ASPECTS OF EMPIRICAL DUST MODELLING ASSOCIATED WITH QUARRIES

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Abstract

An empirical technique to model dust dispersion beyond the quarry boundary of a sand and gravel working is described starting with the use of linear source-to-receptor dust monitoring. Base-line monitoring shows how dust levels vary between monitors and provides one element of the basic data used in this method of predicting off-site dust. Meteorological data is the other element and this data is best collected using on-site weather stations which are now readily available. Using wind speed, rainfall and temperature (key constraints in dust dispersion) and the recorded levels of dust for the same periods, linear regression methods can be used to establish relevant factors for site specific modelling and for the prediction of dusting based on future weather conditions. Good correlations were achieved between predicted and measured dust levels at the site boundary resulting from a range of quarry activities. Dust levels at a receptor beyond the quarry boundary could also be estimated.

The key sources of quarry dust are listed, the need to determine dust emission factors for specific dust sources is noted and first steps in the estimation of source emission factors are outlined.

Bruce, J., Walton, G. and Datson, H. 2015. Aspects of empirical dust modelling associated with quarries.
Pp 170-175 in Hunger, E. and Brown, T.J. (Eds.)
Proceedings of the 18th Extractive Industry Geology Conference 2014 and technical meeting 2015,
EIG Conferences Ltd, 250pp.
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Introduction

This paper is concerned with the prediction of off-site dust arising from quarries or other dust generating sites. Quarries are recognised dust sources and operators are often required to address the potential impact of dust in base-line studies for Environmental Impact Assessments, by formulating Dust Management Schemes and by preparing Dust Action Plans.

The investigation described herein relates to a small sand and gravel working in southern England and considers variations in levels of dust across the quarry, related earthworks and beyond the curtilage of operations using software analyses of levels of dust collected by directional dust monitoring. The objective was to predict dust levels at off-site receptors on the basis of routine baseline dust and meteorological monitoring. The mineral workings lie in a rural area of gently undulating ground in arable and pastoral use with only isolated built development. A dust sensitive receptor occupied one such property, the location of which lies just beyond the right-hand (eastern) end of the pathway shown in Figure 1 (monitor E).

Background

Monitoring dust levels

Dust monitoring is often carried out at site boundaries. However the value of collected data can be greatly enhanced by extending data collection, both into the quarry towards principal dust sources, and outwards towards external receptors (Figure. 1). Directional dust levels, an example of which is given in Figure 2 are for a single monitoring period, and at a point along the source-receptor pathway; they are measured as dust coverage (Average Area Coverage - AAC %) and dust soiling (Effective Area Coverage - EAC %) (Walton et al, 2008). Levels of dust vary depending on the direction from which dust is coming. In this case, the level of dust recorded increases across the operation from the south and west, up to the second monitor (B on Figure 1) on the northeast corner of the site. From that position, the levels of dust recorded fall progressively eastwards, towards the receptor just beyond the eastern end of the pathway (monitor E).

Data was collected over several months to cover variations in operational activity and weather conditions. From this it is possible to investigate the relationship between the dust levels at the quarry boundary and those further to the east towards and including the receptor.

