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THE ASSESSMENT OF MAJOR HAZARDS: THE DENSITY AND OTHER CHARACTERISTICS OF THE EXPOSED POPULATION AROUND A HAZARD SOURCE

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Summary

The estimation of the societal risk from a major hazard necessitates the determination of the density of the population around the site. Other information required on the population includes the proportion present at different times of day, the proportion more vulnerable to the hazard and the proportion outdoors. A methodology is presented for the estimation of the population density and for the determination of the other population characteristics.

Introduction

If the assessment of a major hazard is taken to the point of determining the societal risk, it is necessary to estimate the density and other characteristics of the exposed population. The people exposed consist of two groups, those working on the site and those living and/or working in the area around the site.

It is usually straightforward to obtain the necessary information on the on-site workforce, but this is not so for the off-site population. Here the information required includes the number of people normally resident in the area, the numbers who go out of and come into this area at different times of day, the proportion of people particularly vulnerable to the hazard and the proportion of people outdoors.

It is the purpose of this paper to provide some guidelines for characterising these populations, particularly that off site. In developing these guidelines the aim has been to strike a balance between accuracy and practicality. The accuracy of the estimate of the population characteristics should accord broadly with that of the other stages in the assessment. The methodology should call for detail only where this is really necessary.

The methodology described is intended primarily for use in estimating the societal risk of fatalities for sets of scenarios where typically in a large propor-

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tion of cases the fatal effects may not extend sufficiently far for the more approximate methods of estimating population density to give sufficient accuracy.

Risk estimates in hazard assessment

In order to achieve this balance between accuracy and practically it is necessary to consider how information on the population characteristics is actually used in the hazard assessment. There are a number of ways in which the risk results of an assessment may be presented. Some of the principal forms of presentation are listed in Table 1.

Contours of the physical effect (thermal radiation, overpressure, toxic load) from a single hazard may be shown on a map of the site. These may then be converted using probit equations or other methods to contours of individual risk from the hazard. Contours of individual risk from all the hazards on the site may also be constructed. An alternative way of showing individual risk at particular locations is in tabular form. Again the risk may be that from a single hazard and/or that from all the hazards on the site. This form is also convenient for presenting the individual risk from more than one site.

Societal risk likewise may be shown in tabular form. Alternatively, it may be presented as a frequency-number plot, or FN curve. Again the risk may be that from a single hazard on the site, all the hazards on the site, or all the hazards in the area.

A form of presentation which does not appear to have been much used, but which is quite revealing, is the risk transect, which is a plot of individual risk vs. distance. In effect, this plot is the elevation view corresponding to the plan view given by the conventional plot of risk contour on the site map. A typical risk transect is shown in Fig. 1.

If consideration is limited to individual risk, there is no need for data on population density. These are required only if an estimate is to be made of

TABLE 1

Forms of presentation of assessed risks

Site map contours and transects
Physical effects
Individual risk
Individual risk
Tables
Societal risk
Tables
Frequency-number (FN) curves
Average annual fatalities

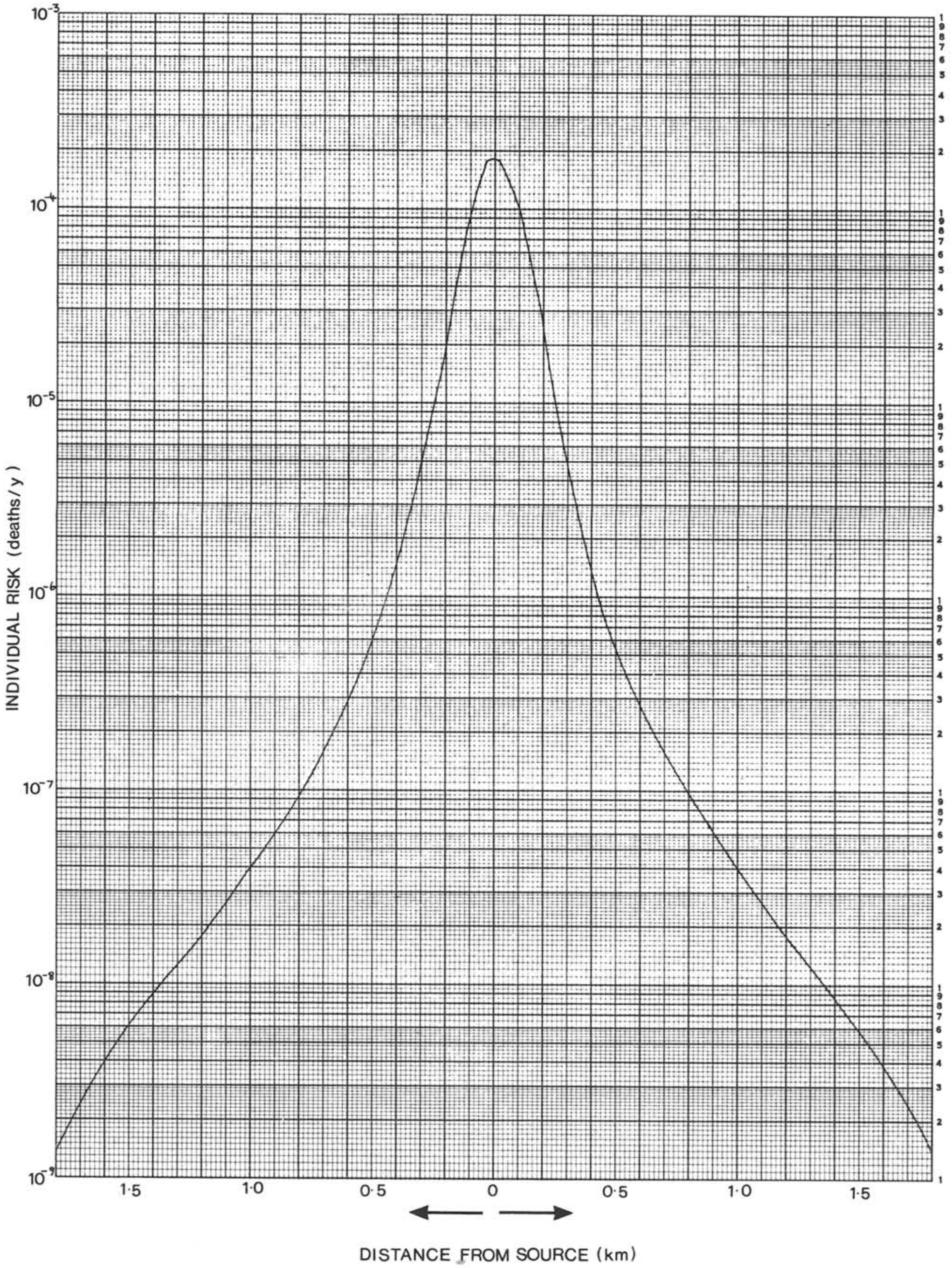

Fig. 1. Typical risk transect.

societal risk. Information on other characteristics of the population, particularly on vulnerability to the hazard, is relevant to individual risk also.

