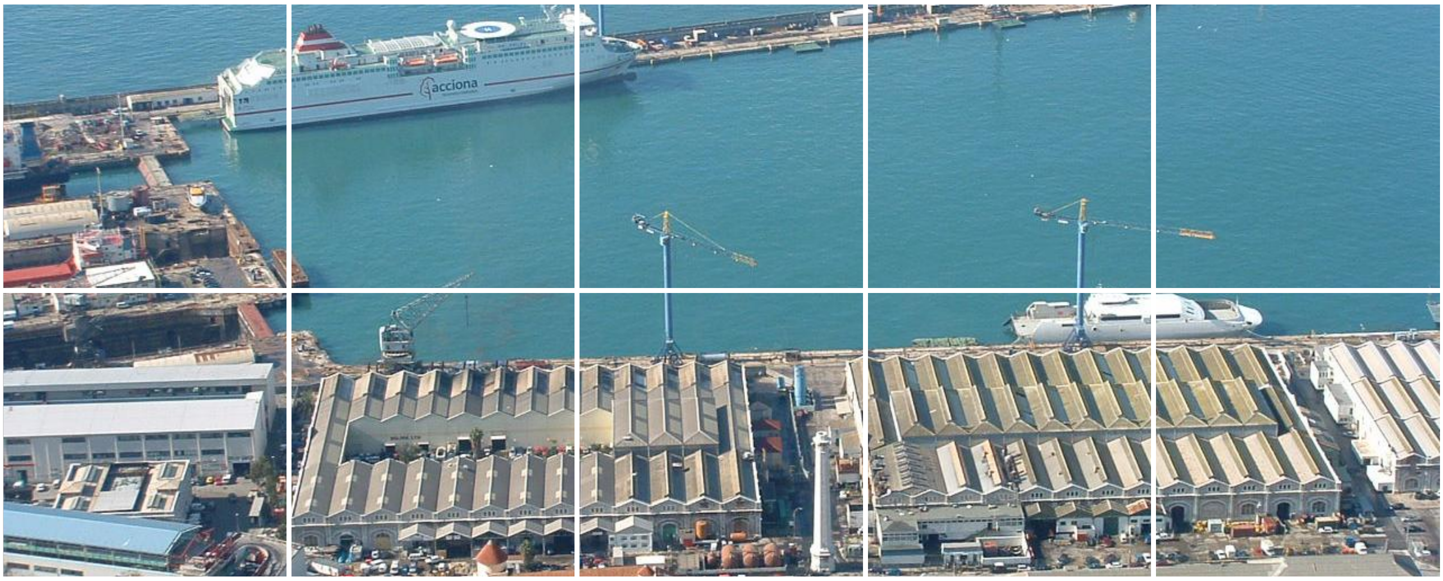

# Dispersion modelling of MOD and OESCO power station $PM_{10}$ discharges

**Report to Environmental Agency, Gibraltar**

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AEA
The Gemini Building
Fermi Avenue
Harwell International Business Centre
Didcot
OX11 0QR

t: 0870 190 6401
f: 0870 190 6318

AEA is a business name of
AEA Technology plc

AEA is certificated to ISO9001
and ISO14001

| | | |
|---|---|---|
| **Author** | Name | John Abbott |
| **Approved by** | Name | Andrew Kent |
| | Signature | |
| | Date | |

# Executive summary

AEA manage a programme of monitoring of particulate matter concentrations on behalf of the Environmental Agency, Gibraltar. The monitoring results in 2007 and 2008, highlighted consistently high concentrations of particulate matter, $PM_{10}$ at the Rosia Road monitoring site. The concentrations measured at this site exceeded the EU limit value for the annual mean $PM_{10}$ concentration and the number of permissible exceedences of the 24-hour limit value.

Many sources of pollutant emission can contribute to $PM_{10}$ concentrations. These include the exhaust emissions and resuspended dust from road traffic in Gibraltar, construction dust, shipping emissions, emissions from industrial sources in Spain and Morocco, wind-blown Saharan dust, secondary particulates resulting from emissions throughout Europe and sea salt. AEA is currently carrying out studies to quantify the contributions from these sources.

The Rosia Road monitoring site is approximately 500 m from two of the three power generation facilities in Gibraltar and preliminary pollution rose analysis has suggested that the generation plant contributes significantly to the local concentrations. This report describes a modelling study to quantify the contribution made by the power stations to $PM_{10}$ concentrations

The modelling study indicates that the power stations contribute 0.8 $\mu g\ m^{-3}$ or less to the annual mean concentrations at the monitoring site. Directional analysis of the monitoring data suggest that concentrations at the monitoring site are likely to be influenced by contributions from the south-southwest but that the influence from this direction is not significantly larger than other wind directions.

However, the model predicted that, even in the absence of complex terrain effects, the power station emissions result in substantial increases in the annual mean concentration at Red Sands Road. Adding the power station contribution to background concentrations from the Bleak House background monitoring site indicates that the concentrations potentially exceed the annual average limit value of 40 $\mu g\ m^{-3}$ in the Red Sands Road area.

# Table of contents

# 1 Introduction

AEA manage a programme of monitoring of particulate matter concentrations on behalf of the Environmental Agency, Gibraltar. The monitoring results in 2007 and 2008 highlighted consistently high concentrations of particulate matter, $PM_{10}$ at the Rosia Road monitoring site. The concentrations measured at this site exceeded the EU limit value for the annual mean $PM_{10}$ concentration and the permissible number of exceedences of the 24-hour limit value.

Many sources of pollutant emission can contribute to $PM_{10}$ concentrations. These include the exhaust emissions and resuspended dust from road traffic Gibraltar, construction dust, shipping emissions, emissions from industrial sources in Spain and Morocco, wind-blown Saharan dust, secondary particulates resulting from emissions throughout Europe and sea salt. AEA is currently carrying out studies to quantify the contributions from these sources.

However, the Rosia Road monitoring site is approximately 500 m from two of the three power generation facilities in Gibraltar and it has been suggested that the generation plant contributes significantly to the local concentrations. This report describes a modelling study to quantify the contribution made by the power stations to $PM_{10}$ concentrations

The modelling study was carried out using the dispersion model ADMS4.1. ADMS4.1 is a practical dispersion model that uses an up-to-date description of the atmospheric boundary layer. Modules within the model allow the effects of complex terrain and buildings to be taken into account. Various approaches can be taken in modelling what is a complex real world situation, each involving some compromises because the modelling of pollutant dispersion over Gibraltar's complex terrain represents a considerable challenge. Sensitivity studies have therefore been carried out to assess the sensitivity of the model predictions to the modelling approach adopted and the meteorological input data used.

Section 2 of this report provides a summary of recent measurements of $PM_{10}$ concentrations in Gibraltar. Section 3 of the report describes the model inputs. Section 4 presents the results of the modelling study and Section 5 discusses the contribution made by the power generation facility to the measured exceedences of the EU limit value. Section 6 presents the conclusions of the modelling study.

# 2 $PM_{10}$ monitoring

## 2.1 Air quality objectives

Gibraltar will comply with the European Air Quality objectives as detailed in the European Council Directives 1996/62/EC, 1999/30/EC, 2000/69/EC, 2002/3/EC and 2004/107/EC.

These Directives have been transposed into Gibraltar Law by the Public Health (Air Quality Limit Values) Rules 2002 as amended by the Public Health (Air Quality Limit Values) (Amendment) Rules 2003 and the Public Health (Air Quality) (Ozone) Rules 2004.

The European Union Limit Values for particulate matter are shown in Table 1.

**Table 1: Limit Values for particulate matter, $PM_{10}$**

| | Averaging period | Limit value* | Date by which value is to be met |
|---|---|---|---|
| 24-hour limit for the protection of human health | 24 hours | 50 $\mu g\ m^{-3}$ not to be exceeded more than 35 times a calendar year | 1 January 2005 |
| Annual limit for the protection of human health | Calendar year | 40 $\mu g\ m^{-3}$ | |

* Measured using the European gravimetric transfer sampler or equivalent.

