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Sustainable management of urban pollution: an integrated approach

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This paper presents a new decision-support framework and software platform for an integrated assessment of options for sustainable management of urban pollution. The framework involves three steps: (1) mapping the flow of pollutants associated with human activities in the urban environment; (2) modelling the fate and transport of pollutants; and (3) quantifying the environmental, health and socio-economic impacts of urban pollution. It comprises a suite of different models and tools to support sustainability appraisals including life cycle assessment, substance flow analysis, source and pollutants characterisation, pollutant fate and transport modelling, health impact analysis, ecological impact assessment, and multi-criteria decision analysis. The framework can be used at different levels, from simple screening studies to more detailed assessments. The paper describes the decision-support framework and outlines several case studies to demonstrate its application. The software tool is available free of charge at www.pureframework.org.

Practical applications: The PUrE framework and software platform can be applied to assess and compare the sustainability of different technologies, products, human activities or policies. Example applications of the framework have so far included sustainability comparisons of technologies for thermal treatment of municipal solid waste; generation of electricity from coal and biomass; environmental and health impacts of a mixture of pollutants in Sheffield; the role of urban green space in reducing the levels of particulate matter in London and the impacts of environmental policy on legacy pollution in Avenmouth.

1 Introduction

Urban living provides significant benefits to society, including employment, education and access to services. Consequently, urban areas are gaining an estimated 67 million people each year. By 2030 about 5 billion people, or 60% of the world population, may be living in urban areas.[1] Growth may be even faster – in

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2008, 50% of the world's population lived in cities.[2] Such rapid urbanisation leads to the growth of road transport, housing needs and a rise in household consumption, creating various pollution problems (poor air quality, water waste and solid waste), placing severe pressures on the environment, human health and the quality of urban life.

A number of different approaches and methodologies exist for addressing urban pollution problems, including Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA) and Health Impact Assessment. A range of different models and tools are used either within these methodologies or as stand-alone tools; examples include estimation of emission inventories, air dispersion modelling, and health impact modelling. Whilst these approaches and tools are invaluable they often focus on a single environmental medium, and/or a single or limited number of issues (e.g. particulate emissions to air; nitrates in water; noise) and are typically used in isolation. Arguably, sustainable management of urban (or any other) pollution requires a more integrated approach, bringing together within a single decision-support framework different approaches to enable consideration of multiple pollution issues.[3] Such a framework would take a systems approach to addressing both the urban and wider environment that supports life in cities through the provision of eco-system services.[4] It would also need to consider the huge variety of pollutant sources in the urban environment; the wide range of urban pollutants and their interactions with each other across the three environmental media (air, water and soil); and various impacts of pollution on human health and the environment. Developing a framework capable of meeting these various demands would represent a significant improvement on existing media-specific or issue-specific approaches to urban environmental management.

In an attempt to contribute towards a more integrated sustainable management of urban pollution, this paper presents a new decision-support framework and software platform developed by the UK consortium *Pollutants in the Urban Environment*.[5] The next section outlines the framework, followed by an overview of the models and tools integrated within the PUrE software. The paper then presents several case studies to demonstrate the application of the framework and the software tool.

2 The conceptual approach and decision-support framework

The conceptual approach of the PUrE (Pollutants in the Urban Environment) framework involves three main steps:

- mapping the flows of pollutants associated with human activities in the urban environment;
- modelling the fate and transport of pollutants; and
- identifying and quantifying the environmental, health and socio-economic impacts of urban pollution.

Figure 1 shows the three steps represented by three interlinked spheres set in the urban environment and within the three sustainability dimensions (economic, environmental and social). The decision-support framework developed using this conceptual approach is illustrated in Figure 2; Figure 1 also shows the link between the conceptual approach and the decision-support framework.

Based on the approach developed by Azapagic and Perdan,[6,7] the framework involves three stages (Figure 2):

- problem structuring (steps 1–3);
- problem analysis (steps 4–9); and
- problem resolution (step 10).