Population estimates in hazard assessment

There have been a number of hazard assessments in which estimates have been made of the risks to the public, including societal risks. These assessments have necessarily involved estimates of the density and other characteristics of the exposed population. Two of the principal hazard assessments are those given in the two Canvey Reports [1,2] and in the Rijnmond Report [3].

The first Canvey Report [1] is a collection of separate studies. A map of the site and surrounding area is shown in Fig. 2. The general approach adopted is to define the built-up zones on the map and to use for these zones a uniform population density of 4,000 persons/km^2.

However, in some of the studies there are variations. In Appendix 3 of Ref. [1], Beattie describes an investigation of escape from a toxic gas cloud, taking chlorine as the toxic gas, although this chemical was not one of the hazards considered at Canvey. Since this is a generalised study, he assumes a uniform density around the hazard source of 5,000 and 100 persons/km^2 for urban and rural areas, respectively.

In Appendix 14 of Ref. [1], Fryer et al. present casualty estimates for a large ammonia release. In this case the population figures used were obtained from Census data. They first obtained the number of people in 100 m squares around the hazard source and then converted these data to the numbers in the segments of $12 \times 30°$ sectors. The population data thus obtained are shown in Table 2. It may be noted that in this study the population profile was obtained as far as 32 km from the hazard source. The number of people within 1.5 km of the source was very small.

The studies presented in the report are apparently based on the populations just described, which are the night time populations. No distinctions are made between night and day time populations or between less and more vulnerable populations.

In the second Canvey Report [2] the method used by Fryer et al. is apparently adopted generally.

The Rijnmond Report [3] is again a collection of separate studies, but in this case a uniform approach is used as far as population characteristics are concerned. A map of the sites and surrounding area is shown in Fig. 3.

For the on-site population data on the number of workers at each industrial site were obtained and the numbers present during the working day N_d and at other times N_n were determined. Then assuming 3-shift, 7-day working, the number of manshifts worked per week is $5N_d + 16N_n$ and assuming that each employee has n_h weeks off for holiday and sickness, etc., and therefore works $(52 - n_h)$ weeks per year, the average number N_s of employees on site is

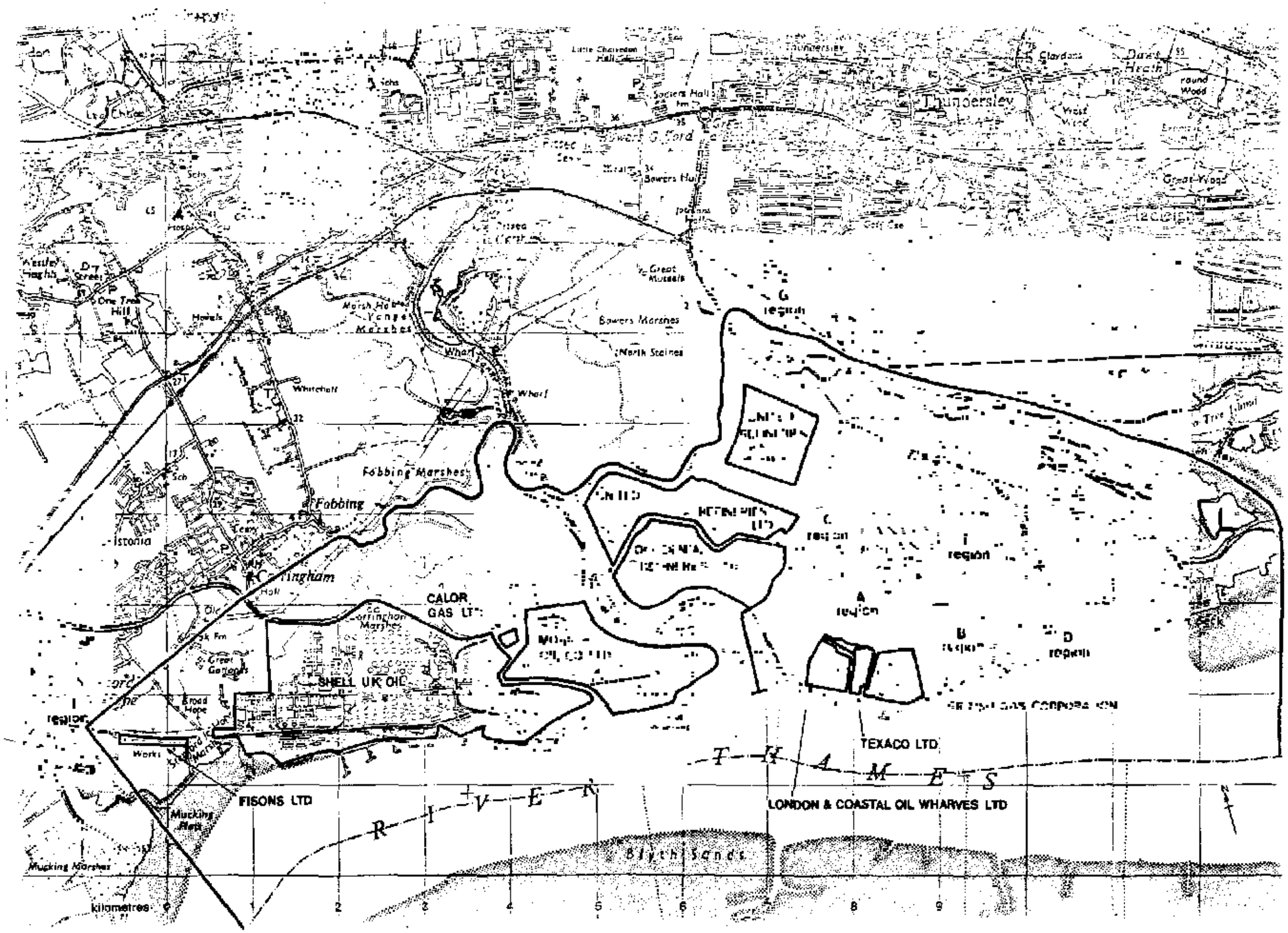

Fig. 2. Map of Canvey/Thurrock area showing populated areas and installations studied in the Canvey report [1] (Courtesy of H.M. Stationery Office).

