LASTFIRE data includes tank top fires started by lightning strikes. No adjustment to QRA.

4.5.3. Summary of natural hazards effects in QRA

In summary, natural hazards effects due to earthquakes (increase in both frequency and consequence compared to base QRA) and slope instability cliff collapse (with an increase in frequency only compared to base QRA) have been included in the QRA.

Table 4.6: Summary of natural hazards included in QRA

Damage/Outcome	Frequency included in QRA	Consequence included in QRA
Earthquake - Ground movement damaging/collapsing tanks		
RS3 Tank collapse, serious damage resulting in a large loss of containment	Earthquake with a PGA of 2g or more would need to occur to cause a high probability of significant damage resulting in	Potential to result in a worse consequence than occurs from a catastrophic mechanical failure scenario (single tank spill contained

Damage/Outcome	Frequency included in QRA	Consequence included in QRA
and subsequent fire. May affect multiple tanks and damage bund, failing to contain spilled material.	loss of containment (ie RS3 level). Probability of damage obtained from fragility curves Results in large damage scenario per bund compound of the order of 4 x 10^{-5} per year. Ignited event frequencies in the range of 6 x 10^{-7} to around 8 x 10^{-6} per year per bund compound depending on the storage arrangements and ignition probability assumed.	within the bunded area). Bund is damaged and fails to contain the spilled material. This also covers multiple tanks simultaneously damaged in one compound exceeding bund capacity, resulting in an unconstrained pool. Increase in impact area by around 80 – 100% (e.g. a larger bund compound may limit the maximum spreading area to an equivalent pool diameter of about 80 – 100 m, for the scenarios unconstrained by the bund, impact areas with an equivalent pool diameter of about 170 – 210 m are predicted.
Slope Instability - Cliff collapse damaging tanks		
RS3 Tank, serious damage in a large loss of containment and subsequent fire. May affect 1-2 tanks. No significant damage to bund.	Additional frequency of loss of containment from tanks in Naval Point area and fire has been included in QRA. Large loss of containment of 1 x 10^{-4} per year. Low hazard products (ie combustibles only). The fire event frequency for each main bunded area below the cliff is approximately 2 x 10^{-6} per year.	Not likely that a cliff collapse would cause catastrophic failure of the bund and inability to contain the majority of a spill from a damaged tank. Same consequence as base QRA (i.e. fully developed bund fire constrained by bund).

5. RISK ANALYSIS

5.1. Risk quantification

Quantified risk levels are typically expressed as the number of occurrences of a specified outcome (eg fatality) in a timeframe (typically one year). For land use safety planning a typical expression of risk is “the individual fatality risk is 1 x 10^{-6} per year in the residential area”.

A summary of equivalent risk expressions is given in Table 5.1.

Table 5.1: Equivalent risk expressions

Number of occurrences in ……. years	per year	per year	per year
0.1 in a million years / 1 in ten million years	0.1×10^{-6}	1×10^{-7}	0.0000001
1 in a million years	1×10^{-6}	1×10^{-6}	0.000001
10 in a million years / 1 in one hundred thousand years	10×10^{-6}	1×10^{-5}	0.00001
100 in a million years / 1 in ten thousand years	100×10^{-6}	1×10^{-4}	0.0001
1000 in a million years / 1 in a thousand years	1000×10^{-6}	1×10^{-3}	0.001

5.2. Risk criteria

There are currently no specific land use safety planning risk criteria in New Zealand for use in the vicinity of hazardous facilities, although a number of New Zealand studies (for example Sea and City development in Wynyard Quarter and a prison development near WOSL fuel terminal, both in Auckland) have adopted the Australian risk criteria published in Hazardous Industry Planning Advisory Paper No 4, *Risk Criteria for Land Use Safety Planning,* known as HIPAP 4.

At this stage the QRA Steering Group have not confirmed the risk acceptability criteria to be adopted for evaluation of the Lyttelton Port risk results.

Representative risk criteria are presented in the following sections, and the QRA risk results have been presented to cover the typical range of land use planning risk criteria values adopted in other locations.

5.2.1. Individual fatality risk

Individual fatality risk in land use safety planning in the vicinity of hazardous facilities is defined as the risk of death per year to a notional person present continuously (24 hours per day, 365 days per year) at a particular location.

Individual fatality risk criteria are widely adopted for land use planning in the vicinity of hazardous facilities in a number of jurisdictions (Australia, UK, Europe and parts of Asia). The land use planning criteria values are set so that the risk level posed by industry (regarded as an involuntary risk exposure) is low in comparison to the voluntary risk exposures people accept in everyday life.

Quantitative values generally based around a value of individual fatality risk of 1 x 10^{-6} per year being broadly acceptable to a residential land use, for example, the Australian NSW criteria in HIPAP 4 (Ref 5) and UK HSE criteria (Ref 19).

Table 5.2 provides a comparison of individual fatality risk criteria in various jurisdictions including the HIPAP 4 criteria which have been used for some studies in NZ.

5.2.2. Differences to natural hazards risk estimates

It should be noted that there is a significant body of work in New Zealand covering fatality risk resulting from natural hazards events. This includes studies related to slope instability risks in the Port Hills area at Lyttelton (Refs 12, 13, 14). Risk is presented in the natural hazards risk studies as annual individual fatality risk (AIFR) which includes factors for probability of presence.

The natural hazards AIFR has a different basis to the individual fatality risk definition used in land use safety planning in the vicinity of hazardous facilities as the AIFR calculation includes factors for probability of exposure/probability of presence. As noted in the previous section, individual fatality risk in land use safety planning is expressed as risk to a notional person (‘person most at risk’) assumed to be present continuously (24 hours per day, 365 days per year) at a particular location, i.e. it can be regarded as risk at a location rather than risk to a particular individual. To avoid confusion with the natural hazards work, the term AIFR is not used in this QRA.

5.2.3. Societal risk

Societal risk is a measure of the probability of incidents affecting an actual population (rather than a notional individual as in individual risk). It is usually presented in the form of an FN curve which is a graph indicating the cumulative frequency of fatality (F) of a population of size ‘N or more’ people. Generally societal risk is considered in three regions:

- ‘Intolerable region’ represented by an upper criterion line above which the activity would be regarded as unacceptable.
- ‘Acceptable’ represented by a lower criterion line below which the activity would be regarded as posing acceptable risk levels.
- Region in between where the risk may be acceptable depending on the benefits of the activity, but risk reduction measures should be implemented to reduce the risks where practicable. This is known as the ‘ALARP’ or ‘as low as reasonably practicable’ region.

Indicative societal risk criteria are established in some jurisdictions. As an example, the indicative societal risk criteria from HIPAP4 are shown in Figure 5.1 for the three risk regions. The upper tolerability line comparing fatality societal risk criteria from various other jurisdictions is also shown but are more variable than individual fatality risk criteria as shown in Figure 5.1.

5.2.4. Acceptance of risk

In the absence of agreed risk criteria it is not possible to provide the risk evaluation component of the risk assessment in this report.

Therefore interpretation of risk results against criteria, subsequent assessment of the risk acceptability, the need for risk reduction measures and resulting decisions as to whether the benefits of providing for future developments outweigh any identified risks or other negative impacts are not within the scope of this report.

5.3. Risk software

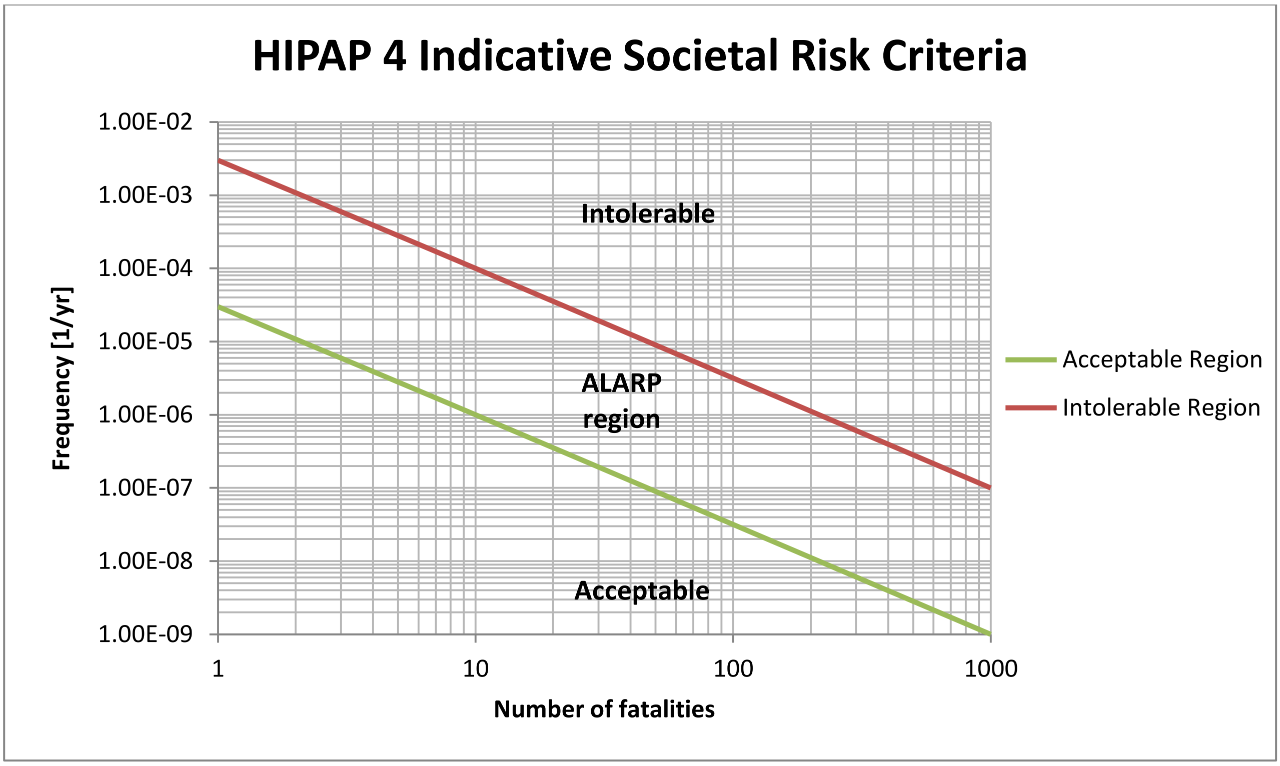
Risk quantification was performed using TNO Riskcurves v9.0.26, which combines consequences and frequencies for each scenario to produce contours of equal risk values.

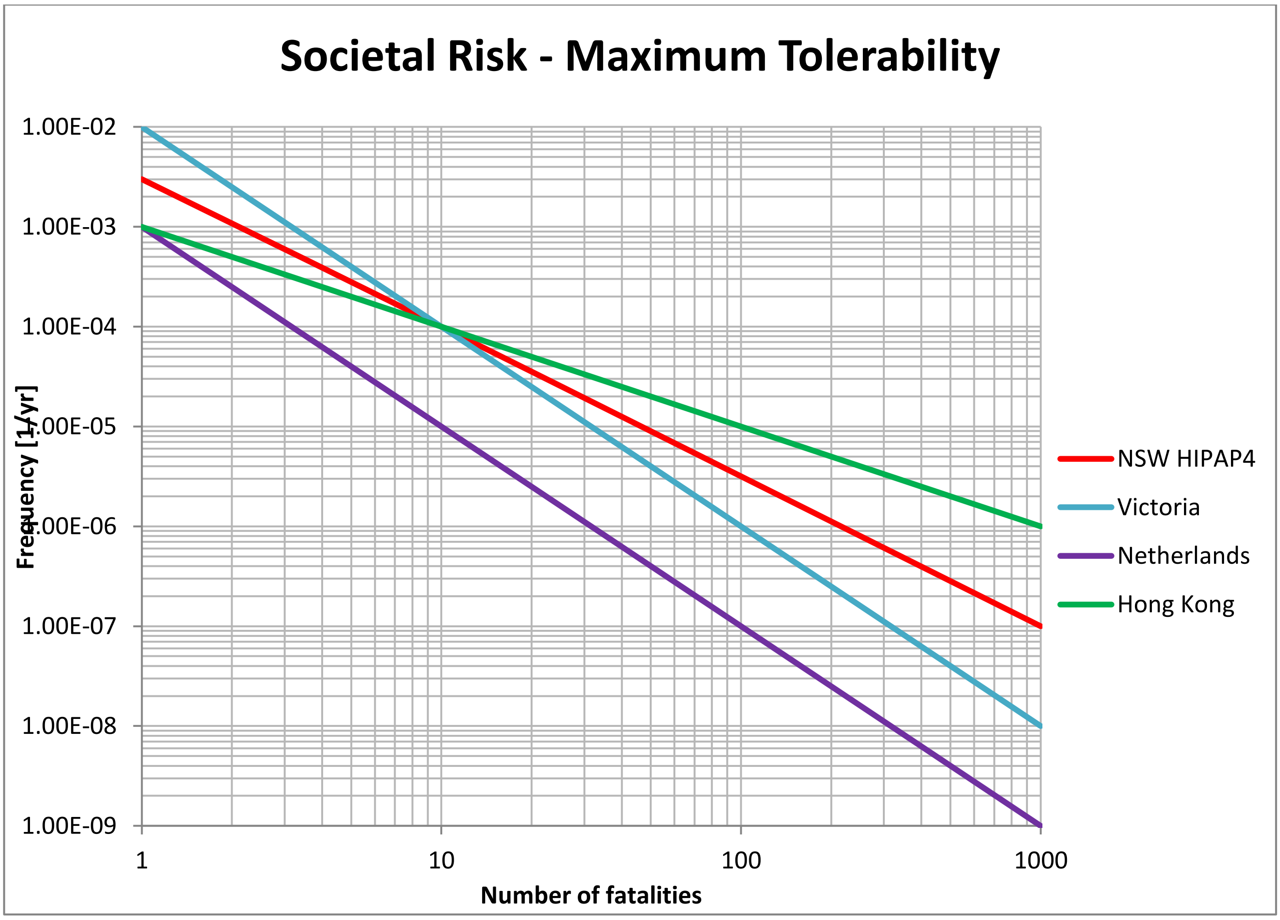
Results have been generated in the form of individual fatality risk contours and as societal risk (FN) curves.

Table 5.2: Comparative individual fatality risk criteria

Individual Fatality Risk Level (fatality/year)	Australia NSW HIPAP 4 (Ref 5)	Australia Qld HICB (Ref 20)	Australia Vic Workcover (Ref 21)	WA EPA (Ref 22)	UK HSE (Ref 23)	The Netherlands (Ref 24)	Singapore (Ref 25)	Hong Kong (Ref 26)
50×10^{-6}	Industrial	Industrial	-	Industrial	-	-	Industrial	-
10×10^{-6}	Sporting complexes and active open space	-	Site boundary All practicable risk reduction measures are to be taken for offsite risk between 10^{-5} and 10^{-7}	Non-industrial and active open space	General population (intolerable)	-		General public
5×10^{-6}	Commercial developments including retail centres, offices and entertainment centres	Commercial or community activity	-	Commercial developments including offices, retail centres, showrooms, restaurants and entertainment centres	-	-	Commercial	-
1×10^{-6}	Residential, hotels, motels, tourist resorts	-	-	Residential	General population (broadly acceptable)	Vulnerable populations (new and existing installations)	General public	-
0.5×10^{-6}	Sensitive - Hospitals, schools, child-care facilities, old age housing	Vulnerable or sensitive	-	Sensitive - Hospitals, schools, child-care facilities, aged care housing	-	-	-	-
0.3×10^{-6}	-	-	-	-	Susceptible populations (broadly acceptable)	-	-	-

Figure 5.1: Comparative societal risk criteria





6. INDIVIDUAL FATALITY RISK RESULTS

6.1. Individual fatality risk

The individual fatality risk results are presented as cumulative contours (ie representing the sum of all risk contributors) of equal risk level on a map of the area for the Current Case in Figure 6.1 and the Future Case in Figure 6.2 (Future Case 1) and Figure 6.3 (Future Case 2).

As specific risk criteria have not yet been adopted the risk contours are presented as order of magnitude levels (ie each contour decreasing by a factor of 10) from 1×10^{-4} to 1×10^{-7} per year as this covers the typical range of individual fatality risk criteria that are in use in other locations as described in Section 5.2.

For comparison, risk contours based on the Australian NSW HIPAP 4 individual fatality risk criteria which have been used for some other QRA studies in NZ are also shown in APPENDIX G.

6.1.1. Existing land uses

It can be seen that:

- The 1×10^{-6} per year contour covers most of the Port area and extends to the roadway along the existing residential area along Brittan Terrace in the Current Case. In the Future Case there is a marginal extension of the 1×10^{-6} per year contour into a single house.
- The 1×10^{-5} per year contour extends into the recreational area along Godley Quay for both Current and Future Cases.
- The 1×10^{-4} per year contour extends outside the risk source sites into the recreational area along Godley Quay for both Current and Future Cases.
- The public roads (Charlotte Jane Quay and George Seymour Quay) running east-west between the different storage facilities are exposed to risk levels well above 1×10^{-5} per year

6.1.2. Future land uses

- The risk levels in the proposed marina development in Dampier Bay are well below 1×10^{-6} per year for both the Current and Future Cases.
- The location of the proposed cruise ship berth is exposed to a risk level of approximately 1×10^{-6} per year
- The risk levels in the disembarkation area on the shore exceed 1×10^{-5} per year.

6.2. Sensitivity studies

A series of sensitivity studies around parameters that are fairly uncertain was undertaken to test the effect on the risk contours as described in the following section. The individual fatality risk results are shown to be relatively insensitive to inclusion of road transport accident data and natural hazards data with these factors resulting in only small increases in the fatality risk contours.

6.2.1. Sensitivity of risk results to natural hazards

The results presented in Figure 6.1 to Figure 6.4 include the effect of natural hazards events. A comparison of risk results excluding the natural hazards event scenarios is provided in APPENDIX G.

It can be seen that these contours (which represent a typical QRA for this type of facility without consideration of location specific natural hazards) are slightly smaller. The natural hazards inclusion slightly increases the overall extent of the risk contours at the 1×10^{-6} per year level, and also elevates the risk within the immediate vicinity of the facilities and generally within the Port area.

A second sensitivity doubling the ignition probability in the event of an earthquake initiated major loss of containment was also included. This shows slightly larger 1×10^{-6} and 1×10^{-4} per year contours.

6.2.2. Sensitivity case around effect of road transport accidents

A comparison of risk results without the contribution from road accident event scenarios is provided in APPENDIX G.

It can be seen that removal of road transport accident scenarios (the majority of tanker traffic is north south along Godley Quay) slightly reduces the extent of risk contours to the west of the bulk storage facilities along Godley Quay, and the risk contours along the road area heading north out of the Port area disappear.

6.3. Future Case

Figure 6.2 (Future Case 1, all export increase via road tanker) shows a small increase in the overall extent of the risk contours compared to the Current Case. The 1×10^{-6} risk contour approaches slightly closer to the proposed cruise ship mooring location. The 1×10^{-6} risk contour also more closely approaches the houses along Brittan Terrace and Park Terrace residential areas. The 1×10^{-4} contour has a larger footprint to the east of Godley Quay, while the risk in the Naval Point storage areas west of Godley Quay is also increased.

Figure 6.3 (Future Case 2, all export increase via road tanker) shows a similar effect as Future Case 1 to the contours around the bulk storage facilities, but with a small contraction of the contours associated with road transport. This is because there is an overall reduction in the number of flammable liquids tankers to jet fuel, cutback bitumen and methanol only as all gasoline throughput is diverted to the expanded pipeline capacity (as per definition of Future Cases in Section 3.5).

6.4. Risk contributors

Table 6.1 provides a summary of the types of scenarios that contribute most significantly to the risk at the 1×10^{-6} per year risk level at various locations. The analysis points are shown in Figure 6.4.

- The residual risk in the far field (i.e. around 100 m from the bulk storage facility boundaries) towards the recreational areas, the hazardous materials berth and the potential cruise ship location is predominantly due to flashfires resulting from a large spill from a catastrophic mechanical failure or overfill of gasoline storage tanks. Note that this does not apply to the risk in the vicinity of the Naval Point area as there is no gasoline in this area.
- Nearer field risks (for example at the sports oval or around the Naval Point tanks) are dominated by tank top fires, pool fire events in bunds or road tanker loading bays nearby.
- In the western area of the Port, ignited releases from failures of the underground LPG pipeline dominate the risk.
- Risks from import pipelines from the berth to the facilities are relatively low as these are infrequently used.
- Toxicity effects from methanol and mercaptan are localised and make minimal contribution to the risk.

Figure 6.1: Individual fatality risk, Current Case

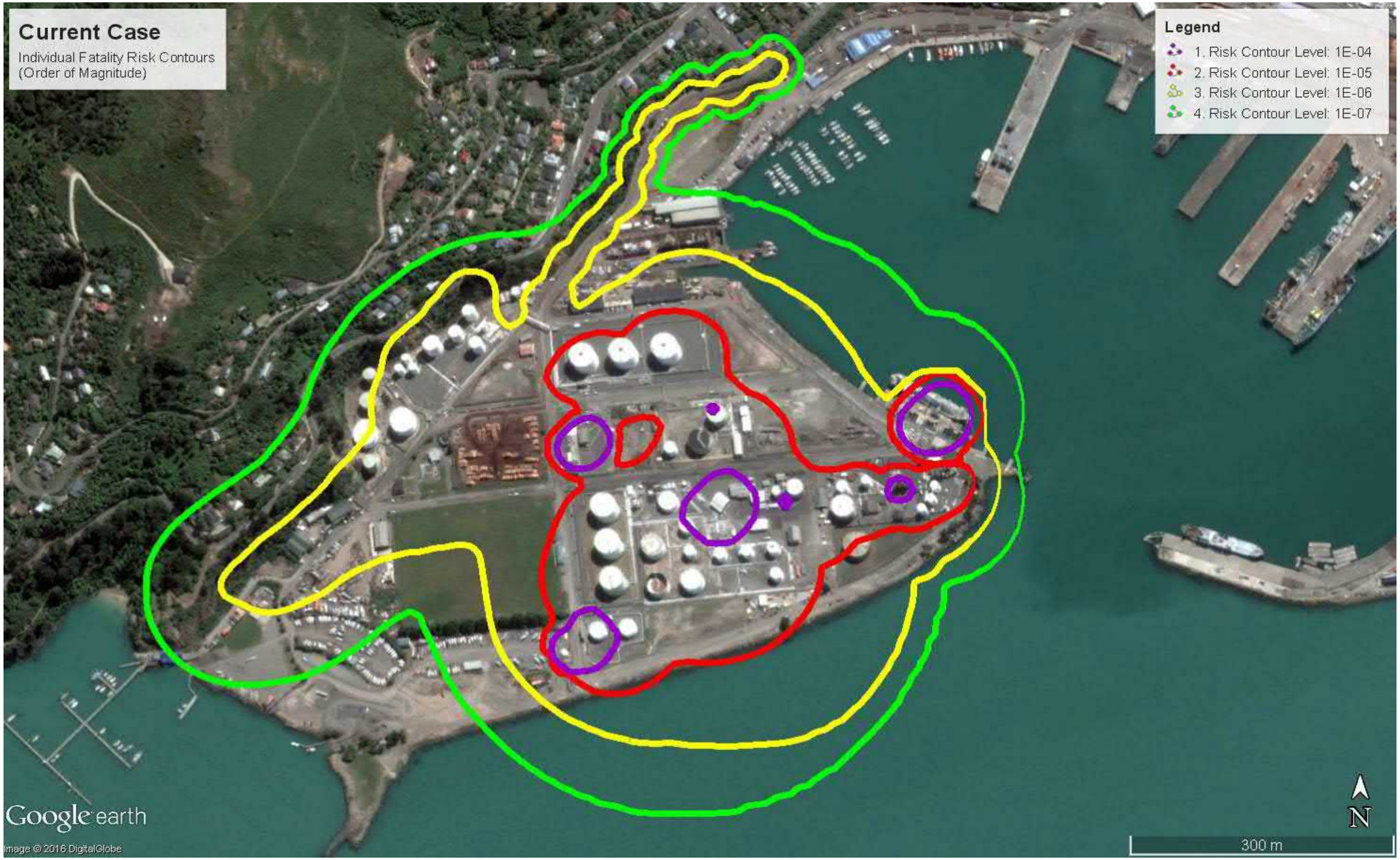


Figure 6.2: Individual fatality risk, Future Case 1 (all throughput increase exported by road tanker)