## 2.2 Monitoring

Particulate matter, $PM_{10}$ concentrations are monitored daily using a gravimetric sampler corresponding to the European reference standard at two locations in Gibraltar at a roadside site on Rosia Road and at a background site at Bleak House. The Rosia Road site has operated since February 2005 while the Bleak house site has operated since May 2008.

Table 2 shows the $PM_{10}$ concentrations measured at the two sites.

**Table 2: Measured $PM_{10}$ concentrations**

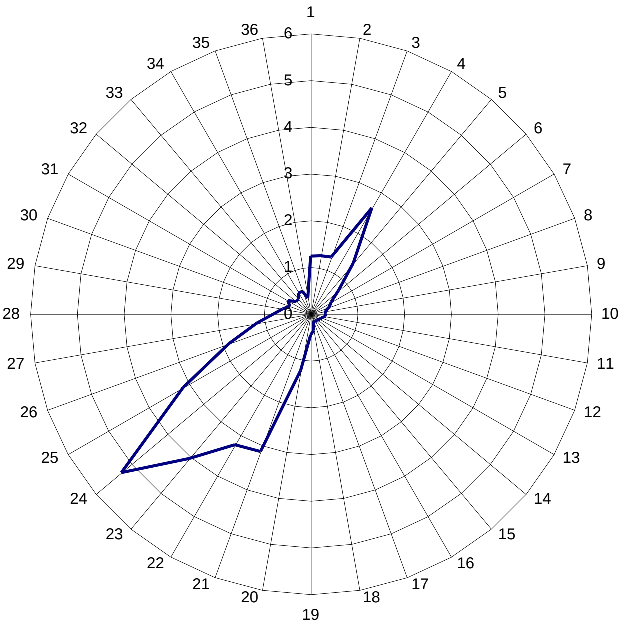
| Site | Period | Number of days | Average, $\mu g\ m^{-3}$ | Number of exceedences of 50 $\mu g\ m^{-3}$ |
|---|---|---|---|---|
| Rosia Road | 02/02/05-31/12/05 | 329 | 35.9 | 16 |
| | 2006 | 357 | 39.9 | 60 |
| | 2007 | 362 | 45.0 | 109 |
| | 2008 | 330 | 40.6 | 63 |
| | 16/05/08-31/12/08 | 195 | 41.4 | 38 |
| Bleak House | 16/05/08-31/12/08 | 176 | 33.7 | 8 |

The annual mean concentration at the Rosia Road site exceeded the limit value of 40 $\mu g\ m^{-3}$ in 2007 and 2008: the concentration also exceeded the daily limit value of 50 $\mu g\ m^{-3}$ on more than 35 occasions in 2006, 2007 and 2008.

The average concentration measured at the Bleak House site over the period 16/05/08-31/12/08 was less than the annual average limit value. Comparison with the measurements at the Rosia Road site over the same period indicates that the measurement period is representative of concentrations throughout the year.

Fig. 1 shows a pollution rose for the Rosia Road monitoring site for 2008. It shows the average $PM_{10}$ concentration for each 10$^o$ wind direction band measured at Rosia Road. It shows that the greatest contribution to the measured concentration is associated with winds from the southwest. However, winds are most frequent from this direction: Fig. 2 shows the wind rose normalised to take account of the frequency of each wind direction at Rosia Road. Fig. 2 shows little apparent influence of wind direction on concentrations measured at Rosia Road: it provides no evidence to suggest that concentrations are increased when the wind comes from the direction of the power stations, approximately 500 m to the south-southwest. These plots are based on the apportionment of daily concentration by the distribution of hourly wind directions. Fig. 3 suggests that this lack of directional signature may be in part the result of using the daily $PM_{10}$ concentration and apportioning by hourly wind direction. Alternative methods[1] are shown in Fig. 3 which shows (on the left) the daily Partisol concentration apportioned by wind direction AND wind speed (distance from origin) using hourly met data vector averaged to daily wind direction and speed. This is compared with the plot on the right that shows more recently available hourly FDMS data from Gibraltar Rosia Road covering the period May 2008 to June 2009. These plots show a specific directional signature and suggest the presence of a stronger source signature from the south-west than the daily data shown by wind direction alone implies. It cannot be concluded with confidence that this signature is associated with emissions from the power stations.

**Fig.1: Average $PM_{10}$ concentrations, $\mu g\ m^{-3}$ for each 10$^o$ wind direction band at Rosia Road**




[1] Analysis using openair toolset under development with NERC grant (http://www.openair-project.org/)

**Fig.2: Average $PM_{10}$ concentrations, μg $m^{-3}$ for each $10^{o}$ wind direction band at Rosia Road, normalised by frequency of wind direction**

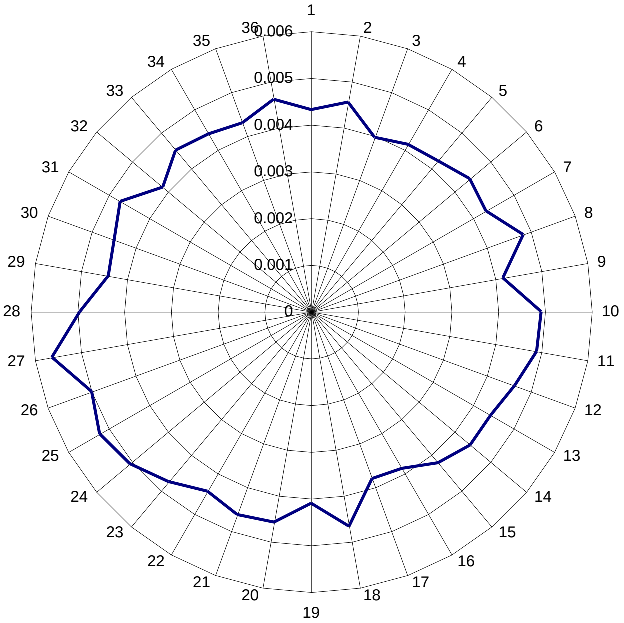
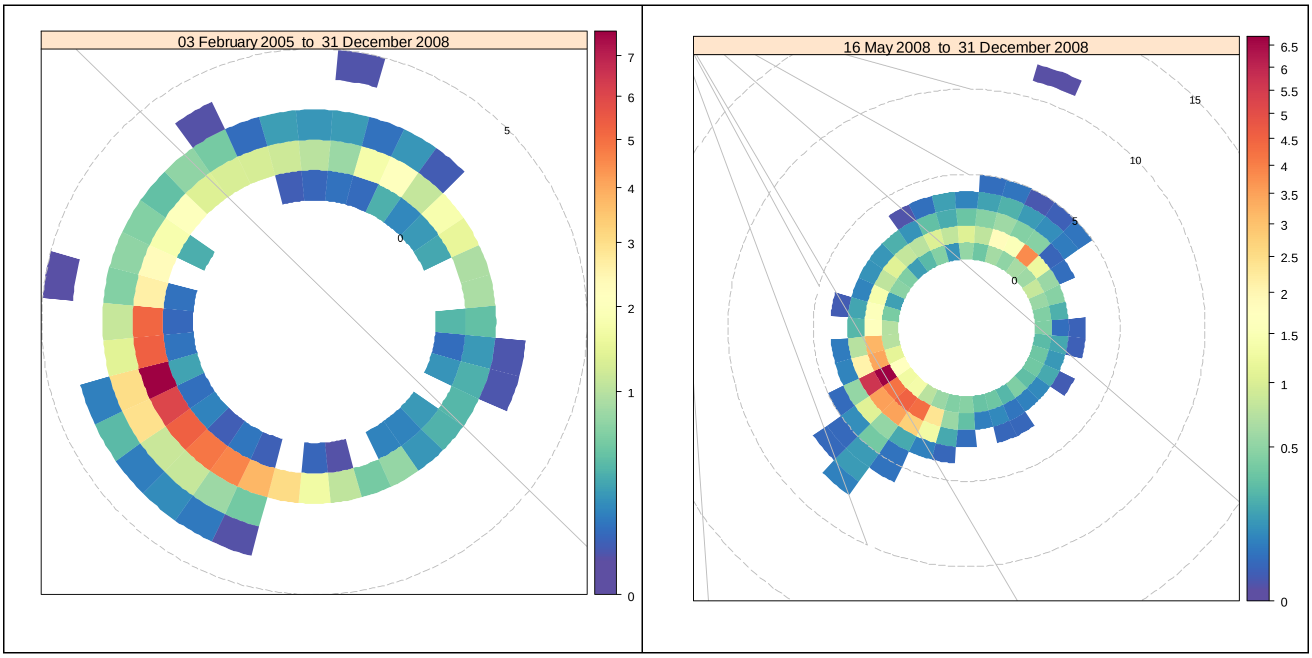



**Fig.3: Average $PM_{10}$ concentrations by daily Partisol measurement (left) and by hourly FDMS measurement (right), μg $m^{-3}$ for each $10^{o}$ wind direction band at Rosia Road, weighted by frequency of wind speed and direction**



# 3 Modelling approach and inputs

The impact of the emission discharges from the two dockyard power generation facilities was modelled using ADMS 4.1, a practical dispersion model that uses an up-to-date description of the atmospheric boundary layer.

