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A consequence model for chlorine and ammonia based on a fatality index approach

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Abstract

In this paper, a simple and transparent consequence model for chlorine and ammonia is proposed based on a fatality index. The parameters for the model can be estimated from historical accident data and avoid the large number of assumptions necessary in traditional models. This approach was attempted for two values of the exponent of the mass (0.75 and 1.0), from which a simple linear model (with exponent 1.0) is proposed. This estimates consequences for three different population density classes: rural, semi-urban (or industrial) and urban. The distribution of the number of fatalities relative to the estimated average number of fatalities was found to approach an S-shaped distribution function. A simple distribution function gives, however, results comparable to the more complex form. For the particular case of assessing the risk of transportation of chlorine by rail in U.S.A. the fatality index model seems to be less conservative, and closer to empirical observations than the traditional models.

1. Introduction

Traditional consequence models, including release, dispersion and vulnerability calculations, can be useful for estimating the risks related to fixed installations storing, producing or using hazardous materials, if care is taken when making the necessary assumptions, but large uncertainties are found in the results (see e.g. [1]).

For accidents related to transportation of hazardous materials, further (uncertain) assumptions have to be made, because the location of the accidents are not known in advance. This introduces even larger uncertainties in results related to transportation.

If the assumptions made during the risk analysis are conservative, pessimistic estimates of the consequences will be found. Especially for toxic releases,

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too pessimistic results are often found, compared to actual accident data. Lees [2] writes (p. 653):

> The contrast between the large number of fatalities given by some theoretical estimates, assuming the most unfavorable and improbable circumstances and using models which may prove to be based on pessimistic assumptions, and the small number of fatalities shown by the historical record is particularly striking in the cases of toxic release. It is especially important, therefore, to consider the historical data on toxic release in order to keep the problem in perspective.

In this paper, a simple consequence model based directly on historical data is proposed and developed. The parameters in the model are estimated for toxic releases of chlorine and ammonia.

2. Fatality index

The fatality index approach was introduced by Marshall [3] who was primarily interested in quantifying risks in connection with explosions and toxic releases. The basic concept of the fatality index is that the number of fatalities increases with an increasing amount of cargo released:

$$N=\beta W^{n}=W[\beta W^{n-1}] \tag{1}$$

where N is the number of fatalities, W is the amount released and $[\beta W^{n-1}]$ is the index.

Two types of indices will be presented. The nomenclature of these are: Fatality index, concerning the number of deaths, injury index, concerning the number of injuries. When both these are discussed, the term "casualty index" will be used.

So far fatality indices have been used without considering population densities. However, it is obvious that the consequences of an accident in terms of casualties, depends on the number of people in the vicinity. A possible semi-quantitative distinction would be between the following areas: urban (U); semi-urban (industrial) (I); and rural (R). This is not a very specific distinction, but neither the sources of information on past accidents, nor the demographic information available for estimation in case of transportation accidents, are very detailed. The subsequent analysis is therefore based on these three population density levels.

3. Available data

The model proposed in this paper is based on actual data of accidents involving the chemical of interest (here, chlorine and ammonia). The accident cases used were found in 13 open sources from the literature (see [4]). The sources are thought to cover most of the accidents from fixed installations, rail, road and pipeline accidents since 1945 that involve large amounts of substance

TABLE 1

Chlorine accidents where estimates of population densities, the mass of chlorine released and the number of fatalities were reported. The number of casualties and the mass released recorded are the mean values of the numbers given in the sources

Year	Place	Mass (tonnes)	No. of fatalities	No. of injuries	Population density
1917	Wyandotte	15	1	–	U
1936	Johannesburg	2.5	0.5	0	U
1944	Brooklyn	0.05	0	208	U
1947	Chicago	17	0	0	U
1963	Philadelphia	1	0	430	U
1975	Niagara Falls	30	4	176	U
1978	Youngstown	(50)	8	94	U
1947	Rauma	30	19	0	I
1962	Cornwall	29	0	89	I
1979	Estarreja	2	0	75	I
1961	La Barre	28.5	1	114	R
1976	Baton Rouge	95	0	0	R
1963	Brandtsville	8.5	0	0	R

TABLE 2

Chlorine accidents where the population densities are unknown but the mass of chlorine released and the number of fatalities were reported. The number of casualties and the mass released recorded are the mean values of the numbers given in the sources

Year	Place	Mass (tonnes)	No. of fatalities	No. of injuries
1914	Chrome	7	0	–
1926	St Auban	25	19	0
1928	Asbotan	2	0	–
1929	Syracuse	24	1	0
1934	Niagara Falls	15.5	0.5	0
1935	Griffith	28	0	0
1939	Zarnesti	25	60	0
1940	Mjodalen	7.5	3	–
1949	Freeport	4.5	0	0
1950	Billingham	0.5	0	–
1952	Walsum	15	7	0
1956	Lake Charles	2.7	0	–
1957	Runcorn	2.5	0	–
1961	Billingham	12	0	–
1966	La Spezia	7	0	–
1967	Newton	53	0	0
1969	Cleveland	1	1.5	0
1970	Javle	2	0	–
1973	Loos	15.5	0	–
1981	Puerto Rico	2	0	2000
1981	Mexico	11	29	1000
1982	West Virginia	29	–	15
1983	Louisiana	0.5	0	7
1983	Louisiana	1.5	0	12

TABLE 3

Ammonia accidents, where the mass of ammonia released and the number of fatalities were reported. The number of casualties and the mass released recorded are the mean values of the numbers given in the sources

Year	Place	Mass (tonnes)	No. of fatalities	No. of injuries	Population density
1968	Lievin	17	5.5	–	U
1969	Crete	77	7.5	–	U
1970	West Virginia	75	0	–	U
1973	Potchefstroom	38	18	–	U
1975	Texas City	50	0	–	U
1976	Enid	500	0	–	U
1976	Houston	19	6	200	U
1976	Landkrona	180	2	–	I
	Unknown	1	0	1	I
1970	Blair	153	0	0	R
1971	Floral	570	0	–	R
1973	Kansas	244	0	–	R
1974	McPharson	360	0	–	R
1981	Minnesota	50	0	30	R
1987	Lampoul G.	4	0	0	R
1981	Indiana	2	2	–	?
1986	Alberta	5	–	6	?

or a large number of casualties. Marine and inland water accidents are probably under-represented.