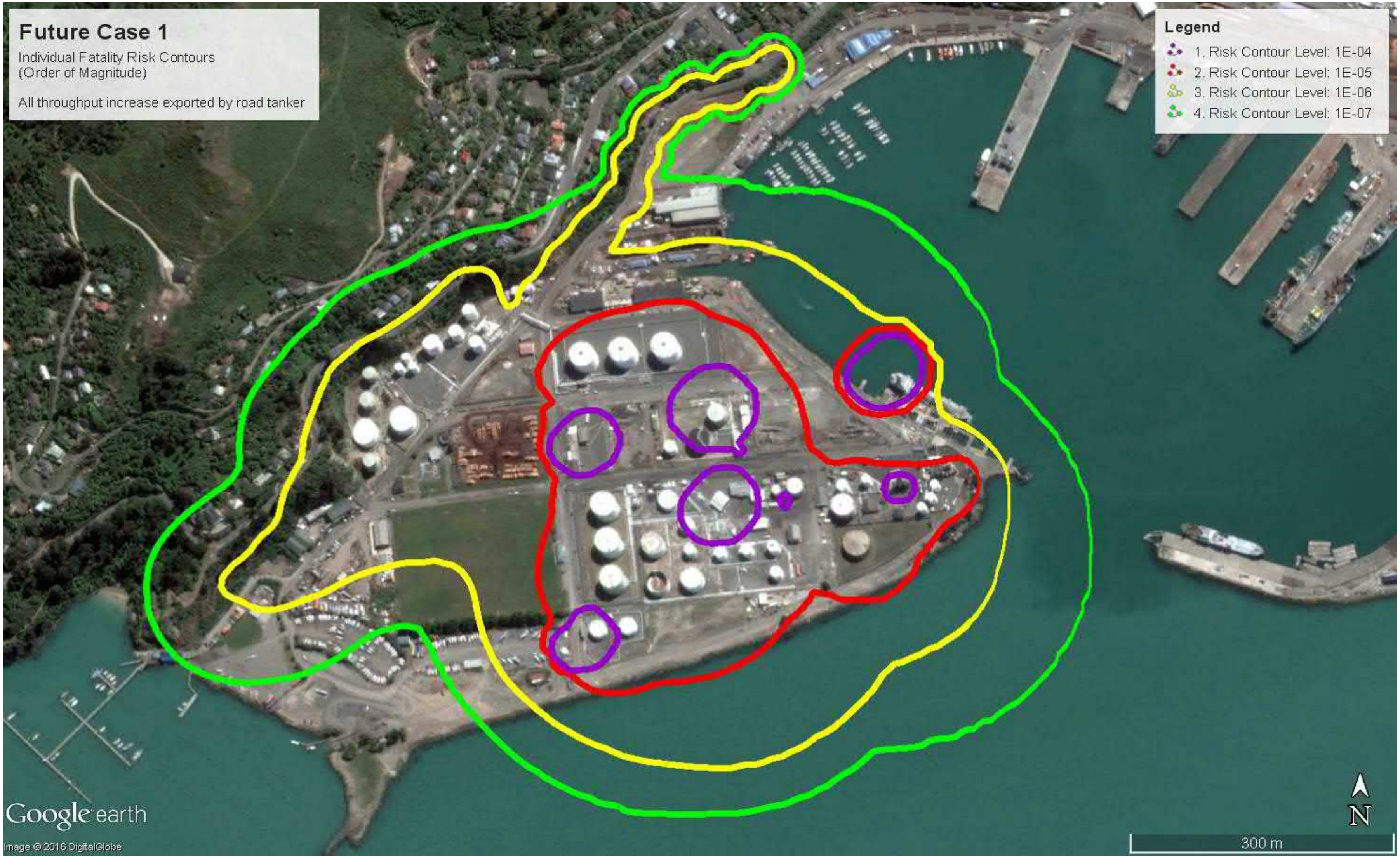


Figure 6.3: Individual fatality risk, Future Case 2 (all throughput increase exported by pipeline)

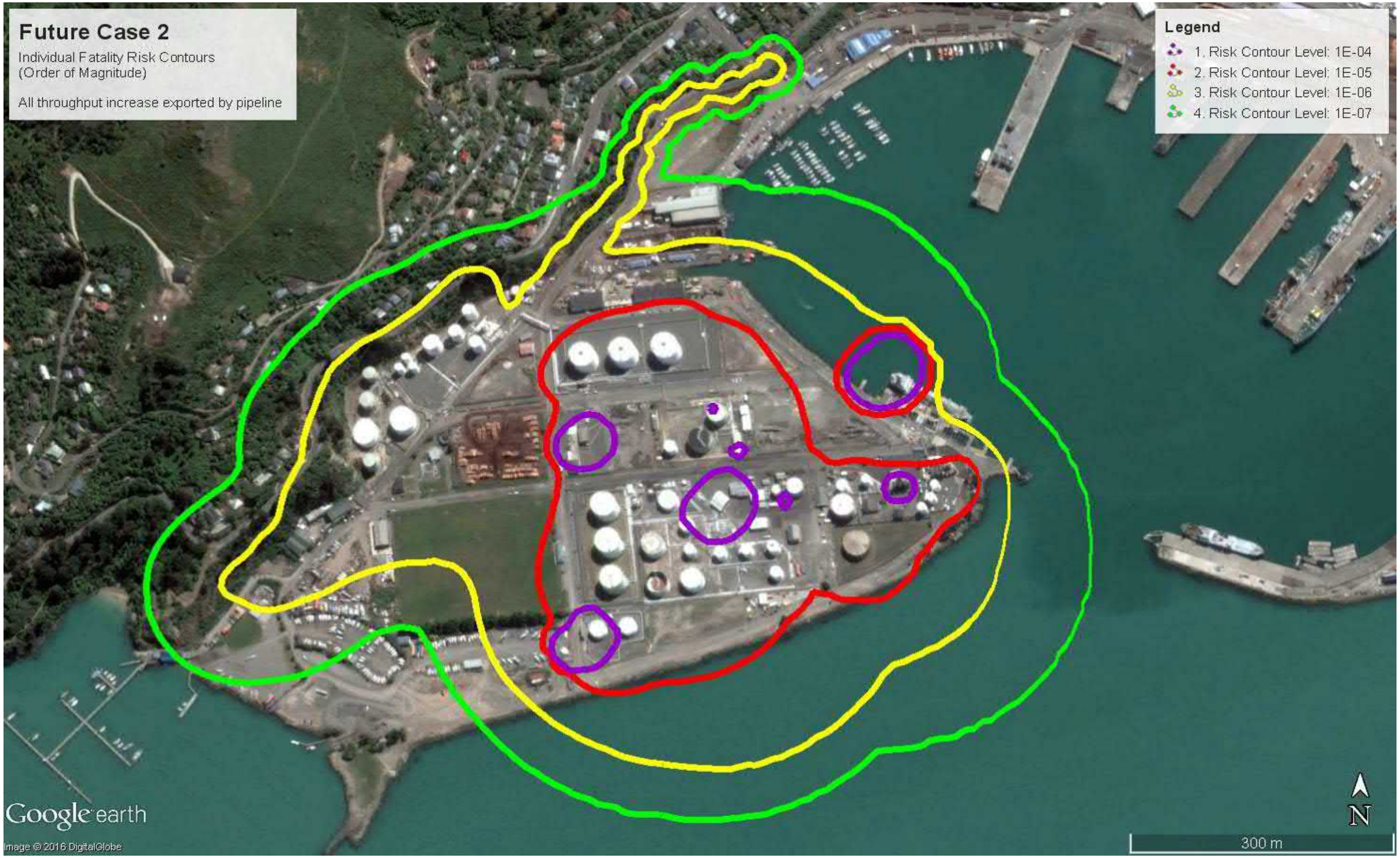


Figure 6.4: Risk contributor analysis point locations

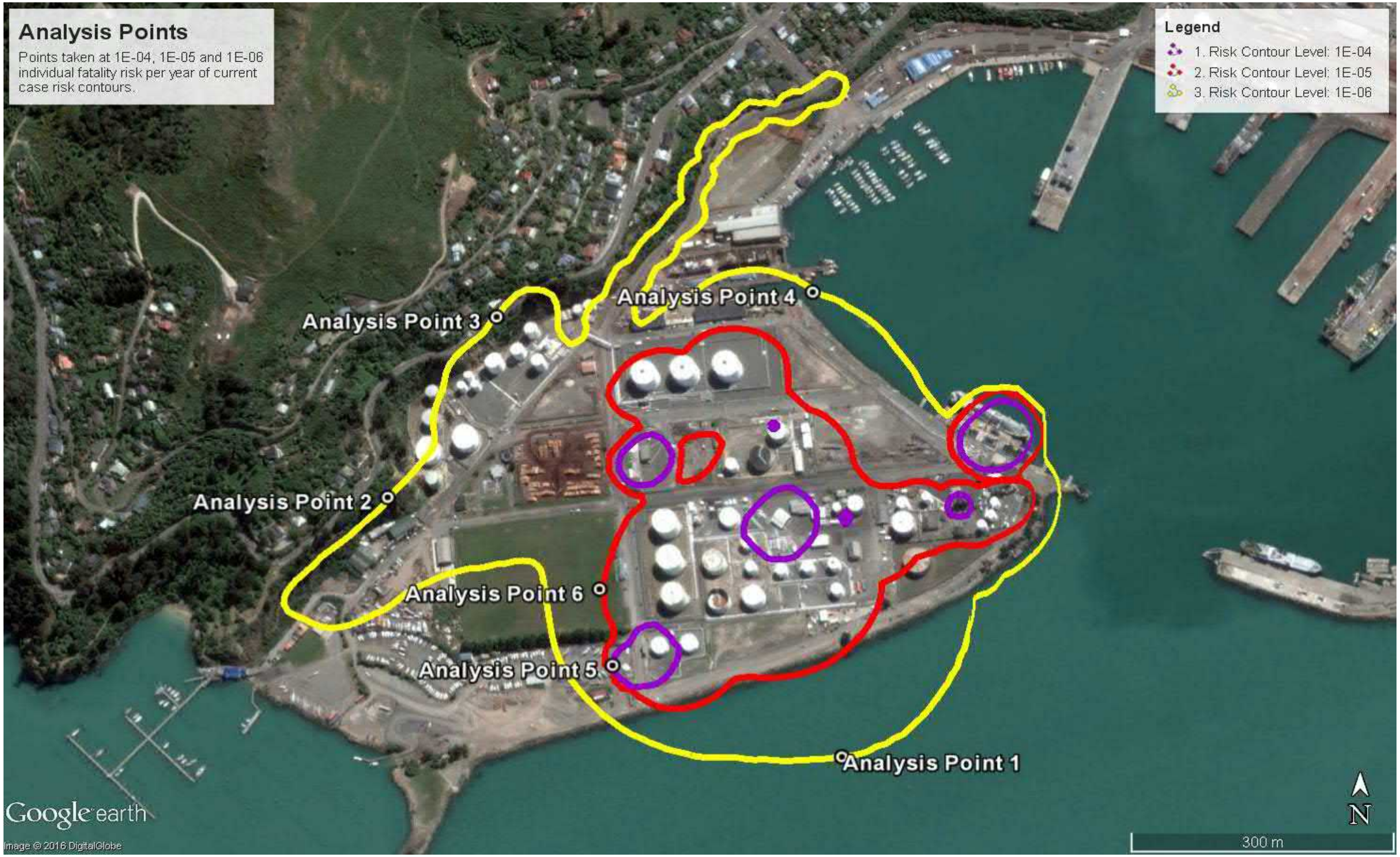


Table 6.1: Major risk contributors at analysis points

Location	Total individual fatality risk at analysis point	Main risk contributors	Contribution at location	
			Current Case	Future Case 1
Analysis Point 1 Cruise ship terminal	1.06 x 10^{-6}/year (Current Case) 1.35 x 10^{-6}/year (future case 1)	Flash fire – gasoline tanks x 4 (mechanical failure)	94%	93%
		Flash fire – gasoline tanks x 5 (tank overfill)	6%	7%
Analysis Point 2 Naval Point cliff south	9.62 x 10^{-7}/year (Current Case) 2.00 x 10^{-6}/year (Future Case 1)	Jet fire – LPG transfer pipeline rupture	53%	25%
		Jet fire – LPG transfer pipeline 50 mm leak	33%	15%
		Pool fire – mechanical failure of Naval Point diesel tanks and spill from bund due to ground movement (earthquake)	11%	21%
		Bund fire – diesel tanks x 5 (mechanical failure)	-	14%
		Pool fire – mechanical failure of Naval Point diesel tanks due to landslip	-	11%
Analysis Point 3 Naval Point cliff north	1.07 x 10^{-6}/year (Current Case) 1.32 x 10^{-6}/year (Future Case 1)	Tank roof fire – diesel tanks x 2	59%	47%
		Pool fire – mechanical failure of Naval Point diesel tanks and spill from bund due to ground movement (earthquake)	20%	18%
		Bund fire – diesel tanks x 4 (mechanical failure)	12%	18%
		Pool fire – mechanical failure of Naval Point diesel tanks due to landslip	6%	10%
		Flash fire – gasoline tank (mechanical failure)	2%	2%
Analysis Point 4 Northwest port area near dry dock and proposed marina	9.54 x 10^{-7}/year Current Case) 2.00 x 10^{-6}/year (Future Case 1)	Pool fire – mechanical failure of gasoline tanks and spill from bund due to ground movement (earthquake)	51%	48%
		Flash fire – gasoline tank (mechanical failure)	40%	43%
		Flash fire – gasoline tank (tank overfill)	9%	8%

Location	Total individual fatality risk at analysis point	Main risk contributors	Contribution at location	
			Current Case	Future Case 1
Analysis Point 5 General recreational area (south west boundary)	1.21 x 10-4/year (current case) 1.22 x 10-4/year (Future Case 1)	Jet fire – methanol road tanker loading hose 22 mm leak	95%	94%
		Bund fire – methanol tanks x 2 (mechanical failure)	2%	2%
		Flash fire – gasoline tanks x 3 (mechanical failure)	2%	2%
Analysis Point 6 General recreational area (north west boundary)	9.15 x 10-6/year (Current Case) 1.02 x 10-5/year (Future Case 1)	Bund fire – gasoline tanks x 3 (mechanical failure)	43%	44%
		Flash fire – gasoline tanks x 3 (mechanical failure)	26%	31%
		Pool fire – mechanical failure of gasoline tanks and spill from bund due to ground movement (earthquake)	11%	8%
		Bund fire – jet fuel tank (mechanical failure)	10%	9%

7. SOCIETAL RISK RESULTS

7.1. Methodology

Societal risk is a measure of the probability of incidents affecting an actual population (rather than a theoretical individual as in individual risk), i.e. takes into account the number of people exposed to risk. Probability of presence is accounted for, and mitigating effects such as whether people are located inside or outside, or emergency response occurs can also be accounted for where relevant.

Within the risk software, a point population or population density is defined at relevant locations in the geographic area around the sites. Inside and outside populations are defined separately to allow for different exposures. For every event scenario the risk software estimates the total number of fatalities (inside and outside) for each grid point with population within the predicted consequence area for each hazardous event scenario. Each wind direction and stability class is considered separately for each scenario and the results are cumulated for each scenario to create a series of frequency (F) – Number of fatality (N) points that are presented as an FN curve.

The FN curve represents cumulative frequency (F) of N or more fatalities occurring over all geographic points within the study area, taking into account populations and their probability of presence. The cumulative FN curve cannot be directly related to individual fatality risk contours which show the probability of fatality per year at specific locations regardless of whether a person is there or not.

7.2. Population data

Population estimates for the areas within the Port Area around the bulk storage facilities as defined in the study area scope in Figure 3.1 are given in APPENDIX A

A current population estimate (reflecting the existing land uses) and a future estimate for potential additional land uses such as the cruise ship terminal and additional recreational facilities as advised by CCC and LPC have been included. These have been grouped into logical areas, a probability of presence allocated for day or night (i.e. number of days per year the population may occur to allow for peak populations) and then entered into Riskcurves which converts the data into population densities.

By convention, population on the sites generating the risk are set to zero. In this case the populations for all bulk storage facilities and the hazardous substances wharf have been set to zero.

7.3. Day and night populations

Weighting factors have been applied to the raw data to distribute population between inside and outside populations and day and night. The factors used are summarised in Table 7.1.

Due to the nature of the area, all populations are assumed to be outside. This may overestimate the actual exposure of populations inside buildings to fire events, however there are few buildings in the vicinity of the bulk storage facilities.

Table 7.1: Population data factors

Factor	Value	Comments
Day and Night Time Weighting Factor	0.5	Assumed that day is 6am to 6pm.
Fraction of people outside	1	Few buildings in the vicinity of the bulk storage facilities

7.4. Societal risk results

7.4.1. Existing populations

The Current Case societal risk results (i.e. Current Case for bulk storage facilities combined with current population estimated for the existing surrounding land uses) are shown in Figure 7.1. Note that the HIPAP 4 indicative societal risk criteria are also shown in Figure 7.1 to provide some context to the FN curve results.

7.4.2. Future populations

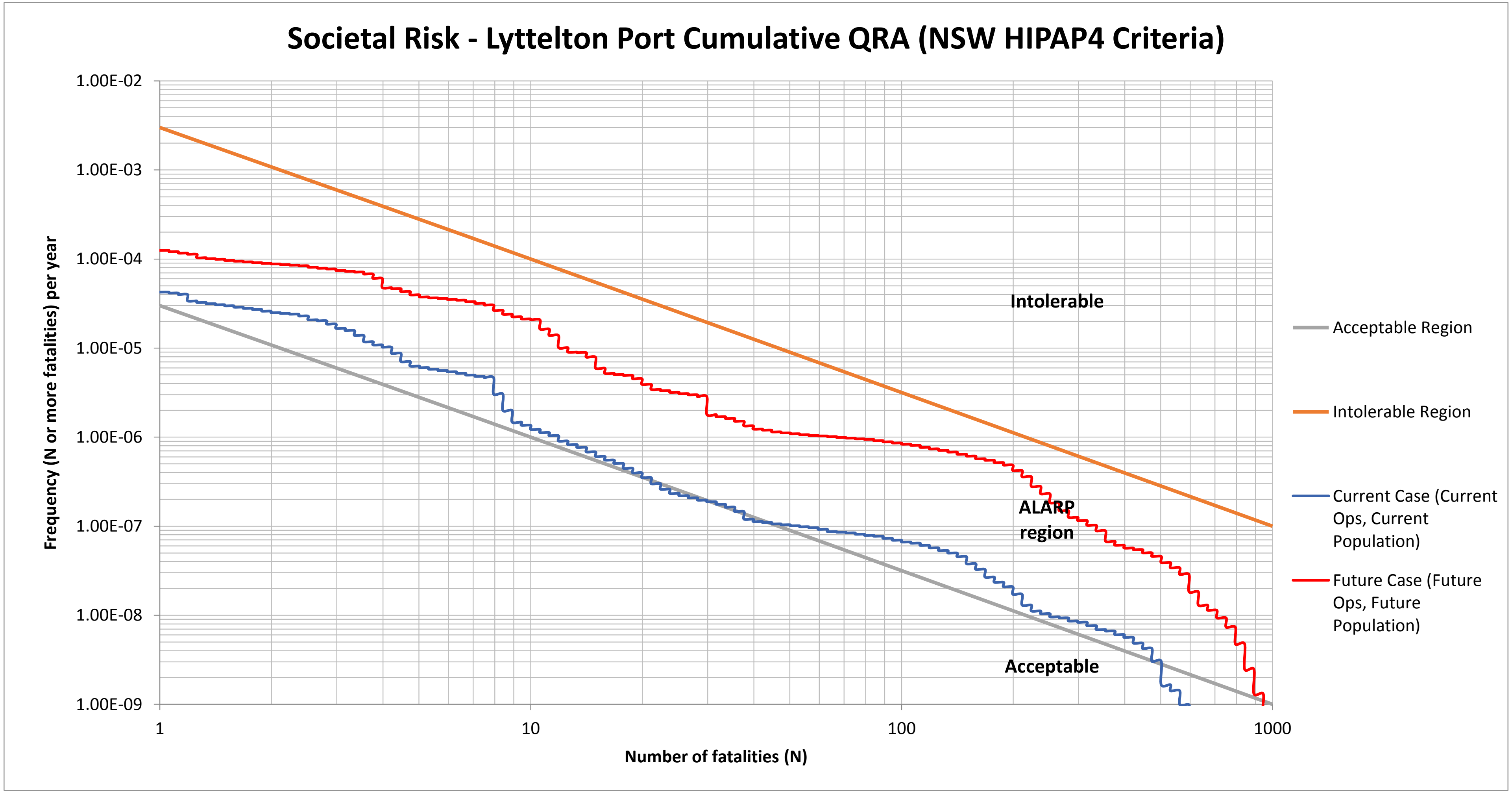
As per APPENDIX A, some increases in potential future populations were advised by CCC. These have resulted in a significant increase in the societal risk results for the Future Case as shown in Figure 7.1 compared against the Current Case with existing land use current population.

APPENDIX G contains a sensitivity study showing the effect on societal risk of the Future Case increase in storage facility operations, but with no population change.

The sensitivity case for increased operations only shows a very small increase in societal risk compared to the effect on societal risk of the large increase in numbers (‘N’ on the FN curve) in the Future Case population.

This means that changes in population density in the vicinity of either the Current or Future storage facility operations results in a far greater risk increase than the effect of increased storage and throughput operations alone (as defined in the Future Case).

Figure 7.1: Societal risk results – FN curve (HIPAP 4 indicative FN criteria also shown to provide context for results)



8. CONCLUSIONS

Based on the risk results presented in Sections 6 and 7, the following conclusions can be drawn relating to the land use safety planning implications for current and future land uses:

- The risk to the existing residential area along Brittan Terrace in either the current or future growth case from incidents involving hazardous substances is approximately 1 x 10^{-6} per year. Only low hazard products are stored in this area and event frequencies hence risk levels are correspondingly low. Storage of higher hazard products (flammables) would increase the risk level in this area. It should also be noted that whilst not on the same basis, the estimated individual fatality risk level due to hazardous substances incidents (which does not include an exposure factor) is at least one order of magnitude below the existing natural hazards annual individual fatality risk (which does include exposure factors) identified in the residential area due to rockfall (which is approximately 10^{-4} to 10^{-5} per year based on the risk results provided by CCC and reproduced in Figure F. 7, APPENDIX F).
- The risk level in the recreational areas in the western Port area is generally below 1 x 10^{-6} per year however is well above 1 x 10^{-6} per year at the recreational sporting oval.
- The public roads running east - west between the different storage facilities (George Seymour Quay, Charlotte Jane Quay) are exposed to fatality risk levels significantly exceeding 1 x 10^{-5} per year. Pipelines are also located in publicly accessible areas alongside these roads which are used for parking during sporting events.
- Godley Quay (running north-south) along the western side of the bulk storage facilities is also exposed to fatality risk levels significantly exceeding 1 x 10^{-5} per year. Godley Quay is the only access route in and out of the Port area.
- The risk level at the proposed cruise ship location is approximately 1 x 10^{-6} per year. Disembarkation would result in large numbers of people on the shore within the immediate vicinity of the risk affected areas at the southern part of the bulk storage facilities. This would result in exposure of high populations to risk levels exceeding 1 x 10^{-5} per year and a corresponding increase in societal risk. It may also introduce elevated probabilities of ignition sources compared to average ignition probabilities assumed in the QRA, further increasing the risk profile (although this effect has not been quantified).
- Sensitivity studies around the societal risk results indicate that increases in population, particularly in near vicinity to the bulk storage facilities such as the cruise ship disembarkation area, result in a significant societal risk increase. Increases in the bulk liquids facilities storage and operational throughputs (as defined in the Future Case), but with no change in surrounding population, have only a very small effect on societal risk. This means that the societal risk

results are more sensitive to the potential population increases than they are to increases in source risk from the defined Future Case storage and throughput growth at the bulk liquids facilities.

- Godley Quay is the only entry/exit route to the Port Area. This runs directly north/south within the risk affected areas alongside of the bulk storage facilities. Whilst emergency response by emergency services is not quantitatively accounted for in the fatality risk calculations, it is an important means of limiting event escalation, managing third party populations, and in limiting consequential losses such as extended fuel supply interruption. An incident may block this route, potentially compromising both access by emergency services in response to an incident, or evacuation of populations in an emergency.
- Whilst outside the scope of land use safety planning, an incident at the bulk storage facilities could also affect other infrastructure in the Port area.

APPENDIX A. POPULATION DATA

CCC and LPC have provided estimates of populations for the existing and potential future land uses in the Port area.

Population estimates used in the QRA are shown in the data table in Section A1 with the definitions of each time period given in Table A.1. The sites where populations have been increased for the Future Case are highlighted in the table. The areas to which the populations apply are shown in Section A2.

For the general recreational area, the population will vary considerably throughout different times during the day and night. For this area, the population taken over an entire 12 hour day or night period was taken as the average of the variable hourly populations provided by Council.

As is standard in land use planning QRA, populations on the sites generating the risk are set to zero. In this case the populations for all bulk storage facilities and the hazardous substances wharf has been set to zero.

Note: There are no populations allocated for areas outside the Port area, i.e. residential populations along Brittan Terrace are not included as these are outside the QRA scope area as per Figure 3.1. The individual fatality risk results show the risk is below 1 x 10^{-6} per year in this area in any case. This is low density housing hence these areas will not substantially affect the Port area cumulative societal risk. In addition, this area is at a higher elevation (top of a cliff more than 30 m high) than the bulk liquids operations, which would provide some exposure mitigation from some hazardous events. This potential mitigation effect has not been accounted for in the individual fatality risk calculations.

