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Short communication

Garbage in, gospel out? – Air quality assessment in the UK planning system

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ABSTRACT

In the United Kingdom, the planning process requires applicants to submit an air quality impact assessment wherever an impact on national limit compliance is likely, and this factors into the resultant decision. We identify flaws in the current methodological frameworks and policies associated with this process that in the worst cases could lead to poor decision making. We give examples of how inaccurate data is certified as good through unsuitable pre-processing, how these errors are then amplified by poor modelling practice, and how the final data is judged against metrics that are evidence impaired to arrive at potentially unsound decisions. We then discuss the implications and propose a way forward.

1. Introduction

In the United Kingdom, local authorities have the power to decide on planning applications within their district boundaries and for infrastructure under their control. After an applicant submits a planning application along with supporting documentation the case is put out for a period of public and statutory consultation before being decided by the authority's planning committee to make a decision (note that some minor developments can be decided immediately by powers delegated to the planning officers).

Planning decisions, and in particular objections, cannot be based on arbitrary or subjective arguments, but must be linked directly to tangible material conditions. These conditions are outlined by the government in its National Planning Policy Framework (NPPF) document (Ministry of Housing, Communities & Local Government, National Planning Policy Framework, 2018), and by each local authority in its respective Local Plan document. Air quality is one of these conditions.

Following the EU's 2008 Ambient Air Quality Directive (Directive 2008/50/EC, 2008) the UK government was in agreement to reduce the levels of key pollutants to specified annual limit values by 2010. Failing to do this, The Air Quality Standards Regulations 2010 (The Air Quality Standards Regulations, 2010) redefined these limits and extended the deadline to 2020. The government is obliged to define an Air Quality Strategy (AQS) with a view to achieving this.

In order for the UK to meet the imposed limits, every location in the UK where the public are regularly present, must meet the imposed limits (The Air Quality, 2000). It is for this reason that practical responsibility for fulfilling this obligation is distributed to local authorities.

Local authorities are required under part IV of the Environment act 1995 (Environment Act, 1995) to assess their compliance to the national AQS objectives by engaging in Local Air Quality Management (LAQM). This requires them to identify areas of concern, known as Air Quality Management Areas (AQMA), that either exceed or are likely to exceed national limits for PM10, O_3, or NO_2. These AQMAs once identified must then be the subject of a defined Air Quality Action Plan (AQAP) whose goal is to eliminate the identified concerns.

The law states that both the AQMA and associated AQAPs must be regularly reviewed and the local authority must submit an Annual Status Report (ASR).

The NPPF lists air quality as a direct material consideration and requires that air quality must be considered whenever there is a likely impact on an AQMA or on the observance of limit values, and a local authority should ensure that developments are consistent with its AQAP.

There is robust evidence linking exposure to air pollution to a variety of negative health outcomes (Royal College of Physicians, 2016; Holgate, 2017), and the emerging evidence base reviewed in Landrigan et al. (2018) indicates that the harms attributed to air pollution may apply to a wider variety of health indicators and diseases than is currently assumed.

In the UK, the Committee on the Medical Effects of Air Pollutants (COMEAP), managed by Public Health England, is tasked with regularly reviewing the health effects of air pollution (England, 2019). The implementation of the regulations discussed above, as enacted through Defra technical guidance (Department for Environment Food & Rural Affairs, 2018a; AEA Technology Plc, 2008), relies heavily on NO_2 measurement. Whilst the specific effects of NO_2 are hard to untangle from co-varying pollutants such as PM mass, it is clear that annual NO_2 measurements are a marker for pollution severity and the associated

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severity of health effects (Associations of long-term average concentrations of nitrogen dioxide with mortality, 2018).

It is important therefore that the air quality impact assessment methodology used by local authorities, produces outputs which reflect the actual risks to health, so that appropriate mitigation may be sought, or in the worst cases, planning refused.

Defra's technical guidance documents, both the general technical guidance (Department for Environment Food & Rural Affairs, 2018a), and the NO_2 specific guidance (AEA Technology Plc, 2008) are used routinely as standards against which to judge a planning applicant's air quality impact assessment. These documents undergo no formal blind peer-review process and contain advice instances that do not reference an evidence base. The general technical guidance implicitly and explicitly allows for the use of data with large uncertainties, and makes no requirement for empirical measurement of current pollution or traffic levels as a basis for pollutant prediction. It is reasonable to ask therefore whether the application of this guidance could lead to unjust planning decisions being made.

In this paper we identify and describe three specific methodological failures. We begin in Section 2 by revealing how much of the data used to make decisions not only has a high degree of uncertainty, but that these uncertainties can be increased by following the guidance. In Section 3 we explain how these data are then used to model the impact of developments and how the guidance permits the amplification of any uncertainties. In Section 4 we explain how the standards against which the resultant impact assessment is judged fall far short of their stated goal of protecting public health. In Section 5 we discuss the implications of these findings and outline the way forward. Section 6 concludes.

2. Diffusion tubes as an authoritative data source: garbage in – gospel out?

A phrase which has been popularised by computer and mathematical sciences, and used in policy literature is garbage-in garbage-out. The phrase serves to underline the importance of using accurate data in modelling and decision processes, both because of the obvious importance of the truth of initial assumptions as well as the tendency of mathematical approximation systems to amplify errors.

A mutation of this phrase garbage-in, gospel-out refers to the situation where computer outputs are treated as unquestionable facts without proper understanding of the transformative processes involved or their relation to the veracity of the inputs (Ault, 1987).

