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ENVIRONMENT AGENCY

Air Dispersion Climate from the Castle Cement Works at Ribblesdale

Report to
Environment Agency, North West Region &
National Centre for Risk Analysis
& Options Appraisal (NCRAOA)

Compiled by

Cambridge Environmental Research Consultants Ltd
D J Carruthers, A M McKeown, K L Ellis
and C A McHugh

Agency Supervisors:

North West Region	: D Coulburn
NCRAOA	: R Timmis

22 September 1997

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Anne McKeown Copy

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The results of this work will be used in the formulation of Environment Agency Policy, but views expressed in this report do not necessarily represent Environment Agency Policy.

22 September 1997

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EXECUTIVE SUMMARY

Executive Summary

1. Background

1.1 Over the last three years there have been a large number of complaints concerning emissions to air from the Castle Cement Works which lies on the north east edge of Clitheroe in Lancashire. These, together with monitoring of emissions and concentrations have resulted in the issue by HMIP, now part of the Environment Agency, of a variation condition to Castle Cement. The variation was dated January 1996 and it contains a condition for improvements to the dispersion, visibility and odour of the plumes from the two kiln stacks at the Works.

1.2 Atmospheric dispersion modelling of the emissions from the Works has been conducted on behalf of the Agency in order to study the current situation and to assess the effect that various improvements put forward by Castle Cement will have on the ground level concentrations of key emitted pollutants.

1.3 The emphasis of the study is on sulphur dioxide (SO_2) and particulates as these are the pollutants which are of greatest significance according to existing and proposed air quality criteria. Oxides of nitrogen (NO_x) and odour have also been considered. SO_2 is emitted in significant amounts from each kiln stack; concentrations close to the new EPAQS standard (100ppb (270$\mu g/m^3$) over 15 minutes) have been measured at ground level and short term concentrations above 50ppb (135$\mu g/m^3$) have often coincided with the occurrence of odour. Particulates are emitted from both of the kiln stacks and also from cement mills within the Works; the EPAQS standard for particulates (50$\mu g/m^3$ for rolling 24 hour average of PM_{10}) has been exceeded in the vicinity of the site.

1.4 The model used for most of the calculations is ADMS (Atmospheric Dispersion Modelling System). This model is based on an up-to-date understanding and hence parameterisation of the structure of the atmospheric boundary layer and includes a range of features which are directly applicable to the modelling required. These include representation of the skewed nature of vertical motions within the atmospheric boundary layer, a plume rise model, allowance for the effects of complex terrain and a fluctuation model which predicts the probabilities of a given concentration being exceeded over short time scales as is necessary for the prediction of odour. As well as being soundly based scientifically, ADMS has been subject to extensive validation.

1.5 Emissions of SO_2 occur from two stacks, one for the wet process kilns 5 and 6, the other from the dry process kiln 7. Emissions of particulates occur from these main stacks and additionally from the cement mill stacks. Other emissions of particulates arise from quarrying but these are not included in the calculations. Options to improve emissions include adding a scrubber to kiln 7 to reduce SO_2 emissions, the addition of effluent gases to the kiln 7 stack to increase plume rise, and using a single taller stack for all SO_2 emissions.

1.6 For the assessment calculations, stack geometry and emission data as shown in Tables 1 and 2 have been used. In the case of comparisons with NPL (National Physical Laboratory) field measurements using a mobile monitoring site (§2.1), emissions data used by the model were measured directly as part of the field test.

2. Comparisons with Data in Situ

2.1 In order to confirm that ADMS was predicting concentrations broadly similar to those observed, comparisons were made with concentrations measured by NPL at their mobile laboratory during a field campaign in summer 1995.

2.2 The fluctuation module of ADMS was used to predict 10 minute means and probability distributions of concentrations for a 1 minute averaging time, this being the time resolution of data obtained by NPL. The model predictions are generally consistent with the measurements, which result tends to support the use of ADMS for assessment of proposed improvement measures.

3. Initial Calculations

3.1 In advance of comprehensive modelling studies, initial calculations were performed to assess the effect of complex terrain and in-plume condensation/evaporation on the dispersion.

3.2 Calculations taking account of the surrounding hilly terrain, demonstrated that while the hills did affect the dispersion, in cases when the highest concentrations occurred (unstable and neutral flows) their influence was not large (<20%). In stable conditions the influence of hills on dispersion can be very pronounced with the location of the maximum concentrations being substantially affected. However, in such conditions the ground level maximum concentrations are several orders of magnitude less than in unstable or neutral conditions and generally occur at large distances (>10km) from the site or sometimes high on the side of the larger hills (>400m) if there is plume impaction. As a result of these initial calculations it was decided to generally omit the consideration of terrain when modelling long term impacts of emissions from the Works in the Clitheroe area. For short term impacts, calculations were carried out including complex terrain in every case, and in some cases with flat terrain for comparative purposes.

3.3 Calculations were performed taking account of the effects on plume buoyancy of in-plume condensation and evaporation, in order to evaluate a suggestion that elevated concentrations may be due to downward "sagging" of a cold wet plume. As would be anticipated, effects are small if the temperature of the existing gases is greater than 100°C, with the gain in buoyancy due to condensation approximately cancelling the loss in buoyancy due to evaporation. If the exiting gases have a temperature below 100°C and already contain condensed water, effects can be significant, sometimes leading to a doubling of the ground-level concentration. The current plumes are exiting the stacks at temperature >100°C and therefore "sagging" is not contributing to elevated concentrations.

4. Sulphur Dioxide and Odour

4.1 Short Term Averages

4.1.1 Calculations have been made for 1 hour averages (ensemble means for comparisons with other models), 15 minute averages (ensemble means and fluctuation for comparison with the EPAQS standard) and 10 minute averages (ensemble means with 1 minute fluctuations for prediction of odour).

4.1.2 Current Mode of Operation

4.1.2.1 Ensemble mean ground level concentrations are largest from both the wet and dry kiln stacks in the most unstable (convective) conditions. In these conditions the maxima occur close to the stack (within 1000m). For the 15 minute averaging time the resultant maximum ensemble mean concentration due to emissions from either stack is about 100ppb (270μg/m^3) without consideration of background concentrations. Such concentrations result in exceedence of the 15 minute EPAQS standard for SO_2. The most unstable meteorological conditions are *very* infrequent (a few hours per year at most). More frequent but less unstable conditions result in maximum ensemble means up to about 50% less than 100ppb (270μg/m^3) again without consideration of background.

4.1.2.2 Consideration of the fluctuations of concentration about the mean, however, shows that the 15 minute EPAQS standard can be exceeded in all unstable conditions and in neutral conditions, due to emissions from both stacks treated either separately or together.

4.1.2.3 Calculations of ground level concentrations of SO_2 taking into account fluctuations about the ensemble mean, due to emissions from both stacks were made for Chatburn and Grindleton, both locations from where complaints have been received. These show that taking into account both stacks but ignoring background concentrations, the EPAQS standard is likely to be exceeded for a total of 10 accumulated hours per year at both locations. This means that there is actually a possibility of 40 exceedences of the limit (there are 4 × 15 minute periods in an hour). However, in reality a pollution episode could last around 25 minutes and still only be classed as one exceedence, so the effective number of exceedences is likely to be less than 40. Odour, (assumed to occur when the SO_2 concentration averaged over 1 minute exceeds 50ppb (135μg/m^3)) is predicted to occur during about 40 hours per year at each location. As explained above, this means that there could actually be 2400 exceedences of this 1 minute concentration, but in reality what is registered as an odour episode will normally be a period longer than 1 minute. These exceedences take place in unstable and neutral conditions and can thus occur at any time during the year.

4.1.3 Future Case

4.1.3.1 An increase in the volume flow rate and temperature of the gases exiting from the dry stack by diverting gases from the folax cooler has little effect (<10%) on ensemble mean ground level concentrations.

4.1.3.2 The various options for scrubbing kiln 7 reduce the concentration of SO_2 due to that stack and completely eliminate exceedence of the EPAQS standard of 100ppb (270μg/m^3) over 15 minutes due to that stack. Exceedence of 50ppb (135μg/m^3) is also avoided and this would signify that there would be no odour due to stack 7, if the scrubbing of SO_2 at stack exit results in similar reductions in the concentration of the gases resulting in odour to those of SO_2. The results do not take account of the effect of in-plume condensation/evaporation although test calculations have shown that such effects will be minor (generally <10%) for exit temperatures >100°C. Options in which condensed water exits the stack should be avoided; this generally occurs for exit temperatures less than 100°C unless there is little water vapour in the exiting gases.

4.1.3.3 The scrubbing of kiln 7 has no effect on pollutants which exit the other main stack ie the "wet" stack which discharges emissions from kilns 5 and 6. Exceedences of the 15 minute EPAQS standard will continue to occur due to this stack occurring for a total of approximately 5 hours per year (a possibility of 20 actual exceedences) at Grindleton and Chatburn. The scrubbing of kiln 7 will reduce the overall rate at which odour events occur at Chatburn and Grindleton due to the combined impacts of both stack plumes.

4.1.3.4 The use of a combined stack (ie. one stack to exit all emissions from kilns 5,6, and 7) does not eliminate exceedence of the EPAQS standard or odour threshold even if the stack height is increased to 220m. However ground level concentrations are significantly (~50%) reduced for the highest stack considered (220m); there would also be a significant (>50%) decrease in the number of exceedences of the EPAQS standard for SO_2.

4.2 Long Term Averages

4.2.1 Long term (annual) averages have been calculated for the current mode of operation at the site and for future cases. The calculations have been done using 3 different sets of meteorological data collected at different sites in NW England, in order to show the sensitivity of the results to the choice of site. Maximum concentrations depend on the meteorological data used, however, they are always below 4.5ppb (12µg/m^3) and occur within 3km of the site using ADMS. Use of the CERC R-91 model DISTAR, which is an old generation model without boundary layer scaling, results in lower maximum concentrations (~2ppb) but at a greater distance (~8km) from the stacks.

4.2.2 The various options for proposed improvements to kiln 7 all result in an overall decrease in the long term average concentrations. The magnitude of the decrease from kiln 7 depends on the option considered; it varies between 5-50%. The contribution from kilns 5 and 6 remains unchanged.

5. Particulates

5.1 Ideally, 24 hour rolling averages (overlapping periods of 24 hours) would have been calculated for direct comparison with EPAQS but this facility was not available in version 2.02.3 of ADMS. The approach taken was therefore to calculate daily (midnight to midnight) averages which allowed an approximate comparison with EPAQS.

24 hour (daily) ensemble averages have been calculated for emissions from all the point sources (cement mills and kiln stacks) within the Works based on hourly sequential data from 1995 at Manchester Ringway and 1990 at Blackpool Squires Gate (Wilsden met data could not be used because the data are collected on a 3 hourly basis). These show a maximum value of 31.8μg/m^3 which is below the EPAQS standard of 50μg/m^3. The kiln stacks contribute very little to this maximum since modelling only the cement mills produces a maximum of 31.6μg/m^3. (Note that the maximum concentrations recorded from the stacks only and the cement mills only do not sum to the maximum recorded when all sources are run together as the locations of the separate maxima do not coincide. This is because the stacks are higher with more buoyancy and their maximum occurs further away from the source.) No account is taken of background concentration or emissions associated with quarrying, which may locally increase the concentrations.

5.2 The maximum annual average of particulates from all point sources (cement mills and kiln stacks) within the Works is calculated to be 5.3μg/m^3.

6. Nitrogen Oxides (NO_x)

6.1 Short Term Averages

Assuming all the emitted NO_x occurs as NO_2, there are no predicted exceedences of the WHO guideline for NO_2 (the most stringent standard) except in strongly unstable conditions. Given that only a minor proportion of NO_x is likely to be NO_2 (most will be NO) where the maximum occurs then the standard is very unlikely to be exceeded even in these conditions.

6.2 Long Term Averages

Current emissions from the stacks result in maximum long term averages which are less than 10% of the current air quality standards. It should be noted that all the NO_x is assumed to be NO_2 although a significant fraction of NO_x is likely to remain as NO within a few kilometres of the sources.

7. Conclusions

7.1 In the current mode of operation at Castle Cement, exceedence of the EPAQS standard for SO_2 and occurrence of odour are predicted downstream of the works.

7.2 Dispersion modelling using ADMS shows that the use of a scrubber in kiln 7 will reduce emissions from the kiln 7 stack to the extent that they will cease to cause significant adverse affects by themselves. However, kiln 7 emissions could still make a minimal contribution to adverse affects in the area.

7.3 Emissions from the wet stack will continue to result in exceedences of the EPAQS standard and also of the concentration of SO_2 which has been associated with odour (50ppb (135μg/m^3)).

7.4 Overall, taking into account the reduced emissions from kiln 7, if a scrubber is fitted, the contribution from kilns 5 and 6 and background concentrations, it is likely that exceedences of the EPAQS standards and the level of 50ppb of SO_2 (associated with odour) will occur approximately half as often as currently. This is based on the assumption that odour is scrubbed pro rata with concentration of SO_2. Future modelling should include modelling at site(s) further downstream to investigate the possibility of exceedences at more distant locations.

7.5 The dry and wet stacks contribute less than 10% to the maximum concentration of particulates. Reducing particulate emissions from kiln 7 will not give any noticeable improvement on ground level concentrations of particulate matter in the Clitheroe area.

REPORT

1. Introduction

1.1 Background

Castle Cement currently operates three cement kilns at its Works on the north east edge of Clitheroe in Lancashire. Two kilns (5 and 6) use the wet process and emit gaseous and particulate by-products through one stack, while kiln 7 uses the dry process and emits to the atmosphere through a separate stack.

All three kilns have been in operation together since 1983. During the period 1985-1993 there was a low frequency of complaints related to air pollution due to the Works averaging about 3 per year. In 1994 and 1995 there was a significant increase in the number of complaints, averaging 15 per month. This marked increase in complaints appears to have followed the introduction of recovered solvents (cemfuel) for partial firing of the kilns in 1992, which raised the public profile of the Works, although it did not markedly change the concentrations of the exiting gases and particles. Complaints have included eye and throat irritation, breathing difficulties and coughing, odour and visibility reduction.

In response to these complaints and to quantify the nature of any problem, air quality measurements were made in the vicinity of the works during August and September 1995, using mobile monitors and LIDAR ([1] and [2]). These measurements have confirmed the occurrence of plume grounding and odours, but have not shown any unequivocal exceedence of the 15 minute EPAQS standard for SO_2. More field measurements were recently conducted in October to December 1996, to provide further data on the dispersion of the plumes.

On 23 January 1996 HMIP issued Castle Cement with a variation condition for the Castle Works at Clitheroe in Lancashire. This included an improvement condition, which required Castle to investigate the constituents and behaviour of the plumes from the chimneys serving the kilns and to submit proposals, to be agreed in writing with the Chief Inspector, for improvements to the dispersion, visibility and odour of the plumes. These improvements had the following aims:

(a) to render the releases harmless and inoffensive by 31 December 1996; and
(b) to minimise the release of polluting substances.

1.2 Focus on Sulphur Dioxide and Particulates

This report details a comprehensive assessment of the impact of emissions from the site using dispersion modelling. Emphasis throughout is on the concentration of SO_2 and particulates, as these are the main polluting species emitted from the site and have been observed in concentrations near or above the appropriate EPAQS standards.

1.2.1 SO_2 is the main pollutant emitted from the kiln stacks and ground level concentrations close to the EPAQS standard (15 minute average of 100ppb) have been observed [1]. Additionally it has been observed that odour incidents have been associated with concentrations of SO_2 exceeding 50ppb, thus, calculation of exceedence of this value allows the incidences of odour to be predicted assuming this association to be true.

1.2.2 Particulates in the vicinity of the Works have been observed [1] to exceed the EPAQS standard (24 hour average of 50μg/m^3). These are emitted from the kiln stacks, mills and from the quarrying within the Works.

2. The Site

2.1 Topography

The Castle Cement Works are located on the north east edge of Clitheroe in the Ribble Valley in Lancashire at an altitude of approximately 90m (Figure 1). There is high ground both to the north and south east, the highest point being Pendle Hill which rises to 537m, some 450m above the Works and 6km to the east south east of the Works. An isometric projection of the site showing the main topographic features is given in Figure 2. A site plan showing the location of the various cement kilns is shown in Figure 3, and a more detailed illustration of the quarry topography is shown in Figure 4.

2.2 Climatology

There are no long term meteorological records inclusive of wind speed and direction from the Clitheroe area. However the climatology is likely to be broadly similar to that prevailing in the upland areas of north-west England, the principal local influence being the tendency of the Ribble Valley to channel the wind in the south-west or north-east direction. Figure 5 shows the locations of the nearest Meteorological Office sites to Clitheroe which are Wilsden, Blackpool (Squires Gate), Liverpool (Speke) and Manchester (Ringway). Figures 6(a-d) show long term average wind roses from each of the sites. These all exhibit significant local effects, the prevailing winds being respectively for each site, from the west south-west, west, south and west north-west. In view of the fact that Wilsden which is situated in the Pennines is closest to the Works, 35km, greatest use is made of data from this site, however, the sensitivity of long term concentration to met station location is investigated in this report. Of the four stations, only Manchester Ringway is still recording.

2.3 Sources

Emissions from the Castle Works are discussed in §3. Other local sources which need to be considered as part of an overall air quality assessment include ICI Kalalco (NO_2) and Tarmac (SO_2, NO_2, PM) which are immediately to the south-west and south-east of the Castle Works. Domestic sources of SO_2 and PM_{10} from Clitheroe also need to be considered since the area has not been designated a smokeless zone, and is thus still a potential source of SO_2 and particulates, particularly in the winter months. In this study, however, the focus is on emissions from the Castle Works alone.

3. Emissions

3.1 Current Emissions

Principal emissions of SO_2, particulates and NO_x from the Castle Works are from the combined stack for kilns 5 and 6 (wet stack), and the stack for kiln 7 (dry stack). Other emissions of particulates occur from the cement mills, which have a total of 10 stacks, and from the quarrying activity in the area.

Table 1 lists the basic parameters of each stack; these are stack location, height and diameter, volume flow rate and exit temperature, together with emission rates for SO_2, NO_x and particulates (kiln stacks) and particulates only (mills). Stack emissions monitoring in the summer of 1995 show that the tabulated rates are reasonably representative of measurements for the wet kiln, but during that period were an overestimate for the dry kiln. Emission rates for particulates for both kilns and mills are calculated from the maximum authorised concentrations. In the case of the kilns the relative contribution (% by volume) of N_2, O_2, CO_2 and H_2O to the exiting gases are also given.

3.2 Future Emissions

Alterations to the stack configurations assessed in this report are all concerned with proposed measures to reduce concentrations of SO_2. These include thirteen principal options, they are:

(i) increasing volume flow rate by the addition of Folax Effluent (Case 6)
(ii) scrubbing kiln 7 to reduce SO_2 emissions from that kiln (Case 7)
(iii) scrubbing kiln 7 and adding Folax Effluent (Cases 8 and 9)
(iv) scrubbing kiln 7 and adding a heat exchanger (Case 10)
(v) using a single combined stack for emissions from all three kilns (Cases 11, 12 and 13).

In the latter cases a maximum height of 220m for the combined stack is the highest that could reasonably be considered.

The stack and emission parameters of the cases considered are given in Table 2. There are currently no measures proposed for reducing SO_2 emissions from the wet stack.

Note: During the preparation of this report it was noted that a superceded value of dry stack diameter (2.3m) had been used in the calculations for Case 6 and Case 8. Subsequently, the calculations were redone using the revised diameter (3.2m), the results of which are presented in this report. It was observed that changes of up to 25% in concentration and probability results occurred due to changing the dry stack diameter to 3.2m for Cases 6 and 8.

4. Model Selection

4.1 Scientific Requirements

4.1.1 General Features

In this section we discuss the various features of a dispersion model which are required for the study and support our choice of model. A basic requirement is that any model used for the dispersion calculations must be soundly based scientifically. Much comment has been focused on the 'looping' and 'grounding' of plumes in the vicinity of the Works. These are processes which take place on scales of the boundary depth and thus require a model using a boundary layer parameterisation (based on boundary layer height h and Monin Obukhov length L_{MO}) rather than a model based on a surface layer parameterisation. Another key consideration is that a model used should have been subject to appropriate scientific evaluation. This includes assessment of the key elements of the model, verification that the code performs according to the specification, and validation of the model against data sets.

4.1.2 Specific Features

In addition to these general requirements there are also requirements specific to the modelling of emissions from the Castle Cement Works in Ribblesdale. These are as follows:

(i) Allowance for the effects of complex terrain. (Necessary to perform initial calculations of the effect of terrain on dispersion but concluded as non-essential for the bulk of this study.)

(ii) Calculation of concentrations for small averaging times when there are significant fluctuations about the ensemble mean are required for prediction of exceedence of the EPAQS standard for SO_2 or of odour. This requires a fluctuation module which allows calculation of the probability density function of concentration. (It is not possible to calculate precisely the transport and dispersions of exiting gases because of inherent uncertainty caused by turbulence, unless the turbulence is resolved explicitly which is not possible with current computer model technology in a practical model - hence the need for a probabilistic approach.)

(iii) The model must include an instantaneous plume model to allow calculation of the effects of evaporation/condensation on plume buoyancy.

4.2 Model Options

There are three principal models currently used for calculating dispersion from point sources in the UK:

(i) The NRPB report R-91 [Clarke 1979] has been used as a basis for many computer codes. Algorithms from this and subsequent reports allow treatment of the dispersion of buoyant point sources; however they are based on the Pasquill Stability approach, which is a surface layer parameterisation of the atmospheric boundary layer; there is no allowance for complex terrain nor fluctuations of concentrations about ensemble means. The DISTAR model written by CERC is an R-91 model.

(ii) ISC (Industrial Source Complex) is the US-EPA preferred model for buoyant releases from point sources. The model has a similar basis to R-91. There is no allowance for fluctuations about the mean or averaging times of less than 1 hour, and while complex terrain is considered, the treatment is very simplistic with no calculation of the effect of the underlying terrain on the mean airflow or turbulence.

(iii) ADMS (Atmospheric Dispersion Modelling System) has been developed by CERC with technical assistance from National Power and the Meteorological Office. It is a more recent model than R-91 and ISC using as its basis boundary layer scaling. It also includes in its options all of the requirements discussed in §4.1 above. The model has been subject to extensive evaluation and validation [3] and has been found to perform well for low and high level sources. ADMS is the only operational model available which can calculate fluctuations of concentrations. For these reasons the model is used throughout the current study. For comparison purposes only, long term average concentrations are in some cases calculated using R-91 and ISC.

4.3 Local Testing

In view of the significant interest in dispersion from the Castle site, HMIP commissioned NPL (National Physical Laboratory) to conduct two separate studies related to plume dispersion and grounding in late summer 1995. In the first study [1], NPL made ground based measurements over periods of a few hours of sulphur dioxide, nitrogen oxides and particulates using a mobile laboratory in response to reports of grounding/odours communicated to a 24 hour hotline. In the second study [2], measurements of plume concentration were made with a DIAL (Differential Absorption Lidar). Results from the first study have been used here for in situ comparisons with ADMS. These comparisons have used NPL measurements made on a 1 minute resolution. Given that comparisons are only being made between ADMS and measured data at one location, it is not possible to conduct a comprehensive validation of the model (this would require arrays of monitors to pick out the meandering of the plumes). However the comparisons undertaken here do provide a useful indication of model performance and add confidence to our use of the model at the site.

Five periods (two on the same day) in August 1995 during the period of the NPL measurements were selected based on the higher concentration measurements being made on those days (Table 3). The periods covered measurements at five sites whose locations are shown in Figure 7. The prevailing weather conditions were predominantly hot and sunny, so the boundary layer was very unstable resulting in rapid vertical and horizontal dispersion and grounding events quite close to the sources. Such conditions generally result in large variations in concentrations at a particular receptor point.

Table 3 Periods of High Recorded Concentration From the NPL Monitoring, Summer 1995

Event No	Date	Test Time	Site	Bearing and Distance from Works
1	7/8/95	15:30 - 18:15	Clitheroe Cemetery	227° 1375m
8	16/8/95	12:40 - 16:00	Chatburn Police Station	9° 2550m
11	18/8/95	12:40 - 13:40	Moorland School	220° 650m
		14:40 - 17:20	Waddington & West Bradford Primary School	298° 1375m
12	20/8/95	11:00 - 12:30	Waddow Hall	242° 1675m

Pollutant emission rates were obtained from in-stack concentration measurements made at 10 minute intervals (using on-line continuous monitors). Emission rates were assumed to be constant over each 10 minute period. Wind speed and direction were also averaged over each 10 minute period. Ten minute average concentrations calculated at receptor points were assumed to correspond to each period of 10 minutes commencing when the emission measurement was made. No account has been taken of the lag time of the plume reaching the receptor.

ADMS was used to calculate both the 10 minute average concentration and also the very short term, 95th percentile of 1 minutes averages, ie the 1 minute average concentration which is exceeded for 5% of the time, giving an indication of the expected variability in the observed concentrations; the latter calculation was performed using the fluctuation module of ADMS. For each period, calculations were made first using the complex terrain option with the measured wind direction and secondly the flat terrain option to predict concentrations below the plume centreline. The first calculation would be expected to give more accurate predictions, but only if the measured wind is representative of the wind direction in the area unaffected by complex terrain. The second (flat terrain) calculation provides an approximate upper bound estimate of the concentrations, assuming the wind direction is straight from the stacks to the receptor (the complex terrain option could not be used for calculating this upper bound as concentrations below the plume centreline are not readily output when this option is used).

The Figures (9-12) show for each period meteorological parameters, emitted concentrations of SO_2, measured concentrations at the mobile sites (10 minute mean and raw 1 minute averages) and finally calculated concentrations (10 minute means, 95th percentile of 1 minute means for each 10 minute period). Considering first the calculations using complex terrain, we see that where the model is predicting non-zero concentration (the wind is blowing from the stacks to the receptors) then the measured 10 minute mean is generally similar to the predicted mean and is less than the predicted 95th percentile. An exception is on 16.8.95 (Figure 10b) at Chatburn Police Station where observed peaks are higher than the 95th percentile. The graphs showing flat terrain centreline concentrations generally indicate (eg 18.8.95, 12.40-13.40; 20.8.95, 11.50-12.30) that periods where the complex terrain calculations show zero concentrations are a consequence of the wind direction being affected by the terrain. Figure 8(a) below illustrates how for a given wind direction and a single receptor location the plume trajectory can be influenced by the local complex terrain; the exact location of the plume is very sensitive to the specified wind direction. As a result, the plume centreline may not pass over the receptor and measured concentrations are very low. The latter case Figure 8(b) illustrates the plume trajectory over flat terrain when the plume centreline maximum concentration occurs at the receptor with the wind blowing directly from the source to the receptor; this gives an upper bound to the concentration measurements.

4.3.1 Probability Distribution Functions

As a further method of comparing model predictions with data, Probability Distribution Functions (PDFs) have been constructed. PDFs constructed from measured values make use of 1 minute averages. For those constructed from model predictions the fluctuation model is used with an averaging time of 1 minute to calculate the probability distribution of the concentration from each stack. There is no definitive method for summing the probabilities of exceedence for the two stacks operating concurrently. However, for the five periods used in the validation exercise, either:

(a) one of the two stacks was the dominant emitter of SO_2 (16.08.95 and 20.08.95), or

(b) both stacks were emitting low concentrations simultaneously (7.08.95 and 18.08.95).

It was decided simply to sum the PDF values from each stack in order to assess the total probability of exceeding chosen concentrations on each day.

In (a) the difference between the two stack emissions is large, so summing them does not change the general pattern of the PDF. In (b) both emissions are small, so summing the PDF's produces very little change to the overall pattern, ie that ADMS is broadly predicting similar PDF's to the monitored data.

Each curve in Figure 13 shows the probability, over the period of measurements, that a particular concentration is exceeded. Background concentrations are estimated at 1ppb in each case. Given the difficulty of making comparisons of concentrations at one point and because of the sensitivity to wind direction there is close similarity between the curves.

In the comparisons with measured data the model performed well. The fluctuation module of ADMS is particularly useful in predicting concentrations for comparison with short time period measurements.

5. Preliminary Calculations and Modelling Plan

In advance of undertaking the comprehensive series of calculations described in sections 6-8, some preliminary calculations were performed to assess the influence of various special features likely to influence dispersion from the Works, and to help with planning the main calculations.

5.1 Effects of Complex Terrain

As discussed in §2, the topography in the Ribble Valley area is quite complex, while the quarry to the north-east of the site has a maximum depth of 70m. A broad indication of the effect of complex terrain is presented in a series of contour plots of ground level concentrations for a range of boundary layer stabilities (equivalent to convective, neutral and stable) for three different wind directions. The plots are shown in Figures 14 to 16. Except for the stable cases where the complex terrain can affect the position of the plume, the influence of complex terrain is not large, and in particular the quarry has only a limited effect. Except in stable conditions the introduction of complex terrain causes small changes to the plume direction (<5%) and changes in the maxima are less than 20%. The maxima are reduced in convective conditions and increased in neutral conditions. In stable conditions, the concentrations are several orders of magnitude less than in convective and neutral conditions and occur outside the area of complaints (ie >10km from the Works).

Figures 17 and 18 contrast contour plots of annual average ground level concentrations of SO_2 due to emissions from the dry kiln stack with and without the effects of complex terrain included in the model runs. These show that the effect of the complex terrain is to reduce the maximum annual average concentration by 9%, although the maximum still occurs in the same location around Chatburn and the spatial pattern of the contours is very similar. There is some tendency for the regions of higher concentrations to be more confined within the Ribble Valley with an axis more in the SW-NE direction when the complex terrain is considered. Because long term average calculations taking account of complex terrain require much more computer time than flat terrain runs, and the effects on long term averages are small, the other long term average calculations shown in this report are made without considering the underlying topography. However all short term average calculations take account of the complex terrain and flat terrain is also used in some cases for comparative purposes.

5.2 Effects of plume water contents on ground level concentration

One author (Harrison 1996 [4]) has raised the possibility that the effect of water vapour emitted from the kiln stacks could lower the height of the plume and thus increase the frequency of grounding and the ground level concentrations, the reasoning being that evaporation of the plume liquid water reduces its buoyancy. The fact that the stack exit temperatures of the plumes are greater than 100°C, ensuring that condensation takes place after stack exit, would seem to refute this suggestion since the plume will gain buoyancy due to condensation before loosing buoyancy to evaporation. However, calculations were performed using a slightly modified version of ADMS which included the effect of plume moisture on plume height and concentration to assess the magnitude of any effects. Figures 19 - 21 show the effects on ground level concentration, plume height and associated liquid water content of inclusion of water effects (both the effects of the density of water vapour and liquid water droplets, and evaporation/condensation are included) for kiln 7, kilns 5 and 6, and also the scrubbed kiln 7 option (see §5). The model has been run assuming flat terrain, but complex effects will not significantly influence the conclusions as indicated by the results presented in §5.1. Results are presented for 2 conditions, neutral flow, with a temperature of 3°C and relative humidity of 90% and unstable flow with a temperature of 15°C and a relative humidity 50%. The possibility of doing similar calculations for stable conditions was also considered, but it was found that there was no ground level concentration in flat terrain within the calculation domain (>10km from the Works), and so no results are presented for these conditions.

The calculations show that in unstable conditions for the stacks in their current modes of operation, the effect of allowance for liquid water and water vapour increases the plume height and decreases the maximum ground level concentration, the density of the plume being significantly reduced by water vapour while no condensation takes place. In neutral conditions the presence of liquid water and subsequent evaporation offsets the effect of water vapour with concentrations being slightly increased. In order to show the possible effect of "sagging" of a wet plume, one of the situations modelled is for a plume from the scrubbed kiln 7, exiting the stack at a temperature less than 100°C ie 60°C so containing condensed water. This situation corresponds to Case 7. The effect of evaporation on the buoyancy of the plume is not compensated for by the condensation and the plume sinks significantly in neutral conditions. Note however that the temperature of the effluent gases could be raised above 100°C at the stack exit and thus sinking of the plume can easily be avoided in practice.

5.3 Modelling Plan

We have established that the ADMS model is an appropriate model with which to conduct the calculations, and we have determined the extent to which the effects of complex terrain and in plume condensation/evaporation are important. This enabled us to construct a modelling plan, the implementation of which is shown in §§6-8. As previously discussed, the emphasis of the calculations is on sulphur dioxide; for this gas we have calculated both short term and long term average concentrations in §6. We have not further considered plume condensation/evaporation, but effects of complex terrain are considered for the short term average calculations. They are not considered for the long term average calculations as we have shown that its impact is minor (<10%) for annual averages.

Calculations of concentrations of NO_x have focused on the current mode of operation at the site, as this pollutant is of secondary importance and there are no proposed changes in emissions. Calculations of particulates have focused on 24 hour (daily) averages (ie midnight to midnight) for both current and proposed cases since the facility to calculate 24 hour rolling averages is not available in the model (this is explained in more detail in §7.2).

N.B. The focus of the calculations in this study is on the impact of Castle Cement sources. In general the impact from other background sources are not considered.

5.4 Model Version

ADMS version 2.02.3 has been used for all the calculations in this report.

5.5 Calculation Areas and Grid Spacing

5.5.1 Area of terrain included when calculating the effects of hills on short term averages at Chatburn and Grindleton

When calculating short term average concentrations and probabilities of exceeding certain limits, the area of terrain considered was 16km×16km centred around the dry stack at Castle Cement. Results were obtained at two specific receptor locations at Chatburn and Grindleton.

5.5.2 Area of terrain included when comparing the effects of complex and flat terrain for stability categories B, D and F.

When comparing the effects of complex terrain and flat terrain on ground level concentration of SO_2, in stability categories B, D and F, the area of terrain included was 24km×24km centred around the dry stack at Castle Cement. The grid spacing was 700m. This larger area was used in order to try and locate the area of maximum concentrations in stable conditions.

5.5.3 Area used when calculating long term averages with and without complex terrain

For each of the long term average calculations carried out in this report a calculation grid of 12.5km×12.5km with 500m spacing centred around the dry stack at Castle

Cement was used. When complex terrain was included, the area of terrain was 16km×16km.

5.5.4 Spacing used when calculating plume centreline concentrations in flat terrain

The grid spacing used varied depending on the stability category being modelled. In general, it was 25m for category A, 100m for categories B, C and D and 4000m for category E. The varied grid spacing ensured that maxima in concentrations could be clearly identified.

6. Sulphur Dioxide and Odour

6.1 Limits and Guidelines

Most interest in sulphur dioxide concentration in the Clitheroe area has focused on short averaging times, in particular the 15 minute average corresponding to the EPAQS standard (100ppb). We highlight this averaging time since adherence to the EPAQS standard will imply adherence also to the various other short term limits and standards. We also calculate 1 hour averages for comparison with the WHO guideline, which although out of date is often used for comparative purposes. Long term averages are also calculated for comparison with WHO and EU guidelines which illustrate the long term impact of the site in its current and proposed modes of operation. For the purpose of predicting odour, we calculate probability distributions of 1 minute averages and use the fact that exceedence of the concentration of SO_2 of 50ppb (as measured with a 1 minute averaging time) has been found to correspond to the occurrence of odour.

Table 4 Limit and Guideline Values for SO_2

Limit or Guideline	Averaging Time	Value
EPAQS	15 minute	100ppb; 270μg/m³
UKNAQS	15 minute	100ppb 99.9th percentile**
WHO	10 minute *Hourly Annual	500μg/m³ 100ppb (270μg/m³) 50μg/m³
EU	24 hour Annual	98th percentile** 350μg/m³ 40-60μg/m³
US NAAQS	Annual	80μg/m³

*Historical, not listed in WHO latest set of guidelines.
**Percentile based on annual datasets.

The Limit and Guideline terms are described in the Glossary.

6.2 Short Term Averages

6.2.1 Current Mode of Operation

We first present some calculations using the flat terrain module of ADMS to give a general picture of how the ground level concentration of sulphur dioxide (SO_2) varies with distance from first the dry kiln stack emission (kiln 7) and then the wet kiln stack emission (kilns 5 and 6) for a range of different weather conditions. The model is used to calculate the ensemble mean over 15 minutes and also the concentration averaged over 15 minutes that is exceeded for 5% of 15 minute periods due to short term fluctuations. The latter quantity is calculated using the concentration fluctuation module and is included to give a more complete picture of where and in which meteorological conditions exceedences are most likely to take place. This value is referred to as the peak 15 minute concentration.

Figures 22 and 23 show that the highest ensemble mean and the peak 15 minute average concentrations occur in the most unstable conditions (very infrequent occurring on typically a few hours per year in Ribblesdale). In these conditions the ensemble and peak maxima are both predicted to exceed the EPAQS standard of 100ppb (≡270μg/m^3 at 1013mb and 15°C) but over rather a small area (up to 1km downstream) for each stack. As the conditions become less unstable the area of maximum impact moves downstream and becomes less localised, the ensemble mean maximum occurring further downstream than the peak maximum; the maxima also decrease in magnitude. Changes in concentration are greater than an order of magnitude at the transition between neutral and stable conditions. Between neutral and unstable conditions the changes are smaller (about 50%).

6.2.2 Concentrations at Chatburn and Grindleton

6.2.2.1 Current Mode of Operation

In the next set of calculations, ADMS is used to predict concentrations of SO_2 at two key inhabited locations where significant concentrations are expected in some weather conditions and from where a number of complaints have been received. In order to examine a range of features we have calculated concentrations and the probability of exceedence of different concentrations for a range of averaging times; these are:

(i) mean concentration (10 minute average) and probability of exceedence of 50ppb (135μg/m^3) for a 1 minute averaging time, 50ppb being recognised as the concentration of SO_2 which corresponds to detection of odour. Detection of a 50ppb SO_2 concentration signifies that the concentration of the odorous gas emitted from the stack or created after stack exit exceeds its odour threshold,

(ii) mean concentration (15 minute average) and probability of exceedences of 100ppb (270μg/m^3) for 15 minute averaging times corresponding to exceedence of the EPAQS standard for SO_2,

(iii) mean concentration (60 minute average) and probability of exceedences of 100ppb (270μg/m^3) for 60 minute averaging times corresponding to the now out of date WHO guideline for SO_2 and used here for comparitative purposes.

Table 5 shows the range of meteorological parameters used in ADMS for these calculations. These parameters approximately represent the Pasquill Stability Classes A-F.

Tables 6 - 7 show calculated concentrations and probabilities of exceedences for the three averaging times detailed above assuming that the wind direction is from the works to the receptor for the range of prevailing meteorological conditions approximately corresponding to Pasquill Stability Categories A through to F (very unstable to stable). The most stable conditions G were omitted since in these conditions, no ground level concentrations were predicted within 10km of the stack.

We have considered in turn the effects of the dry stack (kiln 7) and the wet stack (kilns 5&6) both together and singly at Chatburn, some 2km to the east north-east of the site, and at Grindleton, 2.5km to the north-east of the site.

Considering first the 10 minute average and 1 minute fluctuations we see that the 10 minute average does not exceed the odour threshold of 50ppb for either the wet or dry stack although the sum of the contributions from the two kilns does exceed 50ppb in some stability conditions. However, probabilities of exceedence of 50ppb of 1 minute average concentrations are significant for a range of unstable flows (not the most unstable) and neutral flow, at both Grindleton and Chatburn, even when only one kiln is emitting to the wet stack. The reason why significant exceedences of 50ppb are likely with only one kiln emitting through the wet stack is that the plume rise is reduced compared to that when both kilns (5 and 6) are emitting. This causes the zone of higher probability of exceedences to move closer towards Chatburn and Grindleton.

Probabilities of exceedence of the EPAQS limit for 15 minute averages are much lower, but nonetheless significant (eg in slightly unstable flows (stability category C)) the model predicts that the standard will be exceeded over 3% of the time at Chatburn when the current dry kiln is in operation with only kiln 6 emissions through the wet stack when the wind is blowing towards Chatburn. Some calculations were repeated, this time without effects of complex terrain. The results are shown in Tables 8 and 9. The probabilities of exceedence show very little change (<5%) when flat terrain is modelled which implies that terrain causes little change to plume trajectories between the Castle Works and the 2 villages.

6.2.2.2 Proposed Future Modes of Operation

Tables 10 and 11 show the effects at Chatburn and Grindleton of the various stack options discussed in §3. Considering the dry stack only (kiln 7), we see that the addition of the folax effluent (case 6) has little effect on the probability of exceeding the EPAQS limit, compared with the current mode of operation (Case 1). By contrast the various scrubber options (Cases 7-10) all eliminate exceedences of the EPAQS standard, and reduce the probability of exceedence of the odour threshold to insignificant values (ie reduce them from up to 18% to <1%). In these calculations we have ignored the effect of evaporation/condensation on the plume trajectory, it being assumed that acceptable options will have effluent temperatures of >100°C. It must be noted that exceedences due to the wet kiln would still occur regardless of which of the proposed modes of operation of kiln 7 were used.

Emitting all the effluent gases out of one stack also decreases ground level concentrations and the number of exceedences at both sites, however, even in the case of the highest practicable stack (220m) significant odour nuisance is still likely to occur at Chatburn (11%) and Grindleton (22%) in slightly unstable conditions.

6.3 Long Term Averages

6.3.1 Current Mode of Operation

Long term (annual average) concentrations of SO_2 have been calculated using ADMS and 3 different data sets (Wilsden, Blackpool Squires Gate and Manchester Ringway) for kilns 5, 6 and 7 operating separately and together. Contours of concentration are shown superimposed over maps of the area for Wilsden meteorological data (Figures 24 - 27), while contour plots alone are shown for Squires Gate and Ringway meteorological data (Appendix A). Additional runs were performed using DISTAR and ISC for Wilsden meteorological data. Contour plots of these are shown (Appendix B).

Tables of maximum concentrations and their location are also shown for each case (Table 12). The maps and tables show that the dry kiln gives the greatest contributions to the annual average, the maximum contribution ranging from 3.96μg/m^3 (1.5ppb) to 6.48μg/m^3 (2.4ppb) depending on the meteorological data used. The wet kiln's contribution ranges from 2.7μg/m^3 (1ppb) to 5.2μg/m^3 (2ppb). The DISTAR model leads to significantly lower maximum concentration (maximum 6.3μg/m^3 as opposed to 11.6μg/m^3 for all stacks), however the maximum occurs over a much larger area much further downstream. The ADMS model predicts cumulative maxima due to all stacks of 10.6μg/m^3 with complex terrain and of 11.6μg/m^3 with flat terrain; this shows that the effect of complex terrain on annual average concentrations is small.

6.3.2 <u>Future Mode of Operation</u>

The maps (Figures 28 - 35), contour plots (Appendix C) and Table 13 show the effect on long term average concentrations of the various options for reducing the impact of kiln 7 and using one stack for all emissions. All the scrubbed kiln 7 options (Cases 7-10) lead to a greatly reduced impact of SO_2 from kiln 7 (reduced by up to 89%). The combined stack also reduces the total impact of SO_2, for the 160m stack by 75% and for the 220m stack by 85% although in these cases the reduced impacts are spread over a much larger area than for the scrubbed kiln 7 options.

7. Particulates

7.1 Standards and Criteria for Averaging Times

By far the most stringent air quality standard for particulates is the UK NAQS standard for PM_{10} which is that the 99th percentile of the 24 hour running average of PM_{10} should not exceed 50µg/m^3 (see Table 14). Accordingly the maximum 24 hour (daily) average (ie midnight to midnight) has been calculated for all sources in their current mode of operation. For the purposes of assessment of the effect of the proposed small changes in particulate emissions from the dry kiln, annual average concentrations are also calculated for the current and proposed site configurations.

Table 14 Limit and Guideline Values for Particulate Matter

Limit or Guideline	Average Time	Value
EPAQS	24 hour running mean	50µg/m^3
UK NAQS	24 hour running mean	50µg/m^3 99th percentile*
WHO	No Guideline	-
EU	24 hour	98th percentile* 250µg/m^3
US NAAQS	Annual 24 hour	50µg/m^3 150µg/m^3

*Percentiles based on annual datasets.

7.2 Short Term Concentrations

Ideally, 24 hour rolling averages (overlapping periods of 24 hours) would have been calculated for direct comparison with EPAQS, but this facility was not available in ADMS version 2.02.3. In these circumstances it was decided to estimate relevant PM_{10} levels by calculating daily (midnight to midnight) average concentrations, which is a facility in ADMS version 2.02.3.

A contour map of the maximum 24 hour (daily) concentrations due to all point sources on the site and using sequential meteorological data from Manchester Ringway for 1995 is shown in Figure 36. The maximum value is 31.8µg/m^3. For cement mills only the maximum was

31.6μg/m^3 (Figure 37). The calculation was repeated for data from Blackpool Squires Gate for 1990 and the results for all point sources and cement mills only are shown in Figures 38 and 39 (Wilsden met data could not be used because the data are collected on a three hourly basis). The maximum value for all sources in this case is 27μg/m^3, and 23.6μg/m^3 for cement mills only. (Note that the maximum concentrations recorded from the stacks only and the cement mills do not simply sum as they occur at different locations. This is because the stacks are higher with more buoyancy and their maximum occurs further away from the source.) Both values are less than (about half) the EPAQS standard, however the quarry and other sources may of course have a significant influence and these are not included in the calculations. It can be observed that the contribution from the stacks to the maximum concentration is small (ie 0.2μg/m^3 of 31.8μg/m^3 for Ringway meteorology and 3.4μg/m^3 of 27μg/m^3 for Squires Gate meteorology) and proposed changes to the stack emissions will not affect the maximum. For this reason no further calculations for future configurations have been performed.

7.3 Long Term Averages

Maps of annual average concentrations calculated using Wilsden meteorological data are shown in Figures 40 - 45. Maximum annual averages are tabulated in Table 15. The maximum annual average for all emissions in the current mode of operation is 5.3μg/m^3 using Ringway met data, but only 2.44μg/m^3 for Wilsden met data and only 2.14μg/m^3 for Squires Gate met data. The proposed emissions changes to the kiln stacks have only a minor effect since we can see from Table 15 that the stacks contribute only a small amount (<20%) to the maximum concentration downstream.

8. Nitrogen Oxides (NO_x)

8.1 Standards and Averaging Times

Relevant air quality standards for 1 hour averages and NO_2 are shown in Table 16.

Table 16 Limit and Guideline Values for NO_2

Limit or Guideline	Averaging Time	Value
EPAQS	1 hour	150ppb
UK NAQS	1 hour	150ppb maximum
WHO	1 hour	200μg/m^3
EU	98th percentile* of 1 hour means	200μg/m^3
US NAAQS	Annual mean	100μg/m^3

*Percentile based on annual datasets.

Long term guidelines are approximately 20ppb for each of EPAQS, WHO and EU limits. Both short term (1 hour) and long term (annual averages) have been calculated for each of the kilns.

For the purposes of calculating and presenting model results, it is assumed that all NO_x occurs as NO_2 as a worst case assumption.

8.2 Short Term Averages

Figures 46 - 47 show 1 hour mean concentrations of NO_x as a function of distance downstream of first the dry then the wet kiln for a range of weather conditions; the 95th percentile of concentration calculated using the fluctuation module of ADMS for a one hour averaging time is also shown. Except in strongly unstable conditions (A and B) there are no predicted exceedences of the concentration of NO_x of the WHO guideline for NO_2 (the most stringent standard). Given that only a minor proportion of NO_x is actually likely to be NO_2 (most will be NO) where the maximum occurs, the standard is very unlikely to be exceeded even in these conditions. For class A, up to 20% of NO_x can be NO_2 without any exceedence (at the 95th percentile of fluctuations) and similarly for class B, up to 50%.

8.3 Long Term Averages

Long term average concentrations of NO_x are shown in Figures 48 - 52 (Appendix D for ISCLT3 calculations) and in Table 17. Comparing the maximum annual average concentration, 6.07μg/m^3, with the maximum obtained when complex terrain was modelled, 5.5μg/m^3, it can be seen that the effect of complex terrain is small in this case. Current emissions from the stacks result in maximum long term averages which are small (ie <10%) of the air quality standards. This is based on the assumption that all the NO_x is NO_2. In reality a significant proportion of the total NO_x emitted will generally remain as NO within a few kilometres of the works.

9. Conclusions

9.1 Validation of ADMS in situ supports the use of ADMS for calculating concentrations due to emissions from the Castle Cement Works.

9.2 The modelling shows that the EPAQS standard for SO_2 is likely to be exceeded due to current emissions from the Works.

9.3 The introduction of a scrubber in the dry kiln stack is predicted to bring probabilities of exceedences of the EPAQS standard for SO_2 and odours due to emissions from that stack to very low levels under most meteorological conditions. The conclusions for odour assume that scrubbing will abate odour emissions in line with those of SO_2.

9.4 Exceedences of the SO_2 EPAQS standard and odour events will continue to occur at Chatburn and Grindleton due to emissions from the wet kiln stack. However, exceedences due to the dry stack will decrease significantly if certain proposed options are adopted, in particular the options for scrubbing the dry kiln (Cases 7-10). Future modelling should include modelling at site(s) further downstream to investigate the possibility of exceedences at more distant locations.

9.5 The impact of the local complex terrain on occurrence of odour and exceedence of EPAQS standards is minor, increasing the probability of occurrence by <10% at both Chatburn and Grindleton.

9.6 Evaporation of in plume condensed water can lead to sagging of the plume for efflux temperature <100°C, thus the temperature of the exiting gases should be maintained above 100°C in order to prevent such effects.

9.7 The stacks contribute less than 15% of the maximum 24 hour (daily) mean concentration of particulates. Point sources alone do not result in exceedence of the EPAQS standard of $50\mu g/m^3$ over 24 hours (midnight to midnight).

9.8 The maximum annual average concentration of NO_x due to current emissions from the stacks is less than 10% of current air quality standards for NO_2.

10. Glossary

DIAL	-	Differential Absorption Lidar
DISTAR	-	Dispersion model based on NRPB report R-91
Ensemble Mean	-	Mean that is obtained from conducting a large number (tending to infinity) of experiments with the same set up conditions, in this case the same hourly averaged met data and stack parameters, and taking the average. The values obtained from each experiment are not identical because within each hour although the meteorology and stack parameters are the same the details of the boundary layer turbulence vary.
EPAQS	-	Expert Panel on Air Quality Standards
EU	-	European Union
Fluctuation	-	The meteorology used as input to the model uses hourly averaged values. However, within each hour on timescales shorter than an hour the velocity at any point in the boundary layer varies and this causes the concentration values to fluctuate i.e. gives rise to fluctuations in concentration. The turbulence and hence fluctuations are best described statistically in terms of mean values and standard deviations
ISC	-	Industrial Source Complex (dispersion model)
LIDAR	-	Laser Detection And Ranging
NPL	-	National Physical Laboratory
NRPB	-	National Radiological Protection Board
UK NAQS	-	UK National Air Quality Strategy
US NAAQS	-	US National Ambient Air Quality Standards
WHO	-	World Health Organisation

11. References

[1] Monitoring of plume grounding events in the vicinity of the Castle Cement Works, Ribblesdale (7th August to 1st September 1995). December 1995. NPL Report Qu S 94.

[2] Measurements of Industrial Plume Dispersion at Ribblesdale, Lancashire using Differential Absorption Lidar Facility. December 1995. NPL Report Qu S 97.

[3] D.J. Carruthers, H.A. Edmunds, M. Bennett, P.T. Woods, M.J.T. Milton, R. Robinson, B.Y. Underwood and C.J. Franklyn. 1995. Validation of the UK-ADMS Dispersion Model and Assessment of its Performance Relative to R-91 and ISC using Archived Lidar Data. Study commissioned by Her Majesty's Inspectorate of Pollution (published by the Environment Agency).

[4] R.M. Harrison. 1996. An Evaluation of the Air Pollution Aspects of Castle Cement Limited, Ribblesdale Works near Clitheroe, Lancashire.

List of Tables and Explanatory Notes

Tables 1&2 show the current emissions data from the stacks at the Castle Cement Works and proposed variations to those emissions.

Table 3 shows the 4 periods during the summer of 1995 when monitoring carried out by NPL showed high recorded concentrations.

Tables 6-9 show the predicted mean ground level concentration of SO_2 and the probability of exceeding given concentrations under 6 met conditions: Pasquill Classes A-F.

In Tables 6-7 the effect of complex terrain is included for the 4 current different combinations of the wet and dry kiln operation, Cases 1-4, but in Tables 8-9 flat terrain is assumed. Results are given at the 2 sites of interest: Chatburn Police Station and Grindleton.

For the mean concentration 3 averaging times were considered: 60, 15 and 10 minutes with associated fluctuations averaging times of: 60, 15 and 1 minutes respectively. The calculation of the probability of exceeding the limit concentrations takes account of short term fluctuations.

Tables 10-11 show the predicted mean ground level concentration of SO_2 and the probability of exceeding given concentrations under 6 met conditions: Pasquill Classes A-F. Results are given for the 8 proposed variations to the kiln emissions, Cases 6-13.
The effect of complex terrain is included and results are given at the 2 sites of interest: Chatburn Police Station and Grindleton.

For the mean concentration 3 averaging times were considered: 60, 15 and 10 minutes with associated fluctuations averaging times of 60, 15 and 1 minutes respectively. The calculation of the probability of exceeding the limit concentrations takes account of short term fluctuations.

Table 10 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Chatburn Police Station for Pasquill Classes A-F, Complex Terrain: Cases 6-13

Table 11 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Grindleton for Pasquill Classes A-F, Complex Terrain: Cases 6-13

Tables 12-13: the maximum predicted annual average ground level concentration of SO_2 and the location of the maximum from combinations of current emission Cases 1-4, and proposed Cases 6-13.

3 different dispersion models have been used: ADMS, DISTAR and ISCLT for the current cases and 1 model, ADMS, for the proposed cases. The ADMS model was run using 3 different met data sets: Ringway, Squires Gate and Wilsden. For DISTAR and ISCLT Wilsden met data were used.

The effect of complex terrain is not included.

Table 12 Maximum Annual Average Ground Level Concentration of SO_2, and Location of Maximum, Calculated Using ADMS, DISTAR and ISCLT Dispersion Models, Met Data From Ringway, Squires Gate and Wilsden, Flat Terrain: Combinations of Cases 1-4

Table 13 Maximum Annual Average Ground Level Concentration of SO_2, and Location of Maximum, Calculated Using ADMS, Met Data From Ringway, Squires Gate and Wilsden, Flat Terrain: Cases 6-13

Table 14 Limit and Guideline Values for Particulate Matter.

Table 15 shows the maximum predicted annual average and 24 hour average ground level concentration of Particulates and the location of the maximum from combinations of current emission Cases 1-4

The ADMS model was run using 3 different met data sets: Ringway, Squires Gate and Wilsden. The effect of complex terrain is not included.

Table 15 Maximum Annual Average Ground Level Concentration of Particulates, and Location of Maximum Calculated Using ADMS, Met Data From Ringway, Squires Gate and Wilsden: Combinations of Cases 1-4, & 6-13

Table 16 Limit and Guideline Values for NO_2. *(Inserted in the text)*

Table 17 shows the maximum predicted annual average ground level concentration of NO_X and the location of the maximum from combinations of current emission Cases 1-4.

3 different dispersion models have been used: ADMS, DISTAR and ISCLT. The ADMS model was run using 3 different met data sets: Ringway, Squires Gate and Wilsden. For DISTAR and ISCLT Wilsden met data were used. The effect of complex terrain is not included.

Table 17 Maximum Annual Average Ground Level Concentration of NO_X, and Location of Maximum Calculated Using ADMS, DISTAR and ISCLT Dispersion Models, Met Data From Ringway, Squires Gate and Wilsden, Flat Terrain: Combinations of Cases 1-4

List of Figures and Explanatory Notes

Figure 8: Comparison of plume trajectory with and without the effect of hills.

Figures 9-13 refer to the 4 events, Table 3, during which high concentrations were measured. Each of Figures 9-11 shows the met parameters, emitted concentrations of SO_2, measured concentrations and calculated concentrations during one of the events. The averaging time is 10 minutes and the fluctuations averaging time is 1 minute. Figure 13 shows the probability of the predicted 1 minute concentrations of SO_2 exceeding a range of values during each of the 4 events.

Figure 10(b) Measured and Predicted Concentrations of SO_2 at Chatburn Police Station, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute: 16/08/95

Figure 11(a) Met Parameters at Moorland School and Waddington & West Bradford Primary School and Emitted SO_2 : 18/08/95

Figure 11(b) Measured and Predicted Concentrations of SO_2 at Moorland School and Waddington & West Bradford Primary School, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute:
18/08/95

Figure 12(a) Met Parameters at Waddow Hall and Emitted SO_2 : 20/08/95

Figure 12(b) Measured and Predicted Concentrations of SO_2 at Waddow Hall, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute: 20/08/95

Figure 13 Probability of the Concentration of SO_2 Exceeding Specified Concentrations at Various Distances from the Works During the Incidents of High Recorded Concentrations.

Figures 14-16: Investigation of the effect of complex terrain using the predicted SO_2 concentrations from the dry kiln, under met 3 conditions, Pasquill Classes B, D & F. Figures 14,15 & 16 shows the results with wind directions of 135° (south-easterly), 225° (south westerly) and 315° (north westerly) respectively.

Figure 14(a) Hourly Average Concentration of SO_2 from the Dry Kiln, Wind from South East (135°), Pasquill Class B
- (i) Complex Terrain Results Superimposed on a Surface Plot
- (ii) Complex Terrain Results Superimposed on a Contour Plot
- (iii) Flat Terrain Results

Figure 14(b) Hourly Average Concentration of SO_2 from the Dry Kiln, Wind from South East (135°), Pasquill Class D
- (i) Complex Terrain Results Superimposed on a Surface Plot
- (ii) Complex Terrain Results Superimposed on a Contour Plot
- (iii) Flat Terrain Results

Figure 14(c) Hourly Average Concentration of SO_2 from the Dry Kiln, Wind from South East (135°), Pasquill Class F
- (i) Complex Terrain Results Superimposed on a Surface Plot
- (ii) Complex Terrain Results Superimposed on a Contour Plot

Figure 15(a) Hourly Average Concentration of SO_2 from the Dry Kiln, Wind from South West (225°), Pasquill Class B
- (i) Complex Terrain Results Superimposed on a Surface Plot
- (ii) Complex Terrain Results Superimposed on a Contour Plot
- (iii) Flat Terrain Results

Figures 22-23: Variation of 15 minute average ground level concentration of SO_2 and the 95th percentile of 15 minute averages with distance downstream of the stack under 5 met conditions: Pasquill Classes A-E, and comparison with the EPAQS limit value of 100ppb. Figure 22 shows the results for the dry kiln, Case 1and Figure 23 the results for the wet kiln, Case 2. The calculation of the 95th percentile concentration takes into account the effect of short term fluctuations.

