INCORPORATION OF BUILDING WAKE EFFECTS INTO QUANTIFIED RISK ASSESSMENTS

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Most risk assessments currently use flat terrain dispersion modelling without considering the effects of building wakes. Where such effects are considered, they are often assessed in an idealised manner, by taking a single building wake model and defining the dimension of an equivalent building, which may not be appropriate to dense releases. The use of computational fluid dynamics (CFD) has facilitated the investigation of such wake effects, enabling source conditions and multiple buildings to be considered. In addition, a simple passive dispersion wake model has been extended to cover dense releases. CFD results have been obtained for a set of realistic releases for a real site, and have been compared with the results of simple modelling. This has demonstrated the effects of incorporating wake models into risk assessments, and allowed the development of an optimum methodology for their inclusion.

Keywords: QRA, CFD, Gas dispersion, Building wakes

INTRODUCTION

Accidental releases of hazardous materials may affect surrounding areas if toxic or flammable vapours disperse in the atmosphere. Calculation of such dispersion, for inclusion within risk assessments, or Safety Cases, is straightforward for uniform unobstructed flat terrain. However, practical releases may be affected by the presence of adjacent buildings, generally resulting in enhanced dispersion. The effects of buildings on dispersion have been reviewed by Lines et al (1) and a substantial effort in the application and validation of CFD modelling to the problem has been presented by Hall (2). An investigation into the extent to which simple models could be used to calculate the dispersion of releases, particularly of dense gases, in building wakes has also been given by Lines and Deaves (3).

The effects of building wakes on the source term for the dispersion of released vapours can be assessed either using simple 'box' or 'zone' type models, or using more sophisticated methods, such as computational fluid dynamics (CFD). The simple approach has been reasonably well developed for single rectangular buildings, and this has been extended to cover dense gas effects. Although there are some models becoming available for the treatment of arrays of obstacles, these tend to be confined to regular arrays, and to focus upon the 'street canyon' effects on urban pollution. For non-regular groups of buildings, there may be some merit in the use of CFD either to determine the dispersion, or to ascertain the appropriate source term for input to a standard flat terrain dispersion model.

This paper considers the application of both simple and CFD modelling to chlorine releases from a real site. It compares the results, demonstrates how the simple modelling may

be used most effectively, and shows the effects on risk calculation of including these building wake effects.

BASE CASE RISK ASSESSMENT

The example that has been chosen to act as the base case is a toxic gas risk assessment for a chlorine bulk storage site, as such sites are relatively common in the UK and can lead to significant risks to off-site populations at some distance from the plant. The particular site that has been chosen is a water treatment works in the North of England. The chlorine bulk store and off-loading bay are located within one of the main site buildings, which is approximately 38 x 30 m wide and 7m high. There are a few other buildings on site of similar dimensions. The site comprises the following main items of equipment which represent major hazards:

- 2 chlorine bulk storage vessels (stored under pressure at ambient temperature)
- a chlorine road tanker off-loading bay
- various sections of 25 mm diameter liquid chlorine pipework

Loss of containment failures involving any of these items of equipment will lead to the formation of a toxic gas cloud.

In order to quantify the risks associated with potential chlorine events, it is first necessary to define a set of representative events which cover all possible significant accidents that could occur. The release rate of chlorine and the frequency of each of these events then needs to be determined. A set of representative scenarios (from Carter, Deaves and Porter (4)), corresponding to a typical small chlorine installation has been used. There is a range of possible weather conditions that may occur at the site, and so each of the 40 events identified is considered in 4 representative weather conditions, namely D2.4, D4.3, D6.7 and F2.4, where the letter corresponds to the Pasquill stability category and the numbers correspond to the wind speed in m/s. The percentage frequencies of these four weather conditions are taken to be 17%, 20%, 45% and 18% respectively, based on the average data over 20 years from a nearby meteorological station; for ease of application, a uniform wind rose has been used.

The dispersion of chlorine vapour clouds has been assessed using the models in the latest version of HGSYSTEM (Version 3.0; Post (5)). Continuous releases have been modelled using the HEGADAS-S code, and instantaneous releases have been modelled using the HEGABOX followed by the HEGADAS-T codes. The risk calculations involve a summation of the risks from each event in each of the representative weather conditions. The risks have been calculated for a typical residential population, which is assumed to be present for 100% of the time, and which is outdoors for 10% of the time, except in F2.4 weather conditions, where 1% is assumed to be outdoors. The population is assumed to be indoors for the remainder of the time.