TABLE 2

Population density at Canvey (after first Canvey Report [1])[a]

Radial zone	Spread of radii (m)	Sector 1	2	3	4	5	6	7	8	9	10	11	12
1	0- 500	0	0	0	0	0	0	0	0	0	0	0	0
2	500- 1,000	0	0	0	0	0	0	0	0	0	3	0	0
3	1,000- 1,500	7	0	0	0	0	0	0	0	0	1	105	0
4	1,500- 2,000	26	0	0	0	0	0	0	0	19	275	1,778	797
5	2,000- 3,000	946	0	51	0	0	0	0	0	64	3,193	7,807	8,040
6	3,000- 4,000	600	16	78	0	0	0	0	0	0	1,335	2,372	697
7	4,000- 5,000	0	0	0	0	0	0	0	1,834	577	1,885	0	0
8	5,000- 7,000	13,385	0	356	0	413	1,662	0	487	7,483	1,151	241	12,212
9	7,000-10,000	25,705	25,416	20,949	0	1,196	1,640	6,888	20,460	30,465	0	1,451	26,515
10	10,000-15,000	26,765	51,618	45,758	2,368	7,805	76,946	25,946	57,369	30,975	15,711	5,741	23,915
11	15,000-20,000	5,810	31,289	104,304	1,481	33,390	97,712	9,964	22,314	59,674	127,544	68,019	13,773
12	20,000-26,000	37,740	3,701	27,282	26,598	20,223	34,959	28,625	26,853	210,488	269,996	19,983	35,689
13	26,000-32,000	26,942	13,640	693	3,998	25,959	66,939	11,304	82,686	274,246	330,349	24,847	23,443

[a]This table shows the population densities in the radial zones of a 12-sector grid around the ammonia storage sphere.

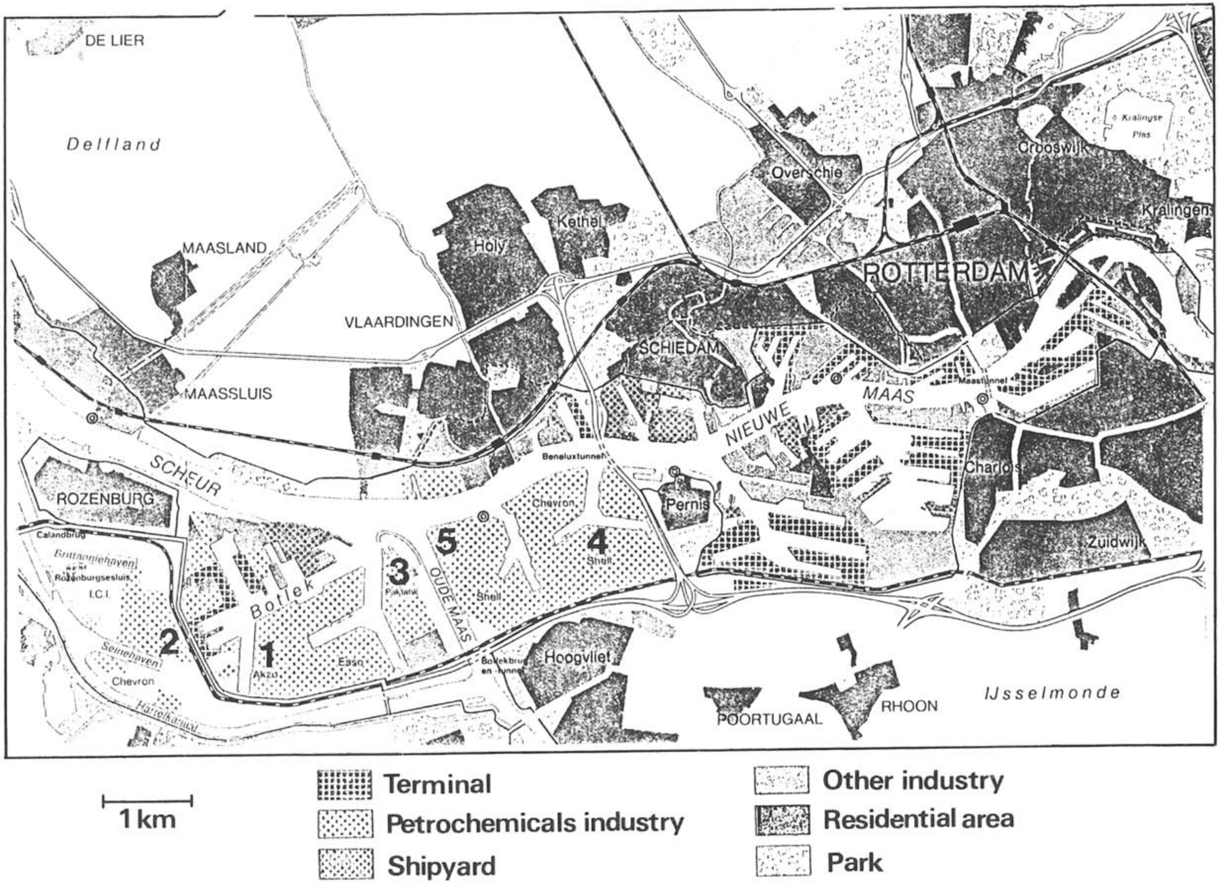

Fig. 3. Map of Rijnmond (Europort) area [4] showing populated areas and five of the six industrial sites studied in the Rijnmond Report [3]. The five sites are: 1, AKZO (chlorine storage); 2, Oxirane (propylene storage); 3, Paktank (acrylonitrile storage); 4, Shell (hydrodesulphuriser); and 5, UKF (ammonia storage).

$$N_s = [(5\,N_d + 16\,N_n) \times 52]/[5 \times (52 - n_h)] \quad (1)$$

The average number of people on site in the day time for the 6 large sites in this study was found to be 200 persons/km^2. The site area used in this computation appears from the map to be filled with process plant and storage and does not contain much open space.

For the off-site population estimates were made of the number of people in 500 m squares around the hazard source. These included the total number of people, the total number of households, and the number of males. Data were also obtained on the number of workers in each district, based on broad industrial classifications. The population data for night time thus obtained are shown in Table 3. The report gives a similar table for the day time population.

The population grid covered an area of some 75 km^2. Outside this area uniform population densities were assumed. These values were used only in a small number of cases where an exceptionally large cloud extended beyond the grid.

In principle the numbers affected off site by each hazard should have been estimated for each point on the population grid, but these calculations required excessive computer time and a simpler approach was adopted. This was to determine the radius at which the probability of injury was 50% and then to assume that the number of those within this radius who escape injury is balanced by the number of those outside it who suffer injury.

Rapid methods of hazard assessment

The experience of hazard assessment in the work just described suggests that there may be value in having rapid methods which can be used to make a ranging estimate (a) of the total number of injuries, and (b) of the radius at which less detailed methods of estimating population density may be used. Two approaches have been developed, one based on an analytical model and the other on a computer program.