The application of the framework starts with consideration of stakeholders' needs, their main drivers for the assessment and the

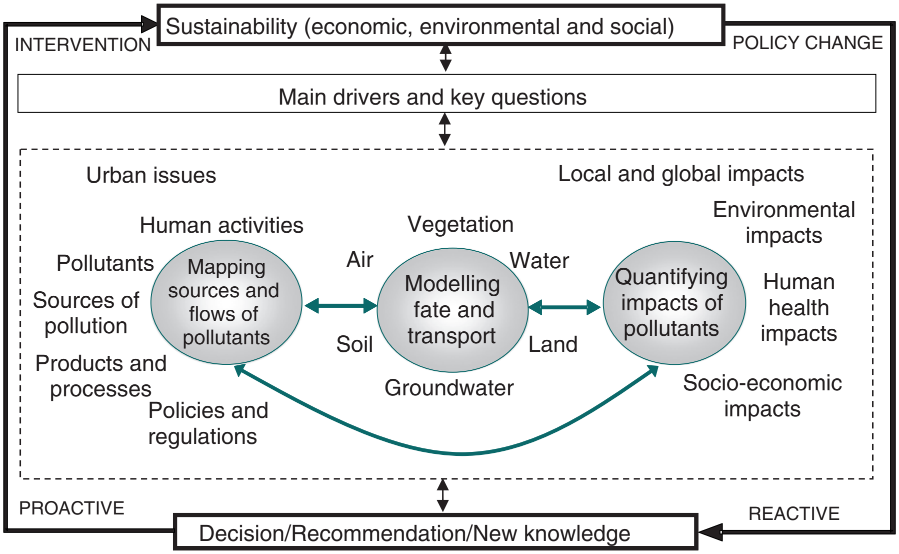

Figure 1 Conceptual basis for the PUrE framework methodology[3]

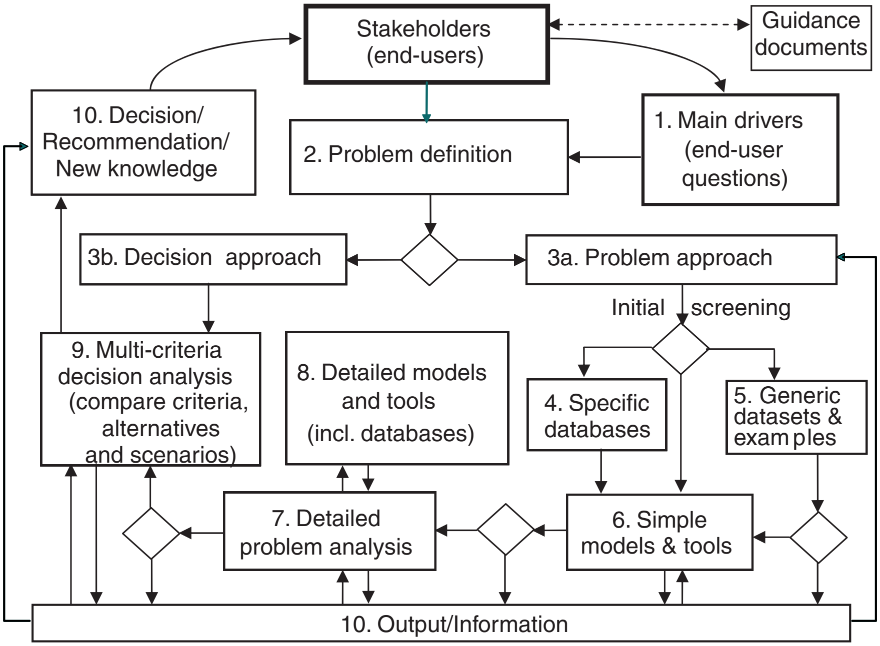

Figure 2 The PUrE decision-support framework.[3] Note: Steps 1–3, problem structuring; 4–9, problem analysis; and 10, problem resolution

Table 1 Steps in the problem definition stage and examples of sustainability issues (decision criteria) that can be considered within the framework