The actual ambient concentration of particulate matter that is experienced at any receptor location in Gibraltar is a function of emissions from all sources of particulate matter and the dispersion of those emissions after they leave the source.

Disperse sources of particulate matter provide a background concentration upon which more local sources such as the power generation facilities are superimposed. The 2008 monitoring data from the Bleak House site has been used to provide the best estimate of the background concentration for Gibraltar.

Modules within the model allow the dispersion effects of complex terrain and buildings to be taken into account. The modelling of the dispersion of pollutants over Gibraltar's complex terrain represents a considerable challenge for any model and various approaches can be taken in modelling this complex situation, each involving some compromises. Sensitivity studies were therefore carried out to assess the sensitivity of the model predictions to the modelling approach and the meteorological data.

## 3.1 Emissions sources

Electricity is generated at three main power plants on Gibraltar. These are operated by the Ministry of Defence, OESCO Ltd and Gibelec Ltd. The Ministry of Defence and OESCO Ltd stations are located in the dockyard area to the west of Rosia Road below Jumpers, while the Gibelec Ltd power station is located on Gibraltar's North Mole. The Ministry of Defence and OESCO Ltd power stations have the greatest potential to affect the particulate matter concentrations in the Rosia Road area and are, therefore, those considered within this study. .

## 3.2 Emissions

### 3.2.1 OESCO Ltd

OESCO Ltd operate seven diesel engines, discharging through eleven stacks as shown in Table 3.

**Table 3: OESCO Ltd Emission points**

| Emission Point | Description | Engine Size |
|---|---|---|
| A1 | Engine No. 1 Stack | 2.5 MW |
| A2 | Engine No. 2 Stack | 1.8 MW |
| A3 | Engine No. 3 Stack | 2.5 MW |
| A4 | Engine No. 4 Stack 4N | 5.1 MW |
| A5 | Engine No. 4 Stack 4S | |
| A6 | Engine No. 5 Stack 5N | 5.1 MW |
| A7 | Engine No. 5 Stack 5S | |
| A8 | Engine No. 6 Stack 6N | 5.1 MW |
| A9 | Engine No. 6 Stack 6S | |
| A10 | Engine No. 7 Stack 7N | 5.1 MW |
| A11 | Engine No. 7 Stack 7S | |

Pollutant emission rates, based on site data are presented in the IPPC permit application prepared for OESCO Ltd by ERM. OESCO Ltd operate the diesel engines in response to electricity demand. Engines are taken out of service to allow efficient operation and for maintenance. Table 4 shows the number of hours run by each engine and load factor for each of the engines in recent years. Table 4 also shows an average loading calculated as the ratio of the actual power generated in a year compared to the theoretical maximum power generation.

The OESCO engines emit various pollutants including particulate matter and sulphur dioxide. It has here been assumed that all particulate matter has diameters less than 10 μm. In addition, it has been assumed that 5% of the sulphur is present as sulphur trioxide which reacts rapidly in the atmosphere to provide secondary inorganic aerosol (SIA).

**Table 4: Engine utilisation at OESCO Ltd.**

| | 2003/2004 | | 2004/2005 | | 2005/2006 | | |
|---|---|---|---|---|---|---|---|
| Engine | Hours Run | Load factor | Hours Run | Load factor | Hours Run | Load factor | Average loading |
| 1 | 3469 | 73.7 | 5071 | 70.08 | 3392 | 69.8 | 0.323 |
| 2 | 3220 | 64.52 | 1465 | 73.62 | 1163 | 73.31 | 0.153 |
| 3 | 3140 | 73.94 | 2456 | 79.74 | 4155 | 77.14 | 0.285 |
| 4 | 3058 | 72.13 | 4892 | 80.6 | 4753 | 74.18 | 0.368 |
| 5 | 5639 | 81.96 | 4527 | 84.25 | 4911 | 83.68 | 0.477 |
| 6 | 6076 | 85.49 | 2915 | 76.59 | 4070 | 77.74 | 0.403 |
| 7 | - | - | - | - | 1406 | 61.04 | 0.098 |

Table 5 shows the annual average rate of emission used for dispersion modelling. The emission rate was estimated from the measured emissions under 90 % load and the average loading. Table 5 also shows the easting and northing grid reference of each of the emission points and the discharge velocity calculated on the basis of the measured gas flow and discharge temperature for a 90% loading and discharge diameters of 0.71 m for A1-A9 and 0.61m for A10 and A11.

**Table 5: Location and rate of emissions of OESCO discharges**

| Emission Point | Annual average emission rate, g/s | | Discharge velocity, m $s^{-1}$ | Diameter, m | Temperature, $^oC$ | Easting, m | Northing, m |
|---|---|---|---|---|---|---|---|
| | Particulate matter | SIA | | | | | |
| A1 | 0.047 | 0.010 | 26.1 | 0.71 | 382 | 288260 | 4001005 |
| A2 | 0.031 | 0.003 | 20.7 | 0.71 | 417 | 288265 | 4000995 |
| A3 | 0.047 | 0.009 | 26.1 | 0.71 | 382 | 288268 | 4000990 |
| A4 | 0.029 | 0.001 | 28.8 | 0.71 | 403 | 288277 | 4000963 |
| A5 | 0.074 | 0.007 | 26.0 | 0.71 | 430 | 288280 | 4000957 |
| A6 | 0.095 | 0.013 | 26.2 | 0.71 | 421 | 288283 | 4000950 |
| A7 | 0.122 | 0.011 | 29.5 | 0.71 | 435 | 288285 | 4000943 |
| A8 | 0.031 | 0.012 | 28.8 | 0.71 | 403 | 288290 | 4000935 |
| A9 | 0.091 | 0.009 | 26.0 | 0.71 | 430 | 288293 | 4000930 |
| A10 | 0.009 | 0.003 | 47.6 | 0.61 | 407 | 288295 | 4000925 |
| A11 | 0.008 | 0.003 | 47.3 | 0.61 | 403 | 288297 | 4000920 |

The stacks discharge at a height of 1.3 m above the roof level of 12.2 m.

### 3.2.2 Ministry of Defence

The Ministry of Defence operate six diesel engines discharging through six stacks. The engine sizes are listed in Table 6.

**Table 6: Ministry of Defence engine sizes**

| Emission Point | Engine Size |
|---|---|
| 7 | 2.16 MW |
| 8 | 2.16 MW |
| 9 | 2.16 MW |
| 10 | 2.16 MW |
| 12 | 4.68 MW |
| 14 | 3.8 MW |

The Institute of Naval Measurement (INM) carried out stack emissions monitoring but standard methods were not used and it was not possible to measure either the discharge flowrate or the total emission concentrations. An emission factor of 0.118 g $MJ^{-1}$ power output based on emissions factors in the US EPA Compilation of air pollutant emission factors AP42 has therefore been used to estimate particulate emissions from the MOD engines. Sulphur dioxide emissions have been estimated assuming an emission factor of 0.22 g $MJ^{-1}$ power output, based on the OESCO data. Similarly a discharge rate of 2 $Nm^3$ $MJ^{-1}$ has been used to estimate the discharge flowrate. The MOD diesel engines have a total generating capacity of 17.12 MW. Typically the electricity demand is 5-7 MW. For modelling purposes, it has been assumed that generators 7, 12 and 14 are running at 66% loading.