Analytical model

An analytical model has been developed [5,6] which describes the impact of a hazard on the surrounding area. The basis of the model is a uniform population density, an inverse power law for the decay of the intensity of the physical effect and the lognormal distribution, or probit equation, for the relation between the causative, or injury, factor and the probability of injury. On these assumptions the number N_i of people injured is given by the equation

$$N_i = \pi r_{50}{}^2 d_p \phi \quad (2)$$

with

$$\phi = \exp\ (2\sigma^2/n^2) \quad (3)$$

TABLE 3

Population density at Rijnmond: partial cross-section of population outside working day (after Rijnmond Report [3])[a]

	Numbers per 500 m square									
	76.0	76.5	77.0	77.5	78.0	78.5	79.0	79.5	80.0	80.5
444.0	5	5	5	5	5	5	5	5	5	5
439.5	5	5	5	5	200	5	5	5	5	5
439.0	5	5	5	710	2,310	310	5	5	5	5
438.5	260	1,700	5	190	440	15	5	5	5	5
438.0	7,460	3,020	1,130	15	260	5	5	5	5	5
437.5	300	1,520	2.630	1,420	90	40	5	5	5	5
437.0	0	1,700	2.370	2,330	410	80	40	5	5	5
436.5	0	440	230	40	0	5	5	5	5	550
436.0	730	130	0	0	0	40	20	40	40	820
435.5	1,550	1,760	1,330	210	0	5	5	5	5	540
435.0	330	1,990	3,160	640	5	0	0	5	5	120
434.5	5	5	500	30	70	30	60	60	0	0
434.0	80	40	0	60	20	10	60	120	0	0
433.5	50	80	40	20	50	20	10	60	30	0
433.0	20	30	20	20	0	20	30	40	30	5
432.5	0	0	15	20	20	10	20	5	10	5
432.0	0	5	5	10	10	40	20	20	20	10
431.5	650	0	0	5	5	20	5	10	10	5
431.0	460	10	200	380	0	0	0	0	0	0
430.5	15	5	490	800	5	5	5	5	5	5
430.0	5	5	5	5	5	5	5	5	5	2,170
429.5	400	5	5	5	5	5	5	5	5	1,020
429.0	360	30	5	5	5	5	5	5	5	5
428.5	5	5	5	5	5	5	5	5	5	5
428.0	5	5	5	5	5	5	5	5	5	5
427.5	5	5	5	5	5	5	5	5	5	5
427.0	5	40	70	5	5	5	5	5	5	5
426.5	30	540	1,200	20	5	5	140	5	5	5
426.0	30	320	1,390	150	5	5	230	5	5	5
425.5	5	5	5	5	5	5	5	5	5	5
425.0	5	5	5	5	5	5	5	5	5	5
424.5	5	5	5	5	5	5	5	5	5	5
424.0	5	5	5	5	5	5	5	5	5	5
423.5	5	5	0	20	400	5	5	5	5	310

[a]This table shows the population densities in a representative cross-section of the population grid.

where d_p is the population density (persons/m^2), n the decay index, r_{50} the radius for 50% probability of injury, σ the spread parameter of the lognormal distribution and ϕ a correction factor.

An approximate method of estimating the number of injured which is sometimes used is to determine the r_{50} distance and then to assume that the number outside this circle who are injured is balanced by the number inside who escape injury. In the above model this is equivalent to assuming that ϕ is unity. Studies suggest that although in many cases ϕ will be close to unity, in others it will not. As mentioned earlier, use was made of the r_{50} distance in the Rijnmond Report, although in this case the population density was not uniform.

Computer program

The rapid assessment of the impact of a hazard on the surrounding area is also one of the uses of a computer program which has been developed by one of the authors. The program, which is interactive, runs on a microcomputer with a bit pad facility.

The plan of the site is entered using the bit pad. The program contains a suite of simplified hazard models and probit equations which are used to calculate for each hazard the intensity of the physical effect and individual risk as a function of distance using an 8-sector polar grid. Physical effect or risk contours on the site map may then be displayed on the screen or printed in a printer.

The polar grid used may be varied. Normally a grid with $8 \times 45°$ sectors is used, but one with $12 \times 30°$ sectors is also available.

Figure 4 shows a computer display obtained for one of the hazard sites in the Rijnmond study. The hazard is a release of ammonia. The risk contours shown are those estimated in the Rijnmond Report [3], but similar contours can be generated from the models in the computer program.

Distance for population density estimation

In much of the early work on hazard assessment it was found necessary to consider effects up to distances of 10 km or more. Since then, estimates of the range of hazards have tended to fall so that distances an order of magnitude less are now more typical. This is due particularly to two factors. One is developments in the modelling of gas dispersion. The other is developments in methods of estimating injury, particularly from toxic gases.

The effect of these changes is to reduce greatly the estimates of the number of injured but also to introduce proportionally greater error into estimates based on generalised population densities. This latter point was recognised, and to some degree compensated for, in the Canvey and Rijnmond work.

This problem has been investigated using the computer program described.

Again the Rijnmond ammonia release has been considered. Figure 5 shows the site plan with an 8-sector grid as displayed on the computer. Six sectors contain one arc and two sectors two arcs. The first arc in a sector is the distance within which the population density may be taken as zero, the second arc is that at which there is a change of population density. The estimated population densities, based on the Rijnmond data, are shown in Table 4.

The program has been used to study the effect of error in locating the boundaries between areas of different population density. A selection of the scenarios considered and risk estimates obtained is given in Table 5. The results of this study are shown in Table 6. The first column of the latter table shows the factor by which the distance of the arcs in Table 4 was varied and the second column the effect of this variation on the estimate of the average annual fatalities. For example, if the factor of error is 0.8, i.e. the distance of the populated areas from the works is only 80% of that assumed, the error in the risk estimate is a factor of almost 2.

This study suggests, therefore, that whereas error in the estimate of the population density gives simply a proportional error in the estimate of societal risk, error in the location of the boundary between areas of different densities gives an error which is much more than proportional to the error in distance.