A total of 1,793 accident case histories were compiled: 93 of these accidents involved chlorine and 77 accidents involved ammonia. However, only accidents for which the amount released *and* the number of fatalities or injuries were known, were included in the present analysis.

Tables 1 and 2 show the 37 accidents involving chlorine and Table 3 shows the 17 accidents involving ammonia, that are available for the calculation of casualty indices. The tables contain information on year and place of the accident (only for identification purposes), released mass, number of fatalities and injuries (— if not reported), and the population density (R, I or U and '?' if unknown) estimated by the authors based on the accident description.

4. Estimation of casualty indices

The concept of fatality indices was discussed briefly in Section 2. Marshall [3] has analyzed the consequences of explosions and toxic releases. For explosions, a simple geometric argument leads to the expectance of a correlation

TABLE 4

Chlorine accidents from Table 1, with estimation of fatality indices based on the assumption of $n=1.0$ and $n=0.75$

Year	Place	Mass (tonnes)	No. of fatalities	No. of injuries	Fatality index for $n=1.0$	Fatality index for $n=0.75$	Population density
1917	Wyandotte	15	1	-	0.07	0.13	U
1936	Johannesburg	2.5	0.5	0	0.20	0.25	U
1944	Brooklyn	0.05	0	208	0	0	U
1947	Chicago	17	0	0	0	0	U
1963	Philadelphia	1	0	430	0	0	U
1975	Niagara Falls	30	4	176	0.13	0.31	U
1978	Youngstown	(50)	8	94	0.16	0.43	U
Total urban		*115.55*	*13.5*		*0.12*	*0.26*	
1947	Rauma	30	19	0	0.63	1.48	I
1962	Cornwall	29	0	89	0	0	I
1979	Estarreja	2	0	75	0	0	I
Total industrial		*61*	*19*		*0.31*	*0.70*	
1961	La Barre	28.5	1	114	0.04	0.08	R
1976	Baton Rouge	95	0	0	0	0	R
1963	Brandtsville	8.5	0	0	0	0	R
Total rural		*132*	*1*		*0.008*	*0.021*	

with the equivalent amount of TNT (trinitrotoluene) in the power of 0.667, but Marshall observes $n=0.50$.

By instantaneous release of liquid chlorine a puff of heavy gas is formed. If there is no wind at all, it can be argued that the resulting cloud will cover an area that is proportional to the amount released (shape of a pancake). If people stay (because they do not get a warning sufficiently early, or are immobile) and are outdoor, and the concentration of chlorine is high enough to be fatal, the number of fatalities may, as a first approximation, be proportional to the population density and the released mass (W), i.e. $n=1$ and the fatality index (as defined in equation 1) $\beta W^{n-1}=\beta$.

Ammonia may be light or a heavy gas depending on the circumstances of the release, but when liquid ammonia is released it often behaves like a heavy gas due to low temperature and droplets in the sky [5]. In this paper it will be assumed that models used to describe chlorine releases are also valid for ammonia.

Simulations of the areas covered by a release of chlorine up to dangerous or lethal concentrations as well as the areas covered within ten minutes, were made with the HEAVYPUFF program developed at Risø National Laboratory (see Appendix A for details). The simulations were made for three instanta-

TABLE 5

Chlorine accidents from Table 2, with estimation of fatality indices based on the assumption of $n=1.0$ and $n=0.75$

Year	Place	Mass (tonnes)	No. of fatalities	No. of injuries	Fatality index for $n=1.0$	Fatality index for $n=0.75$
1914	Chrome	7	0	–	0	0
1926	St Auban	25	19	0	0.76	1.70
1928	Asbotan	2	0	–	0	0
1929	Syracuse	24	1	0	0.04	0.09
1934	Niagara Falls	15.5	0.5	0	0.03	0.06
1935	Griffith	28	0	0	0	0
1939	Zarnesti	25	60	0	2.40	5.37
1940	Mjodalen	7.5	3	–	0.40	0.66
1949	Freeport	4.5	0	0	0	0
1950	Billingham	0.5	0	–	0	0
1952	Walsum	15	7	0	0.47	0.92
1956	Lake Charles	2.7	0	–	0	0
1957	Runcorn	2.5	0	–	0	0
1961	Billingham	12	0	–	0	0
1966	La Spezia	7	0	–	0	0
1967	Newton	53	0	0	0	0
1969	Cleveland	1	1.5	0	1.5	1.5
1970	Javle	2	0	–	0	0
1973	Loos	15.5	0	–	0	0
1981	Puerto Rico	2	0	2000	0	0
1981	Mexico	11	29	1000	2.64	4.80
1982	West Virginia	29[a]	–	15	–	–
1983	Louisiana	0.5	0	7	0	0
1983	Louisiana	1.5	0	12	0	0
Total remaining		*265.2*	*121*		*0.56*	*0.77*
Total All		*573.75*	*154.5*	*4220*[b]	*0.27*	*0.61*

[a]This amount is not included in the total, as the number of fatalities was not reported.
[b]In the accidents resulting in injuries, a total of 352 tonnes was released. The average injury-index is thus 12.0.

neous releases of chlorine (1, 10 and 100 t, respectively) for two different meteorological scenarios (Pasquill F, 2 m/s and Pasquill D, 5 m/s). For stability F and 2 m/s the areas increase by a factor of about 6.0 if the release is increased by a factor of 10. Similarly for stability D and 5 m/s, the areas increase by a factor of about 5.4. Simulations with a time constraint (of 10 minutes) were also performed, with results similar to the results presented above. The conclusion of these computer simulations is, therefore, that the areas covered are proportional to $W^{0.75}$ (which corresponds to an increase in area of 5.6, if the quantity released is increased by a factor of 10). As a first approximation the number of casualties should thus be proportional to $W^{0.75}$.