The main source of empirical data for pollution modelling and decision making is NO_2 diffusion tubes. Diffusion tubes are cheap and easy to use which allows cost-effective indicative monitoring on a wide spatial scale. Defra's diffusion tube guidance (AEA Technology Plc, 2008) makes it clear that *"NO_2 diffusion tubes are an indicative monitoring technique"* which is their fundamental weakness. This diagnosis is confirmed by a systematic review concluding an accuracy of around ± 25% (Stevenson et al., 2001) with a tendency of them to over-estimate relative to reference equipment (Heal et al., 1999).

Whilst it would be unfair to call NO_2 diffusion tube data garbage, but they do have a high degree of uncertainty. Given the heavy use of diffusion tubes to directly inform planning and air quality management decisions it should be of concern that such large uncertainties are permitted. Section 7.179 to Section 7.199 of Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) describes a methodology to compensate for this uncertainty.

This methodology is useful as it creates a normalised view of indicative measurements taken across a wide variety of environments and conditions. This is a helpful low-cost addition to the air quality measurement toolbox, particularly when observing annual changes in well-established AQMAs. Over time it is also a useful way to build evidence for identifying novel areas of concern. However, when it is used without proper consideration, and particularly when it is used with short-term measurements it has the potential to lead to an amplification of errors as explained below.

To compensate for under/over estimation in results local authorities are encouraged, although not required, to co-locate diffusion tubes (usually three, known as a triplicate) with a continuous monitor for at least 3 months. This serves to assess the diffusion tube intra-variability, known as precision, as well as accuracy.

By comparing the averages of co-located tubes with those of the reference equipment a "bias factor" can be derived for the diffusion tube measurements which, when applied, minimises the difference between them and the reference measurements for the given site.

Local authorities are encouraged to send their bias factors to Defra who maintains a database of results, partitioned by measurement year, local authority, tube preparation strategy, and analytical laboratory employed.

Section 7.195 of Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) states that *"local authorities should compare the results of correcting data by the locally derived factor"* and look out for differences. In the case of significant difference the same guidance advises *"the national factor is likely to be more reliable"*.

Defra provides a spreadsheet interface to this database called the "National Diffusion Tube Bias Adjustment Factor Spreadsheet" (Department for Environment Food & Rural Affairs, 2018b) which allows a local authority to select the analytical laboratory employed, tube preparation strategy, and measurement year to obtain the "orthogonally" averaged bias factor across submitted results (Air Quality Consultants on behalf of Defra, 2006).

Examination of the variability of results in this spreadsheet highlights the potential for errors in accuracy. Using the latest available spreadsheet (September 2018) (Department for Environment Food & Rural Affairs, 2018b), statistics were computed for each combination of laboratory and tube preparation method to assess the potential for error in using this spreadsheet tool. The five results with the biggest in-group differences are shown in Table 1.

In the worst case, for Staffordshire Scientific Services/20% TEA in water, diffusion tubes were found to under-estimate the reference by 30.4% (bias factor 1.44) in one study where they were used and over-estimate by 46.7% (bias factor 0.68) in another study. The orthogonal average, and thus recommended bias correction is given as 0.88 for the 19 studies.

In practice if this tool were blindly applied by a developer or local authority to a diffusion tube average of 30 μg/m^3 the recommended bias correction would yield 26.4 μg/m^3. But we know from the evidence above that the actual case could potentially be 20.4 μg/m^3 for the worst

Table 1
Smallest bias, largest bias, and computed bias spread for the five laboratory/method combinations with the largest intra-group difference. Number of studies are also shown.

Laboratory	Method	Smallest bias (%)	Largest bias (%)	Bias spread (abs)	Num studies
Staffordshire Scientific Services	20% TEA in water	−30.4	46.7	77.1	19
Gradko	20% TEA in water	−7.9	59.2	67.1	39
Gradko	50% TEA in acetone	−31.4	28.4	59.8	25
ESG Didcot	50% TEA in acetone	0.9	58.6	57.7	30
Edinburgh Scientific Services	50% TEA in acetone	10	57.3	47.3	6

over-estimator, and 43.2 μg/m^3 for the worst under-estimator. This is significant because 40 μg/m^3 is the annual limit value for NO_2 and the value at which the instantiation of an AQMA would be required. The tool has the potential to make the same measurement look either nothing to worry about or a great concern, and thus is not very informative.

This is not just a theoretical concern, and to give just one example: the Greater Manchester Combined Authority submits a single ASR encompassing the results for ten sub-authorities. The NO_2 results in the ASR for 2016 (2016 Air Quality Annual Status Report, 2017) are bias-corrected using the national factor derived from the Defra spreadsheet, and ignore the locally computed bias factors for each sub-authority. One of the sub-authorities is a contributor to the Defra tool, and appears in Table 1 as a worst case example. The conclusions of the report might therefore be based on misleading data as a result of the recommended processing.

Although the worst case examples are important, and as demonstrated above are directly influencing policy, it is interesting to ask what the general likelihood of data misinterpretation is when using the Defra spreadsheet.

We have seen that in the tool each laboratory/analysis type tuple provides a bias adjustment against which results in the same category should be corrected toward. The dataset allows us to compute for each locally computed analytical result that contributes to a given category, the difference between the recommended bias adjustment and the locally computed result.

We can ask the question for each category, and for each contributory local result: if we assume that after correction with the locally computed bias the local result would equal 40 μg/m^3, then what would the local value look like if corrected using the category bias adjustment? This way we can construct a distribution plot for each category centered around the national limit of 40 μg/m^3 to get an overall view of the practical effect of the tool for the measurement points provided. A histogram of this computation is shown in Fig. 1.

We can now ask the question, how likely is it that a 40 μg/m^3 threshold based decision will be “incorrect” based on correction with the national bias adjustment instead of the locally derived bias adjustment? Approximately 46% of the national bias spreadsheet corrections, underestimate NO_2 with relative to the locally derived bias correction.