Discharge temperature of 400$^o$C has been assumed, typical of this type of diesel engine. The stacks discharge approximately at the level of the roof ridges (12 m).

Table 7 shows the discharge characteristics of each of the modelled stacks.

**Table 7: Discharge characteristic of modelled MOD stacks**

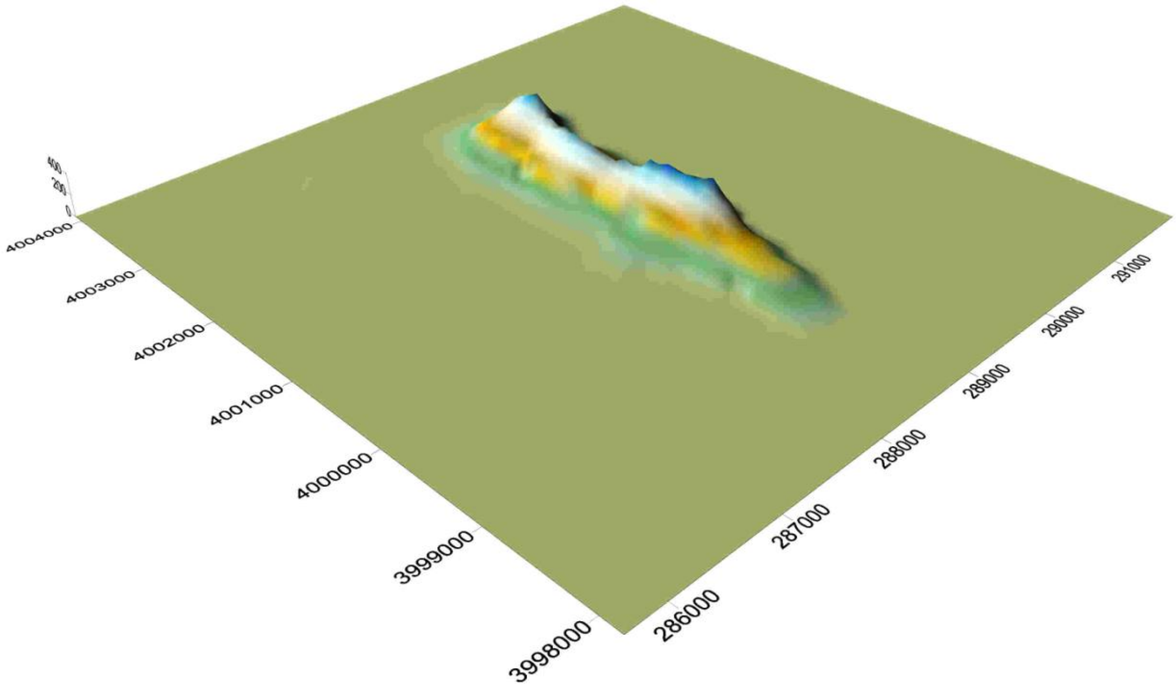
| Stack | Easting, m | Northing, m | Discharge flowrate $Nm^3$ $h^{-1}$ | Emission rate, g $s^{-1}$ | | Discharge velocity, m $s^{-1}$ |
|---|---|---|---|---|---|---|
| | | | | Particulate matter | SIA | |
| 7 | 288335 | 4001068 | 10264 | 0.17 | 0.016 | 16 |
| 8 | 288330 | 4001067 | 10264 | 0 | 0 | 16 |
| 9 | 288325 | 4001066 | 10264 | 0 | 0 | 16 |
| 10 | 288320 | 4001065 | 10264 | 0 | 0 | 16 |
| 12 | 288285 | 4001185 | 22239 | 0.37 | 0.034 | 24 |
| 14 | 288322 | 4001035 | 18058 | 0.30 | 0.026 | 19 |

## 3.3 Terrain

The terrain surrounding the power generation facilities is complex. The power stations are close to the coast on the west and the land rises steeply to the east. The ADMS 4.1 dispersion model has the facility to take account of complex coastline and terrain effects. Ideally, the hills should have moderate slope (say less than 1 in 3) but the model is useful even when this criterion is not met. Model runs were carried out with and without complex terrain to investigate the sensitivity of the modelled concentrations to complex terrain.

Spot heights were digitised from the Military Survey 1:2500 map of Gibraltar at 50 m height and 200 m northing intervals. The digitised map was then interpolated onto a 64 x 64 node rectangular grid extending from 288400, 3997800 to 291950, 4004100 at 100 m spacing between nodes. The height of sea nodes was set to 0 m. Fig. 4 shows the modelled terrain.

**Fig. 4: Gibraltar terrain model**




For the purpose of the modelling the surface roughness of landside areas was set to 1 m: for areas of sea the surface roughness was set to 0.001 m.

# 3.4 Buildings

Dispersion from the diesel engine discharges is affected by the presence of nearby buildings.

The MOD generator, HM Naval Base and OESCO Ltd buildings are located on the dock area immediately below the Rosia Road Promenade, with the building roofs approximately level with the Promenade. Model runs were carried out in which the buildings were included as part of the terrain. The effective stack heights for these model runs were the heights above the roof ridges.

Close to the buildings, the MOD and OESCO Ltd buildings potentially have the most significant effect on dispersion. Separate model runs were therefore carried out for flat terrain, but taking the buildings into account. The two buildings were treated in ADMS 4.1 as rectangular blocks. The position of the centre of the blocks, their dimensions and the angle with respect to north is shown in Table 8. The MOD building was assessed to be the “main building” influencing dispersion from MOD stacks 7-12: The OESCO building was the “main building” for the OESCO discharges and MOD stack 14.

**Table 8: Buildings affecting dispersion**

| | Grid reference of building centroid | | Length , m | Width, m | Angle to north | Height, m |
|---|---|---|---|---|---|---|
| | Easting, m | Northing, m | | | | |
| MOD | 288280 | 4001115 | 125 | 102 | 162 | 12.2 |
| OESCO | 288330 | 4000970 | 125 | 102 | 162 | 12.2 |

ADMS 4.1 has the capability to model the buildings and the complex terrain together. However, the model cannot take account of buildings that are located in “reverse flow” areas where the ground level wind moves in the opposite direction to the general wind. Preliminary model runs showed that reverse flow occurred in the area of the MOD and OESCO buildings for many hours of the year.

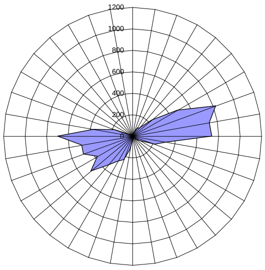
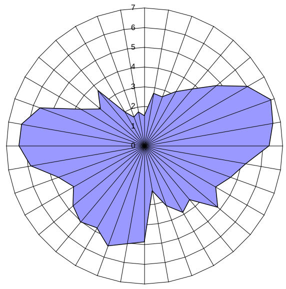
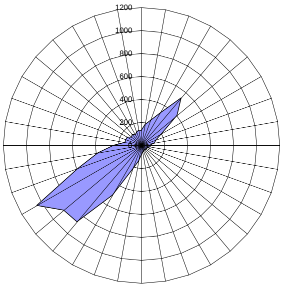
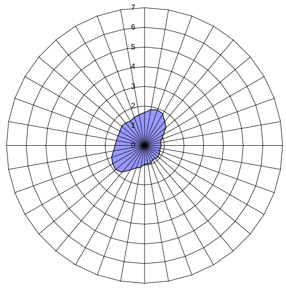
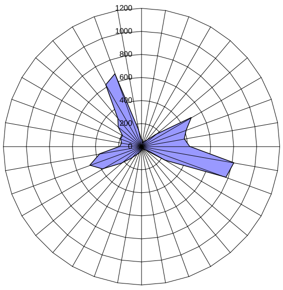
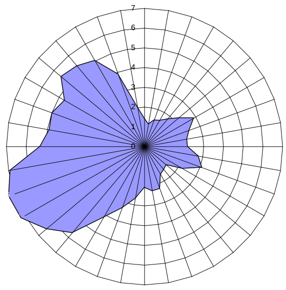
## 3.5 Meteorological data