Figures 24-35: Annual average concentration of SO_2 around Castle Cements using Wilsden Met Data for cases 1-4 & 6-13. The effect of complex terrain has not been modelled.

Figures 36-39: 24 hour average concentration of Particulates from all the Castle Cement sources (Figures 36&38) and from the cement mill only (Figures 37&39). Figures 36&37 show the results using met data from Ringway and Figures 38&39 the results with Squires Gate.

Appendix A : Annual Average Concentration of SO_2, Cases 1-4, Met Data: Squires Gate, Ringway (Model: ADMS)

Figures A1-A2: Annual average plots of SO_2 for Cases 1-4 and (1+2) using met data from Squires Gate, Figures A1(a)-A1(e), and Ringway, Figures A2(a)-A2(e).

Appendix B : Annual Average Concentration of SO_2, Cases 1-4, Met Data: Wilsden (Models: DISTAR, ISCLT3)

Figures B1-B2: Annual average plots of SO_2 for Cases 1-4 and (1+2) using met data from Wilsden, and 2 different models: DISTAR, Figures B1(a)-B1(e), and ISCLT3, Figures B2(a)-B2(e).

Appendix D : Annual Average Concentration of NO_X, Cases 1-4, Met Data: Wilsden (Model: ISCLT3)

Figures D1-D2: Annual average plots of NO_X for Cases 1-4 and (1+2) using met data from Wilsden, modelled using the ISLT3 model.

TABLES

	Case 1	Case 2	Case 3	Case 4	Case 5					
					Cement Mills					
	Kiln 7	Kilns 5 & 6	Kiln 5	Kiln 6	Clinker Cooler Kiln 7	Cement Mills 1,2,4,5,6	Cement Mills 7 & 8	Cement Mills 9 - 11	Cement Mills Separator 9 - 11	Coal Mill 4
No. Release Points	1	1	1	1	1	5	2	1	1	1
Stack Height (m)	92	104	104	104	35	23	30	15	15	18
Diameter (m)	2.3	4.2	4.2	4.2	2.6	0.25	0.63	1.47	1.47	0.56
Volume flow at exit temp (m^3/s)	105	175	79.3	92.3	114.6	0.7	3.35	8.2	30	5.1
Exit temp (°C)	160	220	220	220	240	100	100	60	60	60
Efflux velocity at exit temp (m/s)	25.3	12.63	5.72	6.67	21.58	14	11	5	18	20
Nat Grid Coordinates N E	443621 375053	443577 374819	443577 374819	443577 374819	443621 375053	443694 -443712 374489 -374815	443718 -443731 374832 -374847	443874 374976	443851 374982	443714 374921
SO_2 (g/s)	168	218.5	100.9	117.6	0	-	-	-	-	-
Particulates (g/s)	7.3	8.8	4.0	4.6	3.1	0.035	0.035	0.41	1.5	0.255
NO_x (as NO_2) (g/s)	87.7	114	52.7	61.3	0	-	-	-	-	-
% H_2O	8.4	21.4	21.4	21.4						
% CO_2	27	28.4	28.4	28.4						
% N_2	56.6	43.3	43.3	43.3						
% O_2	7.9	6.9	6.9	6.9						
Exit concentration limit particulates (mg/m^3)	100	90	90	90	50	50	100	50	50	50

Table 1 Current Emissions for the Castle Cement Works

	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13
	Kiln 7 Folax Effluent	Scrubbed Kiln 7	Scrubbed Kiln 7 + Folax Effluent	Scrubbed Kiln 7 + $10m^3/s$ Folax Effluent	Scrubbed Kiln 7 + heat exchanger	Combined 104m	Combined 160m	Combined 220m
No. Release Points	1	1	1	1	1	1	1	1
Stack Height (m)	92	92	92	92	92	104	160	220
Diameter (m)	3.2	2.3	3.2	2.3	2.3	4.2	4.2	4.2
Volume flow at exit temp (m^3/s)	167	96.2	118.4	117.2	101.8	281.63	281.63	281.63
Exit temp (°C)	230	60	161	88	80	164	164	164
Efflux velocity at exit temp (m/s)	28.9	23.2	28.5	28.2	24.5	20.32	20.32	20.32
Nat Grid Coordinates N E	443621 375053	443621 375053	443621 375053	443621 375053	443621 375053	443577 374819	443577 374819	443577 374819
SO_2 (g/s)	168	16.8	16.8	16.8	16.8	306	306	306
Particulates (g/s)	16.4	3.7	6.7	4.2	3.7			
NO_x (as NO_2) (g/s)	87.6	87.6	87.6	87.6	87.6			
% H_2O	4.7	12.6	7.1	11.1	10.1			
% CO_2	14.9	28.0	14.7	23.1	26.6			
% N_2	65.6	53.6	63.6	56.4	55.3			
% O_2	14.8	7.6	14.4	9.4	7.5			

Table 2 Proposed Variations to Emissions Data from Castle Cement Works

(Tables 3 and 4 are inserted in the text)

Category	Stability	Wind Speed U(m/s)	Boundary Layer Height H(m)	Reciprocal of Monin-Obukhov Length $1/L_{MO}$ (m)	Typical Probability in the UK	Typical Conditions
A	Very Convective	1	1300	-0.5	< 1%	Warm sunny afternoons. Clear skies, light winds.
B	Convective	2	900	-0.1	few %	
C	Slightly Convective	5	850	-0.01	~10%	
D	Neutral	5	800	0	Several 10's%	Strong winds, cloudy skies, morning and evening.
E	Stable	3	400	0.01	~10%	
F	Very Stable	2	100	0.05	few %	Clear cloudless night skies. Low winds.

Table 5 Met Parameters Used in ADMS to Approximately Represent Pasquill Classes A-F

		Averaging Time (minutes)		Limit	Limit value ppb	Stability											
						A		B		C		D		E		F	
		Mean	Fluctuation			$\overline{C}$ ppb	probability of exceeding limit value	$\overline{C}$ ppb	probability of exceeding limit value	$\overline{C}$ ppb	probability of exceeding limit value	$\overline{C}$ ppb	probability of exceeding limit value	$\overline{C}$ ppb	probability of exceeding limit value	$\overline{C}$ ppb	probability of exceeding limit value
Case 1	Dry kiln 7	10	1	Odour	50	12.80	0.000	22.10	0.170	26.00	0.180	30.30	0.151	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	12.70	0.000	21.90	0.001	25.70	0.008	29.30	0.038	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	12.10	0.000	20.10	0.000	23.10	0.000	23.50	0.038	0.00	0.000	0.00	0.000
Case 2	Wet kiln (5+6)	10	1	Odour	50	15.50	0.000	24.30	0.190	26.90	0.180	22.00	0.090	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	15.50	0.000	24.00	0.002	26.50	0.015	21.20	0.040	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	14.70	0.000	21.90	0.000	23.50	0.000	16.30	0.024	0.00	0.000	0.00	0.000
Case 3	Kiln 5	10	1	Odour	50	7.10	0.000	12.10	0.016	13.70	0.112	15.10	0.109	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	7.00	0.000	11.90	0.000	13.50	0.000	14.50	0.001	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	6.70	0.000	11.00	0.000	12.10	0.000	11.40	0.000	0.00	0.000	0.00	0.000
Case 4	Kiln 6	10	1	Odour	50	8.30	0.000	14.10	0.036	15.80	0.129	16.20	0.110	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	8.24	0.000	13.90	0.001	15.60	0.030	15.60	0.070	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	7.84	0.000	12.70	0.000	13.90	0.000	12.20	0.000	0.00	0.000	0.00	0.000

Table 6 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Chatburn Police Station for Pasquill Classes A-F, Complex Terrain: Cases 1-4

		Averaging Time (minutes)		Limit	Limit value ppb	Stability											
						A		B		C		D		E		F	
		Mean	Fluctuation			$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value
Case 1	Dry kiln 7	10	1	Odour	50	14.00	0.000	24.20	0.201	28.10	0.175	31.70	0.140	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	14.00	0.000	24.00	0.006	27.70	0.018	30.80	0.057	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	13.40	0.000	22.00	0.000	24.90	0.000	24.80	0.000	0.00	0.000	0.00	0.000
Case 2	Wet kiln (5+6)	10	1	Odour	50	17.10	0.000	25.20	0.210	26.90	0.164	16.30	0.056	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	17.00	0.000	25.00	0.007	26.60	0.023	15.90	0.033	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	16.20	0.000	22.90	0.000	23.90	0.000	13.40	0.000	0.00	0.000	0.00	0.000
Case 3	Kiln 5	10	1	Odour	50	7.81	0.000	13.10	0.040	14.10	0.115	12.70	0.083	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	7.77	0.000	13.00	0.000	13.90	0.000	12.50	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	7.42	0.000	11.90	0.000	12.60	0.000	10.50	0.000	0.00	0.000	0.00	0.000
Case 4	Kiln 6	10	1	Odour	50	9.14	0.000	15.10	0.068	16.20	0.129	13.80	0.081	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	9.09	0.000	14.90	0.000	16.00	0.000	13.50	0.001	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	8.68	0.000	13.70	0.000	14.40	0.000	11.40	0.000	0.00	0.000	0.00	0.000

Table 7 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Grindleton for Pasquill Classes A-F, Complex Terrain: Cases 1-4

		Averaging Time (minutes)		Limit	Limit value ppb	Stability											
						A		B		C		D		E		F	
		Mean	Fluctuation			$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value
Case 1	Dry kiln 7	10	1	Odour	50	13.03	0.000	21.90	0.160	24.81	0.170	29.79	0.140	0.000	0.000	0.00	0.000
		15	15	EPAQS	100	12.90	0.000	21.60	0.001	24.44	0.007	28.81	0.040	0.000	0.000	0.00	0.000
		60	60	For Comparison	100	12.36	0.000	19.38	0.000	21.76	0.000	22.91	0.037	0.000	0.000	0.00	0.000
Case 2	Wet kiln (5+6)	10	1	Odour	50	15.83	0.000	24.07	0.180	26.01	0.170	23.25	0.094	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	15.72	0.000	23.79	0.002	25.60	0.014	22.40	0.042	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	14.95	0.000	21.66	0.000	22.56	0.000	17.30	0.031	0.00	0.000	0.00	0.000

Table 8 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Chatburn Police Station for Pasquill Classes A-F, Flat Terrain: Cases 1-2

		Averaging Time (minutes)		Limit	Limit value ppb	Stability											
						A		B		C		D		E		F	
		Mean	Fluctuation			$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value
Case 1	Dry kiln 7	10	1	Odour	50	14.11	0.000	23.97	0.200	27.77	0.170	31.44	0.140	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	14.04	0.000	23.72	0.010	27.37	0.020	30.44	0.060	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	13.43	0.000	21.79	0.000	24.43	0.000	24.39	0.000	0.00	0.000	0.00	0.000
Case 2	Wet kiln (5+6)	10	1	Odour	50	17.14	0.000	25.17	0.210	25.64	0.150	17.56	0.060	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	17.05	0.000	24.92	0.010	25.34	0.020	17.29	0.040	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	16.29	0.000	22.92	0.000	23.04	0.000	15.05	0.000	0.00	0.000	0.00	0.000

Table 9 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Grindleton for Pasquill Classes A-F, Flat Terrain: Cases 1-2

		Averaging Time (minutes)		Limit	Limit value ppb	Stability											
						A		B		C		D		E		F	
		Mean	Fluctuation			$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value
Case 6	Kiln 7 with folax cooler	10	1	Odour	50	12.92	0.000	20.59	0.150	23.84	0.166	20.91	0.097	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	12.85	0.000	20.37	0.001	23.50	0.006	20.21	0.027	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	12.27	0.000	18.68	0.000	21.08	0.004	15.98	0.013	0.00	0.000	0.00	0.000
Case 7	Scrubbed kiln 7	10	1	Odour	50	1.23	0.000	2.21	0.000	2.66	0.000	3.86	0.003	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.23	0.000	2.19	0.000	2.63	0.000	3.75	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.17	0.000	2.01	0.000	2.37	0.000	3.04	0.000	0.00	0.000	0.00	0.000
Case 8	Scrubbed kiln 7 with folax cooler	10	1	Odour	50	1.29	0.000	2.01	0.000	2.35	0.000	2.01	0.004	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.28	0.000	2.00	0.000	2.31	0.000	1.94	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.22	0.000	1.83	0.000	2.07	0.000	1.53	0.000	0.00	0.000	0.00	0.000
Case 9	Scrubbed kiln 7 with 10m³/s folax cooler	10	1	Odour	50	1.26	0.000	2.23	0.000	2.65	0.000	3.29	0.004	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.25	0.000	2.20	0.000	2.62	0.000	3.29	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.20	0.000	2.03	0.000	2.36	0.000	2.65	0.000	0.00	0.000	0.00	0.000
Case 10	Scrubbed kiln 7 with heat exchanger	10	1	Odour	50	1.25	0.000	2.22	0.000	2.67	0.000	3.61	0.003	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.24	0.000	2.20	0.000	2.64	0.000	3.50	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.19	0.000	2.02	0.000	2.38	0.000	2.38	0.000	0.00	0.000	0.00	0.000
Case 11	Combined stack 104m	10	1	Odour	50	21.90	0.000	32.00	0.280	35.40	0.190	24.30	0.070	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	21.80	0.000	31.70	0.260	24.90	0.060	23.30	0.070	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	20.70	0.000	28.80	0.000	30.90	0.000	17.90	0.000	0.00	0.000	0.00	0.000
Case 12	Combined stack 160m	10	1	Odour	50	22.00	0.000	30.40	0.260	28.10	0.160	7.80	0.020	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	21.90	0.000	30.10	0.170	27.70	0.030	7.47	0.020	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	20.80	0.000	27.40	0.000	5.55	0.000	0.00	0.000	0.00	0.000	0.00	0.000
Case 13	Combined stack 220m	10	1	Odour	50	22.00	0.000	28.60	0.040	19.04	0.110	1.12	0.020	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	21.90	0.000	28.20	0.012	18.71	0.010	1.06	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	20.86	0.000	25.70	0.000	16.33	0.000	1.03	0.000	0.00	0.000	0.00	0.000

Table 10 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Chatburn Police Station for Pasquill Classes A-F, Complex Terrain: Cases 6-13

		Averaging Time (minutes)		Limit	Limit value ppb	Stability											
						A		B		C		D		E		F	
		Mean	Fluctuation			$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value	$\bar{C}$ ppb	probability of exceeding limit value
Case 6	Kiln 7 with folax cooler	10	1	Odour	50	14.12	0.000	21.80	0.176	25.67	0.163	22.16	0.080	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	14.05	0.000	21.93	0.003	25.32	0.013	21.18	0.030	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	13.44	0.000	19.87	0.000	22.66	0.000	16.84	0.000	0.00	0.000	0.00	0.000
Case 7	Scrubbed kiln 7	10	1	Odour	50	1.36	0.000	2.48	0.000	2.97	0.000	4.13	0.007	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.35	0.000	2.46	0.000	2.93	0.000	4.02	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.29	0.000	2.26	0.000	2.64	0.000	3.27	0.000	0.00	0.000	0.00	0.000
Case 8	Scrubbed kiln 7 with folax cooler	10	1	Odour	50	1.43	0.000	2.13	0.000	2.51	0.000	2.03	0.000	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.40	0.000	2.11	0.000	2.48	0.000	1.96	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.34	0.000	1.94	0.000	2.22	0.000	1.55	0.000	0.00	0.000	0.00	0.000
Case 9	Scrubbed kiln 7 with 10m³/s folax cooler	10	1	Odour	50	1.39	0.000	2.46	0.000	2.89	0.000	3.58	0.007	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.38	0.000	2.44	0.000	2.85	0.000	3.48	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.32	0.000	2.25	0.000	2.60	0.000	3.02	0.000	0.00	0.000	0.00	0.000
Case 10	Scrubbed kiln 7 with heat exchanger	10	1	Odour	50	1.28	0.000	2.48	0.000	2.93	0.000	3.83	0.000	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	1.37	0.000	2.45	0.000	2.90	0.000	3.72	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	1.31	0.000	2.25	0.000	2.60	0.000	3.02	0.000	0.00	0.000	0.00	0.000
Case 11	Combined stack 104m	10	1	Odour	50	23.90	0.007	32.70	0.280	34.70	0.170	17.20	0.050	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	23.80	0.004	32.40	0.040	34.30	0.080	16.80	0.050	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	22.72	0.000	29.68	0.000	30.84	0.000	14.12	0.000	0.00	0.000	0.00	0.000
Case 12	Combined stack 160m	10	1	Odour	50	23.90	0.007	29.80	0.250	25.30	0.130	4.35	0.010	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	23.80	0.004	29.50	0.020	25.00	0.040	4.26	0.010	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	22.70	0.000	27.00	0.000	22.38	0.000	3.56	0.000	0.00	0.000	0.00	0.000
Case 13	Combined stack 220m	10	1	Odour	50	23.86	0.006	26.48	0.220	14.97	0.070	0.39	0.000	0.00	0.000	0.00	0.000
		15	15	EPAQS	100	23.73	0.000	26.19	0.020	14.75	0.010	0.38	0.000	0.00	0.000	0.00	0.000
		60	60	For Comparison	100	22.66	0.000	23.95	0.000	13.14	0.000	0.32	0.000	0.00	0.000	0.00	0.000

Table 11 Predicted Mean Ground Level Concentrations of SO_2 and Probability of Exceeding Limit Values at Grindleton for Pasquill Classes A-F, Complex Terrain: Cases 6-13

	Case 1					Case 2					Case 3					Case 4					Case (1+2)				
	Dry Kiln 7					Wet Kilns 5 + 6					Wet Kiln 5					Wet Kiln 6					All Kilns 7 + (5 + 6)				
	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCST Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden
Max Conc SO_2 (ug/m^3)	3.96	5.97	6.48	4.27	7.23	2.74	4.61	5.15	2.29	7.72	2.12	3.17	3.47	1.39	5.21	2.28	3.46	3.8	1.54	5.70	6.7	10.6	11.6	6.56	14.95
Distance & Bearing From Dry Stack (m)	1000 98°	1000 98°	1500 95°	7500 90°	2500 90°	1000 98°	1000 98°	1000 98°	4000 90°	2500 90°	1000 98°	1000 98°	1000 98°	4000 90°	2000 90°	1000 98°	1000 98°	1000 98°	4000 90°	2000 90°	1000 98°	1000 98°	1000 98°	6000 90°	2500 90°

Table 12 Maximum Annual Average Ground Level Concentration of SO_2, and Location of Maximum, Calculated Using ADMS, DISTAR and ISCLT Dispersion Models, Met Data from Ringway, Squires Gate and Wilsden, Flat Terrain: Combinations of Cases 1-4

The maximum annual average of SO_2 from all sources in complex terrain is 10.6μg/m^3 with Wilsden met. data.

	Case 5 Kiln 7 with Folax Cooler			Case 6 Scrubbed Kiln 7			Case 7 Scrubbed Kiln 7 with Folax Cooler			Case 8 Scrubbed Kiln 7 with $10M^3/2$ Folax Cooler		
Model and Met Data	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden
Max Conc SO_2 ($\mu g/m^3$)	2.51	4.16	4.92	0.64	0.86	0.92	0.36	0.55	0.61	0.47	0.68	0.73
Distance and bearing from dry stack (m)	1000 98°	1500 95°	1500 95°	1000 98°	1000 98°	1000 98°	1000 98°	1000 98°	1500 95°	1000 98°	1000 98°	1000 98°

	Case 9 Scrubbed Kiln 7 with Heat Exchanger			Case 10 104m Combined Stack			Case 11 160m Combined Stack			Case 12 220m Combined Stack		
Model and Met Data	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden
Max Conc SO_2 ($\mu g/m^3$)	0.54	0.76	0.82	3.2	5.41	6.2	1.45	2.54	2.86	0.76	1.32	1.53
Distance and bearing from dry stack (m)	1000 98°	1000 98°	1000 99°	1500 95°	1500 95°	1500 95°	2000 94°	2000 94°	2000 94°	3000 92°	2500 102°	2500 102°

Table 13 Maximum Annual Average Ground Level Concentration of SO_2, and Location of Maximum, Calculated Using ADMS, Met Data from Ringway, Squires Gate and Wilsden, Flat Terrain: Cases 6-13

(Table 14 is inserted in the text)

	Case (1+2+5)			Case 5			Case (1+2)			Case (2+5+8)			Case (2+5+9)			Case (2+5+10)		
	All Sources (Current)			Cement Mills Only			Current Stacks Only			All Sources (Scrubbed Kiln 7 with Folax Cooler)			All Sources (Scrubbed Kiln 7 with 10m³/s Folax Cooler)			All Sources (Scrubbed Kiln 7 with Heat Exchanger)		
Model and Met Data	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden
Max Annual Average Particulates (μg/m³)	5.3	2.14	2.44	5.26	1.94	2.26	0.28	0.45	0.48	5.27	2.1	2.39	5.3	2.11	2.41	5.3	2.39	2.38
Distance and Bearing from dry stack (m)	400 8°	600 52°	600 52°	400 8°	600 52°	600 52°	1000 97°	1000 97°	1000 97°	400 8°	600 52°	600 52°	400 8°	600 52°	600 52°	400 8°	600 52°	600 52°
24 Hour (Daily) Average Particulates (μg/m³)	31.8	27.0	-	31.6	23.64	-	-	-	-	-	-	-	-	-	-	-	-	-
Distance and Bearing from dry stack (m)	400 8°	400 8°	-	400 8°	400 8°	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -

Table 15 Maximum Annual Average Ground Level Concentration of Particulates, and Location of Maximum Calculated Using ADMS, Met Data from Ringway, Squires Gate and Wilsden: Combinations of Cases 1-4 & 6-13

(Table 16 is inserted in the text)

	Case 1					Case 2					Case 3					Case 4					Case (1+2)				
	Dry Kiln 7					Wet Kilns 5 + 6					Wet Kiln 5					Wet Kiln 6					All Kilns 7 + (5 + 6)				
	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden	ADMS Ringway	ADMS Squires	ADMS Wilsden	R91 Wilsden	ISCLT Wilsden
Max Conc NO_x (ug/m^3)	2.07	3.12	3.38	2.24	3.77	1.43	2.4	2.69	1.19	4.03	1.11	1.66	1.81	0.73	2.72	1.19	1.8	1.98	0.8	2.97	3.5	5.52	6.07	2.43	7.8
Distance & Bearing From Dry Stack (m)	1000 98°	1000 98°	1500 95°	7500 90°	2500 90°	1000 98°	1000 98°	1000 98°	4000 90°	2500 90°	1000 98°	1000 98°	1000 98°	4000 90°	2000 90°	1000 98°	1000 98°	1000 98°	4000 90°	2000 90°	1000 98°	1000 98°	1000 98°	6000 90°	2500 90°

Table 17 Maximum Annual Average Ground Level Concentration of NO_x, and Location of Maximum Calculated Using ADMS, DISTAR and ISCLT Dispersion Models, Met Data from Ringway, Squires Gate and Wilsden, Flat Terrain: Combinations of Cases 1-4

The maximum annual average of NO_x from all sources in complex terrain is $5.5 \mu g/m^3$ with Wilsden met. data.

FIGURES

Figure 1 Ribble Valley, Lancashire: Contour Map

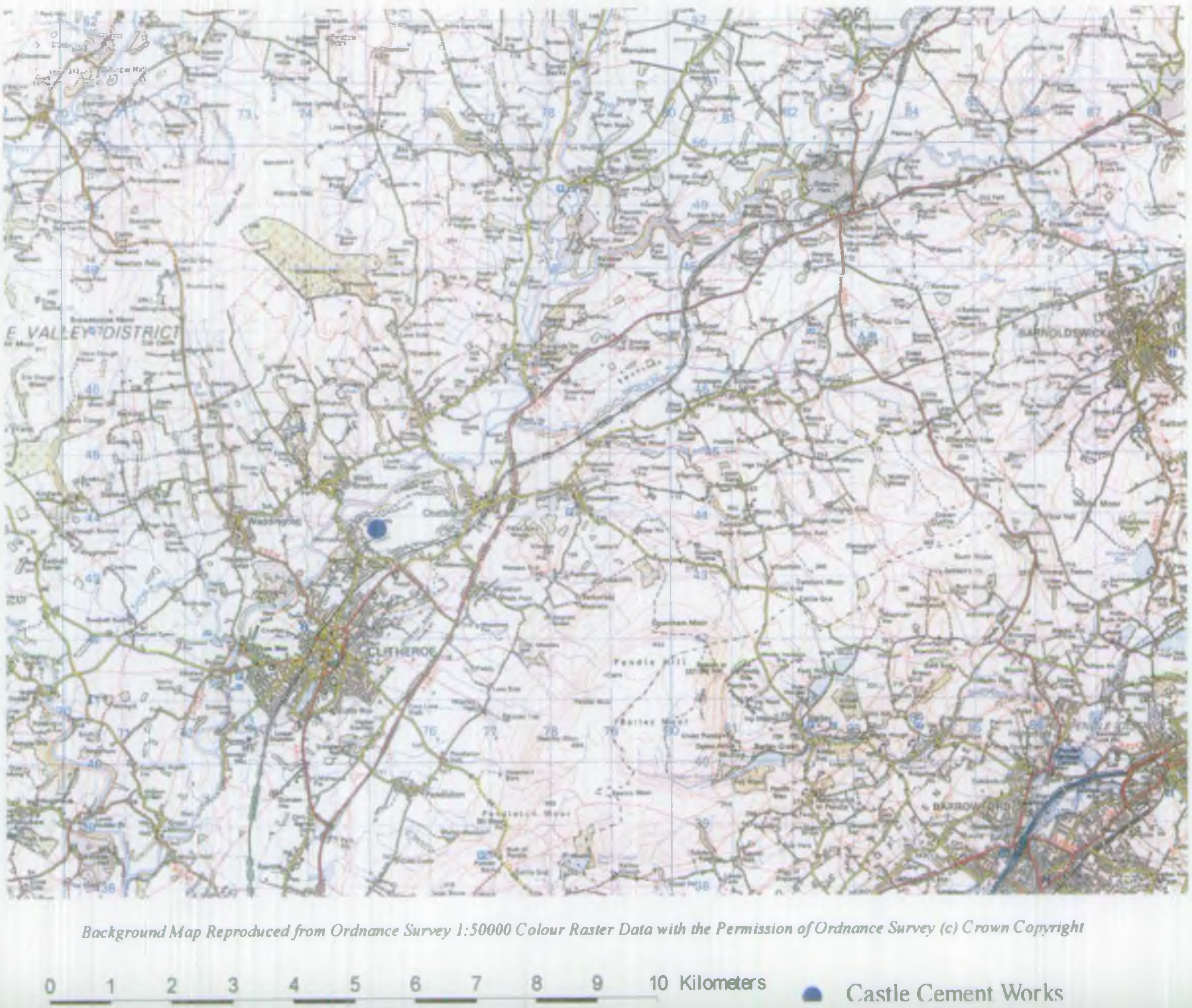
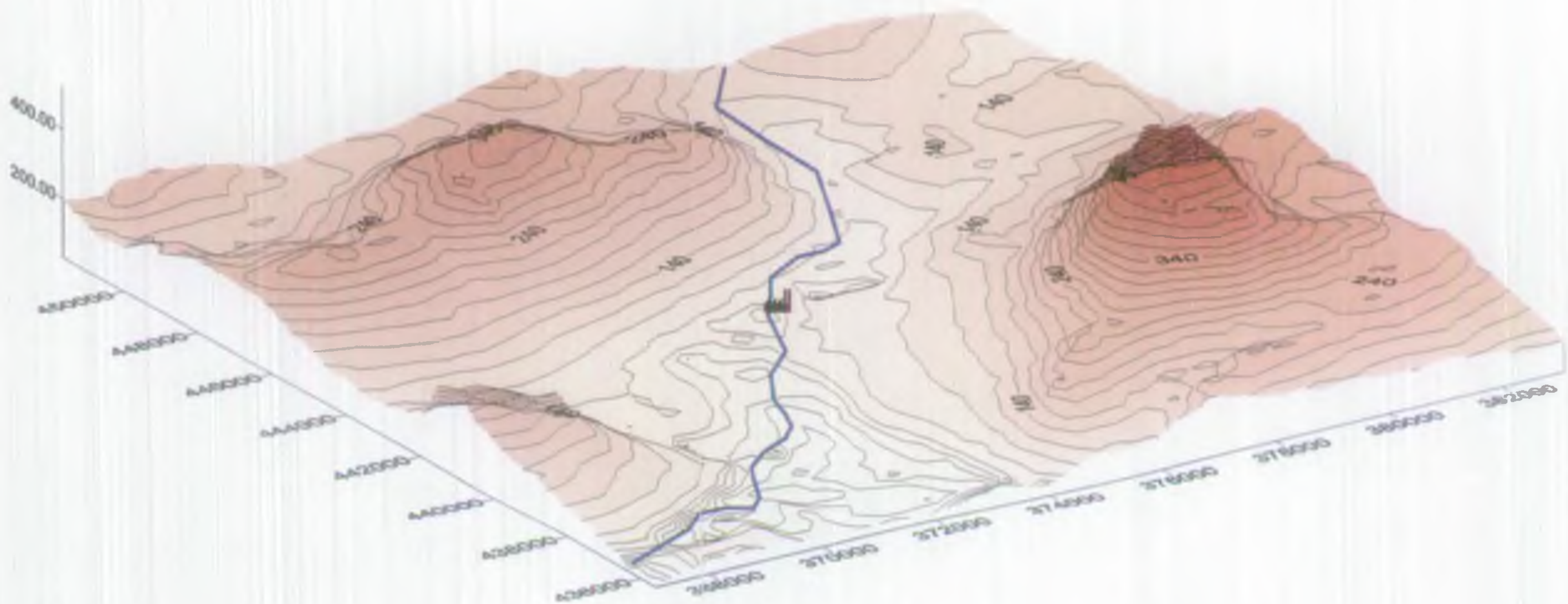


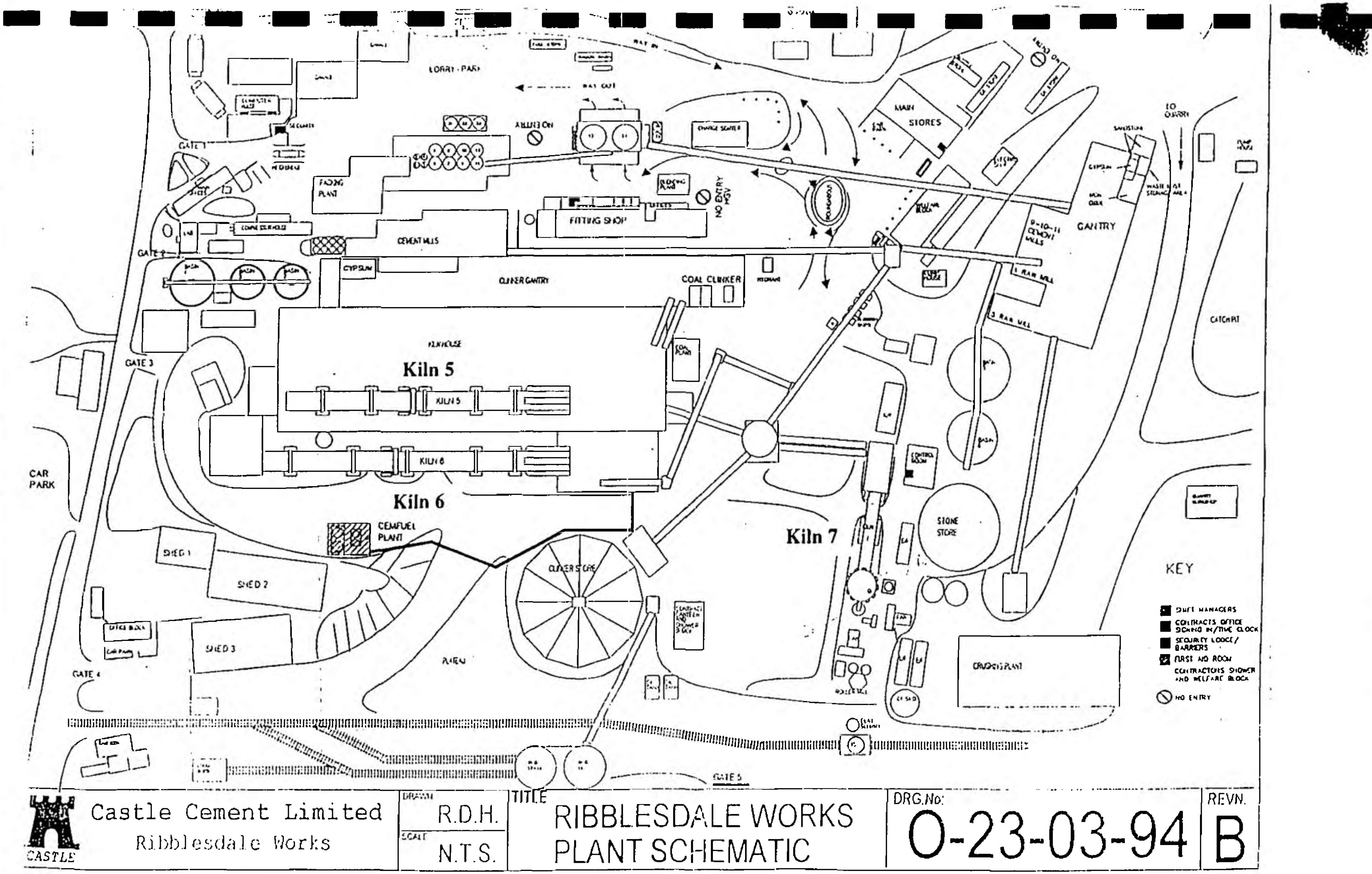
Figure 2 Ribble Valley, Lancashire: Surface Plot



Vertical scale is enhanced approximately 8 times to highlight topographic detail

Castle Cement Works

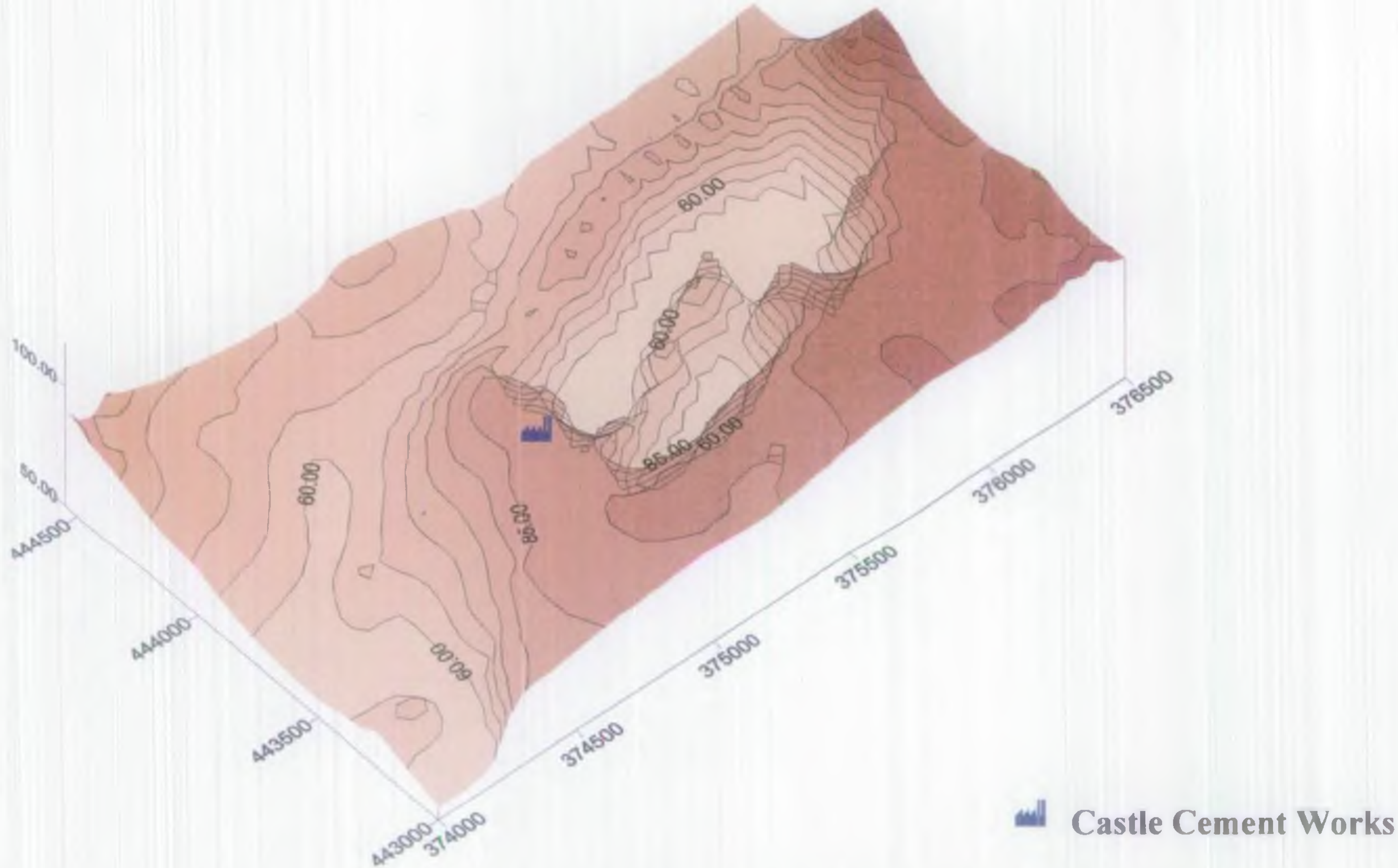
River Ribble



LORRY PARK
WAY OUT
FITTING SHOP
CEMENT MILLS
CLINKER GANTRY
COAL CLINKER
MAIN STORES
GANTRY
TO QUARRY
CATCHPIT
Kiln 5
KILN 5
KILN 6
Kiln 6
Kiln 7
CEMFUEL PLANT
CLINKER STORE
STONE STORE
CRUSHING PLANT
SHED 1
SHED 2
SHED 3
CAR PARK
GATE 1
GATE 2
GATE 3
GATE 4
GATE 5
NO ENTRY HGV
KEY
SECURITY LODGE/ BARRIERS
FIRST AID ROOM
NO ENTRY
Castle Cement Limited
Ribblesdale Works
CASTLE
DRAWN
R.D.H.
SCALE
N.T.S.
TITLE
RIBBLESDALE WORKS
PLANT SCHEMATIC
DRG.No:
0-23-03-94
REVN.
B

Figure 3

Figure 4 Isometric Projection of the Quarry Topography



Vertical scale is enhanced approximately 8 times to highlight topographic detail

Figure 5 Map of Meteorological Measuring Sites Relative to Clitheroe

1 Clitheroe

2 Blackpool Squires Gate

3 Liverpool Speke

4 Manchester Ringway

5 Wilsden

Figure 6(a) Windrose for Wilsden 1974-1983 Met Data – Showing Frequency (Number of 3 Hour Periods), Wind Direction and Wind Speed

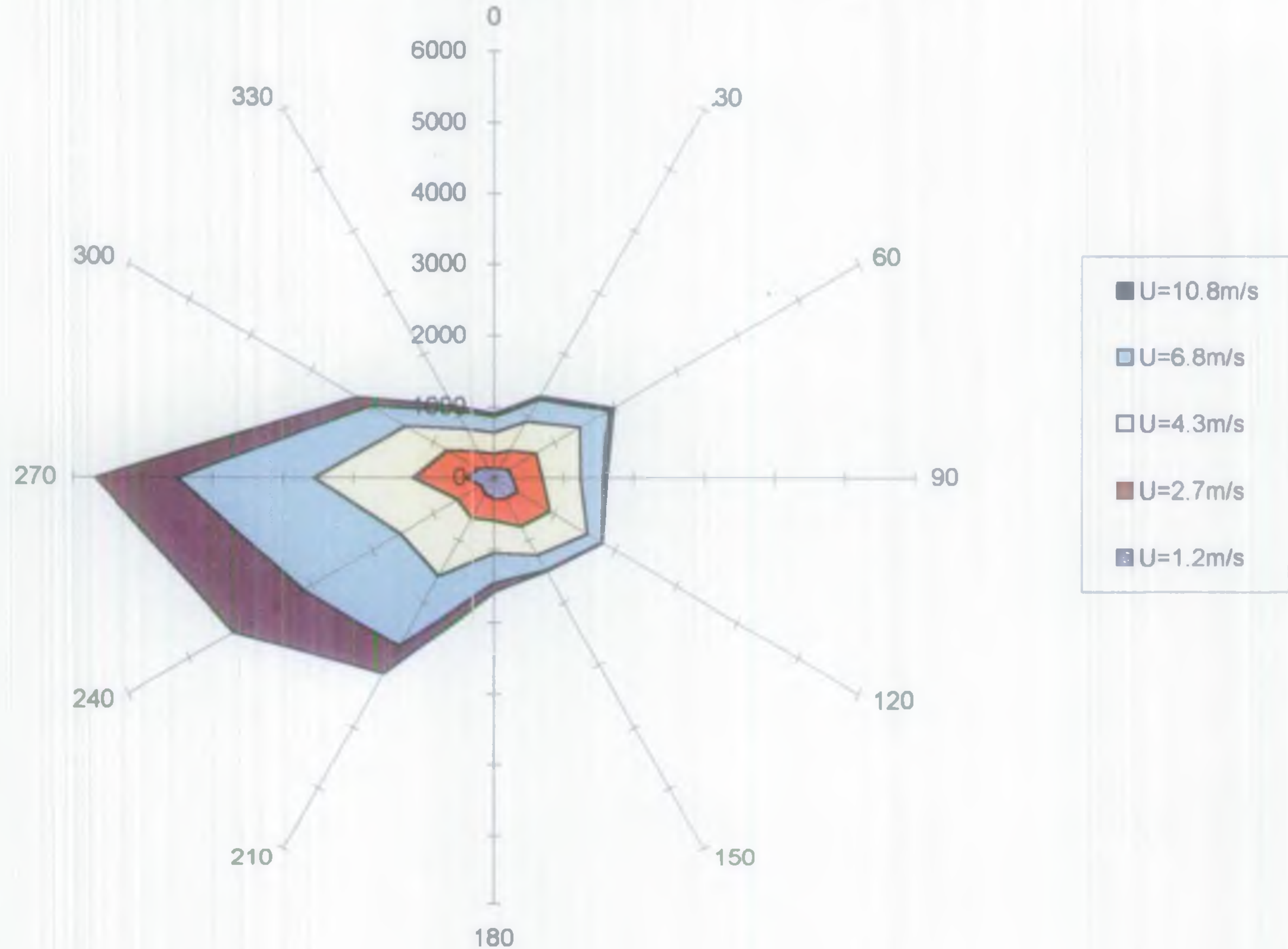


Figure 6(b) Windrose for Squires Gate, Blackpool, 1981-1990 Met Data – Showing Frequency (Number of Hours), Wind Direction and Wind Speed

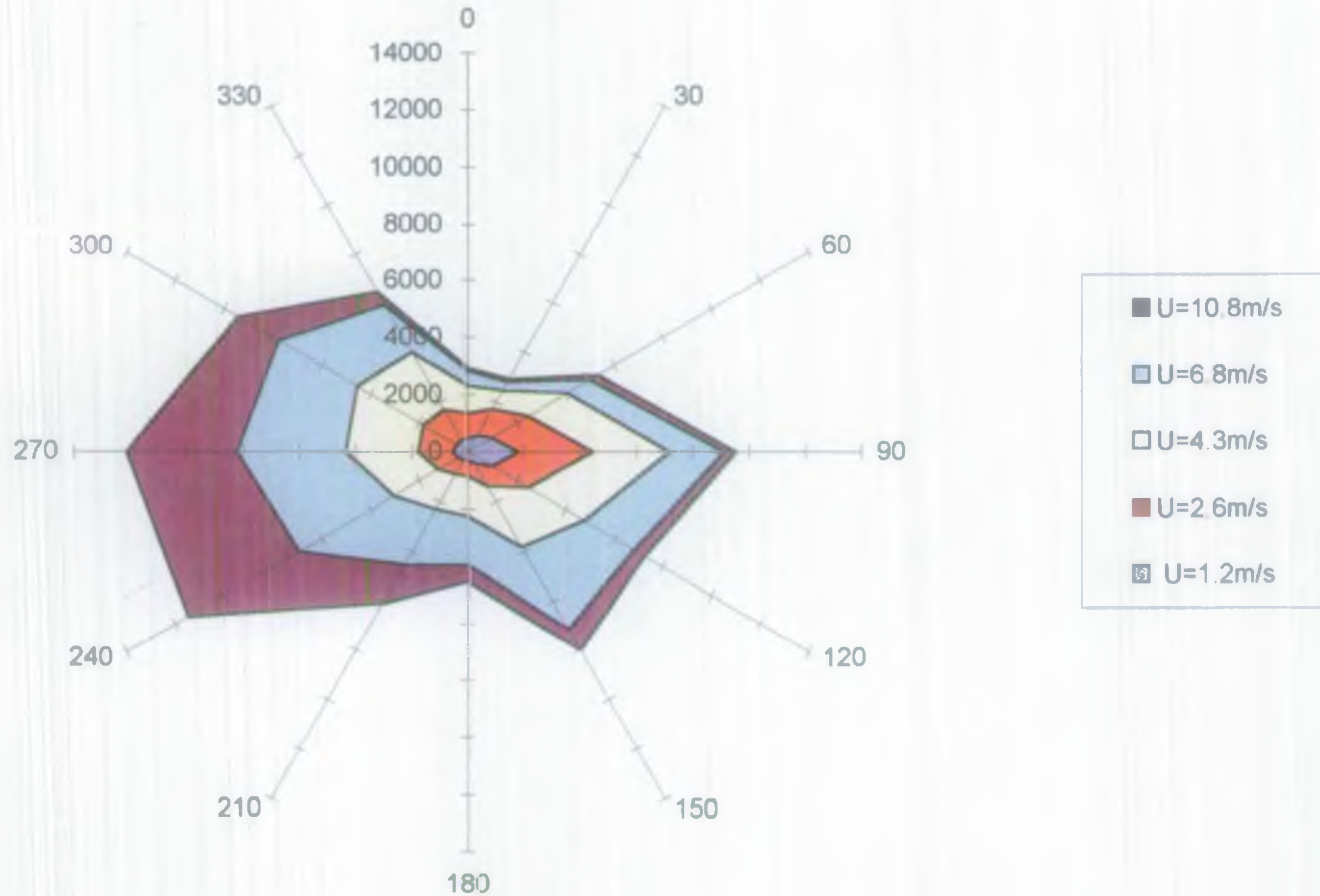


Figure 6(c) Windrose for Ringway, Manchester, 1986-1995 Met Data – Showing Frequency (Number of Hours), Wind Direction and Wind Speed

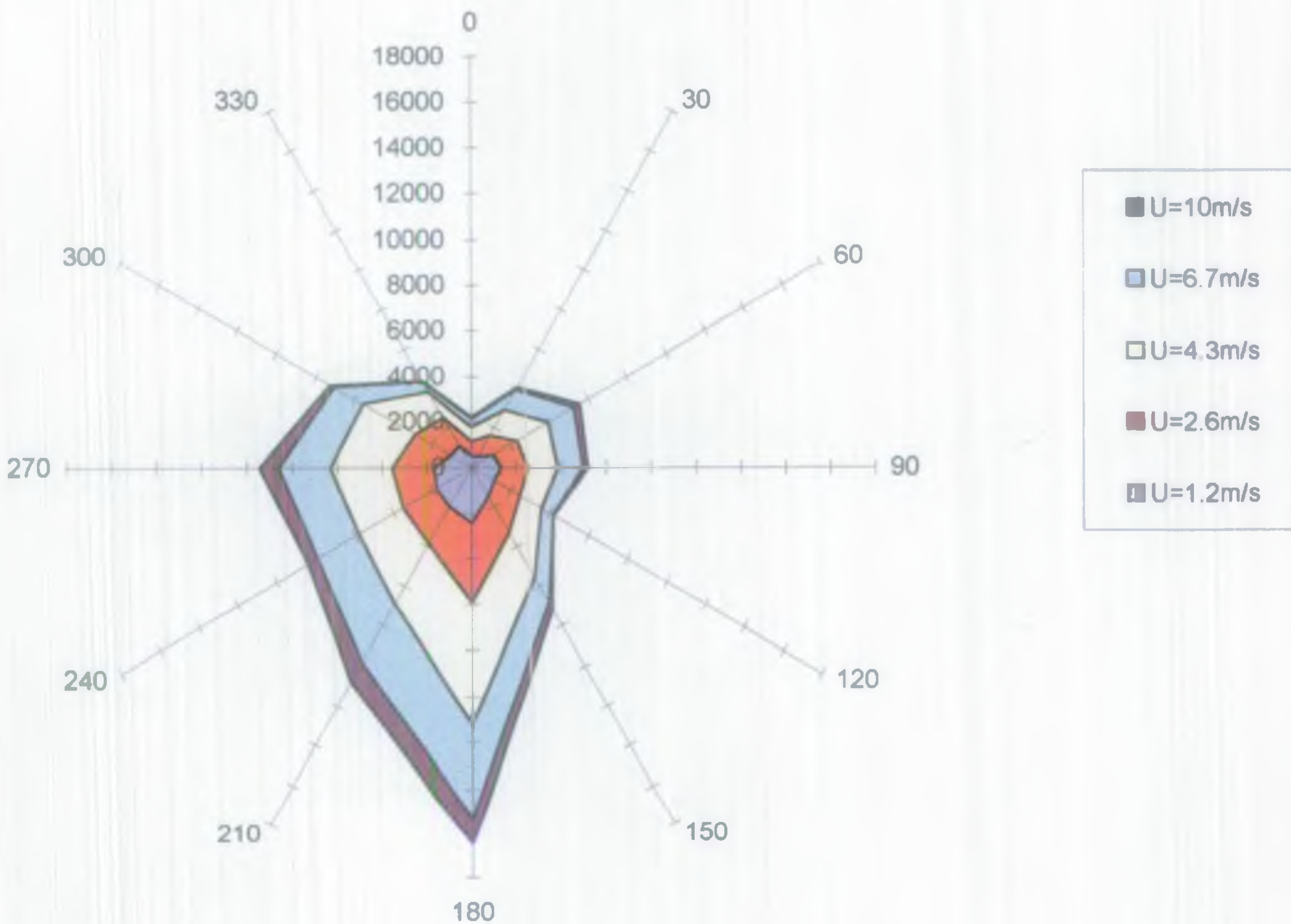


Figure 6(d) Windrose for Speke, Liverpool, 1974-1976 Met Data – Showing Frequency (Number of Hours) and Wind Direction

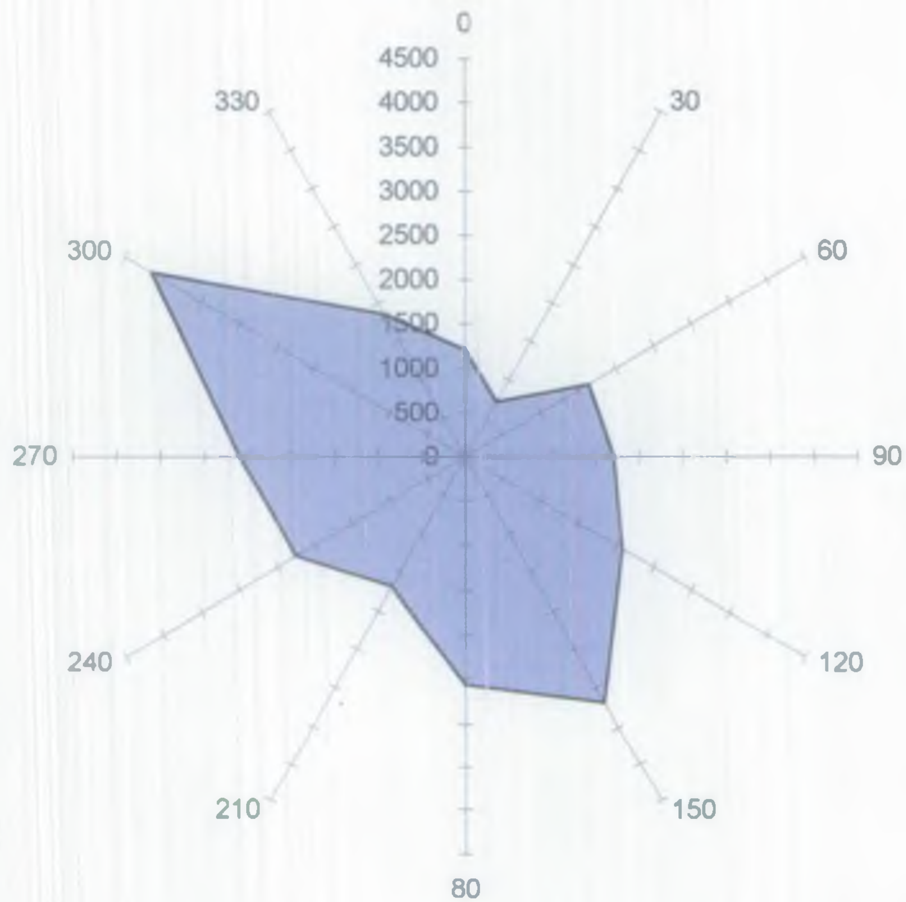


Figure 7 Location of NPL Monitoring Sites Used in the ADMS Validation Study

Background Map Reproduced From Ordnance Survey 1:50000 Colour Raster Data with the Permission of Ordnance Survey (c) Crown Copyright

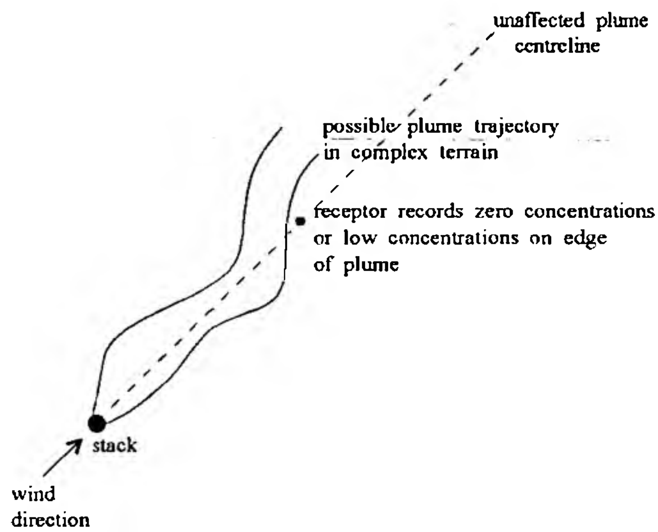


Figure 8a Possible plume trajectory in complex terrain for one specified wind direction. The plume centreline does not pass over the receptor and zero or very low concentrations are detected. The exact location of the plume is very sensitive to the specified wind direction.

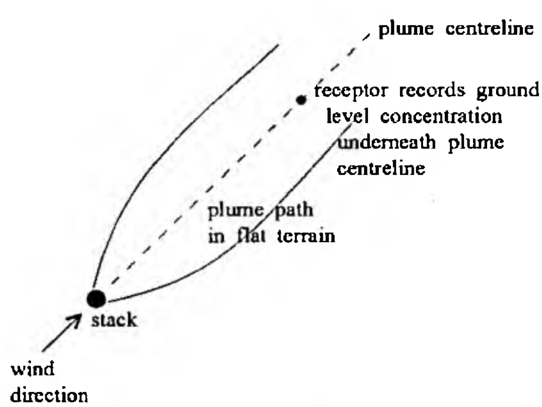
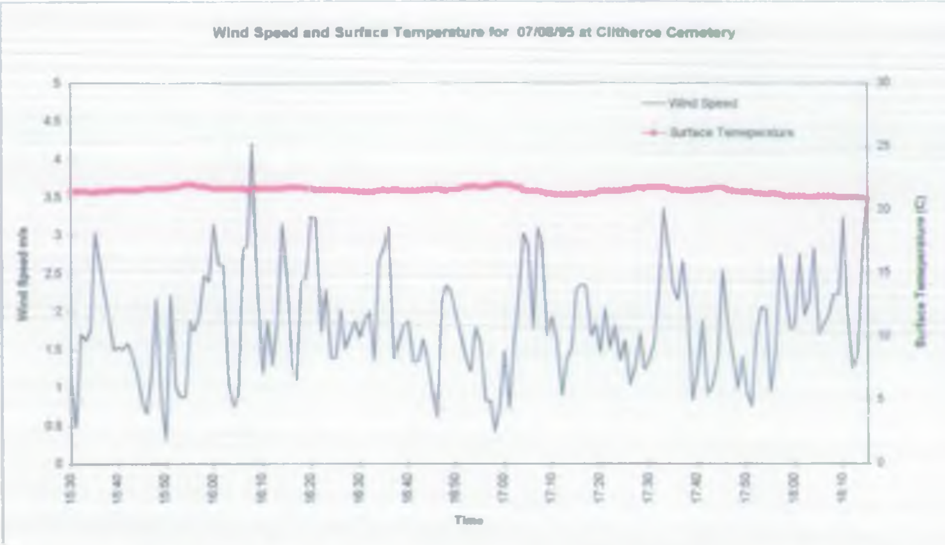
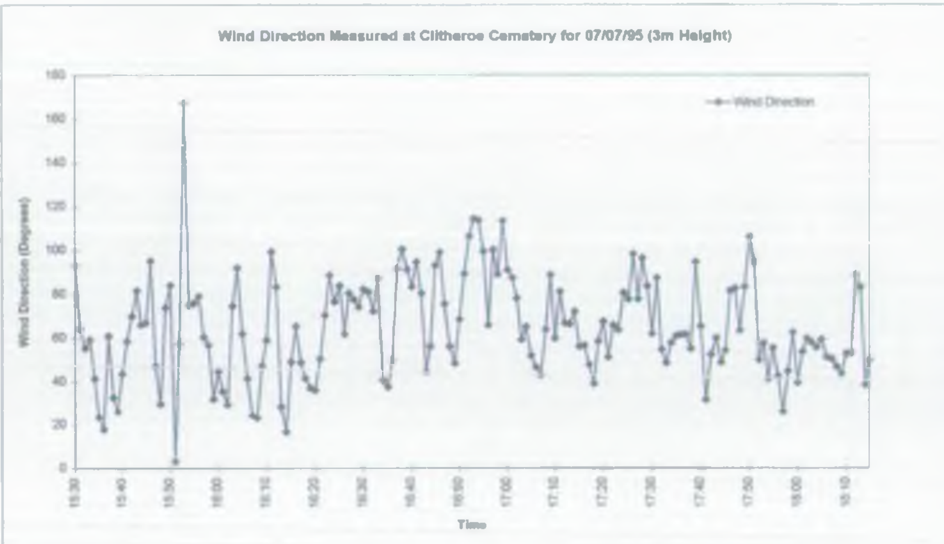


Figure 8b Plume trajectory in flat terrain for one specified wind direction. The wind direction specified in the model is unaffected by complex terrain and blows directly from the stack to the receptor. The plume centreline maximum concentration occurs at the receptor giving an upper bound to the concentration.