Table A.1: Time period definitions

Time period	Applicable population area	Definition (i.e. probability of presence)
Day	All areas	12 hour daylight period from 6am - 6pm
Night	All areas	12 hour overnight period from 6pm - 6am
Weekday	All areas	5 days per week, 52 weeks per year
Weekend	All areas	2 days per week, 52 weeks per year
Peak	General recreational area	6 days per year, 12 hour day period (current case) 9 days per year, 12 hour day period (future case)
	Cruise ship terminal and disembarkation area	70 days per year, 12 hour day period (typical cruise ship) 2 days per year, 12 hour day period (large cruise ship) Note: As advised by LPC ships are not expected to stay overnight except in abnormal circumstances hence there are no night time cruise ship populations included in the model. Typically LPC advised that only 50% of passengers would disembark and pass through the disembarkation area.
	All other areas	2 days per year, 12 hour day period

A1. Population data

	Population increase in Future Case

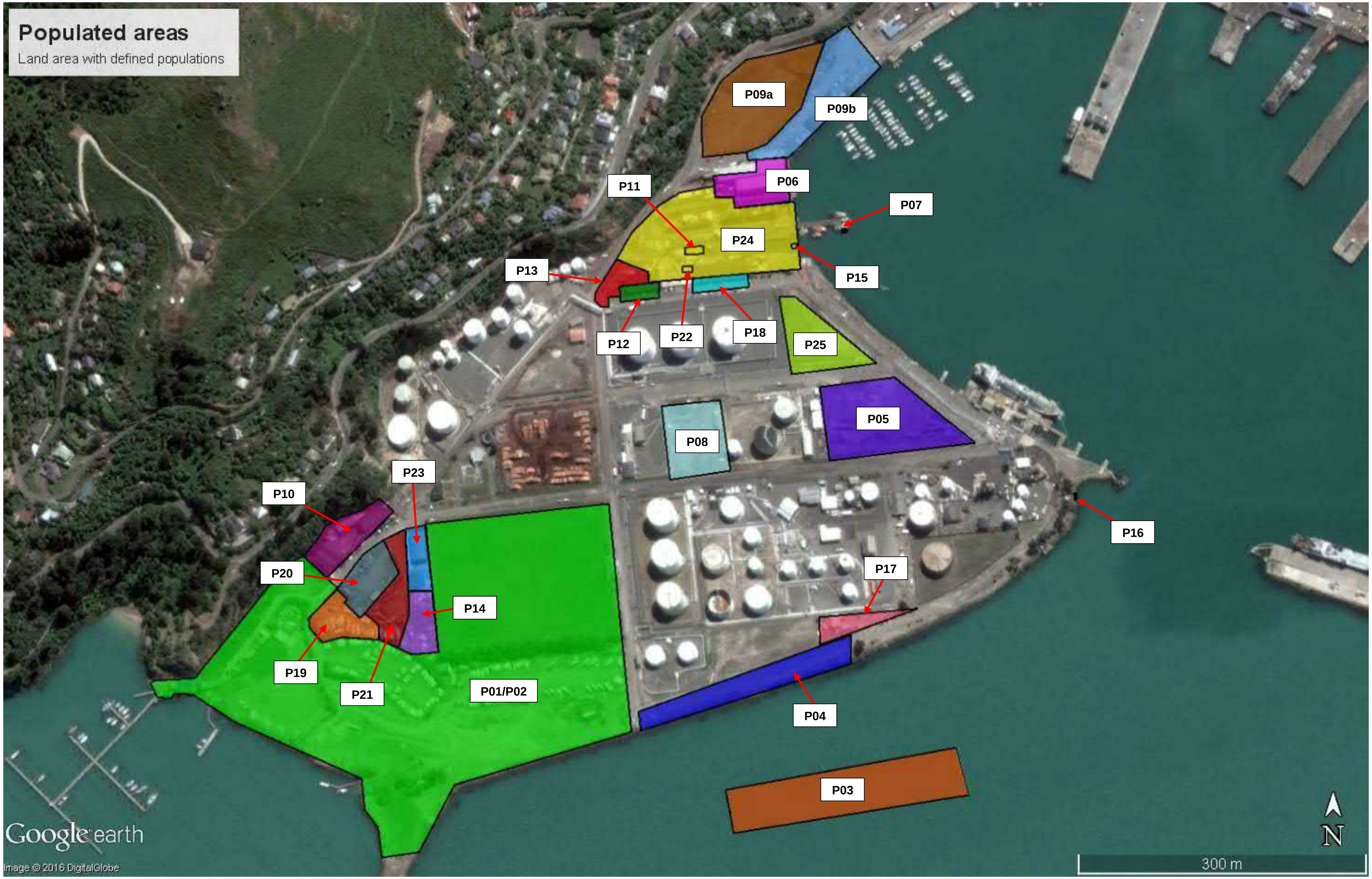
Population area	LPC lot number (if applicable)	Site area (m²)	Land owner	Current occupier	Future occupier	Current case: Weekday day population	Current case: Weekday night population	Current case: Weekend day population	Current case: Weekend night population	Current case: Peak population (any time)	Future case: Weekday day population	Future case: Weekday night population	Future case: Weekend day population	Future case: Weekend night population	Future case: Peak population (any time)
P01/P02			CCC	General recreational area	No change	72	45	155	55	3,700	87	50	196	102	3,860
P03			LPC	No infrastructure / current occupier	Cruise Ship Terminal	0	0	0	0	0	0 (See Note 1)	0	0 (See Note 1)	0	2,000 and up to 5,200 (See Note 1 and Table A.1)
P04			LPC	Area used for fishing	Land connecting to cruise ship terminal / disembarkation area	2	0	10	0	25	2 (See Note 2)	0	10 (See Note 2)	0	25 (See Note 2)
P05	8	9,017	LPC	Construction storage yard - Lyttelton Port Company, not currently leased	Port Activities, possible construction staging yards, grain or fertilizer silos (15-20,000 tonne capacity). See Note 3	0	0	0	0	2	10	1	10	1	30
P06	9	3,908	LPC	Litchfield Holdings / Lyttelton Eng	No change	2	0	0	0	5	2	0	0	0	5
P07	10	216	LPC	Lyttelton Engineering Ltd	No change	2	0	0	0	5	2	0	0	0	5
P08	19	3,819	LPC	Vacant	Potential development (Oil Companies)	0	0	0	0	2	0	0	0	0	0
P09a	37a	9,030	LPC	Vacant (used for steel pile storage)	Car parking, (circa 100 parks) - commercial/retail development, ie; bar, café, restaurant, chandlers, offices	5	0	0	0	50	150	20	200	20	1,000
P09b	37b		LPC	Marina users, public carpark, publicly accessible		20	3	20	3						
P10	56	2,559	LPC	Stark Bros Holdings Ltd	No change	2	0	0	0	5	2	0	0	0	5
P11	59	119	LPC	Grout Seal Ltd	No change	2	0	0	0	5	2	0	0	0	5
P12	68	1,170	LPC	Stark Bros Holdings Ltd	No change	2	0	0	0	5	2	0	0	0	5
P13	69	1,014	LPC	Tissiman House Repairs Ltd	No change	2	0	0	0	5	2	0	0	0	5
P14	69a	13,416	LPC	Vacant (Ex Lyttelton Marina)	No change	0	0	0	0	2	0	0	0	0	2
P15	77	18	LPC	Lyttelton Fishing Co Ltd	No change	2	0	0	0	5	2	0	0	0	5
P16	88	78	LPC	Vodafone NZ Ltd	No change	0	0	0	0	2	0	0	0	0	2
P17	90	1,132	LPC	San-I-Pak Ltd	No change	2	0	0	0	5	2	0	0	0	5
P18	97	961	LPC	Stark Bros Holdings Ltd	No change	2	0	0	0	5	2	0	0	0	5
P19	111	2,415	LPC	Mr David Patchett	No change	2	0	0	0	5	2	0	0	0	5
P20	112a	2,777	LPC	Stark Bros Holdings Ltd	No change	2	0	0	0	5	2	0	0	0	5

					Population increase in Future Case	Current case					Future case				
Population area	**LPC lot number (if applicable)**	**Site area (m²)**	**Land owner**	**Current occupier**	**Future occupier**	**Weekday day population**	**Weekday night population**	**Weekend day population**	**Weekend night population**	**Peak population (any time)**	**Weekday day population**	**Weekday night population**	**Weekend day population**	**Weekend night population**	**Peak population (any time)**
P21	112b	2,717	LPC	Stark Bros Holdings Ltd	No change	2	0	0	0	5	2	0	0	0	5
P22	114	58	LPC	Grout Seal Ltd	No change	2	0	0	0	5	2	0	0	0	5
P23	128	1,584	LPC	Fishing Support Ltd	No change	2	0	0	0	5	2	0	0	0	5
P24	DP 74279		LPC	Dry Dock	No change	15	2	4	2	145	15	2	4	2	145
P25	Unmarked		LPC	Vacant (east of lot 51)	Possible yachting club use (or possibly other port activities).	0	0	0	0	2	10	1	10	1	30
					Total	**142**	**50**	**189**	**60**	**4,000**	**302**	**74**	**430**	**126**	**10,364**

Notes:

1. Proposed future case population for cruise ships is not a permanent population. LPC estimate that cruise ships of typically 2,000 people would dock at the port (assumed during the day). At peak, a cruise ship of up to 5,200 people may dock at the cruise ship terminal.
2. Proposed future case population for cruise ship disembarkation area is not a permanent population. LPC estimate that up to half of those on board the cruise ship would disembark and pass through the disembarkation area. Therefore this areas may have up to 2,600 people for several hours each time a cruise ship docks. This is accounted for in the societal risk model as a temporary population
3. LPC advised that there are no specific plans for activities involving non-hydrocarbon storages such as fertilisers, grains etc. They are not included as part of the future growth case. They have very different hazards to the existing hydrocarbon materials handled, a development consent would be required and the risk would require assessment at that time. They are not covered in the QRA.

A2. Populated area map



APPENDIX B. HAZARDOUS MATERIAL PROPERTIES

B1. HSNO classifications

Hazardous substances in NZ are classified according to the Hazardous Substance and New Organisms legislation (HSNO). A subset of classifications applicable to the types of materials handled at the Lyttelton bulk storage facilities is given below.

Class 2.1.1, 3.1 and 6.1 are relevant classifications from a QRA perspective as these materials have properties that may have acute effects and potential offsite fatality effects if a loss of containment occurs.

Classification no.	Hazard description
2.1.1	Substances that are flammable gases
3.1	Substances that are flammable liquids
6.1	Substances that are acutely toxic
6.3	Substances that are skin irritants
6.4	Substances that are eye irritants
6.7	Substances that are carcinogenic
6.8	Substances that are reproductive or developmental toxicants
9.1	Substances that have aquatic ecotoxicity
9.3	Substances that have ecotoxicity to terrestrial vertebrates

B2. Representative hazardous material classifications and properties

Property	Gasoline (ULP91, ULP95, ULT98)	Diesel (AGO)	Jet-A1	Avgas	LPG (50/50 propane/ butane)	Ethyl Mercaptan	Methanol	Bitumen
HSNO Classification	3.1A, 6.1E, 6.3B, 6.7B, 9.1B	3.1D, 6.1E, 6.3B, 6.7B, 9.1B	3.1C, 6.1E, 6.3A, 9.1B	3.1A, 6.1E, 6.3B, 6.7A, 6.8A, 9.1B	2.1.1A	3.1A, 6.1C, 6.3B, 6.4A, 6.9B, 9.1A, 9.3C	3.1B, 6.1D, 6.4A, 6.8B, 6.9A, 9.3C	-
Boiling Point (atm.) (ºC)	30-210	216	140-280	40-170	-42	35	65	250-450
Density (kg/m³ at 15-20ºC)	750	750	775-840	710	500	840	795	960-1030
Vapour pressure (kPa at 20ºC)	27-45	0	< 0.1	< 39	740-840	45-60	12	<0.1
Auto-ignition temperature (ºC)	> 350	203	> 220	> 250	450	299	464	400
Flash Point (ºC)	< -40	74	> 38	< -40	-104	-48	11	>215
Lower Flammability Limit (LFL) (ppm)	14,000	6,000	10,000	10,000	20,000	28,000	73,000	7,000
Upper Flammability Limit (UFL) (ppm)	76,000	49,000	60,000	80,000	95,000	180,000	360,000	60,000
AEGL1 (irritation – 30 min)	-	-	-	-	6,900	1.0	670	-
AEGL2 (injury – 30 min) (ppm)	-	-	-	-	-	150	4,000	-
AEGL3 (onset of fatal effects – 30 min) (ppm)	-	-	-	-	-	450	14,000	-
Flammable (Note 1)	Yes	Combustible	Yes	Yes	Yes	Yes	Yes	Cutback bitumen only is flammable

Property	Gasoline (ULP91, ULP95, ULT98)	Diesel (AGO)	Jet-A1	Avgas	LPG (50/50 propane/ butane)	Ethyl Mercaptan	Methanol	Bitumen
Toxic (Note 2)	No	No	No	No	No	See Note 5		See Note 3

Notes:

1. ‘Flammable’ is defined as flash point > 61ºC.
2. ‘Toxic’ means acutely toxic. Some hydrocarbons also have potential chronic toxicity and carcinogenic health effects - these are not addressed in the QRA.
3. Bitumen generates fumes containing hydrogen sulfide which is toxic. Concentration in tank vapour space and vents is typically up to around 1000 ppm. This is a significant hazard to workers in the immediate vicinity of tank vents but does not present a significant risk offsite although odours may be an issue.
4. This table shows a range of fuels and products that are most commonly handled at the sites. There are other grades of fuels and oils however these have very similar properties.
5. Small quantities of mercaptan at wharf for odourising LPG. Mildly toxic and highly odourous.

APPENDIX C. METEOROLOGICAL DATA AND MODELLING INPUTS

C1. Meteorological data

Historical meteorological data was obtained for the bulk liquid sites in the Port of Lyttelton area. The data sets obtained were for the Z Berth (located within 1.5 km of each of the sites) from April 2011 – April 2016.

Analysis of the data was performed using the methodology outlined in the TNO Purple Book to obtain the representative weather conditions (including wind speed and stability classes) appropriate for the QRA, (Ref 4).

As cloud cover data was unavailable, representative atmospheric stability conditions were determined based on the wind speed and whether occurrence was during the day or at night. This is less accurate than including cloud cover data.

All low wind speed data (< 4 m/s) during daytime was allocated to a B stability class. An overview of the rule set used to determine the representative weather conditions using the TNO Purple Book approach is shown in Table C.1.

Table C.1: Rule set for representative weather conditions

Time of day	Wind speed range (m/s)	Pasquill stability class	Average wind speed (m/s)
Day	< 4	B	2.0
	4 – 7	D	5.3
	> 7	D	9.3
Night	< 2.5	F	1.3
	2.5 – 4	E	3.1
	4 – 6	D	4.9
	> 6	D	8.2

For the QRA model, the D classes were further consolidated into two weather classes due to similarity resulting in five different representative weather conditions which are:

- Pasquill Stability Class: B; wind speed 2.0 m/s (B2.0)
- Pasquill Stability Class: D; wind speed 5.1 m/s (D5.1) [2]
- Pasquill Stability Class: D; wind speed 8.7 m/s (D8.7) [3]
- Pasquill Stability Class: E; wind speed 3.1 m/s (E3.1)
- Pasquill Stability Class: F; wind speed 1.3 m/s (F1.3).

[2] D5.1 is the average wind speed from both the day (D5.3) and night (D4.9) data, as these are very similar.

[3] D8.7 is the average wind speed from both the day (D9.3) and night (D8.2) data, as these are very similar.

A summary of the meteorological data sets used for the hazard assessment are presented in Table C.2. An overall wind rose distribution is also provided in Figure C.1, while a distribution by stability class is shown in Figure C.2.

For a fuel terminal QRA, choice of meteorological data has the following implications:

- High wind speeds result in greater flame tilt and larger effect areas for pool and tank top fire scenarios, however once windspeeds are around 8-9 m/s this makes minimal difference to consequence modelling effect areas. High wind speeds also provide better dispersion and dilution of flammable clouds, lessening effect areas compared to low wind speeds. A D8.7 m/s category at 22% occurrence is included in this dataset. Variations in this aspect of the meteorological data have a minor effect on the QRA in the far field as the changes in consequence are quite small
- Low windspeeds and stable conditions (F stability) result in poor dispersion and large low lying flammable vapour clouds from gasoline spills can form under these conditions. These are predicted to be large, wide and shallow clouds and generally have the largest effect areas in fuel terminal QRAs. An F1.3 m/s category at 16% occurrence is included in this dataset. QRAs with large gasoline spill scenarios included can be quite sensitive to this parameter as a large proportion of these conditions will cause an increase in the risk of worst case events and vice versa. A 16% occurrence is already quite a high proportion compared to other port sites hence the results are unlikely to be underestimated.

Directional probabilities seldom vary significantly on an annualised basis and 5 years data is regarded as sufficient. As there are a number of facilities with overlapping risk contours in this QRA, directional effects are not strongly discernible in the cumulative QRA results.

Table C.2: Meteorological data sets used in risk model

Direction wind *from* (degrees true)	B2.0		D5.1		D8.7		E3.1		F1.3		Total Day	Total Night
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night		
0	2.68	0	1.63	1.03	0.78	0.99	0	1.55	0	3.15	5.09	6.72
30	4.38	0	6.54	4.14	2.20	2.78	0	5.06	0	2.62	13.12	14.60
60	7.80	0	14.50	9.15	4.57	5.79	0	3.48	0	2.11	26.87	20.53
90	3.19	0	0.67	0.42	0.04	0.05	0	0.71	0	1.05	3.90	2.23
120	1.05	0	0.04	0.03	0.01	0.02	0	0.12	0	0.48	1.10	0.65
150	0.71	0	0.06	0.04	0.02	0.02	0	0.09	0	0.40	0.79	0.55
180	1.56	0	0.96	0.61	1.34	1.70	0	0.31	0	0.68	3.86	3.30
210	4.73	0	6.21	3.93	6.68	8.47	0	1.61	0	1.73	17.62	15.74
240	6.57	0	3.49	2.21	1.63	2.07	0	2.08	0	4.15	11.69	10.51
270	4.07	0	0.96	0.60	0.64	0.80	0	1.55	0	4.58	5.67	7.53
300	3.17	0	0.92	0.58	1.15	1.45	0	0.57	0	5.62	5.24	8.22
330	3.31	0	1.05	0.67	0.72	0.91	0	0.97	0	6.85	5.08	9.40
Total	43.22	0	37.03	23.41	19.78	25.05	0	18.10	0	33.42	100.03	99.98

Figure C.1: Wind rose distribution (overall - wind from)

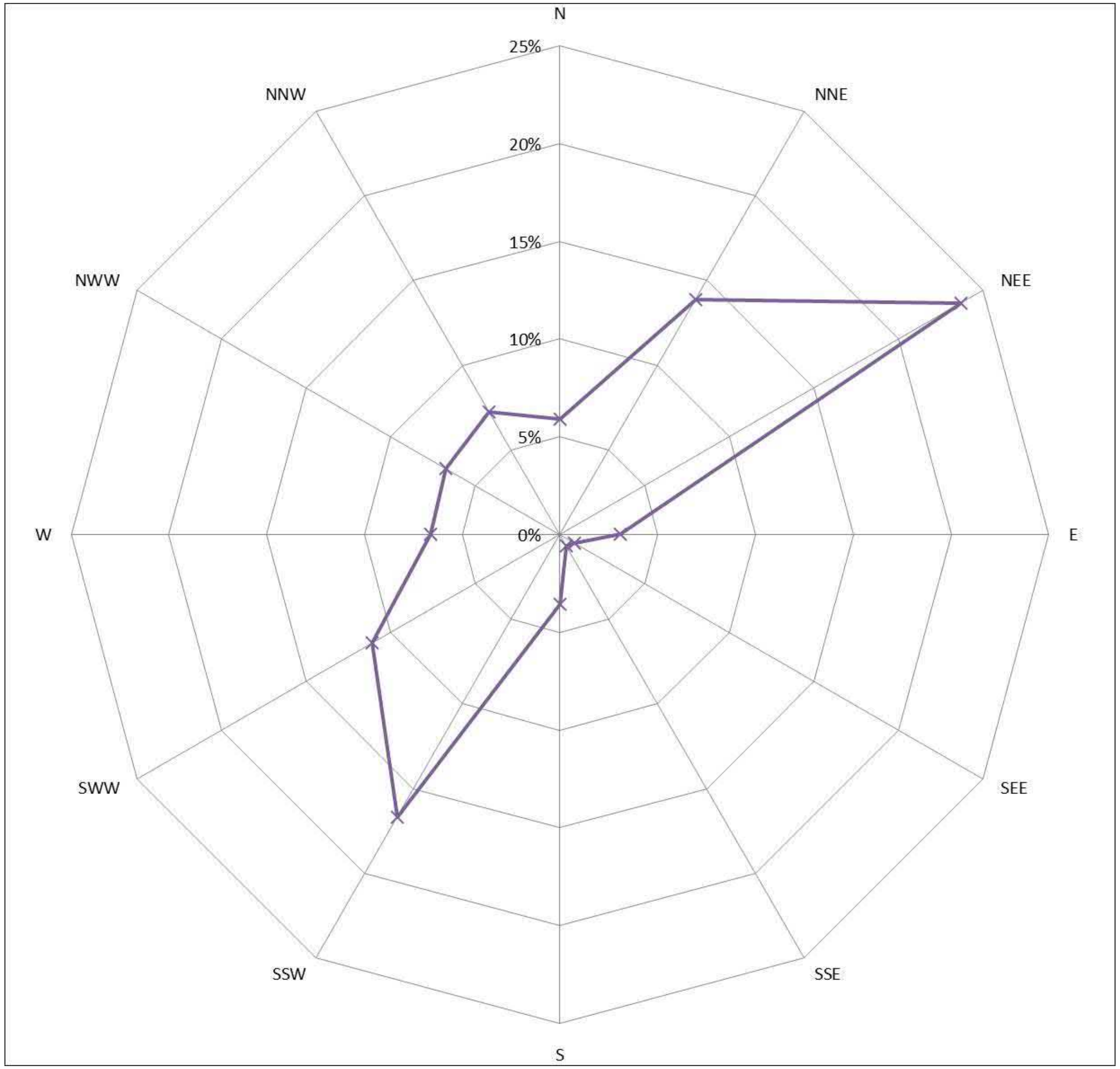
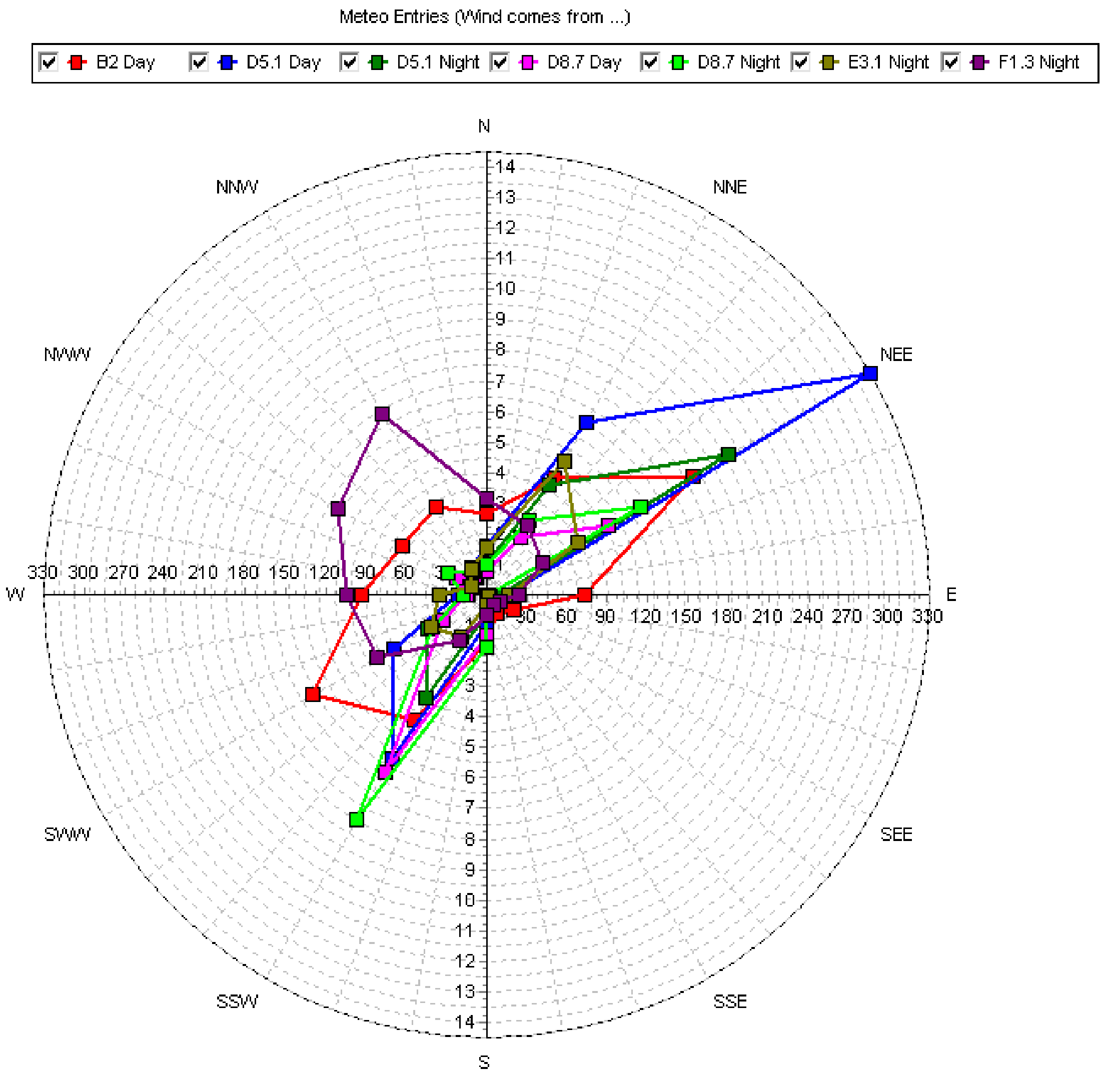


Figure C.2: Wind rose distribution (by stability class)



C2. Overall modelling input assumptions

Standard modelling parameters set for all of the sites and terminals as part of the cumulative QRA are shown in Table C.3.