The risks to persons indoors are based on a calculation of the time-varying concentration inside the building, using an air exchange rate of 2 air changes per hour (ach) for all conditions except D6.7, where the higher wind speed implies a higher air exchange rate of 3 ach. The persons indoors are assumed to remain indoors for 10 minutes after the cloud has passed before evacuating to fresh air, but in no case does evacuation take place until at least 30 minutes has elapsed from the start of the release.

Six of the most significant individual events, contributing 63% of the overall total risk at 500 m and 67% of the risk at 1000 m, were then selected for use in the subsequent analysis in which wake effects are considered in some detail. The conditions for these six events are summarised in Table 1.

Scenario Number	Description		Release Rate (kg/s)	Duration* (min)	Frequency (x10^{-6}/year)	% of Total Risk 500m	1000m
1	**Storage Vessels**						
		Liquid space	44	6.8	2	5.95	9.85
	Pipework: 25mm diameter to vessel						
2		Full	4.6	20	9	6.07	9.42
3		25	3.6	20	45	25.14	38.5
4		Flanges	1.4	20	55	11.73	0.08
	Pipework: 25mm diameter vessel outlet						
5		Flanges	1.1	20	40	6.91	0.05
	Pipework: 25mm diameter Road tanker coupling						
6		Full	7.4	20	6	7.64	8.65

*In Scenarios 2-6, it is assumed that the duration is limited by the correct operation of an isolation valve.

Table 1 Summary of representative scenarios

SIMPLE MODELLING

The program WEDGE is used to evaluate the effects of building wakes on each scenario. WEDGE contains a choice of two models, those of Fackrell (6) and Brighton (7), both of which calculate the wake dimensions and the average concentration in the wake region. The choice of model is dependent on the release conditions and building parameters of each scenario. Fackrell's model is recommended when the resultant release density is low or effectively 'passive', and Brighton's model is recommended when the density of the release gas is high or 'dense'. Values of mass flow rate (kg/s) that will result in a transition from using the Fackrell model to using the Brighton model in the WEDGE program are dependent upon building dimensions and wind speed. For a single building of the size considered, the values range from around 2kg/s at 2.4m/s to 40-50kg/s at 6.7m/s.

WEDGE calculates the wake dimensions and the average mixed concentration of the release within the wake. The released gas is assumed to have no source effects ie. the momentum of the gas is destroyed once it escapes from its primary containment or from the building. This excludes the cases where the jet momentum of the release takes the gas straight through the wake region, without being affected by the building wake. For all scenarios, it is assumed that the incident wind is normal to the face of the building. The results of WEDGE can be incorporated into a HEGADAS-S input file as a TRANSIT block. This TRANSIT block enables the HEGADAS-S model to start the dispersion modelling at the breakpoint, which in this case is the downstream edge of the wake, with cloud width, temperature and concentration that are determined by WEDGE.

The WEDGE results are based on the assumption that the mixing of gas and air occurs throughout the wake region, with an average uniform concentration that extends up to the wake boundary, which is dependent on the building dimensions. In some release cases, large building cross-sectional areas give rise to long wake lengths and the wake concentration emerging from

the downwind end of the wake could be higher than the concentration predicted at the same position by the 'standard' dispersion model, possibly resulting in longer hazard ranges than those predicted by the 'standard' method. Alternatively, the increased mixing in the wake region may lead to lower concentrations and shorter hazard ranges.

The wake conditions were used as input to the dense gas dispersion model, and concentrations at downwind location compared for the with/without building wake calculations. The 'concentration ratio' thus defined was plotted against distance for varying wind conditions (Figure 1) and release rates (Figure 2). Comparison of results in this way allowed the selection of scenarios which were considered further in the CFD studies.

CFD MODELLING

As a result of the initial application of simple modelling, the following conditions were selected for analysis using CFD to model the complete site selected:

Case	Release rate (kg/s)	Wind speed (m/s)	Wind direction	Wind stability
1	3.6	2.4	SW	D
2	7.4	2.4	SW	D
3	3.6	4.3	SW	D
4	7.4	4.3	SW	D
5	3.6	2.4	NE	D
6	3.6	2.4	NW	D
7	3.6	2.4	SW	F

Table 2 Identification of CFD runs

A standard mesh was used for each case described in Table 2 and required a simple modification for the different wind directions. The mesh consisted of a site section which includes all the buildings and is fixed for all of the cases considered. An additional section is attached to the downwind side of the site section to capture the dispersion further away from the buildings. The width of the domain is taken to be approximately twice that of the plume predicted using preliminary HGSYSTEM calculations. Accordingly, a width of 400m is used for the domain. This dimension is also used for the sides of the site section so that the attached downwind section may easily be transferred from one side of the site to another. The downwind length of the attached section is 300m. The chlorine release location is offset 50 metres away from the centre of the site, so that the maximum distance from the release point to the downstream boundary is 550m and the minimum distance is 450m. The domain extends to a height of 80m above ground level.