Figure 9(a) Met Parameters at Clitheroe Cemetery and Emitted SO_2 : 07/08/95





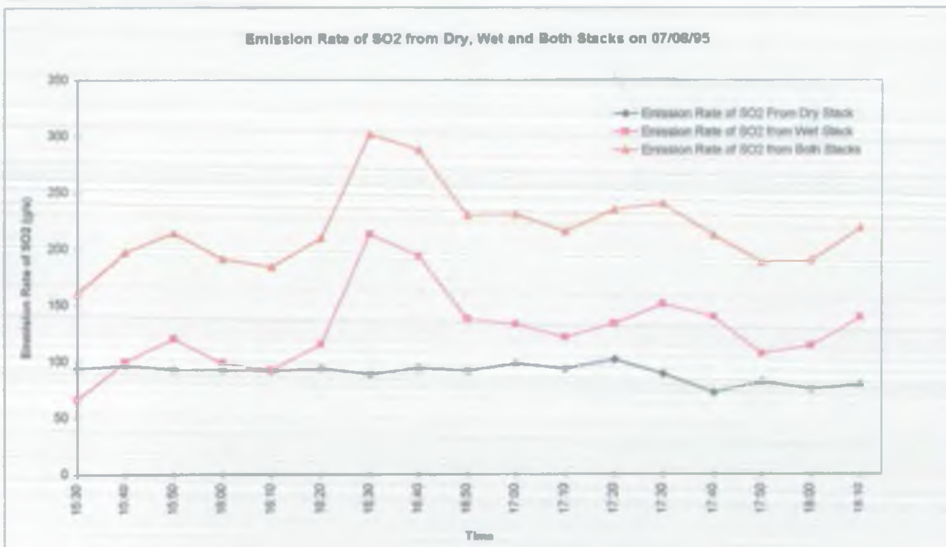
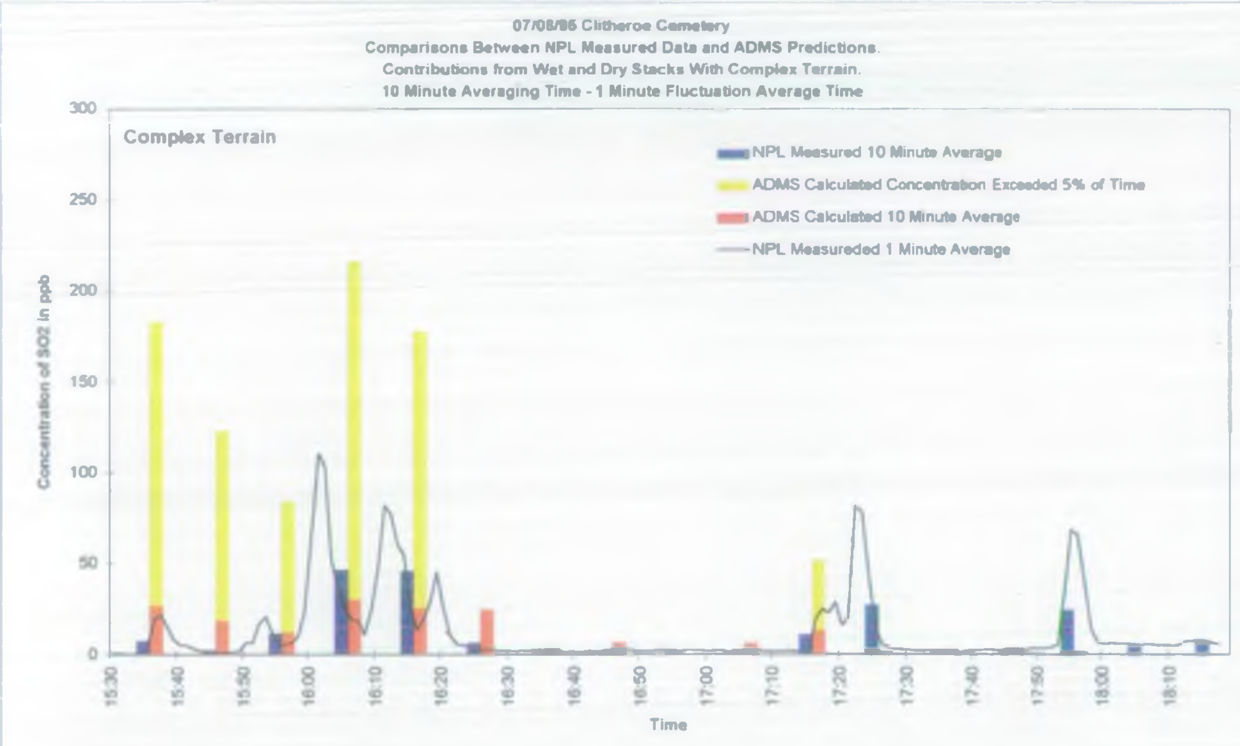


Figure 9(b) Measured and Predicted Concentrations of SO_2 at Clitheroe Cemetery, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute: 07/08/95



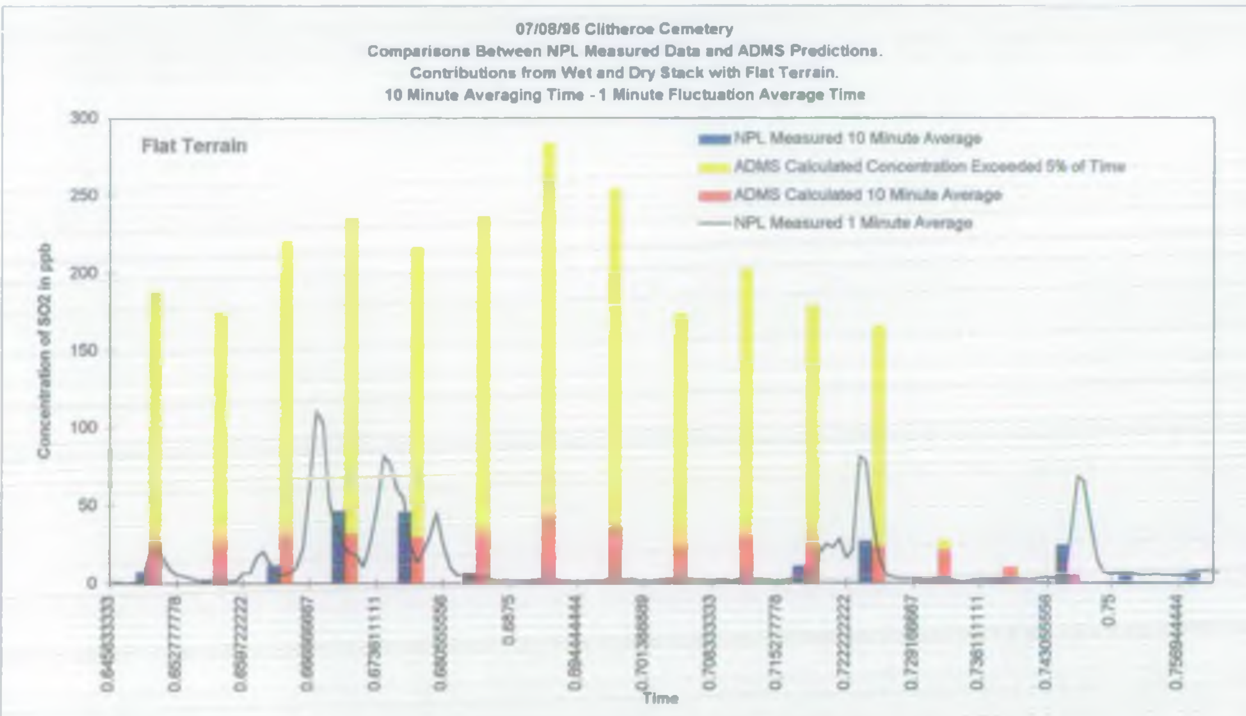
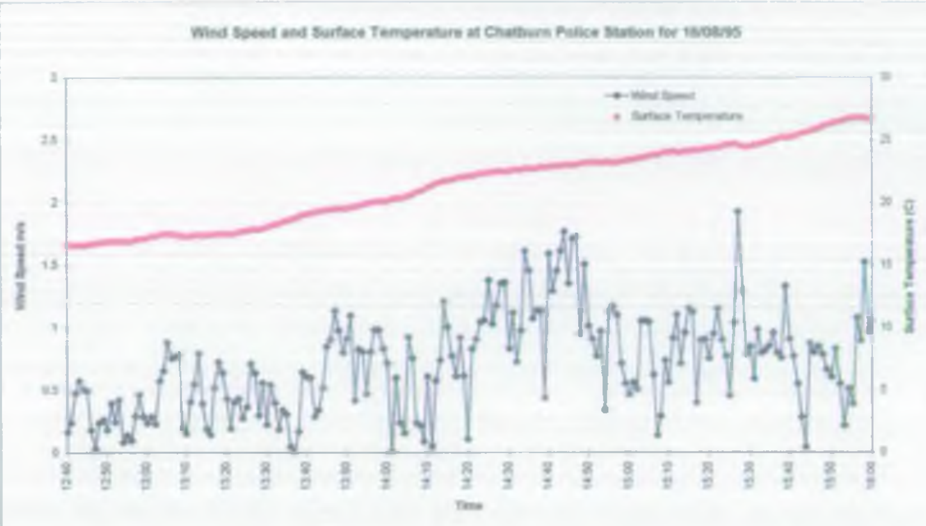
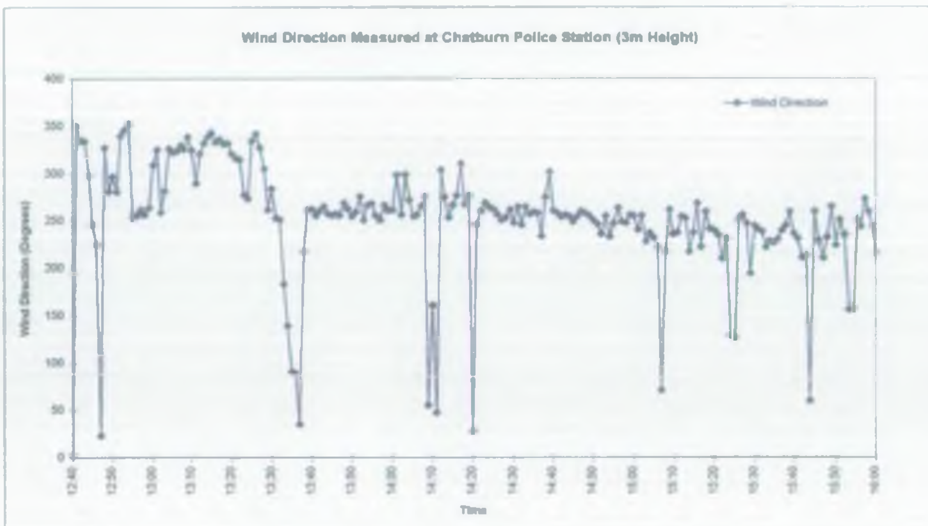


Figure 10(a) Met Parameters at Chatburn Police Station and Emitted SO_2 : 16/08/95





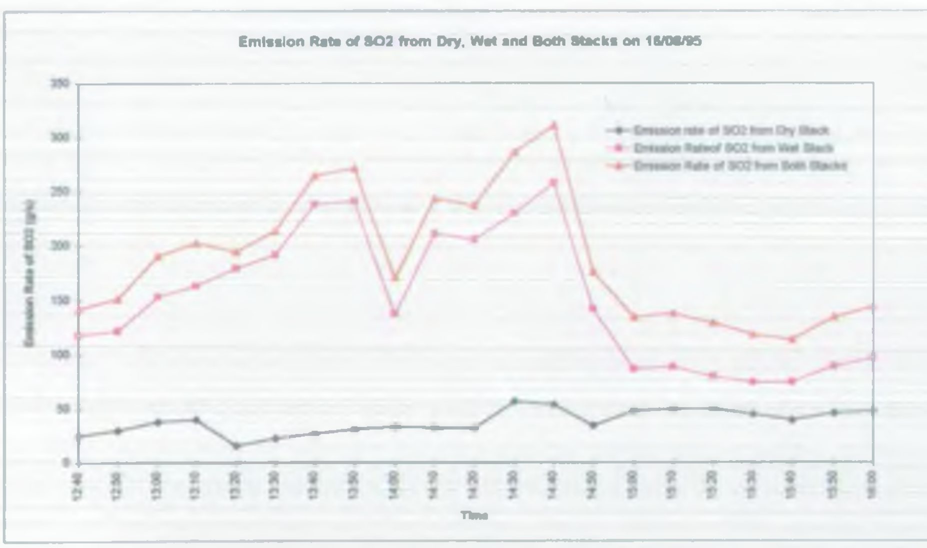
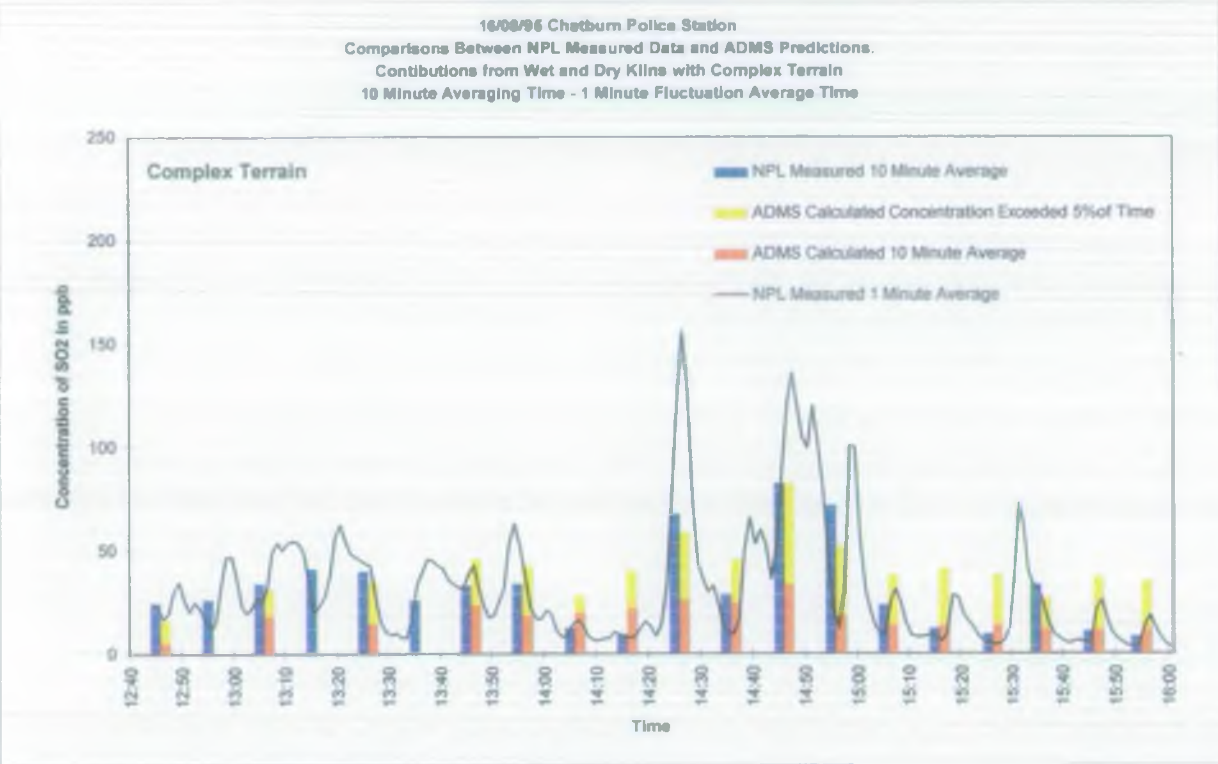


Figure 10(b) Measured and Predicted Concentrations of SO_2 at Chatburn Police Station, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute: 16/08/95



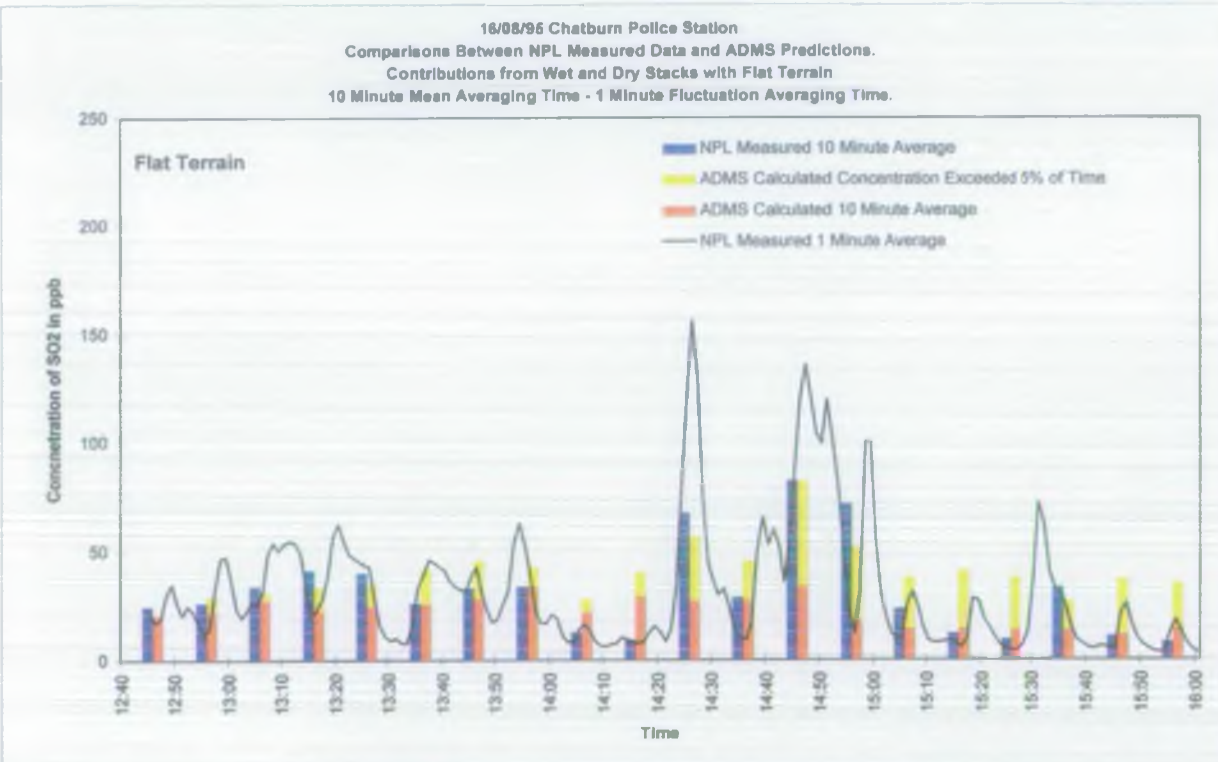


Figure 11(a) Met Parameters at Moorland School and Waddington & West Bradford Primary School and Emitted SO_2 : 18/08/95

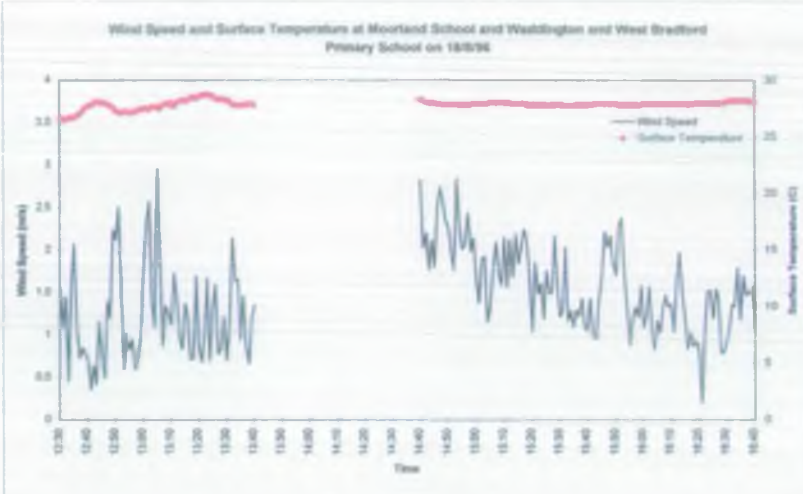
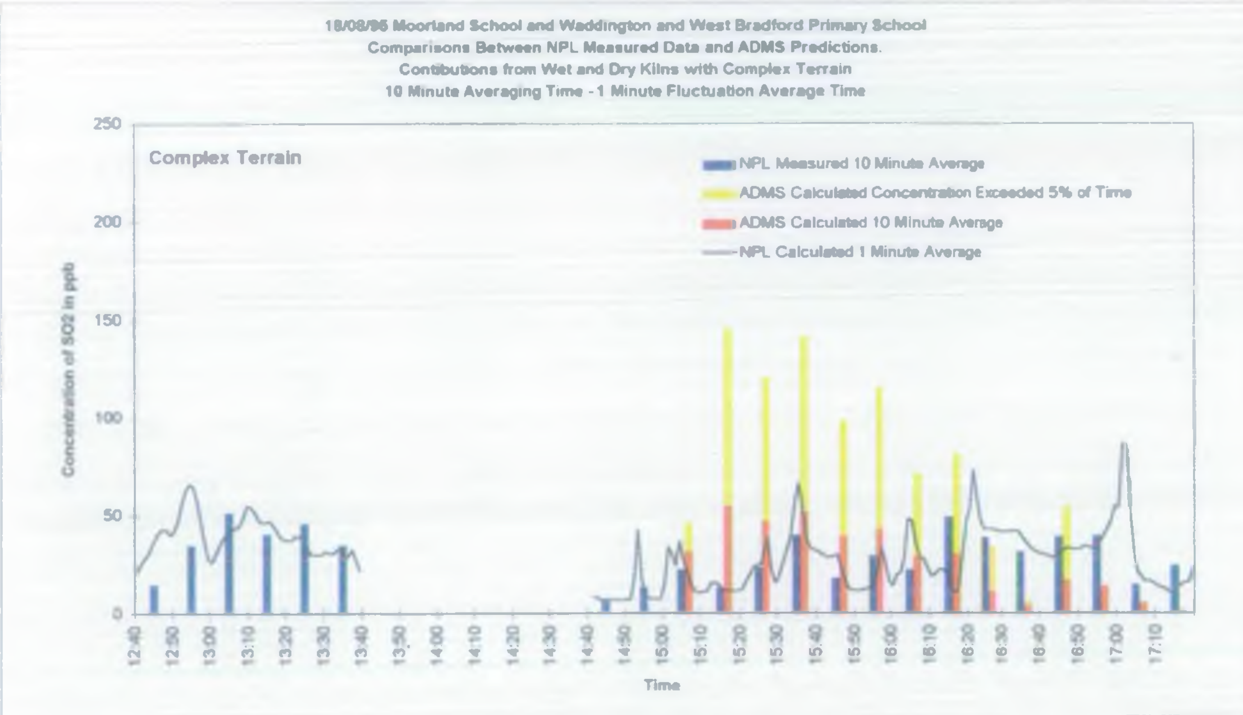


Figure 11(b) Measured and Predicted Concentrations of SO_2 at Moorland School and Waddington & West Bradford Primary School, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute:



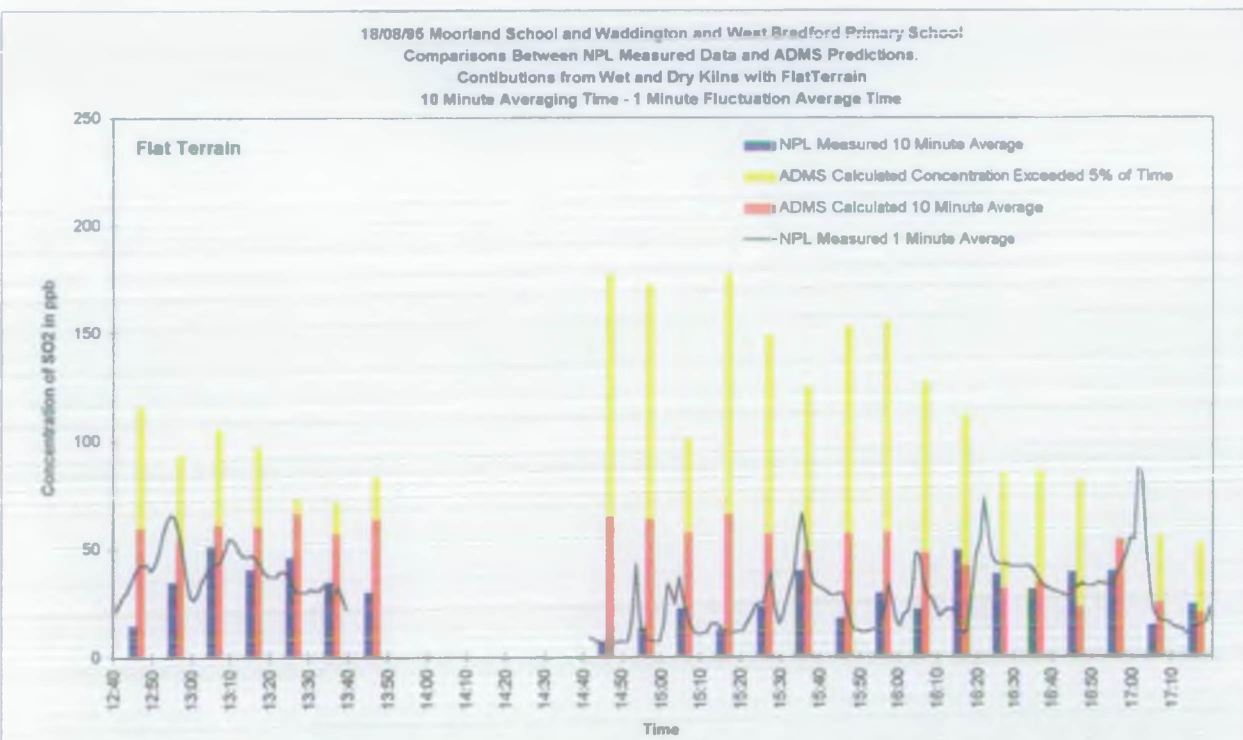
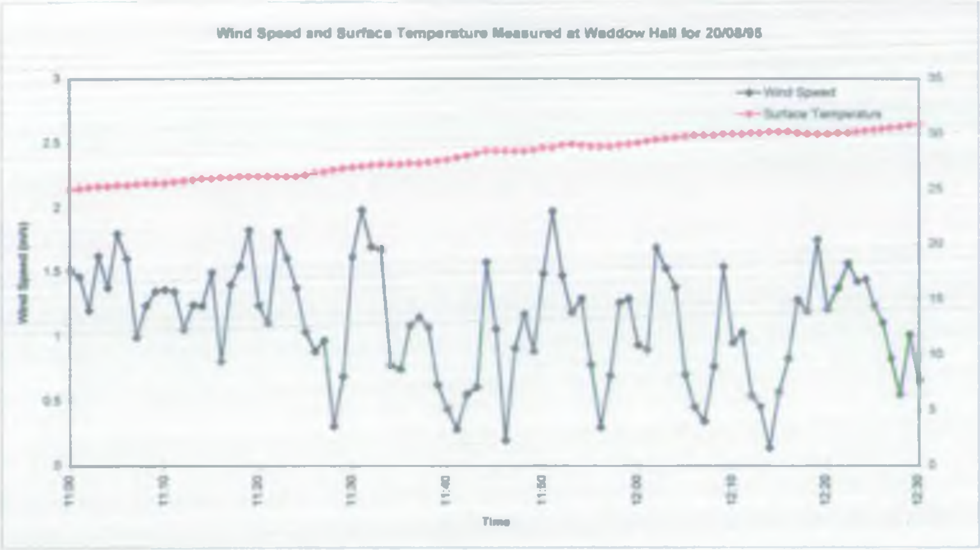
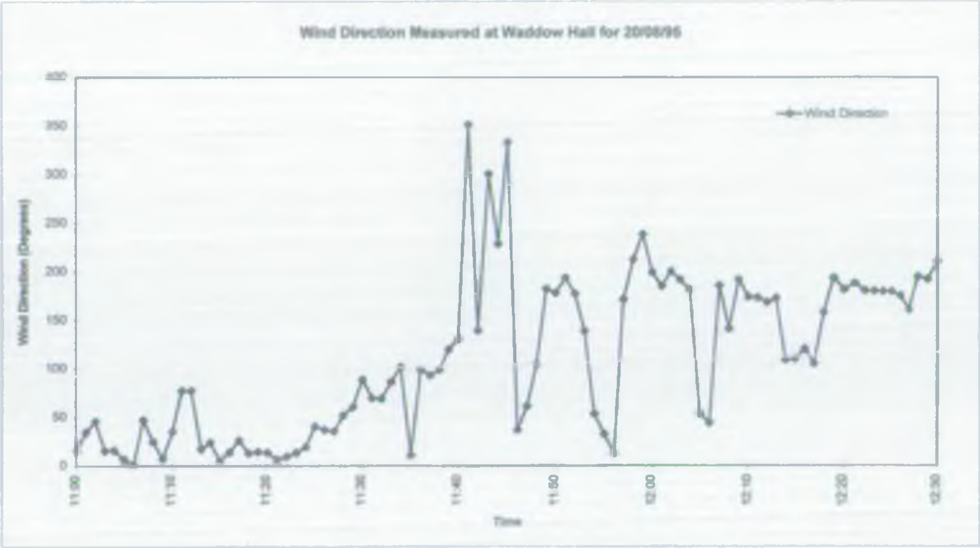


Figure 12(a) Met Parameters at Waddow Hall and Emitted SO_2 : 20/08/95





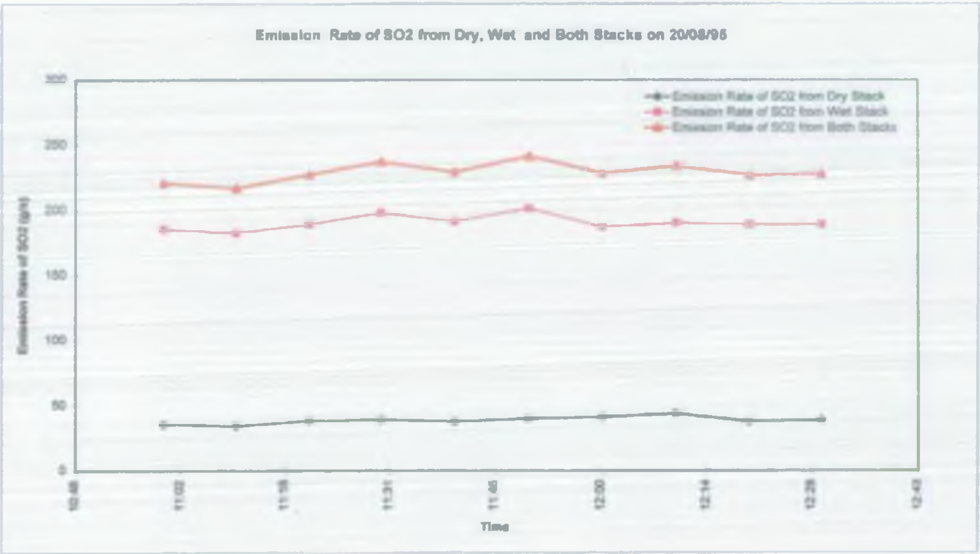


Figure 12(b) Measured and Predicted Concentrations of SO_2 at Waddow Hall, Averaging Time=10 minutes, Fluctuations Averaging Time=1 minute: 20/08/95

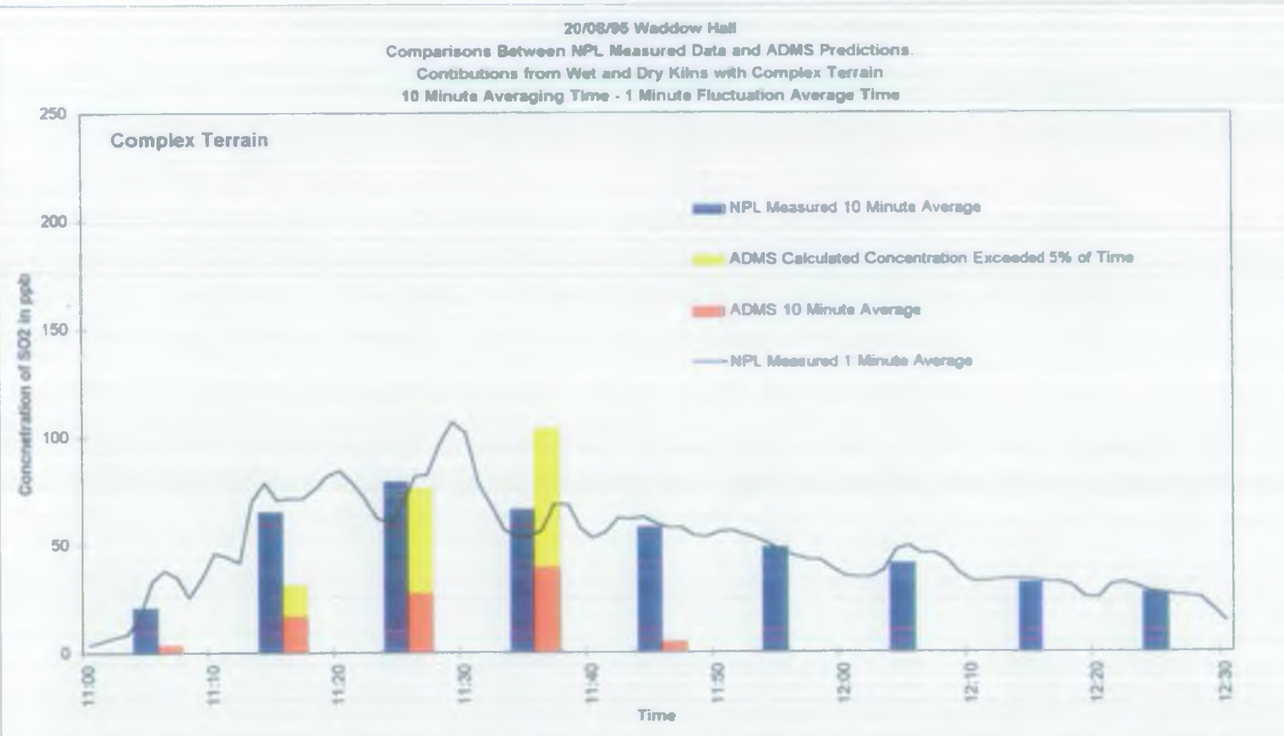


Figure 13 Probability of the Concentration of SO_2 Exceeding Specified Concentrations at Various Distances from the Works During the Incidents of High Recorded Concentrations.

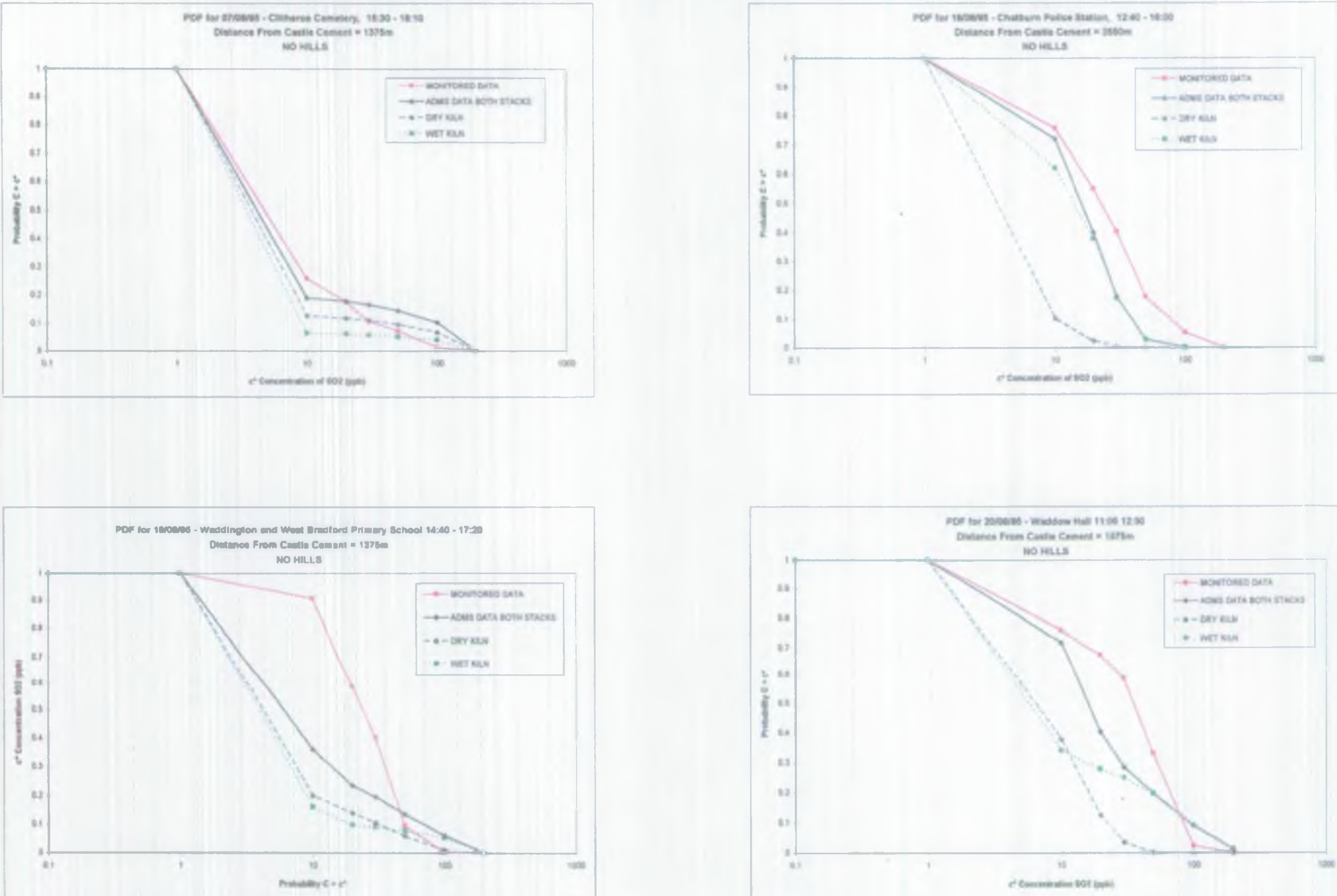


Figure 14(a) Hourly Average Concentration of SO2 ($\mu g/m^3$) from the Dry Kiln, Wind from South East (135°), Pasquill Class B

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot

(iii) Flat Terrain Results

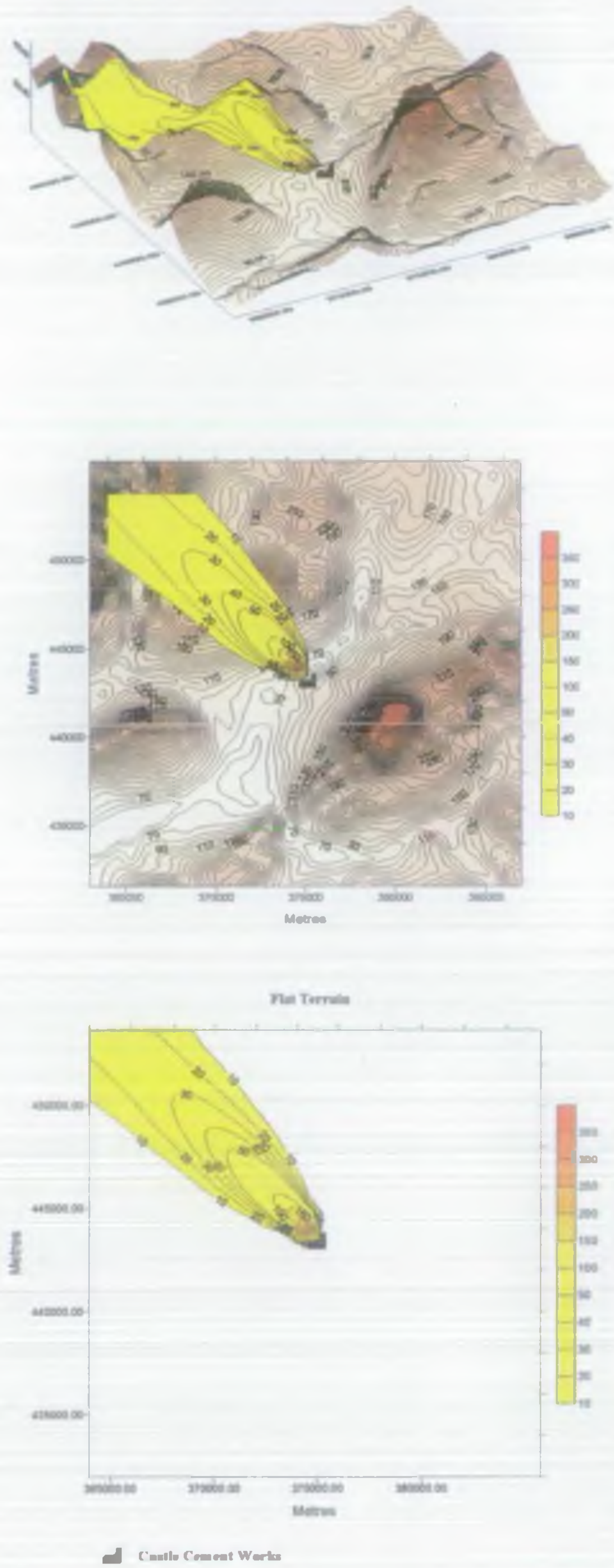


Figure 14(b) Hourly Average Concentration of SO2 ($\mu g/m^3$) from the Dry Kiln, Wind from South East (135°), Pasquill Class D

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot

(iii) Flat Terrain Results

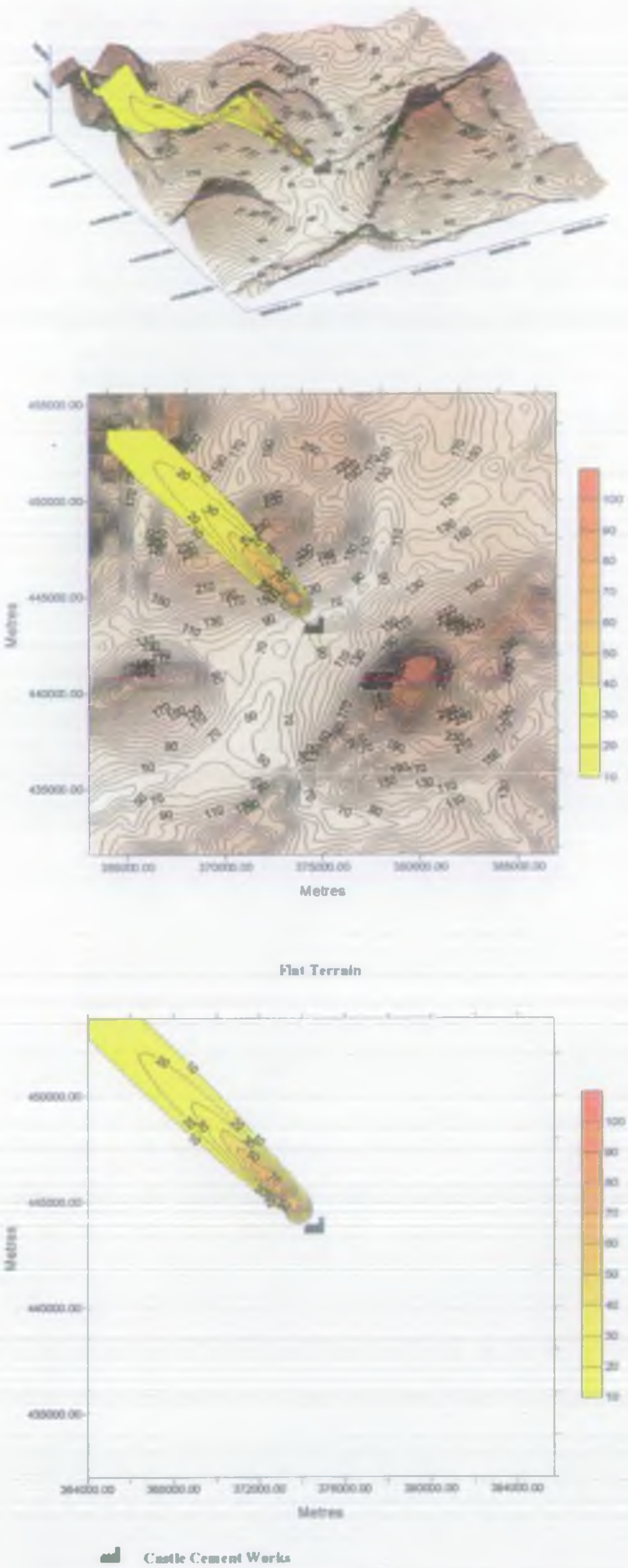
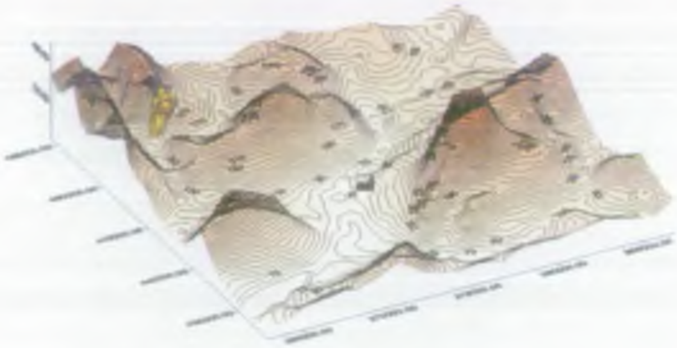
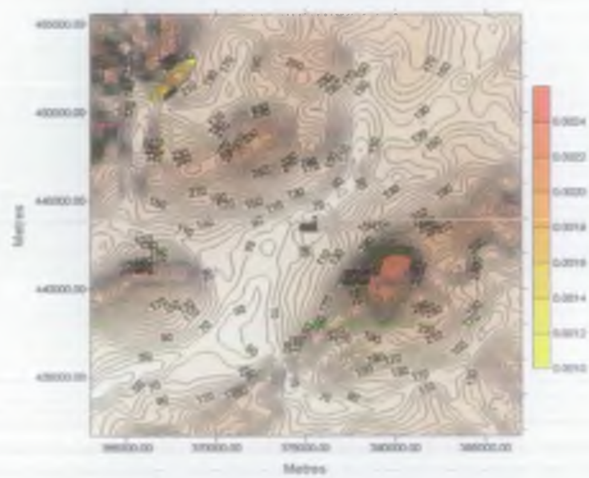


Figure 14(c) Hourly Average Concentration of SO_2 ($\mu g/m^3$) from the Dry Kiln, Wind from South East (135°), Pasquill Class F

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot





Castle Cement Works

There is no ground level concentration within this area for Stability F in flat Terrain

Figure 15(a) Hourly Average Concentration of SO2 ($\mu g/m^3$) from the Dry Kiln, Wind from South West (225°), Pasquill Class B

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot

(iii) Flat Terrain Results

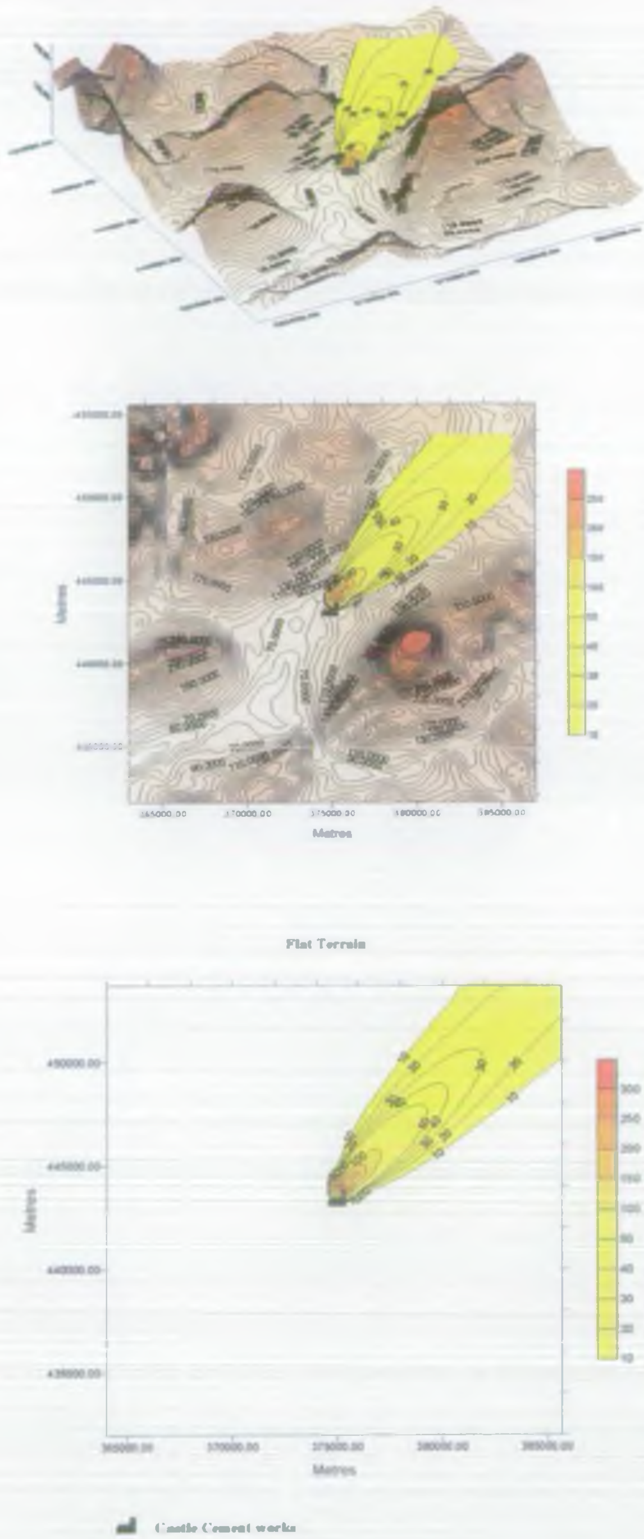
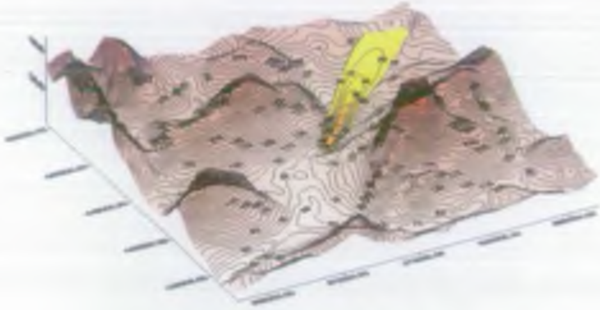


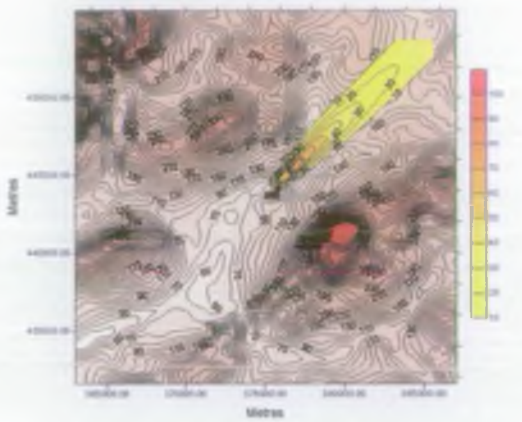
Figure 15(b) Hourly Average Concentration of $SO2$ ($\mu g/m^3$) from the Dry Kiln, Wind from South West (225°), Pasquill Class D

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot

(iii) Flat Terrain Results





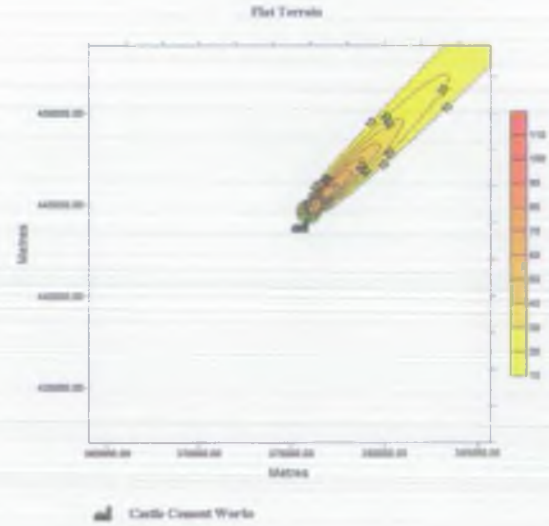
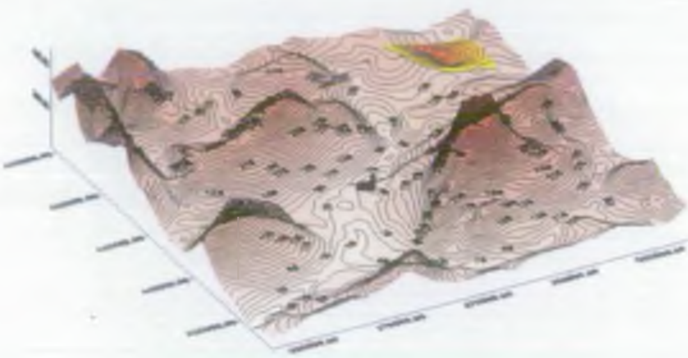
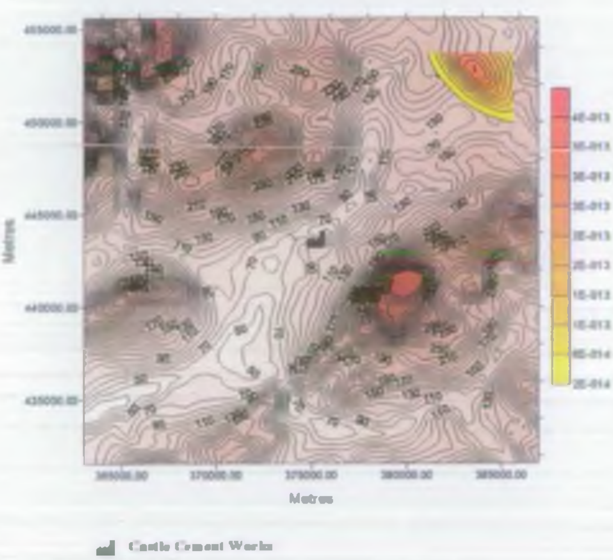


Figure 15(c) Hourly Average Concentration of SO2 (µg/m³) from the Dry Kiln, Wind from South West (225°), Pasquill Class F
(i) Complex Terrain Results Superimposed on a Surface Plot
(ii) Complex Terrain Results Superimposed on a Contour Plot





There is no ground level concentration within this area for Stability F in flat terrain

Figure 16(a) Hourly Average Concentration of SO2 ($\mu g/m^3$) from the Dry Kiln, Wind from North West (315°), Pasquill Class B

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot

(iii) Flat Terrain Results

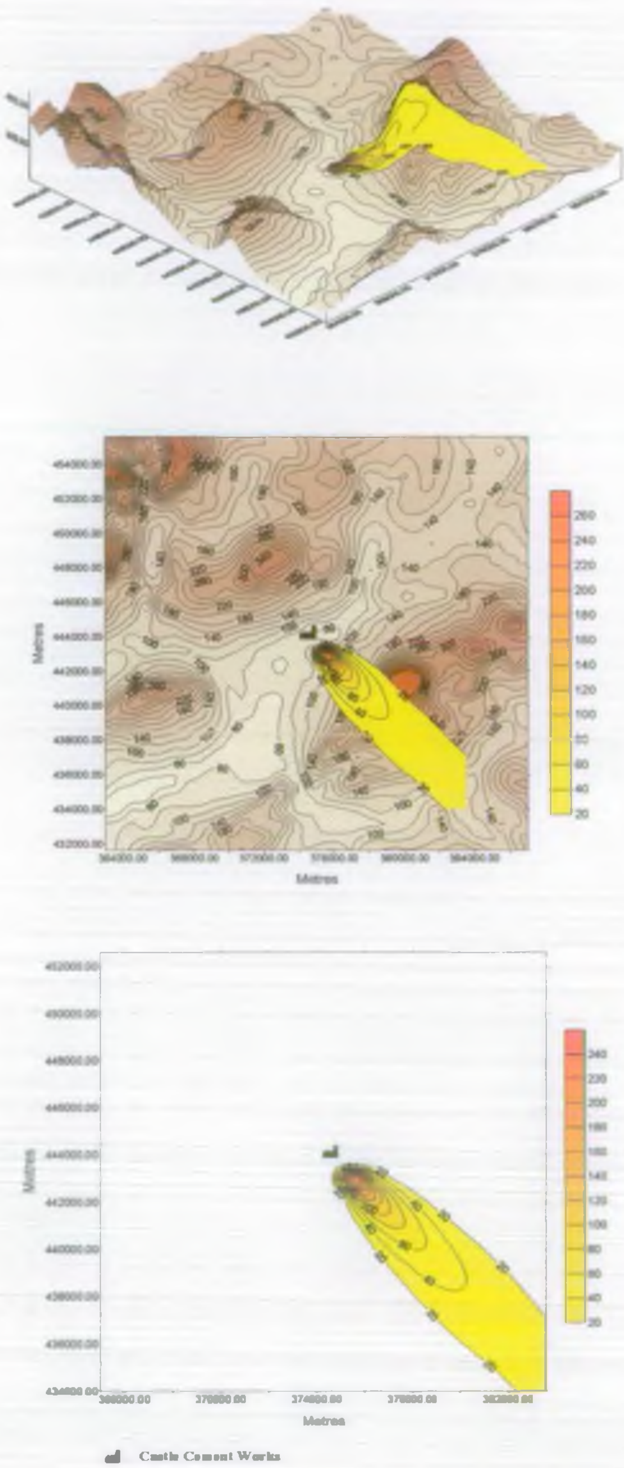


Figure 16(b) Hourly Average Concentration of SO_2 ($\mu g/m^3$) from the Dry Kiln, Wind from North West (315°), Pasquill Class D