It was noted that for the types of modelling undertaken (i.e. releases involving non-boiling, ambient temperature hydrocarbon liquids) the results are relatively insensitive to most environmental parameters, with the exception of the ground roughness length and the receptor height used in dispersion modelling.

Table C.3: Modelling parameters

Item	Value	Comments	Effect on overall modelling
Environment			
Ambient temperature	13 ˚C	Weather data, average annual temperature (same assumed for summer/ winter)	Minor
Soil temperature	13 ˚C	Assumed equal to ambient temperature	Minor
Relative humidity	66%	Weather data, average relative humidity (assumed for summer/ winter)	Minor impact – a lower relative humidity corresponds to a slightly larger consequence distance for radiant heat impacts
Solar radiation	1 kW/m^2	Summer/winter insolation - estimated typical value range (0.1 – 1 kW/m^2)	Minor effect for hydrocarbon fuels which are well below boiling point at atmospheric conditions
Surface type	Concrete/ gravel	Affects pool spreading calculation	Minor effect as majority of larger consequences are constrained pools rather than limited by surface spreading
Ground roughness length	0.1 m	Ground roughness affects turbulent flow properties of wind, hence dispersion of a released material. Terrain effects are taken into account to some degree in dispersion modelling by use of a parameter known as surface roughness length. A surface roughness length of 0.1 m will be used corresponding to an area with occasional large objects/obstacles and isolated trees and structures such as the area surrounding the terminals	Can have a significant impact on dispersion results. Higher surface roughness lengths result in smaller dispersion distances. Choice of 0.1 m may underestimate dispersion distances over still calm water, overestimate them in built-up areas
Other model inputs			
Averaging time (flammables)	20 seconds	TNO Yellow Book	

Item	Value	Comments	Effect on overall modelling
Averaging time (toxics)	600 seconds	TNO Yellow Book	
Event durations and exposures			
Maximum exposure duration	1 hour	Unlikely that any emergency response (e.g. covering surface of pool, pump out to tanker etc.) could be executed with 1 hour	
Maximum pool evaporation duration	1 hour		
Receptor height	1.5 m (1 m for flash fires)	For dispersion to LFL, this is taken at 1 m height as models have been verified against experimental values at this height Other scenarios 1.5 m around face height.	Can have a significant impact on dispersion results if receptor is at different elevation to release point. 1 m height selected based on verification of software models against empirical data as per PHAST technical manual

APPENDIX D. CONSEQUENCE MODELLING APPROACH

D1. Release sizes

Loss of containment from equipment was modelled for the representative range of hole sizes in Table D.1 which are consistent with the historical leak frequency data used for the study.

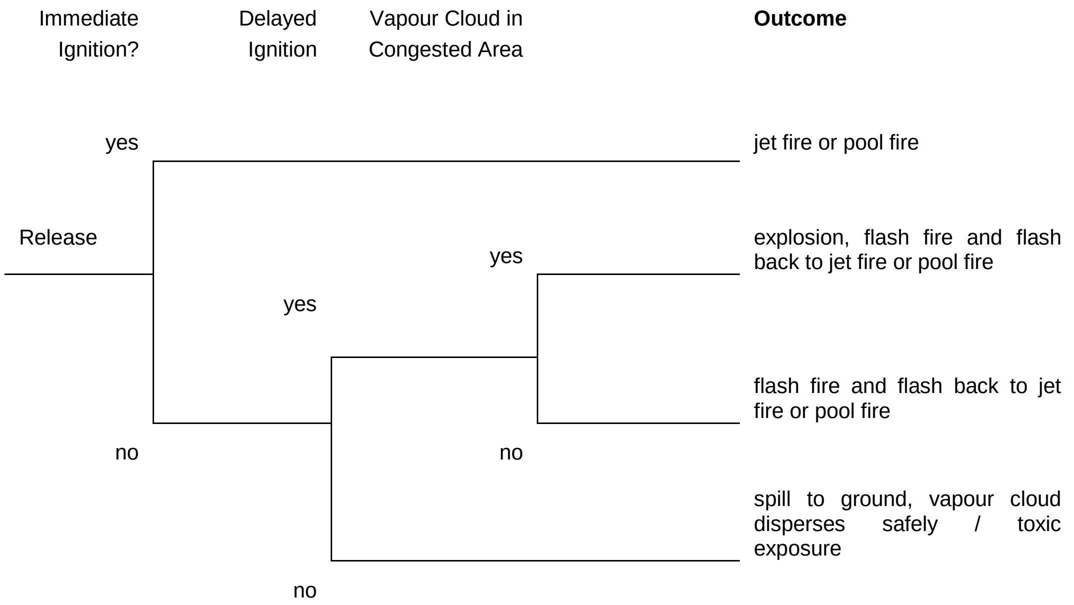
Table D.1: Representative hole sizes for modelling loss of containment

Hole size (mm)	Range (mm)
2	1 to 3
6	3 to 10
22	10 to 50
85	50 to 150
Full bore	> 150

The hole size are the geometric means, which give a weighting towards the lower band, since smaller sized leaks tend to occur more frequently. The hole sizes were assigned as relevant to specific process equipment as per the frequency data in APPENDIX E, Table E.1.

D2. Event tree

An event tree showing the possible outcomes following loss of containment of a flammable or combustible liquid.



D3. Scenarios

When released at pressure, a liquid may form an airborne aerosol and/or fall to the ground and pool. The pressure, hole size and fluid properties including vapour pressure all are factors in whether an aerosol, pool or combination of the two will form.

Only the light components from gasoline such as C4s and C5s will tend to form a vapour cloud from evaporation or an aerosol release. The formation of a vapour cloud depends on the release characteristics and dispersion behaviour as affected by meteorological conditions.

For pumped/pressurised releases, a jet and aerosol is formed except for larger hole sizes where the pressure cannot be sustained (eg pump has insufficient capacity or head).

For liquid releases at low pressure, such as from a tank leak, an evaporating pool and pool fire (given ignition) were modelled.

For loss of containment within a bund, the size of the pool (whether a pool fire or evaporating pool) is limited by the bund size.

Loss of containment of gasoline due to tank overfill (the Buncefield scenario) and the extent of the flammable cloud envelope was modelled following the UK HSE's VCA method (Ref 2), which provides a means of calculating the rate at which the volume of a vapour cloud increases during an overfilling incident, hence predicting the distance to the LFL of the cloud.

The rule set used for the outcome given the material, scenario and ignition is shown in Table D.2.

Table D.2: Scenario rule set for releases

Material	Scenario	Pressure range (barg)	Hole size (mm)	Ignition timing	Consequence modelled
Gasoline	Pumped liquid in pipeline	0-10	2, 6, 22	Immediate	Jet fire
				Delayed	Flash fire
			85, rupture	Immediate	Early pool fire
				Delayed	Flash fire
	Pipeline filled but not pumped	Atmospheric	All sizes	Immediate	Early pool fire
				Delayed	Flash fire
	Storage tank – mechanical failure	Atmospheric	1000 mm hole, rupture	Immediate	Bund fire
				Delayed	Flash fire
Diesel/ Jet Fuel	Pumped liquid in pipeline	0-10	2, 6, 22	Immediate	Jet fire
				Delayed	Late pool fire
			85, rupture	Immediate	Early pool fire
				Delayed	Late pool fire
	Pipeline filled but not pumped	Atmospheric	All sizes	Immediate	Early pool fire
				Delayed	Late pool fire
	Storage tank - mechanical failure	Atmospheric	1000 mm hole, rupture	Immediate	Bund fire
				Delayed	Bund fire

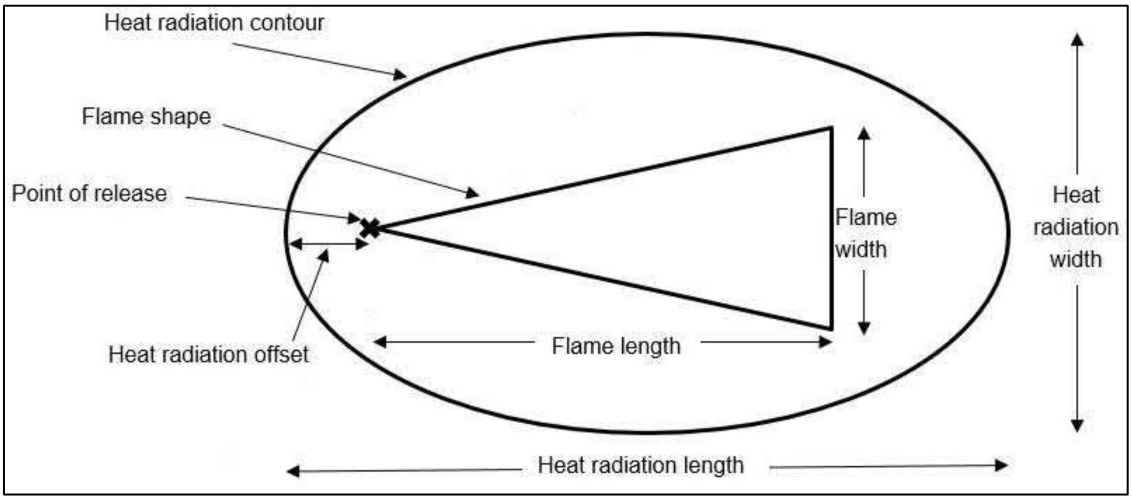
Material	Scenario	Pressure range (barg)	Hole size (mm)	Ignition timing	Consequence modelled
Methanol	Pumped liquid in pipeline	0-10	2, 6, 22	Immediate	Jet fire
				Delayed	Flash fire
				Unignited	Toxic dispersion
			85, rupture	Immediate	Early pool fire
				Delayed	Flash fire
				None	Toxic dispersion
	Pipeline filled but not pumped	Atmospheric	All sizes	Immediate	Early pool fire
				Delayed	Flash fire
				Unignited	Toxic dispersion
	Storage tank – mechanical failure	Atmospheric	1000 mm hole, rupture	Immediate	Bund fire
				Delayed	Flash fire
				Unignited	Toxic dispersion
LPG[1]	Pressurised liquid in pipeline	10-50	All sizes	Immediate	Jet fire
				Delayed	Flash fire

Notes:
1. LPG with a significant proportion of propane that is not refrigerated does not pool on release due to high flash fraction and low boiling point so LPG pool formation is not credible in this case.

D4. Jet/spray fires

A diagram showing the definition of each of the dimensions reported is shown in Figure D.1.

Figure D.1: Jet fire consequence diagram (top view)



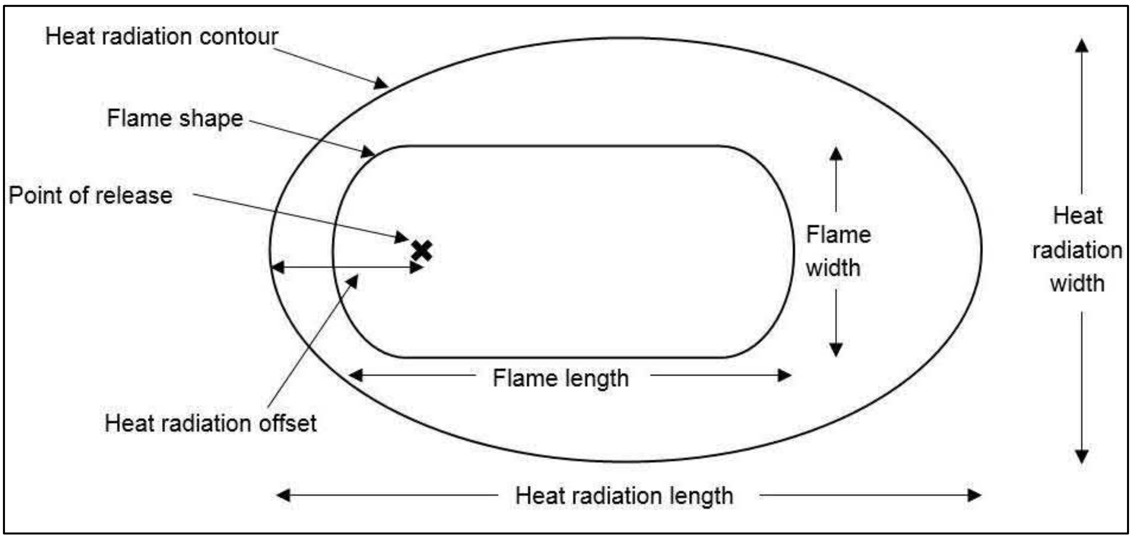
Typical jet fire results for the current and future case operations are summarised in Table D.3.

This table provides the dimensions of the jet/spray fires for each identified release condition for gasoline release sizes less than 25 mm, as per rule set outlined in Table D.2. Distances to heat radiation levels of interest are also reported. These results represent a continuous release without isolation which represents the worst case scenario for any given leak.

D5. Pool fires

In this assessment, spills of a liquid hydrocarbon from a leak were assumed to form a circular pool (spreading in all directions), unless limited by a bund, terrain or drainage. The reported results include the release rate, equivalent pool diameter and distance to heat radiation levels of interest. Early and late pool fires were considered in this assessment. A diagram showing the definition of each of the dimensions reported is shown in Figure D.2.

Figure D.2: Pool fire consequence diagram (top view)



D5.1. Early pool fires

Early pool fires were defined assuming equilibrium where the burn rate equals the release rate of the material. Subsequently, the pool fire dimensions were calculated assuming an equilibrium pool diameter where the burn rate equals the release rate of the material. If the equilibrium pool diameter exceeded the area limited by bunds, terrain or drainage; the consequence distances were set to those predicted by the pool fire limited by the bund dimensions.

Early pool fires were considered as the immediate ignition event for leaks greater than 25 mm for gasoline and less than 25 mm for leaks of diesel and jet fuel. Examples of early pool fire results are summarised in Table D.4.

D5.2. Late pool fires

Late pool fires were defined assuming a delayed ignition where the pool formed is able to spread to an area limited by bunds, the terrain or drainage. Examples of late pool fire results are summarised in Table D.5.

The limiting sizes used in the QRA for different release locations were:

- Fuel wharf: 20 m diameter pool
  - Basis - limited by width of fuel wharf.
  - Kerbed area provided in immediate area around the MLAs would be filled within a few minutes, hence it was assumed all larger releases would spread over the entire wharf.
- Import wharflines: 40 m diameter pool
  - Basis - limited by the width of Charlotte Jane Quay alongside the pipelines.
  - Note: this assumed diameter is conservative as it covers both the road and the adjoining site verge.
- Wharfline manifold: 20 m diameter pool
  - Basis - limited by Charlotte Jane Quay and the Charlotte Jane bund wall.
- Pump and manifold: site specific
  - Basis – Pumps are located within bunded area limiting pool growth for large releases.
- Road gantry: site specific (typically 12m – 20m width)
  - Basis – Gantry is kerbed with drainage limiting pool growth for large releases.

D6. Flash fires

Vapour clouds result from either:

- evaporation of light components of releases of gasoline which pool on the ground. Similar to pool fires, the maximum size of a pool is limited by bund walls. The limiting sizes are described in Section D5.
- momentum jet pressurised releases.

The rate of evaporation and the dispersion characteristics from a spill are dependent on the weather conditions. The modelling results indicate that flammable clouds larger than the source pool develop primarily under low wind speed conditions.

Flash fire modelling was only undertaken for gasoline due to the presence of hydrocarbon ‘light ends’ (typically C4-C5), which are not present in heavier fuel such as diesel and jet fuels. Vapour clouds from gasoline spills are denser than air.

The results of the flash fires assessment for both the current and future operation are summarised as follows:

- Major leaks from storage tanks resulting in pool evaporation of bund contents resulting in flammable vapour clouds (Table D.6)
- Pressurised releases resulting in momentum jet releases (for hole sizes < 22 mm) and pool evaporation (for hole sizes < 22 mm) based on the rule set defined in Table D.2 (Table D.7).

All modelling results for flash fires are reported in terms of the longest dimension (effect zone) to LFL concentration. For pool evaporation releases the length and width of the flash fire were assumed to be equal to the longest dimension as pool evaporation at low wind speed tends to disperse evenly in both downwind and crosswind. For momentum jet releases, both the length and width are input into the QRA model however only the longer dimension is shown in the results tables.

Flash fires were modelled for steady state (equilibrium) case assuming a continuous release without isolation or detection, and therefore represent the worst case cloud size. Ignition of the cloud before equilibrium, for example due to the presence of a fixed high strength ignition source before cloud reaches equilibrium would result in a smaller flash fire.

Table D.3: Typical spray fire consequence results

Component/equipment	Product	Pressure (barg)	Hole size (mm)	Release rate (kg/s)	Spray fire distances at 1.5 m receptor height (m) @ D8.7													
					Flame		4.7 kW/m^2			6 kW/m^2			12.5 kW/m^2			23 kW/m^2		
					Length	Width	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset
Wharfline -	Gasoline	10	2	0.1	3	1	9	10	-1	8	9	-1	6	6	0	5	5	0
			6	0.7	8	4	24	28	-4	21	25	-3	17	18	-1	14	14	-1
			22	9.2	25	11	83	100	-17	74	88	-12	54	61	-4	46	47	-2
Loadout Pumps and Manifold	Gasoline	5	2	0.1	3	1	7	8	-1	7	8	-1	5	5	0	4	4	0
			6	0.5	7	3	20	24	-3	18	22	-2	15	15	-1	12	12	0
			22	6.5	22	10	71	86	-13	63	76	-10	47	53	-3	40	41	-2

Table D.4: Typical early pool fire consequence results

Component/ equipment	Product	Pressure (barg)	Hole size (mm)	Release rate (kg/s)	Equivalent pool diameter (m)	Pool fire distances at 1.5 m receptor height (m) @ D8.7											
						4.7 kW/m^2			6 kW/m^2			12.5 kW/m^2			23 kW/m^2		
						Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset
MLA - Ship Import Wharfline Manifold	Gasoline	10	85	137	20.0	68	65	-14	61	57	-12	38	36	-11	24	25	-11
			RUP	265	20.0	68	65	-14	61	57	-12	38	36	-11	24	25	-11
			RUP	169	40.0	103	98	-23	93	85	-21	53	55	-21	-	-	-
Loadout Pumps and Manifold Road Gantry	Gasoline	5	85	21	15.9	61	60	-13	55	52	-11	38	33	-9	22	23	-9
			RUP	21	15.9	61	60	-13	55	52	-11	38	33	-9	22	23	-9
			RUP	36	34.2	68	66	-13	62	57	-10	38	36	-9	24	25	-9
All scenarios	Diesel	10	2	0.1	1.6	29	10	0	28	9	0	27	6	0	26	4	0
			6	1	4.9	39	23	0	38	20	0	35	13	0	32	9	0
			22	10	18.0	68	51	0	65	45	0	57	29	0	57	29	0
			6	0.06	1.4	9	10	-1	8	9	0	7	6	0	6	4	0
			22	0.82	5.2	24	26	-5	22	23	-4	17	16	-1	14	11	-1
Note: "-" indicates heat radiation level was not reached																	

Table D.5: Typical late pool fire consequence results

Component/ equipment	Product	Pressure (barg)	Hole size (mm)	Release rate (kg/s)	Equivalent pool diameter (m)	Pool fire distances at 1.5 m receptor height (m) @ D8.7											
						4.7 kW/m^2			6 kW/m^2			12.5 kW/m^2			23 kW/m^2		
						Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset
MLA - Ship Import Wharfline Manifold	Diesel	10	85	148	20.0	75	70	-15	68	60	-12	40	37	-11	24	25	-11
			RUP	293	20.0	75	70	-15	68	60	-12	40	37	-11	24	25	-11
			RUP	161	40.0	112	101	-23	95	87	-21	53	55	-21	-	-	-
Loadout Pumps and Manifold Road Gantry	Diesel	5	85	24	20.0	75	70	-15	68	60	-12	40	37	-11	24	25	-11
			RUP	24	20.0	75	70	-15	68	60	-12	40	37	-11	24	25	-11
Pipeline	Diesel	5	85	20	40.0	112	101	-23	95	87	-21	53	55	-21	-	-	-
			RUP	20	40.0	112	101	-23	95	87	-21	53	55	-21	-	-	-
			RUP	106	40.0	94	94	-23	86	82	-21	53	55	-21	-	-	-
Note: "-" indicates heat radiation level was not reached																	

Table D.6: Typical Flash fire consequence results – storage tanks (major leak – pool evaporation)

Component/ equipment	Product	Equivalent pool diameter (m)	Hole size (mm)	Distance to LFL (effect zone) at 1.5 m receptor height (m)				
				B2.0	D5.1	D8.7	E3.1	F1.3
Storage tanks – Current								
TKXX1	Gasoline	105	1000	155	-	-	136	274
			RUP	254	183	142	202	322
			RUP	220	178	141	198	328
TKXX2	Gasoline	77	1000	46	-	-	10	215
			RUP	117	110	111	108	188
			RUP	220	178	141	198	328
Note: "-" indicates LFL was not reached								

Table D.7: Typical Flash fire consequence results – pressurised releases

Component/ equipment	Product	Pressure (barg)	Hole size (mm)	Release rate (kg/s)	Distance to LFL (effect zone) at 1.5 m receptor height (m)				
					B2.0	D5.1	D8.7	E3.1	F1.3
Wharfline - Ship Import	Gasoline	10	2	0.1	-	-	-	-	-
			6	0.7	-	-	-	-	-
			22	9.2	66	61	54	76	88
			85	137	30	-	-	31	59
			RUP	265	36	-	-	38	59
Loadout Pumps and Manifold Road Gantry	Gasoline	5	2	0.1	-	-	-	-	-
			6	0.5	-	-	-	-	-
			22	6.5	48	34	35	53	70
			85	21	-	-	-	-	-
			RUP	21	-	-	-	-	-
Note: "-" indicates LFL was not reached									

D7. Tank top full surface fire

The tank top full surface fire scenario was assessed for all tank types. For a floating roof tank this scenario represents the collapse of internal floating roof resulting in a full surface roof fire and subsequent collapse of the external roof. The tank top full surface fire consequence results are presented in Table D.8.

D8. Tank bund fire

This scenario was assessed to represent mechanical failure/leaks from storage tank forming a large pool which may cover up to the full bund area (e.g. instantaneous release) and subsequently ignite. The tank bund fire consequence results are presented in Table D.9.

D9. Escalation

From the consequence assessment, an assessment was made to check if there is the potential for consequence propagation to tanks both within a Terminal and to tanks at other sites. The distance of the heat radiation contours reported was taken as the maximum distance from the centre of the tank at any height.

For escalation, the radiation levels of interest were as follows:

- 8-12 kW/m^2 – which represents the thermal radiation above which cooling of a tank may be necessary, based on the Energy Institute's Model Code of Safe Practice Part 19 for Fire Precautions at Petroleum refineries and Bulk Storage Installations (Ref 11). The average value of 10 kW/m^2 was chosen.
- 23 kW/m^2 – radiation at which escalation to equipment in the vicinity of a fire could occur, or rapid escalation to a tank inventory as per HIPAP 4 (Ref 5).

Escalation frequency is the frequency of the initiating tank fire multiplied by directional probability of wind direction towards target tank (usually the sum of probabilities to 2 - 3 wind sectors or a nominal 25%), resulting in a tank top fire at target tank.

If remotely activated cooling sprays are available on the target tank and the site is attended, a frequency reduction factor of 0.1 is also taken for failure to successfully apply fire protection. If there is no remotely actuated fire protection or target site is not attended, no mitigation is claimed.

Table D.8: Typical Tank top full surface fire consequence results

Tank number	Diameter (m)	Height (m)	Typical product	Distance (m) to heat radiation at any height @ D8.7														
				Flame			4.7 kW/m²			6 kW/m²			12.5 kW/m²			23 kW/m²		
				Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset
Current operation																		
TKXX1	15	9	PMS (ULP95)	42	15	-8	68	62	-21	63	55	-18	50	38	-12	44	28	-9
TKXX2	25	10	ULT98	62	25	-13	89	79	-26	82	71	-23	68	49	-16	63	37	-13
LY(F4)	25	10	Jet-A1	53	25	-13	79	64	-26	73	56	-22	59	37	-16	54	26	-13

Table D.9: Typical Tank bund fire consequence results

Compound	Bund surface area (m²)	Equivalent diameter (m)	Typical product	Distance (m) to heat radiation at any height @ D8.7														
				Flame			4.7 kW/m²			6 kW/m²			12.5 kW/m²			23 kW/m²		
				Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset	Length	Width	Offset
West	8600	105	Gasoline	193	105	-52	267	250	-90	247	225	-80	206	166	-59	-	-	-
East	4700	77	Avgas	150	77	-39	207	190	-67	191	171	-59	160	125	-43	-	-	-
Note: “-“ indicates heat radiation level was not met.																		

Table D.10: Typical Tank top full surface fire consequence distances to escalation

Tank number	Product	Max distance of heat radiation from centre of tank (any height) (m)		On-site tanks reached by 23 kW/m2 contour	Potential escalation to off-site tanks?	
		23 kW/m2	10 kW/m2		23 kW/m2	10 kW/m2
TKXX1	ULP95	36	39	None	No	No
TKXX6	ULP91	53	58	TKZZ (Jet-A1)	Yes, TYY1 and TY2	Yes, TYY1 and TYY2

D10. Tank overfill – Vapour cloud/flash fire

In addition to the tank top full surface and bund fires historically accounted for in hydrocarbon tank farm consequence assessment, flash fire scenarios due to large spills of hydrocarbons (such as those that have occurred in Buncefield and Jaipur in recent years) have been included. The industry had previously considered these scenarios to be unlikely and historically these scenarios have been excluded from hydrocarbon tank farm QRAs.