For higher accuracy of the solution, grid resolution was considered to be important in the region close to the release point and in regions around the edges of buildings. A cell size of approximately 2.0m x 2.0m x 0.4m was chosen for the mesh at the release point, with an expansion ratio of about 1.2 for cells away from the release. A further level of grid refinement was considered necessary in the region close to the chlorine source. Fluid cell lengths were therefore halved up to about 10m away from the release in the plane of the jet and up to about 1.2m vertically from ground level. Hence, the smallest cell actually solved for was

approximately 1.0m x 1.0m x 0.2m in size. In the vertical direction, 40 cells were used, and the final mesh comprised a total of 179,087 fluid cells.

The inlet velocity profiles were modelled using standard formulae for equilibrium atmospheric boundary layers. The standard k-ε turbulence model is used, and appropriate *equilibrium profiles of k and ε applied at the inlet boundary.*

The chlorine gas release is modelled as an area source located at the loading bay entrance. The gas is discharged horizontally and at right angles to the bay wall. It is assumed that the liquid has flashed to vapour and that air has been entrained by the time it has reached *the loading bay entrance. Exit conditions are obtained by assuming adiabatic conditions prior to* reaching the bay entrance. Turbulence levels for the jet are obtained using a turbulence intensity of 5% applied to the calculated efflux velocity, and an integral length scale of 0.1m is used for calculating ε.

Example CFD results for a 3.6kg/s release into a 2.4m/s wind speed are shown in Figures 3, 4 & 5 for SW and NE directions in D stability, and SW direction in F stability respectively. It is clear from comparing these results that the whole site is affecting the dispersion, and that the width of the dispersed cloud is strongly dependent on both wind direction and atmospheric stability.

COMPARISONS OF CFD AND SIMPLE MODELLING

Initial comparisons were undertaken between the CFD results and results of using the simple wake model for a single building (that from which the chlorine is released). From this comparison, the CFD results indicated:

- The width of the cloud in the very near field (on site between buildings) may be much greater than that predicted by the simple modelling.
- Channelling effects between buildings may be significant in the near field.
- Ground level concentrations immediately downwind of the near wake region may be substantially lower than those predicted by the simple model depending on the building orientation.

It was therefore considered that better agreement between the CFD and simple *modelling results could be achieved if the simple modelling was based on the overall* dimensions of all the site buildings, rather than just the chlorine building. It also appears to be important that the release location and building orientation with respect to the wind should be included within the analysis.

On the basis of these comparisons, the following minor changes were incorporated into the simple modelling:

- threshold on buoyancy parameter for dense gas spreading in wake reduced
- effect of release position (upwind/downwind) incorporated
- methodology for inclusion of all site buildings adopted.

This updated version of WEDGE was then used to model Runs 1-7, as identified in Table 2. In order to set the subsequent discussion in context, preliminary comparisons were undertaken between the simple modelling results of Runs 1, 5 and 6 with those for Run 8, which

is for the same release and wind conditions, but without the buildings, and hence using HEGADAS only. The release is 3.6kg/s in D2.4 wind conditions, and Runs 1, 5 and 6 are for different wind directions. The results are presented in Table 3, which shows the area and hazard range for each of 3 threshold concentrations.

Run	Direction		Threshold concentration (ppm)		
			100	300	500
1	SW	Area (m^2)	$1.2x10^5$	$3.8x10^4$	$1.9x10^4$
		Hazard range (m)	579	240	134
5	NE	Area (m^2)	$1.2x10^5$	$5.2x10^4$	$3.6x10^4$
		Hazard range (m)	703	353	250
6	NW	Area (m^2)	$1.2x10^5$	$4.6x10^4$	$3.0x10^4$
		Hazard range (m)	692	330	220
8	No buildings	Area (m^2)	$1.1x10^5$	$4.5x10^4$	$3.0x10^4$
		Hazard range (m)	827	467	354

**Table 3 Comparison of simple modelling for 3.6kg/s
release in D2.4 wind conditions**

The following observations can be drawn from these results:

- The predicted area of the 100ppm contour is increased by about 10% by the presence of buildings, although the hazard ranges are reduced slightly, by around 15% for Runs 5&6, and by around 30% for Run 1.

- The effects of buildings become more marked with increasing concentration threshold, which corresponds to regions closer to the buildings.

- The predicted area of the 500ppm contour is increased by the presence of the buildings, for Run 5 (by 20%), but reduced by nearly 40% for Run 1 and unchanged for Run 6. Hazard ranges for this concentration are reduced for all runs; by around 30-40% for Runs 5 and 6 and by more than 60% for Run 1.

