DEVELOPMENT OF METHODS FOR GEOGRAPHICAL REPRESENTATION OF LOCAL SOCIETAL RISK†

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This paper presents geographical representations of societal risk developed at the Health and Safety Laboratory that have the potential to inform decisions in Land-Use Planning advice. The risk assessment software tool QuickRisk is used to produce both individual and societal risk outputs, from which societal risk-based maps are derived.

Societal risk-based maps that are discussed are the *Potential Loss of Life* (PLL) *density map*, which shows the geographical distribution of risk linked to existing populations in the vicinity of Major Accident Hazard (MAH) sites. Other risk-based maps are derived by comparison with risk criteria such as PLL *density-based population* maps or geographical representations of the Major Hazard scenarios in terms of their contribution to the PLL density at any given location.

The geographical tools suggested are put into context by comparison with graphical representations of societal risk (FN curves), earlier versions of geographical representations of societal risk based on PLL area and PLL density, and Land-Use Planning advice based on HSE consultation distances from the assessment of Hazardous Substances Consent.

INTRODUCTION

In the UK, according to The Planning (Hazardous Substances) Act 1990, installations wishing to hold hazardous substances above a pre-defined threshold quantity must seek consent from the Hazardous Substances Authority (HSA), which is usually the Local Planning Authority (LPA). The HSA must consult HSE on these applications. Based on the information supplied by the installation's operator, HSE calculates the levels of risk to a hypothetical individual sustaining the dangerous dose or worse and determines a consultation distance around the installation. If consent is granted, then a three zone map is produced informed by levels of individual risk. Where the zones are directly based on individual risk, these zones are: individual risk of 10 chances per million per year (cpm/year) at the boundary of the inner zone, 1 cpm/year at the middle zone boundary and 0.3 cpm/year for the outer zone. The outer zone boundary is known as the 'Consultation Distance' or CD. The LPA must consult HSE on any future applications for planning permission for certain types of development of land within the CD.

In 2007, HSE, on behalf of the UK Cross-government Task Group on societal risk, published a consultation document (CD212) seeking views *on whether information on potential major accidents, known as 'societal risk' should explicitly be taken into account when assessing safety measures at onshore, non-nuclear major hazard installations and for informing land-use planning advice around those sites*. From the responses received, UK government ministers agreed that societal risk should be taken into account.

Societal risk can be defined as *the relationship between frequency and number of people suffering from a specified level of harm in a given population from the realisation of specified hazards* (Jones, 1985). It is therefore about *the chances of more than one individual being harmed simultaneously in an incident*, as opposed to individual risk, and *varies according to the surrounding population (location and density)*.

Considering that the surrounding population determines societal risk levels and that the use of land is best visualised on geographical information systems, it follows that geographical representations of societal risk should be best placed to guide societal risk-based decisions on the use of land by local planning authorities and spatial-planners.

However, the use of geographical representations of societal risk is not straightforward as risk-based maps are open to misinterpretation by the untrained eye and there is still a need for criteria to compare societal risk levels against. The aim of this paper is to explore possible geographical representations of societal risk that could be used to inform land-use planning advice around a major hazard installation.

GEOGRAPHICAL REPRESENTATIONS OF SOCIETAL RISK

Numerical and geographical representations of societal risk used in the UK have recently been reviewed by Saw et al. (2010). The Potential Loss of Life (PLL), also known as Expectation Value (EV) and Nmax, or the maximum number of fatalities resulting from the worst case event at a major hazard installation were some of the societal risk measures suggested. PLL and Nmax have been used in this paper to derive novel geographical representations of societal risk.