Table 7.1 of Defra’s general technical guidance (Department for Environment Food & Rural Affairs, 2018a) lists criteria for screening road traffic sources of pollution for air quality management significance, and recommends that roads within 10% of objectives should be considered for further assessment. This is a more conservative position, and is favourable for health. Still in this case, 15% of national bias spreadsheet corrections would fall out of consideration despite having a value of 40 μg/m^3 after correction with the locally derived bias correction.

The Defra bias correction spreadsheet is always based on the latest annual local authority co-location results submitted, which for the tool examined above was 2017. The tool however embeds all local-authority submissions for every previous version of the tool since 2011, a total of 2376 submissions, 2329 of which have computed bias adjustment factors associated with them.

Each local authority submission lists the co-location result against the automatic analyser result, so it is possible to compare the error associated with no bias-correction with that of correcting with the recommended bias adjustment factor. Table 2 summarises the results of this computation using the 2017 data only (171 studies) and the complete available dataset.

The tool has the effect of reducing both the mean absolute error and also the error variance. Fig. 2 provides a density plot of the complete dataset before and after bias correction.

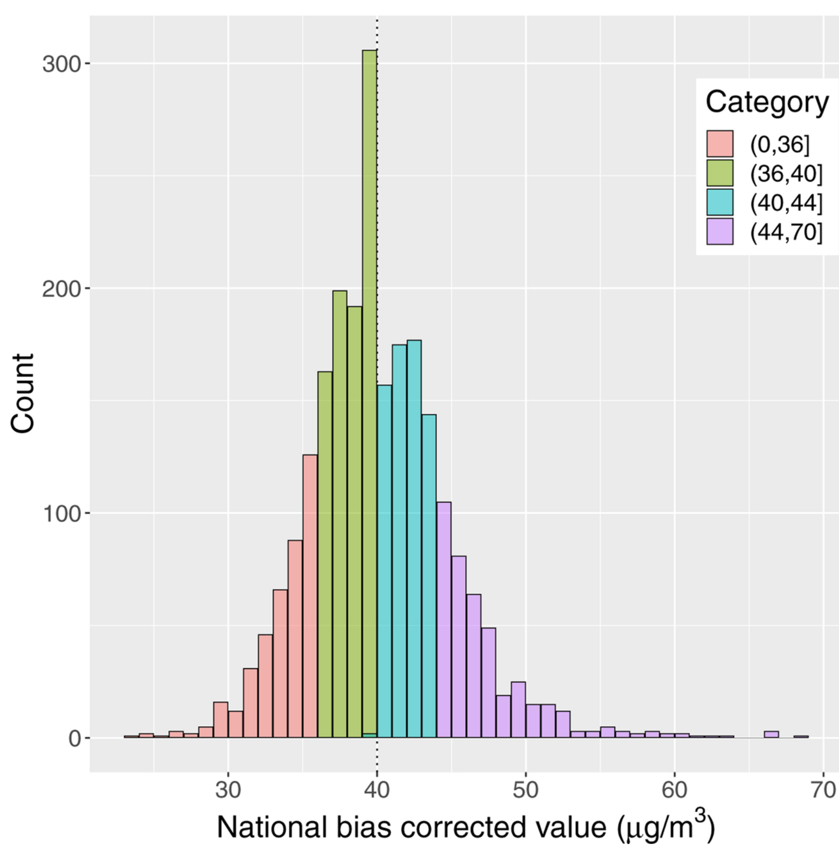

Fig. 1. National bias spreadsheet “correction” applied to all current Defra tool contributory result values that would correct to 40 μg/m^3 if the locally derived bias correction were used.

Table 2
Comparison of pre and post bias adjustment errors for the Defra spreadsheet tool using only the 2017 data (latest tool incarnation), and all of the data contained in the tool.

	Mean absolute error (μg/m^3)	Error variance
2017 before correction	6.70	32.6
2017 after correction	3.35	8.47
2011–2017 before correction	6.87	43.4
2011–2017 after correction	3.63	10.5

The figure illustrates that diffusion tubes tend to over-estimate NO_2 relative to automatic analysers, but that the correction methodology, whilst reducing the error spread, results in an increase in the number of points that under-estimate NO_2 relative to automatic analysers.

Finally we can compare the error pre and post adjustment for each study location, and quantify the extent to which the Defra spreadsheet improves accuracy. The results of this are shown in Table 3.

In the majority of cases, the tool results in an improvement in accuracy relative to no bias correction, but in about 30% of cases, the tool degrades accuracy. Fig. 3 plots the error distributions for the instances where the Defra bias adjustment tool improves or degrades accuracy relative to no bias adjustment.

The figure illustrates that when the Defra bias adjustment tool improves accuracy, it tends to increase the original NO_2 measurement, whereas when it degrades accuracy it tends to reduce the original NO_2 measurement.

What could possibly be causing such large variations in bias calculation even within tubes from the same laboratory and preparation method? In many cases, the co-located tubes are triplicated to rule-out intra-batch inconsistencies so it would seem that the exposure conditions themselves are to blame.

One study that argues for the validity of the UK diffusion tube methodology (Bush et al., 2001) by comparing diffusion tubes with chemiluminescent analysis, found differences in some cases of more than two standard deviations, which highlights the large errors individual locations may be subject to relative to reference equipment. Another study which looked at roadside vs background biases found only a small difference between the two conditions (Air Quality Consultants, 2006), but the scatter plot for the complete dataset showed large bias factor variances overall, consistent with those observed in the Defra tool data.