From these observations it is clear that the greatest effects occur in the near field, and that the effects are enhanced when the release is blown through the building array, rather than away from it or around the side.

Figures 6 and 7 show the results of applying WEDGE/HEGADAS for a single building and for the whole site respectively. The change in width is evident, and it is clear that the wider effective plume of Figure 7 would give a better match to the CFD results of Figure 3.

A quantitative comparison of the hazard ranges and areas covered by various concentration contours has been undertaken for all the cases analysed. It was shown in the preliminary comparisons that there was generally little effect of the building wake on the 100ppm contour, with the greatest effects felt closer to the buildings. It was also found that, for all the CFD runs undertaken, the 100ppm contour extended beyond the end of the computational domain, thus rendering estimation of hazard range and contour area inaccurate. For these reasons, the comparisons presented below relate only to the 300 and 500ppm contours. In the tables which follow, the ratios given in the final columns are the CFD prediction divided by the WEDGE/HEGADAS (W/H) predictions.

Run		CFD	W/H	Ratio
1	Area (m^2)	2.4x10^4	3.8x10^4	0.63
	Hazard range (m)	240	240	1.00
2	Area (m^2)	*7.2x10^4	1.0x10^5	0.72
	Hazard range (m)	*450	457	1.00
3	Area (m^2)	1.1x10^4	1.1x10^4	1.00
	Hazard range (m)	160	113	1.42
4	Area (m^2)	2.5x10^4	3.3x10^4	0.76
	Hazard range (m)	339	270	1.26
5	Area (m^2)	*4.8x10^4	5.2x10^4	0.92
	Hazard range (m)	*450	353	1.27
6	Area (m^2)	3.3x10^4	4.6x10^4	0.72
	Hazard range (m)	399	330	1.21
7	Area (m^2)	>7.3x10^4	1.5x10^5	>0.49
	Hazard range (m)	>450	559	>0.81

* 300ppm contour extended just beyond edge of CFD domain

**Table 4 Comparison of CFD and WEDGE/HEGADAS results
for 300ppm concentration criterion**

Run		CFD	W/H	Ratio
1	Area (m^2)	9.9x10^3	1.9x10^4	0.52
	Hazard range (m)	140	134	1.05
2	Area (m^2)	4.0x10^4	6.2x10^4	0.65
	Hazard range (m)	289	309	0.94
3	Area (m^2)	5.0x10^3	3.9x10^3	1.28
	Hazard range (m)	88	33	2.67
4	Area (m^2)	1.2x10^4	1.8x10^4	0.67
	Hazard range (m)	171	159	1.08
5	Area (m^2)	3.2x10^4	3.6x10^4	0.89
	Hazard range (m)	430	250	1.72
6	Area (m^2)	2.0x10^4	3.0x10^4	0.67
	Hazard range (m)	263	220	1.20
7	Area (m^2)	4.3x10^4	6.3x10^4	0.68
	Hazard range (m)	331	310	1.07

**Table 5 Comparison of CFD and WEDGE/HEGADAS results
for 500ppm concentration criterion**

It can be seen from Table 4 that the results for the 300ppm contour are in reasonable quantitative agreement, with a tendency for the CFD to predict slightly smaller areas and longer hazard ranges. The agreement is slightly less good for the 500ppm contour, with the biggest ratio for the rather short hazard ranges predicted for Run 3. A measure of the goodness of fit can be determined by averaging the ratios in the final columns of these tables. From Table 4, Run 7 is omitted in the averaging because contour extended significantly beyond the CFD domain. From Table 5, Run 3 is omitted because the rather short hazard ranges give rather large ratios. The results of averaging the remaining ratios are presented in Table 6.

	300ppm	500ppm
Area ratio	0.79	0.68
Hazard range ratio	1.19	1.18

Table 6 Average of ratios [CFD/(WEDGE/HEGADAS)] from Tables 4 and 5

The CFD results can also be compared with the HEGADAS results with no building effects (Run 8). Hence, this comparison would represent the effects of ignoring the buildings in the simple modelling. The results are given in Table 7.

	300ppm		500ppm	
	Run 1	Run 8	Run 1	Run 8
Area ratio	0.63	0.50	0.52	0.31
Hazard range ratio	1.00	0.55	1.05	0.44

Table 7 Comparison of CFD against HEGADAS results with (Run 1) or without (Run 8) WEDGE, for 3.6kg/s in D2.4 wind conditions

It is clear from these comparisons that the modelling of building effects using WEDGE gives a significantly better fit of simple modelling to the CFD results than using HEGADAS alone. It is also clear from the other comparisons in Tables 4-6 that there is generally good agreement between CFD and the current implementation of WEDGE/HEGADAS modelling.