(i) Complex Terrain Results Superimposed on a Surface Plot

(ii) Complex Terrain Results Superimposed on a Contour Plot

(iii) Flat Terrain Results

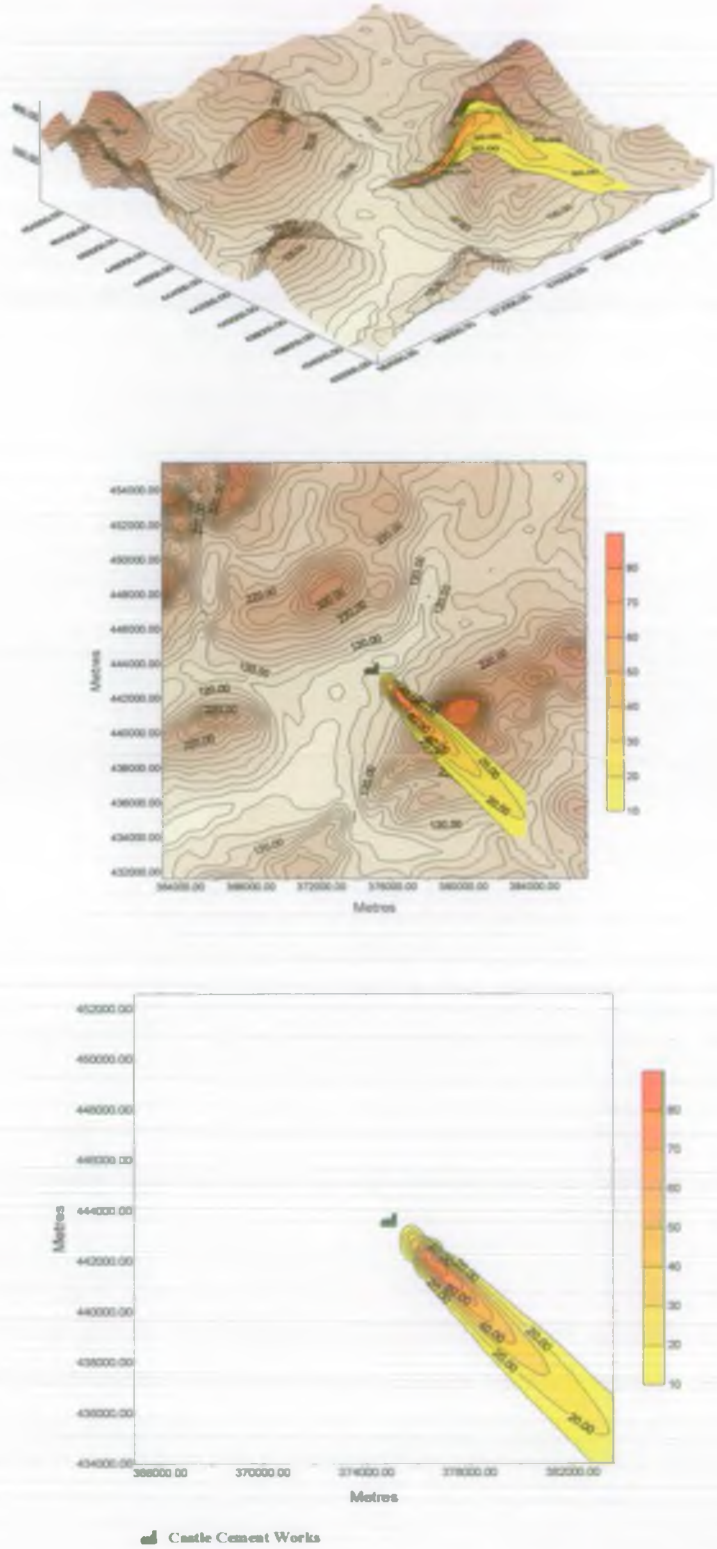
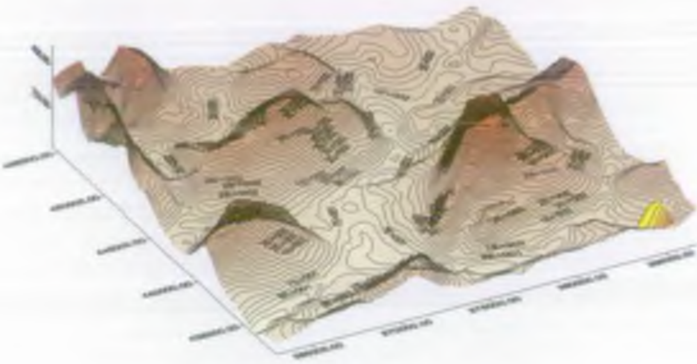
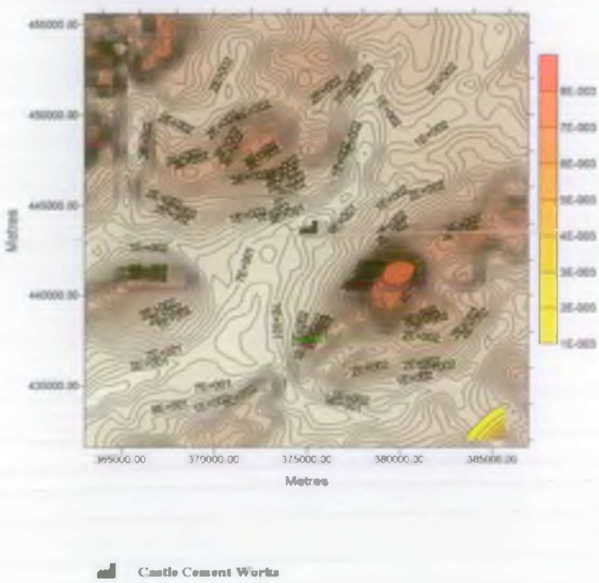


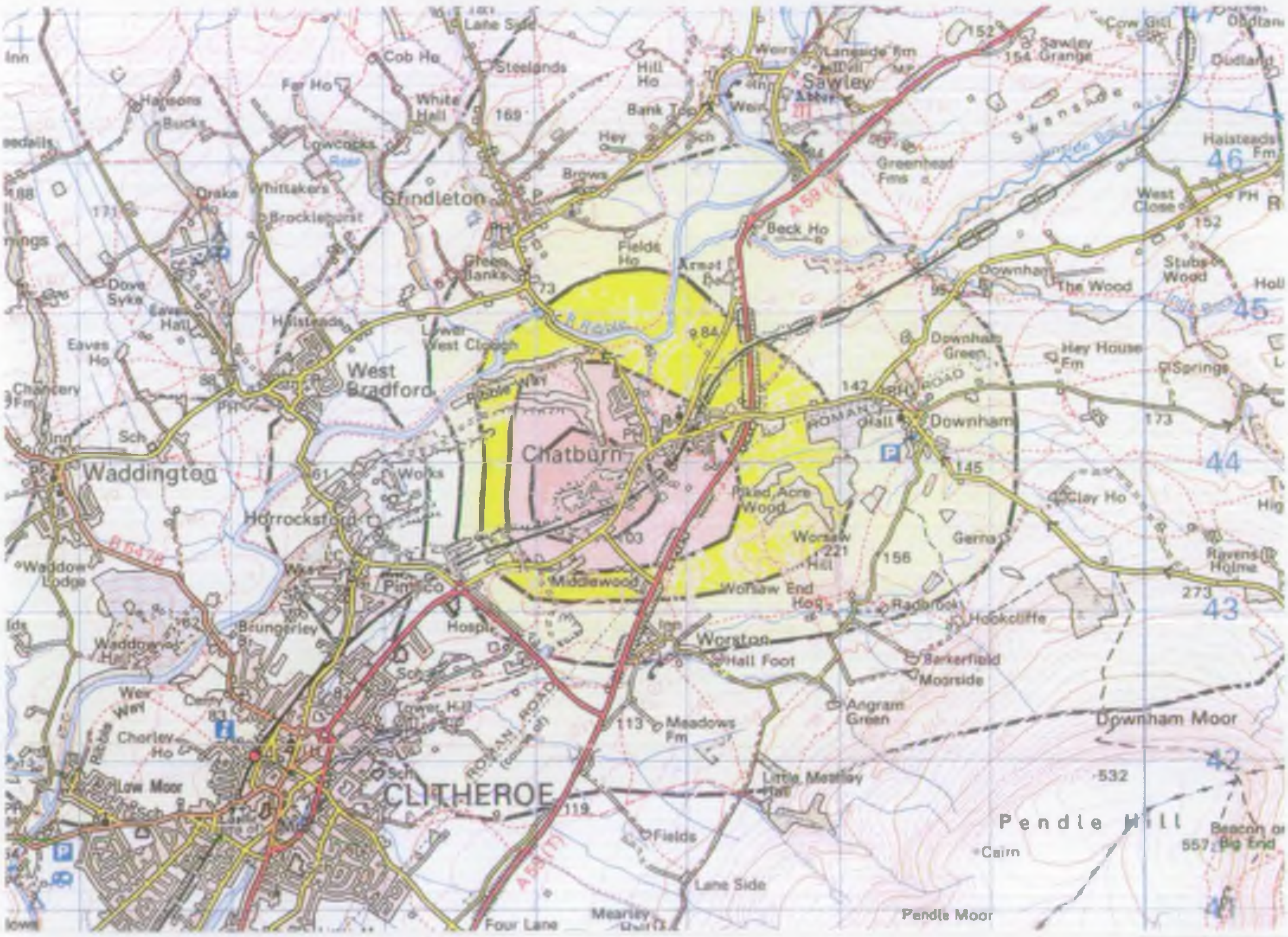
Figure 16(c) Hourly Average Concentration of SO_2 (µg/m^3) from the Dry Kiln, Wind from North West (315°), Pasquill Class F
(i) Complex Terrain Results Superimposed on a Surface Plot
(ii) Complex Terrain Results Superimposed on a Contour Plot





There is no ground level concentration within this area for Stability F in Flat Terrain

Figure 17 Annual Average Concentration of SO_2 From All the Castle Cement Sources, Wilsden Met Data: Complex Terrain



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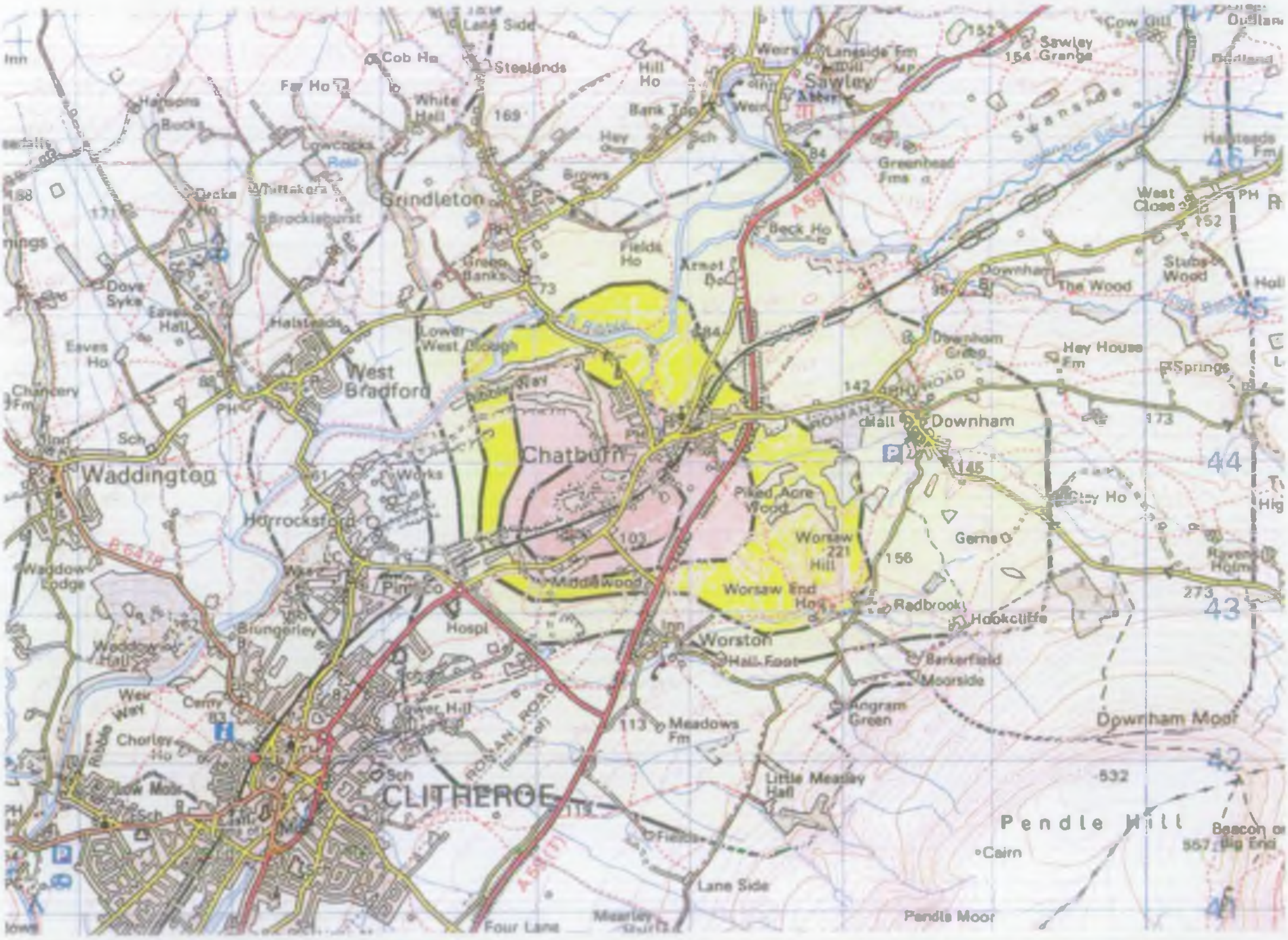
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 2-4
- 4-6
- 6-8
- 8-10
- >10

N

Figure 18 Annual Average Concentration of SO_2 From All the Castle Cement Sources, Wilsden Met Data: Flat Terrain



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0 1 2 3 4 Kilometers

Concentration SO2 (ug/m3)

- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- >12

N

Effects of emitted water on dispersion
b) Dry Kiln (7)

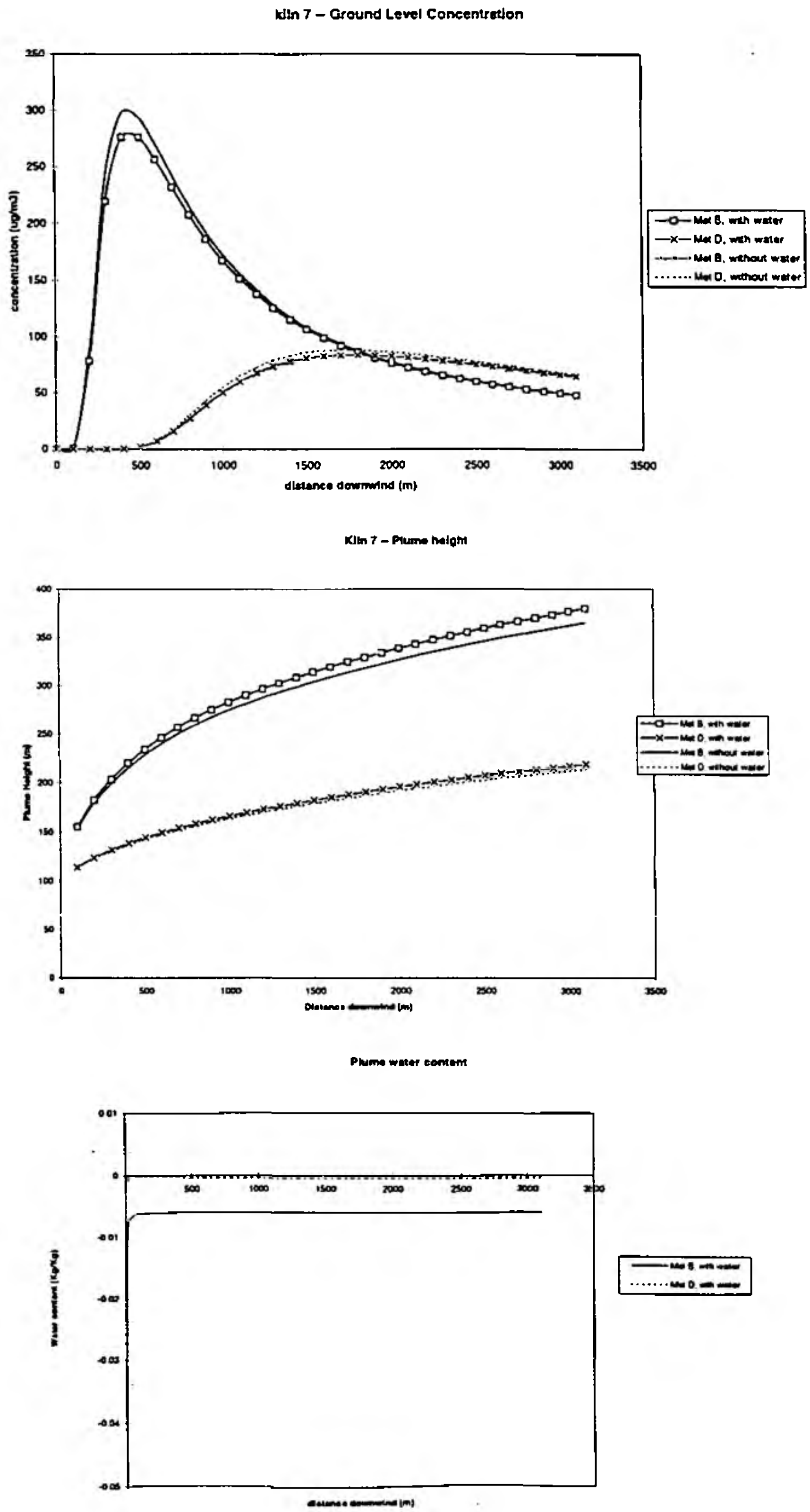


Figure 19 Effect of Emitted Water on dispersion, Pasquill Classes B&D: Case 1 Dry Kiln

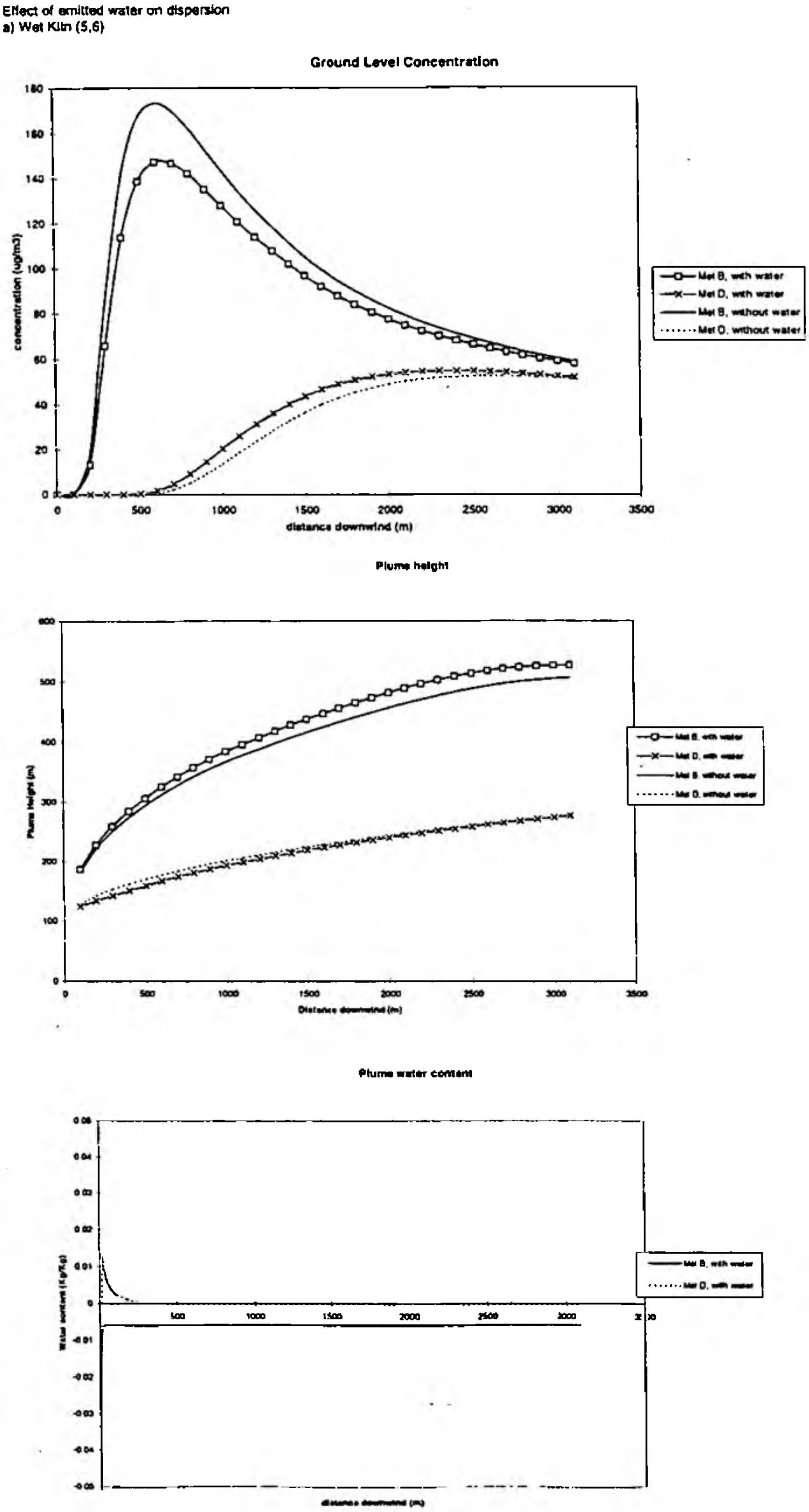


Figure 20 Effect of Emitted Water on dispersion, Pasquill Classes B&D: Case 2 Wet Kiln

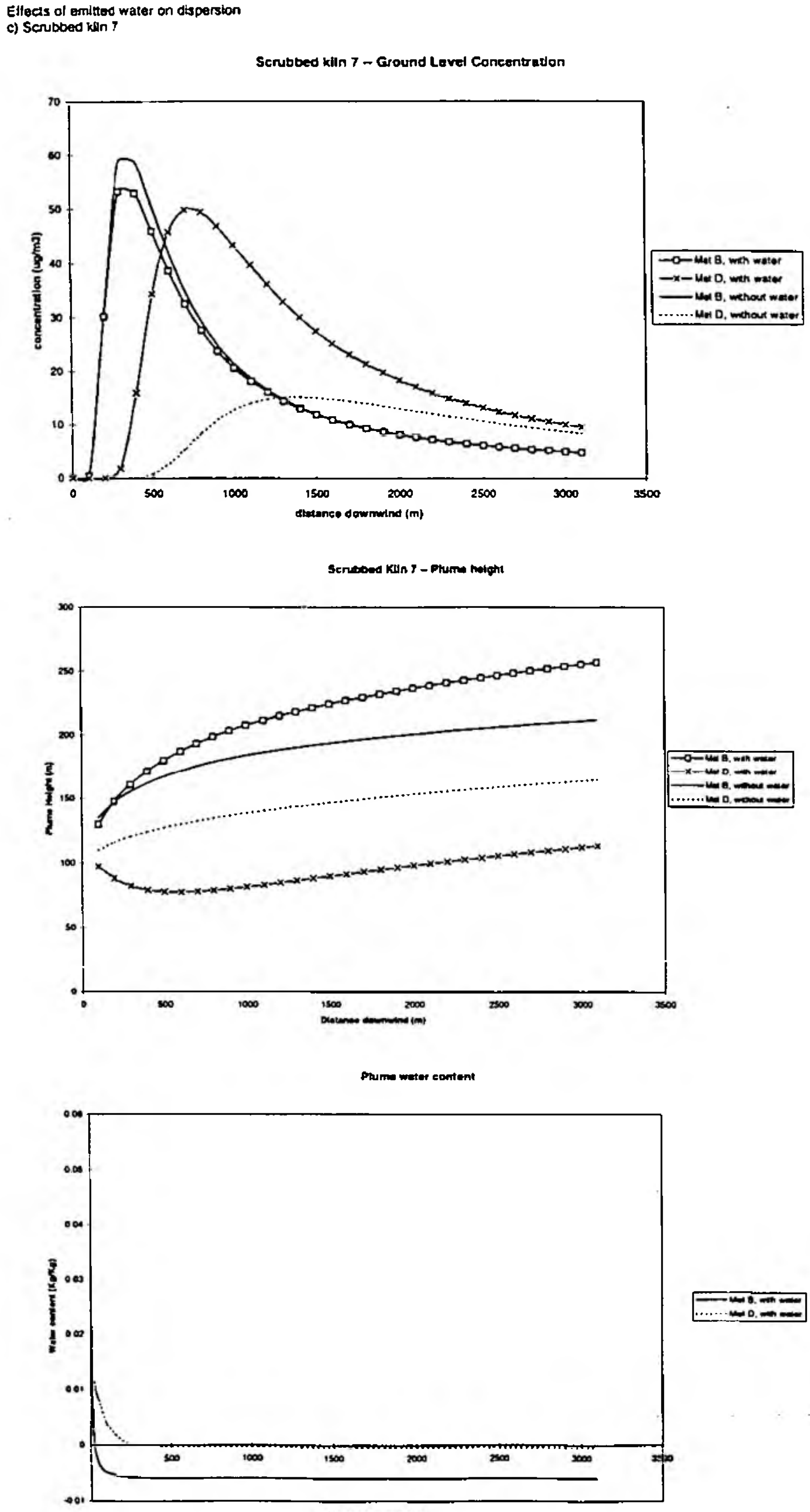
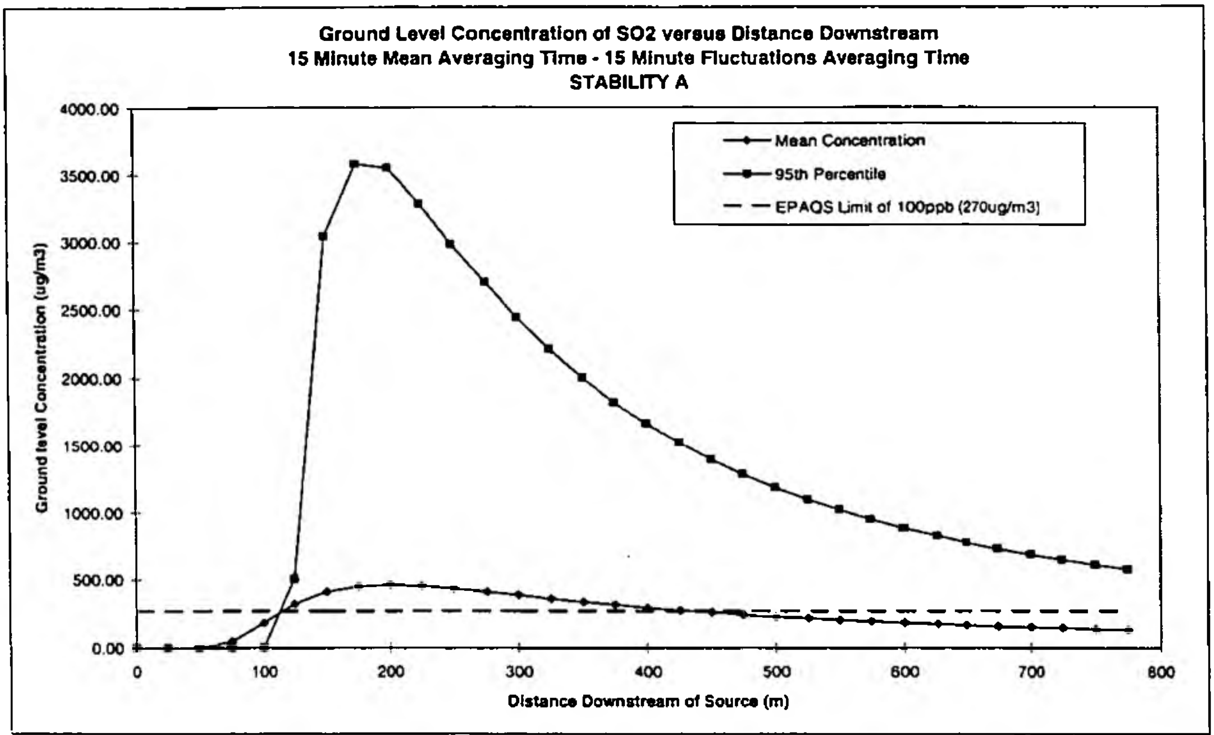


Figure 21 Effect of Emitted Water on dispersion, Pasquill Classes B&D: Case 7 Scrubbed Kiln 7

Figure 22 Variation with distance downstream of 15 minute average and the 95th percentile of 15 minute average ground level concentrations of SO_2, Under 5 Met Cases, Pasquill Classes A-E : Case 1



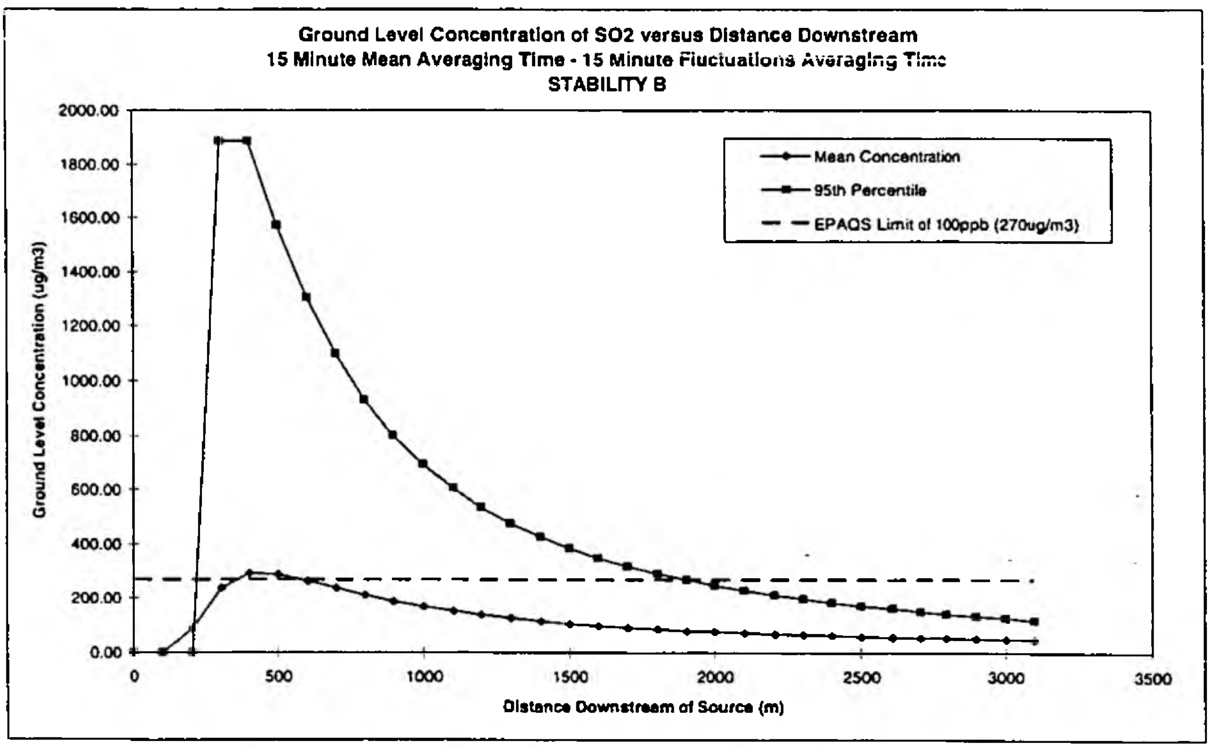
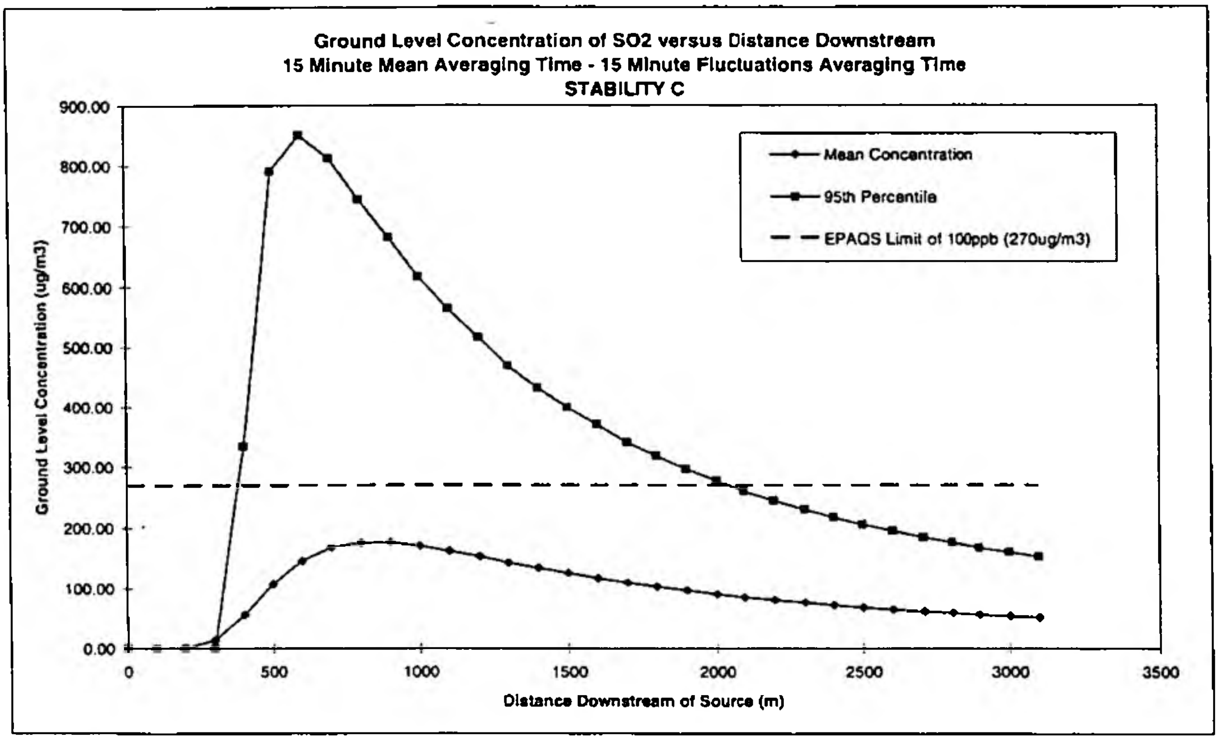


Figure 22 (cont.)



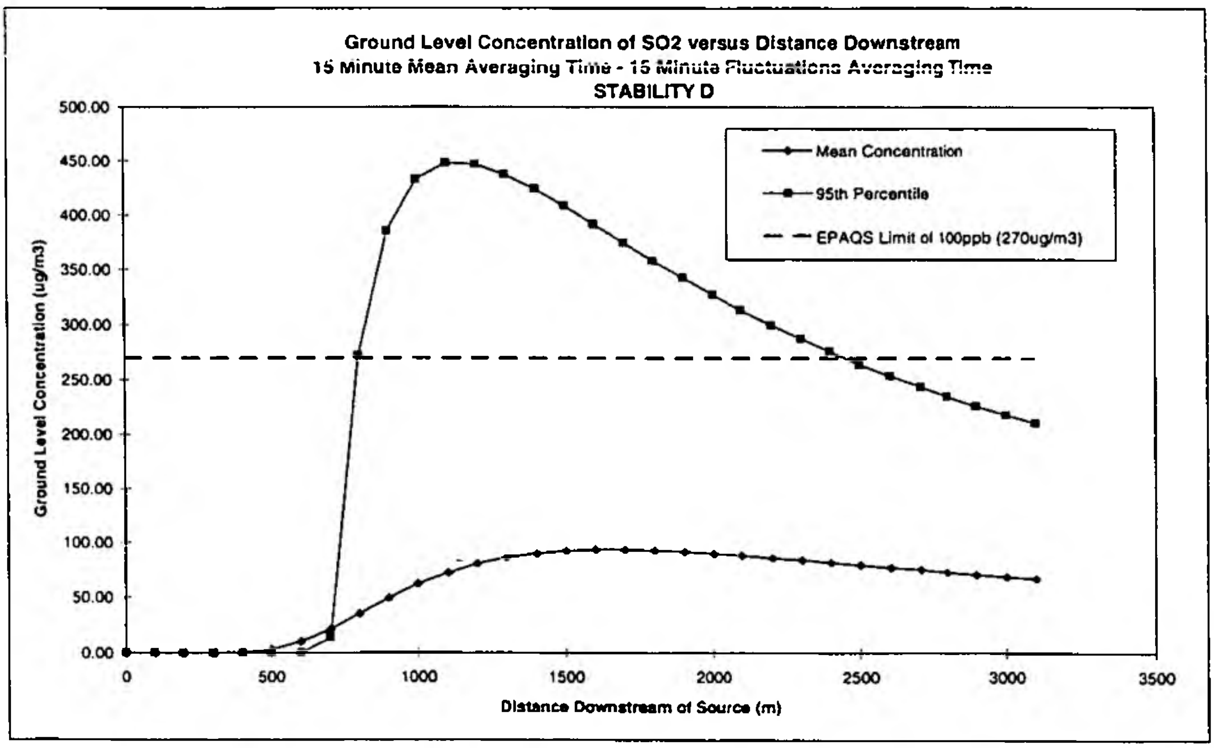


Figure 22 (cont.)

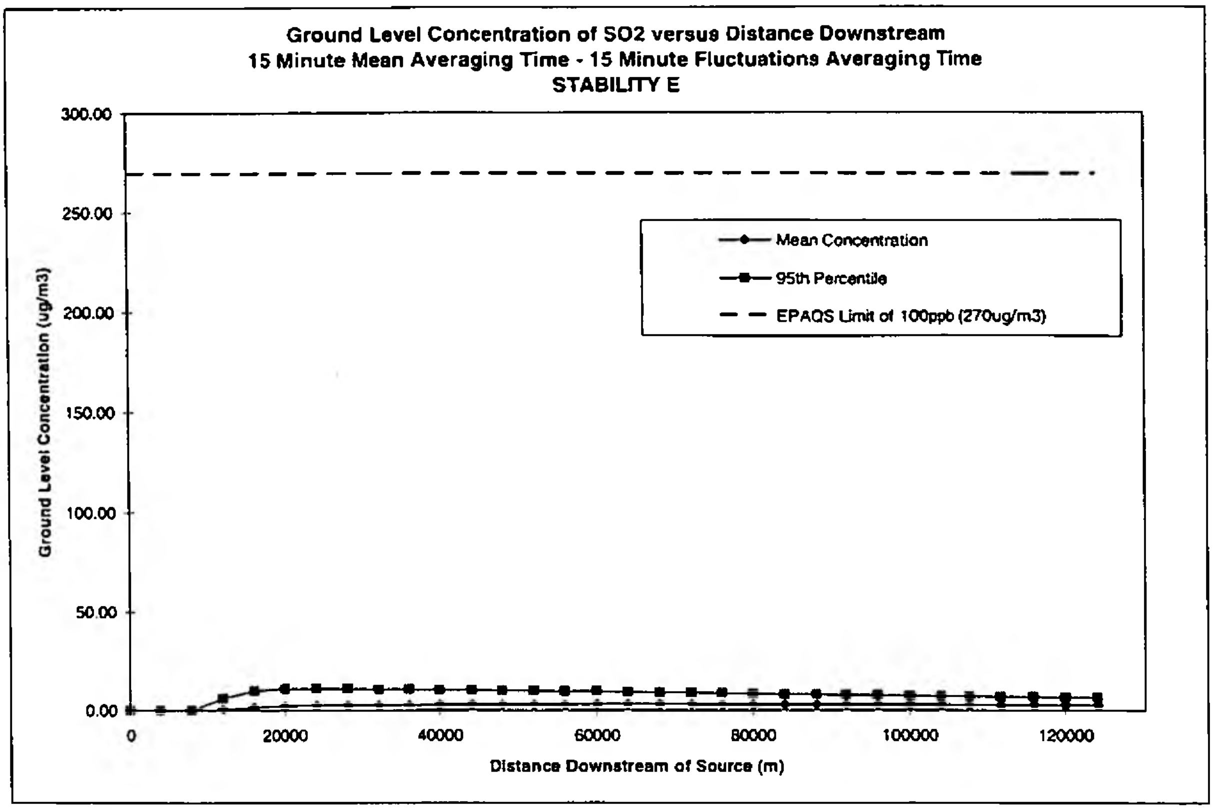
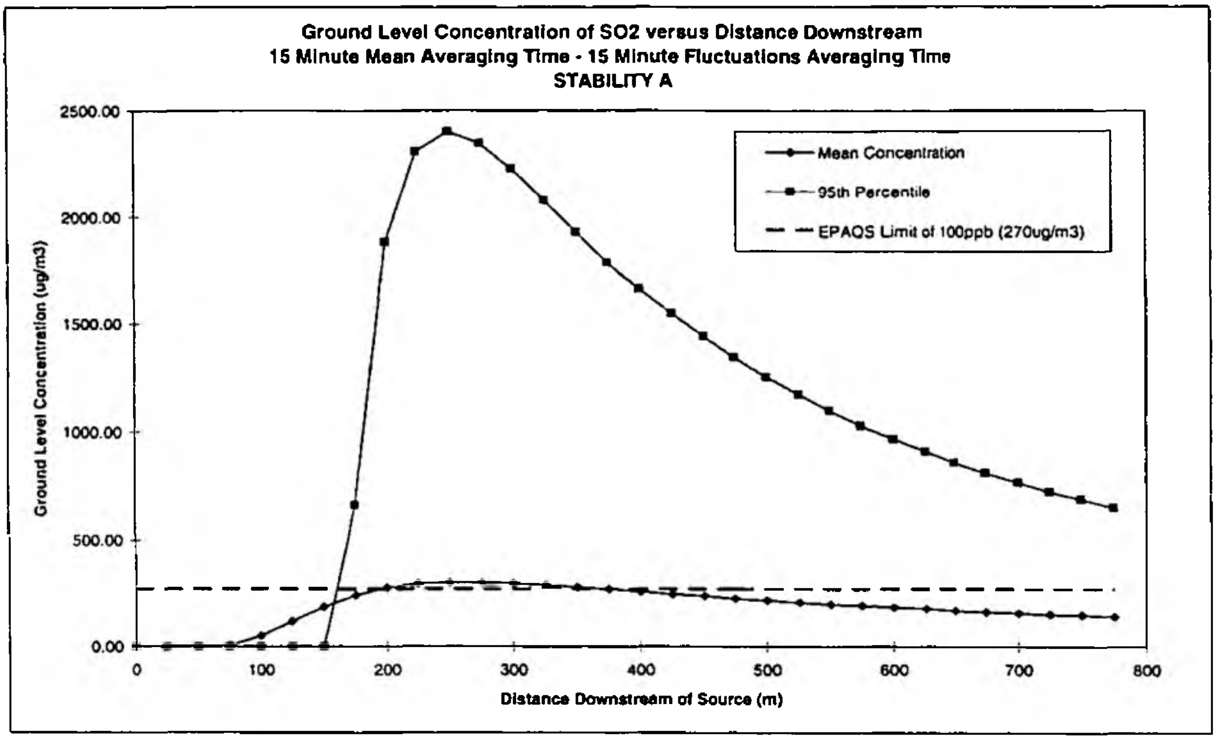


Figure 23 Variation with distance downstream of 15 minute average and the 95th percentile of 15 minute average ground level concentrations of SO_2, Under 5 Met Cases, Pasquill Classes A-E : Case 2



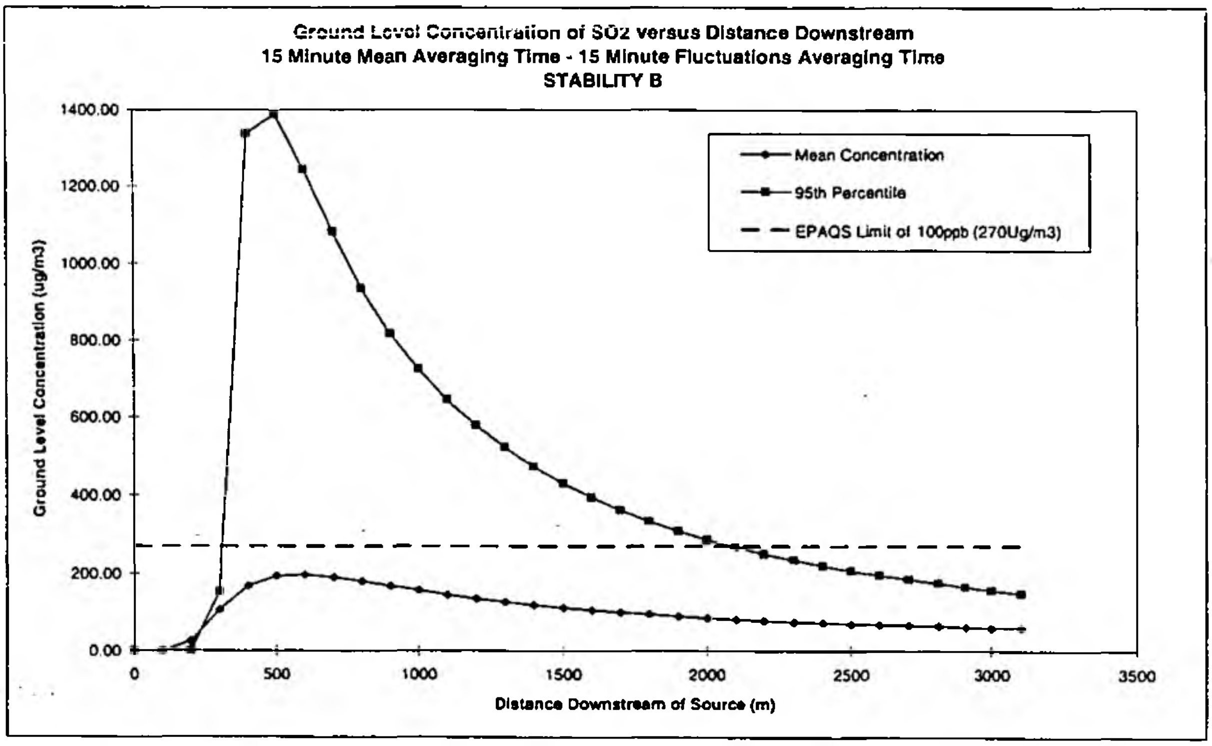
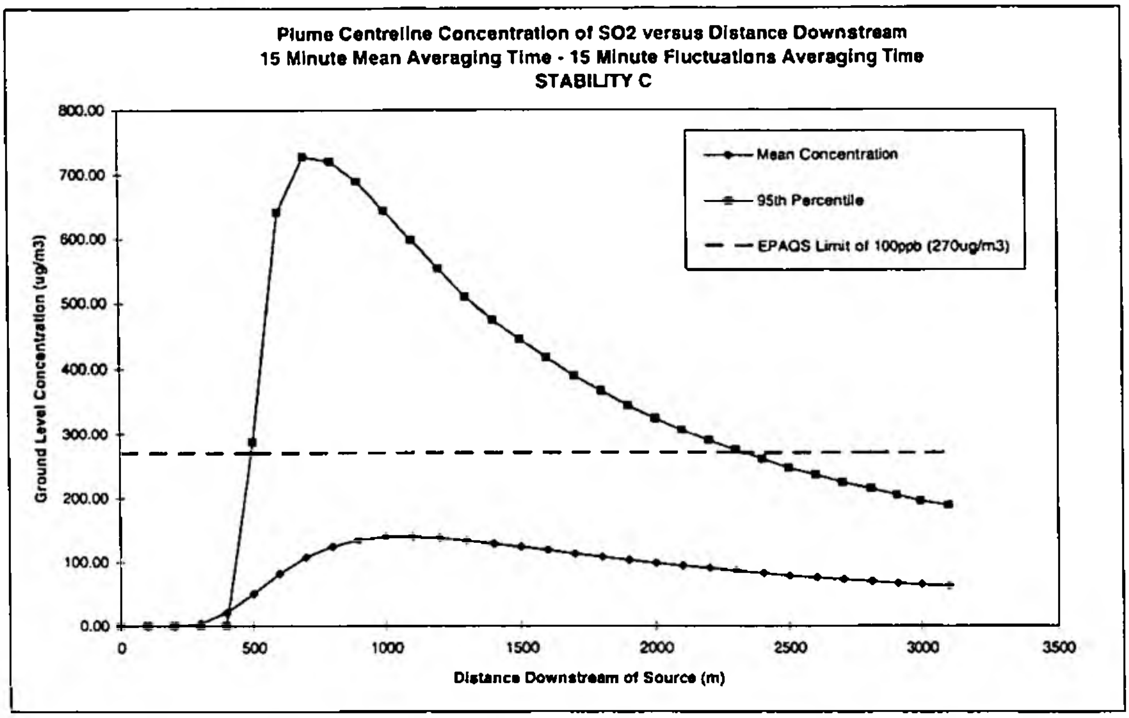


Figure 23 (cont.)



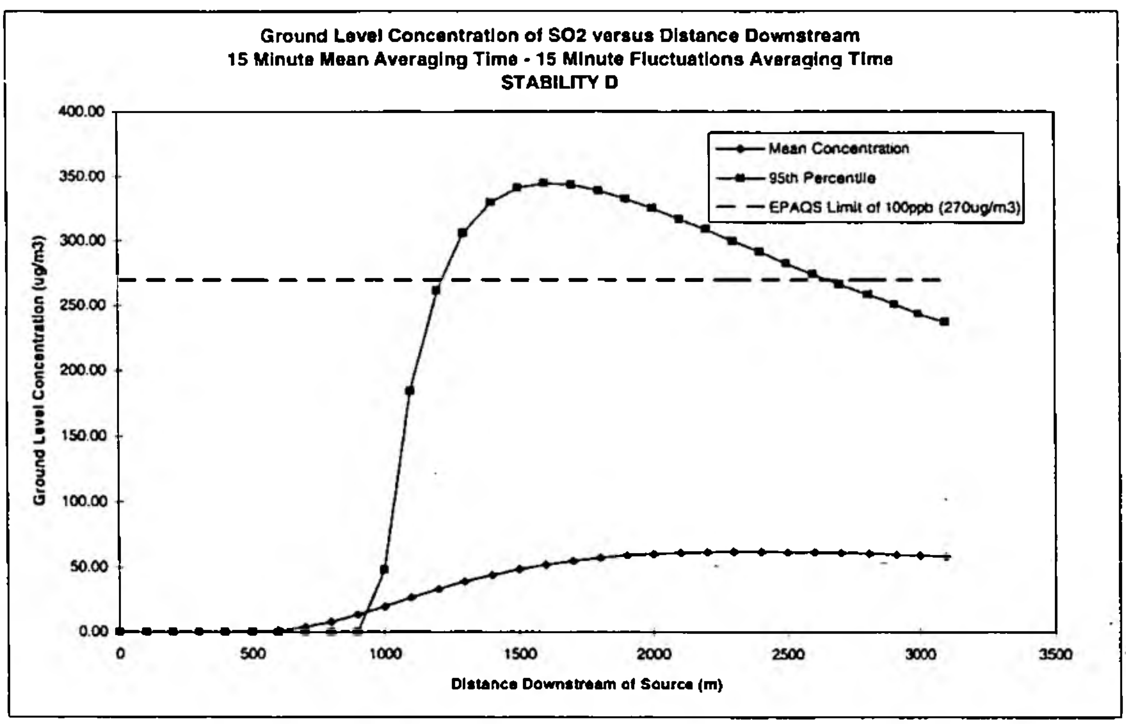


Figure 23 (cont.)

