Odour nuisance – advantages and disadvantages of a quantitative approach

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Abstract The benefits of a quantitative approach to odour nuisance may be thought obvious: much better value for money should be obtained from abatement measures. New works can be appropriately sited and appropriately designed. These benefits are only realised however if the quantitative approach chosen is reliable. The components of possible quantitative approaches, – olfactometry – estimates of emission rates – dispersion models – quality standards, are discussed with the limitations and sources of error in each. When using a quantitative approach it is necessary to distinguish between a poor method in which the levels of error are unknown and a good method for which the levels of error can be defined. A quantitative approach should allow different methods for odour control: septicity control using chemicals, operational modifications to reduce turbulence and covering and treatment of air, to be evaluated on a common footing.

Keywords Odour; hydrogen sulphide; sewage treatment; measurement; emission rate; dispersion modelling

Introduction

Over recent years, controlling odour emission has become a challenge for many sewage treatment works. As a result, the overall spending by water companies for preventing and reducing odour nuisance has increased substantially. Meanwhile, significant advances have been made in diagnostic tools for odour assessments. In particular, olfactometry has been used for measurement of odours from sewage treatment; methods have been developed to determine the odour emission rates from individual sewage treatment processes; dispersion modelling has been used with odour standards for odour impact assessment. Together, the use of these techniques represents a new, quantitative approach to odour control. This approach has received some acceptance by the water industry and some local authorities have expressed a preference for a quantitative approach to dealing with odour issues, though there are no quantitative standards in the UK.

The traditional approach for odour control is, largely, qualitative. Solutions to odour problems commonly involve covering the offending processes and treating the vented air. Processes to be controlled were selected based on experience. Odour control equipment was specified to operate within certain critical limits for hydrogen sulphide concentration and volumetric flow rate. This approach has been applied primarily in dealing with the perhaps the worst odour sources in sewage treatment, which usually include inlet works and sludge handling facilities.

As potential receptors live ever closer to sewage works, controlling the ‘worst’ odours alone is often insufficient to prevent odour nuisance. In this situation, other larger, open processes for sewage treatment have entered the frame as odour sources capable of causing nuisance. Implementing the traditional “cover and treat” solution across the works is not always practical and is generally regarded as too expensive. Tackling selected sources on a trial and error basis may fail to address the whole problem.

This has prompted the emergence of a quantitative approach to odour control. The core of the new approach is to use measurement to determine the emission rates from potential sources. Two parameters are commonly measured. Hydrogen sulphide concentration is measured e.g. using a gold-film resistance monitor, down to the level of 1 ppb. Odour
strength is determined using olfactometry, which measures the number of dilutions the sample must receive until 50% of a trained panel can no longer detect odour or fail to distinguish it from odour-free air. For point sources such as a stack, the emission rate is determined by multiplying the concentration and the volumetric flow rate of the discharge. For open area sources, such as a channel or a primary tank, several indirect methods have been used – e.g. the flux-chamber or Lindvall hood (Kaye, R. and Jiang, J.K., 2000) or the micrometeorological method – meaning in this context the use of a dispersion model to determine by trial and error the source strength which produces the best fit to measured atmospheric concentrations (Yang, G. and Hobson, J. 1999). When the emission rate from every potential odour source in a works is determined, this information is used to prioritise processes for odour control and to select appropriate abatement measures.

Knowing the emission rates also allows the impact of the emission to be assessed. This is performed using dispersion modelling to determine the concentrations of pollutants or odour in the atmosphere after they have been dispersed. A dispersion model can be used to predict the impact of odour at particular receptors under typical meteorological conditions. Using long-term meteorological data, a dispersion model can also determine the frequency of occurrence of pollutant or odour concentrations in the neighbourhood of a sewage treatment works.

The ability to relate odour concentrations in the atmosphere to the emission rate at the sources makes it possible to introduce odour standards. An early odour standard was developed in Holland. The criteria for such odour standard are based on olfactometry and frequency of occurrence. The values of these criteria were determined by surveys of populations around well-characterised odour sources.