Meteorological data for the period 2002-2006 for Gibraltar Airport was obtained from Trinity Consultants. The data provides hourly sequential records of the wind speed and direction, temperature and cloud cover. Fig. 5 shows the frequency of winds from each direction observed at the airport and the average wind speed in each direction. The most frequent winds are from the south-west and north-east. Average wind speeds are typically 6-7 m $s^{-1}$ in these directions. By contrast the wind speed measured on the 7 m meteorological mast at the Rosia Road air quality monitoring site is much smaller, typically less than 1 m $s^{-1}$. The wind speeds predicted by the ADMS terrain module at the Rosia Road site are also substantially less than those predicted at the airport. For example, for winds (10 m above ground) from the north-east ($70^o$ from north) at the Airport with a wind speed of 7 m $s^{-1}$, the predicted wind speed (10 m above ground) at Rosia Road was 0.85 m $s^{-1}$. The modelled wind direction at Rosia Road depends to a considerable degree on the height above ground. Table 9 shows the modelled wind direction at Rosia Road when there are north-east winds at the airport, it can be seen that the wind direction is reversed close to the ground.

**Table 9: The dependence of modelled wind direction at Rosia Road on height above ground**

| Height above ground, m | Wind speed, m $s^{-1}$ | Wind direction, degrees from north |
|---|---|---|
| 0 | 4.6 | 256 |
| 1 | 1.9 | 267 |
| 10 | 0.85 | 27 |
| 30 | 2.9 | 61 |
| 80 | 5.3 | 66 |
| 200 | 7.6 | 68 |

**Fig. 5: Wind roses at the airport, Rosia Road and Bleak House**

| Airport: frequency of wind direction | Airport: average wind speeds |
|---|---|
|  |  |
| Rosia Road: frequency of wind direction | Rosia Road: average wind speeds |
|  |  |
| Bleak House: frequency of wind direction | Bleak House: average wind speeds |
|  |  |

# 3.6 Receptor grids

The model was used to predict ground level concentrations resulting from emissions from the electricity generation on a rectangular receptor grid extending 500 m in each direction from the generating plant, with receptors at 50 m intervals.

# 3.7 Model runs

Table 10 summarises the model runs carried out. Model runs without complex terrain provide an indication of the impact of the power stations in flat terrain. These model runs should be considered representative of the impact at the optimum location. An installation is unlikely to be satisfactory if predicted concentrations under these conditions exceed the limit values. Model runs carried out with complex terrain represent our best attempt to simulate the effects of Gibraltar's terrain.

**Table 10: Summary of main model runs**

| | Meteorological data year | Complex terrain | Buildings |
|---|---|---|---|
| 1 | 2002 | ✓ | × |
| 2 | 2003 | ✓ | × |
| 3 | 2004 | ✓ | × |
| 4 | 2005 | ✓ | × |
| 5 | 2006 | ✓ | × |
| 6 | 2002 | × | ✓ |
| 7 | 2003 | × | ✓ |
| 8 | 2004 | × | ✓ |
| 9 | 2005 | × | ✓ |
| 10 | 2006 | × | ✓ |
| 10R* | 2006 | × | ✓ |

* Modelled using wind speed and direction data from Rosia Road

# 4 Results

The results of the dispersion modelling are presented in this section. Modelled concentrations at the selected receptor locations in the area adjacent to the power generation facilities are listed in a series of tables. The locations of the selected receptors are shown in Fig. 6. The tables show the modelled contribution to $PM_{10}$ concentrations (calculated as the sum of the primary particulate matter emissions and the secondary inorganic aerosol) for each meteorological data set. The tables are listed as follows:

Table 11: Modelled contributions from the power generation facilities to annual average concentrations at selected receptors, $\mu g\ m^{-3}$
Table 12: Modelled contributions from the power generation facilities to $90.1^{th}$ percentile of 24-hour concentrations at selected receptors, $\mu g\ m^{-3}$

The results of the power station modelling are shown as contour plots (isopleths) of the modelled contribution to $PM_{10}$ concentrations superimposed on a map of the area near to the power stations:

Fig. 7: Annual mean contribution, with buildings;
Fig. 8: Annual mean contribution, complex terrain
Fig. 9: Modelled contributions from the power generation facilities to $90.1^{th}$ percentile of 24-hour concentrations, with buildings
Fig. 10: Modelled contributions from the power generation facilities to $90.1^{th}$ percentile of 24-hour concentrations, complex terrain

In each case, the maximum modelled concentration is plotted at each location calculated over all the years of meteorological data.

The 90.1th percentile corresponds to the $35^{th}$ highest 24-hour contribution from the plant to $PM_{10}$ concentrations.

**Fig. 6: Location of selected receptors in the area adjacent to the two dockyard power generation facilities.**

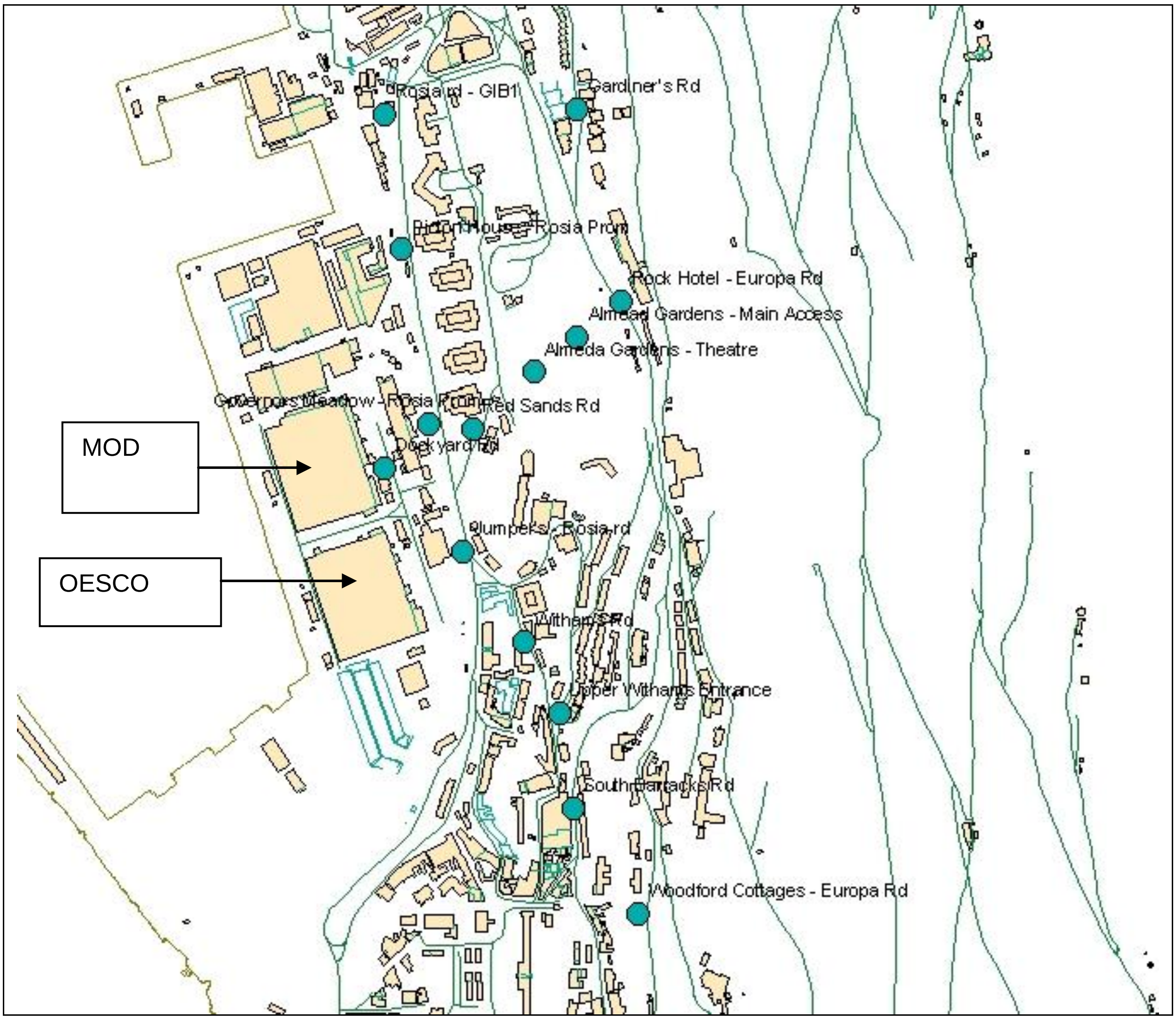


**Table 11: Modelled contributions to annual average particulate matter concentrations at selected receptors, μg m$^{-3}$**