TABLE 6

Ammonia accidents from Table 3, with estimation of fatality indices based on the assumption of $n=1.0$ and $n=0.75$

Year	Place	Mass (tonnes)	No. of fatalities	No. of injuries	Fatality index for $n=1.0$	Fatality index for $n=0.75$	Population density
1968	Lievin	17	5.5	–	0.32	0.66	U
1969	Crete	77	7.5	–	0.10	0.29	U
1970	West Virginia	75	0	–	0	0	U
1973	Potchefstroom	38	18	–	0.47	1.18	U
1975	Texas City	50	0	–	0	0	U
1976	Enid	500	0	–	0	0	U
1976	Houston	19	6	200	0.32	0.66	U
Total urban		*776*	*37*		*0.048*	*0.18*	
1976	Landskrona	180	2	–	0.01	0.04	I
	Unknown	1	0	1	0	0	I
Total industrial		*181*	*2*		*0.01*	*0.04*	
1970	Blair	153	0	0	0	0	R
1971	Floral	570	0	–	0	0	R
1973	Kansas	244	0	–	0	0	R
1974	McPharson	360	0	–	0	0	R
1981	Minnesota	50	0	30	0	0	R
1987	Lampoul G.	4	0	0	0	0	R
Total rural		*1381*	*0*		*0*	*0*	
1981	Indiana	2	2	–	1.0	1.19	?
1986	Alberta	5[a]	–	6	–	–	?
Total remaining		*2*	*2*		*1.0*	*1.19*	
Total all		*2340*	*41*	*237*[b]	*0.018*	*0.070*	

[a]This amount is not included in the total, as the number of fatalities was not reported.
[b]In the accidents resulting in injuries, a total of 232 tonnes was released. The average injury-index is thus 1.0.

In Tables 4 and 5, the calculated fatality indices for chlorine are shown for the accidents shown in Tables 1 and 2. The average of the indices are calculated based on the total mass released and the total number of fatalities, not as an average over the number of cases, because the influence of small releases with small number of fatalities (or none) are thus minimized.

In Table 6 the similar results for ammonia are shown. As in the case of chlorine, the differences in the estimated fatality indices within each population density class are considerable. In the case of $n=1$ the chlorine fatality indices are in the range 0–2.6, with the mean value of 0.3, and the ammonia fatality indices are in the range 0–1.0, with the mean value 0.02. Part of this

TABLE 7

The estimated mean values of β in the fatality indices for chlorine and ammonia

Chemical compound	Average β of the fatality index	
	$n=1$	$n=0.75$
Chlorine	0.27	0.61
Ammonia	0.018	0.07

variation is due to differences in the population densities at the sites of the accidents and part is caused by variations in the accident circumstances in general (release duration, wind direction at the time of the accident, efficiency of warning systems, etc.). (See Sections 6 and 7 for further discussion.)

5. Evaluation of the exponent *n*

Table 7 shows the average β-values calculated for both $n=1$ and $n=0.75$ for fatalities, based on the total data set. As can be seen, the differences between the indices for $n=1$ and $n=0.75$ are considerable (the average mean β of the injury indices are, as shown in Tables 5 and 6, 12.0 and 1.0 for chlorine and ammonia, respectively, for $n=1$). However, the results for $n=1$ and $n=0.75$ can only be compared if the mass released is included in the comparison. Figure 1 shows the average number of fatalities by the release of 1–100 tonnes of chlorine and ammonia, respectively, by the two models.

It should be noted that considerable uncertainty is attached to the accident data used in the models. Especially, the release duration is unknown, and for accidents given by more than one source there can be variation in the observed quantities released and the observed number of casualties.

Most releases from transportation accidents are in the range 5–90 tonnes, where the differences in the predicted number of fatalities between the two values of the exponent n are relatively small. The differences are thought to be well within the inherent uncertainty of the data, and are clearly within the variation of the indices as discussed in Section 4. As the model will be simpler by using $n=1$, this assumption is used throughout the paper.

6. Proposed fatality index values

As already mentioned the values of the fatality indices are shown in Tables 4–6. An evaluation of the differences in consequences between the three population density groups, should ideally be based directly on the data. Table 8 shows the ratios which are calculated from the data that are presented in Tables 4 and 6.