At the present time there is no complete explanation for the observed bias factor variances. Meteorological variables can have a significant impact (Plaisance et al., 2004), and local gas interactions are thought to contribute (Heal et al., 2000). In general however, it seems apparent that bias factors can be location specific which calls into question the very idea of applying a bias correction from one location, to another, which is how local authorities correct their diffusion tube datasets at present.

The Defra spreadsheet, by collating results and deriving an orthogonal average, hides these location effects. This does not make any sense since we are interested in the actual value at a given location, not a corrected value that takes into account the idiosyncrasies of every other location used to derive the bias factor.

The situation is worsened by the frequent absence of diffusion tube data for the areas proposed for developments. To give an example, the 4000 home Mountfield development proposed for Canterbury covers 565 acres on the outskirts of the town: an area not currently monitored by the local authority. This means that the data available is not only inherently uncertain, but also not location relevant to the area being modeled.

The problem outlined here stems from the use of an inaccurate technology: diffusion tubes, applied to a decision making process that treats the outputs as if they were accurate: uncertainty in, gospel out. In the absence of being able to properly account, and correct, for the

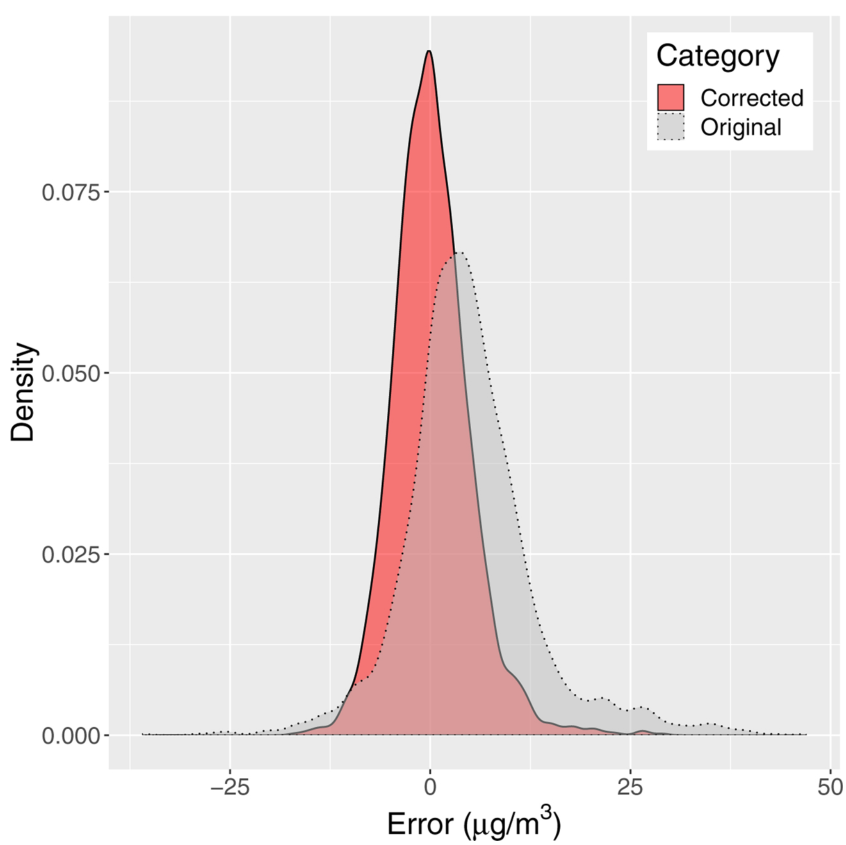

Fig. 2. Complete Defra bias adjustment spreadsheet dataset density plot, comparing error before and after bias adjustment according to the tool recommendations.

Table 3
Performance of Defra's bias adjustment tool relative to no bias correction.

	% of studies improved by tool	Mean improvement (μg/m^3)	% of studies worsened by tool	Mean degradation (μg/m^3)
2017	71.3	7.08	28.7	4.36
2011–2017	67.5	7.18	32.2	3.81

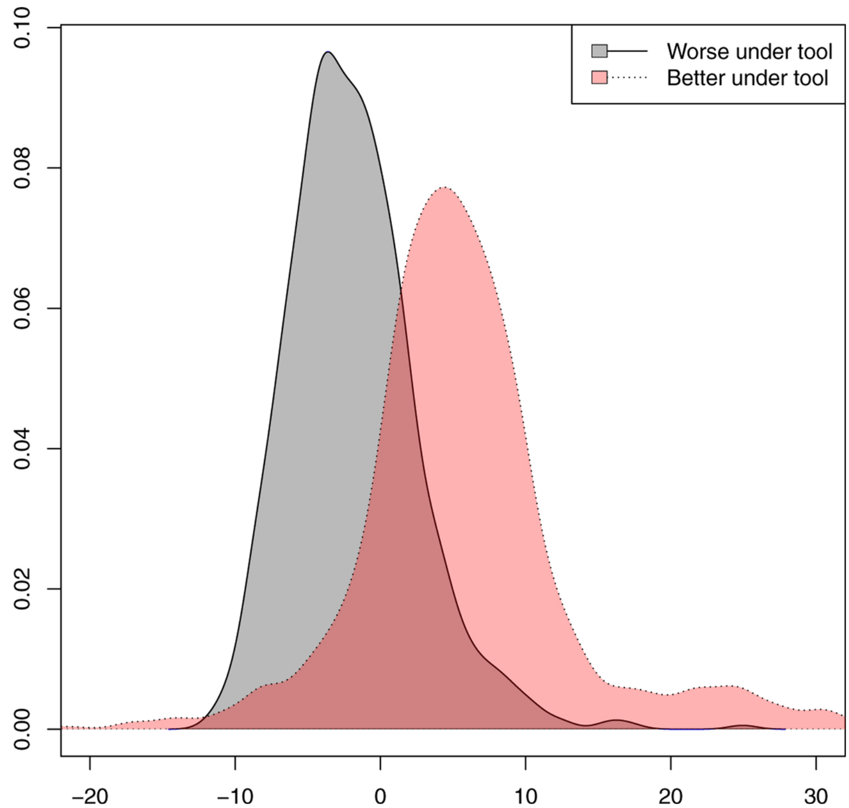

Fig. 3. Comparison of errors for the cases where the Defra bias adjustment tool improves accuracy relative to no bias adjustment, and those where it reduces accuracy.