Population density around hazard source

The estimation and mapping of population densities, for example as an aid to identifying vacant land for large-scale development and service provision

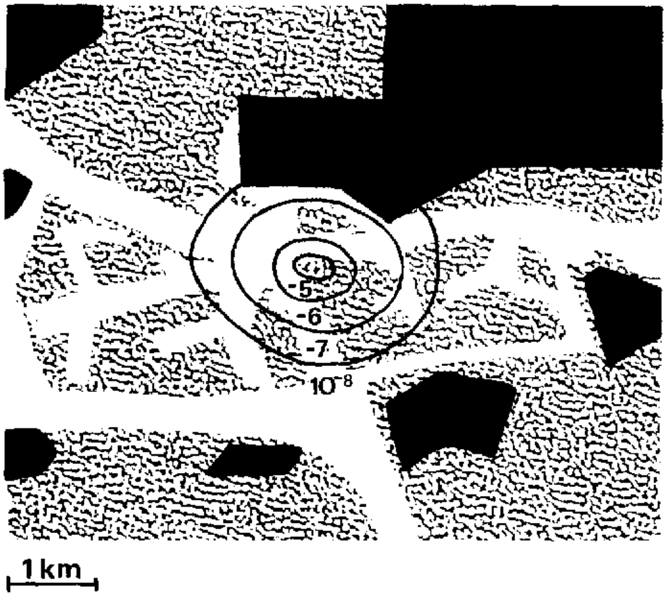

Fig. 4. Computer display of Rijnmond (Europort) area showing contours of individual fatality risk for ammonia release (after Rijnmond Report [3]). Figures denote individual annual fatality risk.

requirements, is commonly undertaken at the regional and/or national level. In relation to industrial development strategic planning and site identification for oil-related development along the Scottish coast and for nuclear power development (e.g. Openshaw [7]) provide two examples of the use of popu-

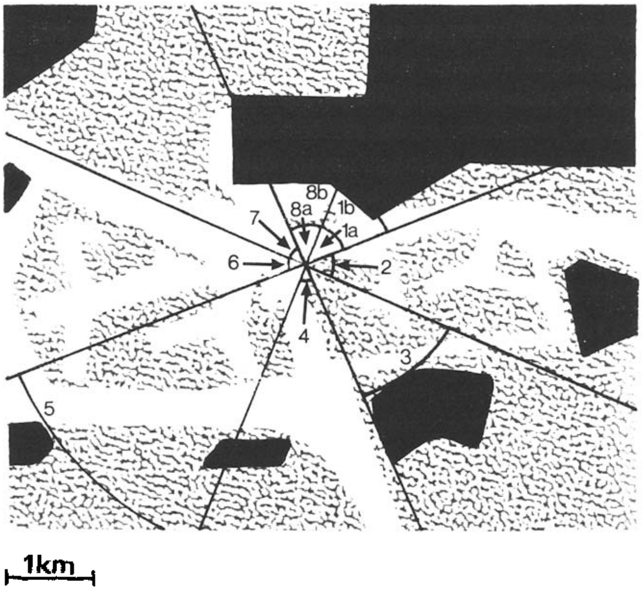

Fig. 5. Computer display of Rijnmond (Europort) area showing population densities. Population density transitions are shown delimited by arcs on an 8-sector grid.

TABLE 4

Population densities around ammonia site at Rijnmond[a]

Sector	Arc	Radial distance (m)	Population density beyond arc (persons/km^2)
1	1a	0.5	200
	1b	1.5	8,400
2	2	0.4	150
3	3	2.0	4,000
4	4	0.1	0
5	5	3.5	5,000
6	6	0.1	0
7	7	0.1	0
8	8a	0.5	200
	8b	1.5	8,400

[a]See Fig. 5.

lation density estimates on the coarse scale. The scale required for hazard assessment is finer.

A methodology for estimating the density and other characteristics of the population around a hazard source is now outlined.

Population on site

Data on the actual workforce on site should normally be used. This is essential for small sites. These data can then be used in conjunction with eqn. (1) or a similar relation.

For a large process site a default value of 200 persons/km^2 may be used for

TABLE 5

Risk estimates for ammonia release at Rijnmond (one sector, one weather condition only)[a]

Release size (te)	Release frequency (events/y)	Fatalities (deaths/event)	(deaths/y)
500	1×10^{-7}	3,731	$3,188\times10^{-7}$
200	4	509	1,907
100	11	38	436
50	35	0	0
20	154	0	0
10	470	0	0
5	1,437	0	0
2	6,298	0	0
1	19,265	0	0
0.5	58,925	0	0
0.2	258,307	0	0
0.1	790,075	0	0

[a]These estimates of societal fatality risk have been inferred from data on fatalities for various types of release given in the Rijnmond Report [3].

TABLE 6

Effect of error in locating boundaries between areas of different population density

Factor of error on distance	Estimated average annual fatalities (deaths/y)
1.8	7×10^{-5}
1.4	20
1.0 (base case)	62
0.8	114
0.6	220

the day time population. This is the value found in the Rijnmond study. It is applicable, however, only to a fully developed site and should not be applied to large areas of land which may be owned, but have not been developed, by a company.

Population off site

A methodology is now given for the estimation of the off-site population. This methodology is derived for British conditions, but may be adapted for other countries.

Use is made of national census population data. In Britain there is a full census every decade, the most recent being in 1971 and 1981. The 1981 Census is available [8] as is the official user guide [9] and a further guide [10]. Other useful documents are the 1981 Labour Force Survey [11] and the Annual Abstract of Statistics [12]. The basic small geographical unit for the Census is the Enumeration District (ED), which is an area of land defined in terms of number of households representing a suitable Census workload. The average population of an ED in England and Wales is about 5000 in urban areas and 150 in rural areas. The local geography of the Census in Scotland is slightly different in that EDs are built up from the Post Office postcode areas. The main small unit statistical output from the Census is the Small Area Statistics (SAS), which are supplied by the Census Office on magnetic tape, on microfilm or as paper copy. There are delays of several years in the publication of some census data. Naturally the data become out of date and this needs to be borne in mind.

The basic case for the off-site population is the night time population. This is the population given by the census data. The day time population may be estimated from this as described below.

The estimation of the population density off site requires the use of Ordnance Survey maps. Four principal map sizes relevant here are the 1:25000, 1:10000, 1:2500 and 1:1250 scale series. The 1:10000 scale is that normally used by local authorities. It is also the size on which the Census EDs are recorded and maps showing the boundaries of the EDs are available from the Census Office as paper copies of microfilmed 1:10000 scale maps. The 1:2500 and 1:1250 scale maps can be useful in locating more accurately the boundaries between EDs; unfortunately, the whole country is not covered by these series. These maps give the most detailed record of buildings. In the 1:10000 and 1:25000 series there is some loss of detail and accuracy with respect to buildings.

A rapid estimate of population may be made using a map to identify the built-up areas and assuming population densities of 4,000 persons/km^2 for large built-up areas, 100 persons/km^2 for other inhabited areas and zero population for uninhabited areas.

For more accurate work a more detailed approach is necessary. It is proposed that three zones be defined around the hazard source, delimited by distances of 400 m and 1,000 m. For the outer zone ($>1{,}000$ m) the rapid estimation method should be used. For the intermediate zone (400–1,000 m) the map should be used to identify three types of residential area and the uninhabited area. These three types of residential development are dense, usually in-town, terrace housing (and high rise flats); semidetached housing, usually suburban; and sparse, detached housing and population densities of 15,000, 10,000 and 1,000 persons/km^2, respectively, should be used.