| | Complex terrain | | | | | Buildings | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Met. Data Year | 2002 | 2003 | 2004 | 2005 | 2006 | 2002 | 2003 | 2004 | 2005 | 2006 | 2006R |
| Run no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 10R |
| Rosia rd – GIB1 | 0.8 | 0.7 | 0.5 | 0.5 | 0.6 | 0.7 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 |
| Jumper's – Rosia rd | 0.6 | 0.5 | 0.6 | 0.5 | 0.5 | 6.4 | 5.7 | 5.5 | 4.8 | 5.1 | 2.9 |
| Red Sands Rd | 1.7 | 1.3 | 1.1 | 1.2 | 1.4 | 7.6 | 7.6 | 6.4 | 6.1 | 7.3 | 5.7 |
| South Barracks Rd | 0.3 | 0.3 | 0.4 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 |
| Picton House – Rosia Prom | 1.8 | 1.4 | 1.0 | 1.1 | 1.4 | 2.6 | 1.7 | 1.3 | 1.3 | 1.7 | 1.7 |
| Upper Withams Entrance | 0.4 | 0.5 | 0.4 | 0.3 | 0.4 | 1.1 | 1.1 | 1.1 | 1.0 | 1.0 | 0.5 |
| Withams Rd | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 2.1 | 2.3 | 2.3 | 2.0 | 2.0 | 0.8 |
| Almeda Gardens – Theatre | 1.5 | 1.3 | 1.6 | 1.4 | 1.3 | 4.2 | 4.6 | 4.2 | 3.9 | 4.5 | 3.5 |
| Almeda Gardens – Main Access | 2.1 | 1.5 | 1.9 | 1.9 | 2.2 | 3.1 | 3.2 | 2.8 | 2.7 | 3.1 | 2.8 |
| Rock Hotel – Europa Rd | 1.3 | 1.2 | 1.2 | 1.2 | 1.1 | 2.3 | 2.3 | 2.0 | 1.9 | 2.2 | 2.3 |
| Gardiner's Rd | 3.2 | 2.6 | 3.1 | 3.2 | 3.3 | 1.3 | 1.0 | 0.8 | 0.8 | 1.0 | 1.3 |
| Governors Meadow – Rosia Prom | 2.6 | 1.9 | 1.4 | 1.6 | 1.9 | 9.0 | 4.5 | 3.6 | 3.4 | 4.2 | 6.0 |
| Dockyard Rd | 1.7 | 1.3 | 1.0 | 1.1 | 1.4 | 9.6 | 7.2 | 6.0 | 5.9 | 7.2 | 6.0 |
| Woodford Cottages - Europa Rd | 0.3 | 0.4 | 0.2 | 0.1 | 0.2 | <0.1 | | | | | 0.2 |

**Table 12: Modelled contributions to 90.1$^{th}$ percentile of 24-hour concentrations at selected receptors, μg m$^{-3}$**

| | Complex terrain | | | | | Buildings | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Met. Data Year | 2002 | 2003 | 2004 | 2005 | 2006 | 2002 | 2003 | 2004 | 2005 | 2006 | 2006R |
| Run no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 10R |
| Rosia rd - GIB1 | 3.7 | 3.2 | 2.3 | 2.5 | 3.1 | 2.8 | 2.1 | 1.7 | 1.5 | 2.0 | 0.9 |
| Jumper's - Rosia rd | 1.7 | 1.6 | 1.8 | 1.7 | 1.6 | 16.0 | 13.2 | 13.3 | 13.6 | 12.9 | 6.1 |
| Red Sands Rd | 4.8 | 4.3 | 3.9 | 4.2 | 4.5 | 14.7 | 17.1 | 14.9 | 16.2 | 17.5 | 9.6 |
| South Barracks Rd | 0.2 | 0.4 | 0.1 | 0.1 | 0.1 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.8 |
| Picton House - Rosia Prom | 6.3 | 4.9 | 3.9 | 4.3 | 4.9 | 7.1 | 5.6 | 4.8 | 4.4 | 5.6 | 4.1 |
| Upper Withams Entrance | 0.9 | 1.0 | 0.8 | 0.8 | 0.8 | 3.2 | 3.4 | 3.4 | 3.3 | 3.1 | 1.3 |
| Withams Rd | 0.8 | 0.8 | 0.9 | 0.9 | 0.8 | 5.8 | 6.8 | 7.0 | 6.8 | 6.7 | 2.0 |
| Almeda Gardens - Theatre | 4.2 | 3.6 | 4.7 | 4.2 | 4.4 | 8.3 | 9.9 | 9.5 | 9.8 | 10.0 | 5.7 |
| Almead Gardens - Main Access | 6.5 | 3.5 | 7.0 | 5.9 | 7.7 | 6.1 | 7.1 | 6.8 | 7.0 | 7.2 | 4.6 |
| Rock Hotel - Europa Rd | 4.2 | 1.8 | 3.5 | 3.9 | 4.2 | 4.7 | 5.3 | 5.1 | 5.2 | 5.4 | 3.9 |
| Gardiner's Rd | 7.9 | 4.1 | 10.8 | 12.2 | 12.8 | 3.3 | 2.8 | 2.5 | 2.4 | 3.0 | 2.7 |
| Governors Meadow - Rosia Prom | 8.8 | 7.2 | 5.2 | 7.0 | 6.6 | 18.7 | 11.2 | 9.2 | 9.5 | 10.4 | 12.7 |
| Dockyard Rd | 5.6 | 4.6 | 3.7 | 4.6 | 4.7 | 20.2 | 17.9 | 15.6 | 16.0 | 17.6 | 11.2 |
| Woodford Cottages - Europa Rd | <0.1 | 0.2 | <0.1 | <0.1 | <0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.5 |