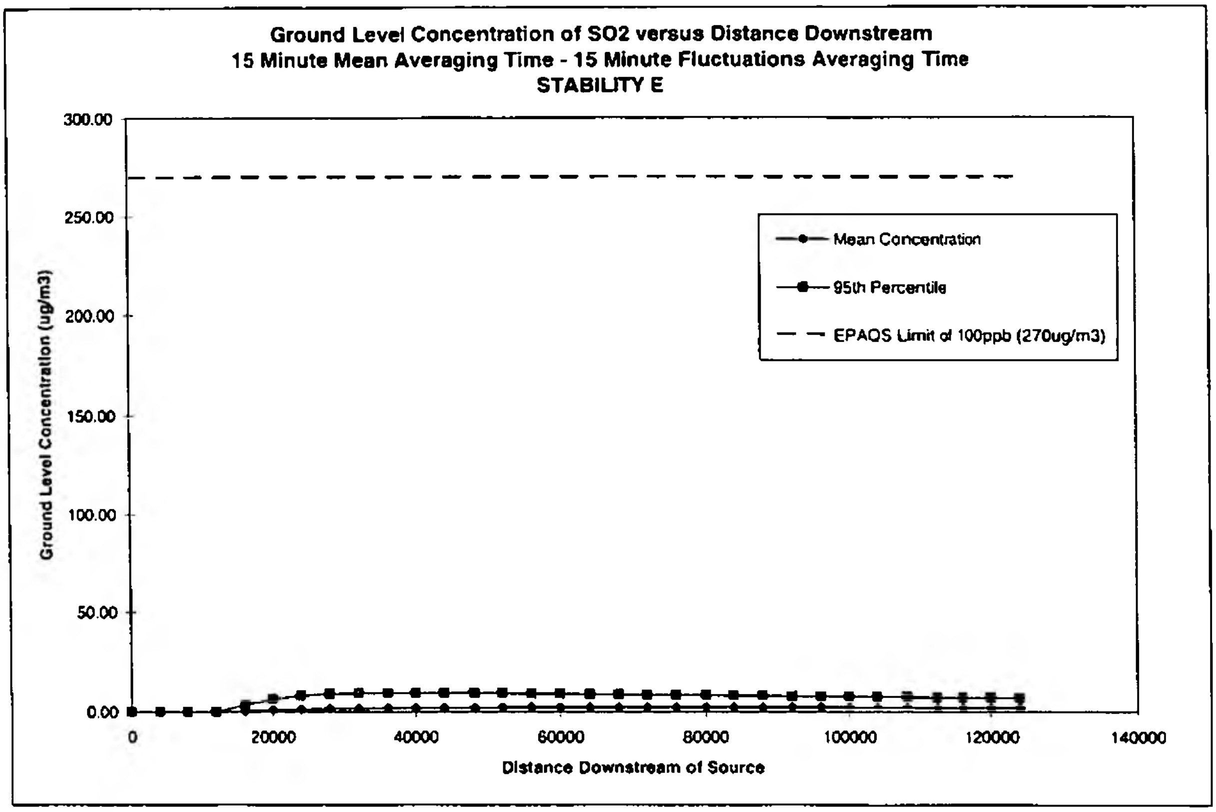
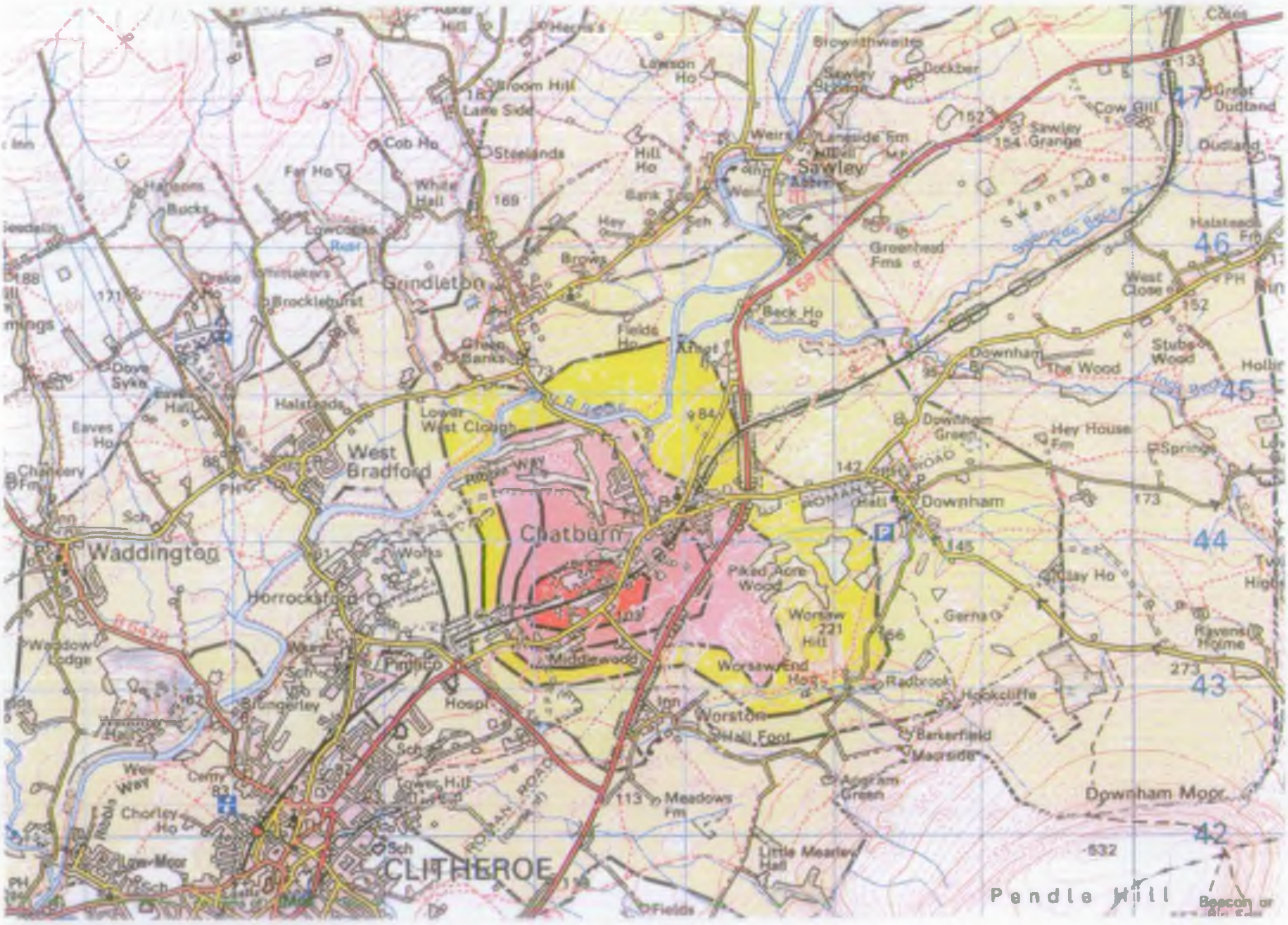


Figure 24 Annual Average Concentration of SO_2, Wilsden Met Data: Case 1



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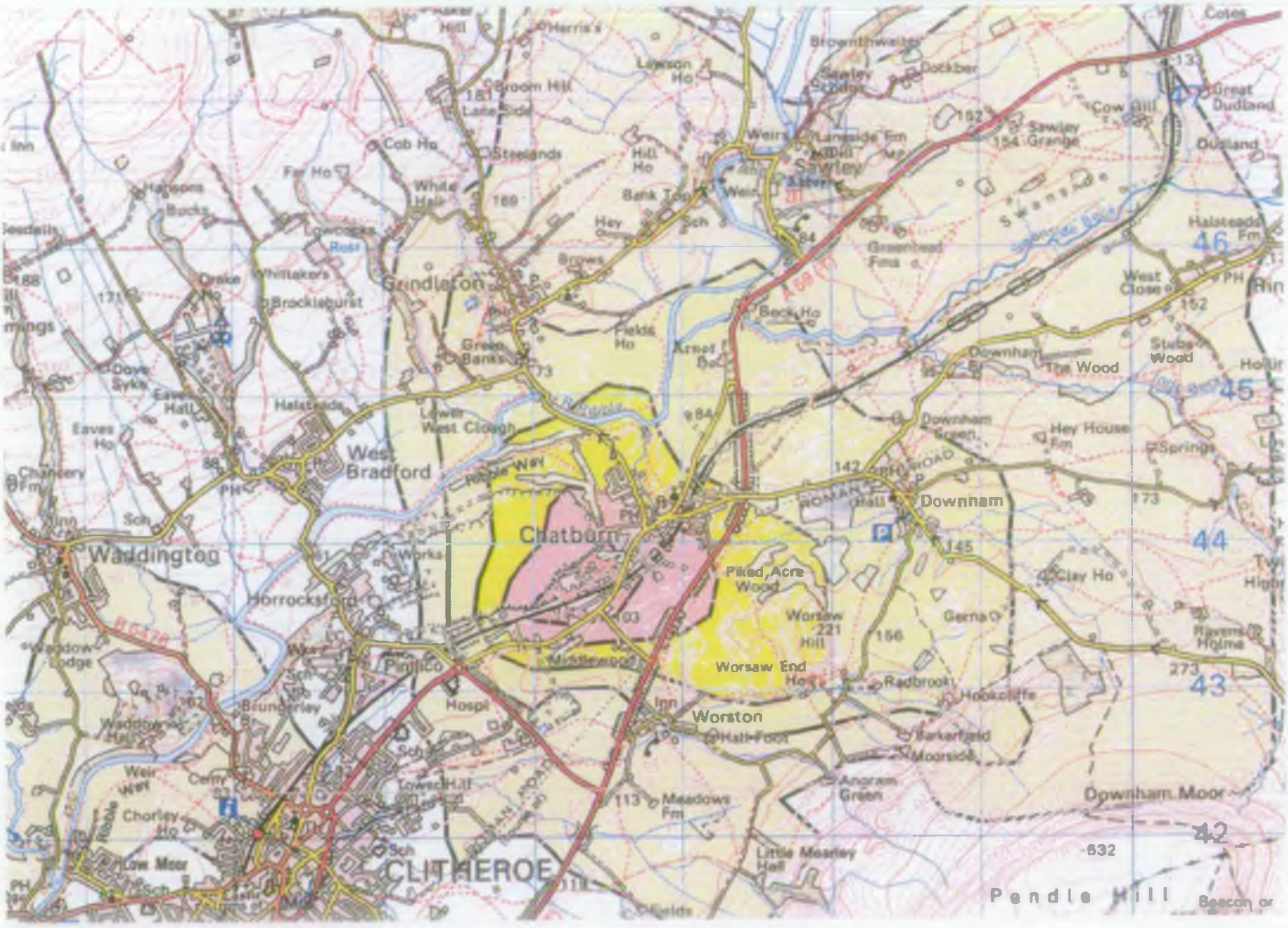
0 1 2 3 4 Kilometers

Concentration SO2 (ug/m3)

- 1-2
- 2-3
- 3-4
- 4-5
- 5-6
- >6

N

Figure 25 Annual Average Concentration of SO_2, Wilsden Met Data: Case 2



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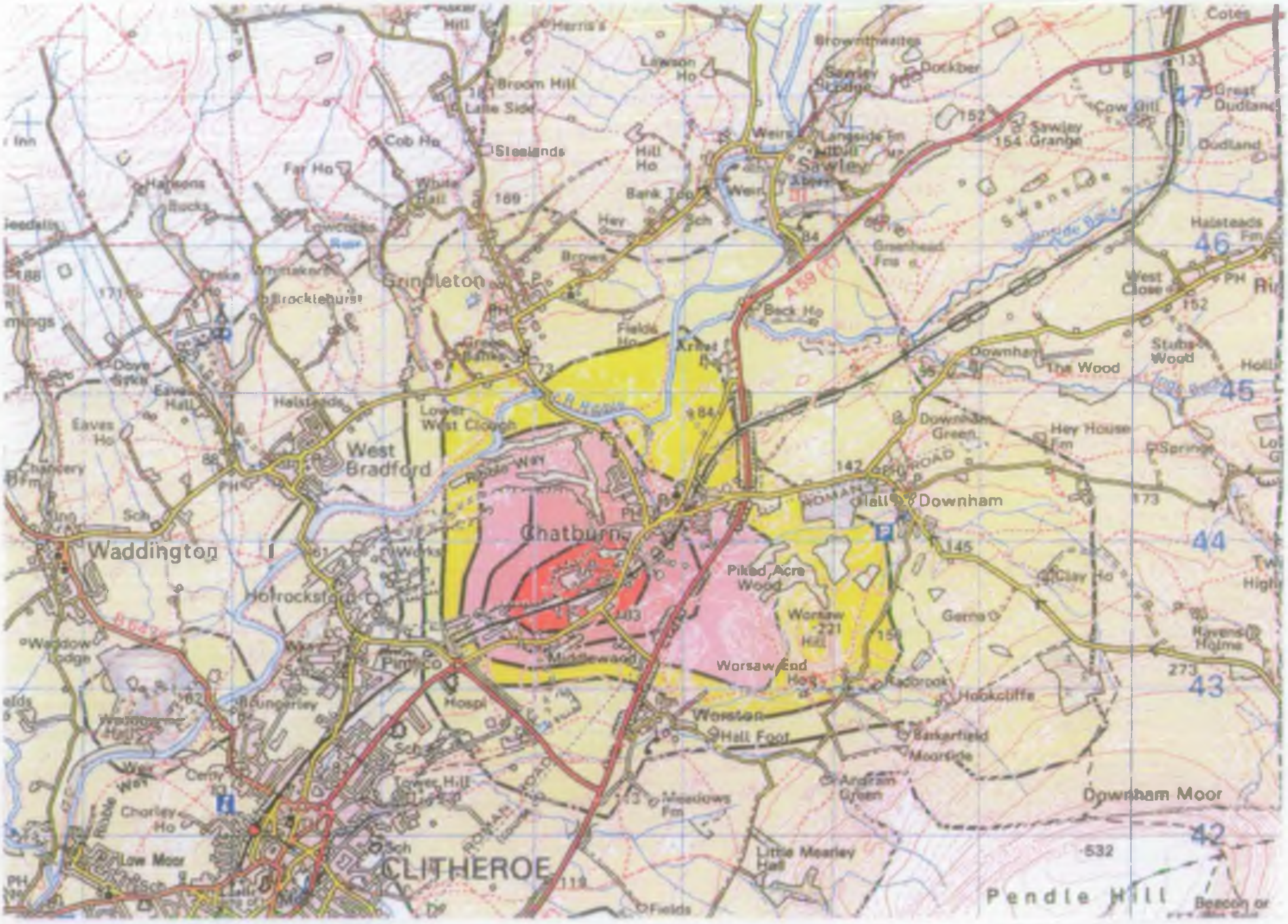
0 1 2 3 4 Kilometers

Concentration SO2 (ug/m3)

- 1-2
- 2-3
- 3-4
- 4-5
- >5

N

Figure 26 Annual Average Concentration of SO_2, Wilsden Met Data: Case 3



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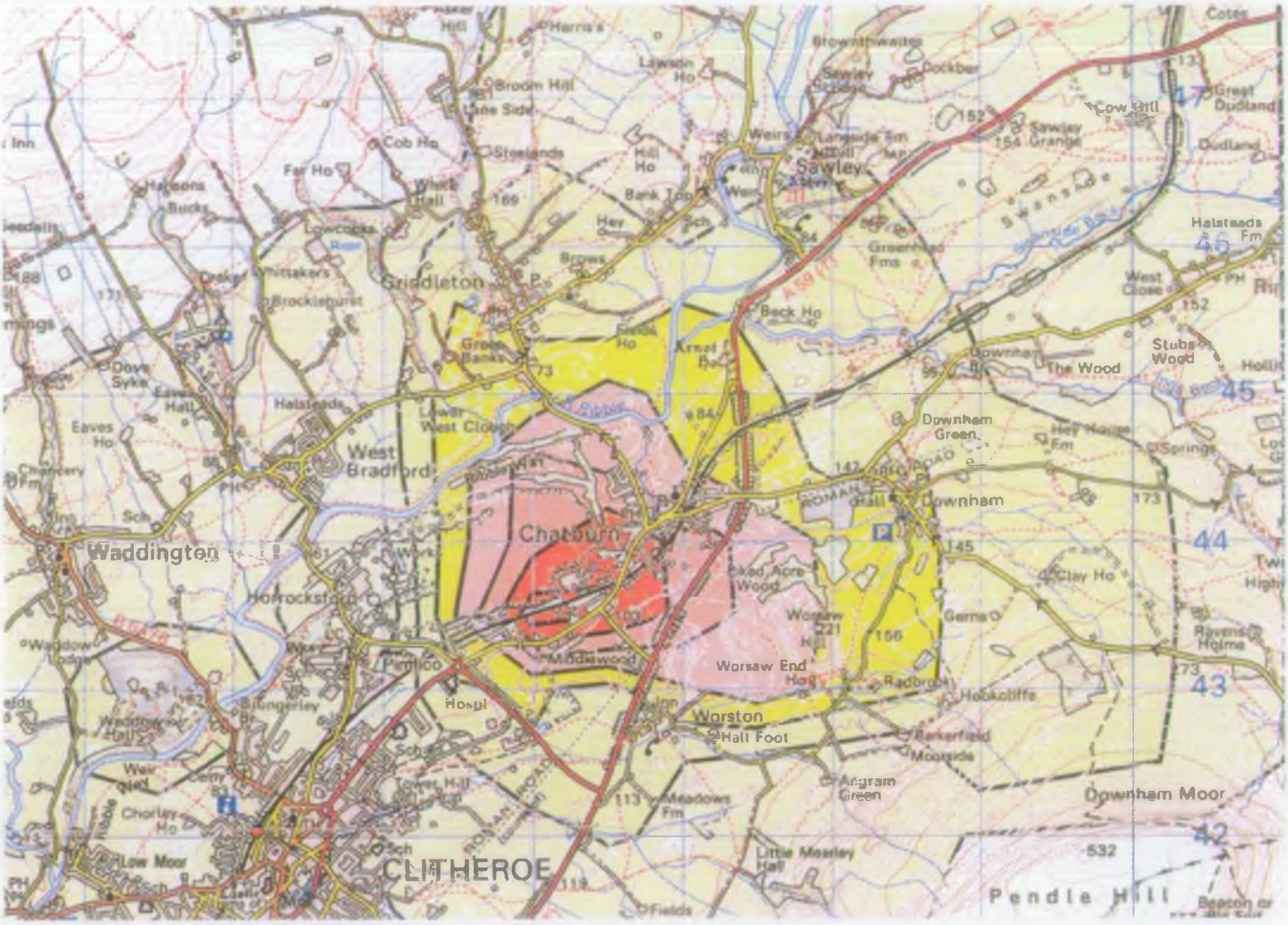
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 0.5-1
- 1-1.5
- 1.5-2
- 2-2.5
- 2.5-3
- >3

Figure 27 Annual Average Concentration of SO_2, Wilsden
Met Data: Case 4



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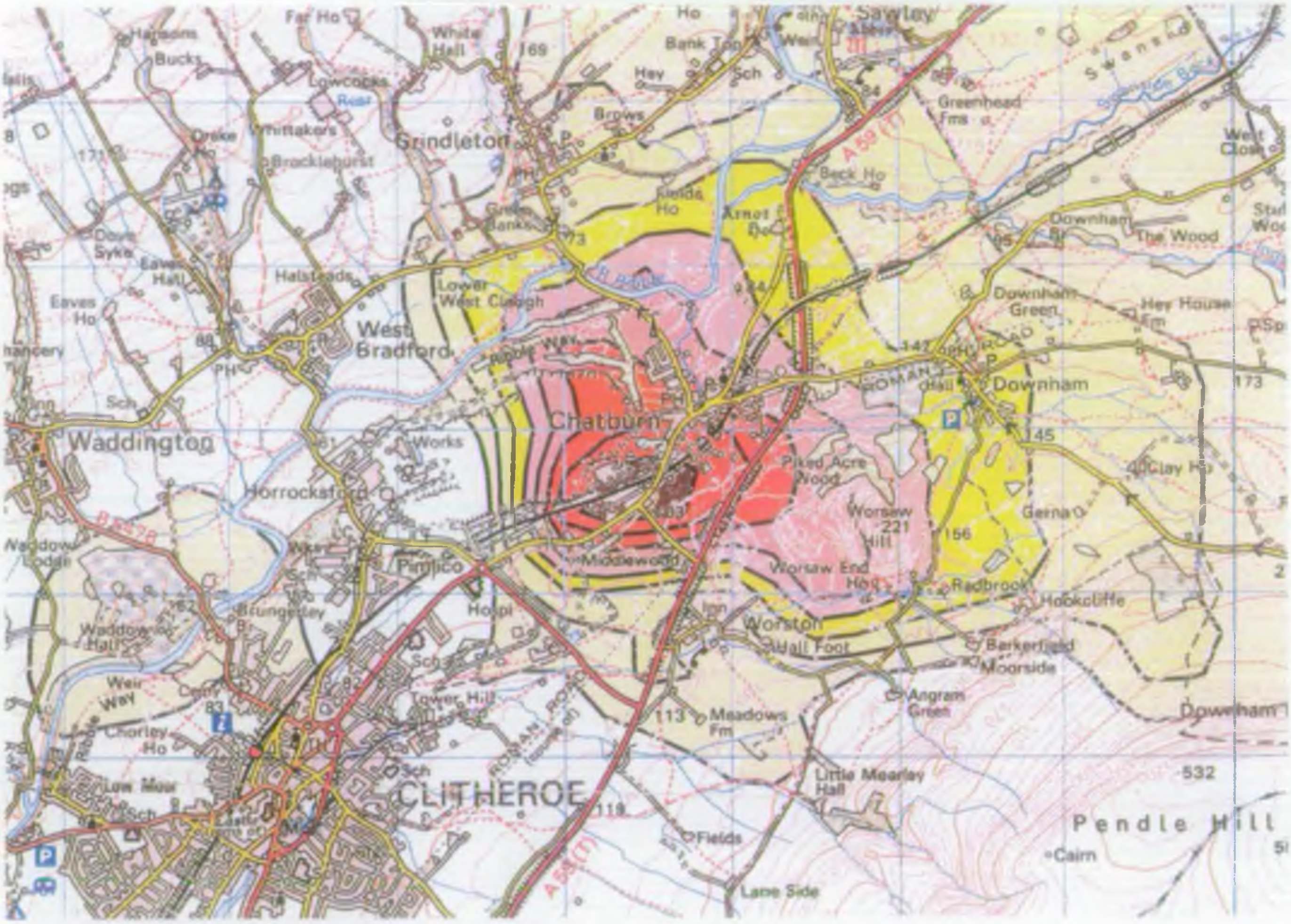
0 1 2 3 4 Kilometers

Concentration SO2 (ug/m3)

- 0.5-1
- 1-1.5
- 1.5-2
- 2-2.5
- 2.5-3
- 3-3.5
- >3.5

Figure 28 Annual Average Concentration of SO_2, Wilsden Met Data: Case 6



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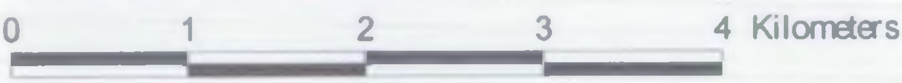
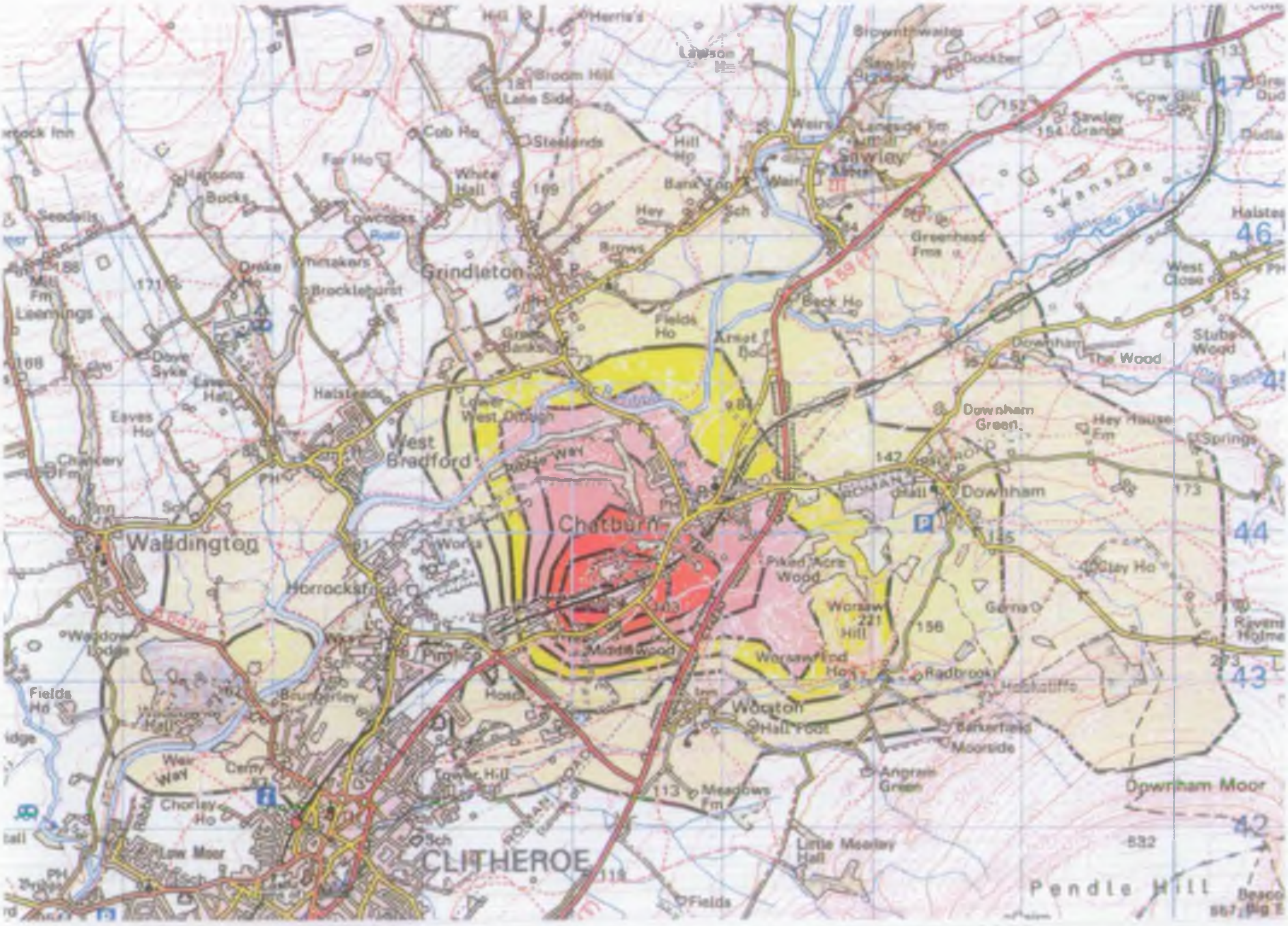


Concentration of SO2 (ug/m3)

- 1-1.5
- 1.5-2.0
- 2.0-2.5
- 2.5-3.0
- 3.0-3.5
- 3.5-4.0
- 4.0-4.5
- >4.5

Figure 29 Annual Average Concentration of SO_2, Wilsden
Met Data: Case 7



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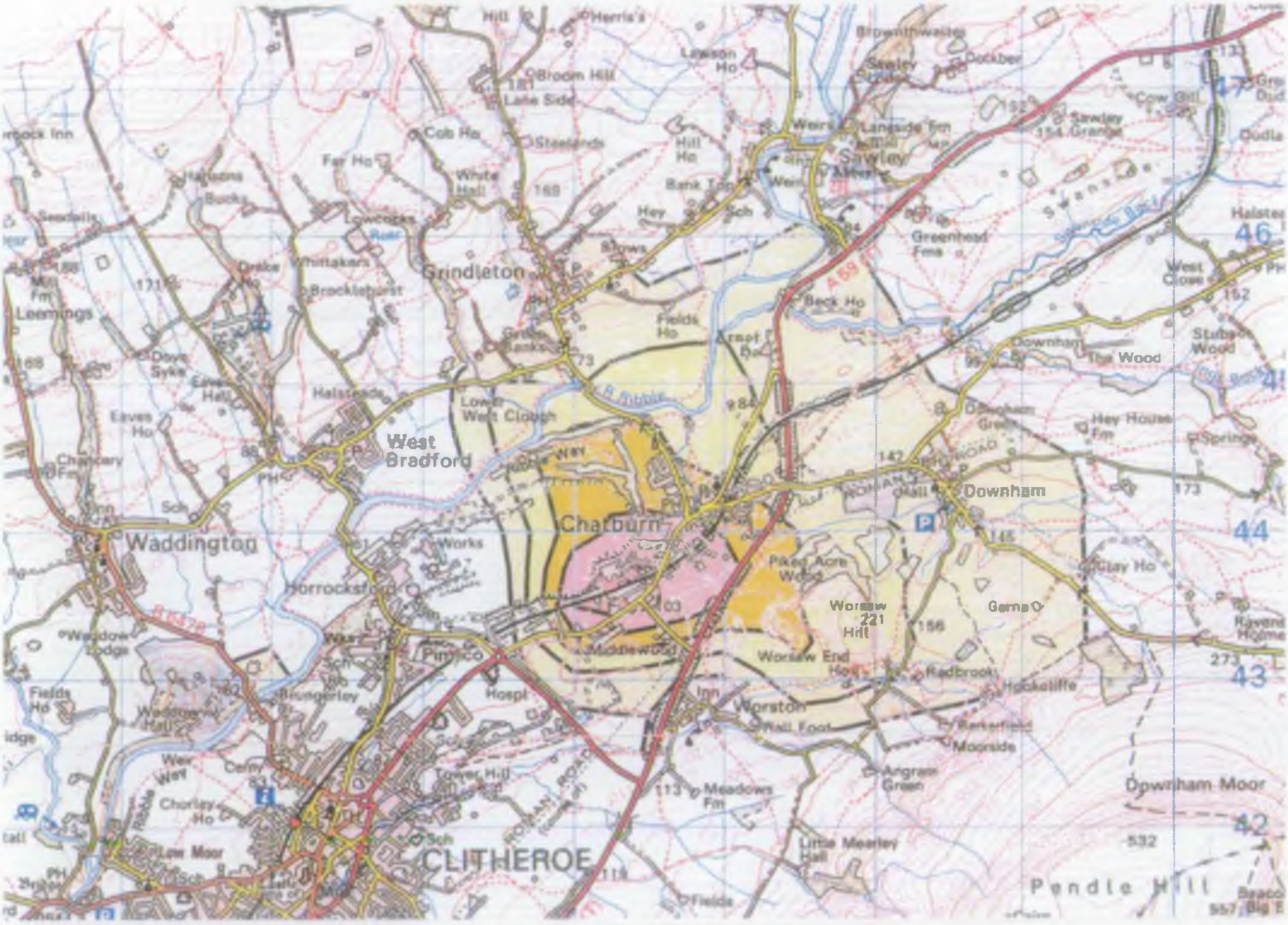
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 0.2-0.3
- 0.3-0.4
- 0.4-0.5
- 0.5-0.6
- 0.6-0.7
- 0.7-0.8
- 0.8-0.9
- >0.9

N

Figure 30 Annual Average Concentration of SO_2, Wilsden
Met Data: Case 8



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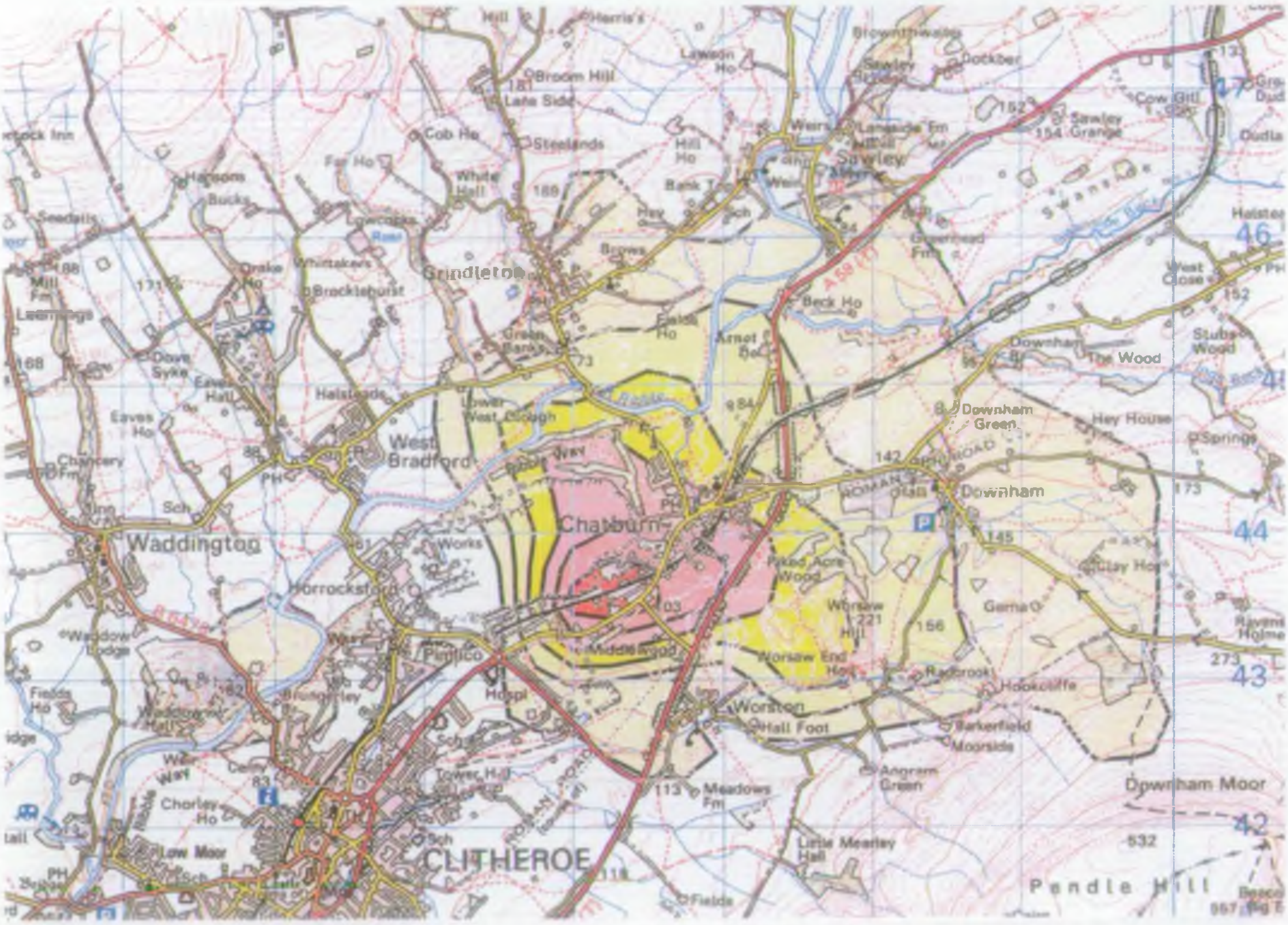
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 0.2
- 0.3
- 0.4
- 0.5
- 0.6

N

Figure 31 Annual Average Concentration of SO_2, Wilsden Met Data: Case 9



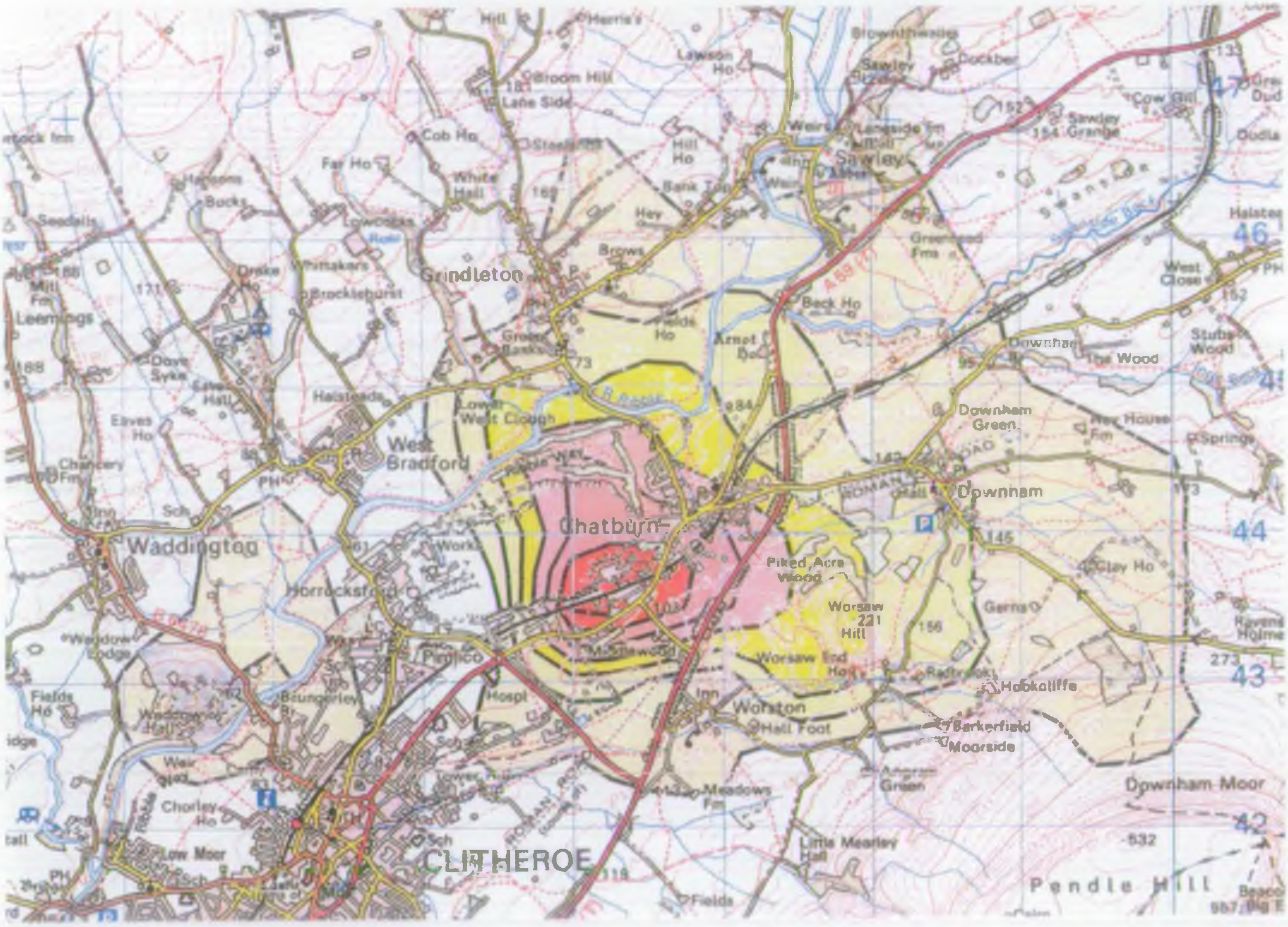
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 0.2-0.3
- 0.3-0.4
- 0.4-0.5
- 0.5-0.6
- 0.6-0.7
- >0.7

N

Figure 32 Annual Average Concentration of SO_2, Wilsden
Met Data: Case 10



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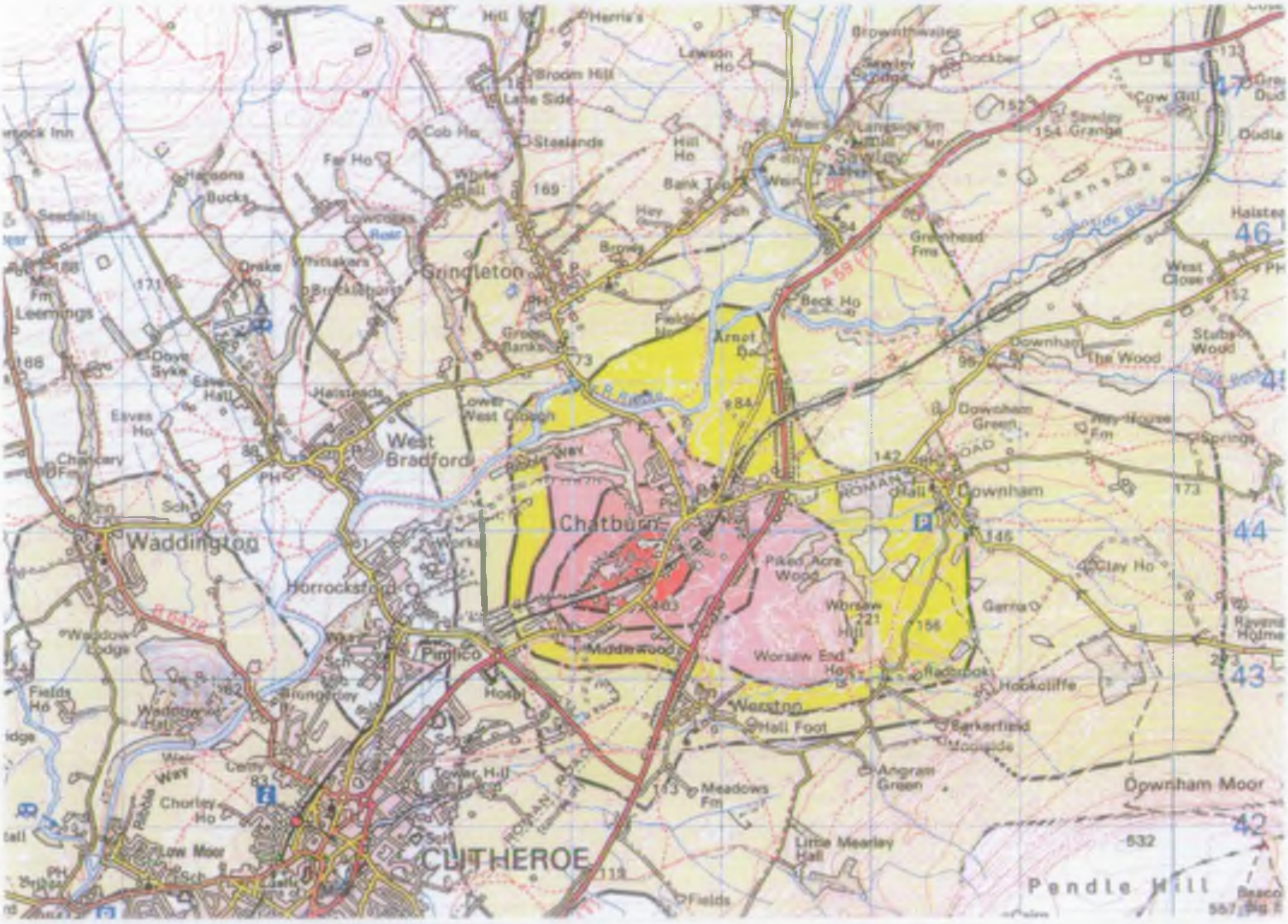
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 0.2-0.3
- 0.3-0.4
- 0.4-0.5
- 0.5-0.6
- 0.6-0.7
- 0.7-0.8
- >0.8

N

Figure 33 Annual Average Concentration of SO_2, Wilsden Met Data: Case 11



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0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 1-2
- 2-3
- 3-4
- 4-5
- 5-6
- >6

N

Figure 34 Annual Average Concentration of SO_2, Wilsden
Met Data: Case 12

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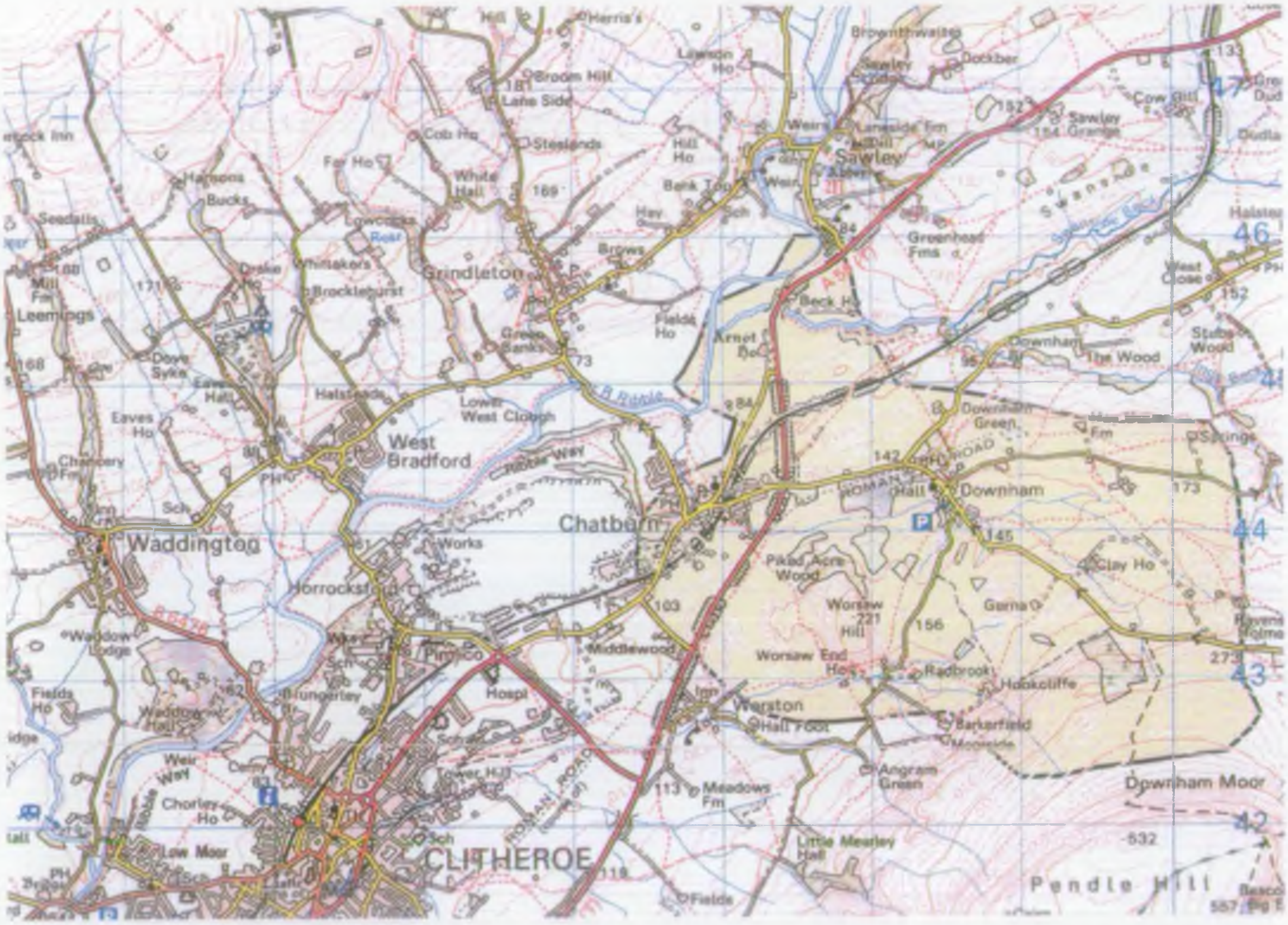
0 1 2 3 4 Kilometers

Concentration of SO2 (ug/m3)

- 1-2
- 2-3
- >3

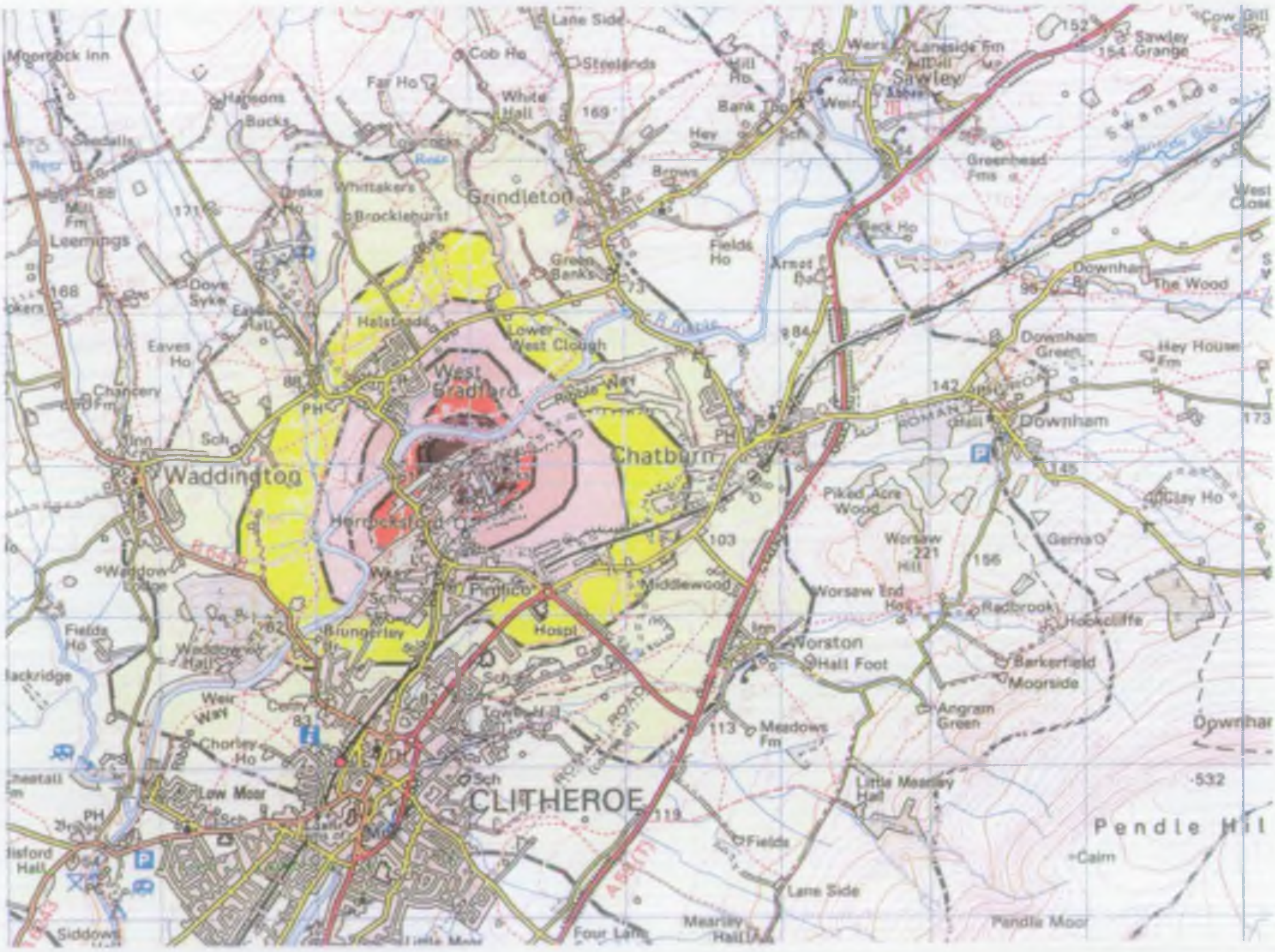
Figure 35 Annual Average Concentration of SO_2,
Wilsden Met Data: Case 13



Concentration of SO2 (ug/m3)

1

Figure 36 24 Hour Average Concentration of Particulates, Ringway Met Data: All Castle Cement Sources



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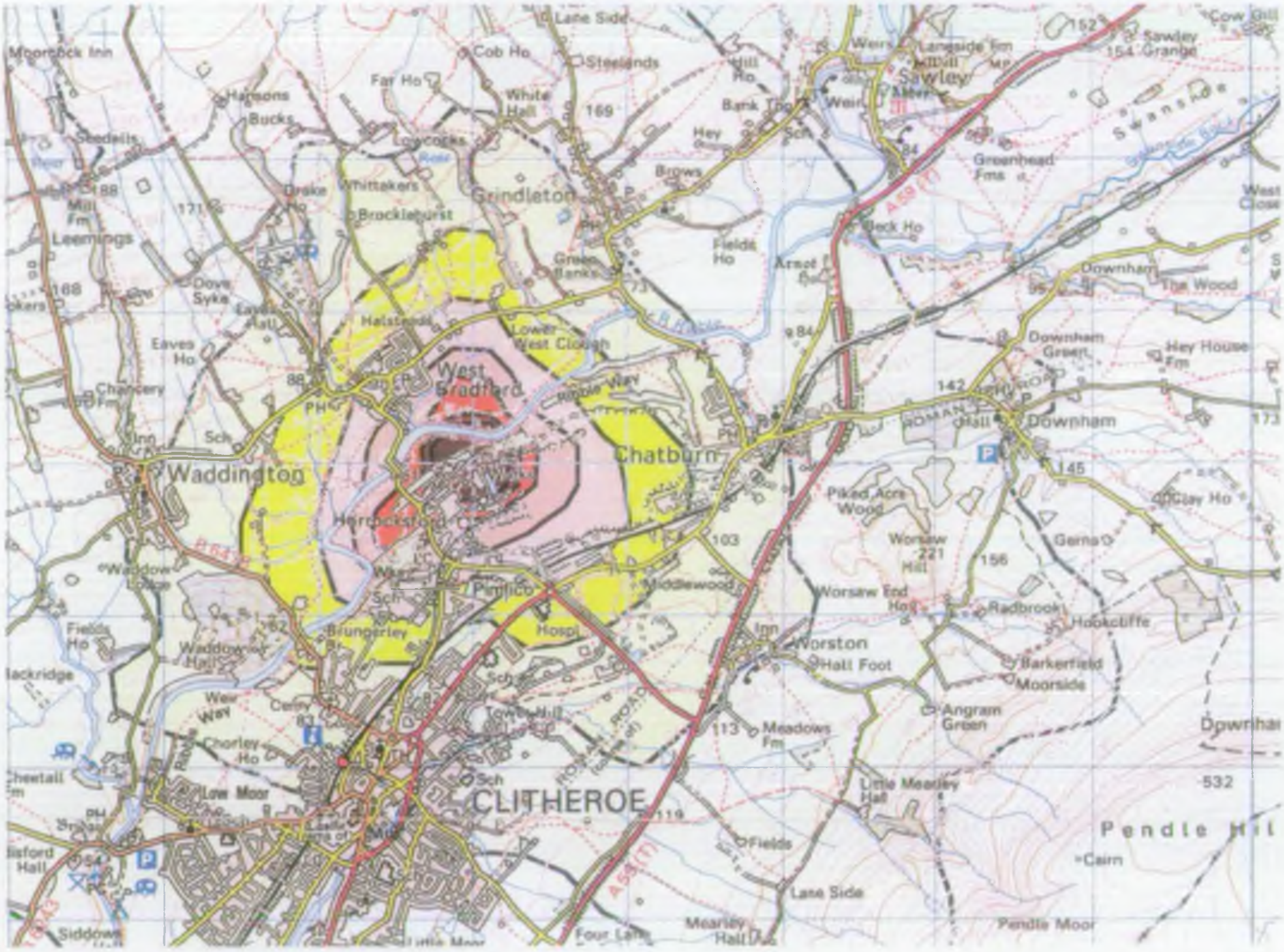
0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- 12-14
- 14-16
- >16

N

Figure 37 24 Hour Average Concentration of Particulates, Ringway Met Data: Cement Mills Only



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0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- 12-14
- 14-16
- >16

N

Figure 38 24 Hour Average Concentration of Particulates, Squires Gate Met Data: All Castle Cement Sources

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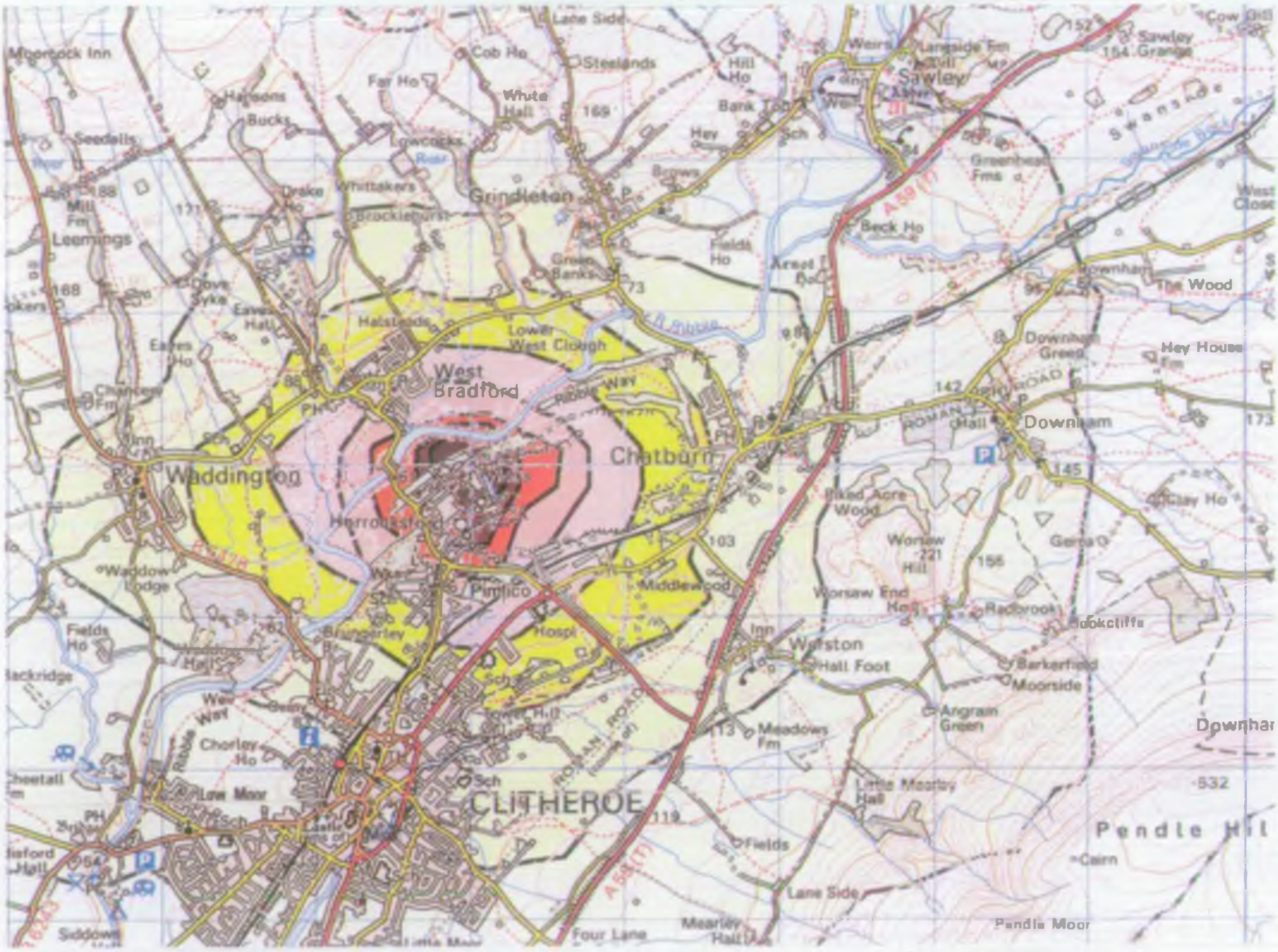
Concentration of Particulates (ug/m3)

- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- 12-14
- 14-16
- >16

Figure 39 24 Hour Average Concentration of Particulates, Squires Gate Met Data: Cement Mills Only



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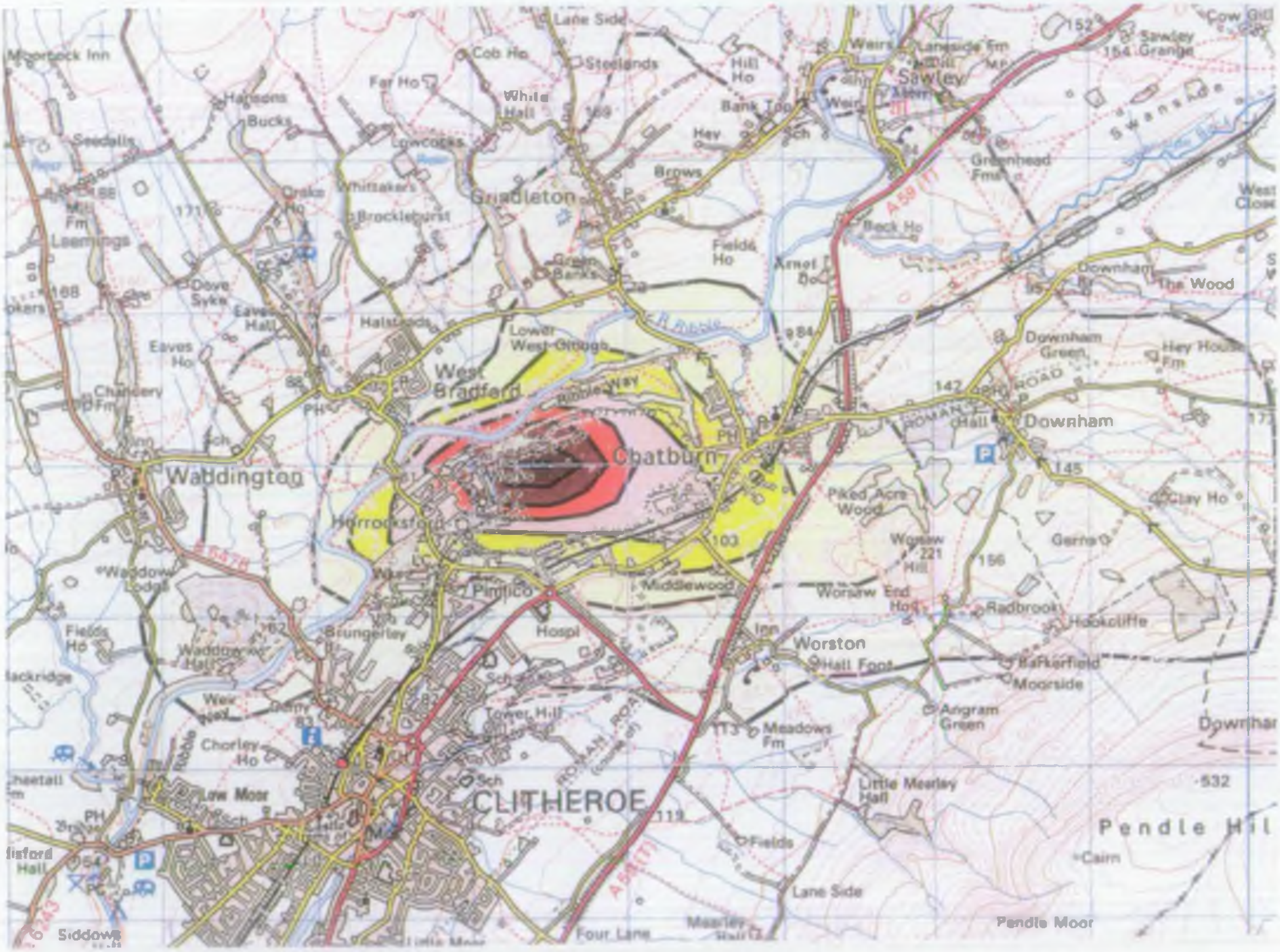
0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- 12-14
- 14-16
- >16

N

Figure 40 Annual Average Concentration of Particulates, Wilsden: Particulates Case (1+2+5).