Summary of Comparisons   Although simple modelling will never predict the detailed features of the dispersion as predicted by CFD, the above comparisons have shown that simple wake modelling can be used effectively to provide a good indication of near field concentrations and plume dimensions, which should be sufficient for typical risk assessment applications. The greatest difficulties arise when channelling between/along buildings is significant, as this will probably require some user expertise in the choice of which buildings should be used to define the wake in WEDGE.

The very near field, inside the wake and between buildings, is also not well predicted by simple modelling, and so the importance of such situations may need to be considered as a separate issue in the risk assessment process. For example, it would probably be appropriate to assume that any location within the building complex would experience a dangerous toxic load for any wind direction for any of the releases considered above.

A revised risk assessment was undertaken, incorporating wake effects for all wind speeds, and for a SW direction. The results are given in Figure 8, which shows that the inclusion of wake effects has surprisingly little influence on the overall risks results for distances in the near field from 150m to about 700m. There are several reasons for this, namely:

- Even in the base case QRA, where building wake effects are not included, dense gas clouds of chlorine tend to spread laterally quite rapidly. In this particular study, it appears that, at distances of around 150m from the release point, this lateral spread is often broadly comparable to the spread that is induced by the building wake, and consequently there is little difference in the associated risks.

- The methodology used to calculate the risks (ie. the typical HSE approach using a Dangerous Toxic Load with different probabilities for escape depending on the concentration) is not particularly sensitive to the precise cloud concentrations in the near field (ie. the cloud has relatively sharp edges and a person is either in the cloud or is outside the cloud). Different approaches, such as using the AIChE probit to calculate the risk, could lead to greater differences.

- Examination of the results for individual scenarios reveals that the inclusion of building wake effects can lead to either greater or lesser risks in the near field, depending on the precise combination of weather conditions, release rate, release duration, etc. When the results for all scenarios are combined, many of these differences cancel out, giving relatively little change in the overall risk. If the choice of events or their frequency were different, then this cancelling out effect may not occur.

- Building wake calculations have only been undertaken for the six most significant scenarios (see Table 1). If these wake conditions were also undertaken for the other 30 continuous releases scenarios in the risk assessment (ie. a total of 4 x 30 = another 120 WEDGE runs), then it is likely that greater differences would be observed in the near field.

Examination of Figure 8 shows that the greatest differences in risk occur in the medium to far field (beyond 700m). For example, at 1000m the inclusion of wake effects increases the risk from 6.8×10^{-7} to 1.0×10^{-6}/yr (a factor of 1.5 increase), whereas at 1500m the inclusion of wake effects reduces the risk from 2.7×10^{-7} to 1.0×10^{-7}/yr (a factor of 2.7 decrease). At most distances, the differences in risk are less than a factor of two, but it should be emphasised that this could still shift the 3×10^{-7}/yr contour by up to several hundred metres, which could have implications for the size of the consultation zone around this type of major hazard site.

CONCLUSIONS

CFD modelling

- The lessons learned from previous studies applying CFD to external atmospheric flows enabled robust and efficient CFD modelling of wake effects to be undertaken.

- Scoping studies using an unobstructed terrain model are useful to set the size of the computational domain.

- CFD modelling enabled certain features of the flow to be identified which could not be predicted with the simple models. These included near source effects such as upwind spreading and overall cloud width, both of which are dependent on source size and momentum.

- The results from the CFD modelling also demonstrated the importance of wind direction, and of including all the nearby buildings on site, at least for the range of release rates and wind speeds considered.

Simple modelling

- Simple wake models can give a substantial improvement in risk estimates, although single building wake models may have limited use on complex sites.

- As a result of the comparison with CFD, improvements were made to the application of WEDGE.

- the wake width has been modified (increased) for moderately dense releases

- modifications have been made to allow for different effects of release location (upwind/downwind/side)

- the model has been applied by treating the group of buildings as a single effective building

- With the improvements outlined above, good correlation was obtained between CFD and simple modelling results, within the range 300-500ppm. Beyond 100ppm, direct comparison was unreliable, since the CFD predicted contours which extended beyond the computational domain. Similarly, for concentrations in excess of 500ppm, near wake effects become important, and again the comparison is unreliable.

- The building wake concentration should be assumed to apply over the whole region of the building complex, which may have the effect of increasing the on-site calculated risk.

Risk calculation

- Wake effects can increase or decrease the risk calculated downwind of a group of buildings, although the overall changes identified for a typical chlorine installation are all within a factor of around 2. While the effects are generally greatest in the near field, they can also extend to the far field (ie. beyond about 1km in this case).