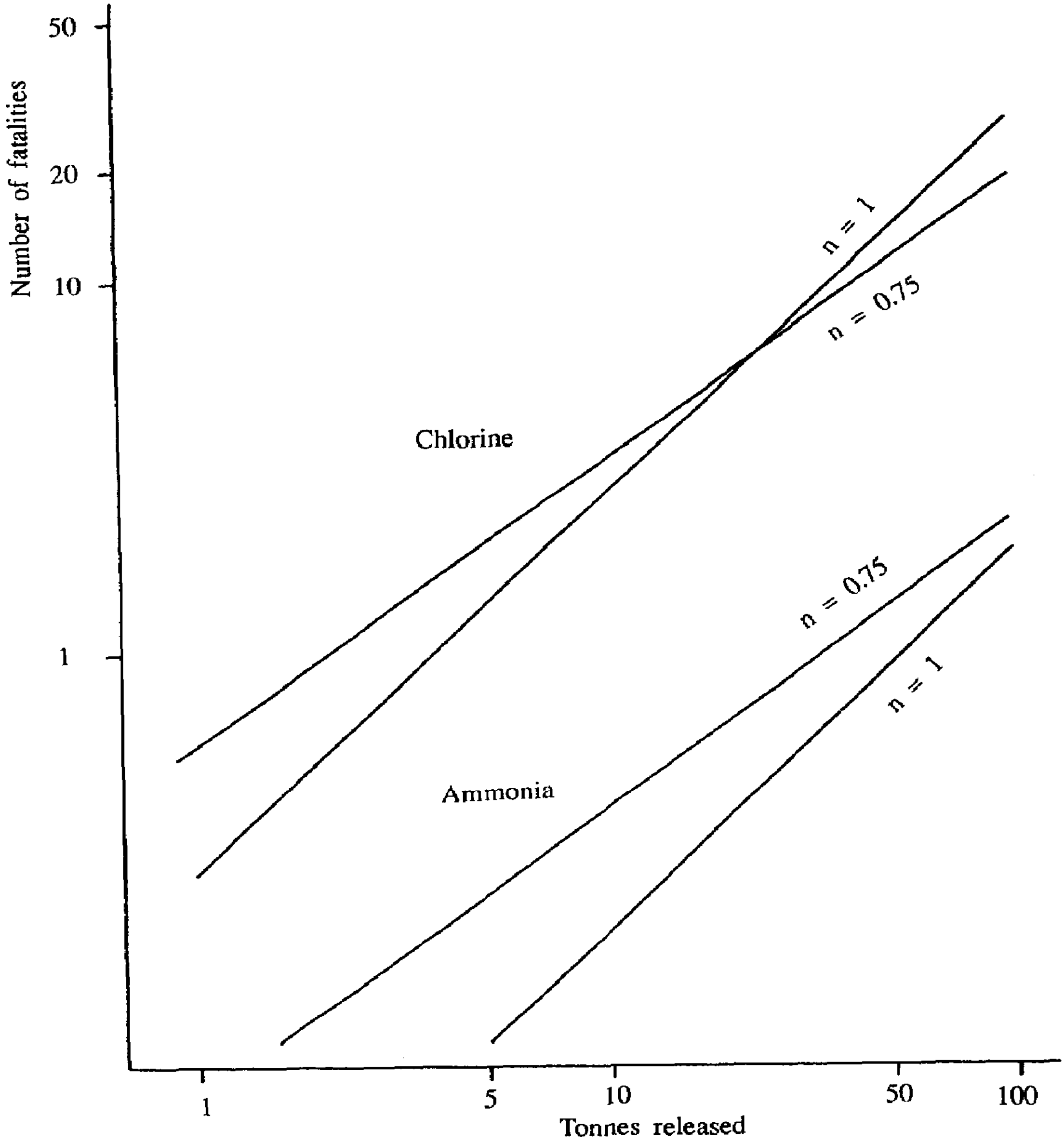

Fig. 1. Comparison of the use of $n=1$ and $n=0.75$ in eq. (1).

TABLE 8

The ratios of $\beta_{urban}:\beta_{indus}$ and $\beta_{indus}:\beta_{rural}$ observed in the accident data

Ratios of β	Chlorine	Ammonia
Urban : industrial	0.4	4.5
Industrial : rural	33	∞

A larger β (fatality index) would be expected for a denser population, i.e. the ratios would be larger than 1, and this is indeed observed in all cases but one. An evaluation of the (large) differences is further complicated by the ratio which is infinity (implying that an ammonia release in rural area will never cause fatalities, which is obviously not true).

The main reason for these (large) differences is the small number of accidents in each group (2–7), and another reason is the uncertainty attached to the identification of population density categories based on the accident reports. Further, more uncertainty is introduced by the duration of release. Obviously the impact of an instantaneous release is much larger than a continuous release of several hours for the same release mass, but unfortunately the release duration is rarely reported.

An alternative method to evaluate the differences in the fatality index in the three population density groups is to consider population density data directly. Table 9 shows the ratio of population densities for Denmark, and selected regions of the United States. The results from Tables 4–6 can be interpreted if two assumptions are made.

1. The overall average fatality index is equal to the fatality index for semi-urban (industrial) area (β_{indus})
2. The number of casualties are proportional to the population density at the site of the accident. As the ratio $\beta_{urban}:\beta_{rural}$ is approximately 64, β for urban areas is assumed to be 8 times bigger than β_{indus}, and β for rural areas is assumed to be 8 times smaller than β_{indus}.

Based on these two assumptions and on the general assumption adopted in Section 5, that exponent $n=1$, the fatality indices for the three population density areas can be calculated. In Table 10 these values are shown.

TABLE 9

Population densities in various American regions and in Denmark. The American data were obtained from [10] and the Danish from Danish National Statistics

Region	Population density (persons per km^2)		Ratio
	Urban	Rural	
Denmark	1600	25	64:1
New England	1040	22	47:1
Middle Atlantic	1760	33	54:1
South Atlantic	1020	21	49:1
E.N. Central	1260	19	67:1
E.S. Central	708	14	50:1

TABLE 10

The estimated values of β in the fatality index for chlorine and ammonia. The values for the industrial area are the overall mean values of β. The urban and rural values are, respectively, 8 times bigger and smaller

Area	Chlorine	Ammonia
Urban	2.2	0.14
Industrial	0.27	0.018
Rural	0.034	0.0023

7. Distribution of the fatality indices

The fatality and injury indices have now been estimated for chlorine and ammonia for each of the three population density categories. The values could be used directly in estimation of the number of fatalities resulting from transportation accidents. However, as discussed in Section 4, considerable variation is observed in the β-values of the single accidents within the single population density groups, which should be included in a consequence model.

The individual data samples for the population density categories do not supply sufficient data to estimate a distribution function. In order to pool the data, a "reduced index" is calculated. The reduced index is defined as the actual β for an accident divided by the estimated mean β for the group of accidents to which the accident belongs. This analysis is thus based only on the accidents for which the population density could be estimated. Furthermore, it is assumed that fatality and injury indices *and* ammonia and chlorine have the same distribution function.