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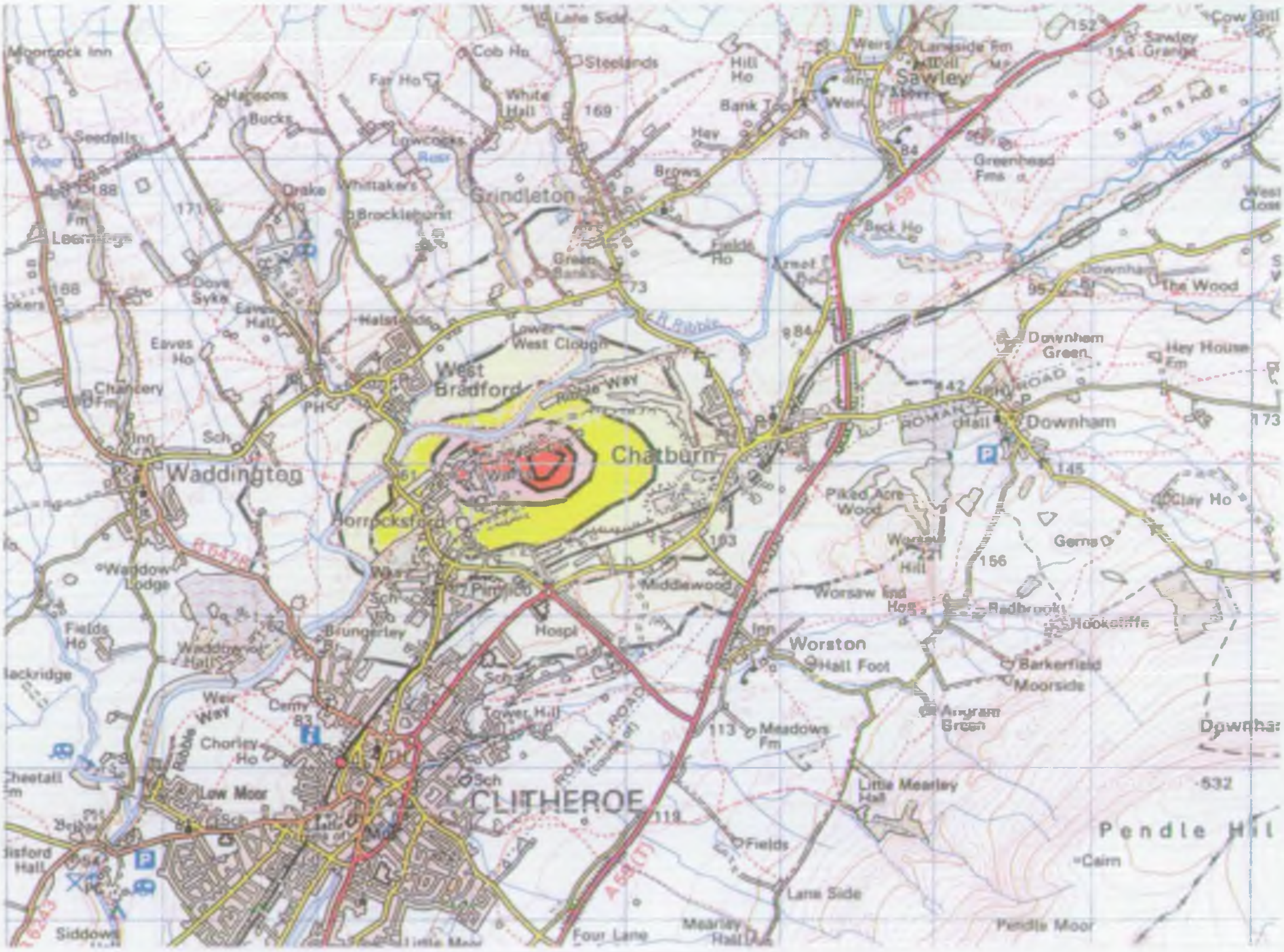
0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 0.3-0.6
- 0.6-0.9
- 0.9-1.2
- 1.2-1.5
- 1.5-1.8
- 1.8-2.1
- 2.1-2.4
- >2.4

N

Figure 41 Annual Average Concentration of Particulates, Wilsden: Particulates Case 5.



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0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 0.3-0.6
- 0.6-0.9
- 0.9-1.2
- 1.2-1.5
- 1.5-1.8
- >1.8

Figure 42 Annual Average Concentration of Particulates, Wilsden: Particulates Case (1+2).

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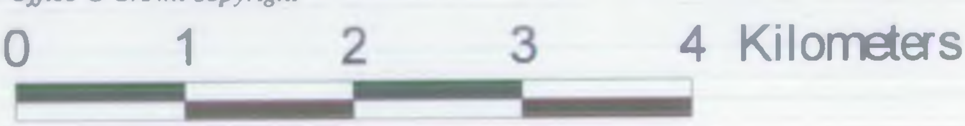
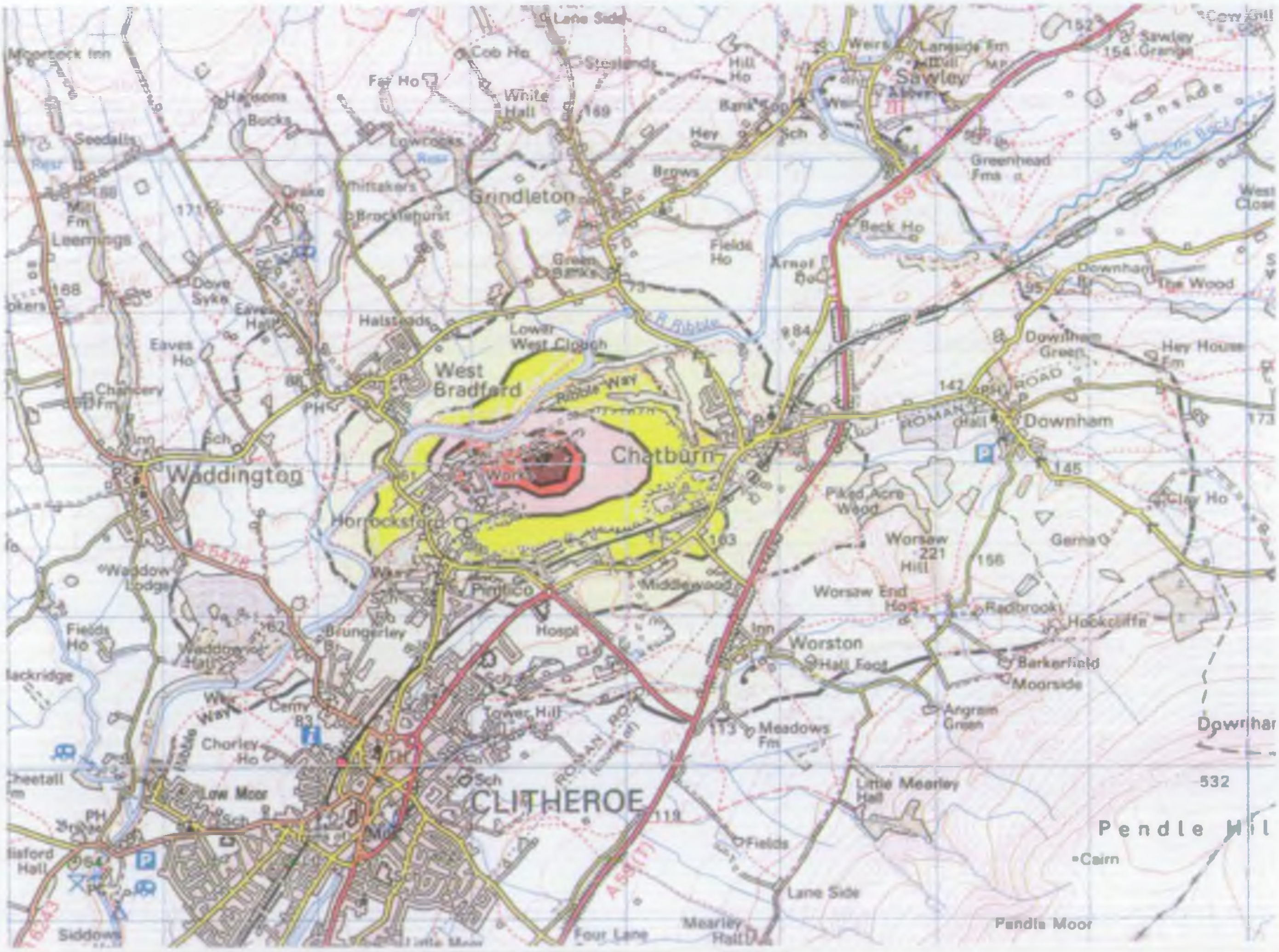


Concentration of Particulates (ug/m3)

☐ 0.3-0.6

Figure 43 Annual Average Concentration of Particulates, Wilsden: Particulates Case (5+8).



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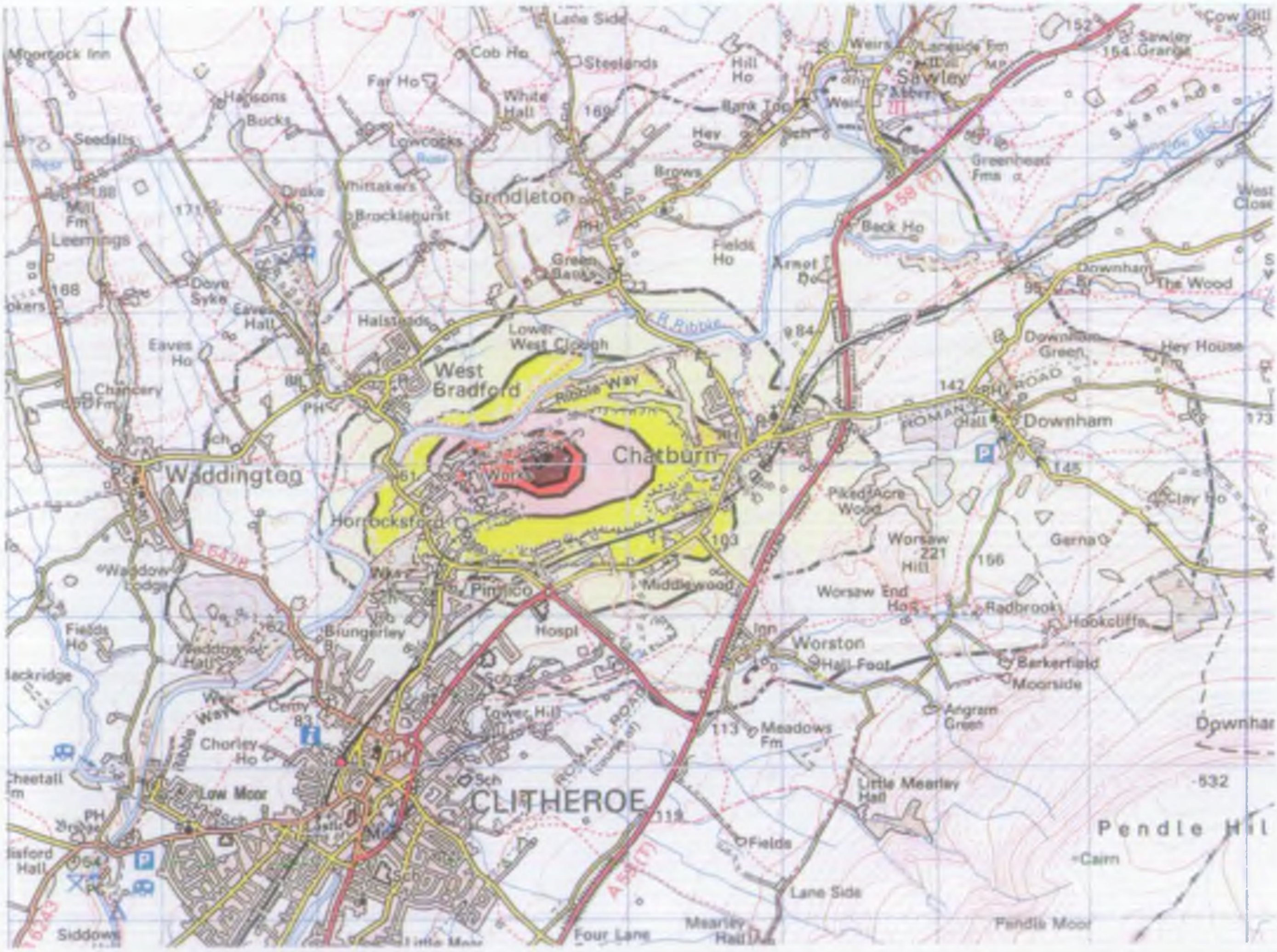
0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 0.3-0.6
- 0.6-0.9
- 0.9-1.2
- 1.2-1.5
- 1.5-1.8
- 1.8-2.1
- >2.1

Figure 44 Annual Average Concentration of Particulates, Wilsden: Particulates Case (5+9).



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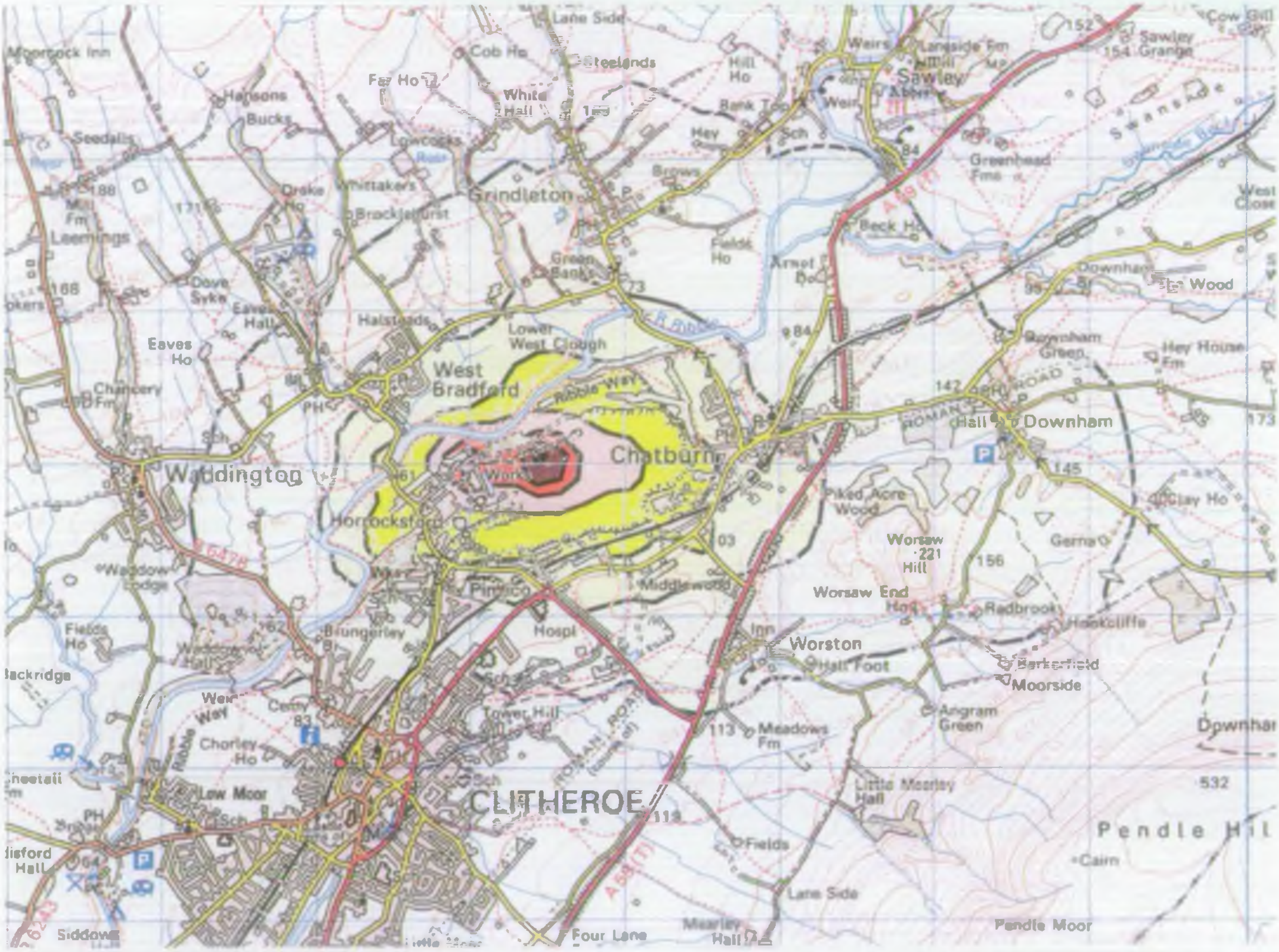
0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 0.3-0.6
- 0.6-0.9
- 0.9-1.2
- 1.2-1.5
- 1.5-1.8
- 1.8-2.1
- >2.1

N

Figure 45 Annual Average Concentration of Particulates, Wilsden: Particulates Case (5+10).



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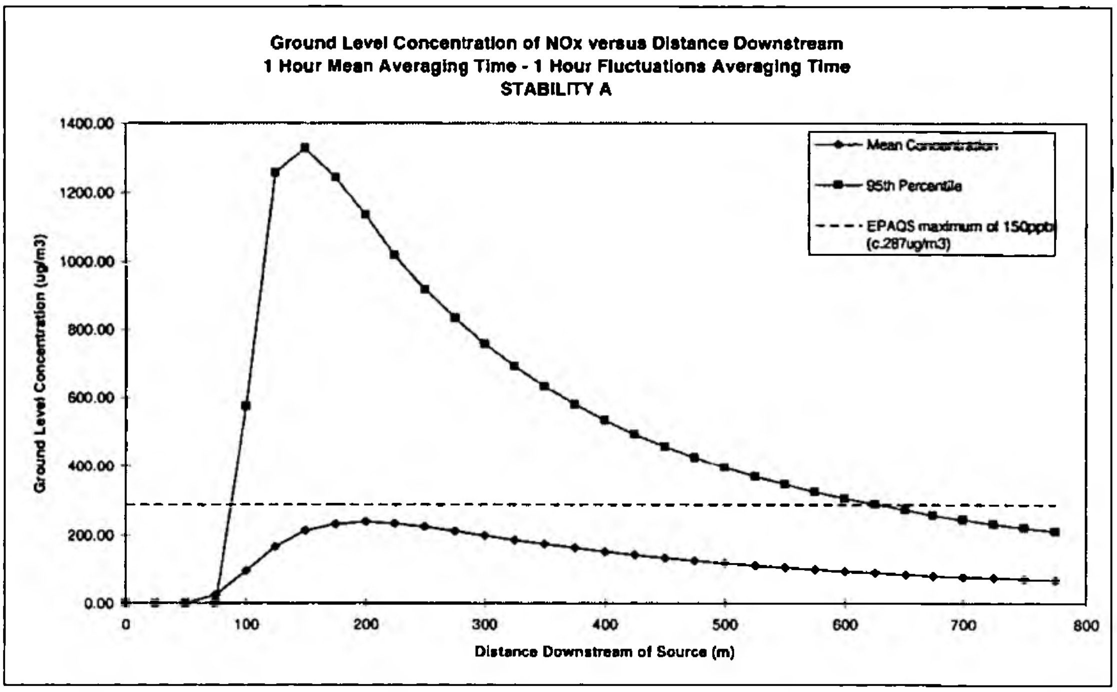
0 1 2 3 4 Kilometers

Concentration of Particulates (ug/m3)

- 0.3-0.6
- 0.6-0.9
- 0.9-1.2
- 1.2-1.5
- 1.5-1.8
- 1.8-2.1
- >2.1

N

Figure 46 Variation with distance downstream of hourly average and the 95th percentile of hourly average ground level concentrations of NOx, assuming all NOx is NO2, Under 5 Met Cases, Pasquill Classes A-E: Case1



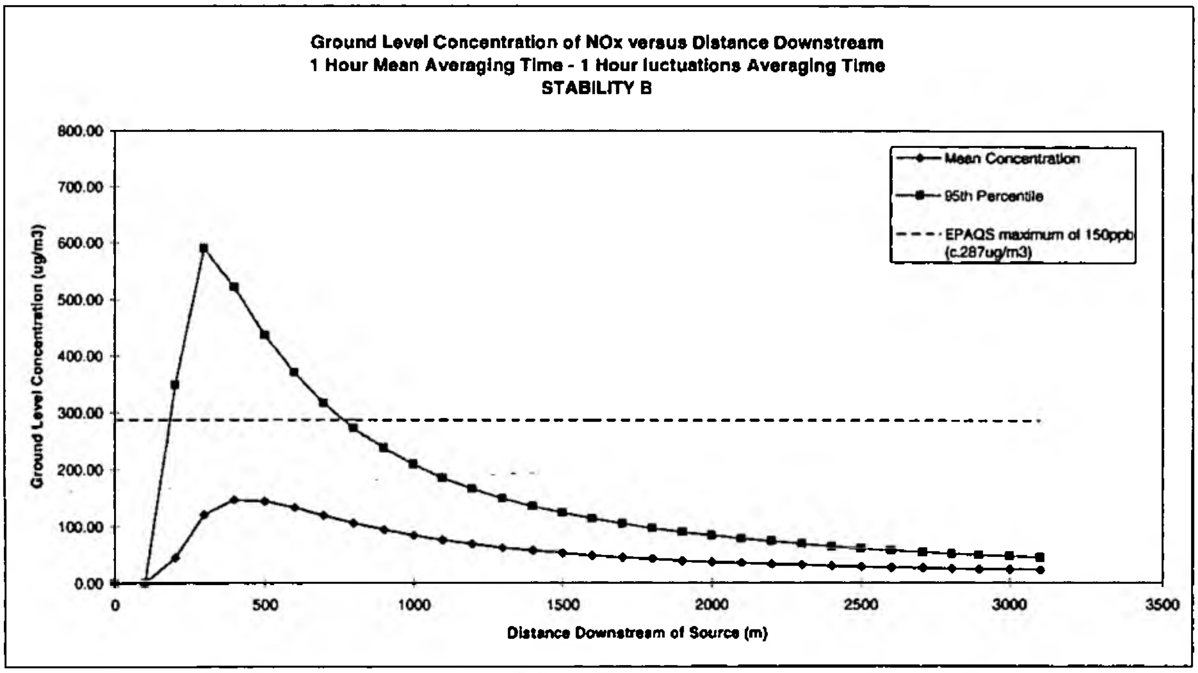
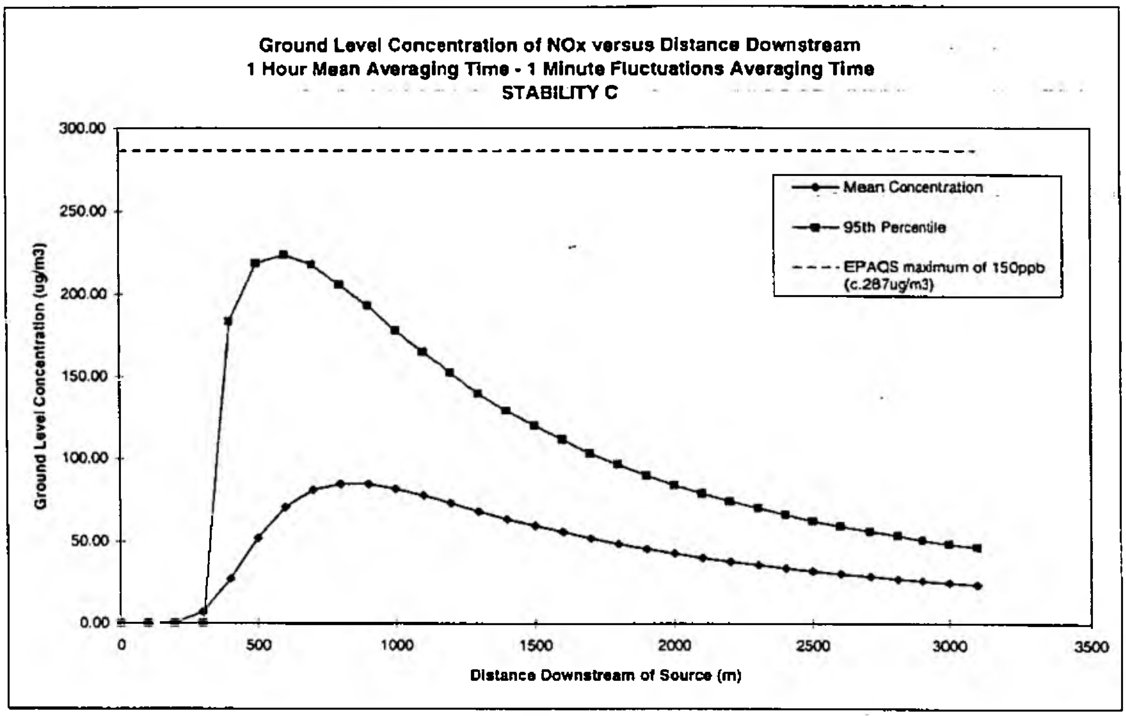


Figure 46 (cont.)



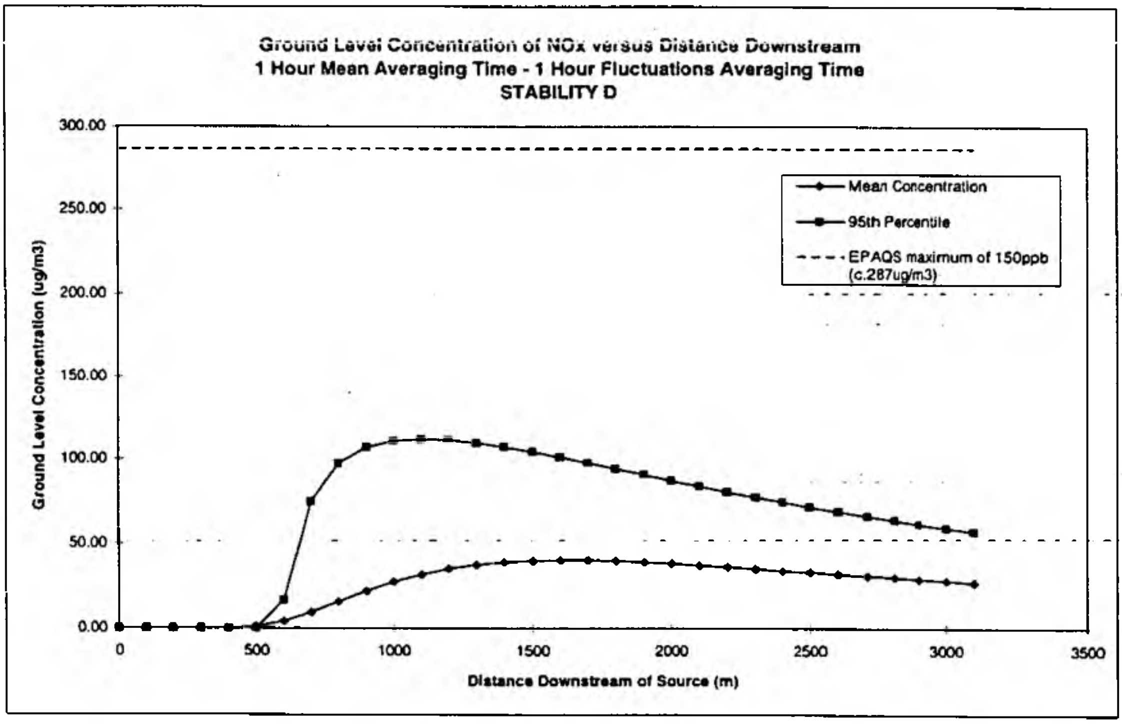


Figure 46 (cont.)

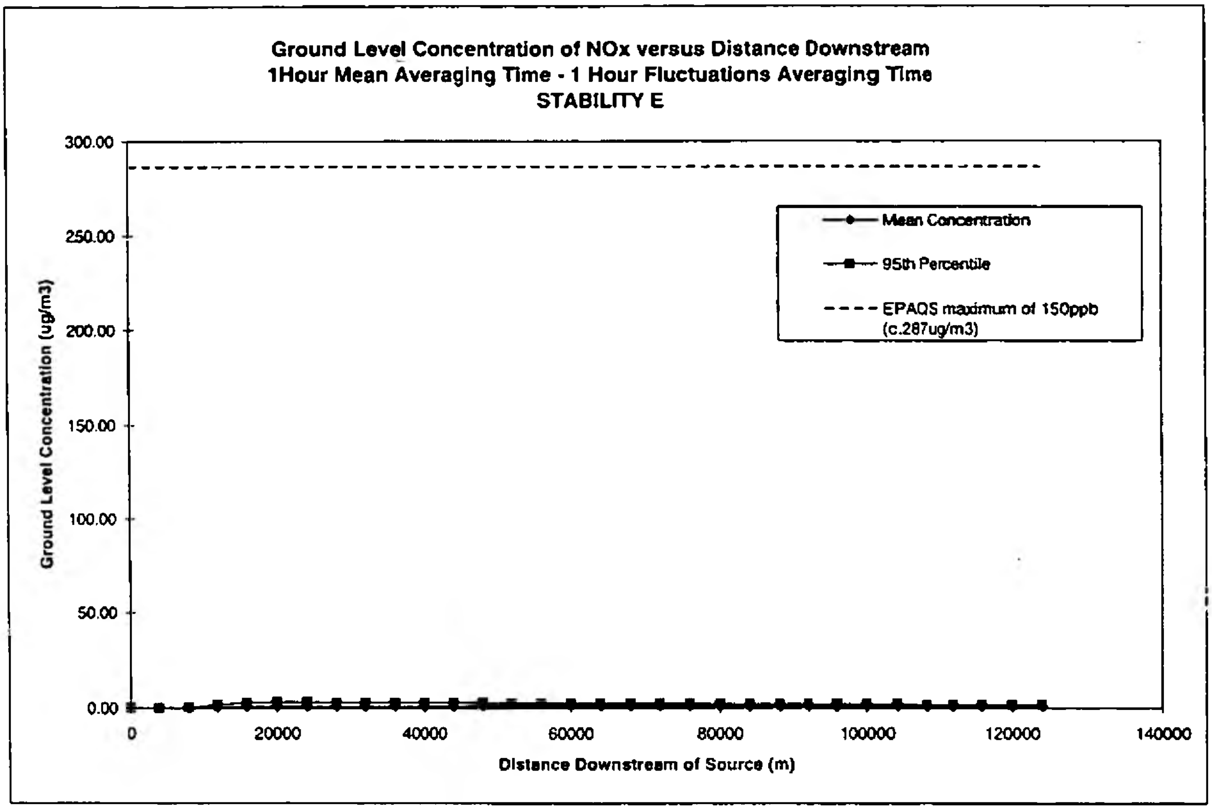
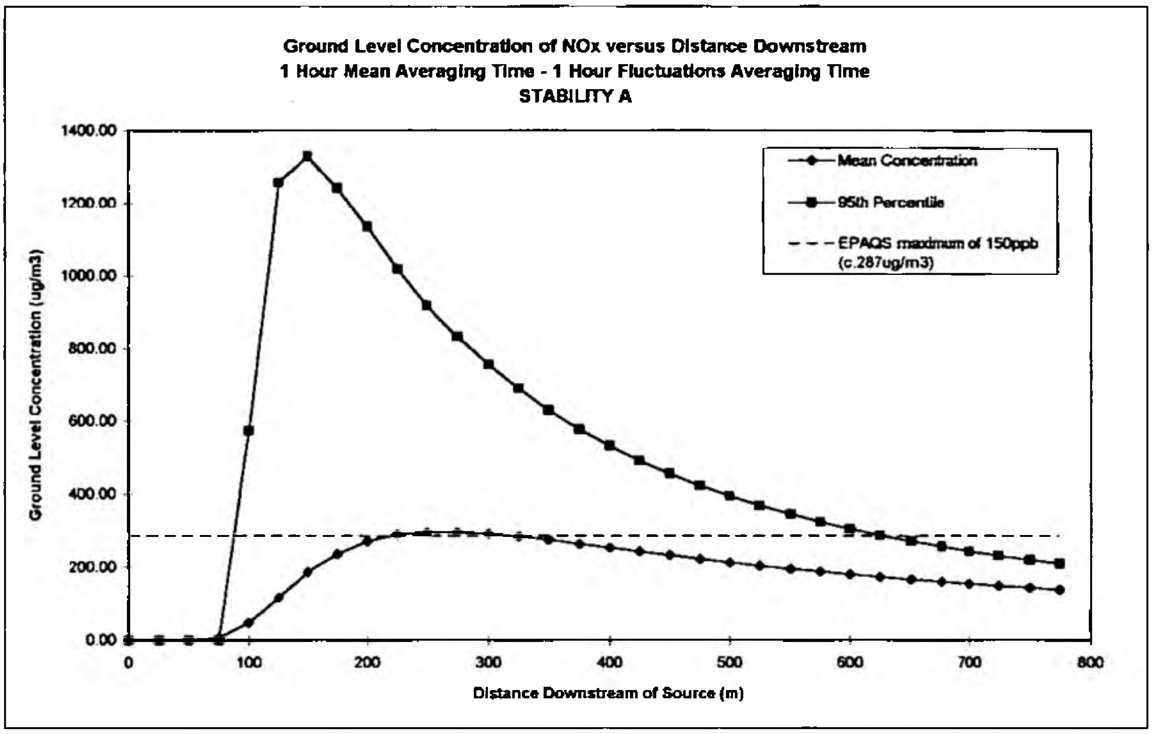


Figure 47 Variation with distance downstream of hourly average and the 95th percentile of hourly average ground level concentrations of NOx, assuming all NOx is NO2, Under 5 Met Cases, Pasquill Classes A-E: Case2



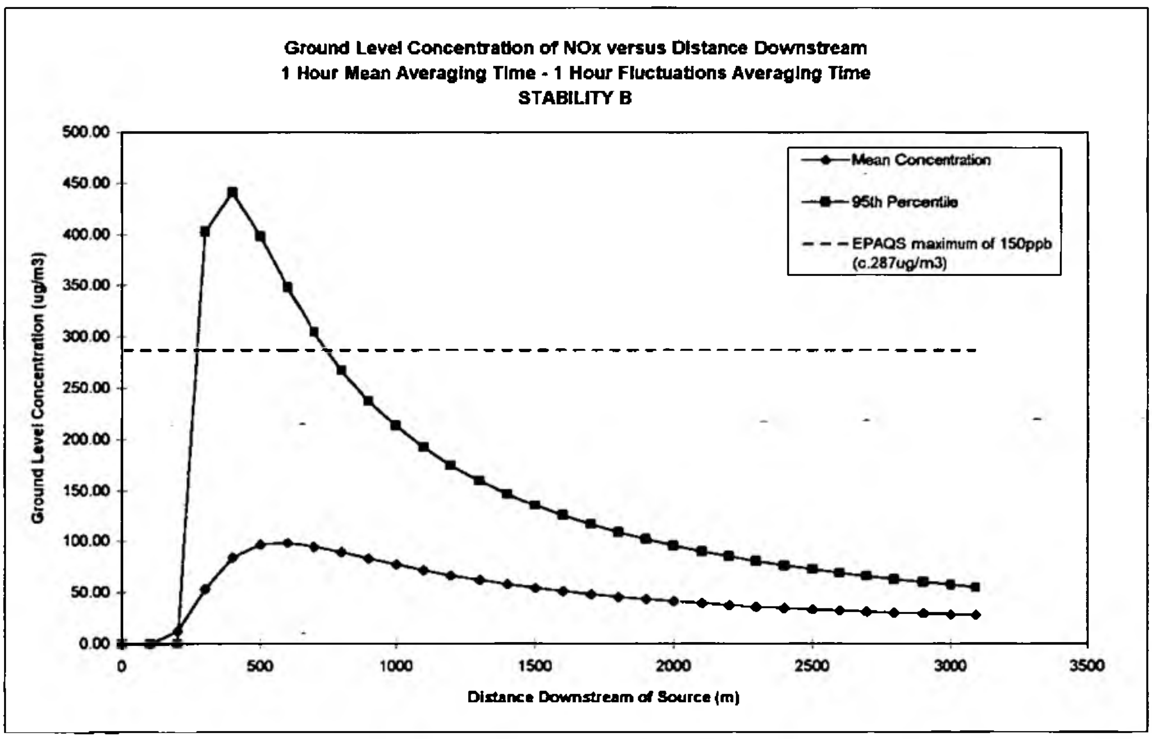
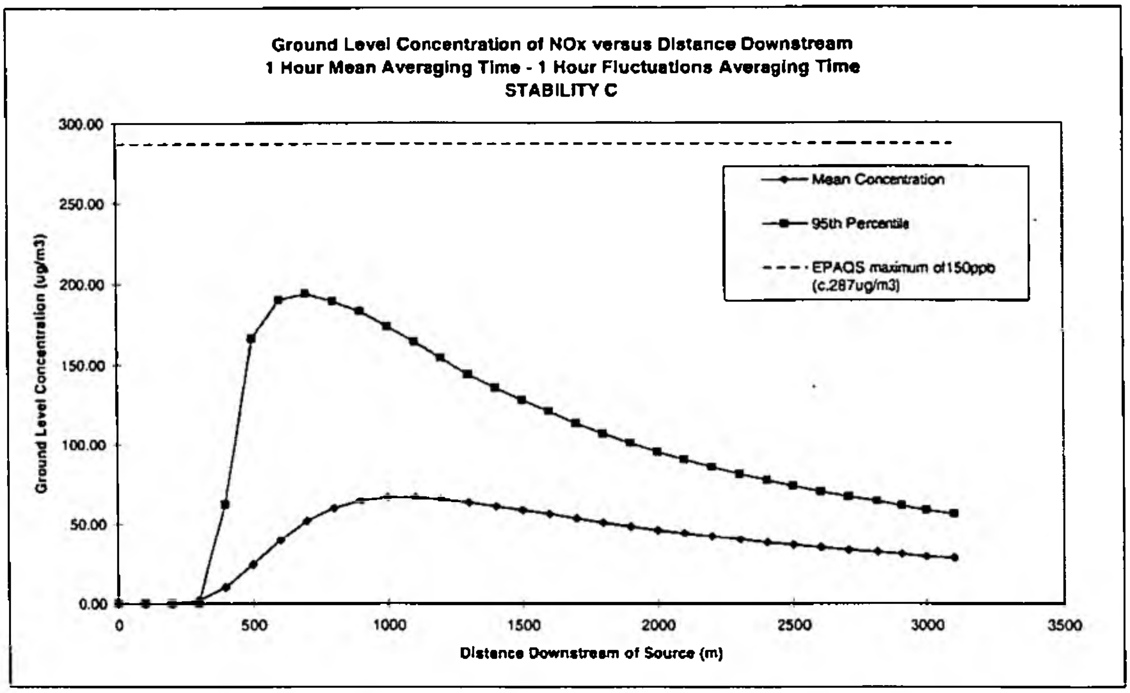


Figure 47 (cont.)



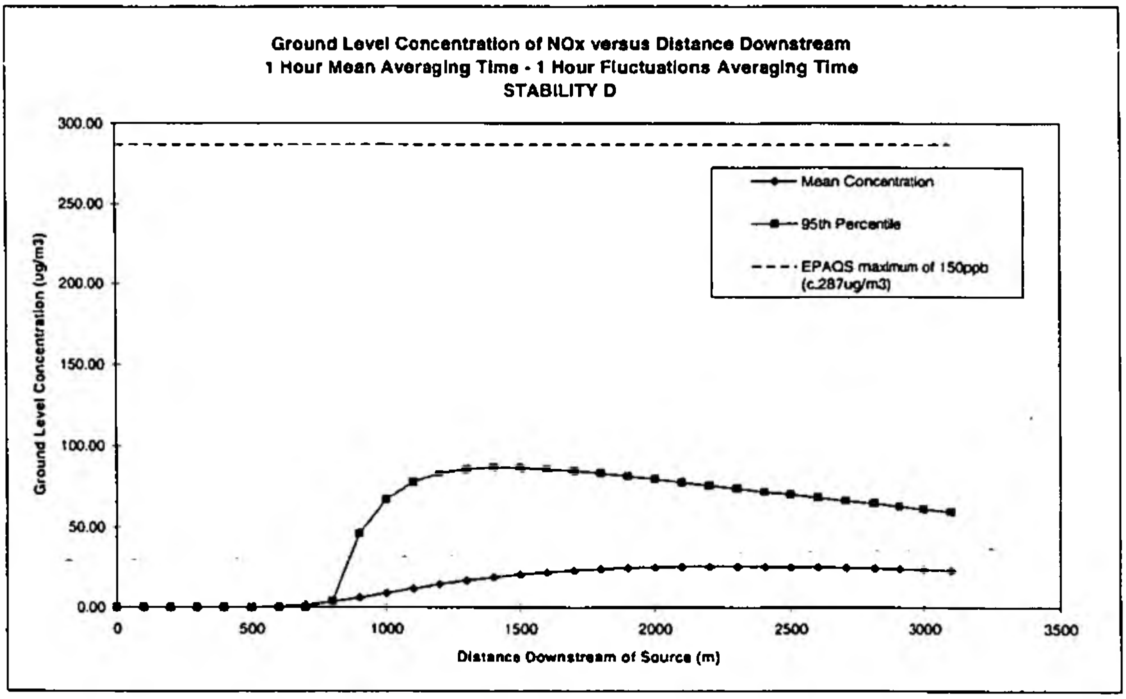


Figure 47 (cont.)

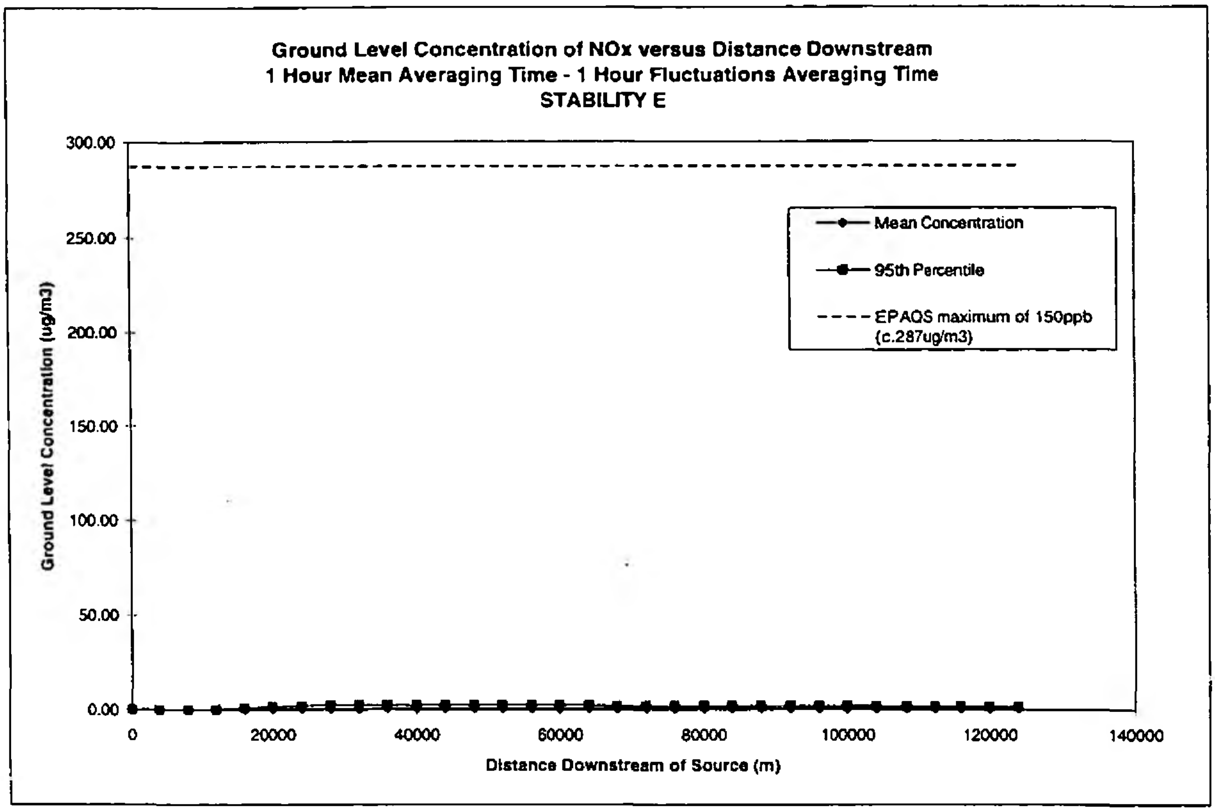
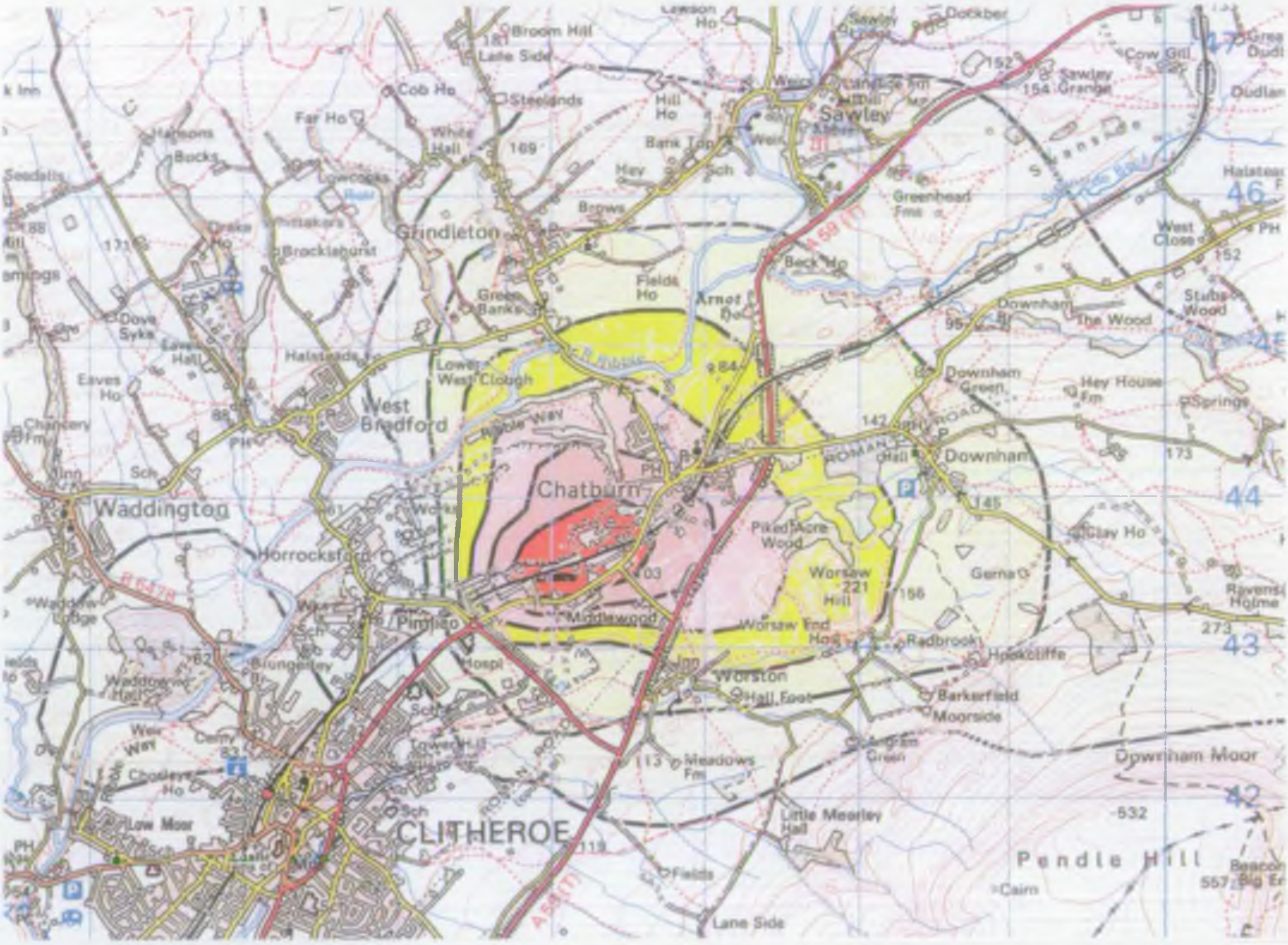


Figure 48 Annual Average Concentration of NO_X, Wilsden Met Data: Case 1



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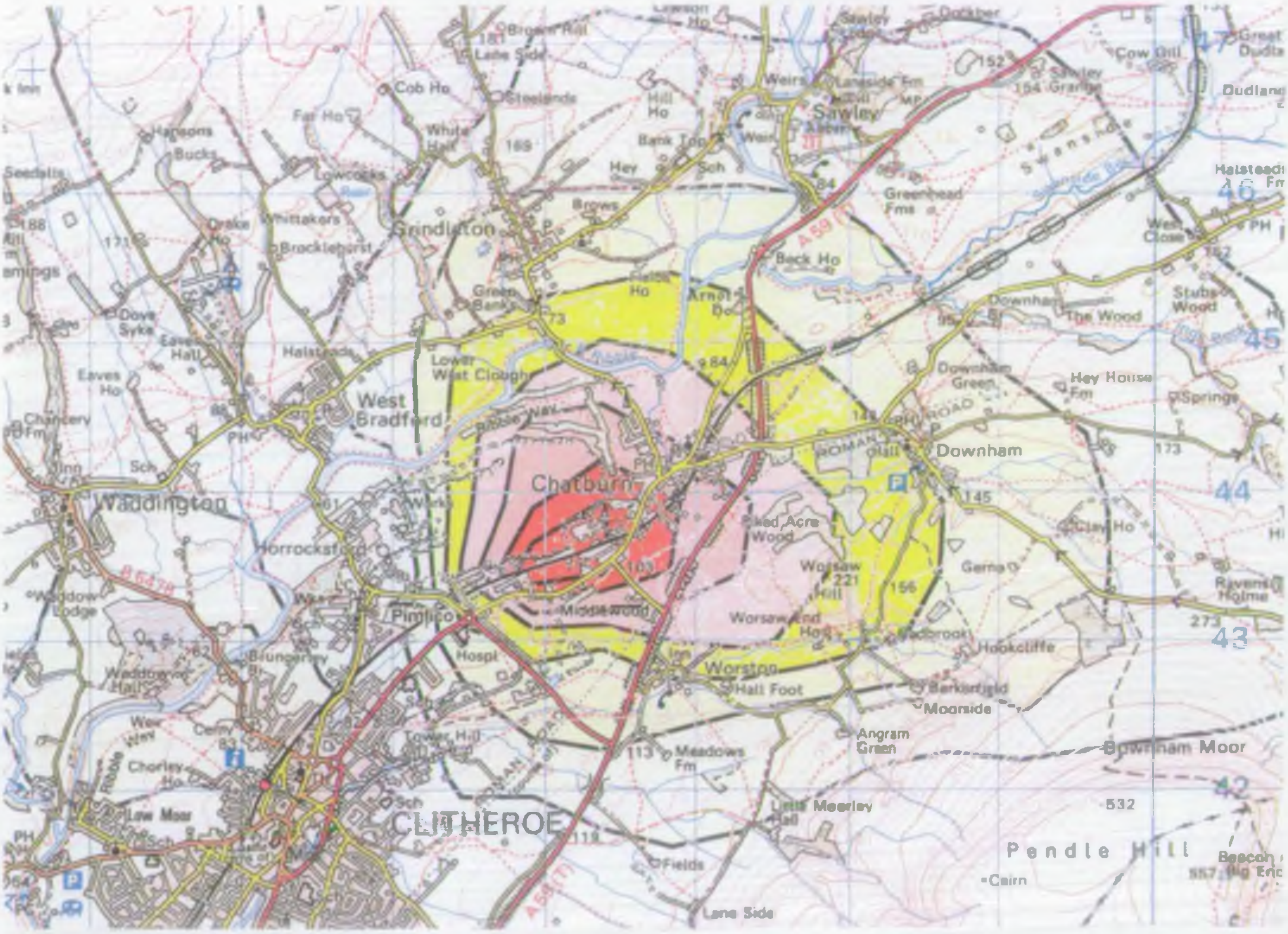
0 1 2 3 4 Kilometers

Concentration of NOx (ug/m3)

- 0.4-0.6
- 0.6-0.8
- 0.8-1.0
- 1.0-1.2
- 1.2-1.4
- 1.4-1.6
- >1.6

N

Figure 49 Annual Average Concentration of NO_X, Wilsden Met Data: Case 2



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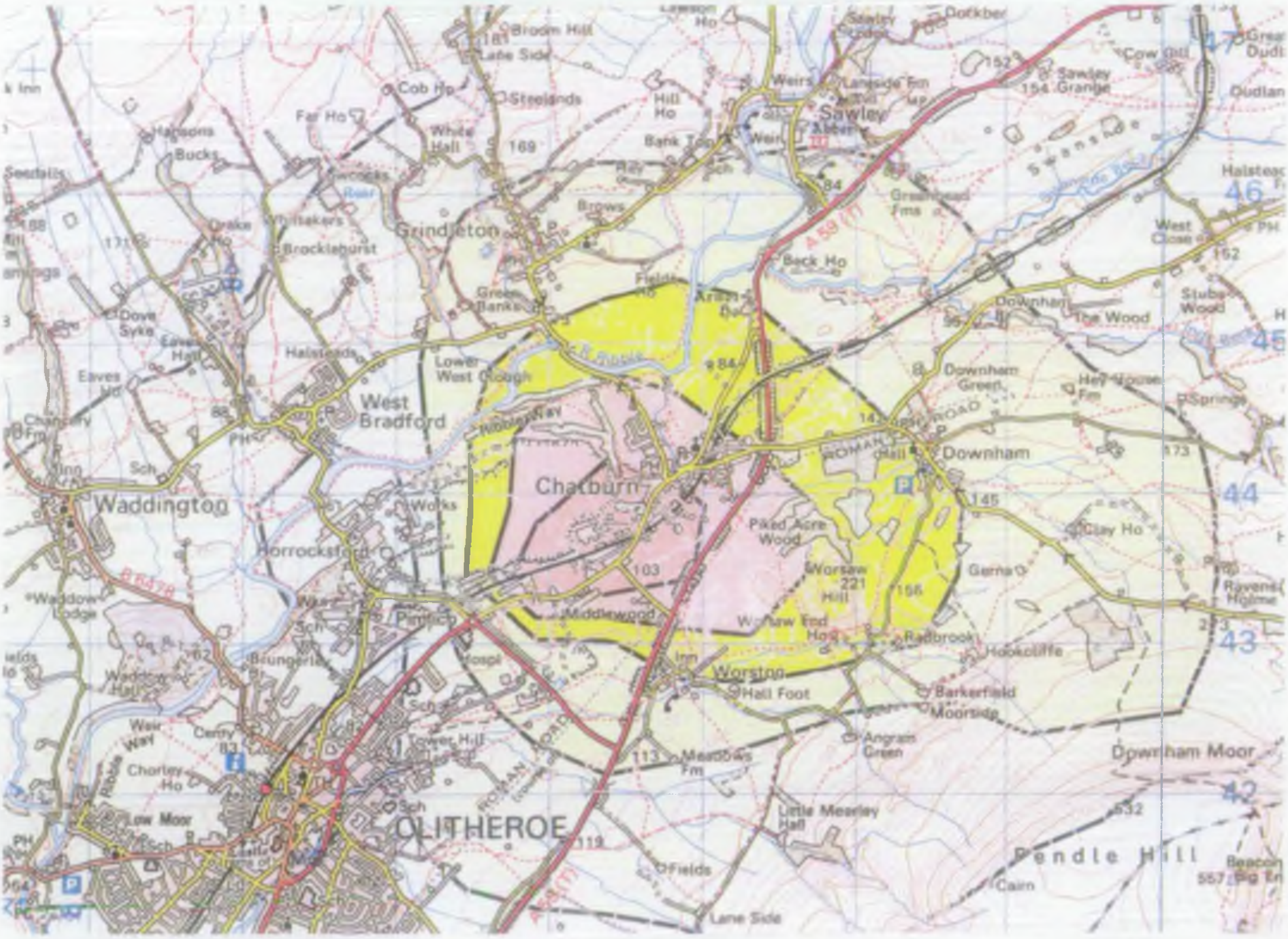
0 1 2 3 4 Kilometers

Concentration of NOx (ug/m3)

- 0.4-0.6
- 0.6-0.8
- 0.8-1.0
- 1.0-1.2
- 1.2-1.4
- 1.4-1.6
- >1.6

N

Figure 50 Annual Average Concentration of NO_X, Wilsden Met Data: Case 3



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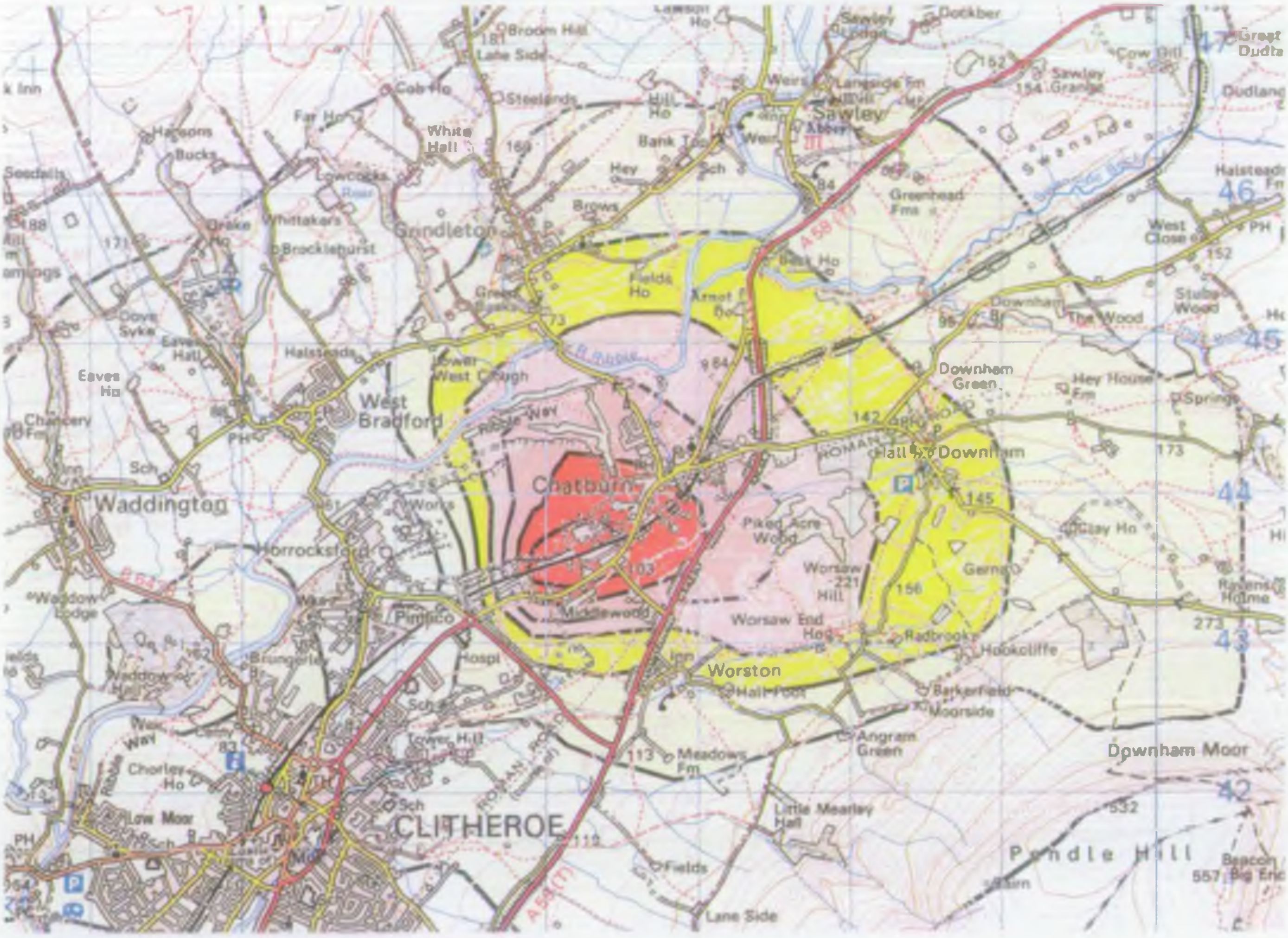
0 1 2 3 4 Kilometers

Concentration of NOx (ug/m3)
- 0.4-0.8
- 0.8-1.2
- 1.2-1.6
- 1.6-2.0
- >2

Figure 51 Annual Average Concentration of NO_X, Wilsden
Met Data: Case 4



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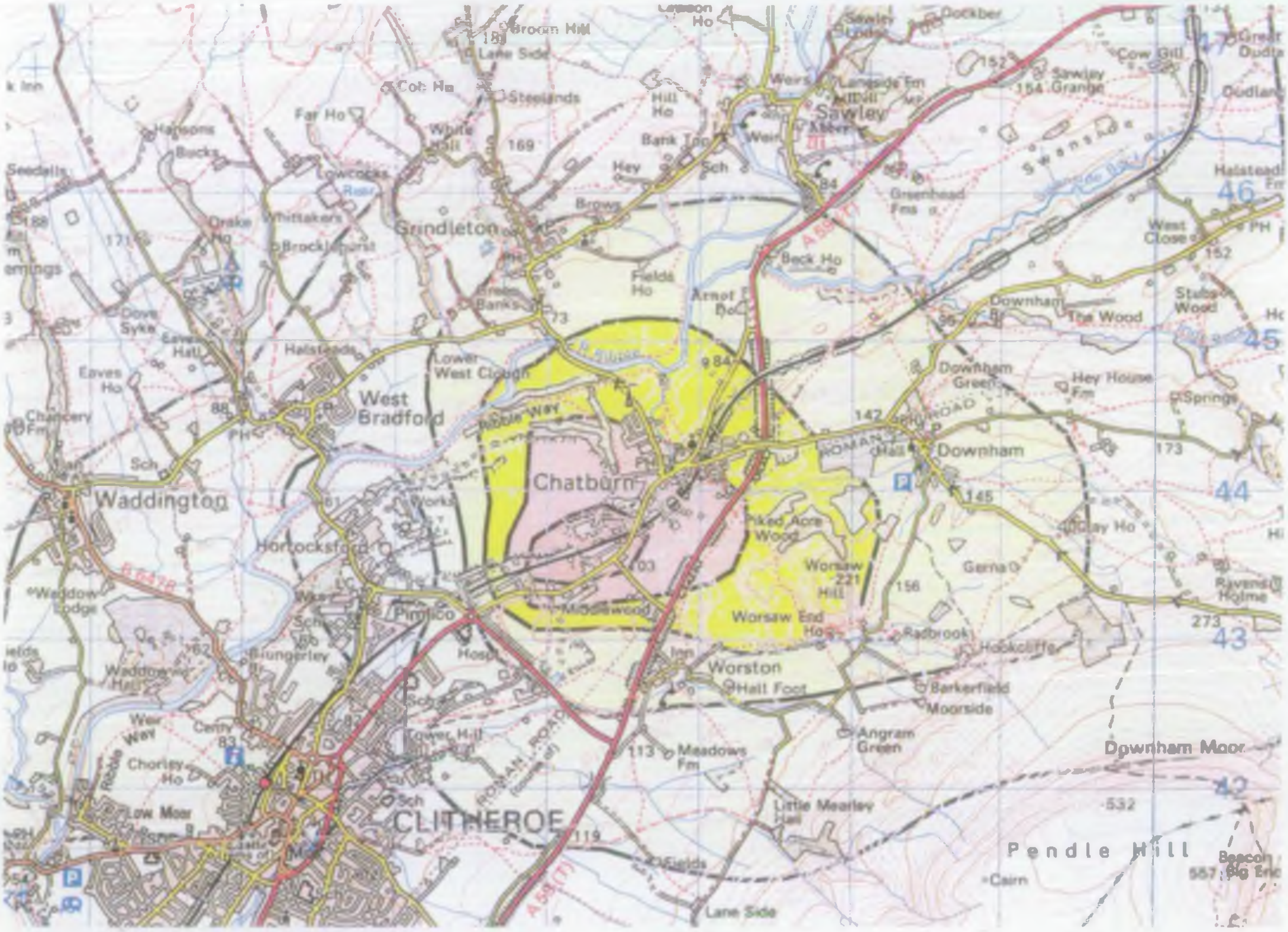
0 1 2 3 4 Kilometers

Concentration of NOx (ug/m3)
- 0.4-0.8
- 0.8-1.2
- 1.2-1.6
- 1.6-2.0
- 2.0-2.4
- 2.4-2.8
- >2.8

N

Figure 52 Annual Average Concentration of NO_X, Wilsden Met Data: Case (1+2)



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0 1 2 3 4 Kilometers

Concentration of NOx (ug/m3)

- 1-2
- 2-3
- 3-4
- 4-5
- >5

APPENDIX A

Appendix A : Annual Average Concentration of SO_2, Cases 2-4, Met Data: Squires Gate, Ringway (Model: ADMS)

The following figures, A1-A2, show long term (annual average) concentrations of SO_2 calculated using the ADMS model and met data from Squires Gate and Ringway met sites. Results for combinations of the current wet and dry kilns emissions, Cases 1-4 and the wet and dry kilns operating together, Case (1+2) are presented.