Problem definition	Examples of sustainability issues (decision criteria)		
	Environmental	Economic	Social
System for analysis/options/scenarios Unit of analysis System boundary (e.g. from 'cradle to grave') Time scale (e.g. hours to 100 years) Spatial scale (e.g. urban area, wider environment)	Emissions to air Emissions to water Solid waste Resource depletion Global warming Acidification Eutrophication Summer smog Winter smog Eco-toxicity	Capital costs Operating costs Profit Pollution prevention costs Pollution treatment costs Value added	Health impacts Safety Employment Nuisance (e.g. noise, visual) Local communities

key questions they wish to address through a framework application. This is followed by the problem definition step which involves specifying the scenarios and options to be examined, system boundaries, and the temporal and spatial scales for the assessment (Table 1). The user also identifies the sustainability issues of interest which will be used as the decision criteria in the assessment. Some examples of sustainability issues that can be considered within the framework are shown in Table 1.

After completing the problem definition step, the user can then choose between two approaches to applying the framework (Figure 2):

(1) the problem-oriented approach which enables both simple and detailed problem analysis; this is then followed by Multi-Criteria Decision Analysis (MCDA) to help reach a decision or simply to understand the problem better *or*
(2) the decision-oriented approach which uses the data and results obtained from previous applications or other assessments to compare the sustainability of different options using MCDA.

The PUrE decision-support framework is accompanied by a software modelling platform. The platform integrates a number of tools as well as the relevant databases. It also has an in-built GIS module enabling the user to map spatially sources of emissions, fate of pollutants and location of receptors.

3 Models and tools within the PUrE decision-support framework

The problem analysis stage (Figure 2) includes the selection and application of different models and tools. Following the PUrE conceptual approach outlined in Figure 1, the tools can be grouped as follows:

(1) Mapping the sources and flows of pollutants:
    - Life-Cycle Assessment (LCA; inventory of emissions to air, water and land);
    - Substance Flow Analysis (SFA);
    - characterisation of sources and emissions.
(2) Modelling fate and transport of pollutants:
    - simple models;
    - detailed models.
(3) Quantifying impacts:
    - LCA (environmental impacts);
    - Health Impact Analysis (HIA);
    - Ecological Impact Assessment (EIA).

In addition to these, MCDA is used to help prioritise decision criteria and structure decision-making process. The following section

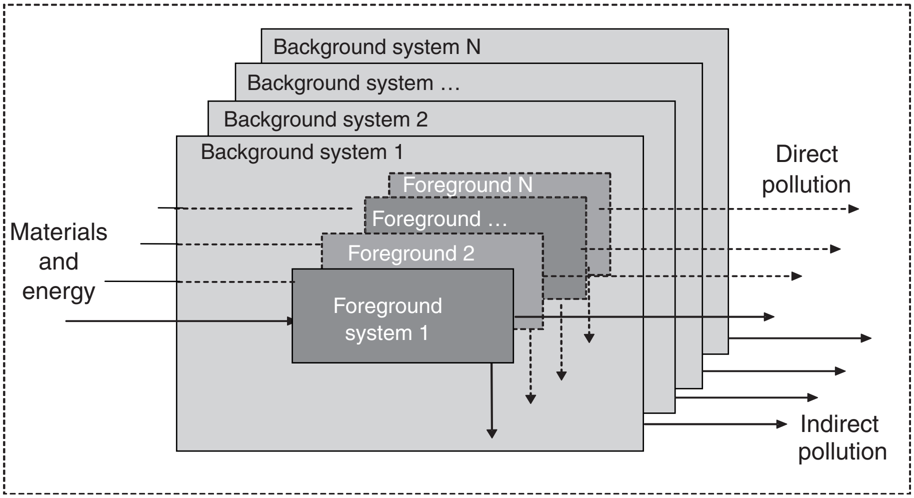

Figure 3 The LCA approach to mapping sources of pollution[4]

gives an overview of the tools and methodologies available within the framework and software platform.