In the Fig. 2 the probability of *not* observing a value larger than the actual reduced indices are plotted as a function of the logarithm of the reduced indices. A table containing the calculated reduced indices is given in Appendix B.

A priori it was assumed that the empiric data could be described with an S-curve (though very unlikely, it is possible to imagine a large release of a highly toxic substance to result in zero fatalities, and a small release of a medium toxic gas to result in several fatalities). In Fig. 2 the similarity with a logistic function is easily recognized.

The mean value of the logarithm of the "reduced indices" is −0.16 and the standard deviation is 0.71. The logistic curve shown in Fig. 2 is given in eq. (2) (see Appendix B for details).

$$F(x)=1\Big/\left[1+\exp\left(-\frac{x+0.16}{0.71}\right)\right] \tag{2}$$

A major concern during this research, has been to develop a simple and thus

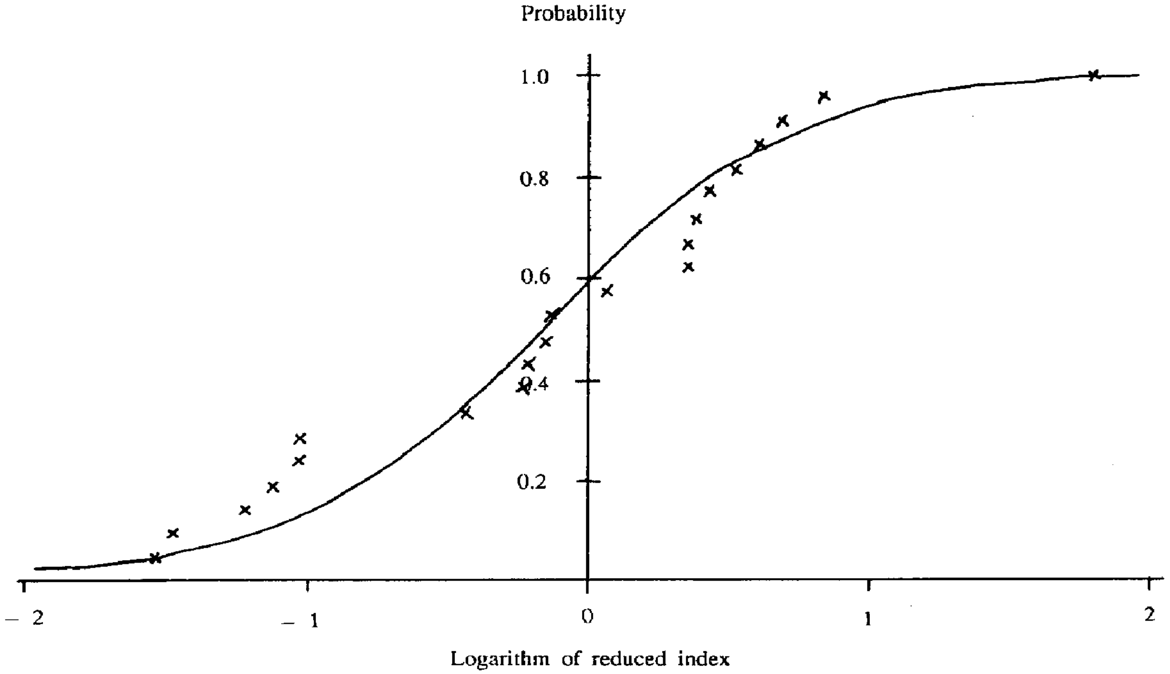

Fig. 2. The reduced indices displayed as the probability of *not* observing a value bigger than the actual value. Also the logistic accumulated probability function given above is shown.

transparent model. A possible model would be to assume that 1 out of 10 accidents have consequences 10 times more severe (than average) and 1 out of 10 consequences 10 times less severe [6]. The probability of observing consequences 10 times more and 10 times less severe, respectively, can be calculated using eq. (2) ($x=\log(10)=1$ and $x=\log(0.1)=-1$, respectively). These probabilities are:

$F(1)=0.93,$

i.e. 7% for 10 times more severe consequences, and

$F(-1)=0.14,$

i.e. 14% for 10 times less severe consequences. The results of the distribution function analysis is thus not contradictory to this simple consequence model.

It is therefore proposed to use the discrete distribution of 83.3% for the average (estimated) consequence, 8.3% for 10 times more severe consequences, and 8.3% for 10 times less severe consequences.

8. Discussion

The consequence model proposed in this paper for chlorine and ammonia is based on the concept of fatality indices, i.e. that a given release amount on average will result in the same number of fatalities. An evaluation of the level of detail in the proposed model, should consider the reliability and the completeness of the data used. The number of fatalities is a parameter which was thought to be easily recorded and reliable. A recent analysis [7] has, however, exposed the fact that considerable uncertainty is attached to this figure.

The stability of the parameters of the model can be evaluated by imaging the appearance of an accident with a 1-tonne release resulting in 100 fatalities of chlorine and ammonia, respectively. Such an accident would cause a rise in the fatality index from 0.27 to 0.44 for chlorine and from 0.018 to 0.06 for ammonia, i.e. with factor 2–3. Such an uncertainty seems to be generally accepted in the traditional approaches.

Furthermore, only a small fraction of the accidents that has actually happened have been useful in the estimation of the casualty indices. There is, however, no reason to believe that either accidents with large amounts released and few casualties or accidents with small amounts released and many casualties are over-represented. Future search in, for instance, commercial databases might, however, supply additional data, and thus be useful in further development of the presented model.

The fatality index approach was attempted for two different values of the exponent (0.75 and 1.0). As shown, the differences between the two are limited and are thought to be within the uncertainties inherent in the accident cases. It is therefore proposed to use the simple linear model with the exponent equal to 1. The index is thus simply β.

The fatality index concept is, in this paper, extended to include a semi-quantitative estimate of the population density. Unfortunately, the accident data at the disposal of the authors do not permit the estimate of the population density in the vicinity, and an estimation of fatality indices for three classes of areas (rural, semi-urban or industrial and urban) is therefore very uncertain.