The investigations into the Buncefield (2005) and Jaipur (2009) events identified a number of common factors have been identified in the incidents that have occurred including:

- Potential for overfill or other release of hydrocarbon containing volatile material that continues undetected for some time
- Low wind speed, stable atmospheric conditions
- An ignition source in the vicinity
- Factors that may result in localised congestion or confinement of the dispersing flammable vapours.

At Buncefield, a tank was overfilled and the released product (gasoline) subsequently cascaded over the tank edge/wind girder resulting in large amounts of spray and vapour formation due to vaporisation of volatile components and formation of very fine hydrocarbon droplets. An ignition of the vapour cloud and explosion with overpressures far higher than what would have been predicted by conventional methods occurred at Buncefield.

Extensive work including large scale experiments and CFD modelling were undertaken as part of the Buncefield investigation resulting in further explanation of the severity of the event.

In 2013, the UK HSE and the industry body the Fire and Blast Information Group (FABIG) issued a model for use based on the Health Safety and Laboratory (HSL) paper that can be used to estimate cloud sizes from overfills of volatile materials for zero wind speed conditions (Ref 2). This is primarily dependent on falling droplets drawing in air as they spray, forming a cold, well-mixed flammable cloud that moves due to gravity and local eddies rather than bulk air wind speed. This is known as the UK HSE VCA model.

The technique provides a specific model for assessing the physical behaviour of an overfill from a specific tank geometry and uses empirical correlations to predict a mass addition rate and concentration of hydrocarbon in the initial cloud from a cascading overfill. An extension of this correlation can also be applied to overfills and large leaks from tank base/flange failures to estimate the extent of the LFL (for zero wind speeds only).

For this QRA, loss of containment of gasoline due to tank overfill and the extent of the flammable cloud envelope was modelled following the UK HSE's VCA method, which provides a means of calculating the rate at which the volume of a vapour cloud increases during an overfilling incident.

Typical distances to LFL resulting from an example tank overfill are shown in Table D.11.

A 'Buncefield' type overpressure scenario has also been considered. As per the findings of the Buncefield investigation (Ref. 27), overpressure diminishes very rapidly outside flammable cloud (large shallow clouds). A correlation for estimating the overpressure from edge of cloud has been published and in this case the overpressure effect distances causing fatality (1 % fatality at 14 kPa) are very similar to the flashfire effect distance. Hence overpressure fatality effects are not explicitly considered in the risk model, as the LFL envelope already is set to 100% fatality probability

Table D.11: Typical tank overfill – flash fire consequence results

Tank number	Product	Diameter (m)	Height (m)	Distance to LFL (m) [1, 2]		Distance to 14 kPa (m)
				Length	Width	
Import rate to tank: 750m^3/hr						
TKXX1	Gasoline	20	18	362	362	387
TKXX2	Gasoline	28	18	407	407	411

Notes:
1. Width of the LFL cloud is assumed to be similar to the LFL downwind distance ('Length'). This is consistent with CFD modelling results undertaken as part of the Buncefield investigation but may be affected by specific bund and building configurations.
2. Overfill assumed to occur for 30 min duration, as a worst case it was assumed that both high level alarm and operator initiated shutdown have failed.

APPENDIX E. FREQUENCY DATA

E1. Overview

The following data was used to determine the overall event frequencies for the Terminal:

- Historical equipment leak frequencies
- Parts count
- Ignition probability
- Effect of safeguards
- Online time
- Storage tank fire frequencies (including tank overfill).

The details for each of the data source selected is outlined in the following sections.

E2. Historical equipment leak frequencies

The main source of historical leak frequencies used is the OGP Risk Assessment Data Directory *Process release frequencies* (Ref 7). The data and sources are included in Table E.1.

Tank top full surface fire frequencies were estimated from the most recent LASTFIRE project (Ref 8) based on the storage tank type.

The frequency of tank overfill was estimated using fault tree analysis since this is dependent on instrument failures and safeguards specific to each site.

The frequency of spills from IBCs of white spirit (LAWS) was estimated from the VROM Risk Assessment Methodology (Ref 28).

OGP and LASTFIRE data were selected as they are specific to the oil and gas industry and are updated relatively frequently based on industry incident reporting. This was supplemented by other sources as needed, for example if there was no data in the OGP reference.

Table E.1: Historical equipment leak frequencies

Equipment type and size	Frequency (per year) by hole size[1]					Source
	2 mm	6 mm	22 mm	85 mm	Full bore	
Process piping (50 mm)	5.5E-05	1.8E-05	7.0E-06			OGP
Process piping (150 mm)	2.6E-05	8.5E-06	2.7E-06	6.0E-07		OGP
Process piping (300 mm)	2.3E-05	7.6E-06	2.4E-06	3.7E-07	1.7E-07	OGP
Process piping (450 mm)	2.3E-05	7.5E-06	2.4E-06	3.6E-07	1.7E-07	OGP
Process piping (600 mm)	2.3E-05	7.4E-06	2.4E-06	3.6E-07	1.6E-07	OGP
Process piping (900 mm)	2.3E-05	7.4E-06	2.4E-06	3.6E-07	1.6E-07	OGP
Flange, raised face (50 mm)	2.6E-06	7.6E-07	1.2E-06			OGP
Flange, raised face (150 mm)	3.7E-06	1.1E-06	9.0E-07	6.0E-07		OGP
Flange, raised face (300 mm)	5.9E-06	1.7E-06	1.4E-06	1.8E-07	3.4E-07	OGP
Flange, raised face (450 mm)	8.3E-06	2.4E-06	2.0E-06	2.6E-07	3.6E-07	OGP
Flange, raised face (600 mm)	1.1E-05	3.2E-06	2.6E-06	3.3E-07	3.8E-07	OGP
Flange, raised face (900 mm)	1.7E-05	4.9E-06	4.2E-06	5.4E-07	4.4E-07	OGP
Valve actuating (50 mm)	2.4E-04	7.3E-05	3.0E-05			OGP
Valve actuating (150 mm)	2.2E-04	6.6E-05	1.9E-05	8.6E-06		OGP
Valve actuating (300 mm)	2.1E-04	6.3E-05	1.8E-05	2.4E-06	6.0E-06	OGP
Valve actuating (450 mm)	2.0E-04	6.0E-05	1.7E-05	2.3E-06	5.9E-06	OGP
Valve actuating (600 mm)	2.0E-04	5.9E-05	1.7E-05	2.2E-06	5.9E-06	OGP
Valve actuating (900 mm)	1.9E-04	5.6E-05	1.6E-05	2.2E-06	5.9E-06	OGP
Valve manual (50 mm)	2.0E-05	7.7E-06	4.9E-06			OGP
Valve manual (150 mm)	3.1E-05	1.2E-05	4.7E-06	2.4E-06		OGP
Valve manual (300 mm)	4.3E-05	1.7E-05	6.5E-06	1.2E-06	1.7E-06	OGP
Valve manual (450 mm)	5.3E-05	2.1E-05	8.0E-06	1.5E-06	1.9E-06	OGP
Valve manual (600 mm)	6.2E-05	2.4E-05	9.4E-06	1.8E-06	2.1E-06	OGP
Valve manual (900 mm)	7.8E-05	3.0E-05	1.2E-05	2.2E-05	2.3E-06	OGP
Instrument fitting	1.8E-04	6.8E-05	2.5E-05			OGP
Filter	1.3E-03	5.1E-04	1.9E-04	3.5E-05	2.0E-05	OGP
Pump centrifugal	5.1E-03	1.8E-03	5.9E-04	9.7E-05	4.8E-05	OGP
Tank rupture					5.0E-06	UK HSE
Major tank failure (1000 mm hole)					1.0E-04	UK HSE
Loading arm – per operation (Road tanker & ship)[2]			3.0E-07 (per hour)		3.0E-08 (per hour)	TNO Purple Book
Loading hose – per operation (Road tanker & ship)[2]			4.0E-05 (per hour)		4.0E-06 (per hour)	TNO Purple Book
IBC rupture - per operation					1.0E-05	VROM

Note: 1. Process piping and pipeline release frequencies are per metre-year.
2. Hole sizes are 10% of diameter up to a max of 50 mm & full bore – also basis is per hour (not per year as for all other items in table).

E3. Transfer pipelines

For transfer pipelines operating at pressures less than 20 barg, leak frequencies were obtained based on CONCAWE's *Performance of European cross-country oil pipelines report* (Ref 29). For pipelines pressurised to greater than 20 barg, leak frequencies were obtained based on the 9th report of the European Gas Pipeline Incident Data Group (EGIG) *Gas Pipeline Incidents* (Ref 30).

Correction factors were applied to the EGIG data to take account of the additional depth of cover (1.5m) for the Lyttelton-Woolston LPG transfer pipeline. A factor of 0.7 is suggested for frequency of external interference reduction for this depth of cover (Ref 31) which is supported by the EGIG historical data which shows lower rates of damage and resulting leaks due to external interference for pipelines with extra depth of cover. As this is a single pipeline without cross connections, in a different route to other pipelines in Lyttelton Port, hot tap errors are also not credible and the frequency contribution has been removed.

The data and sources are included in Table E.2.

Table E.2: Historical equipment leak frequencies (transfer pipelines)

Equipment type and size	Frequency (per metre-year) by hole size			Source
	10 mm	50 mm	Full bore	
Pipeline (aboveground < 20barg)	7.2E-08	1.1E-07	8.7E-08	CONCAWE
Pipeline (underground < 20barg)	5.0E-08	4.0E-08	4.3E-08	CONCAWE
Pipeline (high pressure liquid hydrocarbon)	1.7E-07	1.1E-07	4.6E-08	EGIG
Pipeline (high pressure LPG, extra safeguards risk reduction factors included)	8.8E-08	2.6E-08	1.7E-08	EGIG

E4. Parts Count

Parts count and line length calculations were estimated for the process and based on site layout diagrams and applied to the base historical leak frequencies as relevant to each site.

E5. Operational error frequencies

The frequency of operational errors from incorrect coupling for road tanker transfer and ship imports was determined for each Terminal based on incident history and operational data.

E6. Ignition probability

E6.1. Area wide ignition probabilities

The ignition probability values used in this study were based on the assessment by Cox, Lees and Ang (Ref 9). The probabilities are based on the release rate and the phase of the fluid assessed.

The ignition probability values used in the QRA are provided in Table E.4 and in Table E.5.

Releases of combustible liquids such as diesel are more difficult to ignite due to their high flash point. In this study, diesel is stored in common bunds with flammable liquids and tank product allocations may also be changed from time to time. Hence to ensure a fire scenario was included for all tanks and to take into account possible escalation from a flammable liquid fire, the ignition probability for diesel in mixed storage areas was assumed to be one-tenth (0.1) that of flammable liquids such as gasoline (Ref 32). Likewise, for jet fuel which has a higher flash point compared to gasoline, a factor of 0.3 was included to reduce the ignition probabilities specified in Table E.5.

For dedicated combustible only areas (e.g. Naval Point) ignition probability was assumed to be one-hundredth (0.01) of that of flammable liquids.

Table E.3: Ignition probabilities (Ref 9)

Mass flow rate (kg/s)	Total Ignition probability of a gas or mixture	Total Ignition probability of a liquid	Fraction of explosions given ignition of a gas, liquid or mixture	Explosion probability of a gas or mixture	Explosion probability of a liquid
< 1	0.01	0.01	0.04	0.0004	0.0004
1 - 50	0.07	0.03	0.12	0.0084	0.0036
> 50	0.3	0.08	0.3	0.09	0.024

Table E.4: Calculated ignition probabilities for fires

Mass flow rate (kg/s)	Immediate ignition of gas/mixture resulting in fire	Delayed ignition of gas/mixture resulting in fire	Immediate ignition of liquid resulting in fire	Delayed ignition of liquid resulting in fire
< 1	0.0096	0.0004	0.0096	0.0004
1 - 50	0.0616	0.0084	0.0264	0.0036
> 50	0.21	0.09	0.056	0.024

E6.2. Fixed ignition source

Where a fixed ignition source is identified such as a fired appliance (which will draw dispersing flammable gas into any air intakes hence ignite it) or flare, an ignition probability of 1 at the location of ignition source is used for the proportion of time it is present.

For this QRA the only fixed ignition source that has been identified is a waste incinerator operated by San-I-Pak Ltd (San-I-Pak). The waste treatment process includes a commercial diesel fired boiler that runs two steam autoclaves to treat the waste. San-I-Pak operate Monday to Friday as a daytime only operation. The waste incinerator is located around 10 m from the southern boundary of the Terminal, just south of the existing tank LY12.

The effect of this ignition source is taken into account as a strong ignition source for flash fires resulting from overfills and mechanical failures of the gasoline tanks at the site. When the incinerator is running, it is assumed that vapours dispersing from a gasoline spills will not disperse to its LFL distance but will ignite once they reach the incinerator (limiting the size of the flash fire). When the incinerator is not running, the vapour cloud is assumed disperse to its LFL distance.

E6.3. Public access and effect on ignition source

All sites have safe work practices covering hazardous area classification and hot work permit systems to control ignition sources within their boundaries.

However there is very little access control up to the site boundaries which coincide with bund walls, process equipment such as loading bays is very close to public roads and live aboveground pipelines are in public areas. In addition the proposed cruise ship disembarkation would result in large numbers of people on the shore within the immediate vicinity of the facilities.

Overall, ignition sources are considered to be greater in number and in closer proximity to these sites that would be the case in a secure port site.

The Cox Lees and Ang ignition data is a relatively old data source and generally sets higher ignition probability for scenarios up to around 10kg/s and similar probabilities for larger releases than other more recent ignition probability data sources used in QRA (for example the Energy Institute model).

It is Sherpa's view that Cox Lees and Ang provides a better fit in this case hence this has been selected to account for the possibility of higher ignition probabilities in this location. The effect is to increase the ignited event frequency of smaller releases in the vicinity of the sites, increasing the risk in close proximity to the sites, with a relatively small effect on the larger releases (such as LPG pipeline failures or unisolated gasoline tank overfills which have a high probability of ignition.

E7. Effect of safeguards

Hardware safeguards and instrumentation have been factored into the event frequencies (if provided at a specific terminal) as follows

- high level alarm and shutdown by operator of tanks during ship import.
- gas detection and auto shutdown

Manually initiated shutdown is also allowed in the situation where:

- there are personnel present and shutdown functionality is available
- the event can be readily detected and isolated, particularly if continuous monitoring occurs.

Manual shutdown activation is useful in limiting the duration and inventory released. However, depending on the scenario and inventory between any block valves an un-isolated and isolated release may have similar consequences.

Safeguards relating to fire protection are generally not accounted for in estimating the initial event likelihood, but are used to estimate the likelihood of escalation to equipment on neighbouring sites for inclusion in the cumulative QRA model (as they do not prevent the initial event, but limit the consequences).

E8. Online time

An online factor was applied to the leak frequencies adjusted by parts count for each identified equipment item. The online time factor reduces the leak frequency based on the proportion of time that the equipment is used.

E9. Storage tank incident frequencies

E9.1. Tank overfill

For this study, the frequency of an extended duration tank overfill was calculated as a function of tank level gauging failure, failure of operator during stock reconciliation and failure of independent high level alarm and operator shutdown of transfer to the tank.

EXAMPLE basis:

Failure rate of gauging system = once every 10 years (Ref 33)

Failure of stock reconciliation = 0.1 (estimated based on Center for Chemical Process Safety (CCPS) guidelines (Ref 34). This is a fairly conservative approach and may be adjusted depending on site specific practices).

Failure of independent high level alarm and operator response = 0.1 (estimated based on the instrument being independent instrument, and different operator or time to stock reconciliation. May be adjusted depending on site specific equipment).

EXAMPLE calculation:

Probability of tank overfill

= Level gauging failure x operator stock reconciliation failure x high level alarm failure on demand

= 0.1 x 0.1 x 0.1

= 1 x 10^{-3} per year.

This is then adjusted by the proportion of time that the tank is in filling mode (CCPS enabling condition for overfill) as this would need to coincide with gauging failure to result in a hazardous incident. Depending on the site safeguards and filling frequencies, this results in tank overfill frequencies of around 10^{-4} to 10^{-5} per tank per year

E9.2. Tank top full surface fire

The tank top full surface fire frequencies used in the QRA study were obtained from the most recent LASTFIRE Project Update (2012, Ref 8).

Fixed roof tanks

LASTFIRE Project Update 2012 indicates that the tank top full surface fire frequency for fixed roof tanks (all causes including lightning, hot work etc) is given as 2.1 x 10^{-5} per year. The LASTFIRE data includes all types of hydrocarbon fuel tanks. For flammable materials (e.g. gasoline, jet fuel) the frequency is taken from the data directly, while for combustibles (e.g. diesel) an additional reduction factor of 10% has been applied to the reported data as the vapour space is not within the flammable range under normal circumstances.

Floating roof tanks

LASTFIRE Project Update 2012 indicates that there have been no tank top full surface fires recorded for internal floating roof (IFR) tanks. The rim seal fire frequency for IFR tanks is given as 4.4 x 10^{-5} per year.

The probability that a rim seal fire will escalate to a tank top full surface fire will depend on the response to the seal fire and the behaviour of the floating roof. If tanks at a Terminal are provided with tank top foam pourers that would cover the floating blanket/pan and the rim seals with foam upon activation it is assumed that there is a 10% chance that the foam pouring system fails to prevent a rim seal fire escalating to a full surface roof fire (based on the assumed detection by operator and reliability of the foam pouring system) and a tank fire frequency of 4.4 x 10^{-6} per year was adopted for floating roof tanks in this study.

If there is no fire protection rim seal fires are assumed to escalate 100% of the time giving a tank top fire frequency for IFR tanks of 4.4 x 10^{-5} per year.

There are no external floating roof tanks at these sites.

Escalation to other on-site tanks

Escalation between tanks on site and between sites have been assessed. Escalation scenarios between on-site tanks have not been accounted for quantitatively as the frequency is generally an order of magnitude below the base frequency for tank top full surface fires once wind direction and ability to apply spray cooling to affected tanks are accounted for, and all on-site tanks already have a tank top full surface fire accounted for.

For example, escalation from TKXX (ULP91 tank) to TKXX (Jet-A1 tank):

Basis:

Directional probability factor = 0.25 (assuming fire can occur in all four directions)

Spray cooling failure on demand = 0.1 (estimated based on the escalation being a with-warning event).

Calculation:

Frequency of escalation from TKXX to TKXX

= Probability of tank top full surface fire (TKXX) x directional probability factor x spray cooling failure on demand

= $4.4 \times 10^{-6} \times 0.25 \times 0.1$

= 1.1×10^{-7} per year.

This is greater than one order of magnitude less than the tank top full surface fire frequency of 2.1×10^{-5} per year calculated for TKXX.

Escalation for tanks between sites has been accounted for where estimated radiant heat exceeded $10kW/m^2$ at a neighbouring site tank as per Section D9. An escalation frequency is defined from the original event frequency (combined with a failure probability for safeguards such as activation of fire protection systems such as tank cooling sprays

E9.3. Tank bund fire

Both intermediate and full bund fires were assessed in the QRA. The tank bund fire frequencies were calculated using event tree analyses. Derivation of these frequencies are provided below.

Small bund fire

This frequency was applied for all intermediate bund fire events. An event tree was developed using tank overfill frequency as the base frequency for the analysis. This is appropriate for small bund fires as these type of failures are easier to isolate (e.g. closing valves, shutting down pumps), allowing quicker response and minimising the resulting pool size.

Large bund fire

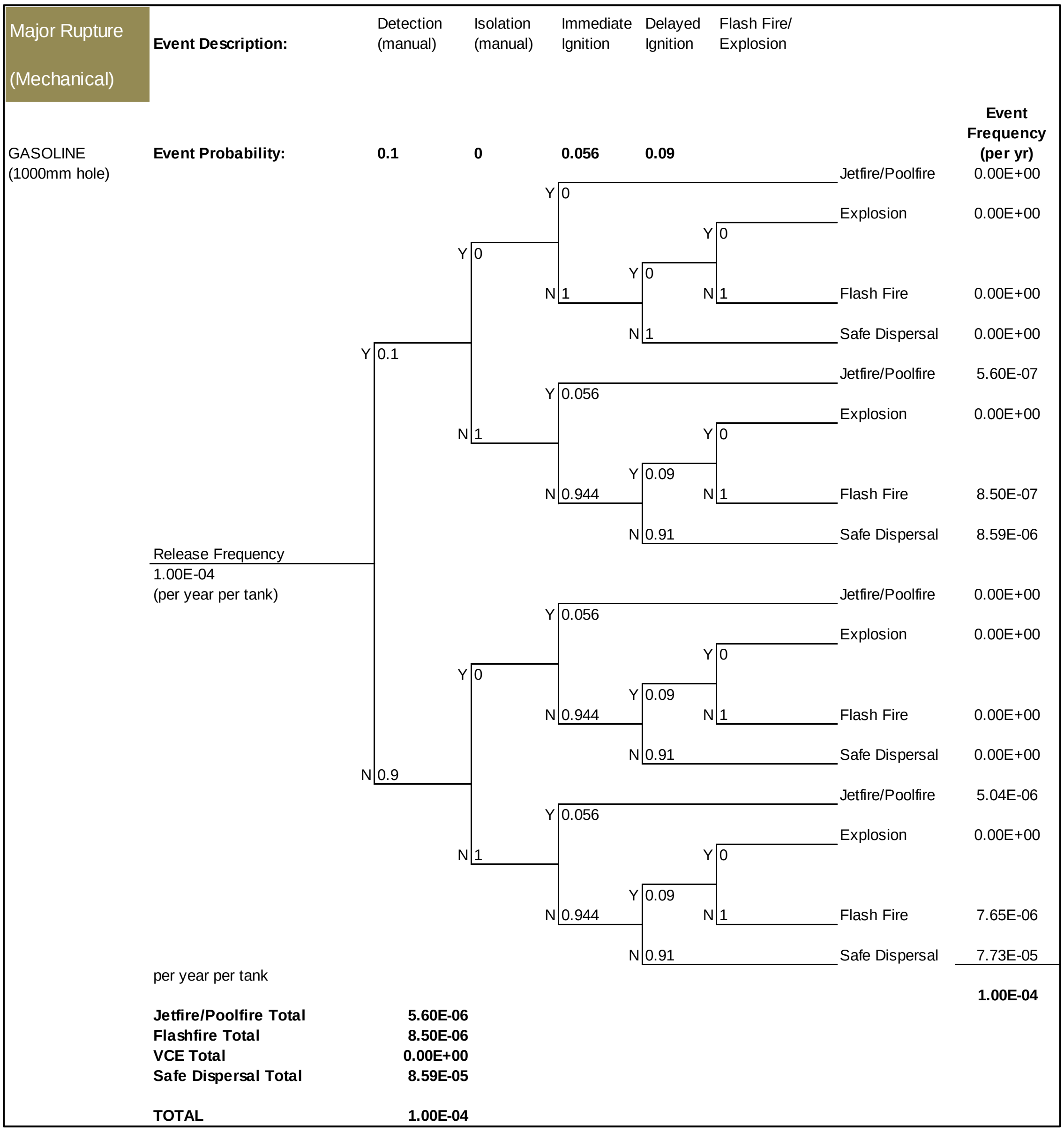
This frequency was applied for all full bund fire events. An event tree was developed for major tank failure and rupture frequencies where:

- Major tank failure (1.0×10^{-4} per tank-year, DNV Buncefield Report, reproduced from UK HSE data, Ref 35).
- Tank rupture (5.0×10^{-6} per tank-year, DNV Buncefield Report).

This is appropriate for large bund fires as these failures are difficult to isolate depending on the leak source location and may result in large pool size (restricted by the bund area).

A sample calculation for the event tree analysis of a major tank failure of gasoline is shown in Figure E.1.

Figure E.1: Tank mechanical failure - event tree



E10. Road accident frequencies

In the absence of any area specific road accident data, OGP data (Ref 36) provides generic data for land transport loss of containment for loaded flammable liquid tankers was applied as follows:

- Release Frequency, amount >1500 kg = 2.1 x 10^{-8} per loaded vehicle km.

This was applied to the total flammable liquid vehicle numbers and an ignition probability of 0.3 applied to estimate a fire event frequency. This primarily applies to the Godley Quay route exiting the Port area and some cross roads from specific sites. Combustible loads were not included.

APPENDIX F. NATURAL HAZARDS

F1. Earthquakes

F1.1. Earthquake frequencies

The GNS risk studies commissioned by CCC provide data showing peak ground acceleration hazard curves (Ref 14) are shown in Figure F. 1. These indicate that:

- PGA of 1g annual exceedance rate is approximately 0.001 to 0.01 (or 1 x 10^{-3} to 1 x 10^{-2} per year or 1 in 100 to 1 in 1000 years).
- PGA of 2g annual exceedance rate is approximately 0.0001 (or 1 x 10^{-4} per year, 1 in 10,000 years).
- PGA of 3g annual exceedance rate is approximately 0.00001 (or 1 x 10^{-5} per year, 1 in 100,000 years).