difference between diffusion tubes and reference locations, a task that is probably impossible due to their inherent uncertainty, the only solution is to use a more accurate technology.

3. Amplifying errors – using uncertain data with permissive modeling

An air quality impact assessment from a planning applicant will contain predictions of key pollutants at representative "receptors" within and around the proposed development based on estimates (or measurements in rare cases) of current levels. Predicted outcomes depend heavily on assumptions made about current pollutant and traffic levels, and predictions based on unsound assumptions are likely to be wrong.

The last section looked at the inherent flaws in the use of NO_2 diffusion tube data and the bias-adjustment methodology recommended by Defra (AEA Technology Plc, 2008). We saw that NO_2 diffusion tubes have large inherent uncertainties. The bias correction spreadsheet (Department for Environment Food & Rural Affairs, 2018b) degrades accuracy in 30% of cases relative to doing nothing, and in 30% of cases by more than 10% relative to the locally derived bias adjustment factor. We have seen then that whilst the intent of the Defra bias adjustment methodology is to improve accuracy, in a not-insignificant percentage of cases, it actually reduces accuracy.

This section explains how NO_2 diffusion tube data (and sometimes other data) is used as a basis for modeling, and how the general technical guidance (Department for Environment Food & Rural Affairs, 2018a) allows for weakened modeling which may lead to the amplification of input uncertainties.

First we outline the air quality modelling approach recommended by Defra (Department for Environment Food & Rural Affairs, 2018a), and which is adopted by most planning applicants. This is to give context for the illustration which follows of how the guidelines allow errors to be amplified.

3.1. An overview of the air quality modeling process

Air quality modeling is necessary for two reasons:

1 To estimate the value of a given pollutant at locations where it is not measured.
2 To estimate the value of a given pollutant for a time period (usually the post-development future) other than the current time.

It is easier to understand these as two separate activities although they are often combined into one process. Estimating the value of a given pollutant at a location where it is not measured is performed as follows:

1 Current values of the pollutant are measured at (preferably multiple), known roadside locations, or historic measurements at known locations are obtained.

2 Traffic flows are apportioned to the road network within the modelled area according to measured traffic counts and then extrapolated to roads for which counts are unavailable according to models of expected vehicle behaviour based on observed route probabilities.
3 A vehicular Emissions Factors Toolkit provided by Defra (Department for Environment Food & Rural Affairs, 2019a) is used to predict pollutant values from the expected traffic flows and observed fleet composition. This gives a model of pollution based on roads (line sources).
4 Dispersal software is used to predict how pollution generated by the line sources computed in the last step, spreads out to the surrounding area. Typically this is done to give values for a number of specific locations known as "receptors".
5 The model is calibrated by comparing its predictions against reference locations where the pollutant values are actually measured, to derive a linear scaling factor that minimises any discrepancy.
6 The scaling factor is applied to all predictions given in step 4 to give a final prediction for each receptor site.

To estimate future pollutant values from current measured and modelled values:

1 Background values for the given pollutant are obtained using values provided by Defra (Department for Environment, 2019).
2 The difference between the background and measured/predicted roadside levels as computed in the above process is taken to be the traffic contribution.
3 Traffic growth estimates are obtained from local authority predictions or the Department for transport (Department for Transport, 2018).
4 The traffic contribution calculated in step 2 is scaled according to the obtained growth estimate.
5 The estimated future background level is obtained from Defra (Department for Environment, 2019).
6 The predicted future traffic contribution is added to the estimated background level to give the predicted future total pollutant concentration.

3.2. How the guidance permits amplification of input errors

As explained above, road dispersal software is used to predict the value of a pollutant based on emission from a series of line sources (to represent roads) (Snyder et al., 2013). Evaluation of commonly used road dispersal software has shown that they can both under and over predict pollutant values (Patterson and Harley, 2019; Dėdelė and Miškinyė, 2015). To correct for this a linear model is regressed, that is a coefficient is determined for a line such that it minimises the distance between modeled and actual pollution, for a number of known data points.

Box 7.14 of Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) states that:

"In order to provide more confidence in the model predictions and the decisions based on these, the majority of results should be within 25% of the monitored concentrations, ideally within 10%"

Since this guidance makes no strong requirements, in the worst case all of the points that underestimate the pollutant could be at −24.9% relative to the actual value and all of the points that overestimate the pollutant could be at +24.9% relative to the actual value.

From the perspective of establishing AQMAs the presence of receptors within 10% of the national AQS limits would motivate an argument for extension of an AQMA. So in the worst case, there will be actual underestimates of up to 25% that would fall by a significant margin of any consideration for creation of an AQMA, yet if their actual values were observed, they would exceed the AQS limits.