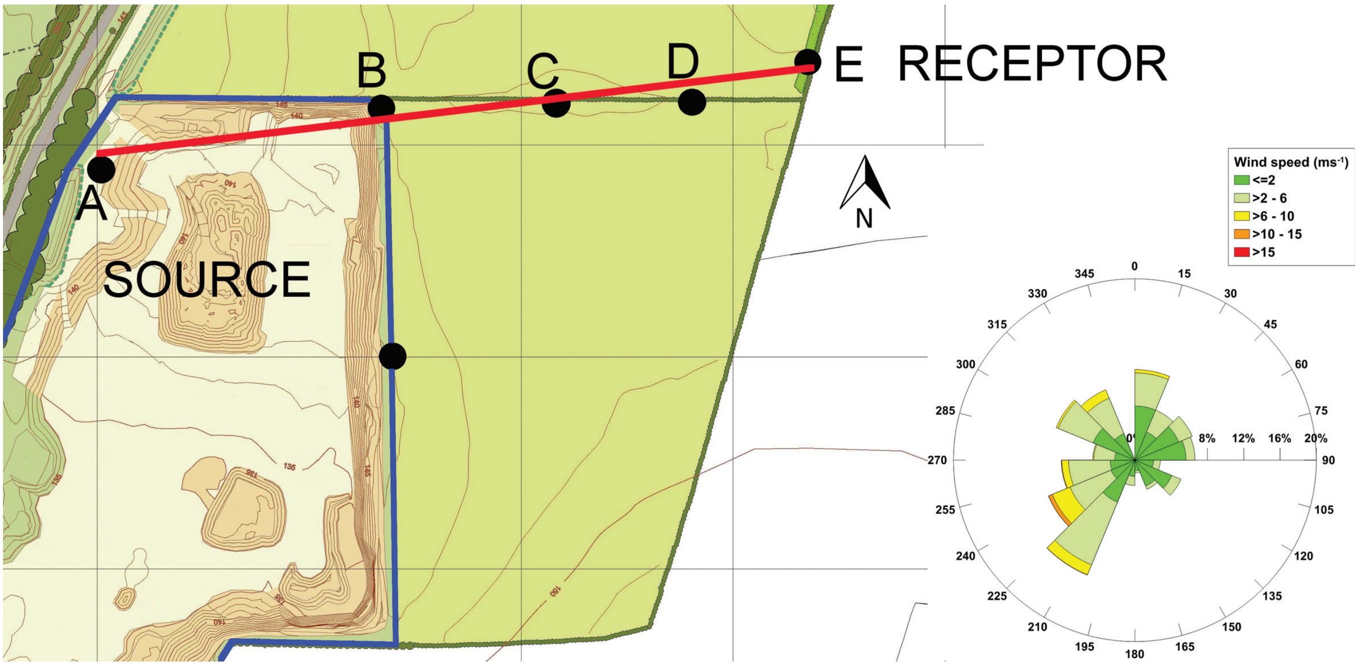

Figure 1. *Left image: The quarry site and surrounding farmland to the north east. Grid lines have a 100m spacing. Solid black dots are monitoring locations, the quarry boundary is shown as a solid blue line and a pathway between the source and receptor is shown as a solid red line. The receptor is at the north eastern end of the pathway. Right image: The wind rose is based on meteorological monitoring at the quarry and relates to the whole sampling period. The coloured segments within the wind rose refer to the proportion of the wind from that direction, and the magnitude of the wind speed is shown in the legend.*

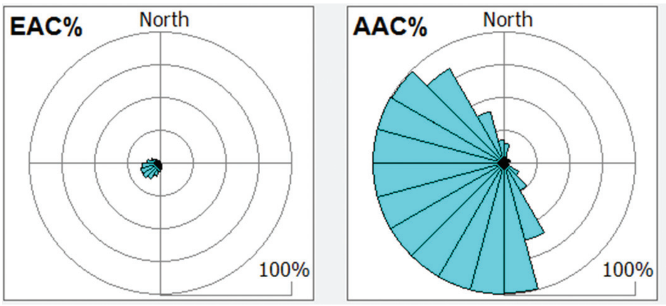

Figure 2. *Effective Area Coverage (EAC) and Absolute Area Coverage (AAC) dust levels indicating the direction of source at one location along the pathway and showing directional differences in dust reflectance and dust coverage respectively for dust arriving from different directions. The dust soiling (EAC) is significantly lower than the dust coverage (AAC), although both are from the same direction. Each concentric circle shows a 25% increment.*

Figure 3 shows a plot of the average EAC% and AAC% dust levels recorded at monitors along the pathway, from the source (between monitors A and B (shown on Figure 1)) to points nearer the receptor. The correlation between off-site dust levels at monitor D, 150m from quarry edge, and at the boundary monitor (B), at the quarry boundary, was moderately positive ($r^2 = 0.51$), but showed a number of 'outlying' data values where dust levels were increased beyond the site boundary. The monitoring periods during which these outlying dust values were recorded were therefore checked for other potential, off-site dust generating activities.