Figure F. 1: Earthquake Hazard Curves (From Ref 14. Figure 2)

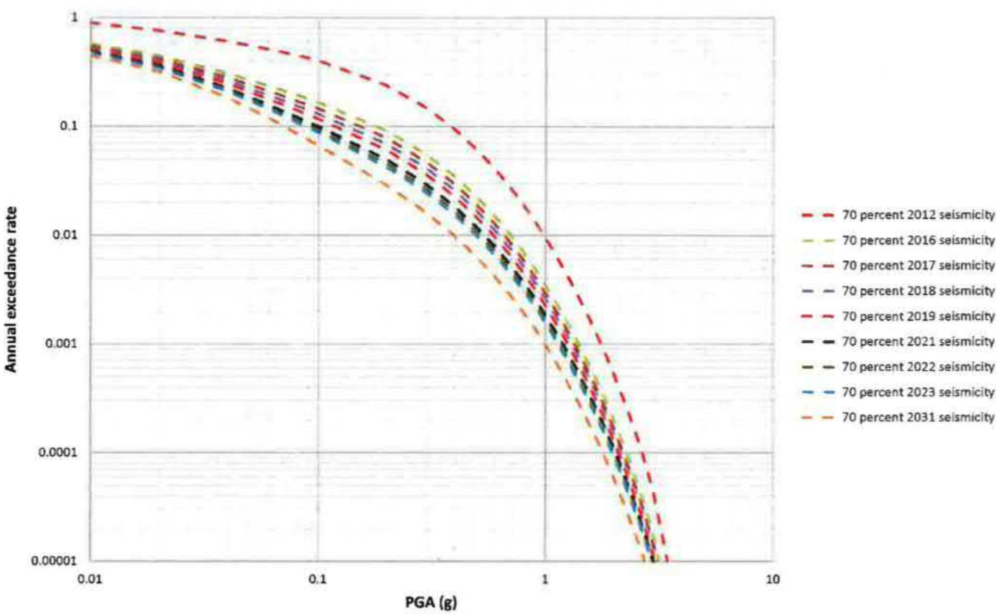


Figure 2 Selected peak ground acceleration hazard curves (annual rate (annual frequency) of a given peak ground acceleration being exceeded) for shallow soil site conditions for a selection of years between 2012 and 2031 based on the "no aftershock exposure" assumption.

F1.2. Earthquake fragility curves for storage tanks

Earthquakes cause damage to tanks through direct shaking or ground uplift, or through soil-liquefaction-induced ground deformation that can affect structures built in susceptible zones. The predominant damage modes are tank buckling, stretching or detachment of bolts, deformation of columns and support structures. Minor to severe releases during earthquakes have been observed due to the failure of flanges and pipe connections, as well as failed tank shells or roofs, while tank overturning or collapse lead to major releases.

Seismic fragility depends on various factors such as whether tanks are anchored or not anchored, and the level of product in the tank. Fragility curves relate the probability of tank damage to peak ground acceleration (PGA, either vertical or horizontal) experienced in an earthquake. (Ref 15).

The curves are available for different damage levels as follows:

- Risk state 1 (RS1) – no loss of containment.
- Risk state 2 (RS2) – moderate loss of containment (e.g. damage to connected piping, tank nozzles).
- Risk state 3 (RS3) – extensive loss of containment (tank collapse, catastrophic failure, may affect multiple tanks).

An RS1 level of event does not affect the QRA as there is no loss of containment.

The curves for anchored tanks (there are no unanchored tanks at the Lyttelton facilities) are shown in Figure F. 3 (which were developed from a probit equation with the coefficients shown in Figure F. 2 and converted to a probability function):

Figure F. 2: Earthquake Fragility Curve Coefficients (from Ref 15)

Probit: Y = k1 + k2 ln(PGA)

Table 1
Seismic fragility and probit coefficients for anchored atmospheric steel tanks

Limit state (RS)	Fill level	μ (g)	β (g)	k_1	k_2
≥2	Near full	0.30	0.60	7.00	1.67
3	Near full	1.25	0.65	4.65	1.54
≥2	≥50%	0.71	0.80	5.43	1.25
3	≥50%	3.72	0.80	3.33	1.25

The Fragility curve in Figure F. 3 also shows the PGA experienced at Lyttelton for the 2010 (Ref 37) and 2011 (Ref 14) earthquakes, and the PGA for the very severe 2011 earthquake in Tohoku Japan (Ref 16).

Whilst there was some damage (settling, minor deformation equivalent to the RS1 level), the tanks at Lyttelton experienced no loss of containment in either the 2010 (PGA 0.3g) or 2011 (PGA 1.3g) earthquakes.

This indicates that the severity (expressed as PGA) of earthquake would need to be greater than 1.3g to significantly increase the consequence/severity (i.e. to the RS3 level) of a loss of containment event compared to the scenarios contained in the QRA.

F1.3. Earthquake (ground movement) risk in QRA

To estimate the effect of earthquake risk in the Lyttelton Port QRA it is assumed that:

- Based on the behaviour of the storage tanks in the 2010/2011 earthquakes, i.e. survival of the 1.3g earthquake as measured at the Port of Lyttelton accelerometer with no loss of containment (compared to 50% probability of RS3 level damage from fragility curve), the tanks performed significantly better than would be predicted. Therefore it was assumed that a more severe earthquake, ie an earthquake with a PGA of 2g or more, would need to occur to cause a high probability of significant damage (i.e. RS3 level with significant loss of containment) to either partly full or full tanks.
  - RS2 level damage is very similar to scenarios already included in the QRA and would not significantly elevate the frequency or consequences already included in the base QRA.
  - A 2g earthquake is assumed to occur at an average frequency of 1×10^{-4} per year with 0.75 probability of RS3 level damage to full tanks as per the fragility curve.
  - There is at least one full tank per compound (full tanks are at greater risk than partially full tanks). The highest hazard product (gasoline) tank is assumed to spill and the probability is adjusted accordingly. For example if a compound (bunded area) with 2 of the 4 tanks storing gasoline, earthquake RS 3 damage frequency (compound) = $0.5 \times 0.75 \times 1 \times 10^{-4} = 3.8 \times 10^{-5}$ per year. (Note that additional frequencies could be added but have a minor overall effect for example, PGA 3g exceedance is 1×10^{-5} with a 0.9 probability of RS3 damage, which would add only another 10% to the estimated frequency so is not included in the calculation).
  - The frequency is applied to each main storage bunded area and an ignition probability applied to estimate the total fire frequency in each area (as per the general QRA ignition rule set for spillages in flammable storage areas). The probability of ignition in an earthquake may be higher (eg due to damage to electricity, widespread loss of containment/water contacting ignition sources) than in a mechanical failure or process upset scenario, hence a sensitivity study doubling the ignition probabilities for earthquake initiated loss of containment has also been included in the QRA (see APPENDIX G).
  - This approach results in ignited event frequencies in the range of 6×10^{-7} to around 8×10^{-6} per year per bund compound depending on the storage arrangements. This is a similar range to the bund fire frequencies included in the base QRA which could be up to around 8×10^{-6} per year per bund compound.

F1.4. Consequences of earthquake damage to tanks

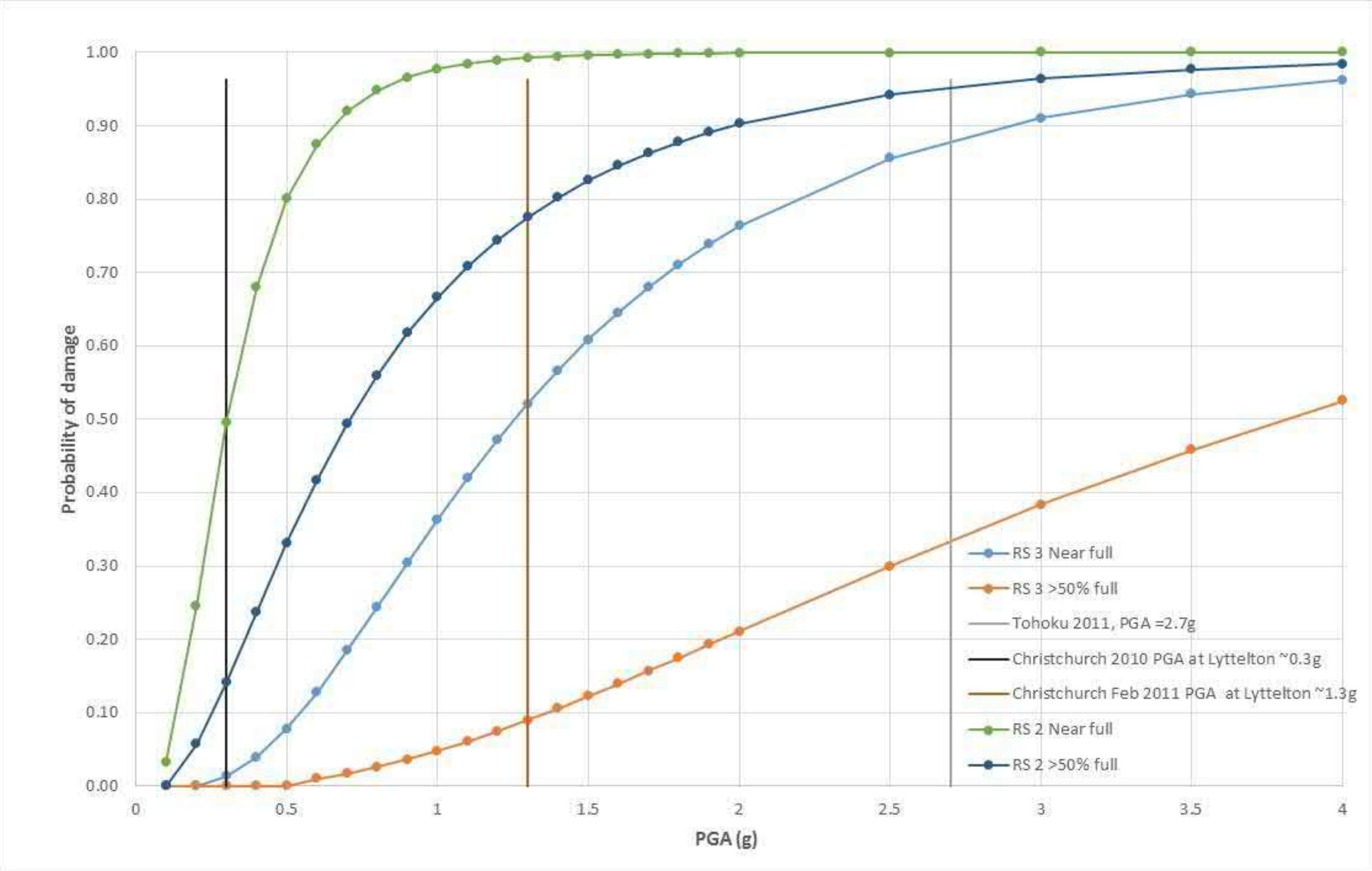
It is noted that the mode of tank damage is related to earthquake PGA directional effects (which can be either horizontal or vertical). However whilst this parameter is measured in an actual earthquake event, there is no predictive information available for earthquake PGA in a particular direction. Hence no attempt has been made to account for a particular mode or type of tank damage (i.e. collapse, buckling), only the likely scale of damage and associated loss of containment.

It is assumed that there is potential for a worse consequence than occurs for the catastrophic mechanical failure scenario for a single tank contained within the bunded area (as is included in the base QRA). There is no particular hole size or rate of product loss correlated to earthquake damage at the RS3 level, it is simply assumed there is at least one full tank per compound which fails catastrophically releasing the entire inventory in an earthquake with strength of PGA 2g and that the bund is damaged and fails to contain the spilled material, resulting in unconstrained spreading of flammable or combustible material. This assumption also covers the case where multiple tanks are simultaneously damaged in one compound and exceeds the bund capacity, also resulting in unconstrained pool spreading.

- Each main spill area is assumed to be broadly constrained by the roads and associated stormwater drainage channels along the roads towards the harbour which would limit the overall extent of the spreading area.
- Areas where the compound is very close to water (i.e. the southern part of the bulk storages) are limited to the water edge as the drainage is towards the harbour. A pool very similar in size to that included in the QRA results would develop and runoff into the harbour would occur. Only a frequency adjustment is made to the scenarios for these compounds (i.e. there is no 'worse' consequence included).
- If some cases the inventory of tanks may be quite small and result in a pool very similar in size to that included in the QRA. In that case only a frequency adjustment is made to the scenarios for these compounds (i.e. there is no "worse" consequence included).
- The default assumption in PHAST is for unconstrained pools to spread to a minimum depth of 5 mm which assumes a relatively smooth surface (for example concrete inside a bund). In the case where there is bund damage and an earthquake has occurred resulting in cracking/deformation of ground, i.e. very uneven surfaces, and unconstrained liquid spreading occurs, a minimum depth of 5 mm is not credible and would result in pool sizes of over 1000 m which is larger than the Port area. The minimum pool depth is therefore assumed to be 300 mm. This is around 50% of the height of an intermediate bund wall, a typical pump plinth and about 50 – 100% of the depth of the drainage channels along the road.

These assumptions result in an increase in the size of the impact areas by around 80 – 100%. For example one of the larger bund compounds will limit the maximum spreading area to an equivalent pool diameter of about 80 – 100m (hence pool fire size), for the scenarios unconstrained by the bund, impact areas with an equivalent pool diameter of between 130 – 200 m are predicted. The slope of the area is towards the harbour so the pools are offset and centred closer to the harbour rather than on the compound centres.

Figure F. 3: Earthquake fragility curves (anchored storage tanks)



F1.5. Liquefaction

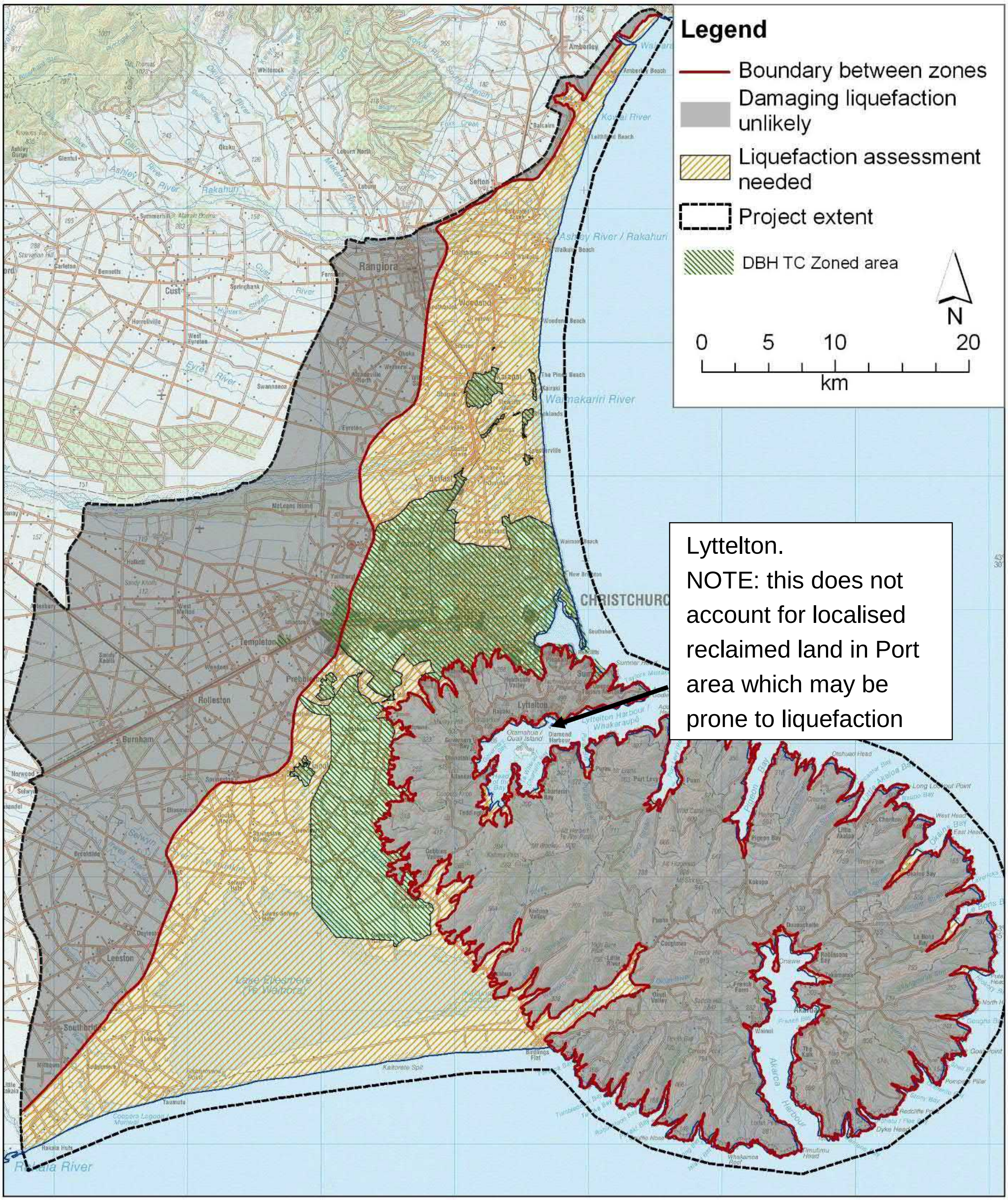
Lyttelton is not identified as subject to risk of liquefaction as per the general Christchurch area liquefaction risk maps from ECAN prepared after the Lyttelton 2010/2011 earthquakes occurred as reproduced in Figure F. 4 on the following page.

However it is noted that this map did not specifically include the parts of the Lyttelton Port area that are reclaimed land. Localised liquefaction did occur in the 2010/2011 earthquakes particularly in areas close to the berth. However there was no loss of containment from any tanks as a result of ground liquefaction damaging tanks. Similarly to the approach to damage due to ground movement it is assumed that a higher strength earthquake than occurred in 2010/2011, would need to occur to cause a high probability of significant damage (ie RS3 level) due to liquefaction.

As noted previously, no attempt has been made to account for a particular mode or type of tank damage (ie collapse, buckling etc), only the likely scale of damage and associated loss of containment in an earthquake from all effects. Any damage specifically due to liquefaction effects is assumed to occur only in the same scale of earthquake as damage due to ground movement/shaking and is covered by the additional loss of containment scenarios included in the QRA as part of the earthquake ground movement effects assessment covered in Sections F1.3 and F1.4.

Figure F. 4: General Area Liquefaction map

Ref 38: http://www.ecan.govt.nz/advice/emergencies-and-hazard/earthquakes/PublishingImages/assessment-area-map-large.jpg



F2. Tsunami

Environment Canterbury (ECAN) has made available a coastal hazard report that maps the predicted inundation depths from a 1 in 2500 year tsunami initiated by an earthquake off South America (Ref 17). Lyttelton Harbour was included in this assessment. Figure 4.19 reproduced from the report shows inundation depths below 2 m in the bulk storage areas. Major damage to tanks has a high probability of occurring at inundation depths of 5 m or greater (Ref 16). This inundation depth is not predicted at Lyttelton so tsunami resulting in significant loss of containment is not included in the QRA.

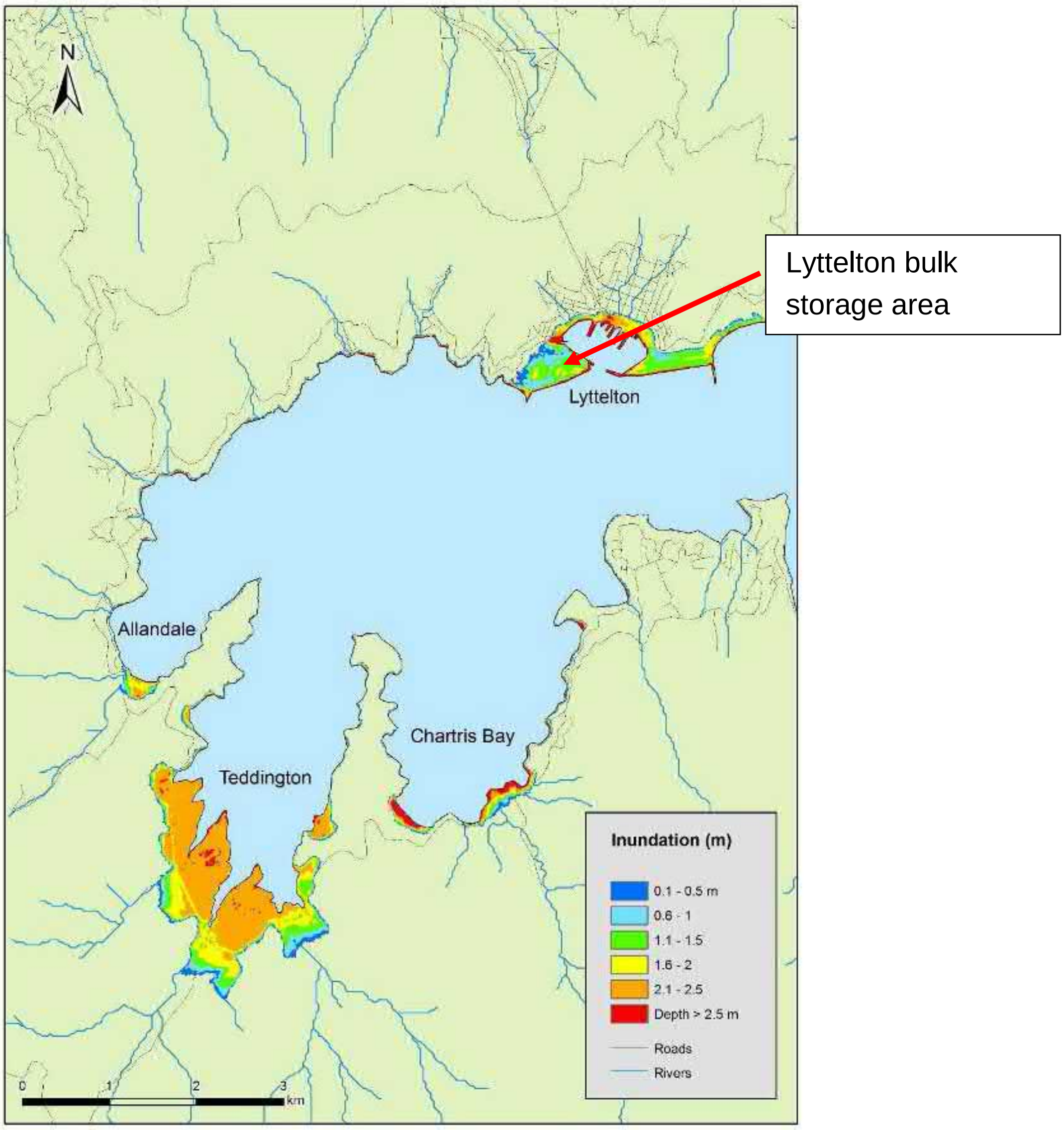
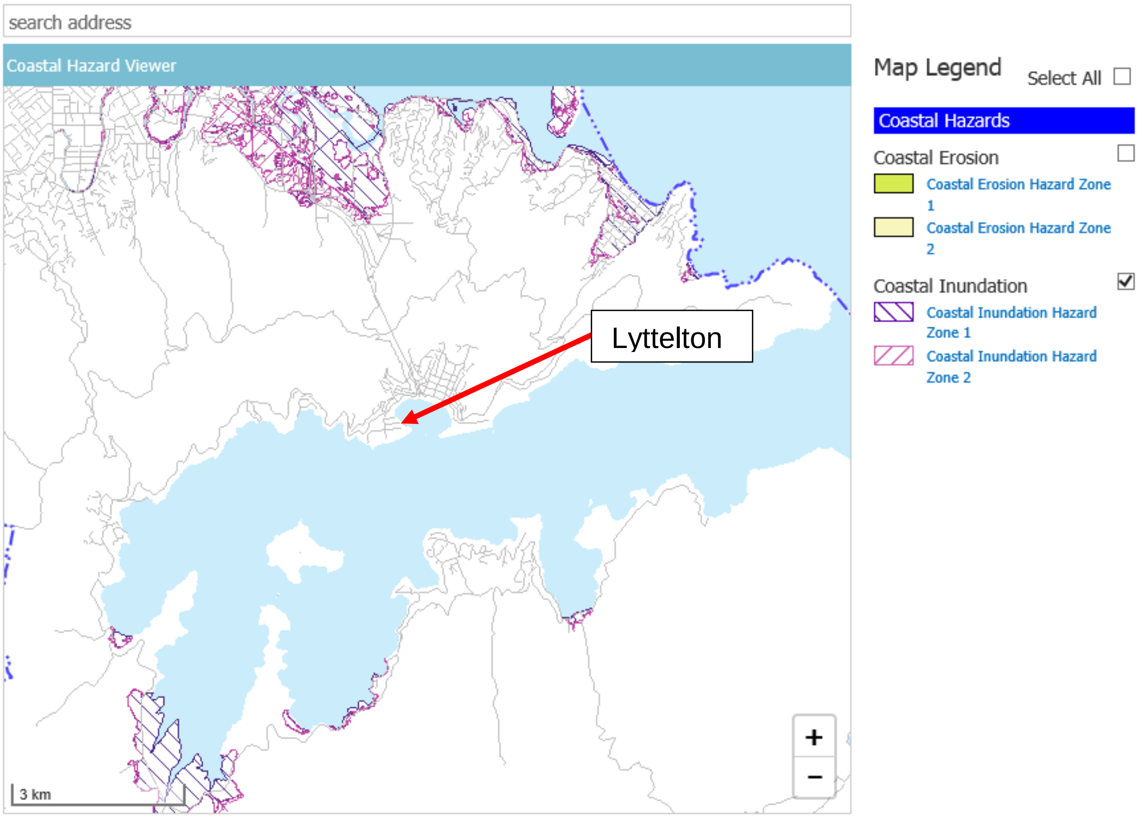


Figure 4-19: Maximum inundation depth for Lyttelton Harbour coastal margin assuming the largest wave arrived at MHWS. Inundation depths are only shown for inundated land.