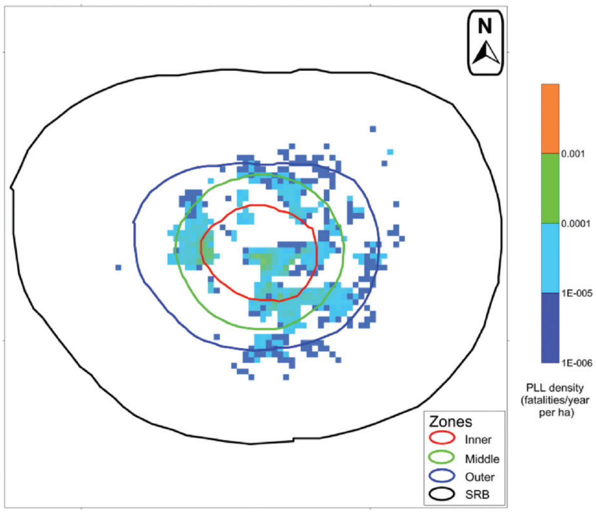

Figure 1. PLL density map

MAP OF PLL-DENSITY

The potential loss of life, PLL, is the average number of fatalities expected per year and is calculated by summing the product of impact frequency (taking account of harm probability) and the number of persons affected.

The potential number of people affected can be calculated at each population grid square or grid location from six footprints per scenario (indoor and outdoor at 3 dose levels LD01, LD10, LD50) according to the *Total Risk of Death* (TROD) methodology (Rushton & Carter, 2007). Figure 1 shows an example of a geographical PLL density map.

Once the PLL density has been calculated, further analysis can be performed to elucidate the main contributing factors to the PLL at each geographical location. For example, each population grid square can be affected by a number of release scenarios. Similarly, release scenarios may originate from one or multiple major hazard installations. Although the weight of each scenario/major hazard site will be implicit in the overall risk picture provided by the PLL-density map, a break down of the PLL density can be calculated by scenario, group of scenarios, area (including LUP zones) and/or major hazard site for each population point location. Breaking down the spatial distribution of PLL density by scenarios or groups of scenarios (e.g. road tanker deliveries) can be useful to identify the scenario or group of scenarios that contributes most to the risk in a local area. Figure 2 is an example of how this information can be shown spatially: the scenario that has the highest contribution to the PLL density at each grid square is shaded. The catastrophic failure of a vessel containing chlorine, dominates the risk in the medium to long-range. Closer to the site, a 50 mm (major failure) hole in the chlorine vessel has the highest percentage contribution.

The map also shows how the catastrophic failure of a chlorine vessel from a different site (beyond the map limits) has the largest share of the PLL to the south end of the map (area shown in yellow in Figure 2). The largest risk reduction at this location would be achieved by acting on the release scenario from the second site. The PLL density in the areas closer to the site is dominated by smaller instantaneous releases of toxic (methyl iodide) and very toxic (paraquat dichloride) substances that had shorter hazard

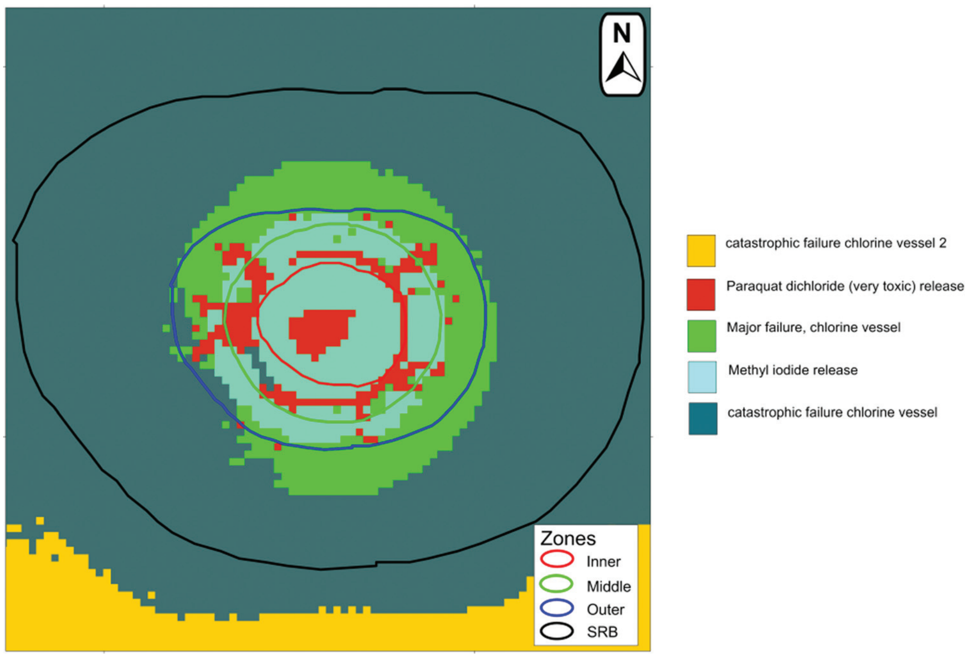

Figure 2. PLL-dominant scenarios in the vicinity of a major hazard site

ranges but higher frequencies than the catastrophic failure of the chlorine vessels. The percentage contribution to the PLL-density from the dominant scenario at each populated location is shown in Figure 3.