In addition to a permissive attitude toward large modeling uncertainties, the general technical guidance offers weak protection against poor calibration. The general technical guidance states in Section 7.562 that NO_2 predictions should be validated using regression against continuous monitoring sites, and in there absence, diffusion tube results. This guidance states that it "*is considered better to have multiple sites at which to verify results rather than just one*" but without strong requirements, this is in practice ignored. For example, air quality modeling for a planning application in Borden Village, Kent (Entran Limited, 2019) used only two diffusion tube sites to verify its model. The planning application was approved.

The lack of a strong requirement for validation opens the door for planning applicants to pick the comparison points to create an overall picture favourable to themselves, either wilfully or through ignorance.

Dispersal modelling also requires accurate wind speed and direction (Snyder et al., 2013). Section 7.476 of Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) says of meteorological data: "*It is particularly important that the data are representative of the area under study.*" Since this is guidance and not a legal or statutory framework, it is possible for data to be used that is not representative, for example in the planning case previously mentioned, a wind rose from 2 years prior to the application date and 45 miles away from the site was used. This showed a different prevailing wind direction and rose shape than that of locally available weather data from Borden grammar school.

We have seen that the technical guidance not only permits the use of highly uncertain data, but allows it to be used carelessly due to a lack of strong requirements, as demonstrated with reference to a specific planning application. In the next section we will look at how these data are examined to arrive at decisions.

4. Unhealthy decision making – the gulf between regulatory limits and health risks

The annual regulatory limits for NO_2, PM10, and PM2.5 in the UK (and EU) are 40 μg/m^3, 40 μg/m^3, and 25 μg/m^3 respectively (Department for Environment Food & Rural Affairs, 2019b). The World Health Organisation reviewed the health risks associated with key pollutants in 2005 (World Health Organisation, 2005) and, adopted 40 μg/m^3 as a guideline for NO_2, the same as the UK limit, but adopted 10 μg/m^3 for PM2.5 and 20 μg/m^3 for PM10, that is half the respective UK limits for particulates.

Since 2005 the research picture has changed significantly, and a 2016 comprehensive review by the Royal College of Physicians concluded that *"Neither the concentration limits set by government, nor the World Health Organisation's air quality guidelines, define levels of exposure that are entirely safe for the whole population."* (Royal College of Physicians, 2016).

Fundamentally, the air quality regulatory framework in the UK does not protect population health. There are an estimated 40,000 annual deaths attributed to air pollution in the UK (Royal College of Physicians, 2016) under the current regulatory regime, and despite repeated calls for action by medical authorities (Iacobucci, 2016; Lancet, 2016), there is no scheduled adjustment to the limit values.

The significance of this with respect to planning is that anything under these thresholds is considered "safe" and not cause for concern, this is reflected in comments made by planning applicants, using Entran Limited (2019) as an example:

"NO_2 and PM10 concentrations are predicted to be below the relevant objective limits across the Site, therefore the impact with regards to new exposure would be low."

The planning inspector's final report (Swale Borough Council, 2019) for Entran Limited (2019) echoes these sentiments, making reference to PM10 averages of 17.2 μg/m^3:

"The values are so low as to make them not significant compared with the guideline value of 40 μg/m^3."

Despite not being significant to the local authority, calculating

PM10 mortality using WHO's AirQ+ tool (World Health Organisation, 2019) indicates that an extra 1 or 2 deaths per year are attributable to air pollution at current levels in Borden village parish where the application was approved. Public Health England's 2014 particulate mortality report (Public Health England, 2014) calculates 68 deaths attributable to PM2.5 for Swale (the enclosing local authority), which proportionately for Borden village is 1 death.

This disregard for sub-limit levels of pollution is codified in planning guidance adopted by many local authorities in Kent (Air Quality Planning Guidance (Mitigation Option A), 2015) where the screening criteria essentially exclude non-major developments and developments that fall outside of existing AQMAs from requiring detailed impact assessment.

5. Discussion

We have shown in Section 2 that inputs to air quality impact assessments are often derived from NO_2 diffusion tubes which have large uncertainties and we saw that the recommended means of "correcting" uncertainty, increases uncertainty in about 30% of cases even relative to no-bias correction. Section 3 showed that modeling using these inputs follows a methodology that allows for the amplification of this uncertainty, and finally in Section 4 we saw that the resultant output is judged against criteria which are divorced from the known public health risks. In this section we discuss the implications of these problems an outline an approach to solving them.

5.1. Sub-optimal outcomes

The identified flaws arise out of a natural conflict between methodologies which are designed to average out uncertainties over space and time, and their application to problems which assume that point predictions are both timely and location specific.

When a planning application is considered, the predicted pollutant values at receptor points with exact locations and at exact times matter. It is not acceptable to employ methodologies that are based in large uncertainties and then apply the outputs so deterministically.

The findings here also have implications for air quality management: AQMAs must be setup wherever annual exceedances of limit values are observed. A new location may be measured for NO_2, for example, for one year and after correction with a bias factor, the local authority may conclude that conditions are satisfactory and discontinue monitoring. But we have seen that it is to some extent a matter of luck whether the bias factor used will accurately represent the appropriate correction for this location: a potential injustice to the local community.

Whilst we focused on NO_2 diffusion tubes as a source of uncertainty, there are other examples we could have used: Section 7.68 of Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) recommends using Defra background maps (Department for Environment, 2019) at a resolution of 1 km × 1 km for model calibration in the absence of local measurements. In Khreis et al. (2018) the impact of using 0.1 km × 0.1 km maps to calibrate air quality models was compared with co-location calibration and results were found to differ by about 30%.

The use of background map data is very common for PM10 and PM2.5 since they are usually only monitored at continuous sites, which a local authority might have one or two of, if at all: the nearest PM2.5 monitoring station to Canterbury for example is 45 miles away and one of only two AURN sites measuring PM2.5 in the whole of Kent and Medway. Section 2.65 of Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) makes a specific point of providing a list of alternative sources for PM2.5 in the absence of local data, highlighting the problem of a lack of accurate and relevant data.