Dust monitoring should always include records of on- and off-site activities with potential for dust generation; dust seldom comes from only one location in a quarry and quarries are rarely the only dust source in the vicinity. In this location seasonal arable farming activities included cultivations and harvesting. The removal of the outlying points, which coincided with agricultural activities, increased the correlation ($r^2 = 0.72$). The basis for such a step can often be confirmed by microscopy and other physical/chemical tests of directional samples, since different dust sources usually have distinctive characteristics. Microscopy was another area of investigation but is not considered further in this paper. The mineralogy of soils commonly reflects that of the superficial deposits and inorganic fertilisers, these in turn may or may not mirror the mineralogy of the materials being excavated in the overburden and bedrock at the quarry.

Meteorological data and dust assessment

Weather conditions have an important impact on dust levels. It is essential that meteorological data are collected or available for interrogation when assessing dust distribution, especially when there may be off-site concerns. This helps to understand source to receptor movements by providing evidence of the provenance of wind-blown dust.

On-site meteorological monitoring is preferable since significant differences in, for example, the frequency and magnitude of wind from specific directions can arise between sites within a few kilometres, especially when the topographic setting differs. The cost of simple electronic weather stations is such that all quarries with dust concerns should have such installations.

The relationship between dust levels and weather conditions is critical to understanding dust dispersion and the key to this is wind speed and frequency in the direction of the dust source-receptor alignment. This can be explored by correlating wind speeds with average dust levels in the relevant direction and monitoring period. Further adjustments are needed to accommodate rainfall and temperature. Active and antecedent rainfall