The overall average value is calculated as the total number of fatalities divided by the total amount released. Assuming that all accidents involving chlorine and ammonia with large amounts released or multiple fatalities are known, the total average of the fatality index is used as a first approximation for semi-urban (industrial) areas. The fatality index for the other two classes is then estimated based on population density statistics.

The average casualty indices can be evaluated by comparing ratios of the estimated indices with the ratios that could be expected using the toxicological data (e.g. using 1000 p.p.m. as the lethal concentration and 30 ppm as the injuring concentration for chlorine, makes us expect a ratio of 33 between the fatality and injury index for chlorine). In Table 11 the general accepted human toxicological data for chlorine and ammonia are given (from the extensive work of Cremer and Warner, [8]). Table 12 shows the ratios of the casualty indices and the "expected" ratios. The differences between the actual and "expected" ratios are thought to be small, considering the uncertainty of both the toxicological data and the empirical data.

TABLE 11

The toxicological data for chlorine and ammonia [8]

Property	Chlorine	Ammonia
Immediate lethal concentration (ppm)	1.000	5000–10 000
Injuring concentration (ppm)	30–50	300–500
Mole weight (g/mol)	70.9	17.0

TABLE 12

The ratios expected compared with the ratios actually found in the analysis

Item	Ratio	Observed value	Expected range
Fatality index	Chlorine : ammonia	15	1–3
Injury index	Chlorine : ammonia	12	2–4
Chlorine	Inj. index : Fat. index	44	20–33
Ammonia	Inj. index : Fat. index	56	10–33

Section 7 tested the proposed (deterministic) model against the accident cases where population density information is available, and the resulting distribution is close to an S-curve. Based on this test it is proposed to use a discrete (probabilistic) model where one out of ten accidents will lead to ten times larger/minor consequences than the average value predicted by the model.

It has been stated that traditional consequence models are (too) conservative, and that a model based on accident data would give more realistic results. This is illustrated by comparing the fatality index approach with the results of the report *An Assessment of the Risk of Transporting Liquid Chlorine by Rail* by Andrews [9].

The results of the consequence evaluation are presented as curves showing the frequency (f) of getting N or more fatalities—the so-called fN-curves. Figure 3 shows the fN-curve from the report of Andrews and a discrete curve, which is obtained by the use of the proposed model. The calculations are shown in Appendix C.

The 1,793 accidents used as the basis of this research include 14 chlorine railtank-car accidents in the U.S.A. in the period 1960–85. Of the 14 accidents, one results in 1 fatality and one in 8 fatalities. This curve is given in Fig. 3. There is reason to believe that not all the chlorine railtank-car accidents are recorded in the compiled list. It could, however, be assumed that all accidents resulting in fatalities are included, and that the frequency estimate of Andrews [9] (approximately two accidents per year) can be used. This fN-curve is also shown in Fig. 3.