These figures can be compared with Figures 24-27 which show the results for the same cases using met data from Wilsden. The contour plots reflect the difference in prevailing wind direction, which is west south-westerly at Wilsden, westerly at Squires Gate but southerly at Ringway. Maximum values of the annual average are highest when the Squires Gate data is used.

Figure A1(a) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data: Case 1

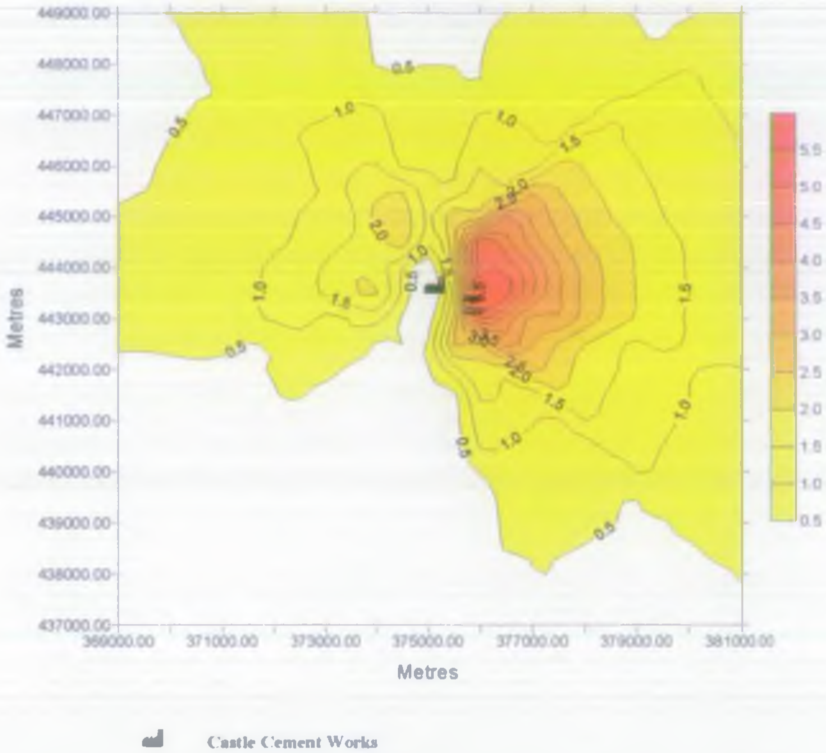

Figure A1(b) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data: Case 2

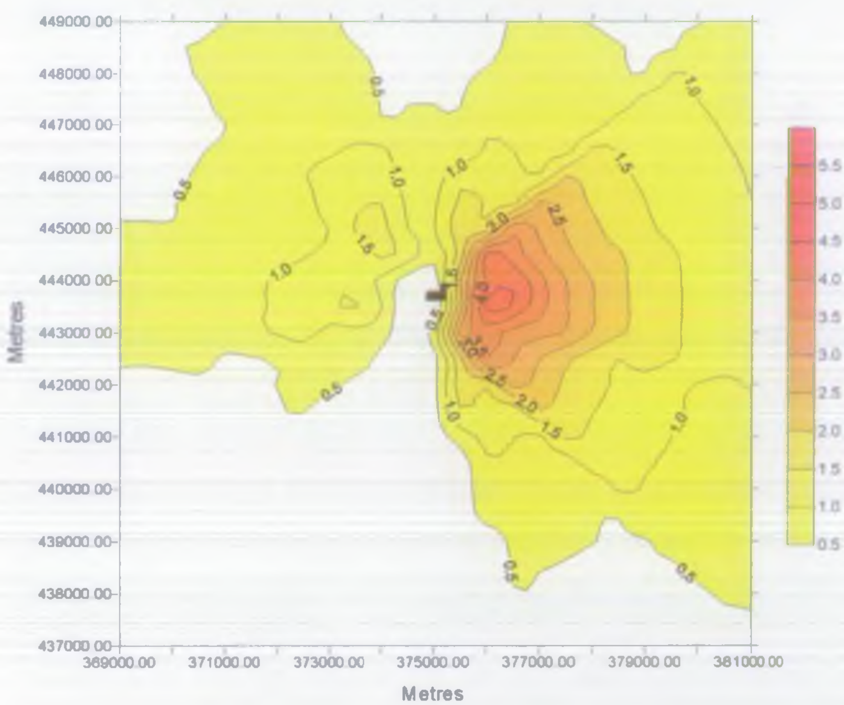

Figure A1(c) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data: Case 3

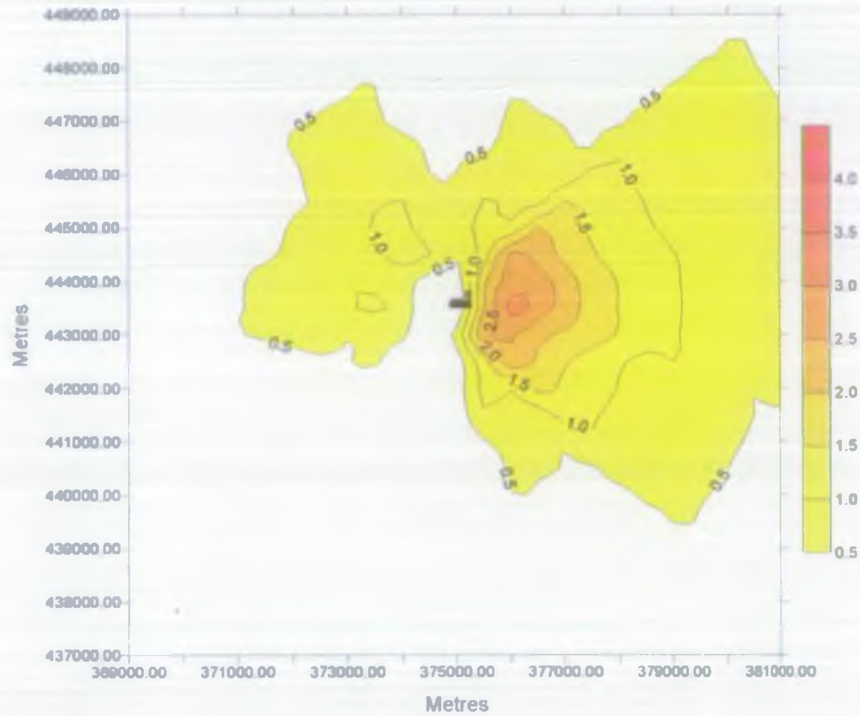

Figure A1(d) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data: Case 4

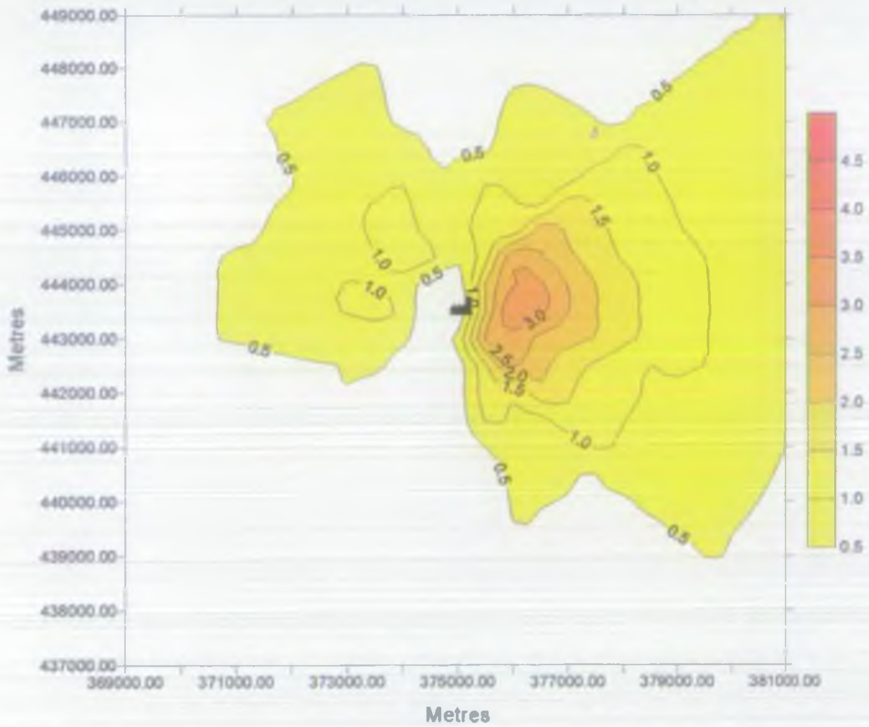

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Figure A1(e) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data: Cases (1+2)

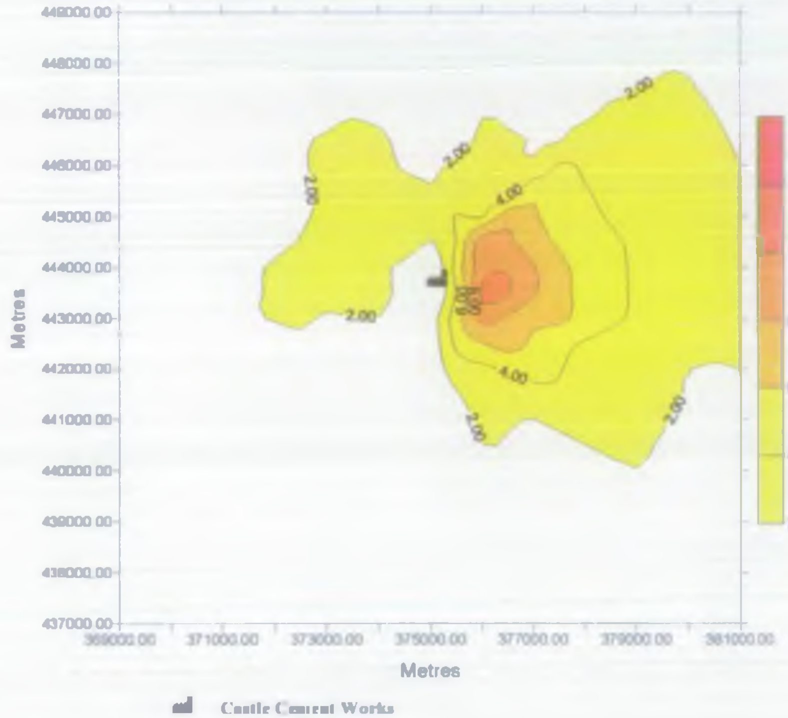


Figure A2(a) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data: Case 1

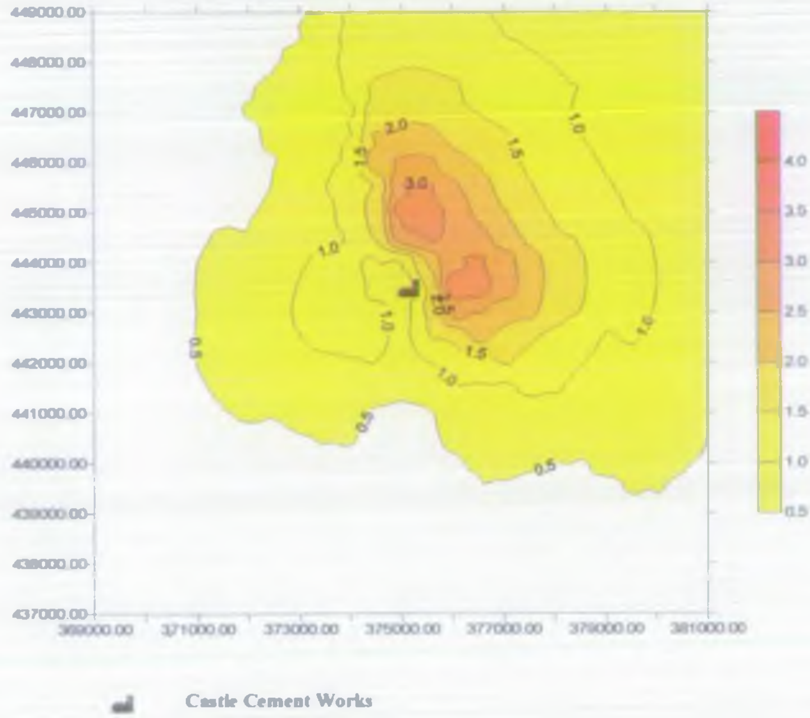


Figure A2(b) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data: Case 2

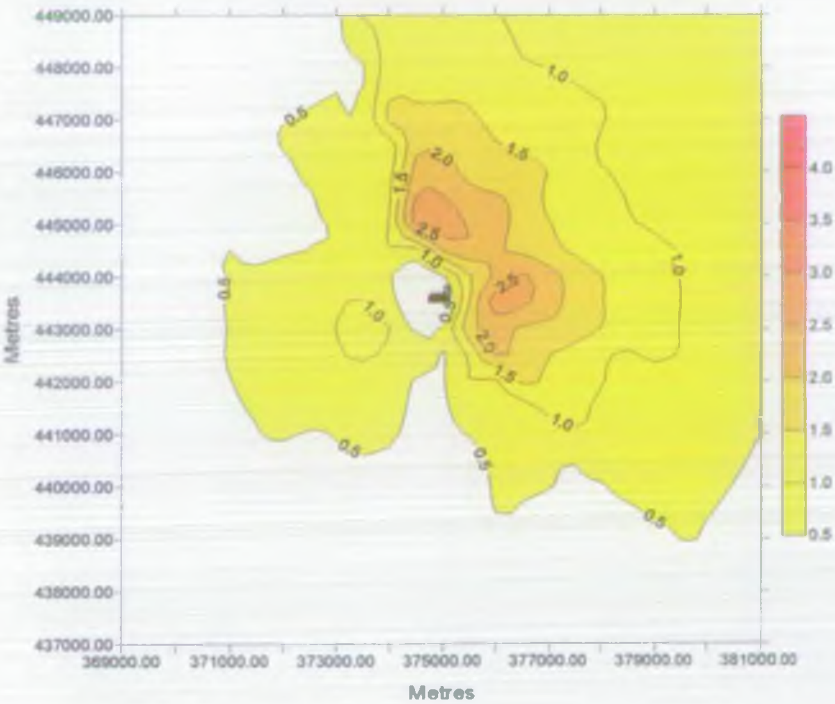


Figure A2(c) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data: Case 3

Figure A2(d) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data: Case 4

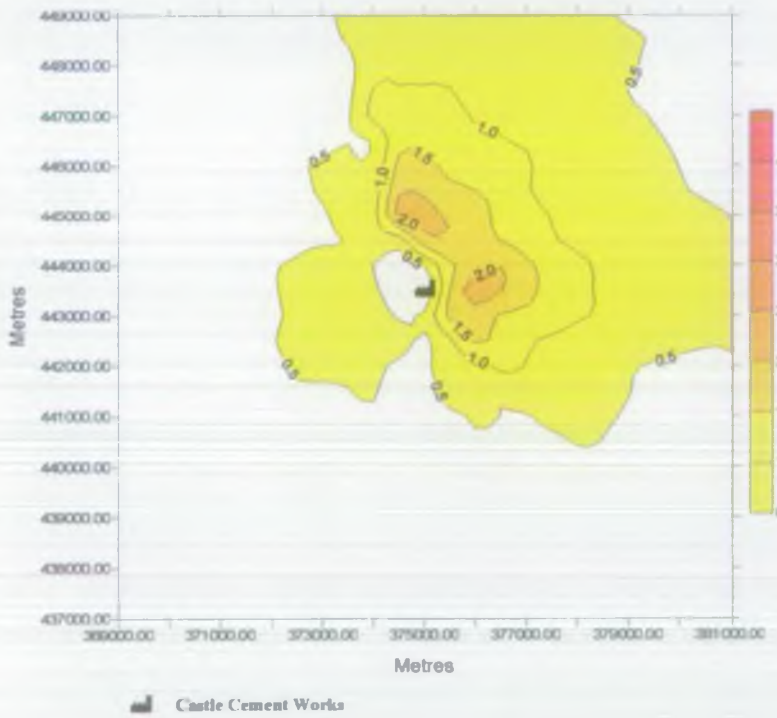
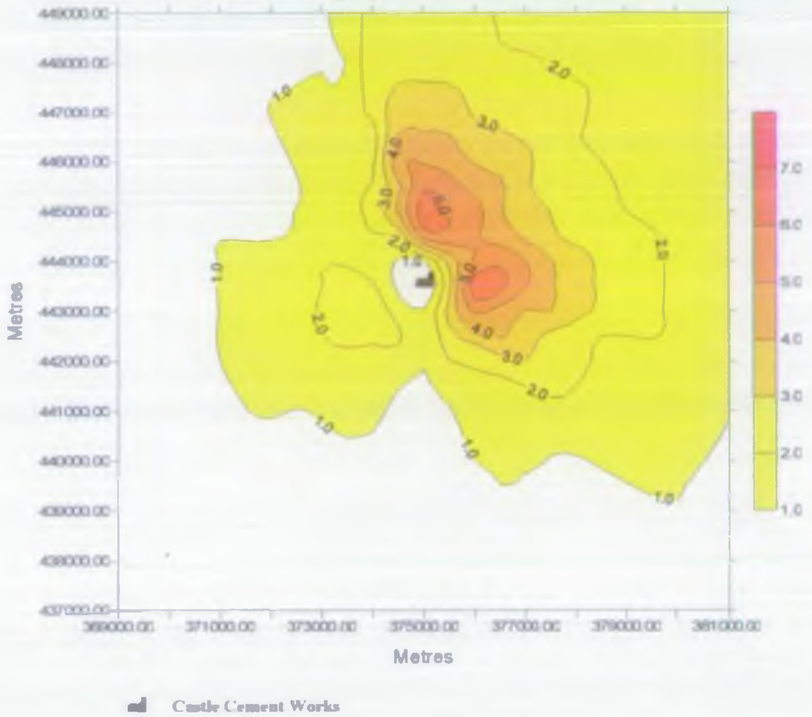


Figure A2(e) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data: Cases (1+2)



APPENDIX B

Appendix B : Annual Average Concentration of SO_2, Case 1-4, Met Data: Wilsden (Models: DISTAR, ISCLT3)

Figures B1 and B2 show long term (annual average) concentrations of SO_2 calculated using the DISTAR and ISCLT3 models respectively. Met data from Wilsden met site has been used. Results for combinations of the current wet and dry kilns emissions, Cases 1-4 and the wet and dry kilns operating together, Case (1+2) are presented.

These figures can be compared with Figures 24-27 which show the results calculated by ADMS for the same cases using met data from Wilsden. The results from ISCLT3 show higher maximum values at distances slightly further from the stacks than the DISTAR results.

Figure B1(a) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, DISTAR model: Case 1

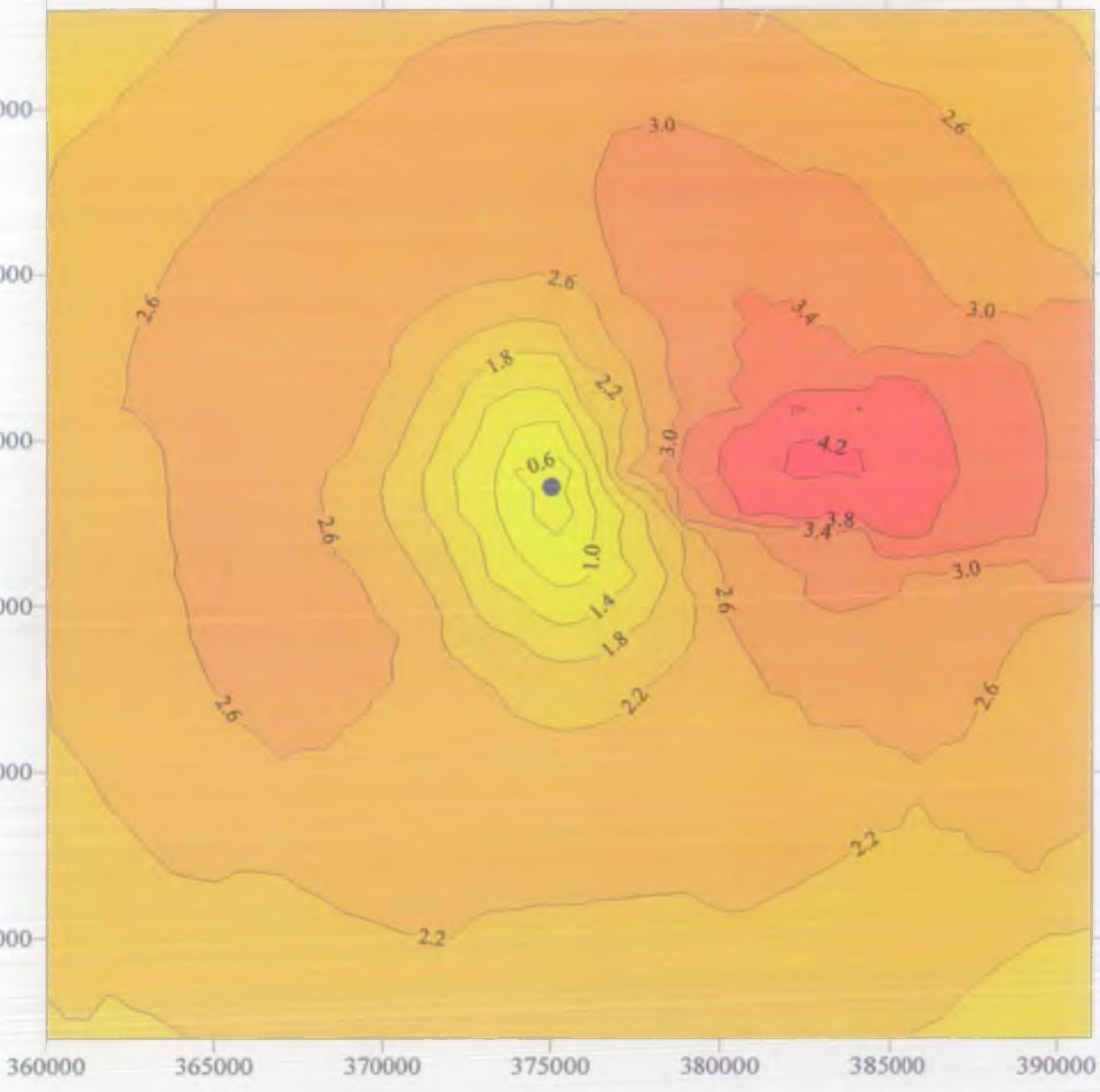


Figure B1(b) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, DISTAR model: Case 2

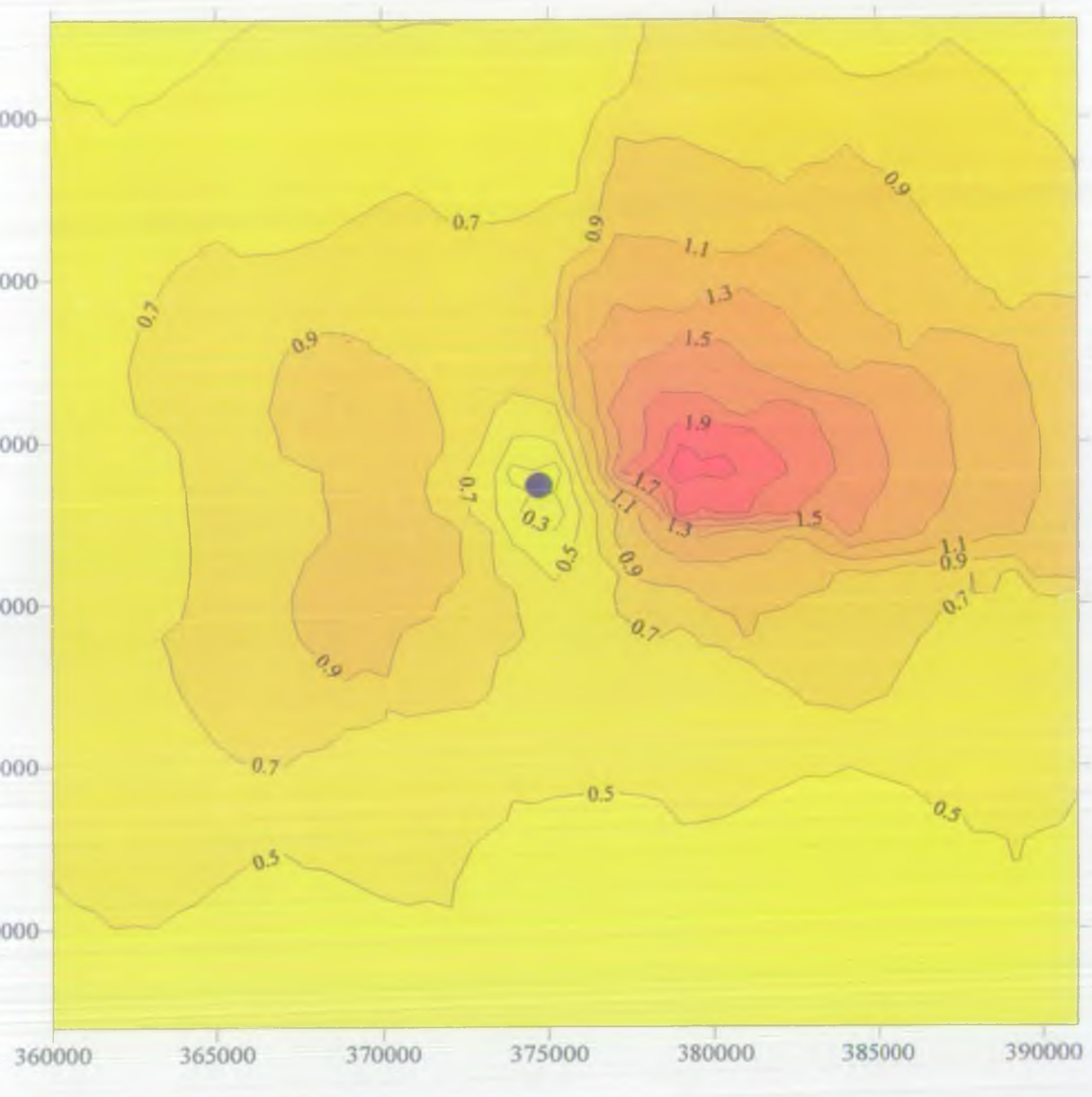


Figure B1(c) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, DISTAR model: Case 3

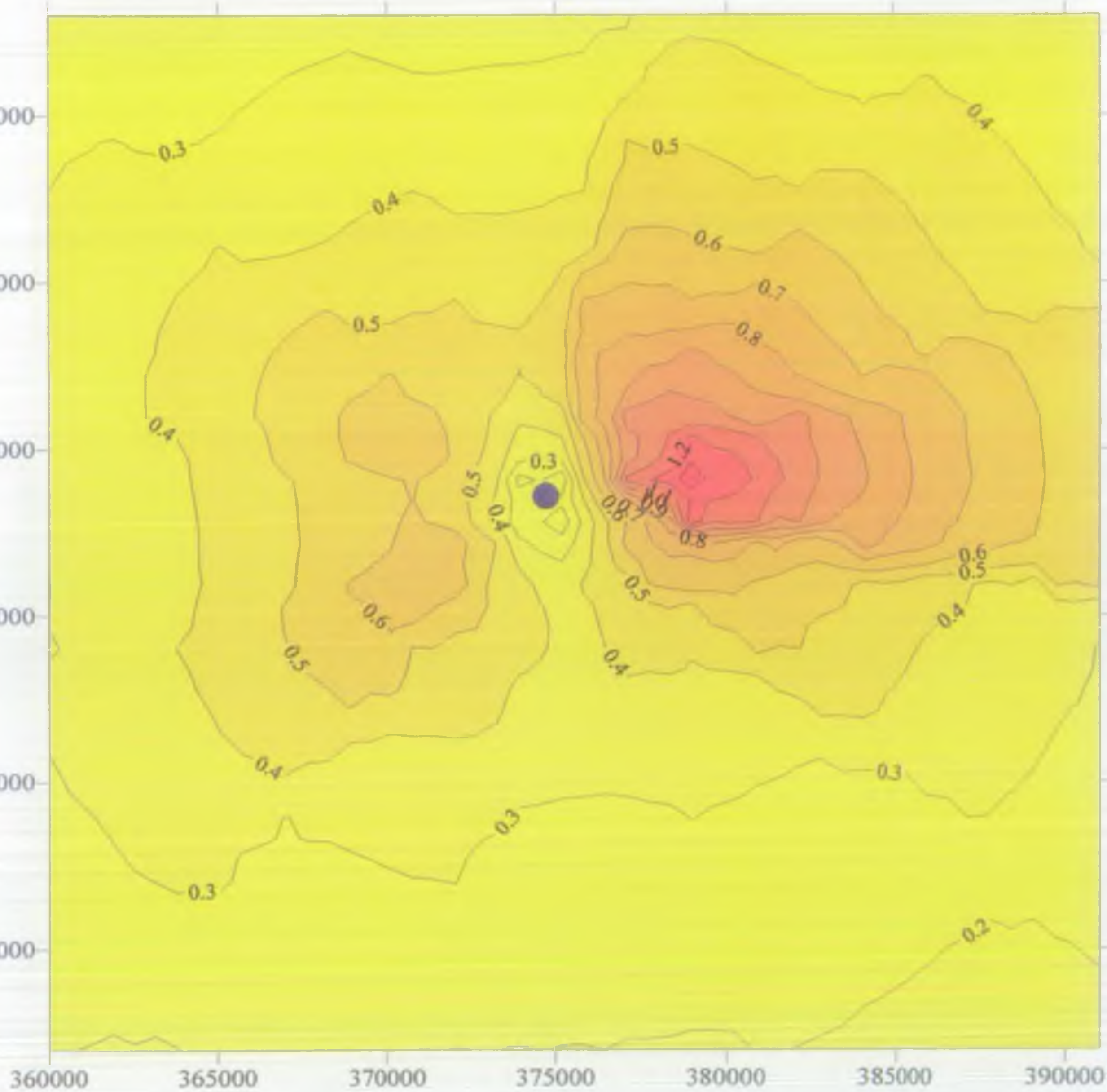


Figure B1(d) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, DISTAR model: Case 4

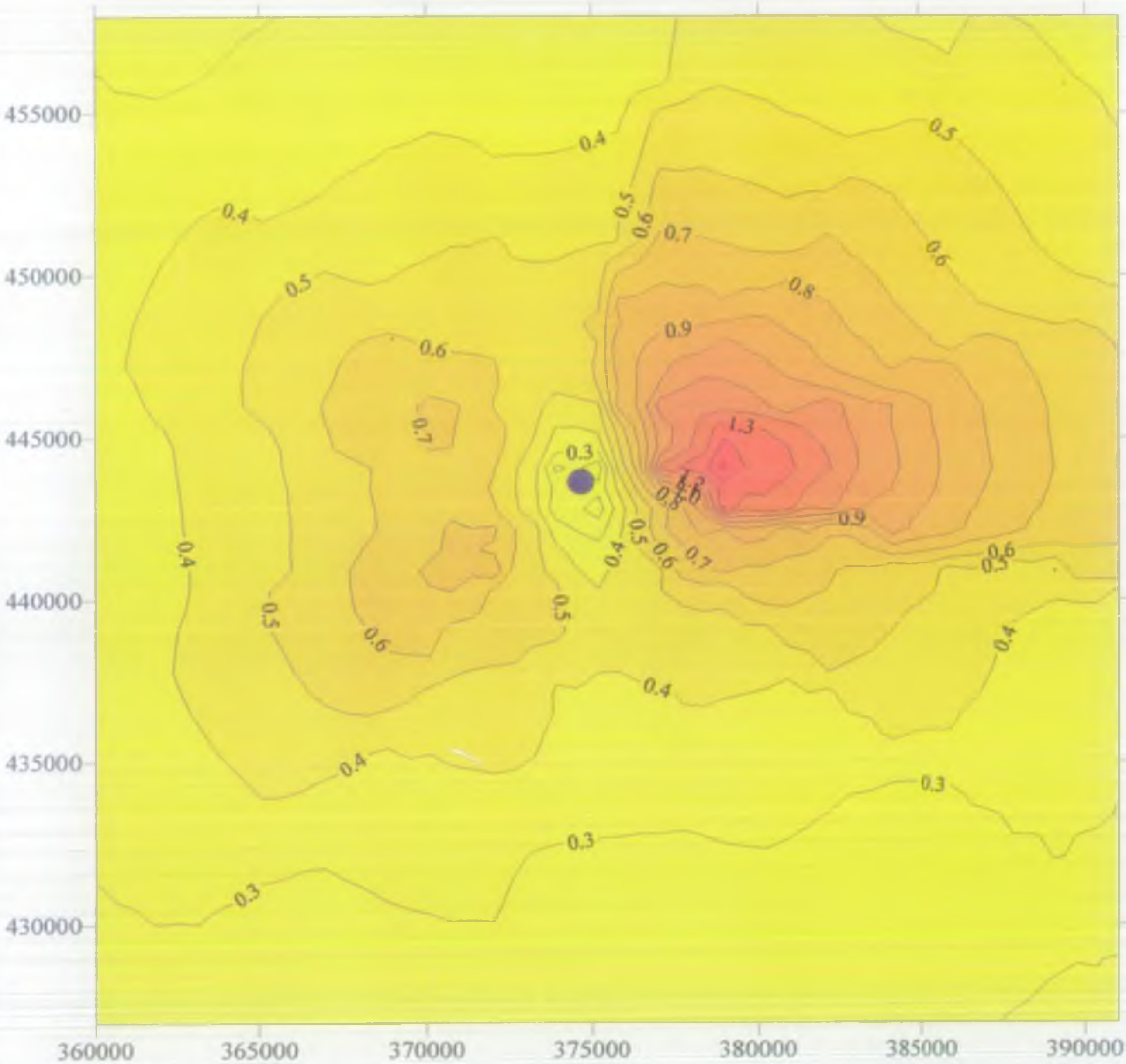


Figure B1(e) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, DISTAR model: Cases (1+2)

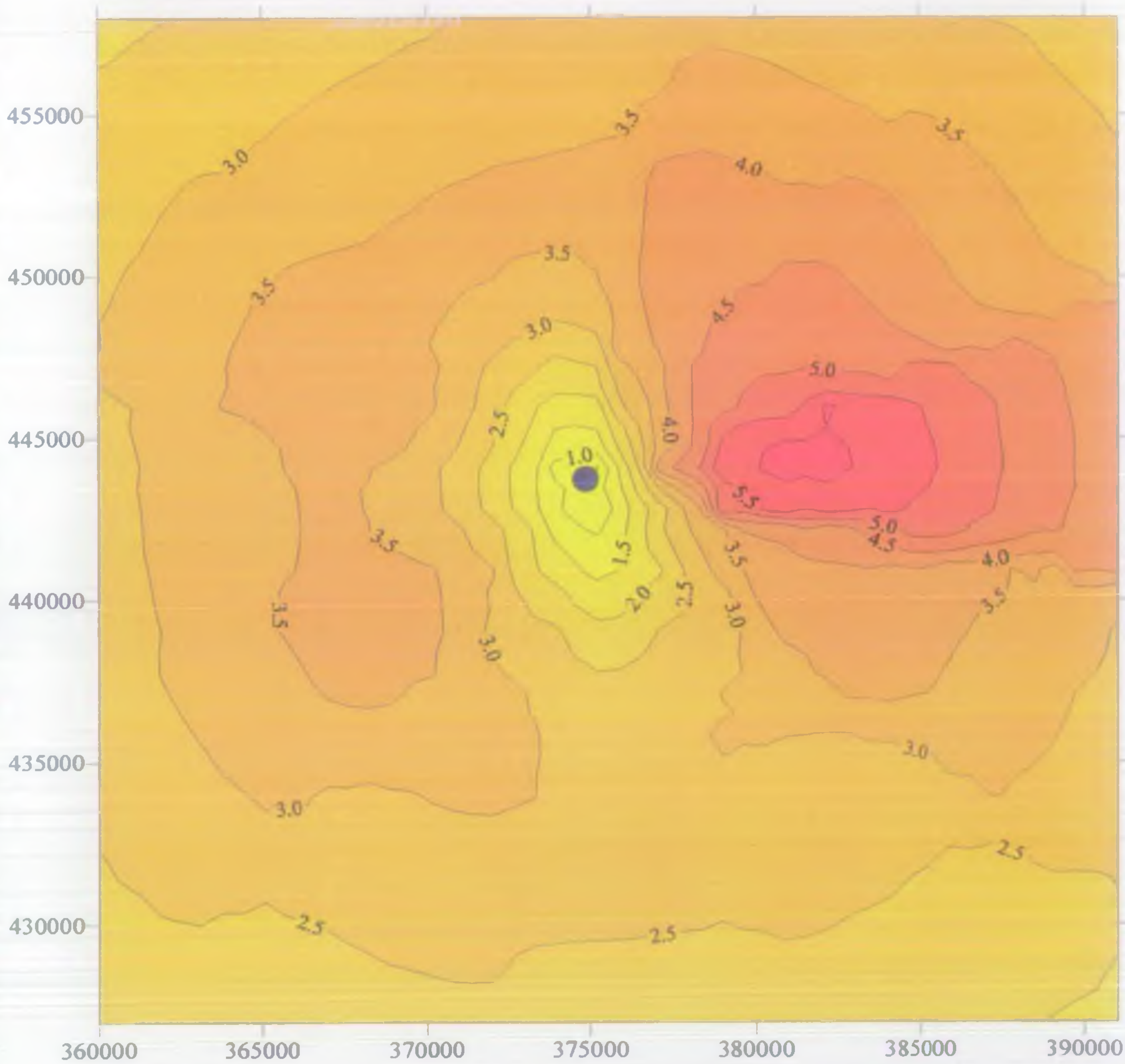


Figure B2(a) Annual Average Concentration of SO_2 (μg/m^3), Wilsden Met Data, ISCLT3 model: Case 1

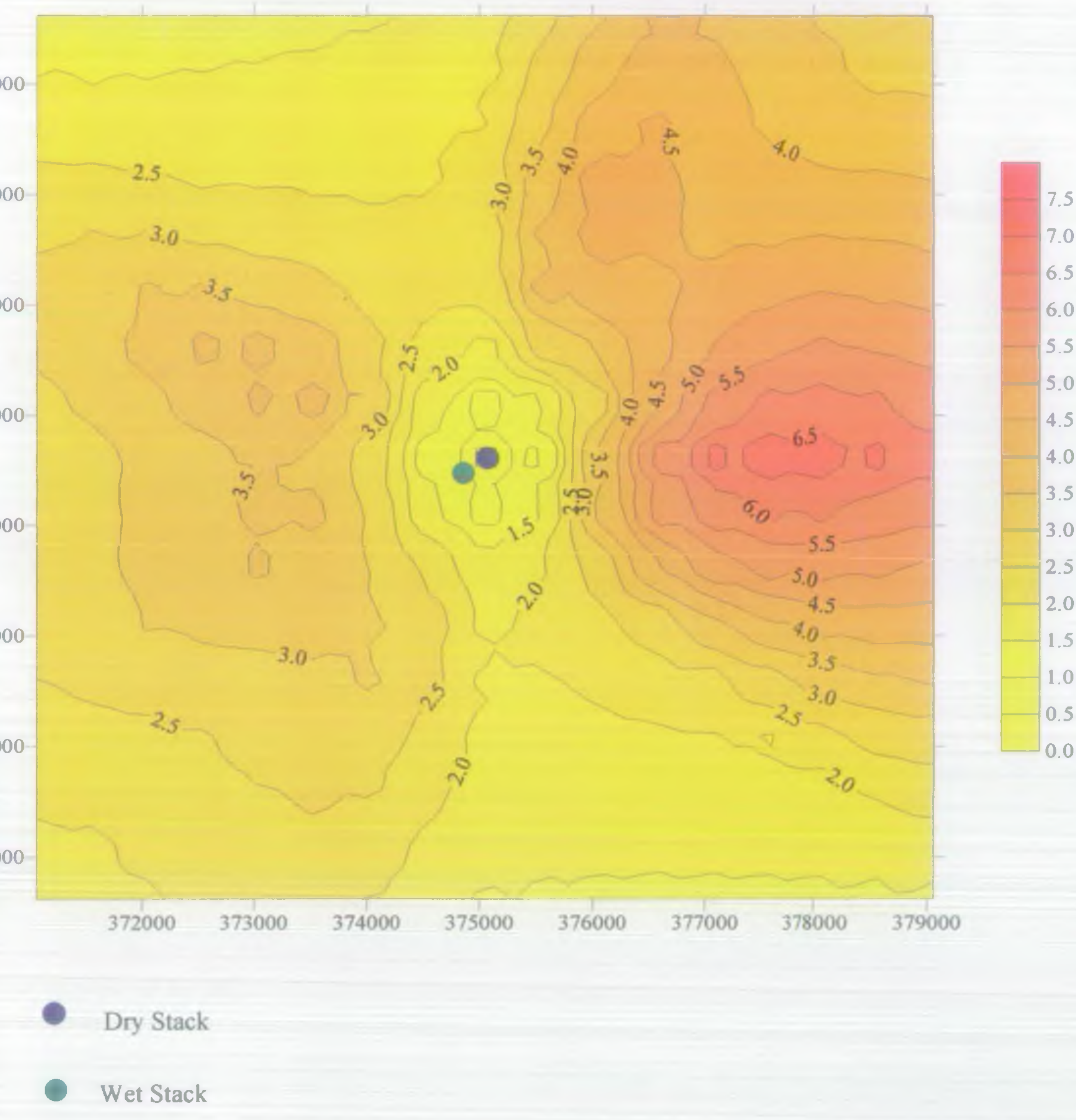


Figure B2(b) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, ISCLT3 model: Case 2

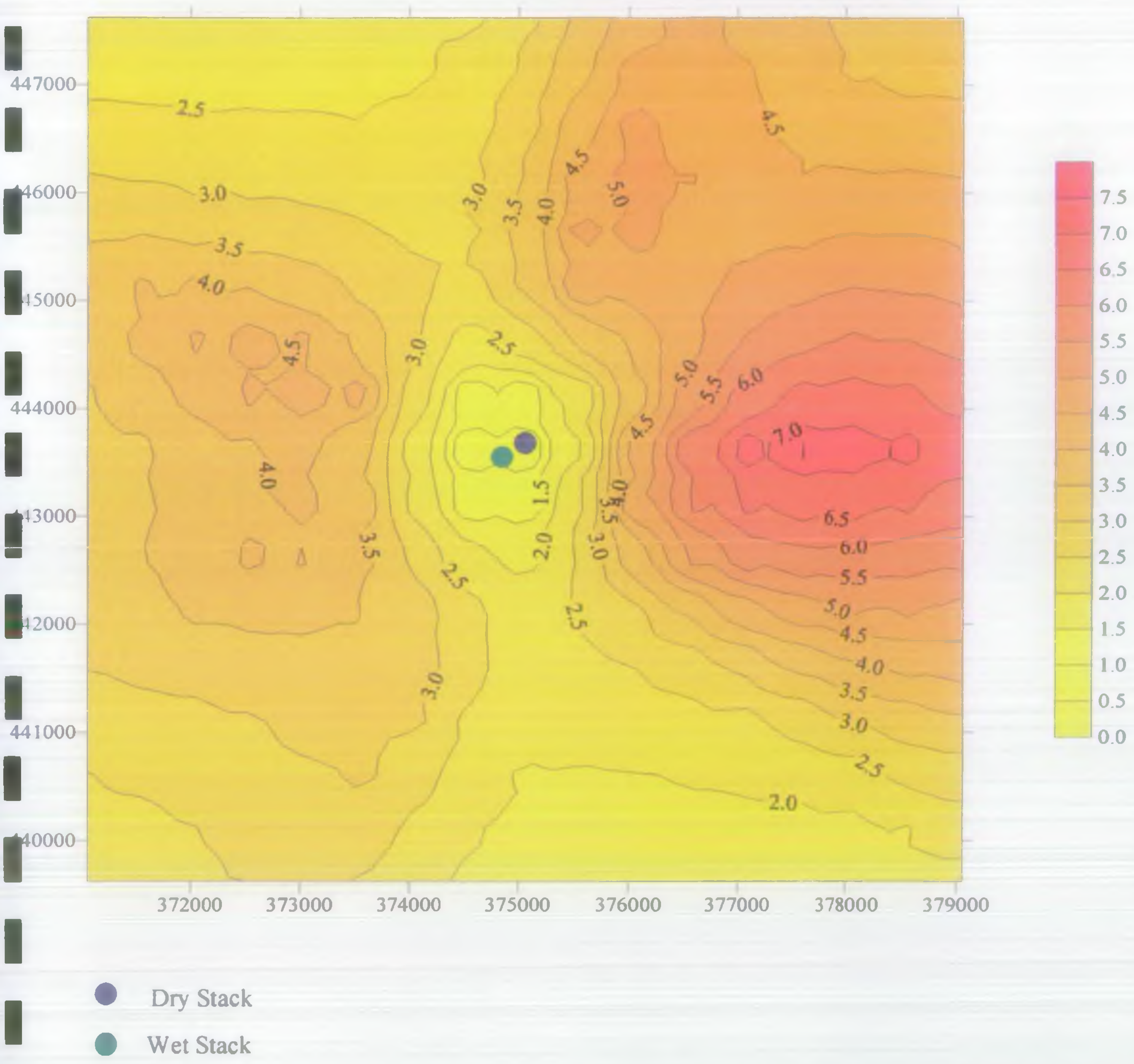


Figure B2(c) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, ISCLT3 model: Case 3

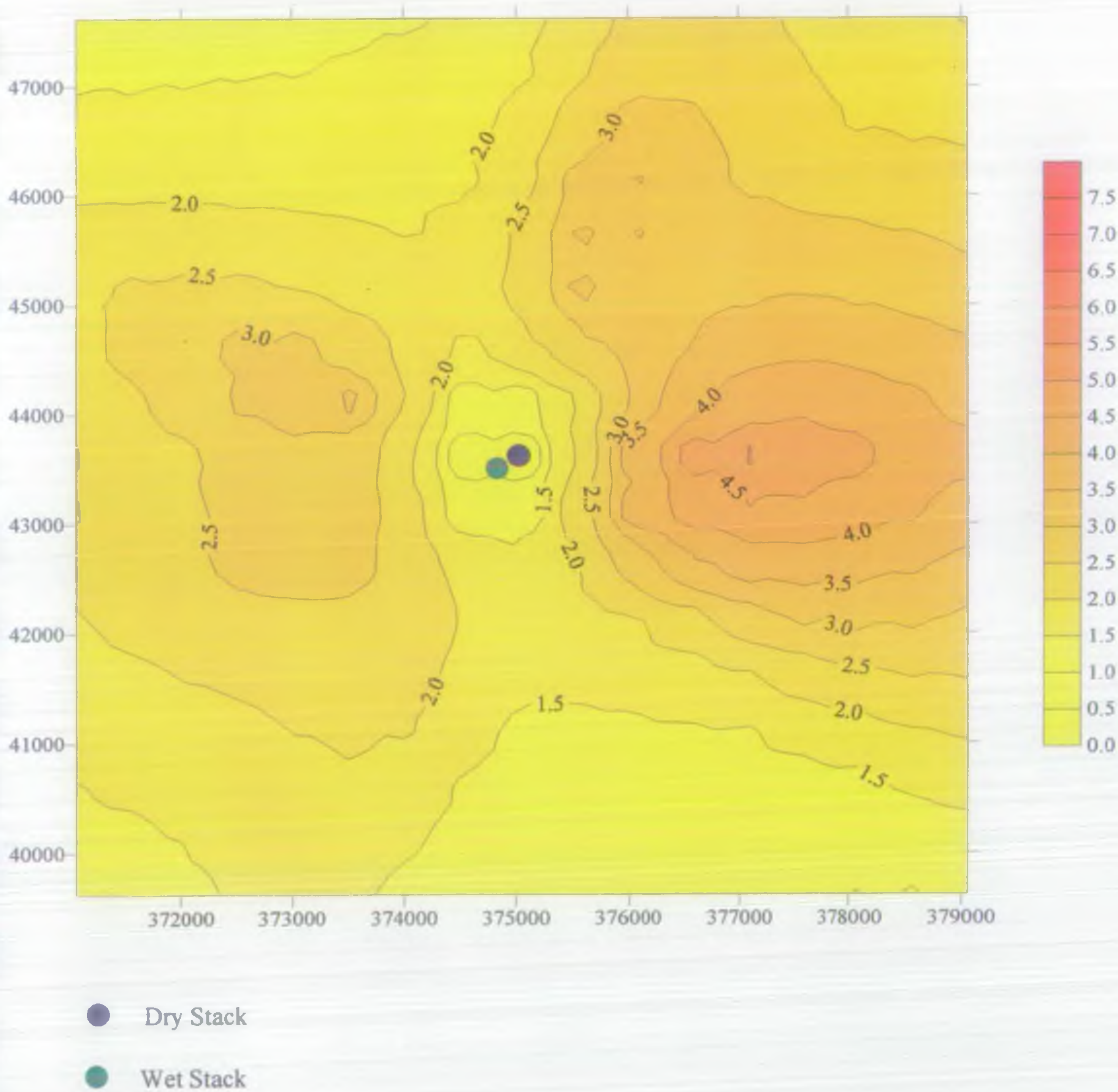


Figure B2(d) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, ISCLT3 model: Case 4

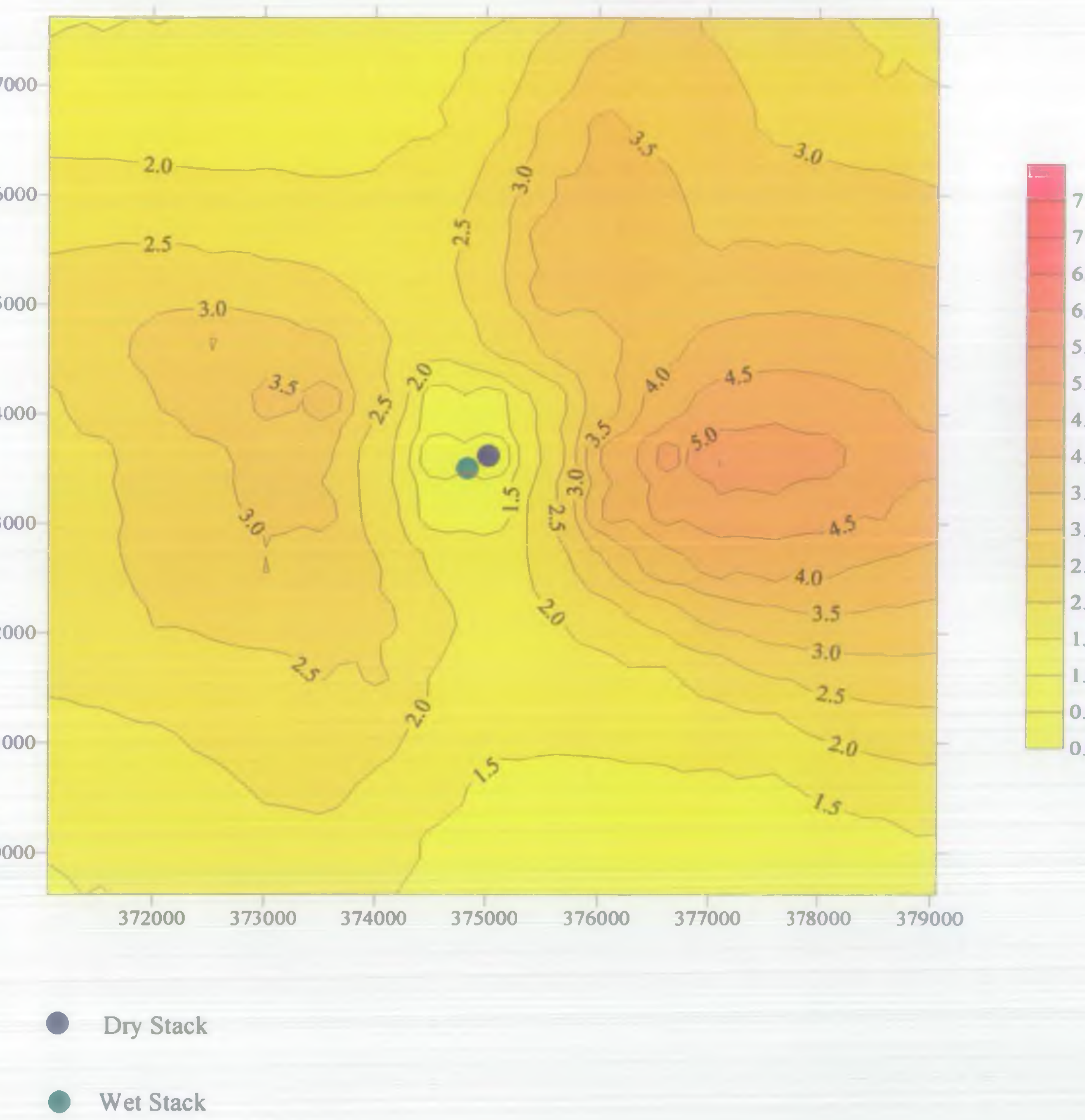
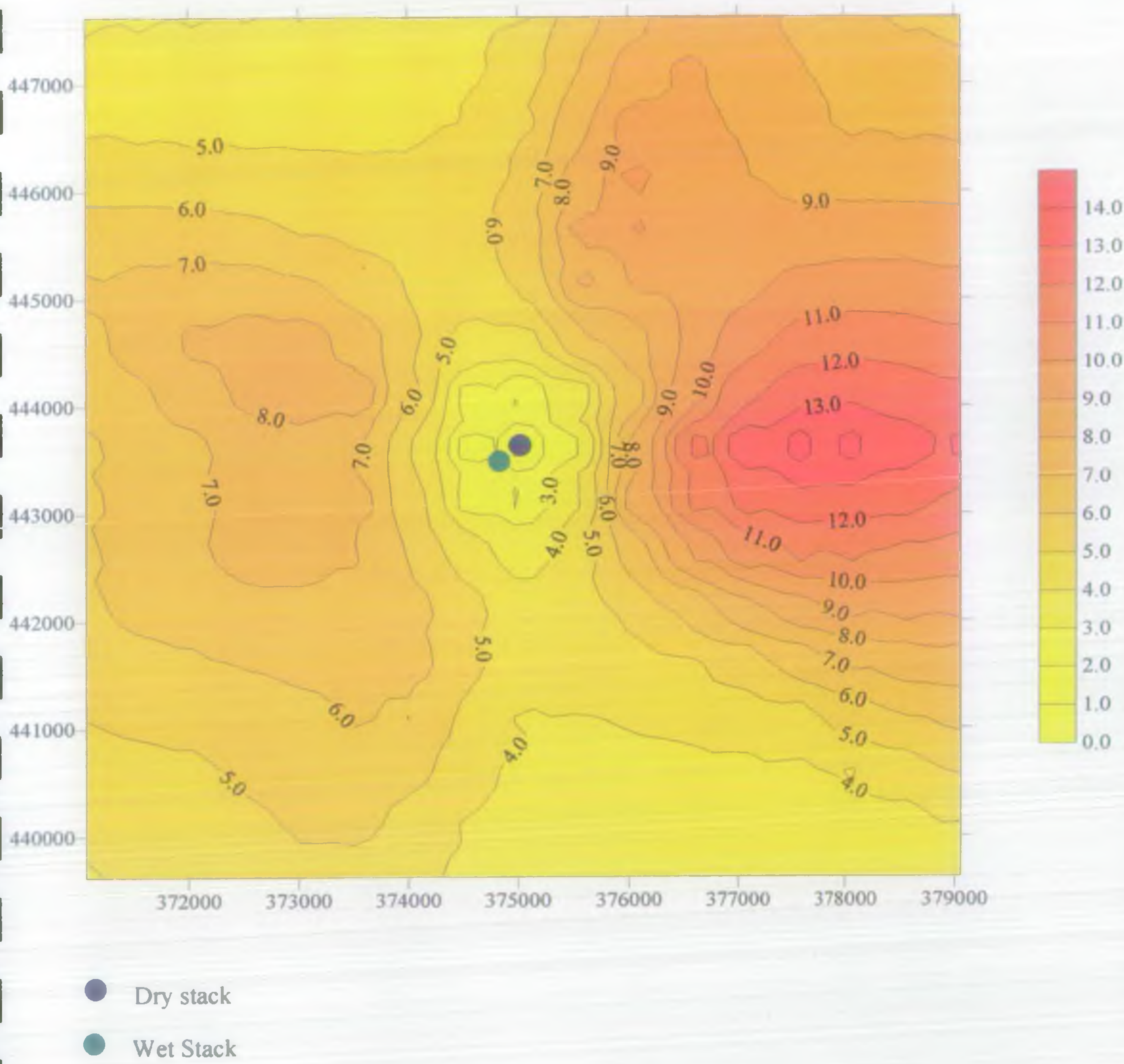


Figure B2(e) Annual Average Concentration of SO_2 ($\mu g/m^3$), Wilsden Met Data, ISCLT3 model: Cases (1+2)



APPENDIX C

Appendix C : Annual Average Concentration of SO_2, Cases 6-13, Met Data: Squires Gate, Ringway (Model: ADMS)

The following figures show long term (annual average) concentrations of SO_2 calculated using the ADMS model and met data from Squires Gate and Ringway met sites. Results for the proposed dry kiln cases, Cases 6-13, are presented.