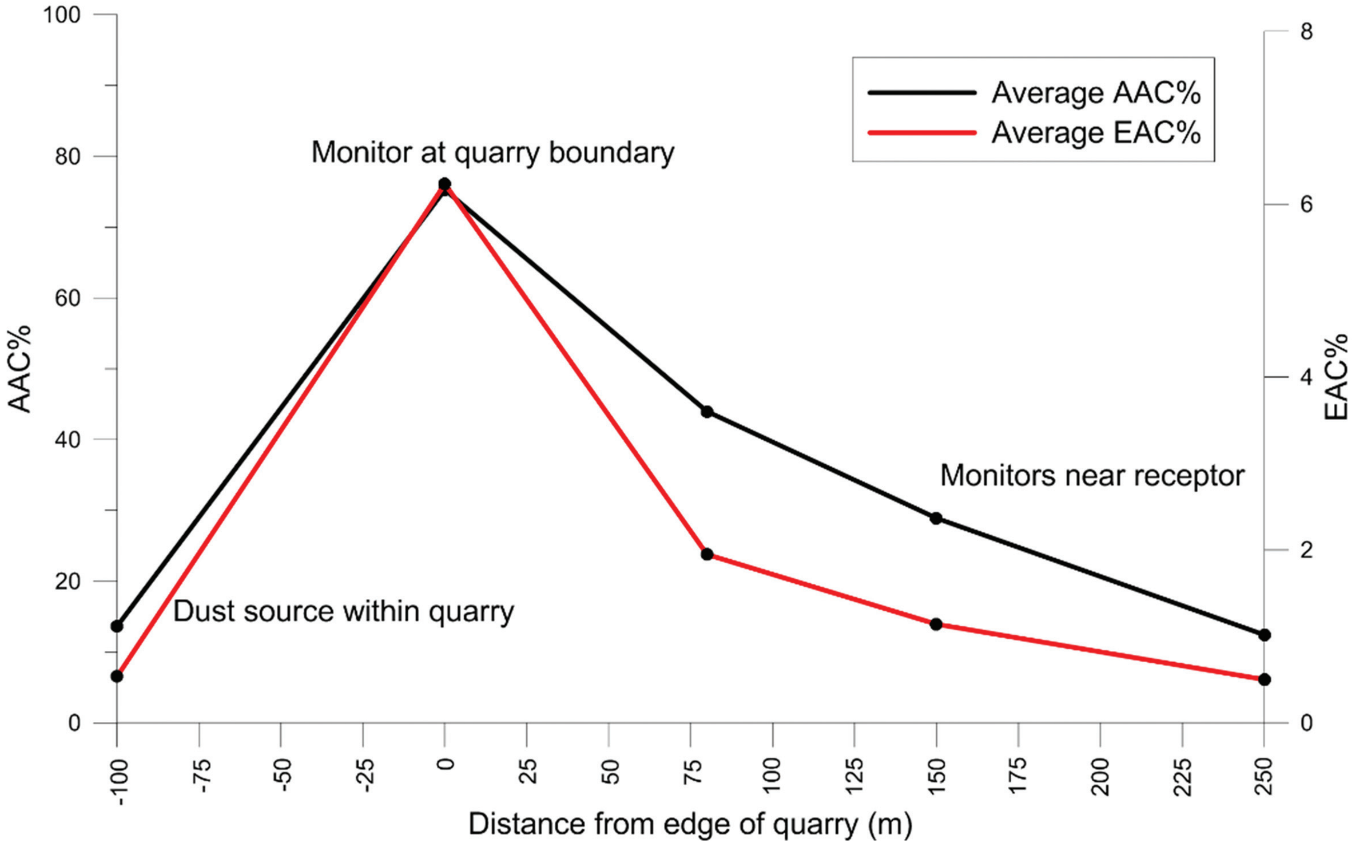

Figure 3. *Directional dust levels from quarry floor to the receptor measured in AAC% and EAC%.*

suppresses dust dispersion and higher temperatures tend to dry out surfaces and promote dust emissions (Holman et al, 2014).

For this study, dust levels recorded at monitoring locations and meteorological data were collected for a 6 month period from April to October 2013. Using linear regression models it has been possible to develop a numerical relationship between measured dust levels at the quarry boundary and weather data. Coefficients were derived empirically for wind speeds in both the source-receptor direction and all directions, for rainfall, and average temperature for each monitoring period. Monitoring took place over consecutive 7 day periods and the weather data was based on the average of 30 minute intervals throughout the 7 day periods.

The equation thus defined is as follows:

$$\frac{EAC\%}{day} = m+0.19u_1+0.026u_2+1.08u_3+0.094t+ 0.054p$$

Where:-

m = -3.14

u_1 = Average wind speed from the SW (m s^{-1}, 180-270°)

u_2 = Proportion of wind from SW

$$\left(\frac{\text{No. half hour periods of wind from SW}}{\text{No. half hour periods of wind}}\right)$$

u_3 = Average wind speed (all directions)

t = Average temperature (°C)

p = Ratio wet days $\left(\frac{\text{Days with} \geq 0.2\text{mm precipitation}}{\text{Days in monitoring period}}\right)$

A plot of measured and modelled EAC% is shown on Figure 4. The model based on six months of weather data (April to October 2013), showed an excellent correlation (r^2 = 0.75). The subsequent testing period of one year to September 2014 was used to compare the predicted and measured dust levels. The model had a good correlation for the total testing period (r^2 = 0.66) but was more accurate during the summer of 2014 (r^2 = 0.69) compared with the previous winter (r^2 = 0.40): this may be because the model was based on summer monitoring. The predictions were over- rather than under-estimated possibly relating to estimating the longer term impact of rainfall and falling temperatures during winter. Dust concerns tend to be greatest between March and October in southern England, so base-line monitoring at that time is appropriate.

Other techniques for correlating weather and dust data have been attempted, for example using Microsoft's Excel Solver tool to help create non-linear equations. Similar levels of correlation were found for the same basic data but work is ongoing.

Referring back to Figure 3 it can be seen that the dusting level at the receptor was about 10% of the EAC% level at the site boundary. Hence the possible level of dust arriving at the receptor could be established in relation to that figure, although the potential for dust arising from agricultural activities in the ground between the quarry boundary and the receptor remain.