A quantitative approach to odour control means that: objectives of odour control can be met first time; better value for money should be obtained from abatement measures; new works can be appropriately sited and appropriately designed. However, these benefits can only be realised if the quantitative approach chosen is reliable. The components of the quantitative approach, i.e. olfactometry, determination of emission rates, dispersion modelling and quality standards are discussed in this paper with the limitations and sources of error in each highlighted.

Elements of the quantitative approach for odour control
Olfactometry
The use of olfactometry in odour control is both natural and necessary. The aim of odour control is to avoid nuisance, thus the success of achieving this aim is ultimately judged by the human nose. Meanwhile, the human nose is still superior at sensing odours to any available instrument. The methodologies for olfactometry have been described by several authors and have been standardised by the CEN draft European Standard (CEN 1997, Schultz, T.J. and van Harreveld, 1996). Nevertheless, two issues remain of concern with the use of olfactometry in sewage treatment.

First, it is argued that since olfactometry does not distinguish the offensiveness of odours, use of olfactometry may not be appropriate where the objective is not to eliminate all odours but only those odours, which may cause a nuisance. This argument is supported by the experience that most people would find the septic odours from crude sewage and sludges to be more offensive than the musty odours from activated sludge plants. On the other hand, the hedonic tone (acceptability) of an odour is not independent of the strength of the odour. Septic odours are usually stronger than odours from secondary treatment and little work has been done to separate offensiveness from strength.

One way to evaluate the relative offensiveness of different odours is by diluting them to the same strength and then asking a panel to determine their relative offensiveness of each.
WRc has carried out such a test in the past; comparing odours from activated sludge plants and aerated biological filters with odours from septic sewage. The odour samples were pre-diluted to around 5 ou/m³ and presented to the panel. The panels were asked to decide which of the two odours was more offensive. On both occasions, roughly equal numbers of each panel identified the septic sewage odour and the secondary treatment odour as being more offensive. These tests appear to suggest that both types of odour when highly diluted to equal odour strength, were equally offensive, though more work is needed to draw a conclusion. Measurements on a greater number of samples in a more systematic manner could offer conclusive evidence one way or the other. Even if different types of sewage odour were found to be qualitatively differently offensive, care would be needed. Psychological factors may mean that any odour associated with sewage treatment is offensive. An example of the use of odour descriptors is given in Winter and Duckham (2000).

Another (and potentially more serious) concern when using olfactometry is the reliability of the data obtained. A measurement could be regarded as reliable if its margin of error is known and accepted. The minimum criterion for precision, defined for olfactometry according to the CEN standard is:

\[ 10^r = 10^{\sqrt{2}S_r} = 3 \quad \text{or} \]
\[ S_r = 0.1721 \]

where:

- \( r \) = repeatability
- \( S_r \) = standard deviation for repeated measurement
- \( t \) = significant value of \( t \) in the test of significance, a value of 2 is used (\( n = \), 95% confidence interval)

This means that if two readings are made on the same sample, they should fall within 48% and 209% of the true value. The background odour strength in open air is often around 100 to 200 ou/m³ (WRc odours database). When measuring ambient air samples, the results are only meaningful if the readings are greater than, and can be distinguished statistically from, the background values. The number of measurements required to get a meaningful result depends on how close the sample odour strength is to the background. This can be calculated using the following formula (Cox, G.M. and Cochran, W.G. 1957):

\[ n = 2\left(\frac{S_r}{\delta}\right)^2 (t_1 - t_2)^2 \]

where:

- \( \delta \) = true difference between two samples
- \( t_1 \) = significant value of \( t \) in the test of significance, a value of 2 is used (\( n = \), 95% confidence interval)
- \( t_2 \) = value of \( t \) corresponding to \( 2(1-P) \)
- \( P \) = probability of obtaining a significant result, a value of 0.9 is used

Table 1 shows an example of the number of samples needed to obtain a significantly different result to a background measurement of 200 ou/m³. It indicates that many samples are required in order to obtain a meaningful result unless the target odour strength is several times greater than that of the background. The cost of olfactometry and the fact that each panel is only able to process up to 8 samples imply that this method is not suitable for measuring small increases in odour strength, up to double the background level or more, even
though such levels of contamination could be easily detected by the human nose. Another example of using the olfactometry to determine the efficiency of odour control equipment is given in the Appendix of the draft European Standard for Olfactometry (CEN, 1997). It also demonstrates that multiple samples may be required to prove the efficiency of odour treatment equipment with reasonable confidence.