These three maps could be used in conjunction to identify the main contributors to societal risk at different geographical locations: whilst the geographical distribution of the PLL identifies populations at higher risk, knowing the effect of each individual release scenario, group of scenarios or major hazard site generating the risks could help in directing advice on potential risk reduction measures that are more likely to be effective at any given area. This would help to inform discussions with land use planners, developers and dutyholders on societal risk.

POPULATION DENSITY MAPS BASED ON RISK

The PLL density values in Figure 1 identify local high risk areas and areas under comparatively lower societal risks. However, the absolute value of the PLL density may hold little meaning to land-use planners, and a PLL density criterion to aid decision-making would be needed.

The HSE document 'Reducing Risks Protecting People' (R2P2) defines one criterion as *the risk of an accident causing the death of 50 or more people in a single event should be regarded as intolerable if the frequency is estimated to be more than one in five thousand per annum.* This frequency-consequence criterion point in R2P2 could be used to derive a criterion boundary in a FN curve by plotting a line of slope $= -1$ (with no scale aversion) passing through the R2P2 point and truncated at $N = 1000$. The criterion line would provide a distinction between 'unacceptable' and 'tolerable if ALARP' societal risks but comparison of FN curves against it is not straightforward.

The R2P2 point may not be directly expressed in terms of a PLL density criterion that could be applied to identify local areas above an upper tolerability limit. Atkins (2009) suggested a value of 10^{-5} fatalities per year per hectare (ha) as a PLL criterion point, which is an order of magnitude lower than the value used by Wiersma et al. (2007). Suppose that PLL density criterion values were to be identified and adopted, then calculations making a comparison with that criterion value could be made and used to examine the existing societal risk situation. This could be used to show areas where the criterion is exceeded and areas where it is not exceeded. In this paper, a PLL density criterion of 10^{-5} fatalities per year per ha, as suggested by Atkins (2009), has been used. This is for a basis of discussion only and does not reflect any current HSE policy. The comparison rationale that could be applied is as follows.

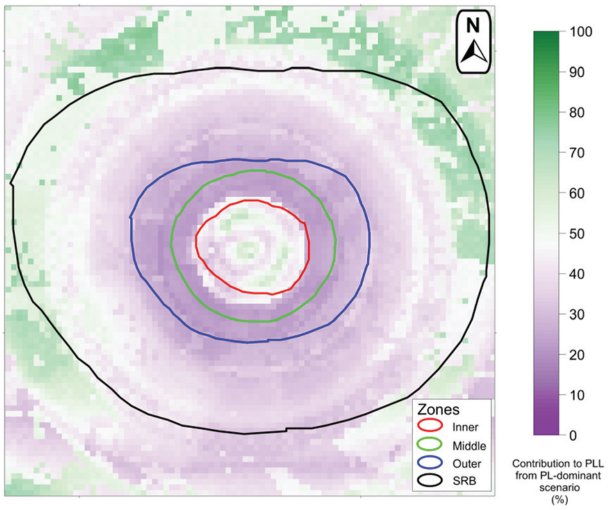

Figure 3. Percentage of PLL from the risk dominant scenario at each population point/location

By definition, the PLL value at each population location/area *i* is the average number of persons expected to receive the specified level of harm per year and is calculated by summing the product of frequency of each event *e* affecting the grid location and the number of persons affected at that grid location (Eq. 1)

$$\mathrm{PLL}_i = \sum_e f(N) \times N_{[\mathrm{fatalities/year}]} \qquad (1)$$

The summation of the frequencies at a grid location *i* represents the *individual risk (IR)*, or the risk that one single individual will experience at that grid location (Eq. 2)

$$IR = \sum_e f \qquad (2)$$

When the individual risk is based on a harm criteria weighted TROD approach, the individual risk and PLL density at each single grid location are linked as shown in Eq. 3.

$$\mathrm{PLL}_i = IR_{\mathrm{TROD}_i} \times N_i \qquad (3)$$

where N_i represents the existing population at that particular grid location.