For the inner zone (< 400 m) the population should be estimated from Census ED data. It is recommended, however, that for this inner zone this estimate should be checked against visual inspection and local inquiry. It may be noted that the radius of the inner zone was originally set at 250 m, but risk studies combined with site inspection indicated that this may be too short a distance for acceptable accuracy, bearing in mind the fact that the hazard range tends to be shorter for the more frequent releases. The distance of 400 m is therefore preferred as the boundary of the inner zone.

This methodology for the estimation of the density of the population around a hazard source is summarised in Table 7.

It is necessary to define the point from which the circles defining these zones are drawn. There appears at present to be some difference of practice. In some cases this point is taken to be the plant itself, in others the site boundary. The former makes more sense for a plant at a specific point, but the latter allows for relocation of the plant within the site boundary.

The use of the Census data is not entirely straightforward. The method used by the authors has been first to identify the codes of the required EDs from 1:10000 scale maps provided by the Census Office and then to obtain the ED data by interrogating the Census computer data bank at UMIST in Manchester.

TABLE 7

Methodology proposed for estimation of density of population around a hazard source

Distance from hazard source (m)	Method	Population density (persons/km^2)
< 400	Use of Census data[a]	from Enumeration District data
400–1,000	Use of Ordnance Survey maps	Dense terrace housing: 15,000 Semi-detached housing: 10,000 Sparse detached housing: 1,000 Uninhabited areas: 0
> 1,000	Use of Ordnance Survey maps	Built-up areas: 4,000 Other inhabited areas: 100 Uninhabited areas: 0

[a]Combined with visual inspection where possible.

The method just described gives the night time population. An approximate estimate of the number of people over the whole 24 h is 80–85% of this value. However, the probability of some hazards may be a function of time of day and it then becomes necessary to estimate population by time of day also.

There are in existence several computer programs which process population data. The 1971 Census provided data on population in 100 m squares. It is understood that the program TRIP, developed by the Safety and Reliability Directorate (SRD), originally for work on transport hazards, and referred to in the second Canvey Report [2], uses the population density information from the 100 m squares just mentioned to estimate the density in the sectors around the hazard, and that this program has now been superseded by another program, INTRAM. There are, however, difficulties in using 100 m square data for hazard assessment of the type considered here. The 1981 Census data are not available in 100 m square form, but in addition there are problems of statistical accuracy in converting grid square data into the required polar coordinate data on the small scale (say <2 km from the hazard source).

An alternative approach to that just described is simply to use the Census ED data throughout. This is perfectly possible. However, there are reasons why the method given here may be preferable in many cases, the main one being the work involved. ED data are provided together with maps showing the boundaries of the ED and the grid reference. These data have then to be used to give the number of people in the grid selected by the investigator around the hazard source. This involves determining how much of each ED lies within each grid area and also whether there are differences of population density within the ED which require any adjustment to be made to the default assumption that the population is uniform within the ED. The use of EDs in this way has been found to be more time-consuming than the method described. The work involved can be reduced if Census data are available for the number of people in each 100 m square, but unfortunately, the 1981 Census does not provide these data so that methods developed to use such data from the 1971 Census cannot be utilised. Another reason is that the Census occurs only once every ten years. Maps of urban areas particularly are revised more frequently.

The accuracy of the method described for the estimation of the population density in the middle zone has been checked using three sample cases of hazardous sites. In all cases the estimate is for the night time population.

Table 8 shows the population densities from the 1981 Census at selected locations.

Case 1: Site in Cheshire

A scan of the area around a site at Warrington using a 1:2500 scale map gave the following estimate:

2.1 km^2	with	population	density	of	15,000 persons/km^2,	giving	31,500 people
3.5 km^2	"	"	"	"	10,000 persons/km^2,	"	35,000 people
3.3 km^2	"	"	"	"	1,000 persons/km^2,	"	3,300 people

10.1 km^2 with zero population
hence
19.0 km^2 with population of 69,800 people and population density of 3,674 persons/km^2

A population count was carried out using a sample of 12 EDs which taken as a group appeared to be representative of the whole area around the site. The number of people in the sample was then scaled up by the ratio of the total area to the sample area. The estimate of the population thus obtained was 75,996 people, indicating a density of 8,539 persons/km^2 in the populated areas and 4,000 persons/km^2 overall. This compares with the actual Census value of 82,522 for the number of people given in Table 8. The percentage difference between the ED-based estimate and the actual Census value is 8% and that between the map-based estimate and the actual Census value is 15%.

TABLE 8

Population densities from 1981 Census at selected locations [8]

A

County	Average population density (persons/km^2)	District	Average population density (persons/km^2)	Total population
Cheshire	399	Halton	1,652	122,094
		Ellesmere Port	1,010	82,309
		Warrington	962	169,372
Essex	402	Castle Point	1,950	85,560
W. Midlands	295	Sandwell	3,598	307,992
Cleveland	974	Middlesbrough	2,789	159,430

B

District	Place	Total population	Family size
Halton	Widnes	55,926	2.94
	Runcorn	64,212	2.97
Ellesmere Port	Ellesmere Port	65,803	2.96
Warrington	Warrington	82,522	2.69
Castle Point	Canvey	35,338	2.87
Sandwell	Oldbury/Smethwick	153,461	2.73
Middlesbrough	Middlesbrough	159,421	2.90

Case 2: Site in Essex

A scan of the area around a site at Canvey using a 1:10000 scale map gave the estimate:

0.56 km^2 with population density of 10,000 persons/km^2, giving 5,600 people
0.85 km^2 " " " " 1,000 persons/km^2, " 850 people
1.41 km^2 with zero population
hence
2.82 km^2 with population of 6,450 people and population density 2,287 persons/km^2

The small area in this case is due to the fact that the populated area lies within one sector of the circle around the hazard source, the rest being sea or empty land.

A population count was carried out using a sample of 10 EDs which taken as a group appeared to be representative and the numbers were scaled up as in Case 1. The estimate of the population thus obtained was 5,446 people, indicating a density of 1,931 persons/km^2 overall. This compares with the actual Census value for the population density of 1,950 persons/km^2 given in Table 8. The percentage difference between the ED-based estimate and the actual Census value is 1% and that between the map-based estimate and the actual Census value is 17%.

Case 3: Site in West Midlands

A scan of the area around a site at Oldbury using a 1:25000 scale map gave the estimate:

0.69 km^2 with population density of 15,000 persons/km^2, giving 10,350 people
2.44 km^2 " " " " 10,000 persons/km^2, " 24,400 people
0.55 km^2 " " " " 1,000 persons/km^2, " 550 people
5.32 km^2 with zero population
hence
9 km^2 with population of 35,300 people and population density 3,922 persons/km^2

In this case no count was made of Census EDs. The actual Census value for the population density is given in Table 8 as 3,598 persons/km^2. The percentage difference between the map-based estimate and the actual Census value is 9%.