- The effects on the individual contribution to risk will vary between scenarios, and may exceed the factor of 2 identified above at certain distances from the source.

- The significance of wake effects on risk depends on release rate and wind speed, being generally greatest for low wind speed and small to moderate release rate. Large releases tend to engulf buildings, whose presence then has only a minor effect on the dispersion.

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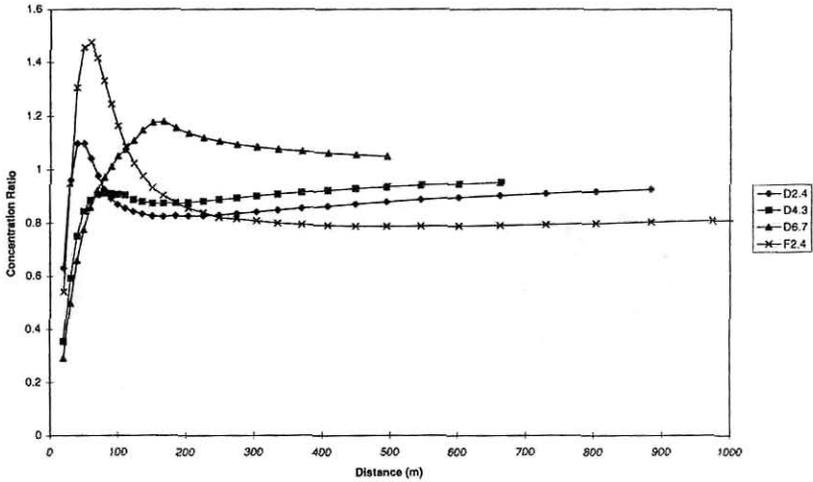
Figure 1. Effect of varying wind speed on the concentration ratio for a 3.6kg/s release
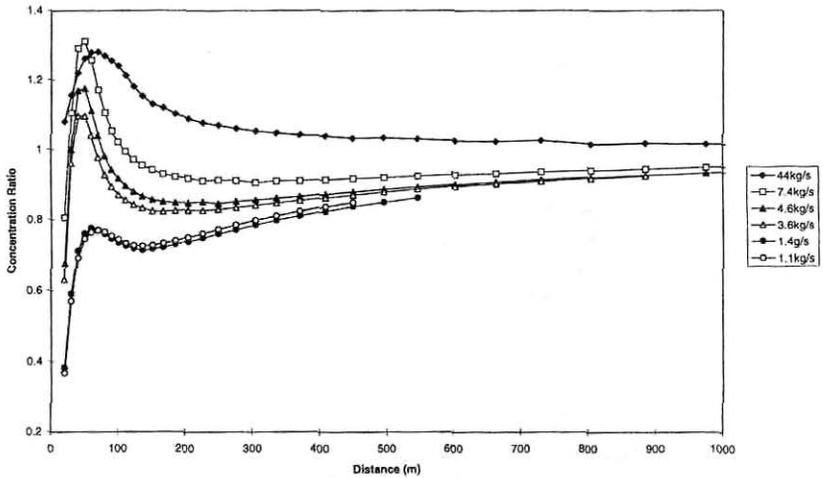
Figure 2. Effect of varying the release rate on the concentration ratio
at a constant wind speed of 2.4m/s

LOCAL MX= 1406

A	1400.
B	1300.
C	1200.
D	1100.
E	1000.
	900.0
	800.0
	700.0
I	600.0
J	500.0
K	400.0
L	300.0
M	200.0
N	100.0
O	0.0000E+00
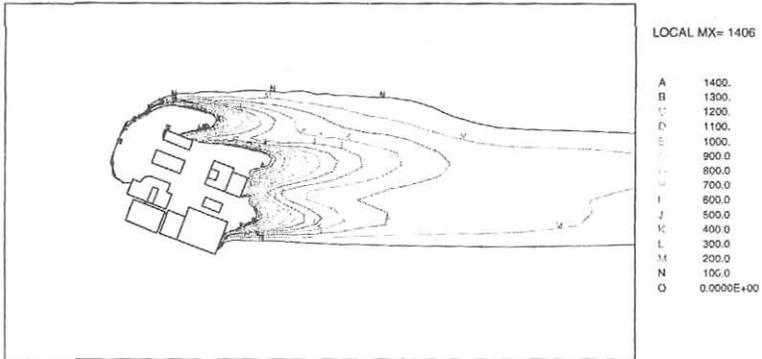
Figure 3. Ground level concentration contours for Run 1
(3.6kg/s, 2.4m/s, D stability, SW wind)