At each grid location the following relationship (Eq. 4) applies:

$$\mathrm{PLL}_{\mathrm{criterion}\,i} = IR_{\mathrm{TROD}_i} \times N_{\mathrm{criterion}\,i} \qquad (4)$$

Where $N_{\mathrm{criterion}\ i}$ represents the maximum number of people at the grid location *i* that would meet the specified PLL density criterion. Figure 4 shows the maximum population map for the PLL density distribution shown in Figure 1 with a PLL density criterion of 10^{-5} fatalities per year per ha. Areas whose population density can be 300 people per ha or higher without exceeding the PLL density criteria are not shaded.

The maximum population value could be compared with the existing population (Figure 6) and shown in terms of the population change that would be required to

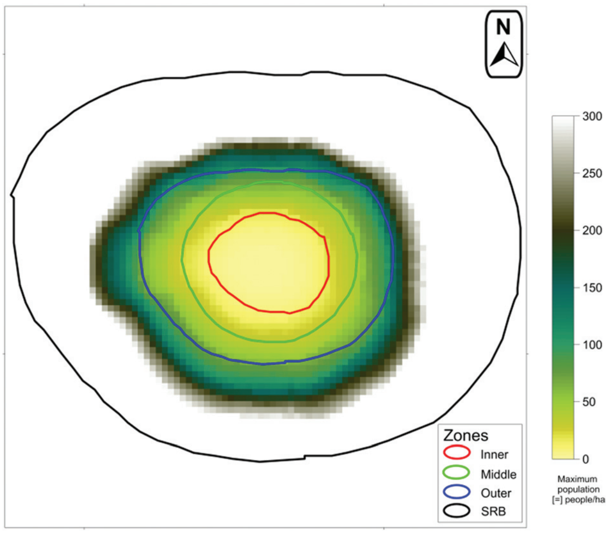

Figure 4. Maximum population at each population grid square that would meet the preset PLL density of 10^{-5}/year per ha

meet the PLL density criterion (Figure 5).

$$\Delta N_i = N_{\text{criterion}\,i} - N_i \tag{5}$$

As defined in Eq. 5, the ΔN_i can be a positive number, representing the maximum number of additional people that would be advisable at that grid location so that the PLL density criterion is not exceeded; but ΔN can also be a negative number. The absolute value of this number represents the number of people at that particular location that are taking the PLL density above the specified threshold.

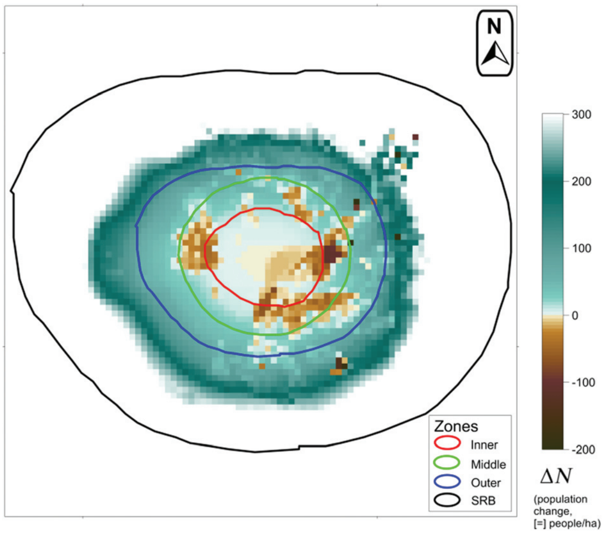

Figure 5. ΔN (Population change) map according to existing population, *IR*-TROD and PLL density criteria of 10^{-5} fatalities/year per ha