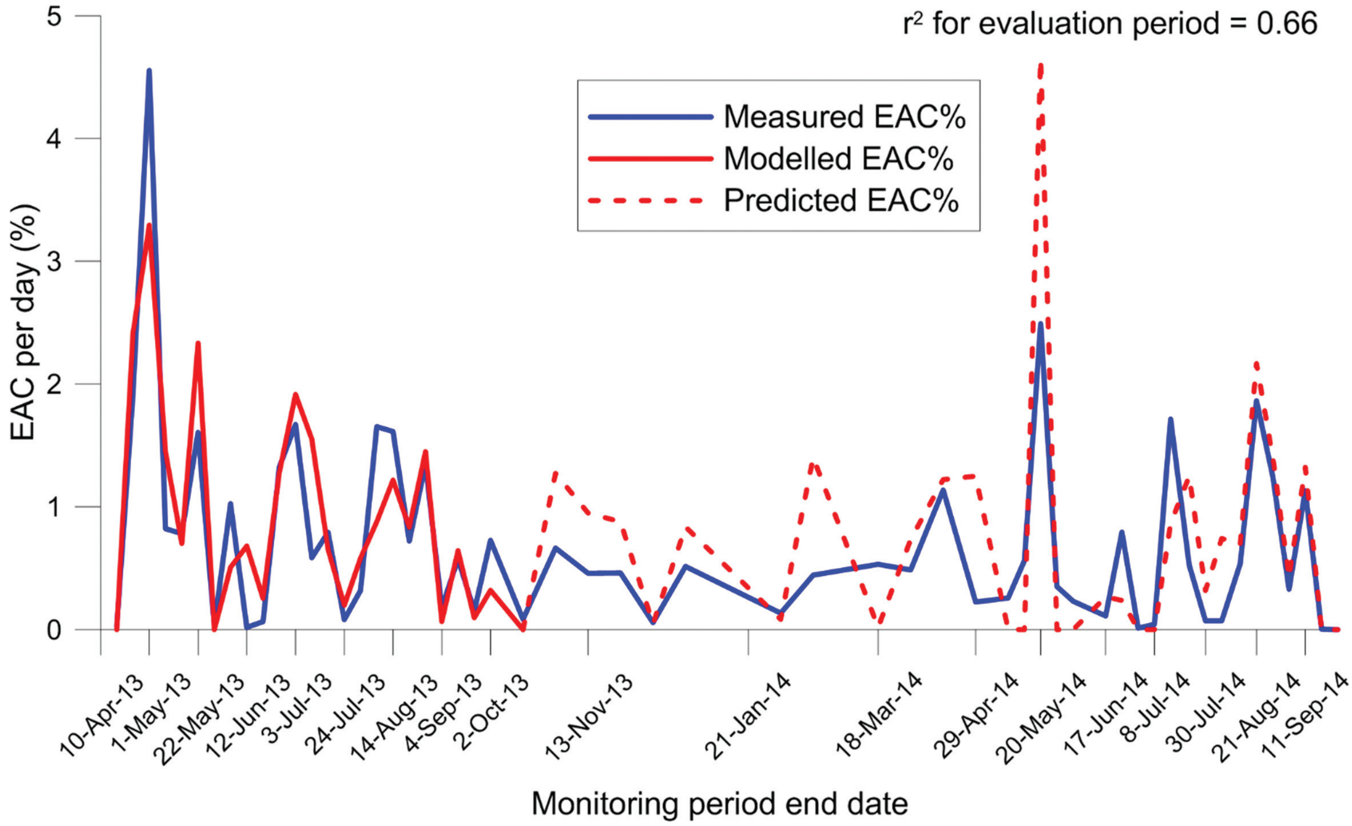

Figure 4. *Plot showing directional EAC% levels at the site boundary and modelled and predicted EAC% levels based on linear regression modelling. The period of monitoring was from April to October 2013, followed by the predicted period from October 2013 to September 2014.*

Implications

The benefit of this form of analysis is that it enables determination of those weather conditions during which significant dust impacts might occur at the receptor. Based on relationships such as those shown in Figures 3 and 4 it seems possible to assess when, and how often, dust might become a nuisance at the receptor. Similarly dust levels should be predictable on the basis of real-time weather conditions. Clearly if the dust and meteorological monitoring has only been undertaken as part of a short base-line monitoring programme it is important to compare the meteorological data with that of a longer established weather station. This enables the variations in wind speed and wind direction at other times of the year to be assessed, although adjustments might be necessary to account for differences in weather data collection.

Figure 5 is a proposed matrix of potential dust impacts relating to general weather conditions in southern England using wind speed, temperature and rainfall data; this is based on experience and analysis. Clearly this has to be related to the source of dust, the frequency, levels and direction of prevailing winds and especially to the distance and barriers between the source and receptor.