The average difference between the map-based estimates and the actual Census values is therefore 14%, one map-based estimate being low and two high.

Population composition

In order to obtain a more detailed picture of the population at risk it is necessary to define the population composition. This information is relevant to the probability that an individual is at his home base by day, that he is a member of the more vulnerable population and/or that he is outdoors.

Information on population categories and numbers in each category is available in the 1981 Labour Force Survey [11] as shown in Table 9. A population composition model may be derived from these data as follows. It is assumed that the proportions of adults in full-time and in part-time employment, of school children and of students who are at home sick or on holiday are 10, 30 and 40%, respectively, and that 10% of the self-employed work at home. The category of housewives is widened to homekeepers, to include men fulfilling this role. The number per household is determined from the total population and total number of households as given by the 1981 Census. Then noting that the level of unemployment in Table 9 corresponds to some 9%, population compositions for 5% and 10% unemployment are given in Table 10, Sections A and B, respectively. The effect of the level of unemployment is relatively slight. No attempt has been made to allow for the effect of other activities which may modify the numbers at home during the day or for those not at home at night. This is considered to be a refinement which will not be justified in most cases.

In order to use this population composition model it is necessary to define

TABLE 9

Population categories and composition: 1981 Labour Force Survey [11][a]

	Number (thousands)	Number per household
Adults in full-time employment	16,595	0.85
Adults in part-time employment	4,042	0.21
Self-employed	2,164	0.11
Unemployed[b]	2,447	0.13
Housewives	7,092	0.36
Children: 0–4 years	3,222	0.17
Children: school age	8,753	0.45
Students	1,415	0.07
Retired[c]	6,266	0.32
Others (including permanently sick and disabled)	1,100	0.06
Total	53,096	2.73[d]
Total number of households	9,442	

[a]All figures are taken from 1981 Labour Force Survey [11] except those for children (0–4 years, school age) and total number of households, which are taken from 1981 Census [8].
[b]This corresponds to 9% unemployment.
[c]Normal retirement ages in Britain are 65 for men and 60 for women, but the survey states that women respondents over 60 classified themselves either as retired or as housewives and respondents' classifications were used.
[d]1981 Census gives total number in households (in thousands) as 52,700, which combined with total number of households (in thousands) gives as number in household 2.71.

TABLE 10

Population categories and composition: population composition model

A. Unemployment 5%		Number per household	Proportion (%)
1a.	Adults in full time employment: at work (including self-employed)	0.89	32.9
1b.	sick, on holiday, working from home	0.10	3.7
2a.	Adults in part time employment: at work	0.21	7.7
2b.	sick, on holiday	0.02	0.7
3.	Unemployed	0.07	2.6
4.	Homekeepers	0.35	12.9
5a.	Children of school age: at school	0.31	11.4
5b.	sick, on holiday	0.14	5.2
6a.	Students: at college	0.04	1.5
6b.	sick at home, on vacation	0.03	1.1
7.	Children under school age	0.17	6.3
8.	Retired people	0.32	11.8
9.	Others (including permanantly sick and disabled)	0.06	2.2
Total		2.71	100.0

B. Unemployment 10%		Number per household	Proportion (%)
1a.	Adults in full time employment: at work (including self-employed)	0.84	31.0
1b.	sick, on holiday working from home	0.10	3.7
2a.	Adults in part time employment: at work	0.19	7.0
2b.	sick, on holiday	0.02	0.7
3.	Unemployed	0.14	5.2
4.	Homekeeprs	0.35	12.9
5a.	Children of school age: at school	0.31	11.4
5b.	sick, on holiday	0.14	5.2
6a.	Students: at college	0.04	1.5
6b.	sick at home, on vacation	0.03	1.1
7.	Children under school age	0.17	6.3
8.	Retired people	0.32	11.8
9.	Others (including permanently sick and disabled)	0.06	2.2
Total		2.71	100.0

the times of day. A proposed set of times of day is shown in Table 11, Section A. These are to be used with the population categories at home by time of day as shown in Table 11, Section B.

Population changes by time of day

Using the definitions of population composition and of times of day just given, it is possible to obtain estimates of the population changes by time of day. From the data given in Table 10 and Table 11, Sections A and B, the estimates of the proportion of the population at home during the school day and the non-school day shown in Table 11, Section C, are obtained. Again, no attempt has been made to allow for seasonal and weekly variations.

It is also instructive to consider these ratios at specific sites. Table 12, Section A, gives the night and day time populations for a random selection of EDs

TABLE 11

Population composition at home by time of day

A. Time of day categories

	Time of day	Duration	
		(h)	(%)
School day	8.00–16.00	8	33
Work day	8.00–18.30	10.5	44
Night	18.30– 8.00	13.5	56

B. Population categories at home

	Categories
School day	1b,2b,3,4b,5b,6b,7–9
Work day	All except 1a
Night	All

C. Proportion of population at home

	Proportion at home	
	Unemployment 5% (%)	Unemployment 10% (%)
School day	46.5	49.1
Work day	67.2	69.0
Night	100.0	100.0

TABLE 12

Night and day time populations at Canvey and Rijnmond

A. Canvey

	Enumeration district	Number of people			Number of vulnerable people[c]
		Night[a]	Day[b]	Day/night (%)	
Corringham	AD03	430	130	30	64
	AD16	500	221	44	106
Stanford-	AD18	711	225	32	109
le-Hope	AD21	305	138	45	76
	AL06	627	194	30	65
	AL17	556	220	40	107
Canvey	AG01	369	175	47	84
Island	AG03	659	239	36	119
	AN06	790	448	57	103
	AN09	920	503	55	109
Total		5,867	2,493		
Mean				42[d]	

B. Rijnmond

	Grid square	Number of people[e]		
		Night	Day	Day/night (%)
78.0 ×	440.0	5	5	(100)
	439.5	200	100	50
	439.0	2,310	1,240	54
	438.5	440	220	50
	438.0	260	130	50
	437.5	90	40	44
	437.0	410	210	51
	436.5	0	0	–
	436.0	0	0	–
	435.5	0	0	–
	435.0	5	5	(100)
	434.5	70	200	–
	434.0	20	60	33
	433.5	50	150	33
Mean				46[f]
Standard deviation				7.7[f]

[a]Values obtained from Census return of persons present at midnight.
[b]Values obtained by subtraction of defined categories of employed adults and school children.
[c]Persons aged <5 years or >65 years.
[d]This is the value both of the ratio of the totals of the day and night time populations and also the sum of the individual day/night ratios.
[e]Values obtained from Rijnmond Report [3].
[f]This is the mean and standard deviation of the individual day/night ratios, neglecting the squares at 440.0 and 435.0 (farms), at 436.5, 436.0 and 435.5 (sea) and 434.5 (a factory).

in the Canvey area. These data show that the ratio of the day time to the night time population as measured by ED has a mean of 0.42.