F3. Storm surge

CCC commissioned Tonkin & Taylor Ltd (T&T) to identify areas susceptible to coastal hazards (inundation and erosion) due to storm surges and rising sea levels, for the main coastal settlements selected by Council. Lyttelton Harbour was included in this assessment (Ref 18). Interactive maps to allow viewing of the Coastal Hazard Inundation Zones (CIHZ) were also developed. Lyttelton Port has not been identified as an area likely to be affected by inundation due to storm surge as shown in the figures below.

http://www.ccc.govt.nz/environment/land/coast/coastalhazards/is-my-property-affected/coastal-hazard-zone-property-search/



F4. Slope instability

F4.1. Risk data for cliff collapse and rockfall

The GNS slope instability risk studies commissioned by CCC after the 2010/2011 earthquakes provide maps which present the annual individual fatality risk (AIFR) due to cliff collapse/debris avalanche (Ref 12) reproduced in Figure F. 5, and also boulder roll/rockfall (Ref 13, 14), reproduced in Figure F. 6.

A combined figure showing the AIFR on a single map from both outcomes has been prepared by CCC in 2013 and is reproduced in Figure F. 7. This combined figure shows a lower (by around a factor of 10) rockfall risk than the initial study (Figure F. 6) but a similar risk of cliff collapse to Figure F. 5.

The risk studies provide data for the total risk of landslip due to either earthquakes or high rainfall events and include the landslip area along Brittan Terrace at the top of the cliff above the Naval Point storage tanks.

The dominant risk at the base of the cliffs at Naval Point where some of the Oil Companies' storage tanks are located is due to cliff collapse and associated debris avalanche (fatality risk of 1×10^{-1} at base of cliff to 1×10^{-3} at first row of tanks per year as per Figure F. 5 (Ref 12) rather than boulder rockfall (fatality risk of less than 1×10^{-3} per year as per Figure F. 6, and this further reduced to less than 1×10^{-4} per year in the revised CCC map in Figure F. 7).

It is also noted that

- since the Christchurch earthquakes the Oil Companies have carried our remediation works to stabilise the cliff and provide barriers that should further minimise the risk of any damage to the tanks in the event of a landslip and associated debris avalanche. This effect is not included in the risk maps in Figure F. 5, Figure F. 6 or Figure F. 7.
- After a landslip in 2014, only low hazard products (e.g. no flammables, combustibles such as diesel only) are now stored in this area.

F4.2. Cliff collapse frequency in QRA

For the purposes of the QRA it is assumed that any of the tanks in the first row of tanks (ie those within about 30 m of the cliff base and within the AIFR contours) may be at risk of damage due to cliff collapse. These areas are highlighted on Figure F. 5.

It should be noted that the AIFR contours in the GNS risk studies include factors for probability of presence and vulnerability of people exposed to hazard. However (these factors are quite high, e.g. 1 for probability of presence and 0.5 for probability of fatality on impact by rocks/debris as per Section 3 of Ref 12). This indicates that the cliff collapse frequency is of the same order of magnitude as the fatality risk contours shown on the maps.

To correlate the available cliff collapse risk information to a frequency of significant damage and loss of containment from the tanks, the following assumptions have been made:

- The initiating frequency of a cliff collapse event of sufficient magnitude (all causes including earthquake and non-seismic causes) to potentially affect the tanks in the Naval Point area is of the order of 1×10^{-2} per year (based on the risk zones reproduced in Figure F. 5 which show fatality risk of 10^{-2} to 10^{-3} extending over the closest tanks).
- The probability of the additional stabilisation works and barriers installed by the Oil Companies (since the 2014 cliff collapse) failing to prevent collapse impacting tanks is nominally assumed to provide an extra layer of protection with a risk reduction effectiveness of 0.1.
- It is noted that cliff collapse will not occur evenly along the whole cliff face at any one time and resulting debris may not directly impact a tank. It is also noted that more vulnerable equipment (ie tank nozzles and connecting pipework) has been relocated away from the cliff face side since 2014 hence is less vulnerable than previously. The probability of impact by cliff collapse debris on a specific tank shell or associated nozzles resulting in a large scale loss of containment is therefore assumed to be 0.1 for any single tank.
- Therefore the frequency of cliff collapse resulting in catastrophic damage to a tank and a significant loss of containment is set to 1×10^{-4} per year per tank for the purposes of testing the sensitivity of risk results in the QRA.

This frequency is then applied to each tank in the risk affected area and an ignition probability applied to estimate the total bund fire frequencies (as per the general QRA ignition rule set for combustible only storage areas).

This results in a fire event frequency for each main bunded area below the cliff of approximately 2×10^{-6} per year due to loss of containment and associated ignition.

F4.3. Consequences of slope stability damage to tanks

A landslip occurred in March 2014 (attributed to slope destabilisation from 2010/2011 earthquakes and a subsequent very high rainfall event) that displaced more than 3000 m^3 of rock and damaged several tanks resulting in a large loss of containment from one tank (over 1000 m^3 of flammable product) due to damage to the attached pipework that was sheared off at a tank nozzle of one tank. Most of the spill was contained within the bund with an escape of about 1.5 m^3 of product to the harbour. Ignition did not occur.

As evidenced by the 2014 event, it is not likely that a landslip would cause catastrophic failure of the bund and inability to contain the majority of a spill from a damaged tank. A landslip will also damage a small number of tanks (i.e. 1 or 2 – not all tanks in the bund damaged due to relatively localised effect of soil/rock displacement).

Therefore the QRA assumes that the worst case consequence of tank damage due to damage from cliff collapse remains as a bund fire involving the inventory of the largest tank in a bunded area that is constrained by the area of the bund.

Figure F. 5: **Slope Instability - Cliff Collapse risk area (from Ref 12, Appendix B, Figure F9d)**

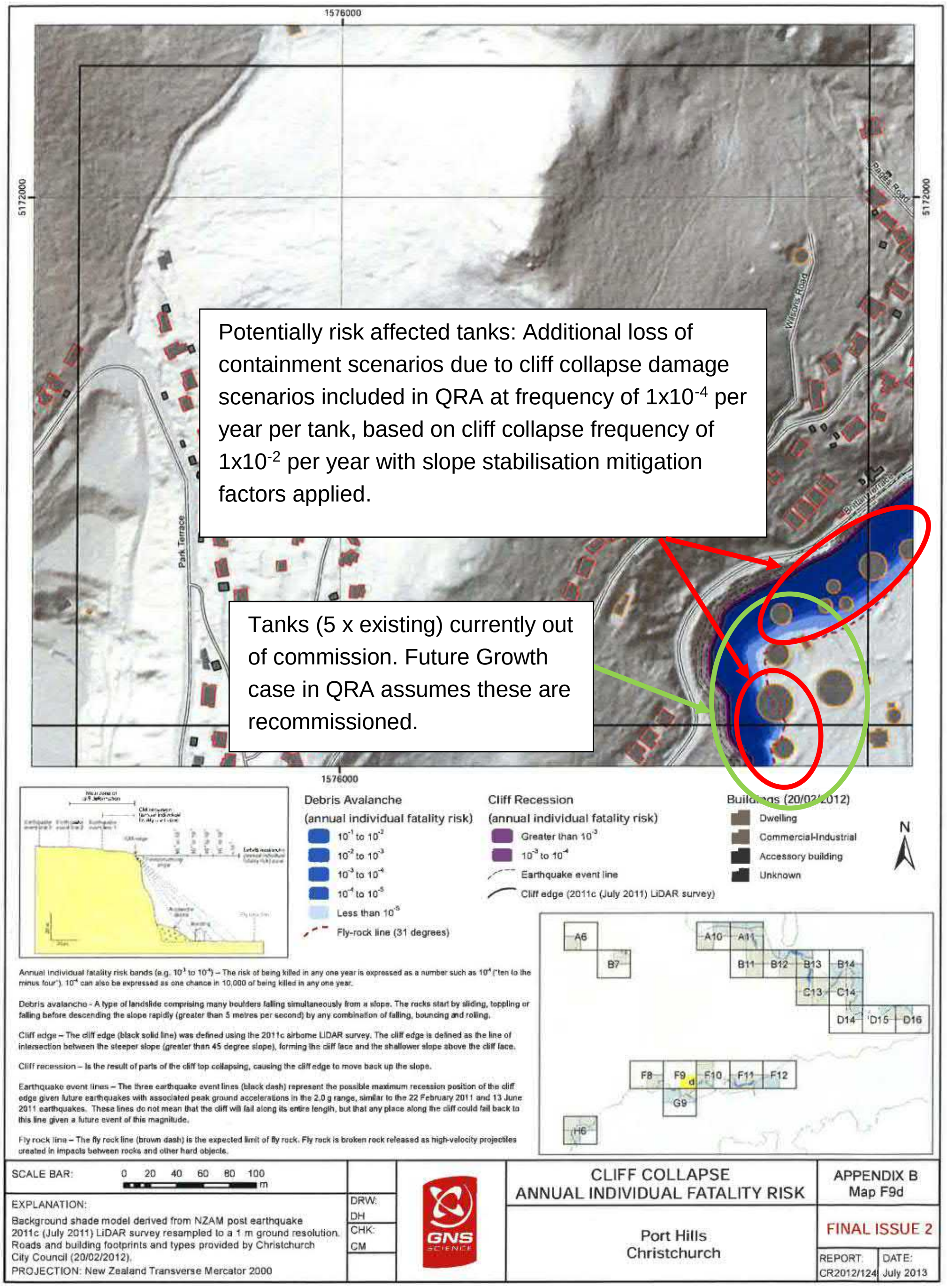


Figure F. 6: Slope Instability - Rockfall Risk Area (from Ref 14, Appendix C, Figure F9)

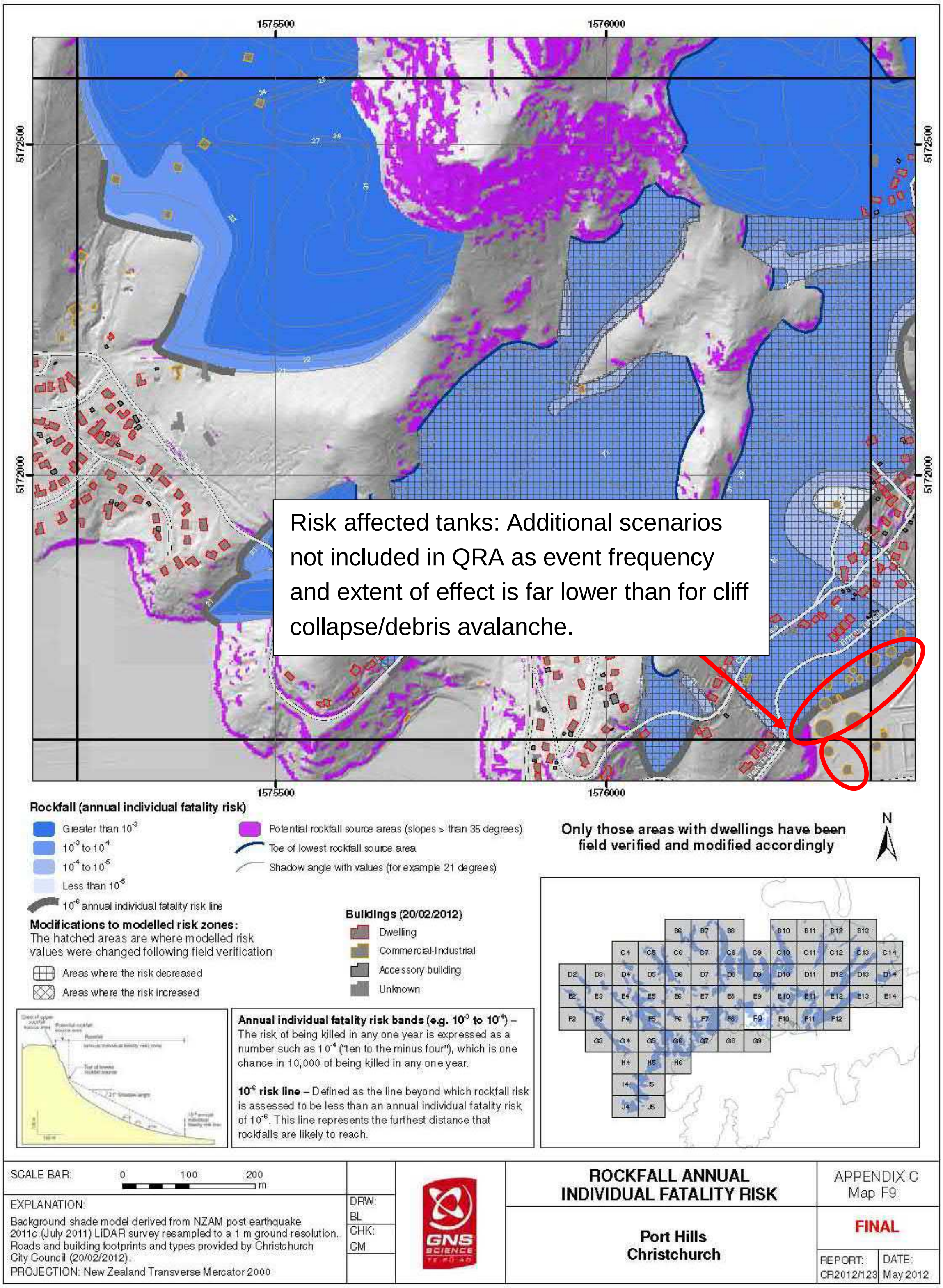


Figure F. 7: Combined map showing AIFR from Cliff Collapse and Rockfall (supplied by CCC)

APPENDIX G. COMPARATIVE RISK RESULTS

G1. Overview of cases

This Appendix provides comparative individual fatality risk contours to show:

- Section G1: A comparison of individual fatality risk contours on “order of magnitude“ basis and HIPAP 4 criteria basis.
- Section G2: The effect of doubling the assumed ignition probability for releases from tanks and bunds due to potential increased ignition likelihood in an earthquake initiated loss of containment as described in Section F1.3.
- Section G3: The effect of inclusion of natural hazards scenarios compared to a standard QRA covering mechanical failures and operational upsets with no location specific natural hazards effects.
- Section G4: The effect of inclusion of road tanker incidents for flammable liquids tanker transport within the Port area only

Also provided in Section G5 is an FN curve comparison which shows the sensitivity of the societal risk results to changes in population and operations. A summary of the differences between the societal risk cases considered is shown in Table G.1.

In Section G6 the societal risk results are plotted against a range of societal risk criteria from other jurisdictions.

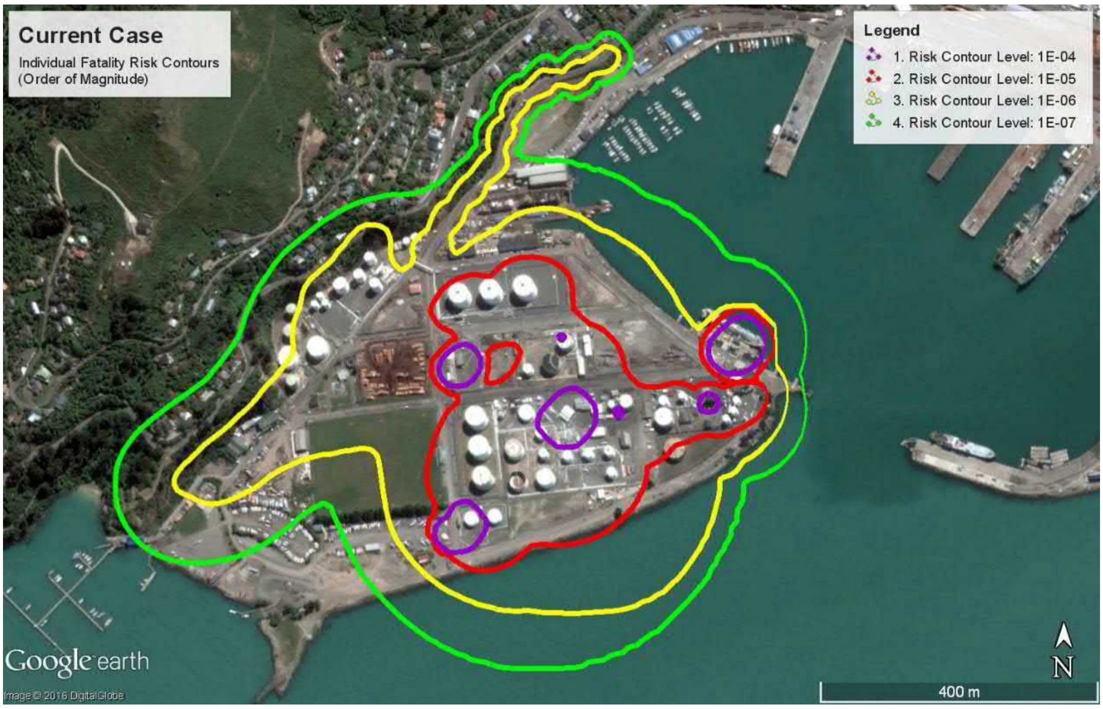
Table G.1: Societal risk sensitivity scenario definitions

Scenario name	Operations			Population	
	Current Case	Future Case 1	Future Case 2	Current Case	Future Case
Current Case (lower limit risk case)	✓			✓	
Future Case 1 (upper limit risk case)		✓			✓
Future Case 2			✓		✓
Current Ops, Future Pop	✓				✓
Future Ops, Current Pop		✓		✓	

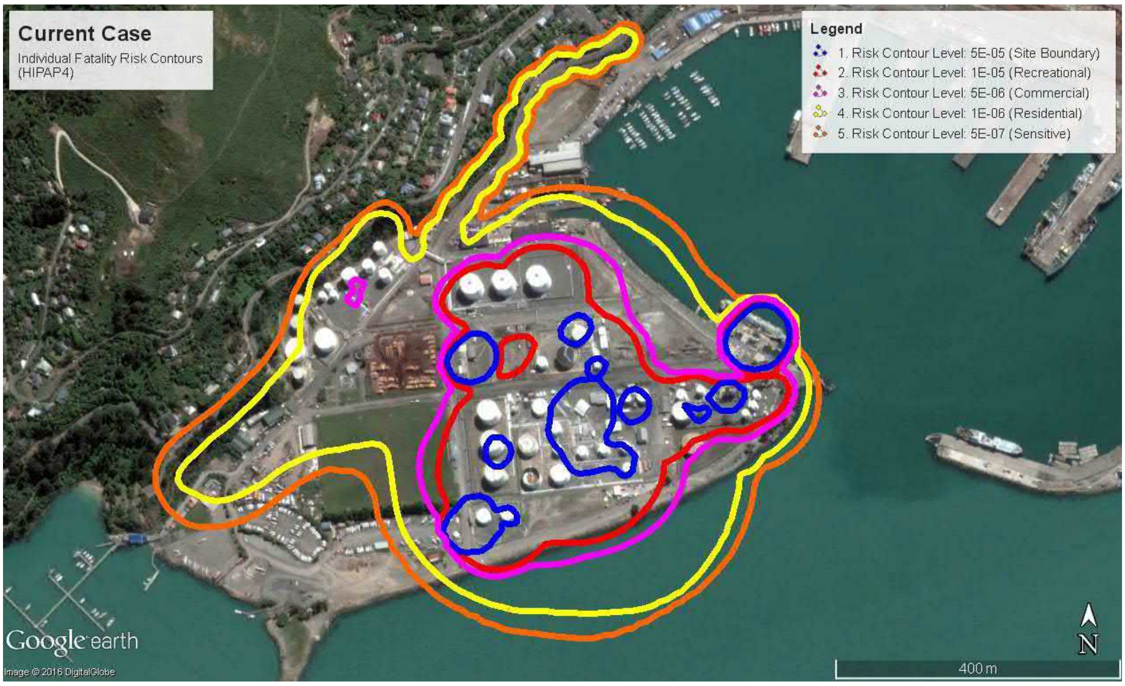
G2. Individual fatality risk contours – HIPAP 4 basis