3.1 Life cycle assessment and substance flow analysis

LCA is one of the key environmental management tools integrated within the PUrE decision-support framework. LCA represents an application of life cycle thinking to environmental systems analysis and enables quantification of environmental burdens and impacts in the life cycle of a product, process or human activity. The results of LCA modelling can be used to identify 'hot spots' in the system, to compare alternatives or to identify opportunities for environmental improvements. The LCA approach to defining an urban system comprising multiple sources of pollution is shown in Figure 3.[4] LCA modelling is used within the PUrE decision-support framework to quantify the environmental burdens (emissions to air, water and land) and the associated potential impacts of human activities within an urban system ('Foreground system') and in the wider environment ('Background system'). The burdens are calculated as part of the step *Mapping the sources and flows of pollutants* and the potential impacts are quantified within the *Quantifying impacts* stage (Figure 1).

Within the framework, LCA is linked with SFA to facilitate mapping of the flows of pollutants in the urban environment on a life cycle basis (as part of the step *Mapping the sources and flows of pollutants*). As neither LCA nor SFA is well suited for a direct use within the PUrE framework, a modified methodology to link the two tools has been developed.[4] Both LCA and SFA can be used as stand-alone tools or in conjunction with other tools within the framework and the platform. One of the advantages of the PUrE LCA module is that it has been developed for non-LCA specialists so that it is simple to use. An extensive LCA database is also included within the platform.

3.2 Characterisation of sources and pollutants

Characterisation of sources involves understanding the sources of pollution in terms of their size, operation and associated emissions of pollutants. An extensive database integrated within the PUrE platform supports

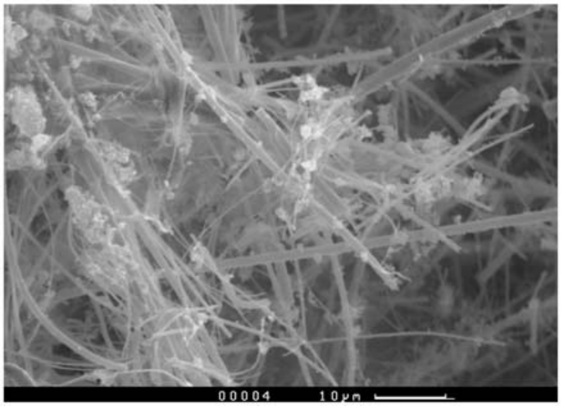

Figure 4 Characterising pollution sources: the shape of particles can indicate its source. Note: An example of $PM_{2.5}$ shown; image obtained using SEM; scale 10 µm

characterisation of a range of sources, including industrial, energy generation and transport.

With regard to pollutants, the PUrE framework supports characterisation of both single pollutants and mixture of pollutants. The latter is particularly important due to the synergistic effects of mixtures of pollutants on health and the environment, which have not been studied extensively so far. The example of Particulate Matter (PM) is a point in case – PM can act as a ‘repository’ for a range of pollutants which can combine and react on the surface of the particle and result in very different mixtures of pollutants, even if emitted from the same source. Figure 4 shows the characterisation results obtained for very small ($PM_{2.5}$) particles, obtained using Scanning Electron Microscopy (SEM). The image shows filter fibres ‘decorated’ with very fine particles. The results of the characterisation analyses in the urban environment show that the PM samples have significantly different compositions depending on where they have been sourced from (see Section 4.2 for further detail).

Thus, characterisation of pollutants is useful in determining the size, distribution and composition of PM as well as other pollutants commonly found in the urban environment. Combined with pollutant fate and transport modelling, this can then help determine the likely health and ecological effects in the urban environment.

3.3 Modelling pollutant fate and transport

Once the emissions from different sources have been identified and characterised using LCA, SFA and/or various characterisation techniques (computational or experimental), fate and transport modelling can be used within the PUrE framework to find out where and how far the pollutants will travel before reaching the receptors of interest. Depending on the type of problem, the necessary complexity of the fate and transport models will vary. For initial problem assessment, a number of simple screening-type models are available to the user of the framework. For example, for consideration of contaminant movement in groundwater, analytical solutions are available for simple advection–diffusion problems whilst for air-pollutant dispersion problems, simple Gaussian models can be employed.