LOCAL MX= 1406

A	1400.
B	1300.
C	1200.
D	1100.
E	1000.
	900.0
	800.0
	700.0
I	600.0
J	500.0
K	400.0
L	300.0
M	200.0
N	100.0
O	0.0000E+00
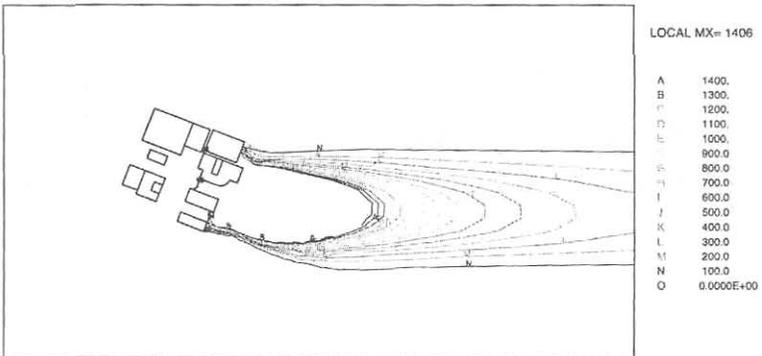
Figure 4. Ground level concentration contours for Run 5
(3.6kg/s, 2.4m/s, D stability, NE wind)
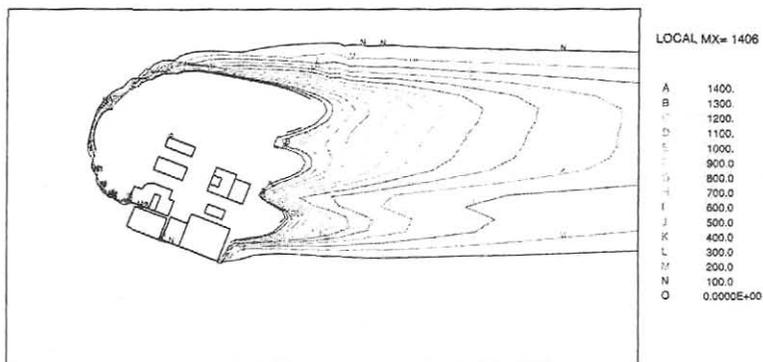
Figure 5. Ground level concentration contours for Run 7
(3.6kg/s, 2.4m/s, F stability, SW wind)