**Fig. 7: Annual mean contribution, with buildings**

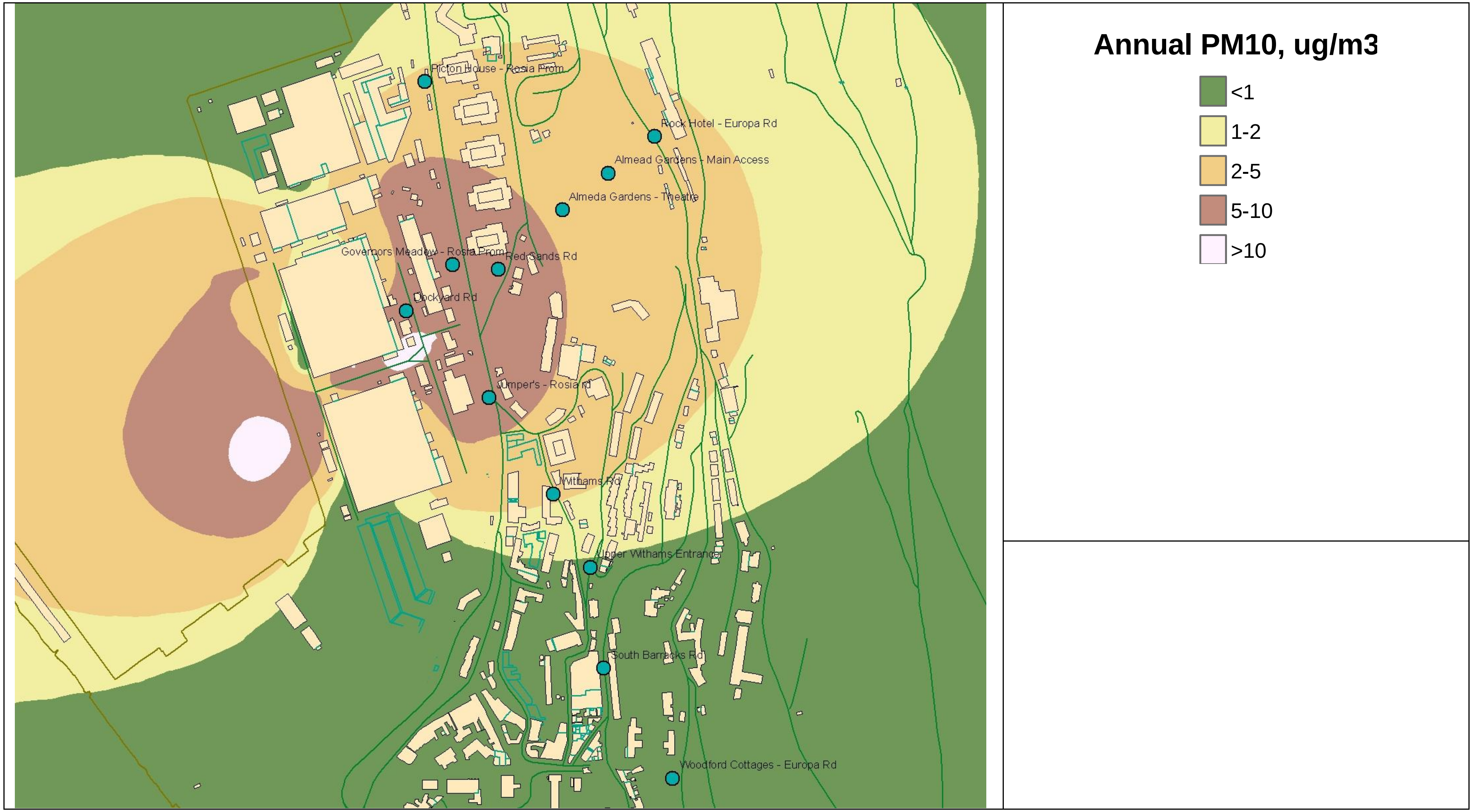


**Fig. 8: Annual mean contribution, with complex terrain**

**Fig. 9: 90.1th percentile of contributions to 24-hour concentrations, $\mu g\ m^{-3}$ with buildings**

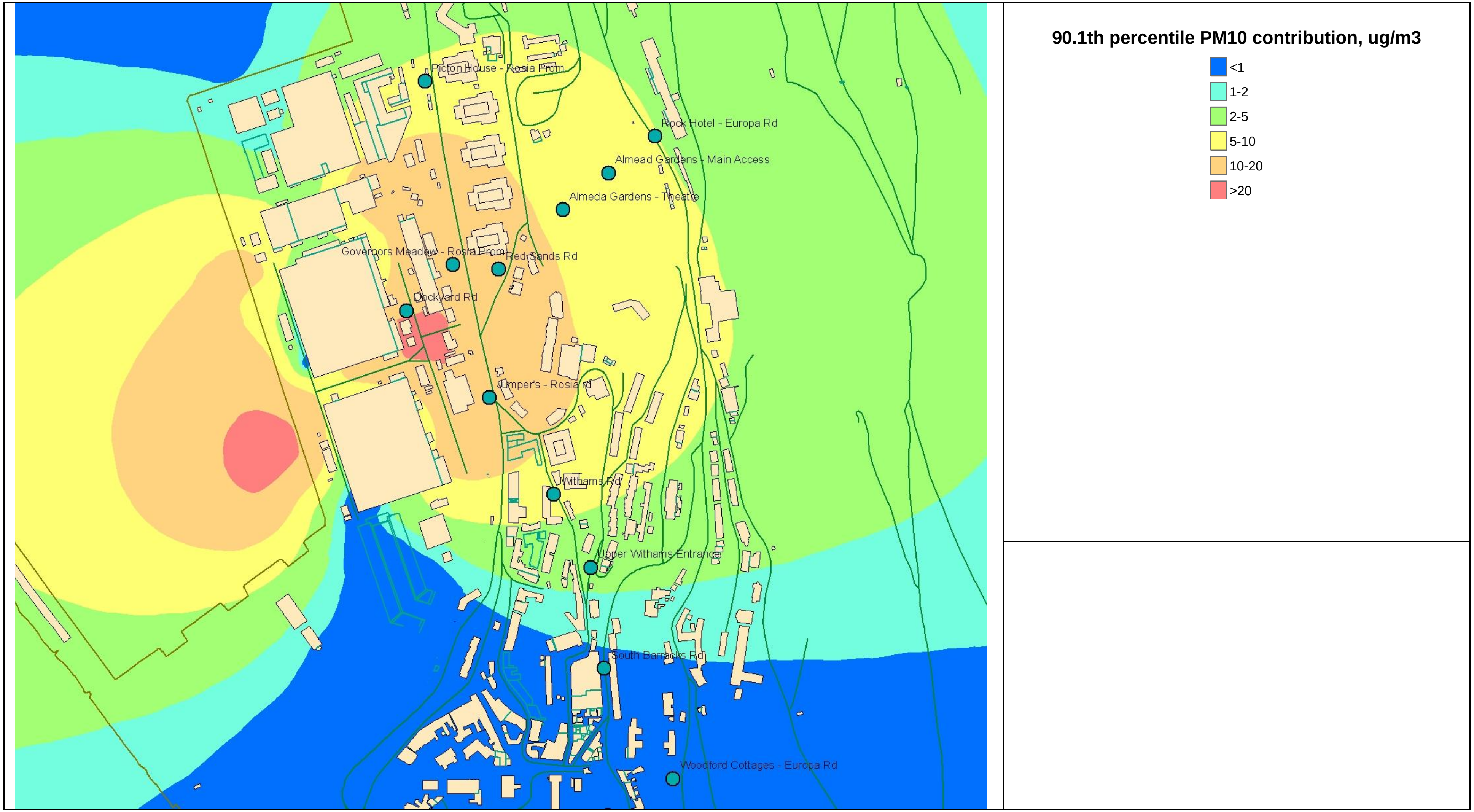
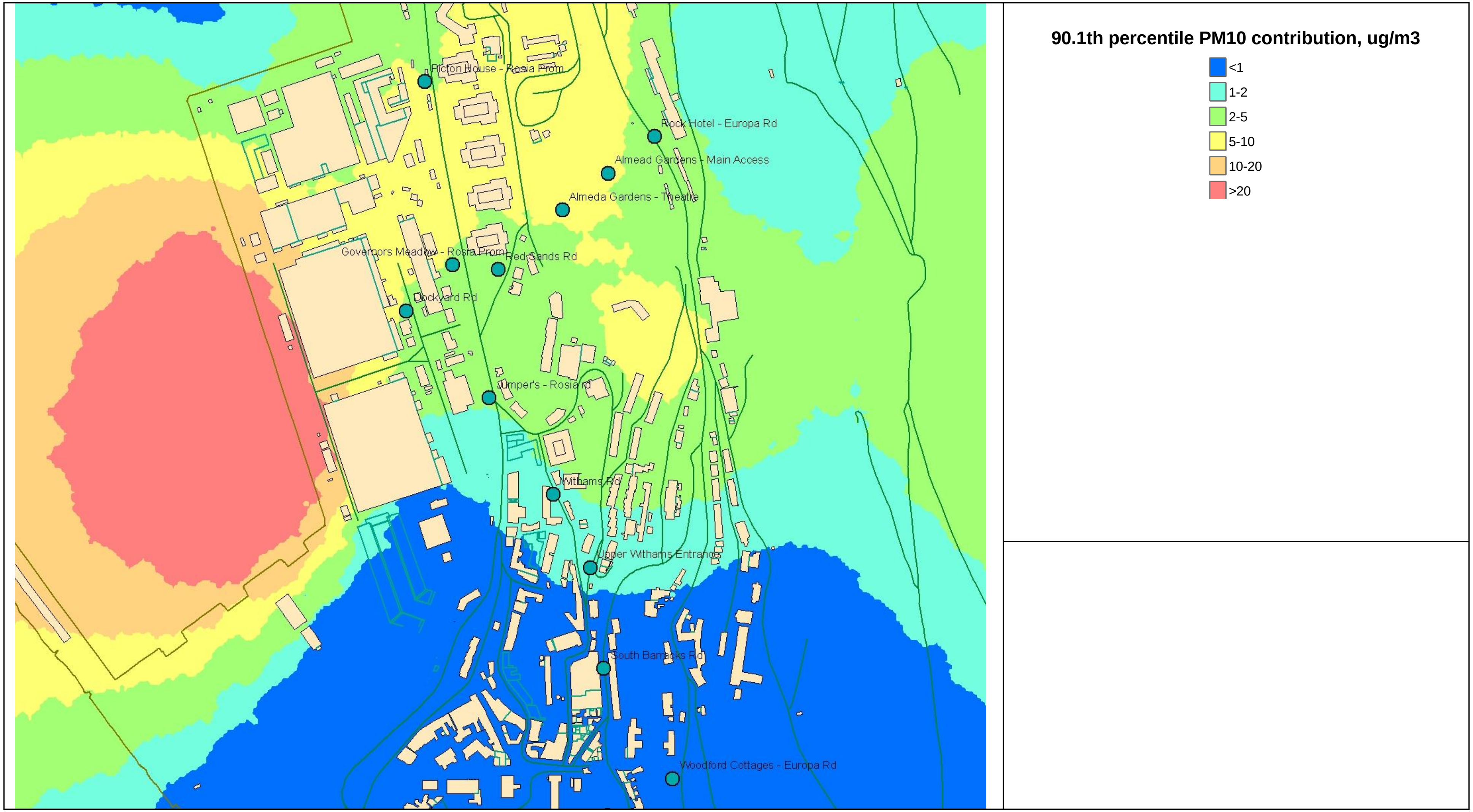