For more complex analysis, detailed fate and transport models are required. For example, complex multi-dimensional chemical transport and geo-chemical interactions can be considered using finite element models such as COMPASS;[8] complex air dispersion problems can be addressed by models such as AERMOD.[9] It may be necessary to consider problems where pollutants are mobile in more than one environmental medium. A typical or generic scenario for modelling the fate and transport of pollutants is shown in Figure 5. In such cases it is necessary to consider the interactions between the media, for example deposition of airborne particulates to the ground or a surface water body. This can be achieved using a multi-media model, or by linking several models together.

Two of the case studies available within the PUrE framework and software platform (Section 4) have focused on the fate and transport of airborne pollutants. This has required the undertaking of detailed air

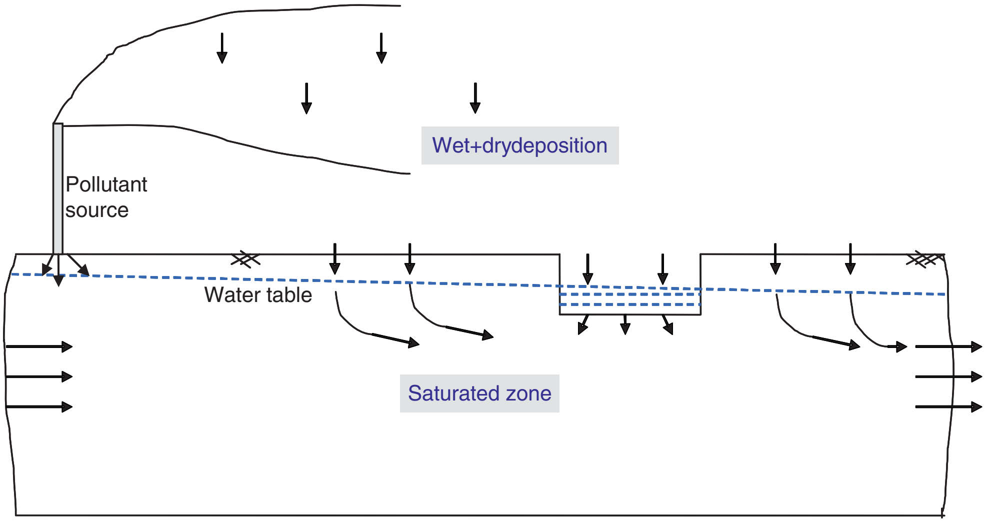

Figure 5 A typical multi-media pollutant fate and transport problem

dispersion modelling of a range of pollutant sources (e.g. road and rail transport emissions, incinerator stack emissions, etc.) and a number of different pollutants (e.g. PM_{10}, SO_2, NOx). The results of the modelling provided an insight into which technological options would have the lowest impact on human health and the environment and where they should be located to minimise the impact.

3.4 Health impacts analysis

HIA is also an integral part of the PUrE framework and the software platform and it can be performed following the fate and transport modelling stage (Figure 1). However, it is possible to carry out HIA independently of the fate and transport modelling, as long as the data on the concentrations of pollutants in the environment are available.

The human health models are divided into three sub-models: population exposure, exposure-response, and population health. The population-exposure model maps changes in the spatio-temporal distribution of pollutants to the affected urban population.[10] These changes could be due to the presence of a new point or diffuse source of pollution, the introduction of an intervention which may impact on environmental health or the implementation of an environmental remediation intervention.