Odour strength is a measure of how much a sample can be diluted until its odour disappears. Its value in predicting the subjective response to an odour is much less certain. For a single odorant, response is believed to reflect the log of the odour strength e.g (Misselbrook, T.H. et al., 1993) following the general physiological rule that measured response is proportional to the log of the concentration of an active agent. A scale based on decibels has been proposed – odour strengths of 10, 100, 1,000 and 10,000 have decibel values of 10, 20, 30 and 40 respectively. On this scale background odours score in the region of 20. Odour strengths in the region of 1,000 ou/m³ score 30 and will not appear intense. Intense odours as low as 5 ou/m³ may however lead to nuisance if they result from an intrinsically unpleasant odour, even though, in terms of intensity, they would be extremely faint.

**Odour emission rate**

When odour is released from a point source, such as a vent or a stack, the odour emission rate can be determined by measuring the odour strength and the volumetric flow rate of the discharge. Typical examples of point sources include covered sludge tanks, ventilated buildings and certain odour control equipment. Emission rates from these sources may be determined by:

\[ E = C_{odour} \times Q \]  

(4)

where:

- \( E \) = emission rate, ou/s or mg/s
- \( C_{odour} \) = concentration of odour, could be expressed as hydrogen sulphide concentration or odour strength, or ou/m³
- \( Q \) = flow rate of air released, m³/s

When odour is released from uncovered sources, such as channels, weirs and open tanks, alternative, indirect methods have to be used to determine the emission rate. One approach, known as the micro-meteorological method, determines the emission rate according to the measured downwind odour concentration profiles. A second method uses a flux chamber placed over the source. The emission rate inside the flux chamber is measured. The value is

<table>
<thead>
<tr>
<th>Odour strength to be measured (ou/m³)</th>
<th>Odour strength above the background (% of)</th>
<th>Number of replicate measurement required</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>25</td>
<td>64</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>19</td>
</tr>
<tr>
<td>400</td>
<td>100</td>
<td>7</td>
</tr>
<tr>
<td>500</td>
<td>150</td>
<td>4</td>
</tr>
<tr>
<td>1000</td>
<td>400</td>
<td>1</td>
</tr>
</tbody>
</table>

1. Assuming a background odour strength of 200 ou/m³
2. For a significant result at the 90% confidence level.
then scaled up to the whole surface area of the process. A third method determines the emission rate according to the theory of gas-liquid mass transfer. Mass transfer equations, which involve the concentration of the pollutant and the mass transfer characteristics of the process, such as $K_{ba}$, are used. For example: the emission rate from a weir is determined using the following equation:

$$E_{\text{weir}} = 7.16 \times 10^{-4} \times OP \times F \times k_{pH}$$  \hspace{1cm} (5)

where:

- $E_{\text{weir}}$ = odour emission rate per length of weir, ou/s/m
- $OP$ = odour potential (Hobson, J., 1995) of the sewage, ou/m$^3$
- $F$ = weir loading m$^3$/h/m
- $k_{pH}$ = pH correction coefficient, has a value of 1.37 at pH 7

Determination of odour emission rates as H$_2$S (mg/s) or odour (ou/s) allows odour problems to be quantified. To put this information to practical uses (for instance, as input to a dispersion model or as the basis for prioritising abatement), the margin of error is a matter of concern. For point sources, the margin of error may be regarded as roughly the same as the that of the measurement used, for example, around ±40% if olfactometry is used and 3 to 10% if hydrogen sulphide (This assumes air flow rates can be measured accurately).