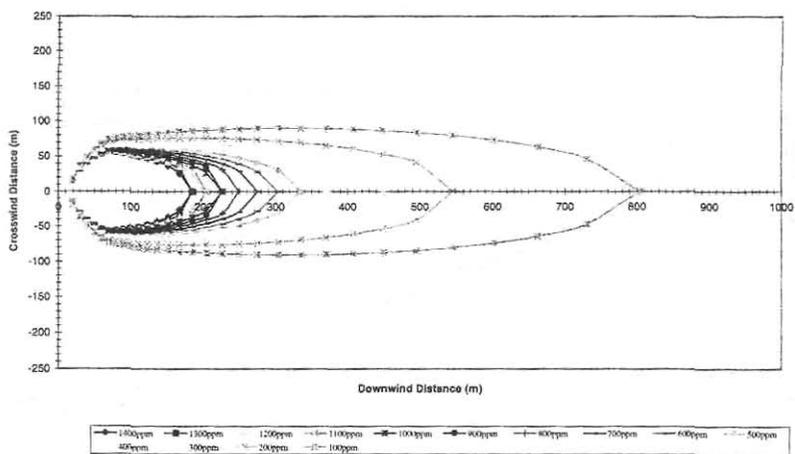
Figure 6. WEGDE/HEGADAS results from Run 1, single building modelling
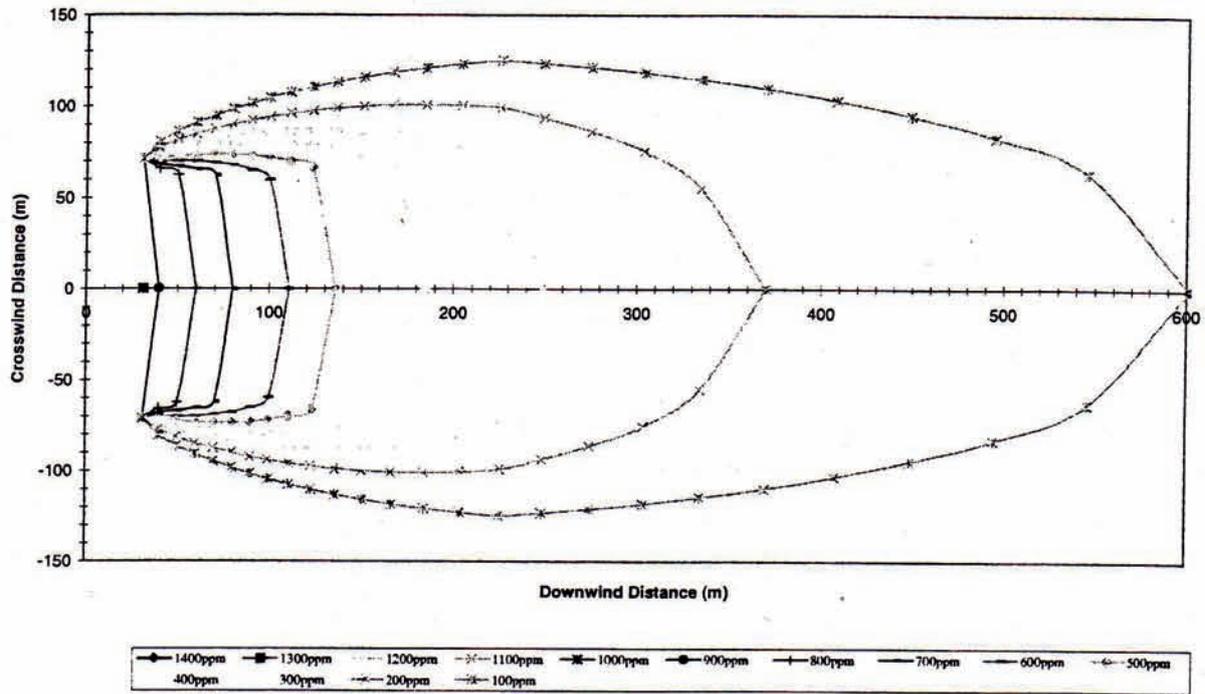
Figure 7. WEGDE/HEGADAS results from Run 1, complete site modelling
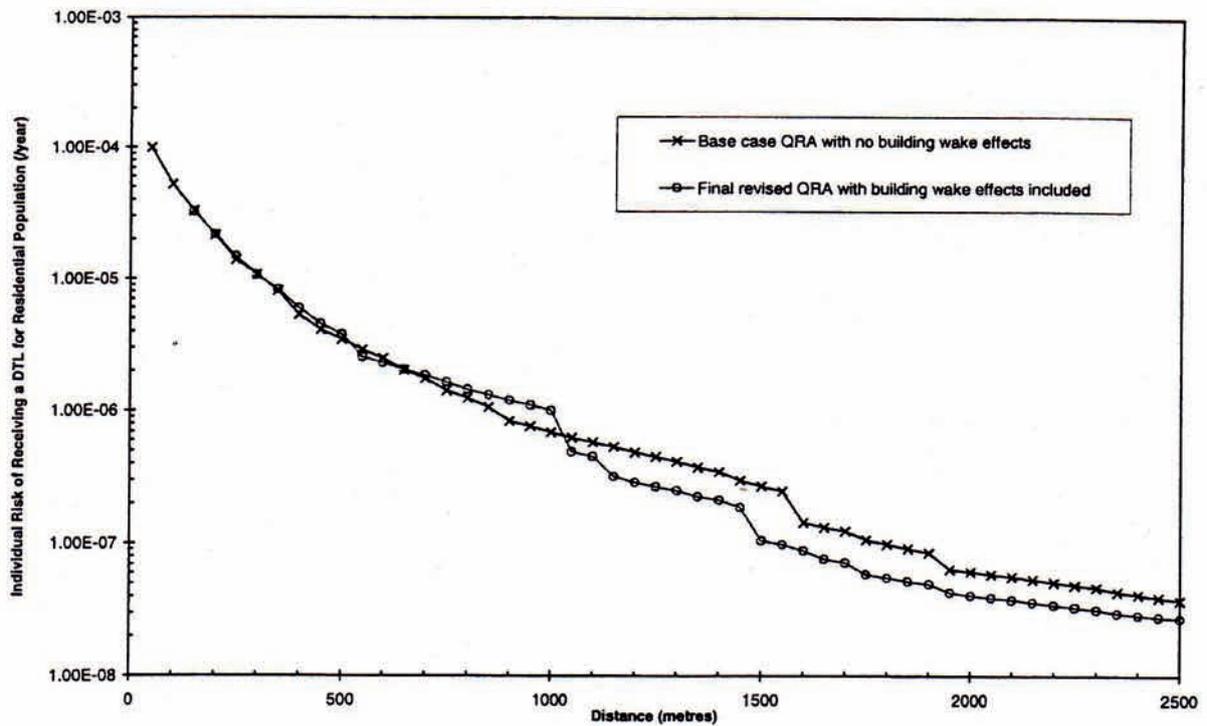
Figure 8. Comparison of base case and revised QRAs for a typical chlorine
bulk storage site, showing the effect of including building wake effects