The exposure-response model estimates the changes in relative risks in the relevant end-disease states (e.g. cancers) due to this exposure. Exposure-response models are disease-specific and cover a wide spectrum of relationships from linear to non-linear.[11] The population health model determines the excess number of disease-specific deaths using life-table methods.[12] For multiple exposure pathways, different methods for aggregating the health impacts are used and compared.[13]

Because of their complexity and lack of epidemiological evidence on some of the causal pathways linking pollutants to health, it is imperative that the modelling framework takes into account the inherent uncertainty and variability in the health models.[14,15] Dealing with model uncertainty is a key aspect of the health modelling framework and methods for characterising and propagating the uncertainties in the various health sub-models have been developed and integrated into the framework.

3.5 Ecological impact assessment

EIA enables users to quantify the influence of pollutants in the urban environment on the health and function of terrestrial ecosystem. Similar to HIA, EIA can be carried out after the fate and transport modelling or as a stand-alone analysis.

EIA integrated within the PUrE framework and software platform can be carried out at three levels: generic, simple, and detailed. The full EIA process is shown in Figure 6. These levels are aligned with the Environment Agency Ecological Risk Assessment Framework for Contaminants in Soil.[16] The EIA uses a combination of:

- a database containing toxic concentrations from the literature (for the eco-toxicological tests as recommended by the Environment Agency[16]);
- modelling; and, where necessary
- eco-toxicological testing.

At the simple level the user is able to compare measured, 'typical' or predicted soil concentrations with Soil Screening Values (SSV) or equivalent, where available, or NOEC, LOEC, EC and LC values (No Observed Effect Concentration, Lowest Observed Effect