Little is known about the accuracy of indirect methods for estimating odour emission rate. In one exercise (Yang, G. and Hobson, J., 1999) estimates based on direct measurement, the mass transfer method and the micro-meteorological method all agreed to within a factor of two, though the flux chamber method gave a very significant over-estimate of emissions. The overall odour impact from the works, predicted using the mass transfer method, was consistent with the historical records of complaints. Since odour emission rates are proportional to the odour potential or H$_2$S concentration in the process flow, they can vary by over two orders of magnitude for a given process depending on the condition of the flow.

**Dispersion modelling**

A dispersion model can be used in several ways to evaluate the impact of an odour source once its emission rate is known. Steady-state modelling, which runs the model with one set of meteorological conditions at a time, can determine the downwind concentrations caused by one or a group of odour sources at a particular time. This can be performed for any one of six atmospheric stability classes and for typical combinations of wind speed and directions to screen out the best or worst case scenarios of a particular odour control strategy.

Another use of dispersion models is to assess the compliance with a given quality standard or the frequency of occurrence of a critical odour strength. The model output can be presented as isopleths of ground level odour strength for a given frequency of occurrence. Alternatively, a model can determine the maximum residual emission rate permitted from a source in order to achieve a particular odour standard. When used in this mode it is desirable to use several years’ worth of meteorological data, preferably five, since there can be significant fluctuation on a year to year basis at a single site.

The most commonly used dispersion models use the steady-state Gaussian plume equation to calculate concentrations downwind from a point source. For example, the hourly average concentration from a continuous source at downwind distance $x$ (m), cross-wind distance $y$ (m) and elevation $z$ (m) is given by:
\[ C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right] \exp \left[ -\frac{1}{2} \left( \frac{z-H_e}{\sigma_z} \right)^2 \right] + \exp \left[ -\frac{1}{2} \left( \frac{z+H_e}{\sigma_z} \right)^2 \right] \]  

(5)

where:

- \( C \) = concentration (mass per volume)
- \( Q \) = pollutant emission rate (mass per unit time)
- \( \sigma_y, \sigma_z \) = standard deviation of lateral and vertical concentration distribution (m)
- \( u \) = mean wind speed (m/s) at release height
- \( H_e \) = effective plume height.

This equation indicates the concentration of odour at any receptor is proportional to the emission rate while it is also a function of the wind speed and atmospheric stability. The most important assumptions made by this type of models include: conservation of mass; continuous emission; steady-state conditions, and the lateral and vertical concentration profiles following normal distribution.

The Gaussian model is widely used in the field of air pollution control. Diosey (Diosey, 1997) in the context of odour modelling, indicates that the model “fits what we see and experience in the real world for a range of conditions”, perhaps in reality implying an accuracy within a factor of 1.5 to 2 for predicting mean concentrations (peak to mean ratios can vary enormously, from 1:1 to 40:1 depending on a range of parameters. The issue of peak concentrations must be dealt with outside of a simple Gaussian plume model. New generation models, discussed below may be able to predict short-term peak concentrations more effectively). The assumptions for the Gaussian model are made for and verified against specific pollutants. With regard to odour, these assumptions are taken as valid.

A number of interesting trends of practical significance have been revealed through the use of dispersion modelling to assess odour impact. First, the proportionality between the predicted concentrations at receptors and the emission rates is generally true not only for a single point source but also for area sources or multiple sources if the distance between the sources and the receptors is considerable (i.e. several times the dimension of the source). Therefore, a reduction of the overall emission rate by 50% would reduce the odour concentrations at the receptors by around 50%.