Table 12, Section A, also gives the number of people vulnerable because they are very young (<5 y) or very old (>65 y). This is not the whole of the vulnerable population as defined below but only part of it. Nevertheless, the data are of interest in that they illustrate that in the day time vulnerable people constitute a much larger proportion of the population at home base than at night time.

Table 12, Section B, gives the corresponding information for Rijnmond based on the Dutch 1971 census as updated to 1975. In this case the data are for 0.5 km squares taken as a vertical slice from the population density grid given in the Rijnmond Report [3]. These data show that the ratio of the day time to the night time population is 0.46.

Vulnerable population

Some members of the population are likely to be more vulnerable to the hazard than others and it may be necessary to take this into account. In general, it is children, old people and infirm people who tend to be most vulnerable and the proportion of vulnerable people may be estimated as a first approximation by determining the proportion in these categories. However, vulnerability must be a function of the particular hazard. For example, children may actually recover better from some burns than adults. Or again, persons with respiratory disease are likely to be more susceptible to irritant toxic gas, but not necessarily to thermal radiation.

As a first approximation, therefore, the population may be divided into two broad groups, (a) adults of working age and older children and (b) young children and old people. The first group is some 75% and the second some 25% of the population. In general, the latter is the more vulnerable group, although for some hazards it may be necessary to have a more specific definition. In this case the proportion of vulnerable people may be assessed in relation to the particular hazard considered using the population composition model given in Table 10.

It is instructive to consider previous work on vulnerable populations. Table 13 shows some estimates made by Hewitt [13] for the proportion of people vulnerable to a toxic irritant gas such as chlorine.

Population outdoors

There appears to be very little information available on the proportion of the population which is outdoors by time of day.

In the Rijnmond Report [3] the proportion of people indoors was taken in the context of toxic gas hazard as 99%, allowing for the fact that some people would seek shelter from this hazard indoors.

Information on the proportion of the population which is initially outdoors (before seeking shelter) is difficult to find, but a simple model may be derived as follows. It is assumed that the regular and vulnerable groups spend 1 hour and 1/2 hour per day outdoors, respectively, that the proportion of the total population outdoors at night (18.30–8.00) is 1% and that those outdoors are drawn exclusively from the regular population. Then the time outdoors and the proportions outdoors by day, by night and overall may be calculated for the regular, vulnerable and total populations. The resultant population outdoor exposure model is shown in Table 14.

A partial crosscheck on the model, or more specifically a crosscheck on the lower bound of the proportion of the population outdoors, may be obtained from wartime data on V-2 rocket bomb casualties. The V-2s fell for the most part without warning and before people had a chance to take shelter. The Ministry of Home Security carried out a study [14] early in 1945 of 12 V-2 incidents in London, of which 8 were at night (18.30–8.00). The number of casualties (dead, seriously injured and slightly injured) within 200 ft (61 m) of the point of burst was determined and also the number unhurt, although no figures were obtained for the number outdoors who escaped unhurt. The fig-

TABLE 13

Vulnerable members of population (after Hewitt [13])

	Number per 1000 people
Children < 6 months	8
< 12 months	8
12 months–5 years	75
5–9 years	82
Old people > 70 years	85
People with chronic heart trouble	5
People with respiratory diseases	9
People with restricted mobility	4
Blind people	2
Healthy youngsters and adults	722

TABLE 14

Population outdoors: population outdoor exposure model

Population	Time outdoors (h/day)			Proportion outdoors (%)		
	Day	Night	Overall	Day	Night	Overall
Regular	0.81	0.19	1.00	7.70	1.33	4.17
Vulnerable	0.50	0	0.50	4.8	0	2.08
Total	0.74	0.14	0.88	7.05	1.00	3.67

ures are shown in Table 15, Section A. It is assumed as before that the proportion of the total population outdoors at night was 1% and that this was drawn only from the regular population. Then from the casualty data the proportion of the population outdoors may be derived as shown in Table 15, Section B. The proportion of the total population which was outdoors is 1.86%. This may be regarded as a lower limit both because in wartime people are presumably more likely to stay indoors at night and, more significantly, because no account has been taken of the number outdoors who escaped unhurt, although this may well be, say 50%, of the total number exposed. This figure of 1.86% compares with that of 3.67% in the model given in Table 14.

Discussion

A methodology has been presented for the estimation of the density and other characteristics of the population around a hazard source. For the estimation of population density an inner zone of radius 400 m is defined and different methods of estimation are applied inside and outside this zone.

Inside the inner zone the use of Census data (based on enumeration districts) is preferred. It is also very desirable to check by visual inspection and local inquiry whether the population in this zone has changed since the Census was conducted. Outside this zone it is sufficient to use Ordnance Survey maps in conjunction with generalised population density values. The method has been validated by comparing the densities estimated in this way with actual Census densities for three typical sites. The average error found was 14%. The method proposed therefore requires the use of Census data in the inner zone,

TABLE 15

Population outdoors: V-2 incidents

A. Casualties indoors and outdoors

Location	Casualties	Unhurt	Total
Open	23	Incomplete	23+
Other	336	878	1,214
Total	359	878+	1,237+

B. Proportion of population outdoors

Population	Proportion outdoors (%)		
	Day	Night	Overall
Regular	3.39	1.33	2.23
Vulnerable	1.70	0	0.74
Total	2.97	1.00	1.86

but relaxes the requirement outside this zone. For many assessments, where the inner zone is only a small proportion of the total area at risk, this is a worthwhile simplification. A summary of the method is given in Table 7.

Methods have also been presented, based on defined categories of population and of time of day, for the estimation of the proportion of the population at home by time of day, of the proportion of vulnerable people in the population and of the proportion of the population outdoors.

Attention has been drawn to the effect of error in locating the boundaries between areas of different densities. This can be more important than errors in estimating the population densities in the individual areas.

The methodology described is intended for use in Britain, since it utilises data available in British-style Censuses and maps, but it may be applicable with suitable modifications elsewhere provided that comparable data are available.

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List of symbols

d_p density of population (persons/m^2)
n decay index
n_h number of weeks holiday, sickness, etc., per year
N_d number of workers on site in day time
N_i number of people injured
N_n number of workers on site at night time
r radial distance (m)
σ spread parameter in lognormal distribution
ϕ correction factor

Subscript
50 for probability of injury equal to 0.5

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