G2.1. Current Case

Current Case – Order of Magnitude risk contour levels

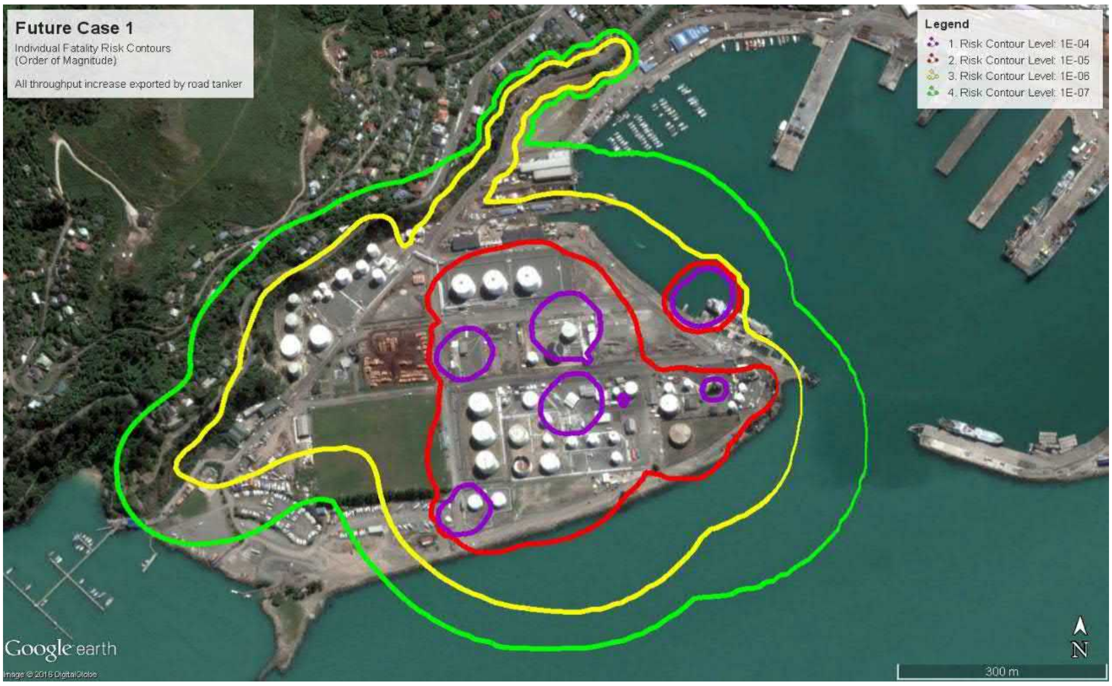


Current Case – HIPAP 4 criteria for risk contours

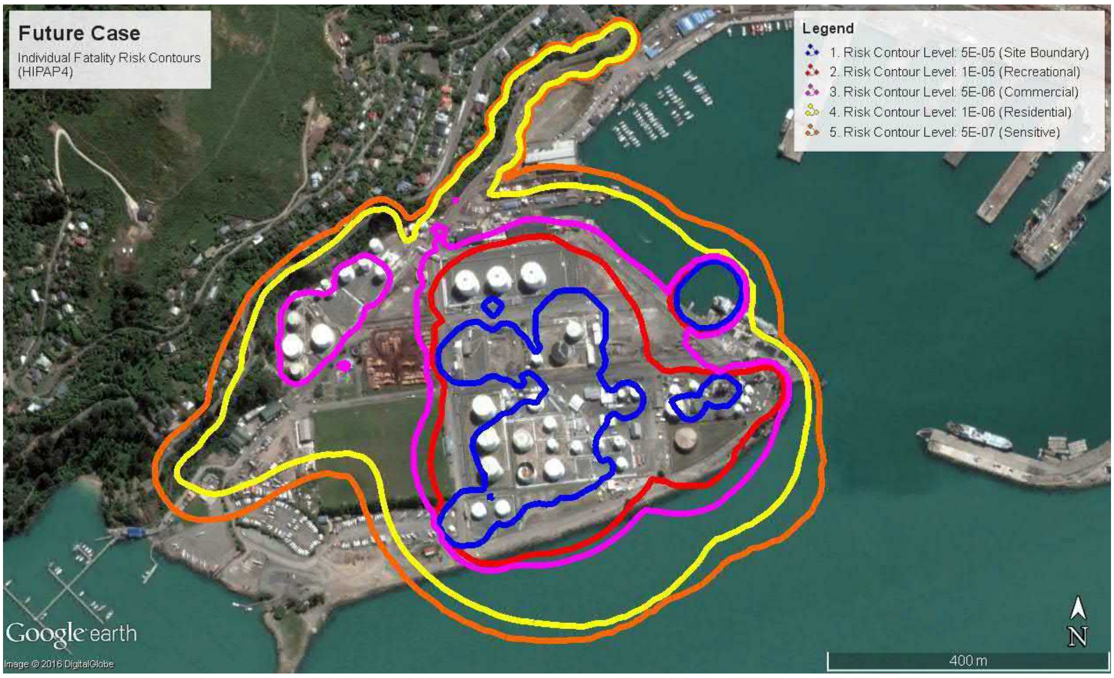


G2.2. Future Case

Future Case 1– Order of Magnitude risk contour levels

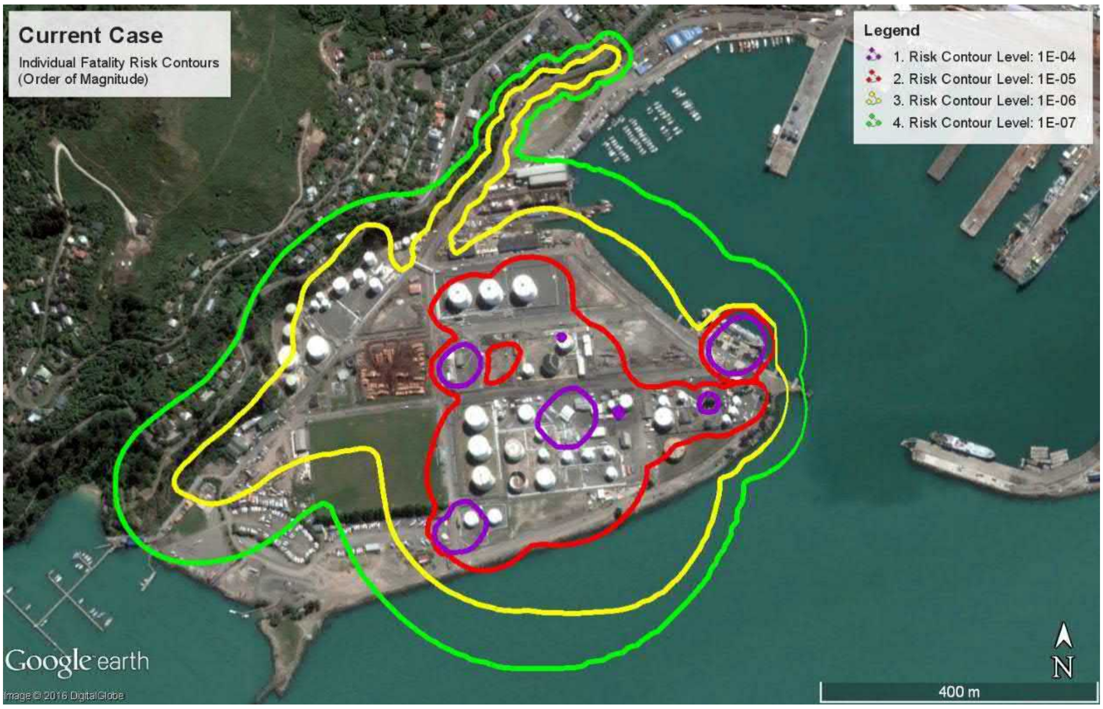


Future Case 1– HIPAP 4 criteria for risk contours

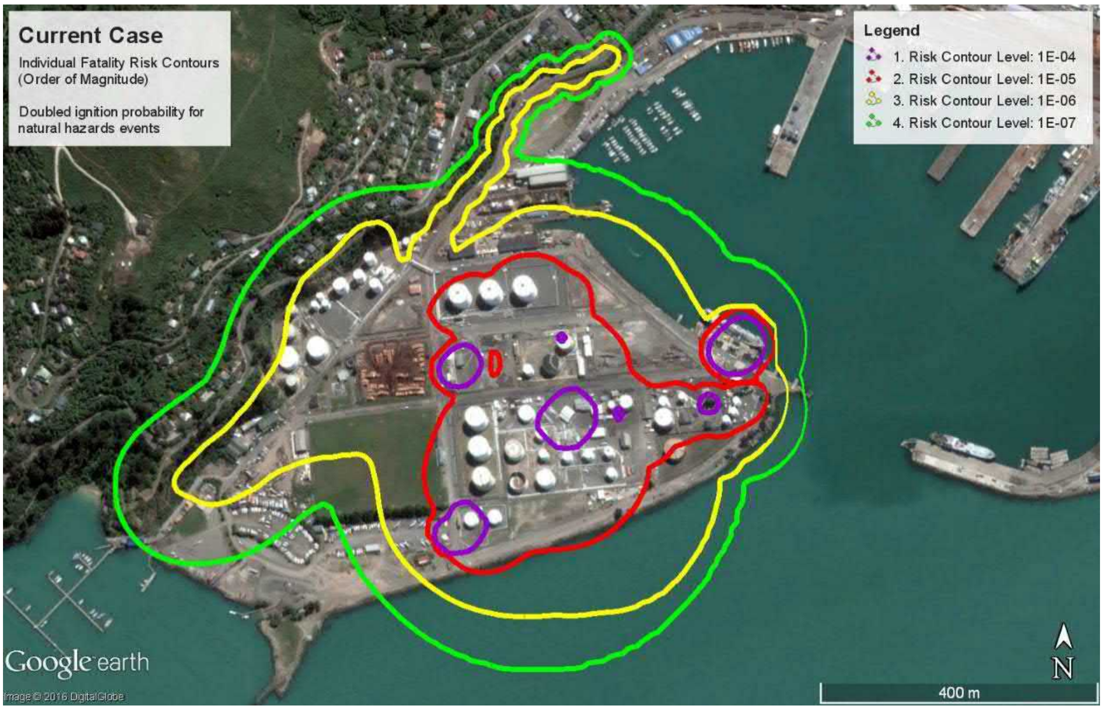


G3. Risk results with doubled ignition probabilities for loss of containment due to earthquake events

Current Case – earthquakes with standard ignition probabilities as per Figure 6.1

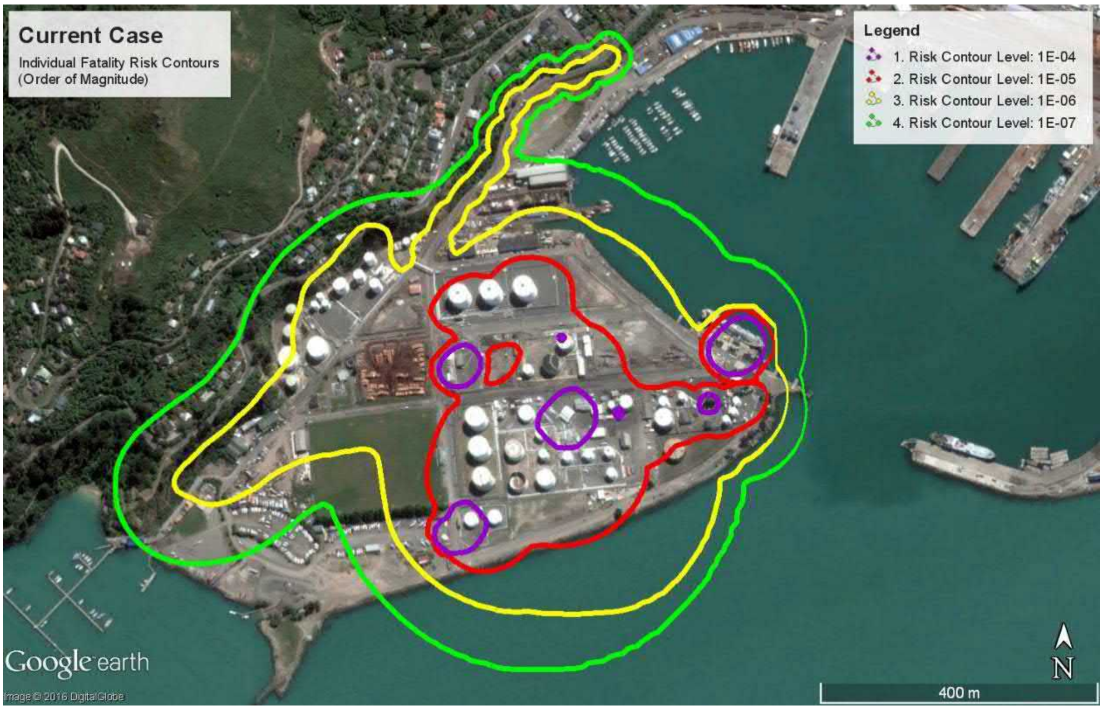


Current Case – with doubled ignition probabilities for earthquakes

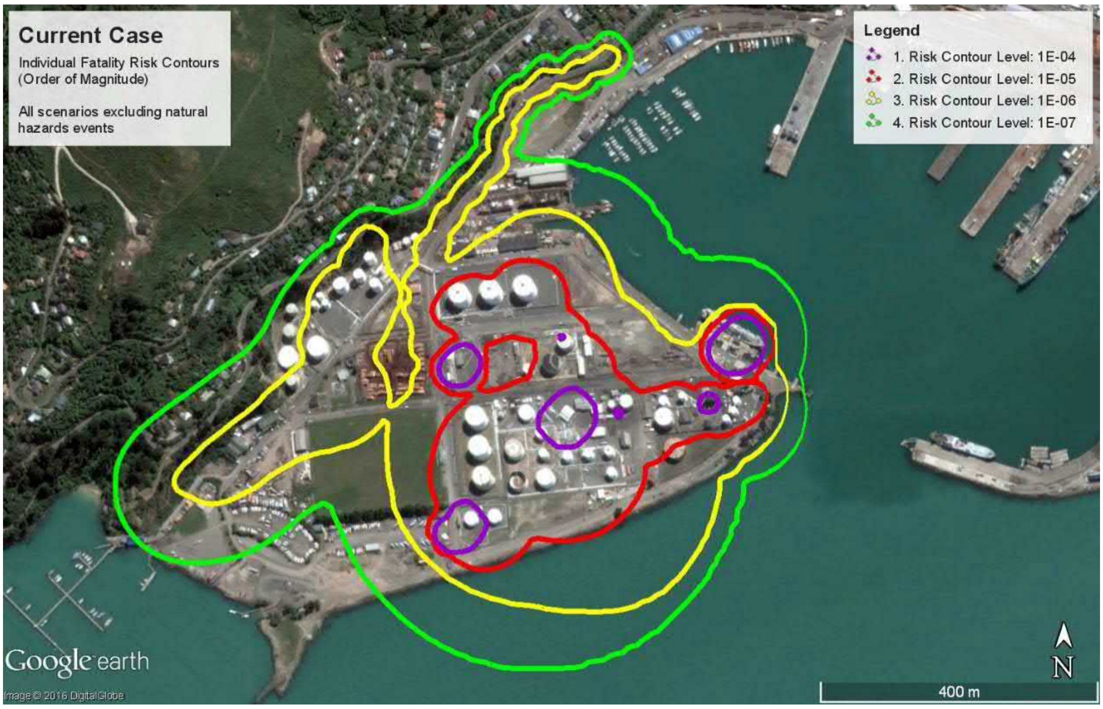


G4. Risk results excluding natural hazards events

Current Case including natural hazards – as per Figure 6.1

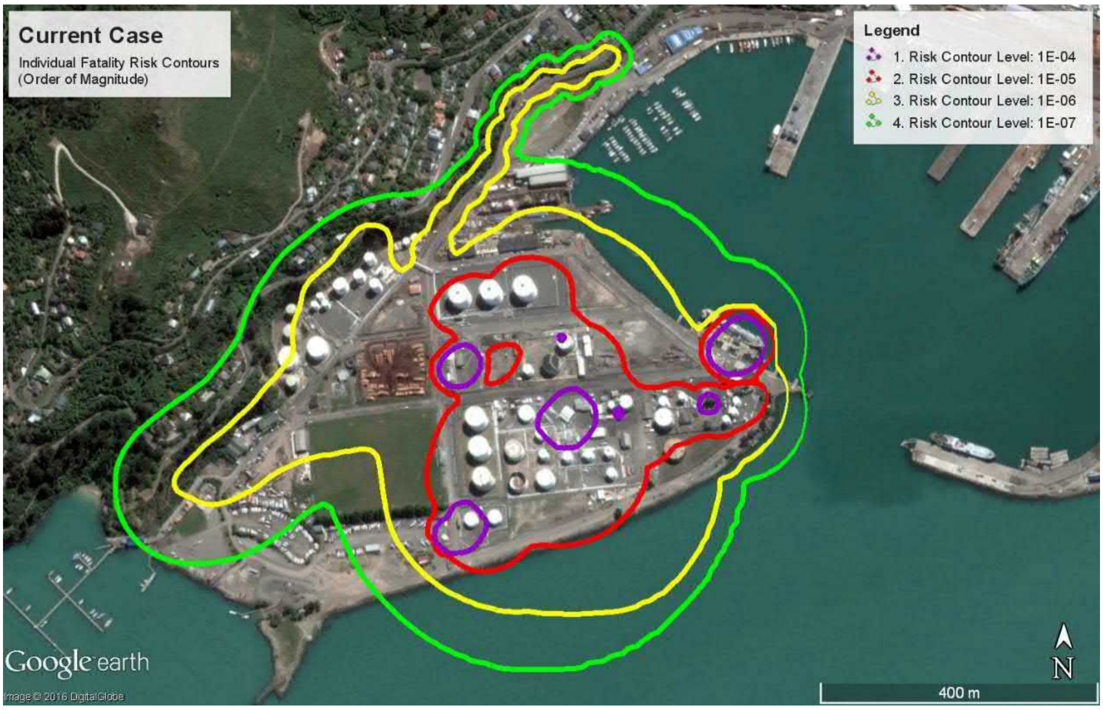


Current Case – excluding natural hazards events

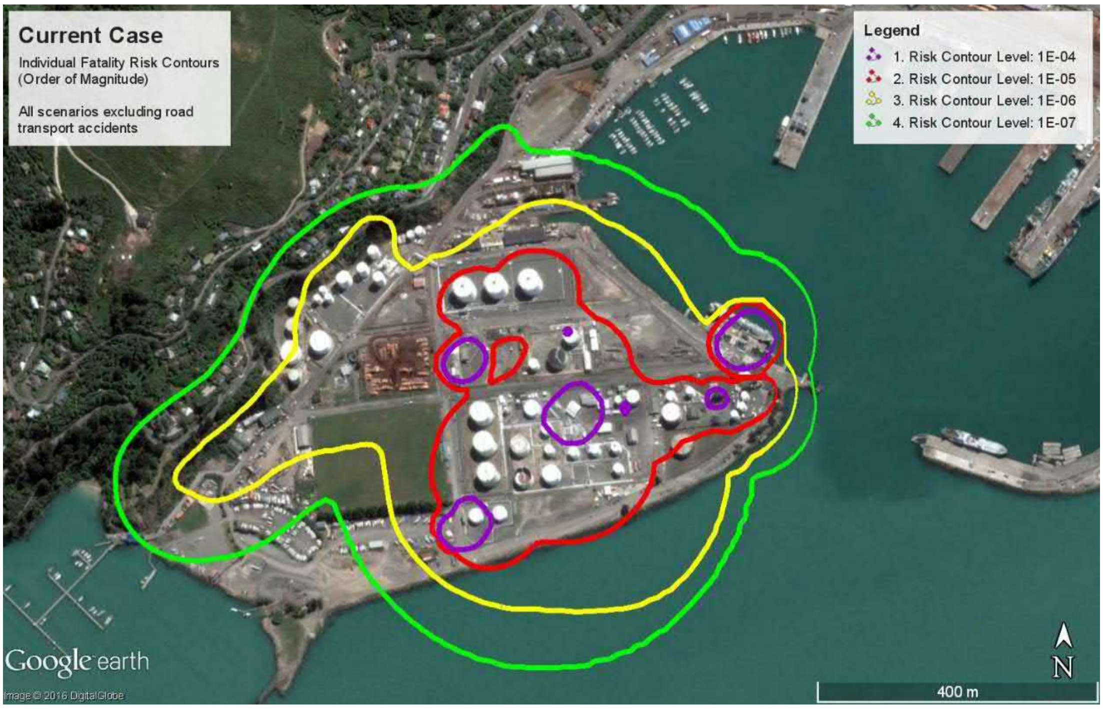


G5. Risk results excluding road accident events within the Port area

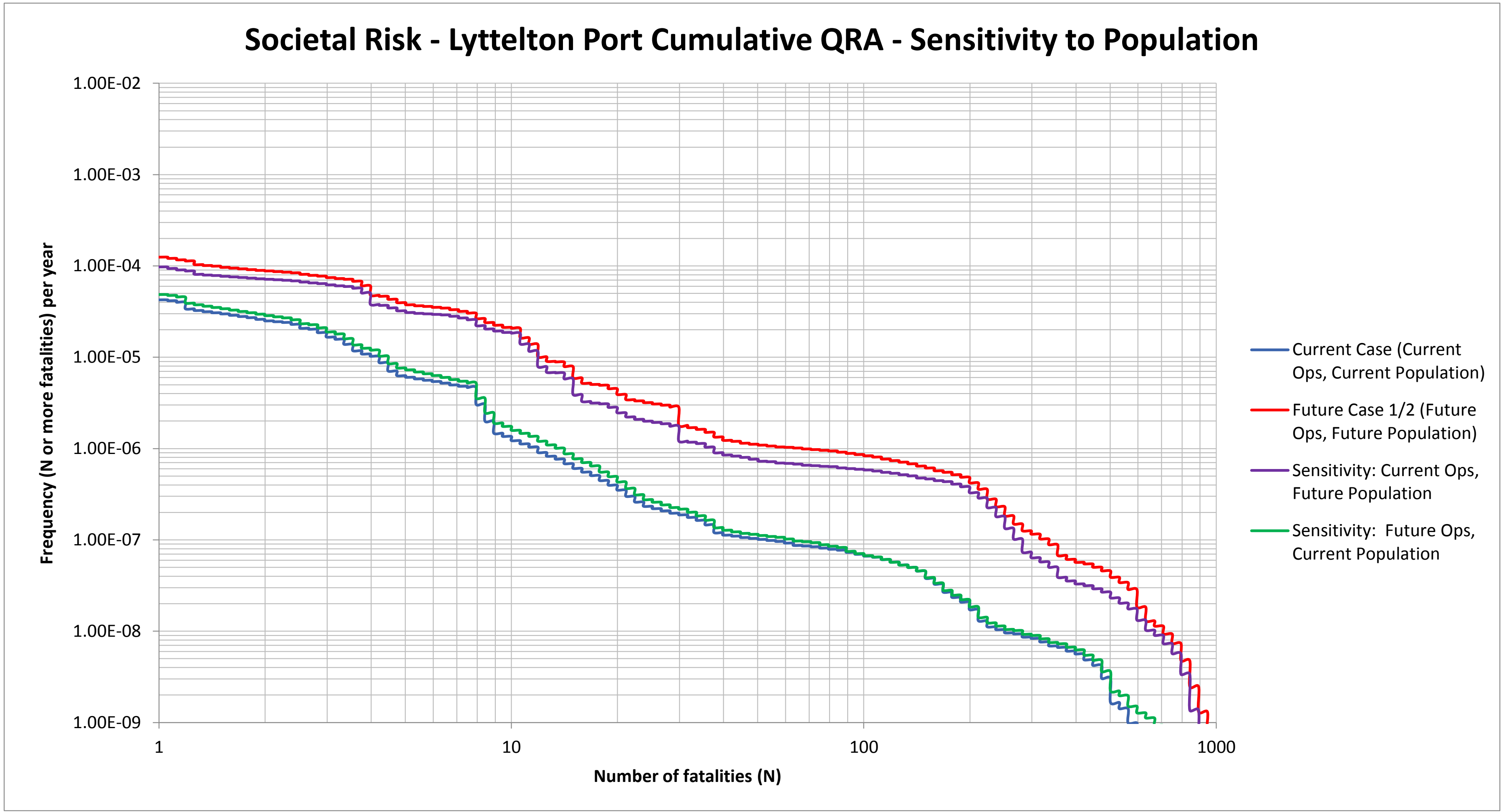
Current Case – including road accidents as per Figure 6.1



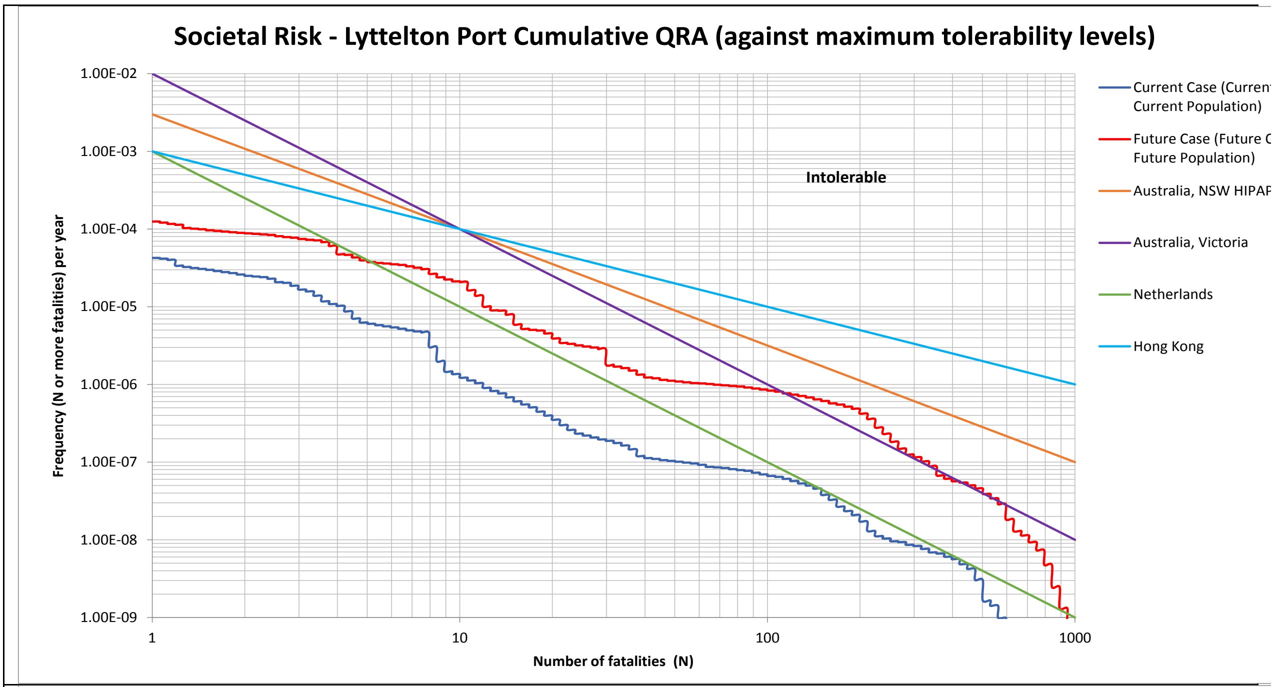
Current Case – excluding flammable liquid tanker road accidents

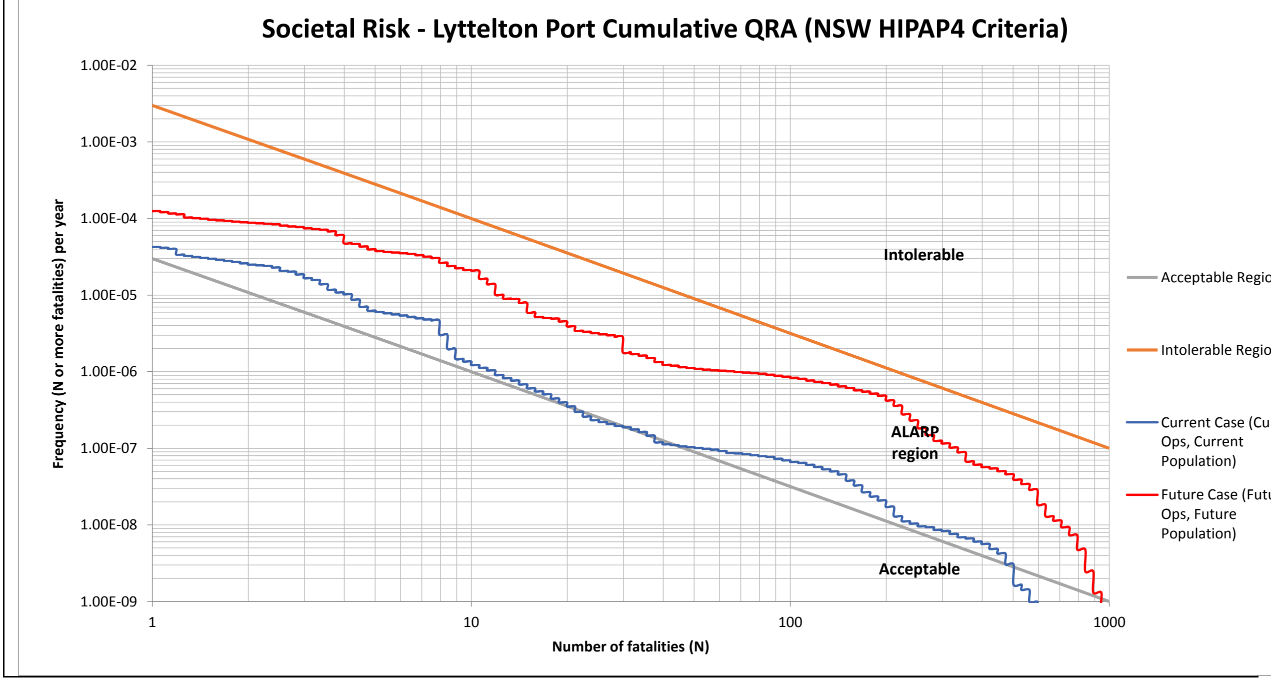


G6. Variance of societal risk to future increases in operations and population – combined FN curve



G7. Societal risk results compared to “intolerable” FN criteria boundary – various jurisdictions and HIPAP 4





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