Secondly, the distance from a source to a potential receptor who will receive a given impact (e.g. resulting in complaints) is proportional to the square root of the emission rate. In other words, halving the emission rate roughly halves the area of the zone, which could receive the critical impact. This agrees well with an empirical formula (developed from the Gaussian plume equation) which estimates the maximum distance for odour complaints, developed at the Warren Spring Laboratory (Keddie, W.C., 1982).

\[ R_c = (2.2 \times E)^{0.6} \]  

(6)

where:

- \( R_c \) = maximum complaint ratio, accurate to within a factor of 2
- \( E \) = odour emission rate, ou/s

A comparison between the distances of critical impact predicted by a dispersion model and by the Warren Spring formula for several works is shown in Figure 1. The comparison was made using hypothetical sewage treatment works of different sizes and long-term meteorological data from two different regions in the Midlands.
Thirdly, the prediction by the Gaussian models is highly sensitive to the selection of dispersion mode. The urban dispersion mode is selected if either the built-up area (as indicated in land use maps) within 3 km radius of the source is greater than 50% or the population lives within a 3 km radius of the source is greater than 750 persons per km². The distance of impact can vary by as much as a factor of 3, depending on which mode is selected. Since many treatment works are on the edge of built-up areas, the selection of the appropriate mode can be problematical.

New generation dispersion models, e.g., AERMOD and ADMS significantly extend the Gaussian plume principle of dispersion modelling by incorporating a more thorough treatment of atmospheric physics. Validation tests have shown that such models can make significantly more accurate predictions but to do so they require significantly more input data. AERMOD defaults back to the Gaussian plume models whenever this extra input data is unavailable. These newer models are likely to become standard over the next few years but there is no requirement for modellers in the field of odour to take the lead in this. Given the range of uncertainties in this field, existing models appear quite adequate for our purposes.

Odour standards
An offensive odour becomes a nuisance if it is received by a receptor for a substantial time. Because of varying atmospheric conditions, most receptors around an odour source may not receive any odour for most of the time because they will not be downwind from the source. Just as is the case with the percentile compliance with liquid effluent quality standards from a sewage works, any odour quality standard with a view to avoid nuisance has to be statistically based. Standards have been proposed in Holland and have been used on an informal basis in the UK. These are based on percentage compliance with hourly average odour concentrations. They are shown in Table 2.

The Dutch standard has left some scope for selection. In the UK, 5 odour units for 98%–ile is commonly selected and has been used in a public enquiry at Newbiggin. A stricter standard, e.g., 1 odour unit for 98%–ile or 99.5%–ile is thought to be more appropriate for green field sites located in a sensitive areas, particularly if emissions are dominated by a single point source. Even when a standard is believed valid, it is not possible to interpret it too literally in terms of what is giving rise to complaint. Figure 2 shows that four different standards: 1.5 ou/m³ at 90%–ile, 3 ou/m³ at 95%–ile, 5 ou/m³ at 98%–ile, and 7 ou/m³ at 99%–ile are equivalent as far as the predicted critical impact zone is concerned. The ability of a
standard to match annoyance does not imply any particular significance for the concentration term used in the standard.

Improving the reliability of the quantitative approach

Of the four elements of the quantitative approach to odour, olfactometry, dispersion modelling and standards each have an uncertainty of the order of a factor of two. Measured odour emission rates have a similar level of uncertainty for the process being measured. Literature values of odour emission rates however have an uncertainty in the region of two orders of magnitude or more because the degree of septicity as measured by the odour potential or sulphide concentration is never stated, nor are the precise details of the process stated – e.g. emission rates from a weir are proportional to the weir-height (Frechen, F.B., 1994, Cha, S.S., 1997). Establishing credible emission rates is potentially the weakest link by far in the quantitative approach.

To improve the reliability of emission rate values, WRc recommends the use of the mass transfer approach. An odour emission rate is broken down into terms describing the level of odour or H₂S in the flow, flow-rate and windspeed and the physical dimensions of the process. When estimates have to be made there is now much more control than simply trying to estimate the emission rate in a single step. Measurements made under one set of circumstances can easily be applied to different circumstances.