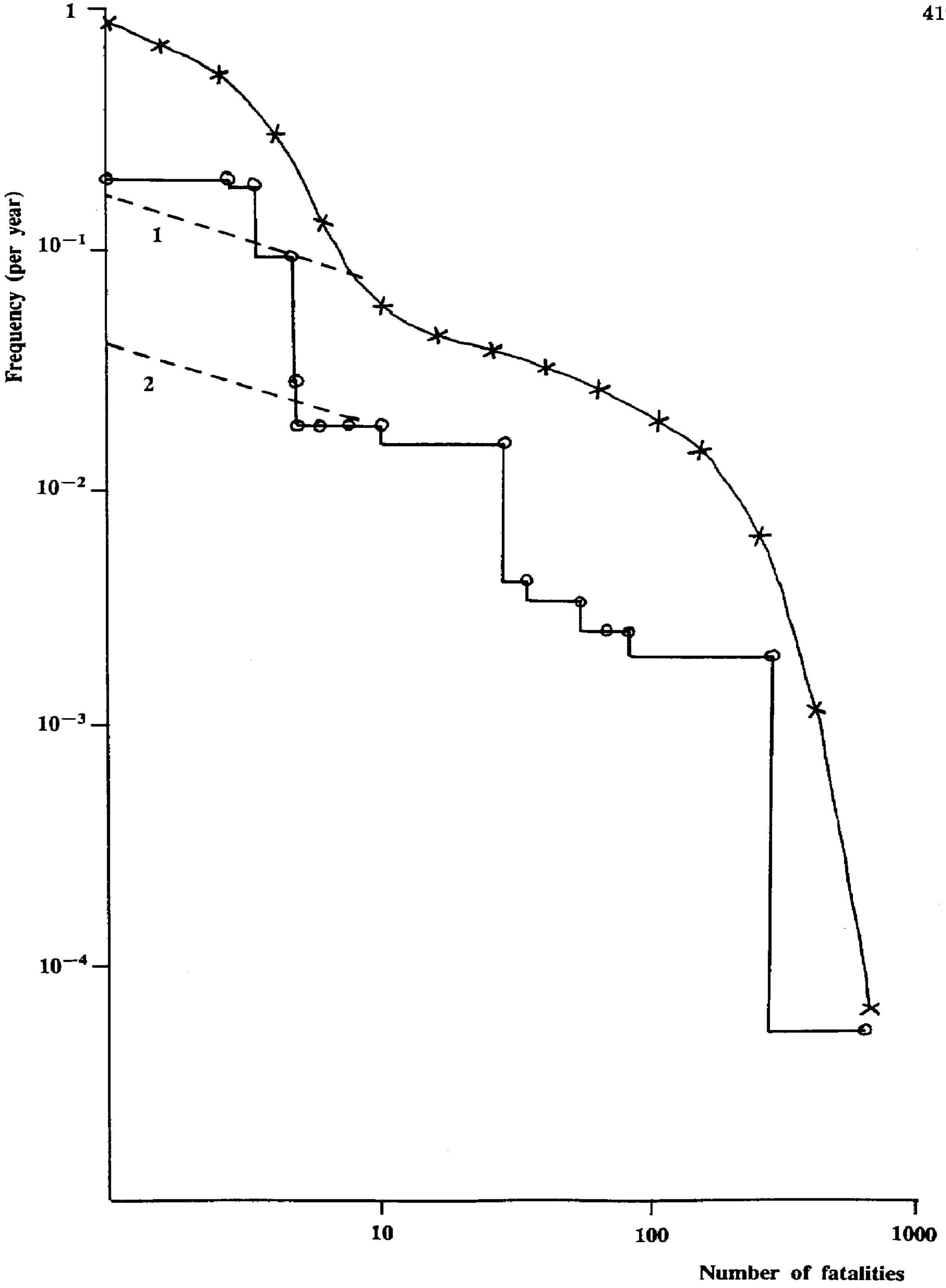

Fig. 3. The *fN*-curve of the risk of chlorine release from a railtank-car in the U.S. in 1985: a comparison of the results of the proposed model (○) presented in this paper, and the dispersion model used by Andrews (×) [9]. Two possible curves (- - -), (1)–14 accidents in 25 y and (2)–50 accidents in 25 y, showing what actually has happened, are also shown.

The fN curves show that the fatality index model give results closer to actual observations than the traditional models do, and is thus a more realistic model.

Both the simple fatality index model and the complex dispersion models are based on numerous assumptions. The simple fatality index model is, however, by far the easiest to use, it gives results closer to actual observations and it is more transparent. The authors therefore recommend use of the proposed model for public policy-related risk assessments, since the decision makers will be better able to understand the limitations of the results—limitations which are present in both approaches.

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Appendix A

Estimation of the correlation of casualty indices with the mass released

As discussed in Section 4 it can be argued that a heavy gas cloud will spread as a pancake, in the absence of wind. Simulations of how large an area is covered with gas were made on the HEAVYPUFF program of Risø National Laboratory [10].

Two computer simulations have been made for three amounts of instantaneous release of chlorine (1, 10 and 100 t, respectively) for two different meteorological scenarios:

(1) Pasquill F, 2 m/s very stable, low wind speed, i.e. a worst case; and

(2) Pasquill D, 5 m/s which is representative for Danish "normal conditions".

The meteorological scenarios are shown in Table 13. In the first series, the areas that were swept with chlorine with a minimum concentration of 1000, 200 and 50 p.p.m. were determined. The effects of a chlorine exposure to humans are [8]:

30–50 ppm: concentration dangerous for exposure of $\frac{1}{2}$ h.

1000 ppm: concentration probably fatal after a few deep breaths.

The results are shown in Table 14.

For stability F and 2 m/s, the areas increase by a factor of about 6.0 (5.7–6.5), if the amount released is increased by a factor of 10. The area is therefore proportional to $W^{0.78}$. For stability D and 5 m/s, the areas increase by a factor of about 5.4 (4.8–6.3), if the amount released is increased by a factor of 10. The area is therefore proportional to $W^{0.73}$. Larger spills cover larger areas,

TABLE 13

The two meteorological scenarios used in the computer simulations of instantaneous release of chlorine

Release data	Pasquill condition	
	F	D
Storage temperature (K)	288	288
Wind speed at 10 m (m/s)	2	5
Air temperature (K)	288	288
Surface temperature (K)	283	288
Surface roughness (m)	0.01	0.01
Monin-Obukhov length (m)	23	−120

TABLE 14

The area covered (km^2) by a chlorine gas cloud at three concentrations of chlorine and the two meteorological scenarios

Release data	Concentration (ppm)					
	1000		200		50	
Pasquill stability class	F	D	F	D	F	D
Wind speed (m/s)	2	5	2	5	2	5
1 t released	0.21	0.11	0.52	0.29	1.36	0.83
10 t released	1.21	0.56	2.97	1.68	7.82	4.01
100 t released	7.74	3.55	18.34	8.62	50.49	20.37

but it does of course take a longer time for the cloud to cover these areas. There will be a possibility of escape, if there is a warning.

In the second series of simulations, it was assumed that it is the area swept by chlorine within the first 10 minutes, that is of importance. The area that was swept by gas with at least 1000 ppm or 400 ppm was determined. An exposure to 400 p.p.m. is probably lethal within 10 minutes. The simulations were made for stability D and 5 m/s. The results are shown in Table 15.

The area increases by a factor of about 5.6, if the amount released is increased by a factor of 10. The area would therefore be proportional in $W^{0.75}$. The conclusion from the computer simulations of chlorine release is that the area covered by fatal or dangerous concentrations of chlorine, or covered within the first 10 minutes, is proportional to $W^{0.75}$.

TABLE 15

The area (km^2) covered by gas of the specified concentration within 10 minutes for stability D and 5 m/s

Amount released (t)	Concentration (ppm)	
	1000	400
1	0.12	0.23
10	0.69	1.25
100	3.81	[a]

[a]The concentration at the border of the cloud was higher than 400 ppm.

Appendix B

Distribution of the casualty indices

As discussed in Section 7, the estimation of a distribution function is based on a "reduced index". This is defined as the actual β for an accident, divided by the estimated mean β for the group of accidents to which the accident belongs. Furthermore, it is assumed that fatality and injury indices *and* ammonia and chlorine have the same distribution function.

As an example, the calculated β for the chlorine release at Wyandotte (1917) is 0.07. The estimated β for chlorine in urban areas is 2.2. The reduced index is thus $0.07/2.2=0.032$.

In Table 16, the calculated reduced indices, the logarithm of these values and the probability of observing a reduced index smaller than the actual are given. Information on substance (chlorine or ammonia), casualty type (fatalities or injuries) and population density class (U, I or R) characterizing the actual casualty index are shown as well.