These figures can be compared with Figures 24-27 which show the results for the same cases using met data from Wilsden. As in Appendix A, the contour plots reflect the difference in prevailing wind direction, which is west south-westerly at Wilsden, westerly at Squires Gate but southerly at Ringway. Maximum values of the annual average are highest when the Squires Gate data is used.

Figure C1(a) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 6

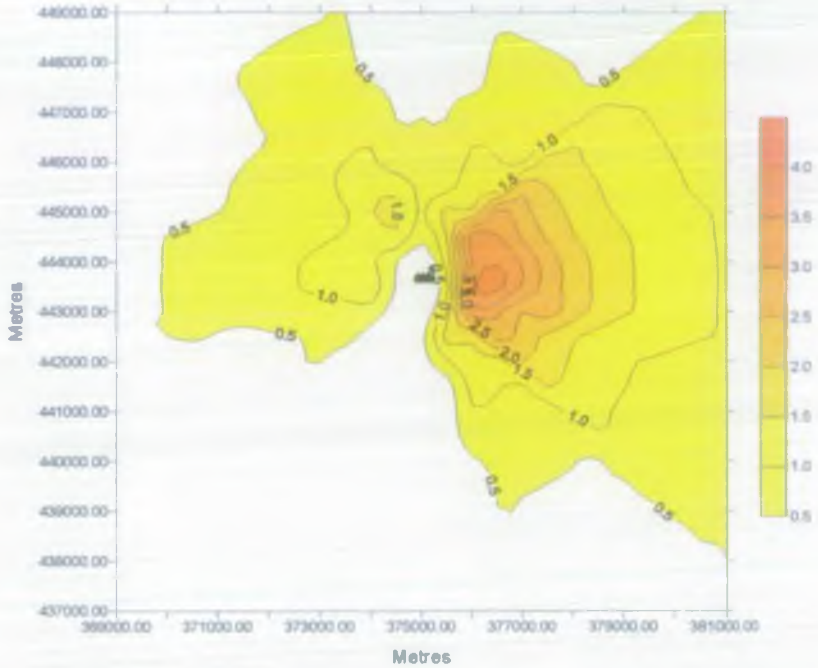


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Figure C1(b) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 7

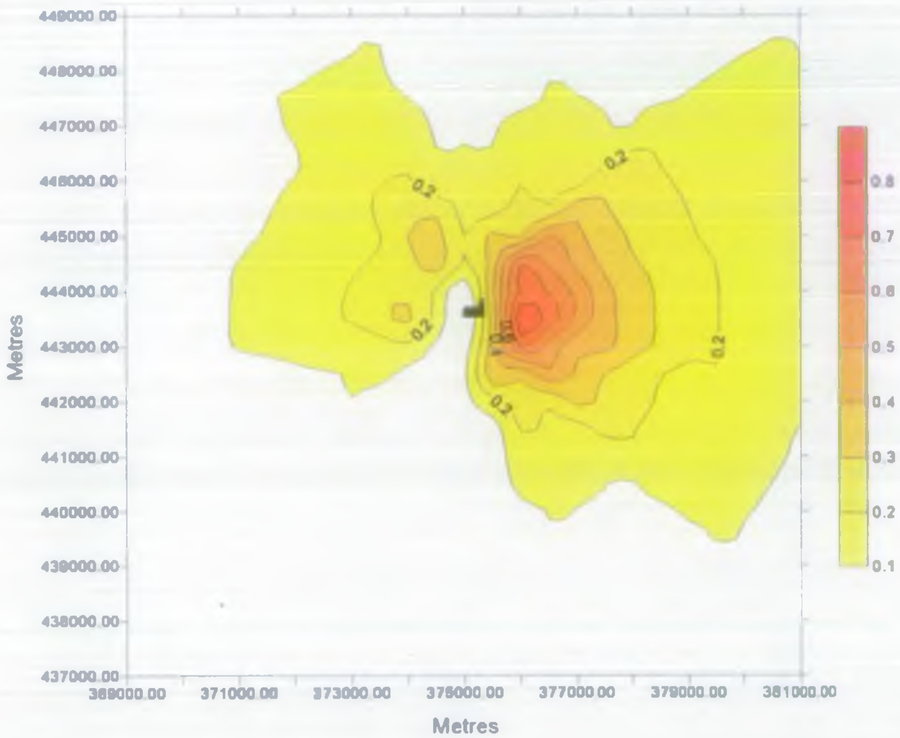

Figure C1(c) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 8

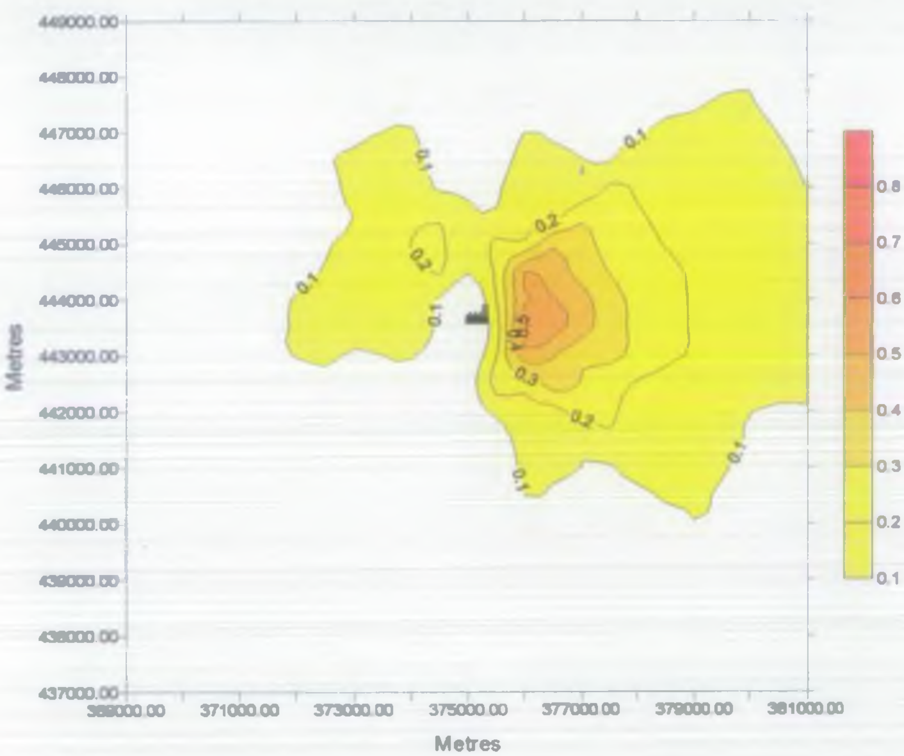

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Figure C1(d) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 9

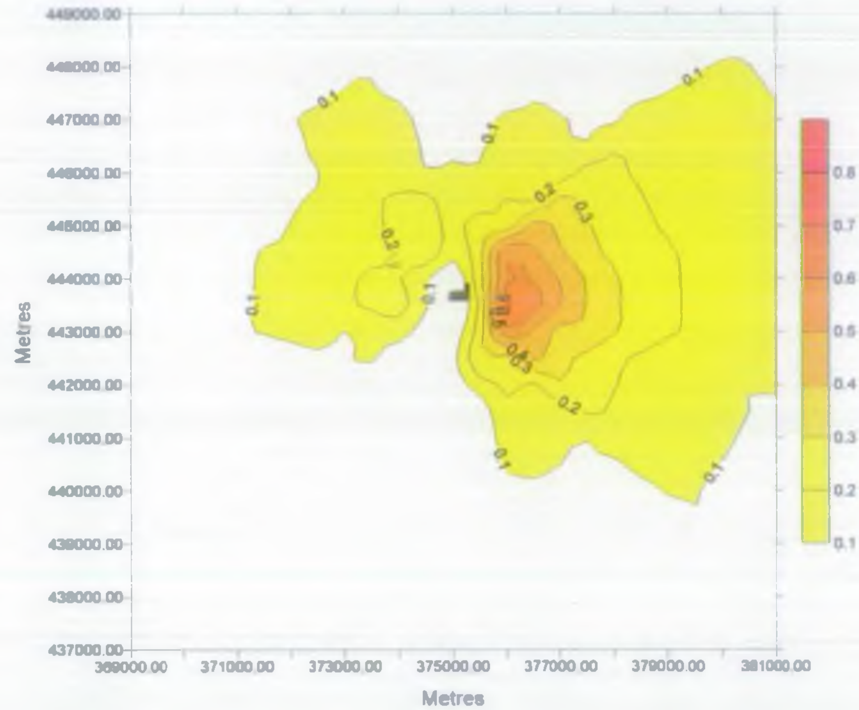

Figure C1(e) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 10

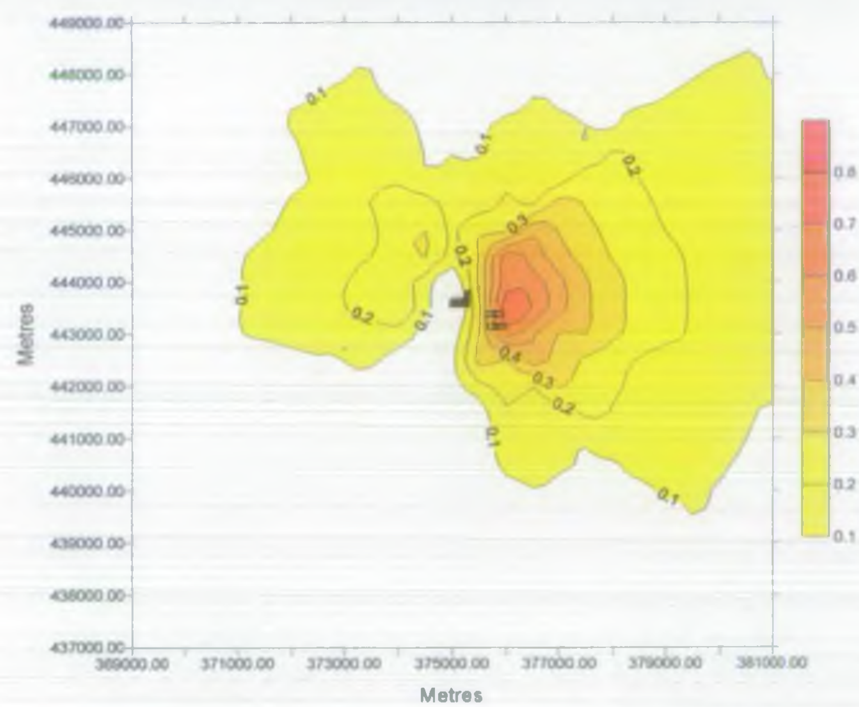

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Figure C1(f) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 11

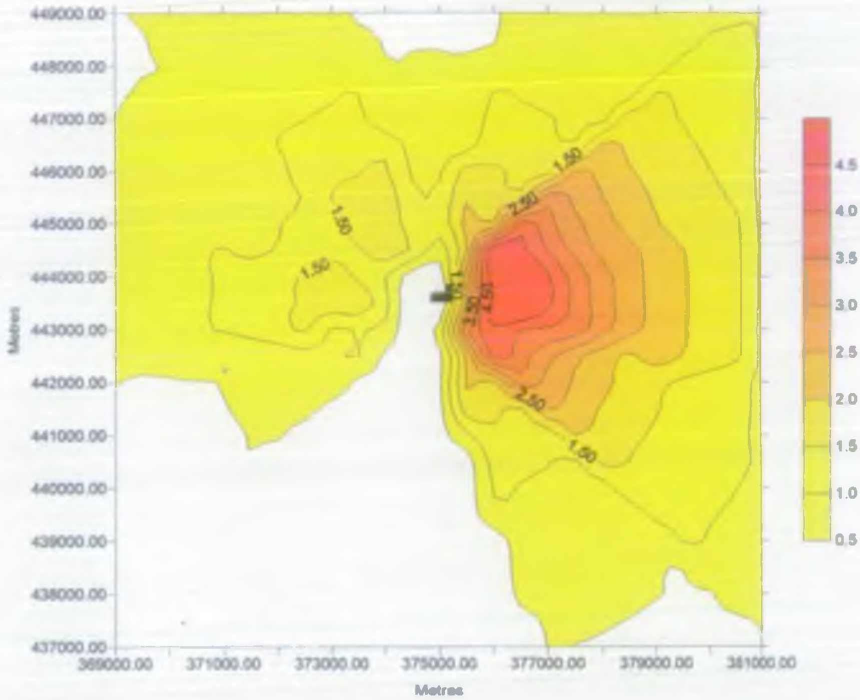

Figure C1(g) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 12

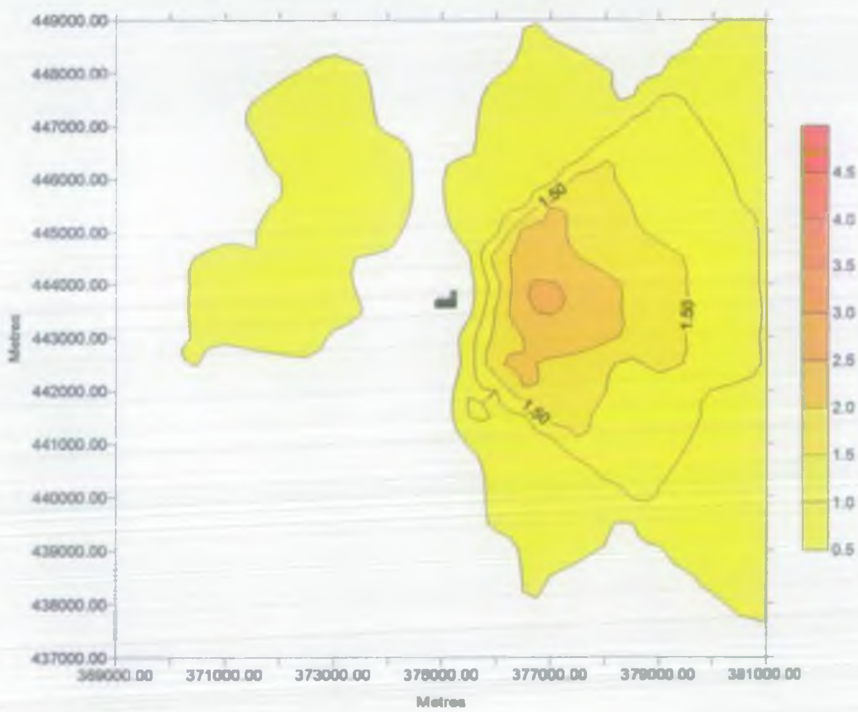

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Figure C1(h) Annual Average Concentration of SO_2 ($\mu g/m^3$), Squires Gate Met Data, : Case 13

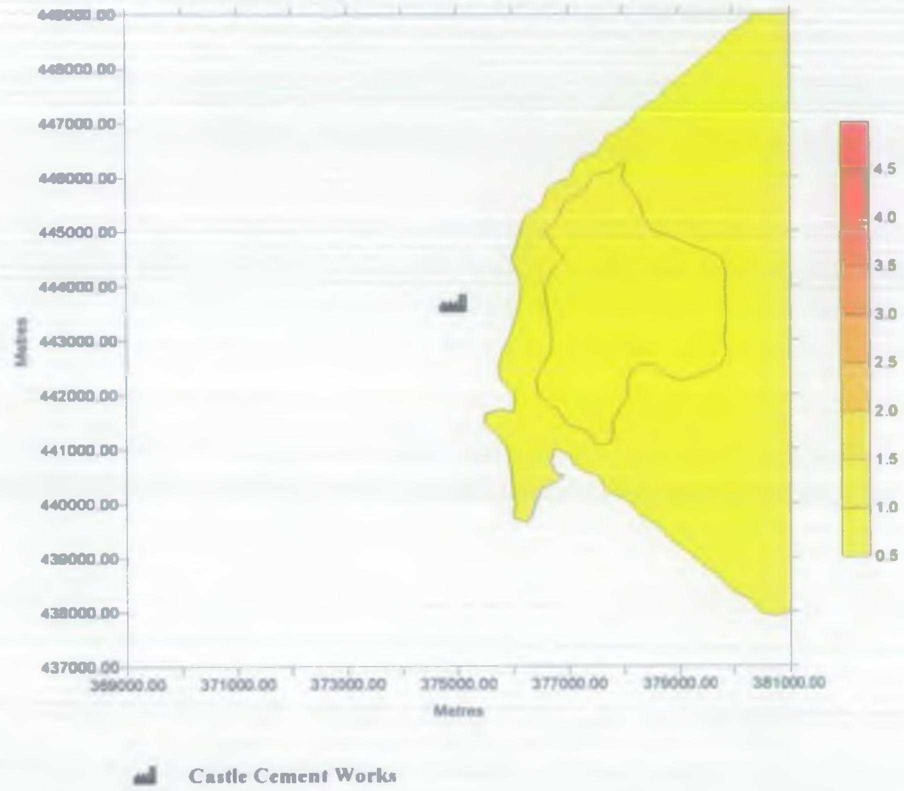


Figure C2(a) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 6

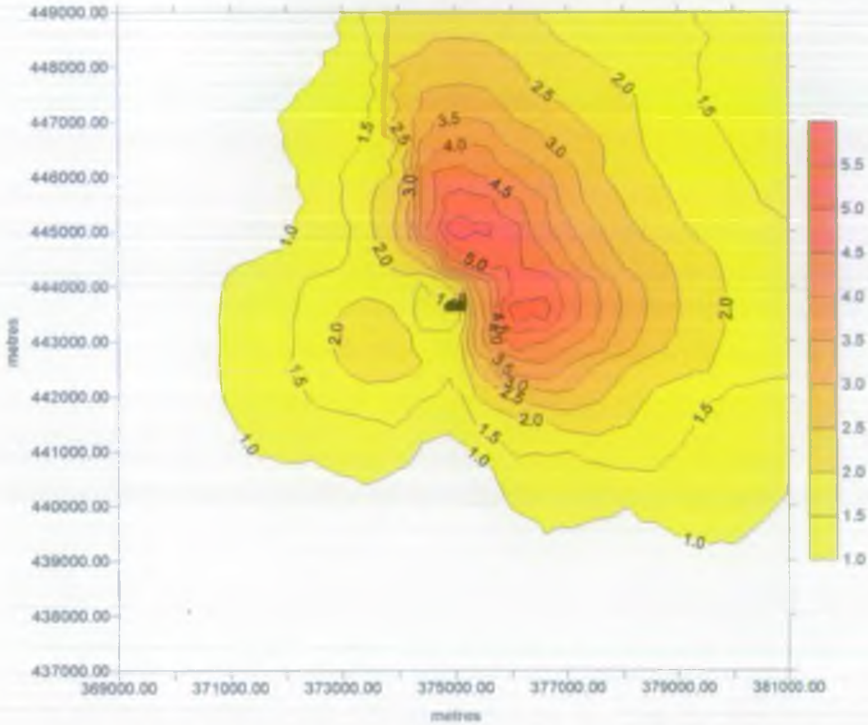


Figure C2(b) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 7

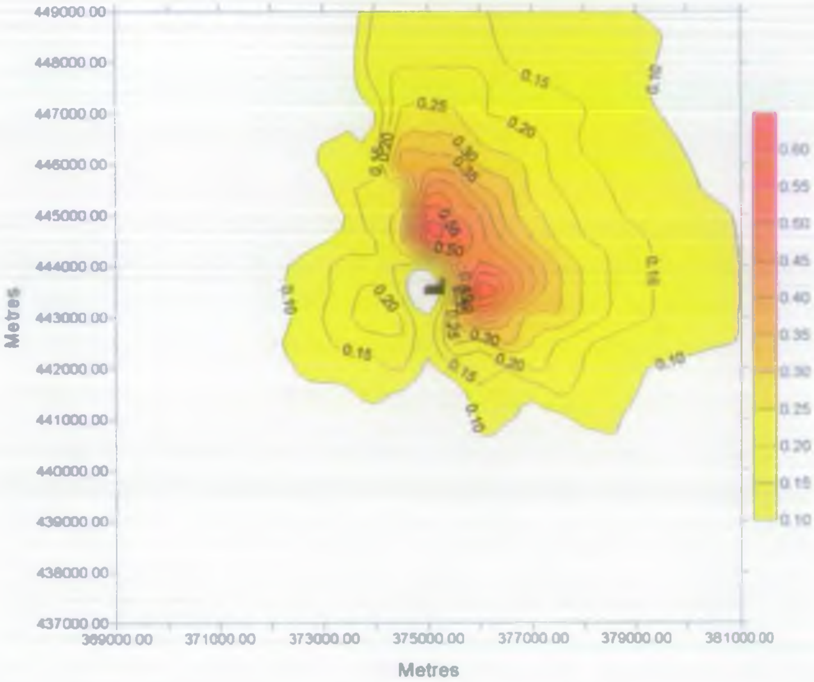
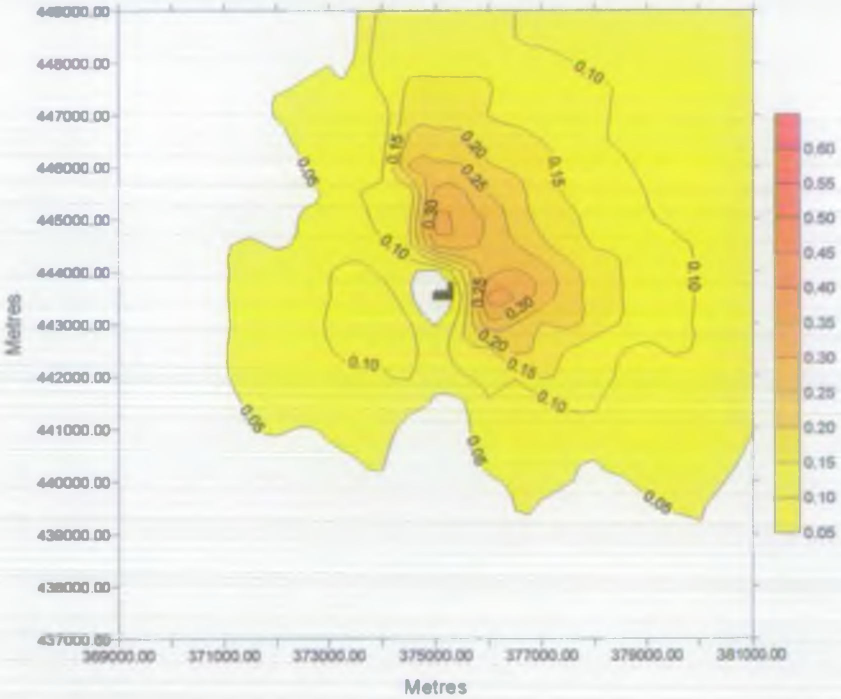


Figure C2(c) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 8



Castle Cement Works

Figure C2(d) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 9

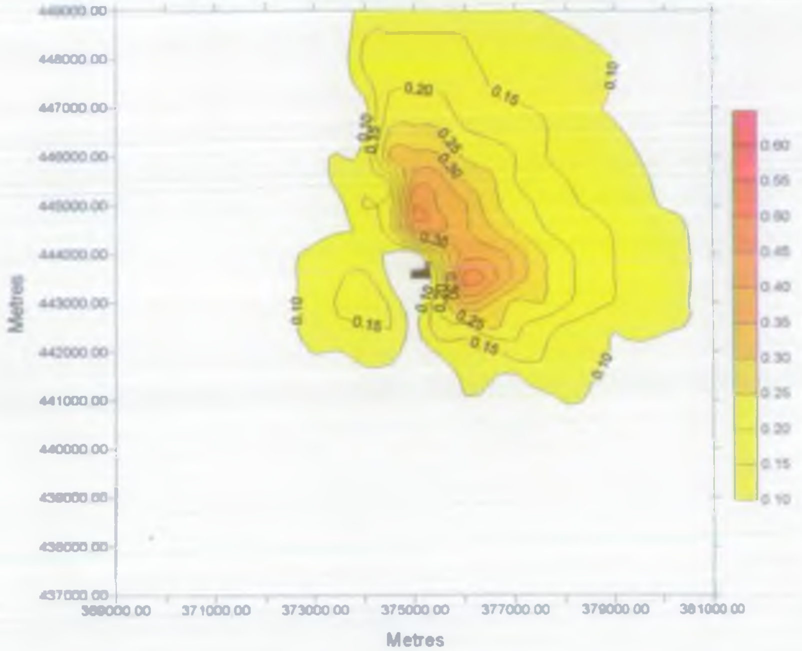


Figure C2(e) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 10

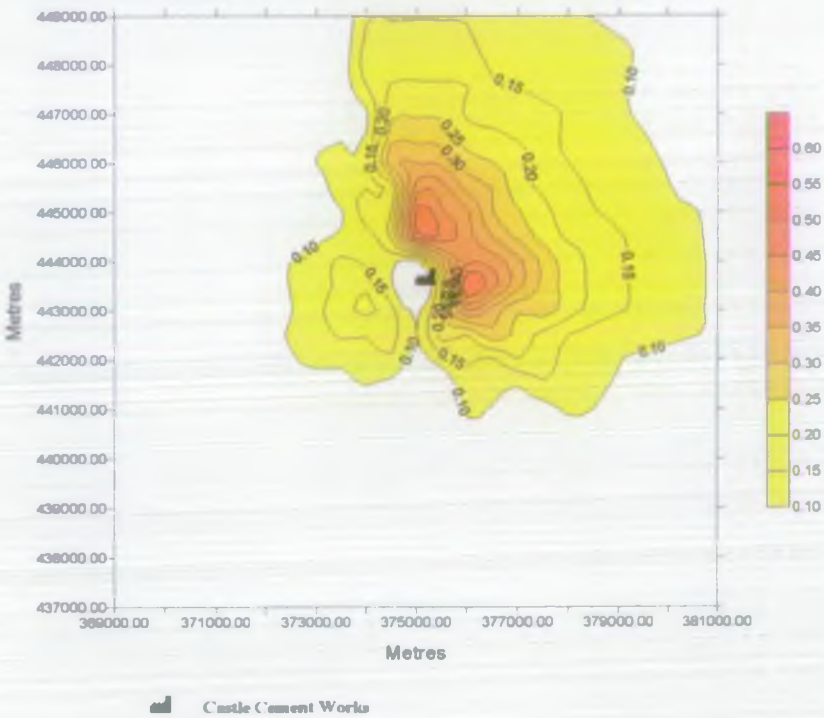


Figure C2(f) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 11

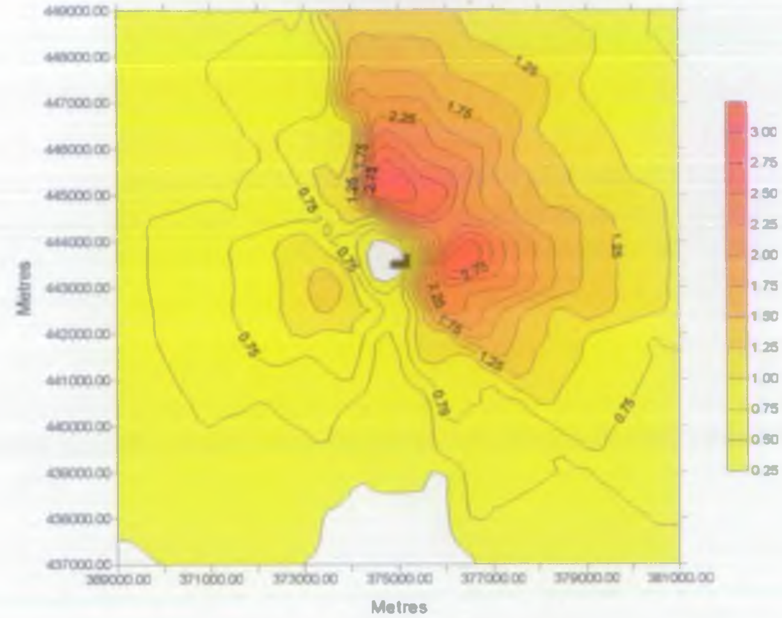


Figure C2(g) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 12

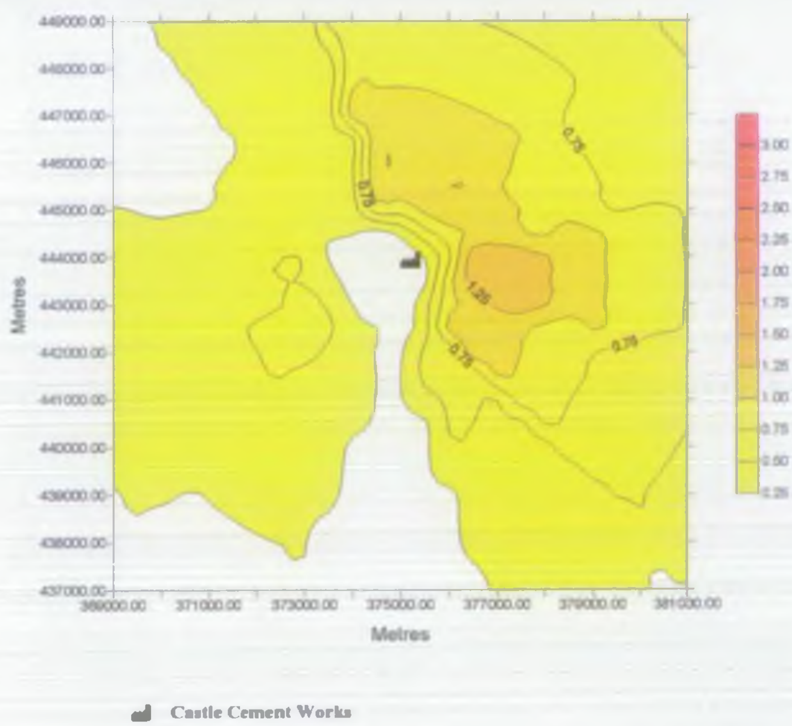
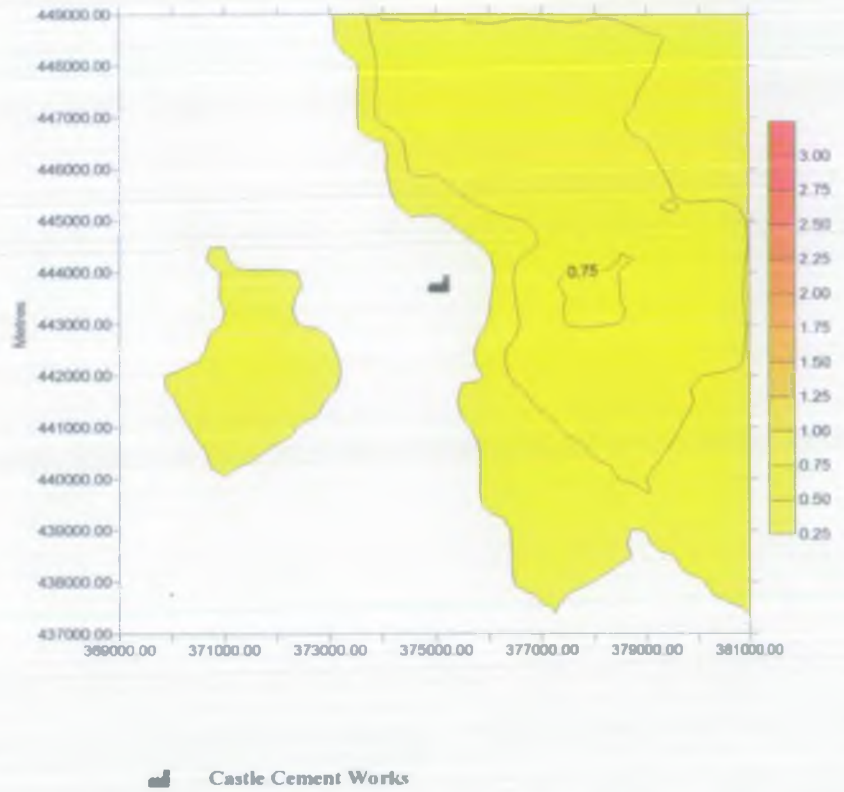


Figure C2(h) Annual Average Concentration of SO_2 ($\mu g/m^3$), Ringway Met Data, : Case 13



APPENDIX D

Appendix D : Annual Average Concentration of NO_x, Cases 1-4, Met Data: Wilsden (Model: ISCLT3)

Figures D1(a)-(e) show long term (annual average) concentrations of SO_2 calculated using the ISCLT3 model. Met data from Wilsden met site has been used. Results for combinations of the current wet and dry kilns emissions, Cases 1-4 and the wet and dry kilns operating together, Case (1+2) are presented.

These figures can be compared with figures 47-51 which show the results calculated by ADMS for the same cases using met data from Wilsden. The results from ISCLT3 show higher maximum values at distances slightly further from the stacks than the ADMS results.

Figure D1(a) Annual Average Concentration of NO_X ($\mu g/m^3$), Wilsden Met Data, ISCLT3 Model: Case 1

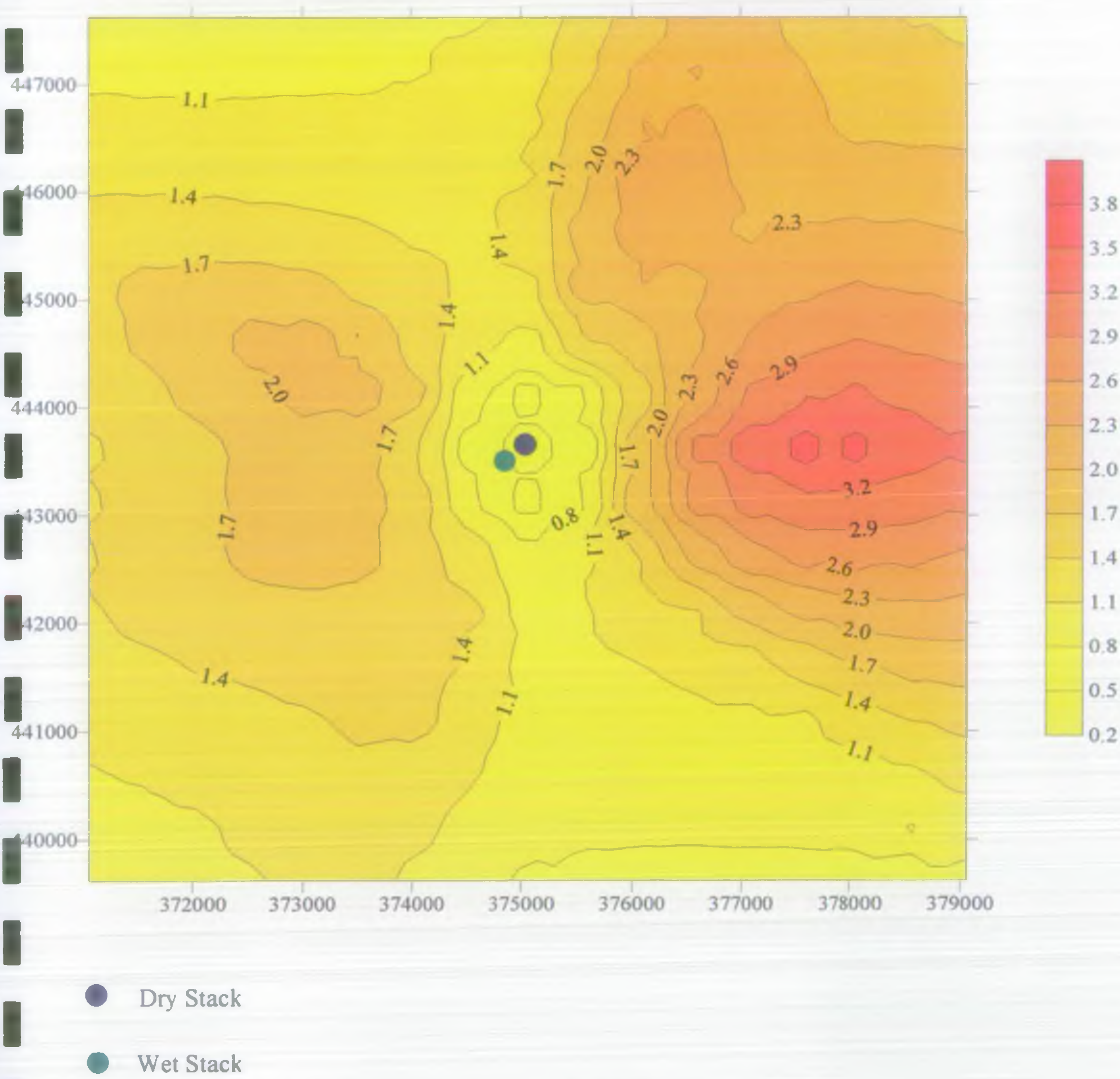


Figure D2(a) Annual Average Concentration of NO_X ($\mu g/m^3$), Wilsden Met Data, ISCLT3 Model: Case 2

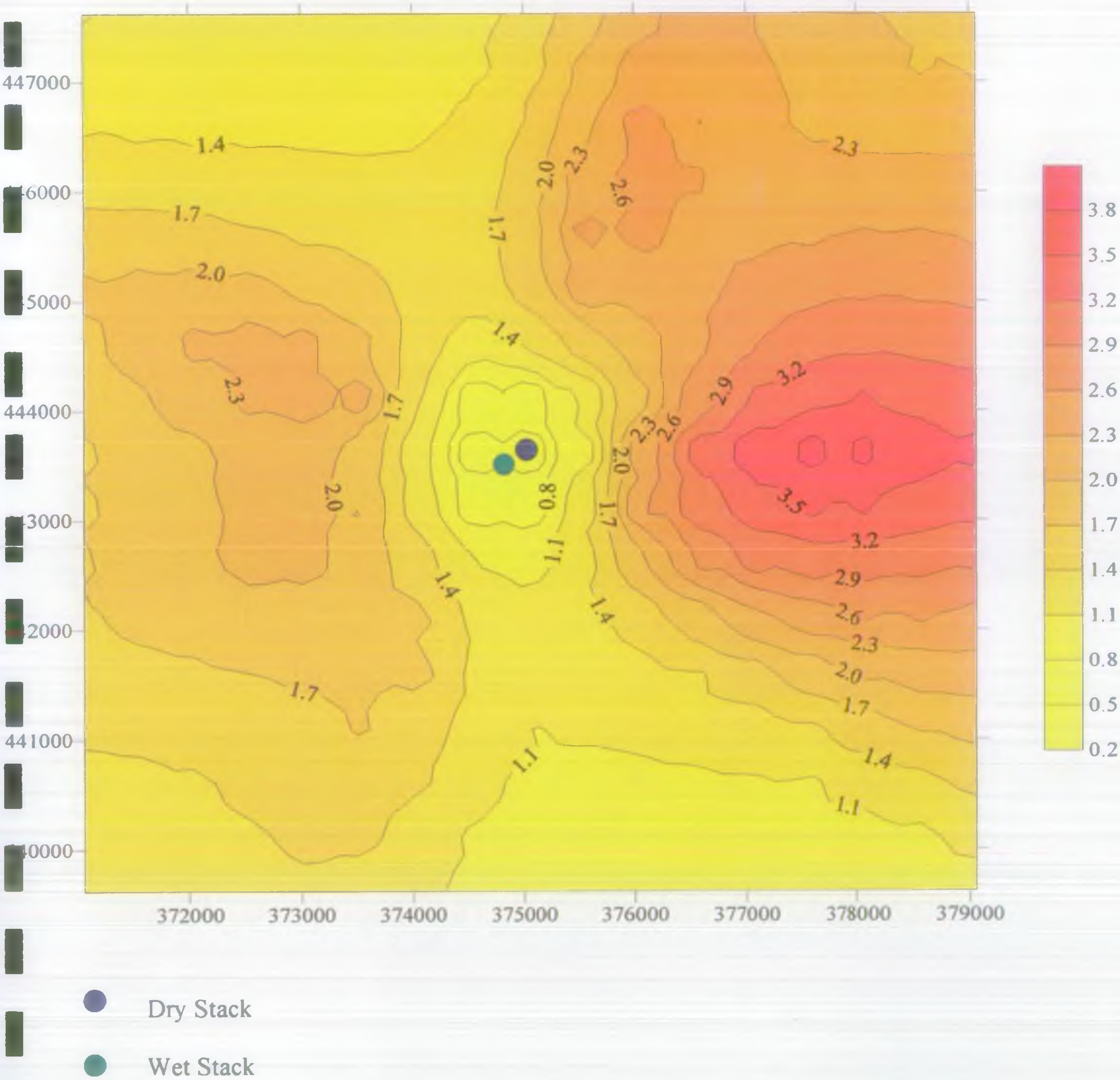


Figure D3(a) Annual Average Concentration of NO_X ($\mu g/m^3$), Wilsden Met Data, ISCLT3 Model: Case 3

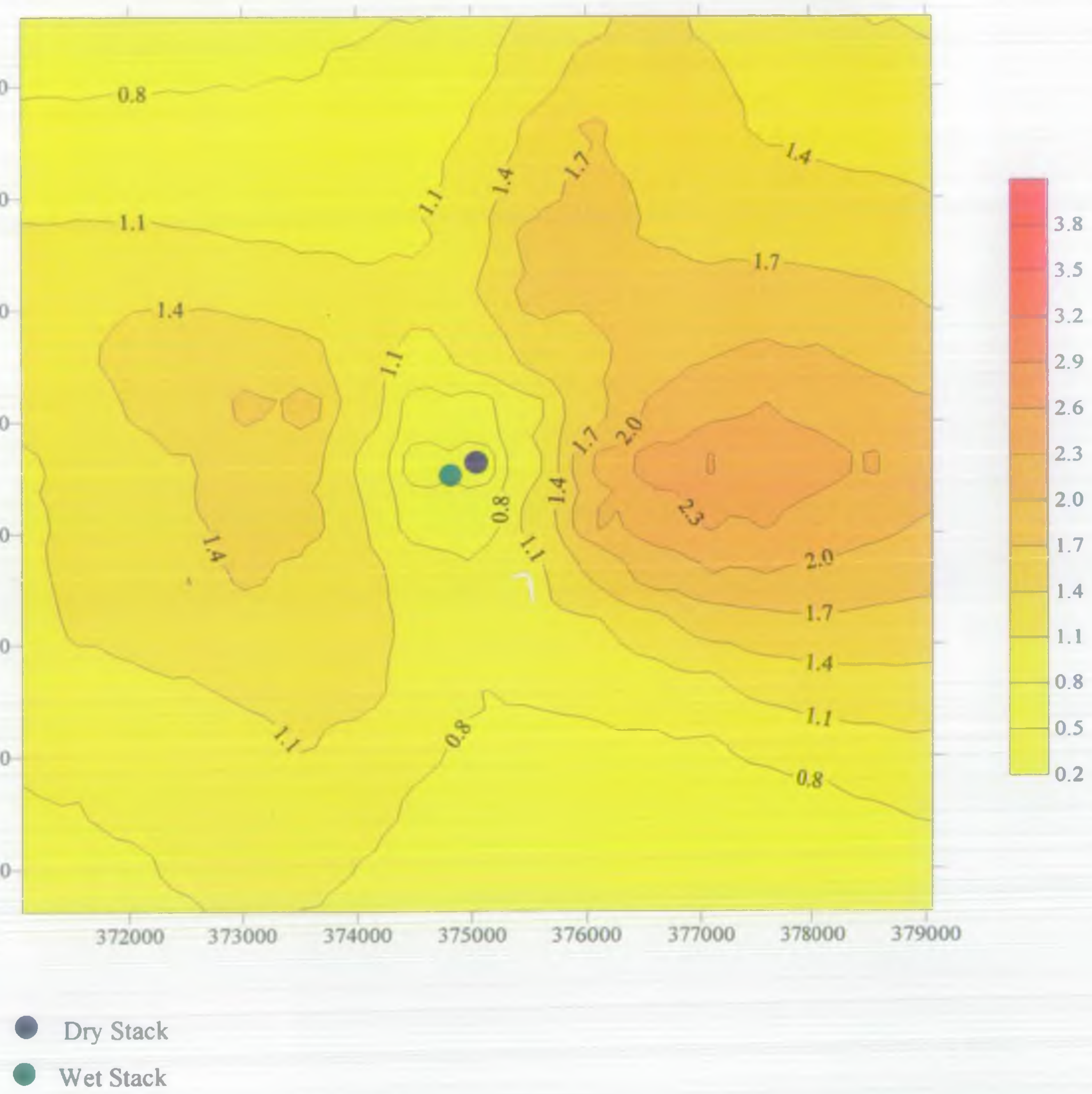


Figure D4(a) Annual Average Concentration of NO_X ($\mu g/m^3$), Wilsden Met Data, ISCLT3 Model: Case 4

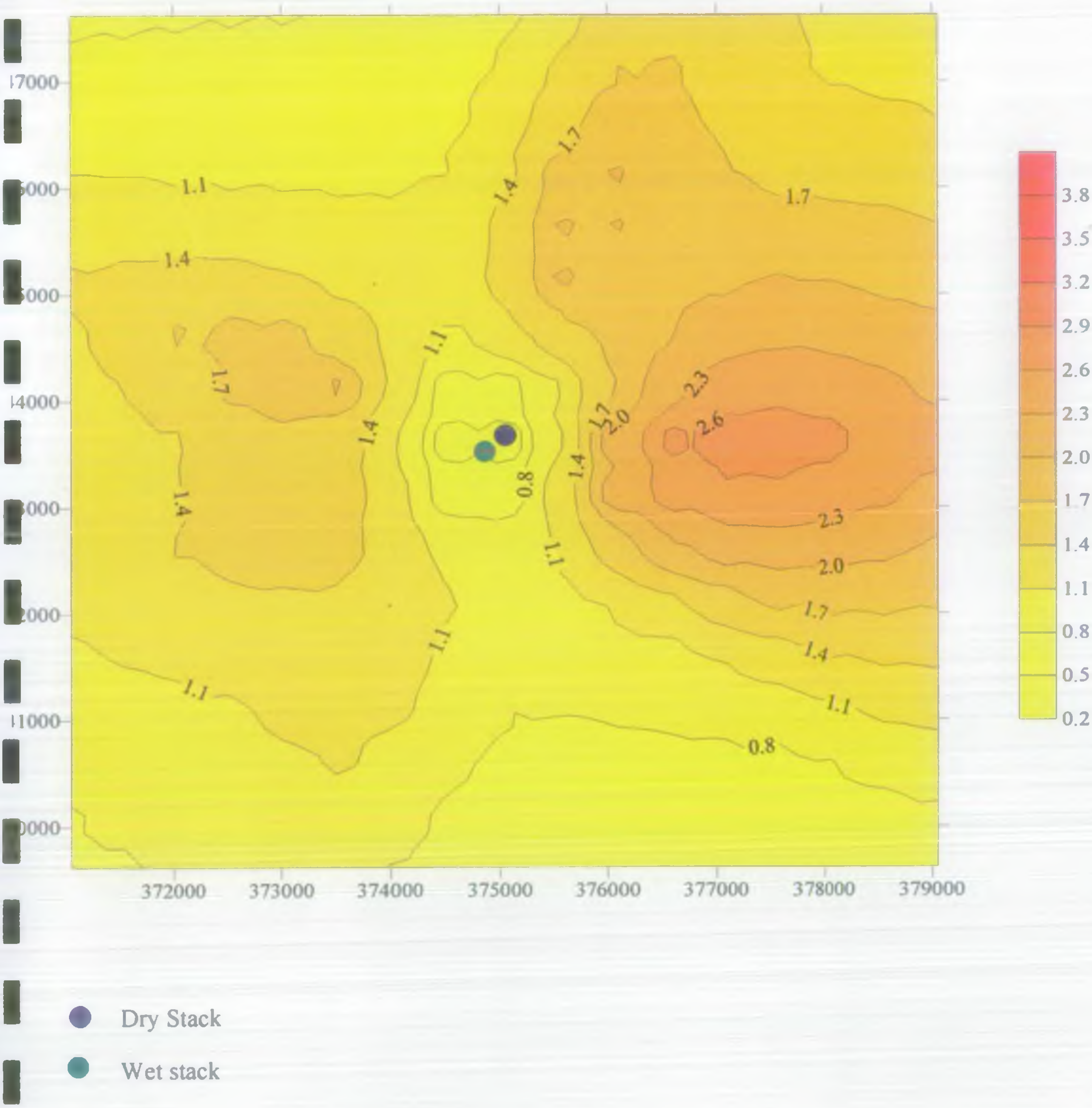
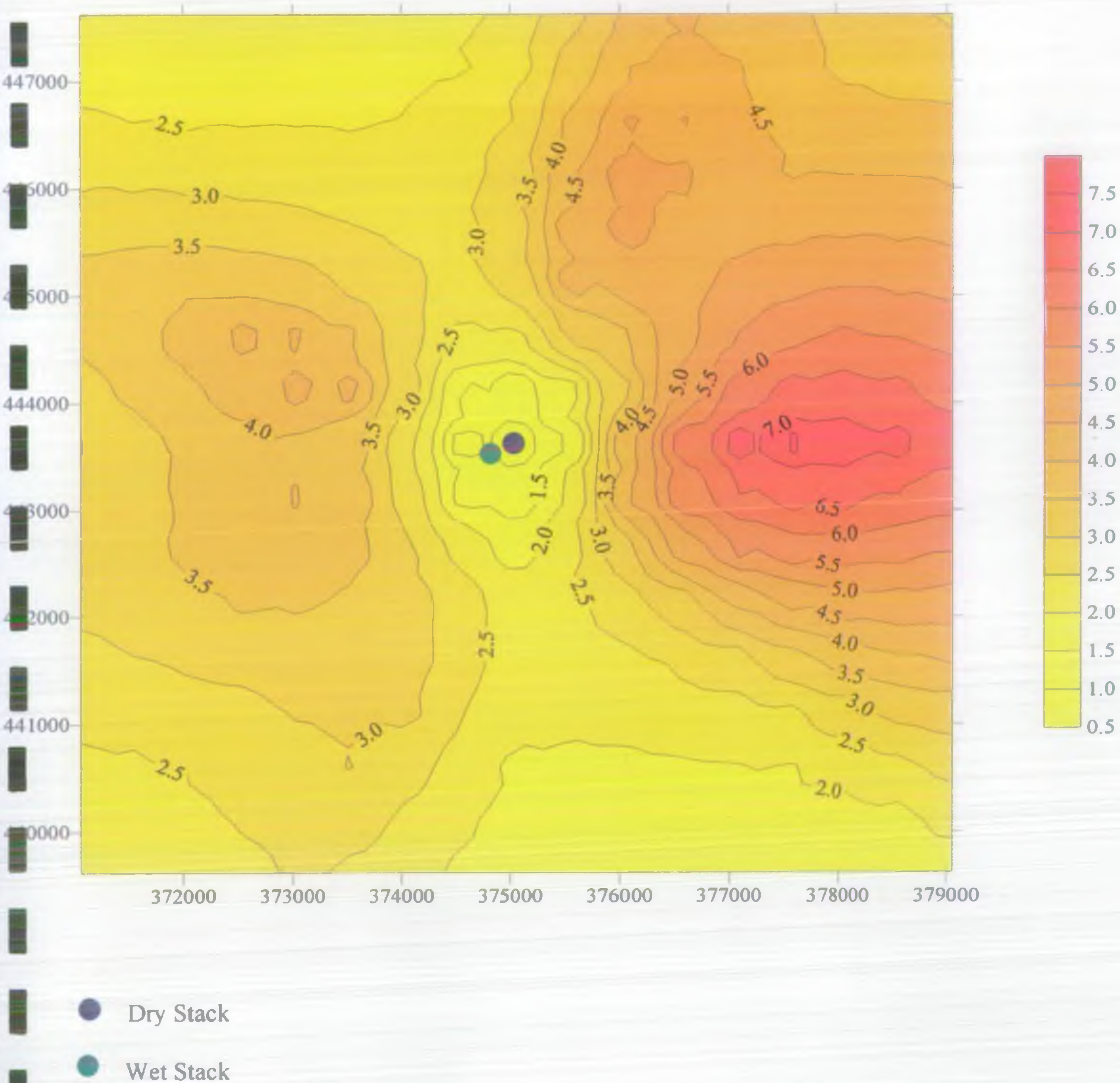


Figure D5(a) Annual Average Concentration of NO_X ($\mu g/m^3$), Wilsden Met Data, ISCLT3 Model: Cases 1+2



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