The current situation then is one where in the worst cases decisions may be informed by data that has a high degree of uncertainty, which may have been transformed in ways that increase uncertainty. But as long as the processes followed are compliant with the Defra guidance documents (Department for Environment Food & Rural Affairs, 2018a; AEA Technology Plc, 2008), the outputs can be treated as accurate representations of reality without further scrutiny.

This is encoded in Chapter 3 of the Defra technical guidance (Department for Environment Food & Rural Affairs, 2018a) which outlines exactly how Annual Status Reports should be prepared by local authorities, which in-turn contributes to the Air Quality Action Plan framework, which is a direct consideration for planning decisions according to the NPPF.

The Environment Act 1995 (Environment Act, 1995) gives power to the secretary of state to force a review of an action plan or action if it is judged *"that the actions, or proposed actions, of a local authority in purported compliance with the provisions of this Part are inappropriate in all the circumstances of the case"* (Section 85, 3(c)).

A Freedom of Information request addressed to Defra asking for the instances when this power has been exercised (Department for Environment, Food & Rural Affairs, 2019a) reveals that the secretary of state has never pro-actively intervened: the short list of actions (Department for Environment, Food and Rural Affairs, 2017) are issued toward large local authorities as delegated responsibility for legal judgements issued against the UK government as a result of successive actions by Client Earth (The High Court of Justice, 2018). A further request asking to whom a local authority is held responsible to for AQAPs (Department for Environment, Food and Rural Affairs, 2018) elicited the response *"Local authorities are responsible for developing action plans and are accountable to their electorate rather than to central Government."*.

At every level of air quality management therefore: from the precision of monitoring tools, the interpretation of data by local authorities, through to the lack of accountability and oversight by central government, there is need for improvement. We now provide some suggestions on how to move forward. In the next sections we visit the three categories discussed above in reverse order, starting with the pollutant regulatory framework which underpins the entire system.

5.2. Health-centred impact assessment and mitigation

Planning and other local authority decisions are currently being made based on comparison to limit values first enacted into law (Directive 2008/50/EC, 2008) in 2008. The limit for NO_2 is defined as an annual average of 40 $\mu g/m^3$ but Public Health England, in a 2018 review of the long-term health effects of NO_2 states that long-term mortality associations have been found in *"cohorts in which the range of outdoor levels reaches as low as 5 $\mu g/m^3$ annual average NO_2 concentration."* The author committee was divided on whether to extrapolate mortality coefficients to zero but the report provides mortality coefficients defined per 10 $\mu g/m^3$. In addition, the authors estimate that by reducing mean NO_2 by 1 $\mu g/m^3$ that *"1.6 million life years could be saved in the UK over the next 106 years, associated with an increase in life expectancy of around 8 days."*

Similarly for PM2.5 and PM10, the limits are defined as annual values of 25 $\mu g/m^3$ and 40 $\mu g/m^3$ respectively, whereas the World Health Organisation's 2005 air quality exposure guidelines (World Health Organisation, 2005) despite acknowledging that *"there is little evidence to suggest a threshold below which no adverse health effects would be anticipated"* arrives at guidelines of 10 $\mu g/m^3$ and 20 $\mu g/m^3$ annual averages for PM2.5 and PM10 respectively. This is challenged by a recent Royal College of Physicians review (Royal College of Physicians, 2016) which concludes that *"Neither the concentration limits set by government, nor the World Health Organisation's air quality guidelines, define levels of exposure that are entirely safe for the whole population"*.

In its 2019 Clean Air Strategy (Department for Environment Food & Rural Affairs, 2019c) the UK government states that it will *"reduce PM2.5 concentrations across the UK, so that the number of people living in* *locations above the WHO guideline level of 10 μg/m^3 is reduced by 50% by 2025.".* Whilst this commitment is positive, the current draft of the UK governments environment bill (Department for Environment Food & Rural, 2018) does not include any corresponding regulatory change for PM2.5, and so at the present time planning decisions are still being decided against the current regulatory limits.

The lives of residents are directly impacted by local authority decisions, but decisions are being made using air quality thresholds which exceed the levels at which harms to health are acknowledged. This permits neglect of areas that fall short of these thresholds despite their potentially having a high health burden.

Besides the obvious health implications, local authorities are awarded Section 106 monies (Town and Country Planning Act, 1990) as mitigation for air quality impacts and Defra provides damage cost guidance (Department for Environment Food & Rural Affairs, 2019d) which provides material cost estimates for each ton of NOx and PM2.5 that a development will contribute. These costs are calculated based on the estimated traffic and boiler emissions from the development. There is no requirement to demonstrate that the mitigation monies be spent on actions that will actually offset the extra pollution. We argue that mitigations should be targeted toward actions that can be shown to have an impact.

In general it is necessary to move towards limit values that reflect health risks. This would undoubtedly mean that more areas would fall under AQMAs, but in many present municipalities AQMAs have existed for years without action that leads to revocation: a total of 900 AQMAs have been declared, 220 of which have been revoked (Department for Environment, Food & Rural Affairs, 2019b). Of the remaining 680 active AQMAs, the mean duration (as of 22/05/2019) is 11.6 years, the minimum 140 days, and the maximum over 20 years. Only 143 of these have ever been amended, with those having never been amended having a mean duration of 11.7 years. We therefore recommend a systematic government review into the effectiveness of AQMAs as a mechanism to achieve timely reductions in key pollutants.

We recommend adopting appropriate health based thresholds combined appropriately spaced stepped targets to reduce pollution to WHO guideline levels by 2025 and to zero by 2035.