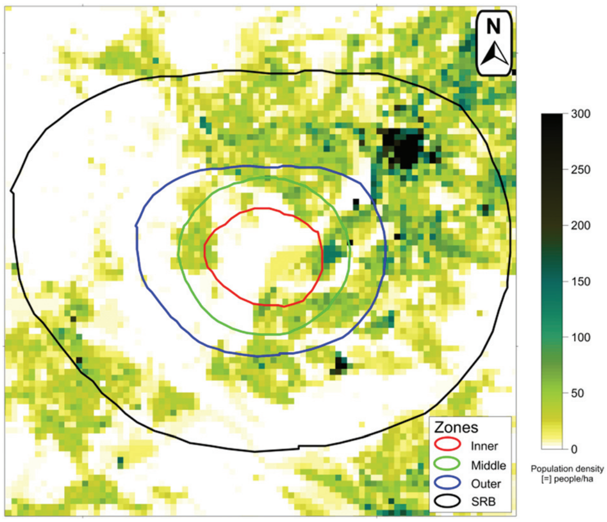

Figure 6. Population density (daytime) around the major hazard site

Locations shaded green in Figure 5 represent areas where population could be increased before reaching the PLL density criteria and areas shaded brown represent locations above the PLL density target.

ΔN quantifies the population change that would be advisable according to the PLL density criterion and therefore identifies areas where there is potential for development and areas where risks are already above PLL density guideline values and additional populations would not be advisable on the basis of PLL density.

This map could provide a direct comparison tool for development plans against a PLL density criterion applied to each population grid individually. Although it could be useful to assess population densities against maximum values on a grid-by-grid basis, it does not factor in risks from neighbouring populated areas in the decision-making process. Proposed development densities may be below the maximum values in the affected grids, as it is the case in some areas within the middle zone in Figure 5, thus conveying the idea that there is room for additional development without increasing the PLL above the PLL density criterion. However, the PLL associated with the middle zone is high, as it can be seen by the numerous grids shaded brown within it. Consequently, the assessment of the acceptability of population increments would benefit from taking into account populations of areas beyond the grid squares affected.

One approach to prevent incremental development and increased populations in areas already at high risk could be by limiting societal risk within the existing individual-risk based land-use planning zones. Table 1 is an example of PLL density values for each of the LUP zones represented in the maps also including a 'Societal Risk Boundary', SRB, which is a function of the consultation distance (approximately twice the distance between the release points and the consultation distance). It is clear

Table 1. PLL and PLL density per LUP zone

	Inner	Middle	Outer	SRB
PLL ($\times 10^6$ fatalities per year)	4500	3800	1700	1900
Area (ha)	260	350	520	3400
PLL density per LUP Area (fatalities per year per ha)	1.7E-05	1.1E-05	3.3E-06	5.6E-07

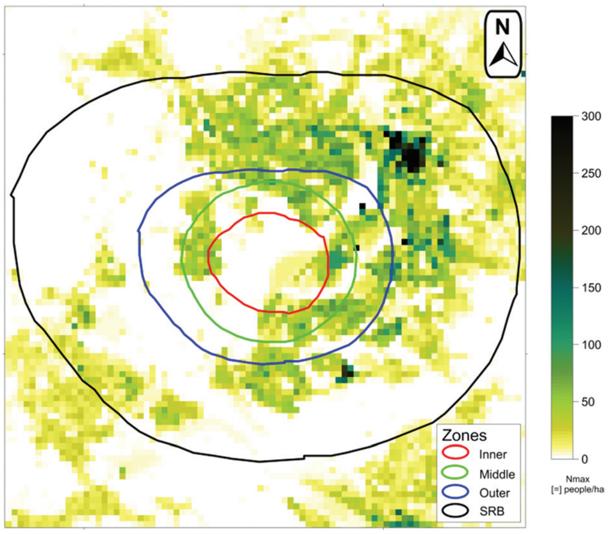

Figure 7. Map showing Nmax per grid square (resolution = 100 × 100 m)

that PLL density for the site is above 10^{-5} fatalities per year per ha within the inner and middle zones, thus discouraging any development within these zones on the basis of existing high levels of societal risk.