Dust emission risk criteria for wind speed, temperature and rainfall		Average temperature & rainfall per day					
		<10°C, ≥ 1 mm	<10°C, < 1 mm	10-15°C, ≥ 1 mm	10-15°C, < 1 mm	>15°C, ≥ 1 mm	>15°C, < 1 mm
Average wind speed	<3m s^{-1}	Very Low	Very Low	Very Low	Low	Low	Medium
	3-4m s^{-1}	Very Low	Low	Low	Low	Medium	Medium
	4-5m s^{-1}	Low	Low	Medium	Medium	Medium	High
	5-7m s^{-1}	Medium	Medium	Medium	High	High	Very High
	>7m s^{-1}	High	High	Very High	Very High	Very High	Very High

Figure 5. *Suggested matrix of potential dust impacts resulting from specified weather condition based on monitoring data from sites in southern England.*

From this, potential problems at receptors could be related to levels of dust measured at the site boundary and/or be based on the frequency of weather conditions likely to give rise to problems, if the quarry is working without suitable dust control measures. At the sand and gravel workings referred to above, the frequency of medium or high impacts from quarry dust over the 17 month period of monitoring was negligible. The highest wind speeds often gave rise to the highest daily EAC% levels at the boundary dust monitor, but as may be inferred from Figure 3, the dust levels at the receptor would have been significantly lower for the same period (<10%). Consistent winds from the west-southwest at speeds in excess of 7m/s in dry conditions may therefore be required for significant off site dust impacts arising from the quarry. As shown, such a situation would not have arisen at the site referred to above; however dust from other sources closer to the receptor (e.g. agricultural dust) might give rise to problems. Such matters can cause disputes, but most can be resolved by investigations of the directional dust components using microscopy, as note previously, and other techniques such as SEM-EDX (Scanning electron microscopy with energy dispersive X-ray spectroscopy), ICP-MS (Inductively coupled plasma mass spectrometry) and particle size analysis (Fowler et al, 2013).

One of the most important matters coming out of this is that it seems possible to assess when off-site dusting is most likely to occur on the basis of high wind speeds in critical directions and dry conditions, and to modify site operations accordingly. Such an approach depends on the site operator being aware of the principal on-site dust sources and to implement appropriate dust control measures in a timely manner. On many sites this control of dust is the subject of a Dust Management Plan (or Scheme), since it has long been recognised as occurring on a frequent, if discontinuous, basis at many quarries (Arup Environmental et al., 1995). Dust sources in quarries can typically include:-

- Haul roads especially when un-metalled and undefined
- Transfer points for materials handling such as truck loading by excavators, feeding, belt cleaning and transfer points with conveyors and elevators, and discharge points of all kinds
- Uncovered stockpiles of minerals, overburden and soils
- Bare surfaces in soils and overburden
- Minerals processing including crushing and screening operations especially when not fully enclosed
- Drilling and blasting
- Materials track-out onto access and public roads

Much can be done, and frequently is, to reduce and remove the risk of high levels of dust arising within, and escaping from quarries. Various techniques have been and are used to suppress and control dust. Some methods have been in use for many years including:-

- Static and mobile spraying of surfaces or the use of mist cannons
- Enclosure of dust generating activities and equipment
- Covering bare surfaces with fabric and other materials, or by seeding
- Removal of loose debris by controlled excavation or sweeping
- Using wheel and vehicle body washing and covering trucks
- Limiting areas of excavation or disturbance by phased working and restoration
- Controlling disturbance due to mobile plant by reducing vehicle movements and speeds, and by controlling drop heights
- Employing screening, such as planting and physical barriers, and alignment of workings to reduce the impact of prevailing wind directions
- Reducing or regulating specific activities when high wind speeds occur.
- Pro-active site management especially regulating activities near dust receptors

There is less certain information, and apparently none from fully monitored trials, regarding the efficacy of surfactants in sprays. However the listed techniques above are known to have some effect in dust suppression and control. On the basis of planning conditions, many quarries in Britain do not appear to have significant nuisance concerns with respect to dust. However it is understood that few quarries specifically investigate the efficacy or management of dust control by controlled monitoring and it is possible that some incur unnecessary costs by not exploring when controls are needed or can be avoided.