Further research needs to be carried out to understand the relationship between short term exposure, cumulative exposure and health outcomes since annual averages are not necessarily representative of actual pedestrian exposure profiles: for example a study that measured black carbon exposure for children walking to school (Alvarez-Pedrerol et al., 2017) found that children obtained 20% of their black carbon daily dose (according to U.S EPA regulations) over a time period that accounted for only 6% of the day.

Air quality relevant activities such as planning decisions can also occur on shorter timescales than a single year so it would be useful to be able to characterise the health risk of a location without having to monitor for a year.

5.3. Modeling regulations rather than guidance

We saw in Section 3 that Defra's general technical guidance (Department for Environment Food & Rural Affairs, 2018a) permits amplification of input errors by permissive bounds on model accuracy. This is a combination of permitting a large margin for error, and allowing a small number of reference points for calibration. We would recommend that:

1. Model predictions must be within 10% of all reference points.
2. Calibration of the model against at least 6 reference points.

At present the guidance can be interpreted to suit the follower, and without the teeth of a legislative framework, there is little or no comeback for residents and even authorities. Defra should work towards creating a legislative instrument in place of the current guidance document which all local authorities and planners must adhere to.

There is currently too much reliance on out-of-area measurements or background maps to predict development impacts. Regulation should see the introduction of stricter controls on data immediacy, and should require measurement for major developments.

This would allow for a consistent appraisal of planning applications and AQMA assessment that is just across the board.

5.4. Data that is accurate at the point of collection

Most local authorities operate a small number of reference equipment stations, where chemiluminescent analysis is applied to measure NO_2 and either gravimetric, beta-emission based, or optical methods are used to measure particulates (Department for Environment, Food & Rural Affairs, 2019c). Local authorities are encouraged to use equipment that is MCERTS certified (CSA Group, 2019) for accuracy and Defra's AURN network uses only MCERTS certified equipment. This type of equipment is however too expensive for wide applicability, and is physically impractical often requiring its own cabinet housing and power supply. These sites are static and cumbersome to re-locate.

This has led to the proliferation of NO_2 diffusion tube use by local authorities, which are cheap, easy to use, and easy to re-locate. They have become the defacto standard for air quality management and calibration of air quality impact assessment models.

But as we have seen, diffusion tubes suffer from inherent uncertainty that is not effectively addressed by present diffusion tube guidance (AEA Technology Plc, 2008) or correction with Defra's diffusion tube bias spreadsheet (Department for Environment Food & Rural Affairs, 2018b). It is also the case that diffusion tubes are not capable of measuring short-term changes, exposure profiles and peak levels, or the dynamic bearing that traffic management or other mitigation might have on pollution.

It seems unlikely that improvements in diffusion tube methodology can rectify their inherent uncertainty. Correction for meteorological and location effects would likely require in-situ measurement of the relevant variables using electronic equipment, which casts doubt on their ongoing viability as a standalone technology pathway.

Diffusion tubes only monitor NO_2 and there is no equivalent technology for particulates: the latter only being monitored at reference sites: an enormous data deficit.

Recently the market has seen the introduction of so-called near-reference equipments (Environmental Instruments Ltd, 2019; Earthsense Ltd, 2019; Envirowatch Ltd, 2019; Vaisala Ltd, 2019), which aspire to bridge the gap between indicative equipment such as diffusion tubes, and reference equipment such as a chemiluminescent analysers. Whilst considerably more expensive than diffusion tubes, they are priced at around 15–20% the cost of reference equipment but like diffusion tubes they are pole-mountable, portable, and easy to use.

Most near-reference equipment combines electrochemical gas sensors with optical particle counting for particulates. Co-location studies show promising accuracy for both low cost NO_2 (Cross et al., 2017; Bigi et al., 2018) and PM sensors (Narayanan et al., 2012; Steinle et al., 2015; Holstius et al., 2014; Crilley et al., 2018). Because the sensors are electronic and have temporal resolutions on the order of minutes rather than months, it is possible to take account and attempt to correct for meteorological variables and pollution concentrations. Such equipment is particularly good for comparative analysis as the intra-variability is very low.

Defra has issued guidance on the use of low cost sensors (Department for Environment, Food & Rural Affairs, 2019d) and points out that there is a wide variability of quality in low-cost sensors, cautions users to understand the accuracy and stability of equipment in the context of each use case and it advocates for in-situ calibration and regular re-calibration. With all the caveats aside the guidance speculates that *"as the technology evolves applications will arise where they do bring new insight to air pollution issues."*

The World Meteorological Organisation has issued a more detailed appraisal (World Meteorological Organisation, 2018) of low cost sensors, again highlighting the wide variability in technology and the lack of ongoing calibration in most cases. They summarise their applicability: *"low-cost sensors are not currently a direct substitute for reference instruments, especially for mandatory purposes; they are however a complementary source of information on air quality, provided an appropriate sensor is used."*

Local authorities, with caution, should therefore begin to replace the ubiquity of indicative diffusion tubes with appropriately sourced electronic near-reference equipment, which over time will become increasingly accurate as the technology is more widely adopted and improved upon. This will lead to decisions being based on local pollution measurements with known error bounds.

6. Conclusion

We have shown, with reference to specific examples that the current methodologies employed for air quality assessment in the planning and air quality management arenas, allow for unsound data to receive a stamp of approval despite flaws that would allow for amplification of uncertainty, providing an unsound basis for decision making. We have explained how this problem can be addressed by taking into consideration the whole picture when it comes to health instead of just regulatory compliance, by adopting legislative instruments instead of guidance, and by improving equipment accuracy.

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