MAP OF THE MAXIMUM NUMBER OF FATALITIES (NMAX)

The maximum number of fatalities (Nmax) from the worst case event at a major hazard installation can be used as an additional measure of societal risk providing that the associated event frequency is known. The maximum number of potential fatalities generated by the worst case event can be directly read from a FN curve. However, a FN curve does not identify the actual locations affected by the scenario, nor the maximum number of fatalities associated to any given populated area. Another type of information that cannot be read from a FN curve is the scenario that is behind the Nmax, which may also vary between grid squares. The absolute maximum number of fatalities associated to a particular scenario can be calculated by the summation of the individual Nmax for the individual population grid squares for the worst case wind direction.

The map of the potential maximum number of fatalities is shown in Figure 7. The potential maximum number of fatalities at each population grid square decreases with distance from the release points as can be seen from the lighter shading of the Nmax map when compared to the population density map in Figure 6. This is expected as areas further away from the site are likely to be encompassed by 1% fatality contours of high consequence scenarios only. Figure 8 identifies the scenarios behind the Nmax at any given grid square. Large instantaneous releases

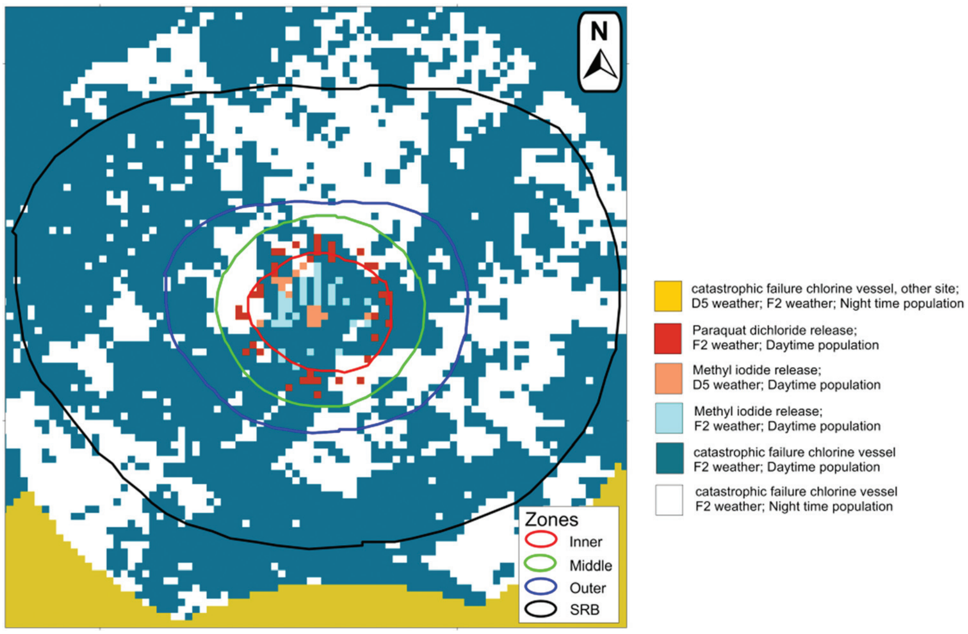

Figure 8. Scenario associated to Nmax per grid square (including weather category and population type: day time/night time)

of toxic substances (chlorine in this example) are responsible at distances further away from the middle zone. Instantaneous releases of other toxics and very toxic substances are behind the Nmax values closer in to the release point.

The geographical distribution of Nmax could be useful to illustrate not only the potential maximum number of fatalities at any given geographical location that is considered for development, but also the scenario that would cause the worst-case consequence. This would help to inform discussions with land-use planners, developers and dutyholders on societal risk (e.g. by identifying development-specific risk reduction measures aimed at the worst-consequence event).

CONCLUSIONS

This paper presents a series of geographical representations of societal risk that could have the potential to be used in a system where planners, developers and industry could work together to take decisions on land use and major hazards. Risk-based maps have been derived from the PLL density map to identify the contribution of each release scenario and the populations affected. Maps based on PLL density compared to a possible criterion value have been produced. These maps might be used to inform decisions on future development proposals by taking into account the existing level of societal risk. Similarly, a geographical distribution of the potential maximum number of fatalities associated to the worst case event, weather category and population combination at each grid square has been produced. This information can help understand societal risk affecting areas in the vicinity of major hazard sites and could be useful for more effective risk visualisation.

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