**Fig. 10: 90.1th percentile of contributions to 24-hour concentrations, $\mu g\ m^{-3}$ with complex terrain**



# 5 Discussion

Fig. 7 shows the predicted contribution to annual mean $PM_{10}$ concentrations in the vicinity of the power generation facilities, taking the effect of the buildings but ignoring the effects of Gibraltar's complex terrain. The predicted concentrations are likely to represent the power generation impact in an 'optimum location for the plant' (i.e. on flat terrain). The contribution from the two power stations is predicted to be more than 5 $\mu g\ m^{-3}$ at Jumpers Flats on Rosia Road and at Red Sands Road. The contribution at Red Sands Road is predicted to be up to 7.6 $\mu g\ m^{-3}$ for meteorological data for 2002 and 2003. Adding this to the average background concentration at Bleak House (33.7 $\mu g\ m^{-3}$ for the period 16/05/08-31/12/08) gives a total concentration of 41.3 $\mu g\ m^{-3}$. It is concluded that there is a substantial possibility that the concentration exceeds the annual mean limit value of 40 $\mu g\ m^{-3}$ at Red Sands Road. Higher concentrations are predicted at locations closer to the power stations, for example at the Governors Meadow and Dockyard Road receptor sites, but there is no relevant non-occupational exposure of members of the public at these locations.

Fig. 9 shows the predicted contribution to the 90.1th percentile of 24-hour mean $PM_{10}$ concentrations in the vicinity of the power generation facilities, taking the effect of the buildings but ignoring the effects of Gibraltar's complex terrain. The 90.1th percentile corresponds to the 35$^{th}$ highest 24-hour contribution from the plant to $PM_{10}$ concentrations. The contribution from the two power stations is predicted to be more than 15 $\mu g\ m^{-3}$ at Jumpers Flats on Rosia Road and at Red Sands Road. The contribution at Red Sands Road is predicted to be up to 17.5 $\mu g\ m^{-3}$ for meteorological data for 2006. Adding this to the average background concentration at Bleak House (33.7 $\mu g\ m^{-3}$ for the period 16/05/08-31/12/08) gives a total concentration of 50.2 $\mu g\ m^{-3}$. This simple addition of the background concentrations potentially results in an underestimate of the total percentile concentration because there will be some days when relatively high background concentrations will coincide with high contributions from the power stations: nevertheless, the predicted total slightly exceeds the limit value of 50 $\mu g\ m^{-3}$. It is concluded that there is a substantial possibility that the concentration exceeds the 24-hour mean limit value of 50 $\mu g\ m^{-3}$ on more than 35 occasions in the year at Red Sands Road.

Fig. 8 shows the annual average contribution from the power stations predicted by the ADMS model taking the complex terrain into account, but ignoring the buildings. Fig. 10 shows the predicted contribution to 90.1th percentile of 24-hour mean $PM_{10}$ concentrations taking account of Gibraltar's complex terrain but not buildings. The highest contribution from the power stations is predicted in the harbour. The model predicts much lower concentrations inland, for example at Jumpers flats. The low concentrations predicted at Jumpers flats may result as a consequence of a limitation of the ADMS model. Under a wide range of meteorological conditions, a zone of recirculating air flow is predicted in the Jumpers area. The ADMS model does not allow pollutant emitted outside the recirculating zone to enter the zone, but rather directs the modelled air flow above the recirculating zone. Thus for these conditions low ground level concentrations are predicted. The nature of Gibraltar's complex terrain means that recirculating flow occurs for a significant number of hours every year, resulting in under prediction of actual concentrations. This is an artefact of the model, rather than a true representation of the reality.

Model runs were carried out with 5 years of meteorological data. Examination of Tables 11 and 12 indicate that while there are significant year-to-year variations in predicted concentrations at receptors, the overall pattern of predicted concentrations remains broadly the same. The variation between years is generally less than the variation between receptors. Tables 11 and 12 also allow the comparison of model runs using meteorological data from Rosia Road with that from Gibraltar airport: again the difference between meteorological sites is generally less than the variation between receptors.

Table 11 indicates that the power stations contribute 0.8 $\mu g\ m^{-3}$ or less to annual mean $PM_{10}$ concentrations at the Rosia Road monitoring site. The contribution from the power stations may be considered to be relatively small compared with the measured concentrations of up to 45.0 $\mu g\ m^{-3}$ in 2007. The normalised pollution windrose shown in Fig. 2 suggests that $PM_{10}$ concentrations are not increased when the wind blows from the power stations towards the monitoring site although the hourly FDMS data in Fig. 3 suggests an apparent though small contribution to the measured concentrations.

# 6 Conclusions

Monitoring of particulate matter, $PM_{10}$ concentrations at the Rosia Road site in Gibraltar has indicated that both the annual mean and 24-hour limit values were exceeded at this site in 2007 and 2008. In order to inform our understanding of the elevated measured concentrations, a modelling study has been undertaken to investigate the MOD and OESCO Ltd power generation facilities contribution to the measured concentrations.

The complex terrain in the region of the OESCO Ltd and MOD power stations on Gibraltar presents a serious challenge for dispersion modelling. The slopes of the rock are steeper than the usual range of application of the ADMS4.1 dispersion model. The flow model predicts that a zone of recirculating air flow develops in the area of Rosia Road and this limits the dispersion model's capability to predict concentrations in the area during these conditions. Model runs were therefore carried out with and without the effects of complex terrain.

The modelling study indicates that the power stations contribute 0.8 $\mu g\ m^{-3}$ or less to the annual mean concentrations at the monitoring site. Directional analysis of the monitoring data suggest that concentrations at the monitoring site are likely to be influenced by contributions from the south-southwest but that the influence from this direction is not significantly larger than other wind directions. This is consistent with the model results for the power station.

However, the model predicted that, even in the absence of complex terrain effects, the power station emissions result in substantial increases in the annual mean concentration at Red Sands Road. Adding the power station contribution to background concentrations from the Bleak House background monitoring site indicates that the concentrations potentially exceed the annual average limit value of 40 $\mu g\ m^{-3}$ in the Red Sands Road area.

AEA

The Gemini Building
Harwell IBC
Didcot
Oxfordshire
OX11 0QR

Tel: 0870 190 6401
Fax: 0870 190 6318