Another source of error for the quantitative approach is in the meteorological data used. This generally comes from the relevant region of the site being examined but may easily

Table 2 Dutch odour standard

<table>
<thead>
<tr>
<th>TON</th>
<th>Percentile</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>98%</td>
<td>TON&gt;10 for &gt;2% of the time. Serious annoyance expected with near certainty.</td>
</tr>
<tr>
<td>1–5</td>
<td>98%</td>
<td>TON&lt;1-5 for &gt;98% of the time. Generally acceptable for existing installations. Emissions from stacks or large area sources may be acceptable at the relaxed end of the range.</td>
</tr>
<tr>
<td>1</td>
<td>98%</td>
<td>98% No serious annoyance expected in majority of cases.</td>
</tr>
<tr>
<td>1</td>
<td>99.5%</td>
<td>Safe target value for new sources.</td>
</tr>
<tr>
<td>10</td>
<td>99.99%</td>
<td>Applicable to highly intermittent sources.</td>
</tr>
</tbody>
</table>

*0.5, 1, and 2% percent of time means 44, 88 and 175 hours per year respectively. Odour concentration exceeding the criteria for 6 minutes in any hour counts for 1 odour-hour.

Figure 2 Dispersion model output showing the equivalence of different numerical odour standards
come from tens of miles distant. In some regions, wind roses are fairly symmetrical and will be less of an issue, but in others they are highly directional. The details of this latter type are less likely to apply further afield. While it is not practical to obtain full meteorological data for each site of interest, it may be possible to add local wind direction and speed to the more complete but more remote data currently available.

All quantitative approaches benefit from validation. In addition, planning authorities are increasingly likely to demand the implementation of a monitoring programme following the construction of new sewage treatment processes. Ideally such a monitoring programme should identify annoyance or lack of and be capable of validating modelling assumptions used in the design. Currently no monitoring technology exists for conclusively demonstrating annoyance or lack of annoyance due to odour. In addition there is currently debate as to whether monitoring should be based on \( \text{H}_2\text{S} \) or olfactometry. WRc believes that olfactometry is the bottom line measurement for odour but that it fails totally both on technical and practical grounds as a means for confirming annoyance at receptors outside a works. WRc would like to put forward the following as the basis for a standard for monitoring odour. On grounds of practicality this is based largely on \( \text{H}_2\text{S} \) but takes into account that the ratio between \( \text{H}_2\text{S} \) and odour can vary greatly between processes and before and after the passage of air through odour treatment.

- Monitor using \( \text{H}_2\text{S} \) at the ppb level.
- Establish and periodically check the ratio between \( \text{H}_2\text{S} \) and odour strength at source for the major sources.
- Use the established ratios to convert \( \text{H}_2\text{S} \) measurements to most likely odour strength.
- Periodically prepare \( \text{H}_2\text{S} \) maps, otherwise the significance of off-site peaks may be misleading due to road traffic.
- Investigations for diagnostic purposes should include olfactometry.

The quantitative approach can also be validated directly against complaints, which restricts measurement to that necessary to characterise the sources. Many modelling exercises are performed for new works where the opportunity for validation does not exist. WRc has carried out the full procedure on several occasions for existing sites with a record of complaints. On two occasions the match was extremely good – on two different occasions the distance to complainants was matched very well but in these two cases the wind-roses (from sites some miles distant) were highly directional and the direction of complaints was not predicted quite so well – on the fifth occasion a substantial area of impact was predicted but well short of the 3-miles from which complaints were received. In any modelling exercise, quantification of the odour sources may miss some short-lived peak emissions, which would lead to under-estimating impact.

Conclusions

A quantitative approach is necessary for odour control because a rational and consistent means is needed for justification, evaluation and specification of solutions for preventing and reducing odour nuisance.

The components of possible quantitative approaches: olfactometry, \( \text{H}_2\text{S} \) measurement, estimates of emission rates, dispersion modelling and quality standards, all have considerable margins of error which should not be ignored.

Several ways are available to improve the reliability of the procedures so that the full benefits offered by the quantitative approach can be realised.

References