Concerns can and do arise if dust-sensitive activities are located close to significant dust sources, such as mobile screens and materials handling, and particularly if those are near the site boundary. One particular example of interest in southern England is the attention being given to solar power installations on and near quarry workings. Dust can significantly reduce power generation and, in such cases, it is appropriate to consider in detail the estimation of the extent to which dust dispersion might occur and to use modelling techniques akin to those described above.

Future Developments

Using linear regression models it has been possible to develop a numerical relationship between measured dust levels at the quarry boundary and weather data over a period of several months (Figure 4). It is important to know which activities are the most significant in emitting dust, both on- and off- the site, and where they are located. The empirical approach outlined above effectively takes the general quarry dust at the site boundary and uses this to compare with off-site dust levels. In practice this boundary dust level is difficult to estimate by any other means since, as shown above, there are many component dust sources in a quarry. It should be possible to approach the net, boundary dust level on the basis of compiling data on site specific dust levels from actual sources, factoring the component source areas and summing the net dust output. In practice little has been done on measuring the dust emitted by individual components of quarry activities in the UK. Apart from estimates made based on some form of dust level measurement at active quarry boundaries, it seems that many attempts at computer based nuisance dust distribution models may be little better than educated guesses. Significant data on UK site specific dust emission factors is absent.

To overcome this inadequacy, simple trials have been started to explore methods of arriving at dust emission factors and how dust levels at a source may vary with those at the site boundary and the receptor. Preliminary trials have taken place at a large gravel pit where a multi-height unit containing 5 monitors at different heights above ground level was placed as close as practicable to a dust source, with a second multi-height monitor at a separation distance of 8 to 12m (Figure 6). Multiple trials were undertaken and monitors were left out for successive 7 day intervals. The locations selected were an entry haul road (as shown in Figure 6) and a screening plant with stockpiles.

Figure 6. *Two multi-height dust monitors adjacent to a quarry haul road.*

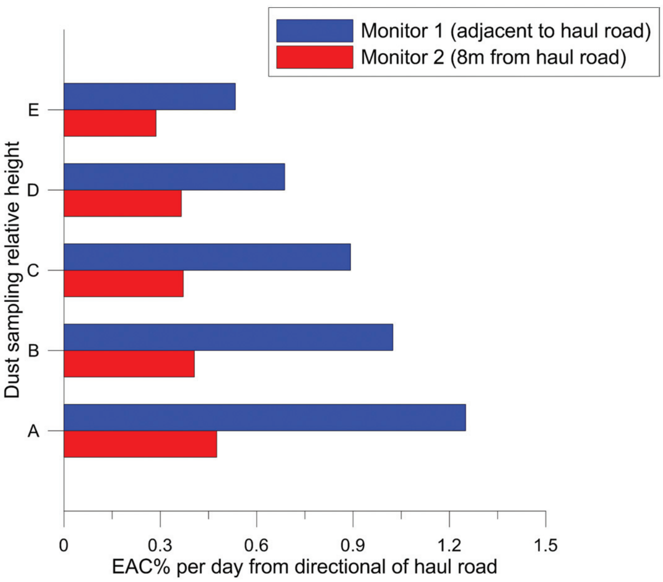

Figure 7. *Initial results from multi-height sampler trial.*

Figure 7 shows the preliminary findings from monitoring next to an entry haul road. There is a decrease in dust levels from the ground surface upwards, and the dust levels similarly reduce away from the dust source. By adjusting the spacing between multi-height units the proportion of dust adjacent to the source that effectively 'takes off' can be estimated. These investigations together with studies of the 'characterisation' of particles during initial emission, in terms of mass, mineralogy, size and shape, are currently in progress.

Acknowledgements

This study was supported by a Knowledge Transfer Partnership project funded by the Technology Strategy Board through the School of Earth and Environmental Sciences (SEES) at Portsmouth University and by DustScan Ltd. The authors are particularly grateful to Professor Jim Smith and Dr Mike Fowler of the SEES at Portsmouth and various clients of DustScan.

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