Figure 2 (in Section 7) shows the probability of *not* observing a value bigger than the actual reduced indices as a function of the reduced indices. As discussed in Section 7 similarity with a logistic function is recognized. The mean value, $M(x)$ of the "reduced index" is -0.16 and the standard deviation, $V(x)$ is 0.71. The logistic curve is given in eq. (A1) and eq. (B2) gives the parameters as functions of the mean value and the standard deviation.

$$F(x)=1/\left[1+\exp\left(-\frac{x-a}{b}\right)\right] \tag{B1}$$

$$a=M(x), \qquad b=\sqrt{\frac{3V(x)}{\pi^2}} \tag{B2}$$

In eqs. (B1) and (B2) the symbols are: $F(x)$, the probability of having a value smaller than x; x, the reduced indices; a and b, scalar parameters; $M(x)$,

TABLE 16

The calculated values of the reduced indices based on the actual indices for the single accidents and the estimated values of β. The probability of observing a reduced index smaller than the actual (the accumulated probability) is given as well. To facilitate the identification of the single reduced indices, the substance, the casualty type (cas. type) and the population density (pop.) is shown

Reduced index	Logarithm reduced index	Accumulated probability	Substance	Cas. type	Pop.
0.029	−1.54	0.048	Chlorine	inj.	U
0.032	−1.49	0.095	Chlorine	fat.	U
0.060	−1.22	0.143	Chlorine	fat.	U
0.074	−1.13	0.190	Chlorine	fat.	U
0.092	−1.04	0.238	Chlorine	inj.	U
0.093	−1.03	0.286	Chlorine	fat.	U
0.38	−0.42	0.333	Chlorine	inj.	I
0.56	−0.25	0.381	Ammonia	inj.	I
0.61	−0.21	0.429	Ammonia	fat.	I
0.67	−0.17	0.476	Ammonia	fat.	U
0.73	−0.14	0.524	Ammonia	inj.	U
1.18	0.07	0.571	Chlorine	fat.	R
2.22	0.35	0.619	Ammonia	fat.	U
2.22	0.35	0.667	Ammonia	fat.	U
2.33	0.37	0.714	Chlorine	fat.	I
2.61	0.42	0.762	Ammonia	inj.	R
3.26	0.51	0.810	Ammonia	fat.	U
4.00	0.60	0.857	Chlorine	inj.	R
4.69	0.67	0.905	Chlorine	inj.	I
6.72	0.83	0.952	Chlorine	inj.	U
65.0	1.81	1.000	Chlorine	inj.	U

mean value of xs; and $V(x)$, standard deviation of xs. With the values $M(x) = -0.16$ and $V(x) = 0.71$, a is thus -0.16 and b equals 0.46. The logistic curve given by eq. (B3) is also shown in Fig. 2.

$$F(x) = 1/\left[1 + \exp\left(-\frac{x + 0.16}{0.71}\right)\right] \qquad \text{(B3)}$$

Appendix C

Comparison of the proposed model and a traditional model

In the following, it will be shown how the fN-curve presented in Fig. 3, Section 8 is calculated. The main results concerning frequencies of chlorine releases from railtank-cars in the U.S.A. from *An Assessment of the Risk of Transporting Liquid Chlorine by Rail*, by Andrews [10], are given in Tables 17 and 18. From these tables the frequency of various releases in the three area-

TABLE 17

The frequency of various release sizes as they appear in [10]

Amount released (t)	Frequency (y^{-1})
15	0.91
29	0.038
2.5[a]	0.93
5.9[a]	0.010

[a]The values are calculated as the amount released in 10 minutes in continuous releases.

TABLE 18

The ratio areas of the three groups of population density in the U.S. in 1985 according to the assertions concerning future population densities [10]

Property	Urban	Semi-urban (Industrial)	Rural
Area (km^2)	116.6	60.6	7560
Area (%)	1.5	0.8	97.7

TABLE 19

The possible numbers of fatalities calculated by multiplying the released amount and the fatality index is given in the left column. The frequency of getting N fatalities and the accumulated frequency are given in the following two columns

N	$f(x=N)$	$f(x>N)$
626	4.7×10^{-5}	0
324	1.1×10^{-3}	4.7×10^{-5}
78	2.5×10^{-5}	1.1×10^{-3}
62.6	4.7×10^{-4}	1.2×10^{-3}
54	1.2×10^{-3}	1.6×10^{-3}
41	6.1×10^{-4}	2.8×10^{-3}
32.4	1.1×10^{-2}	3.5×10^{-3}
10	3.1×10^{-3}	1.4×10^{-2}
7.8	2.5×10^{-4}	1.8×10^{-2}
6.8	6.2×10^{-4}	1.8×10^{-2}
6.3	4.7×10^{-5}	1.8×10^{-2}
5.4	1.2×10^{-2}	1.8×10^{-2}
5.1	7.4×10^{-2}	3.0×10^{-2}
4.1	6.1×10^{-3}	1.0×10^{-1}
3.2	1.1×10^{-3}	1.1×10^{-1}
1	3.1×10^{-2}	1.1×10^{-1}

types can be calculated. Table 19 shows both the frequency of getting N fatalities and the accumulated frequency (which expresses the frequency of getting more than N fatalities).

As a calculation example, consider the frequency of getting 626 fatalities. A release of 29 tonnes of chlorine in urban area (where $\beta = 2.16$) has the expected number of fatalities, $29 \times 2.16 = 62.6$. One out of ten releases results in consequences that are 10 times worse, i.e. $P(626 \text{ fat.}) = 0.083$. Since the frequency of a 29 tonne release is 0.038, and the probability that this release will occur in an urban area is 0.015, $f(N=626) = 0.083 \times 0.038 \times 0.015 = 4.7 \times 10^{-5}$. The corresponding fN-curve is shown in Fig. 3 (Section 8) together with the fN-curve calculated by Andrews [10].

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