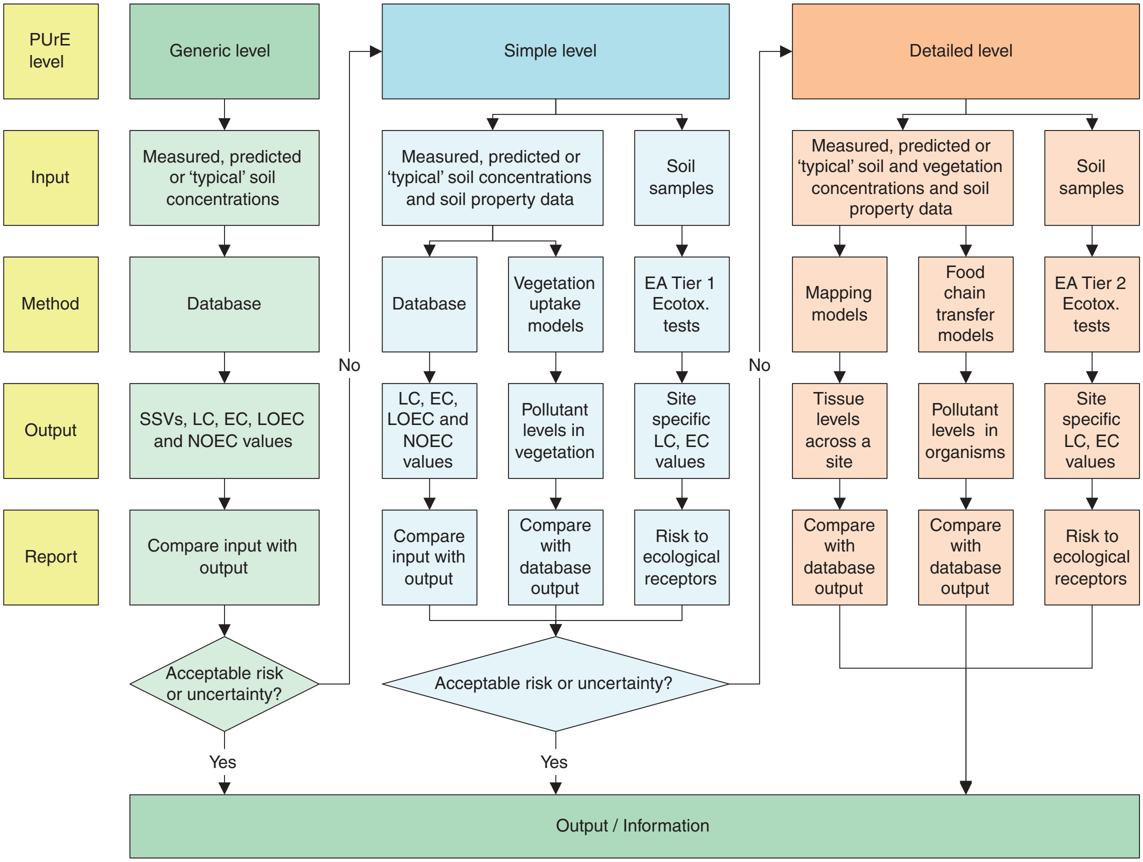

Figure 6 The EIA methodology

Concentration, Effect Concentration and Lethal Concentration, respectively) from the literature. For example, when assessing the risks of deposition of particulates from an industrial process the user can calculate the predicted pollutant soil concentrations at a green space after certain time periods. These values are then entered into the software platform to produce a table giving the SSV and ranges of toxic concentrations from the literature for each indicator species. Depending on the outcome and the objectives of the analysis, the user may then progress to the generic level using more detailed information on the derivation of the EC and LC values (e.g. soil properties, species, test conditions) and simple models to predict metal uptake by vegetation. If the level of uncertainty or risk is still unacceptable, the user may wish to carry out some eco-toxicological testing, as recommended by the Environment Agency.[16]

At the detailed level, the user is able to examine the potential for food-chain transfer of pollutants from a combination of models and, where necessary, eco-toxicological tests. This iterative framework means that the user can exit the process when the objectives of the assessment have been met (i.e. when enough information has been gathered). If uncertainties are unacceptable the user progresses to the next level(s) which require more data but yield a more certain risk assessment result.

In addition to an evaluation of the risks from pollutants, the users are also able to assess the potential for the mitigation of particulate pollution by vegetation. They can run models using simple meteorological data (e.g. wind speed) and planting information (e.g. species-specific leaf area index, tree height) to examine which planting design would result in optimised particulate interception. This enables particulate interception and air quality to be taken into account alongside those factors more commonly associated with urban green space design. Furthermore, the users can assess the particulate interception at different time periods, for different age classes of tree and between broadleaves and conifers or other species.[17]

3.6 Multi-criteria decision analysis

After completing the problem analysis stage during which some or all the above tools would have been used, the user can proceed to the problem resolution step (Figure 2). This step, which may lead to a decision based on the information obtained in the problem analysis stage, is supported by MCDA. Three MCDA methods are available within the PUrE software platform: simple ranking method, Analytic Hierarchy Process (AHP) and Compromise Programming (CP). Each can be used as a method of choice or alternatively two or all three methods can be used consecutively as part of a sensitivity and uncertainty analysis, to find out any influence of the MCDA method used on the decision outcome.[18]

4 Case studies within the PUrE framework

To illustrate its application, a range of examples, test beds and real case studies are available within the PUrE framework and software platform. Some of these are outlined below; note that the intention is not to give a full detail on the case studies but to illustrate the kind of issues and questions that can be explored within the PUrE framework and software platform.

4.1 Test beds

Two test beds have been developed to demonstrate a full integrated application of the PUrE decision-support framework. Both are hypothetical examples and are aimed at identifying a more sustainable technological option: Test bed 1 is related to thermal treatment of Municipal Solid Waste (MSW) and Test bed 2 to comparison of electricity generation from fossil fuels and biomass.

4.1.1 Test bed 1

In this test bed, two options are compared to identify which is more sustainable: one large-scale MSW incinerator or four smaller pyrolysis-gasification units situated at different locations in a city with a population of 500 000 people. Following the problem-oriented approach to problem analysis (Figure 2), the source characterisation and LCA are conducted at a generic screening level to characterise the sources and pollutants of interest; the estimated life cycle environmental impacts are used as an input in the *Quantification of impacts* step (Figure 1). A screening of typical emissions and releases to the environmental media (air and water) shows that the water pathway can be neglected. The next step is air dispersion modelling of emissions from the incinerator, the pyrolysis-gasification units and the trucks transporting MSW to the treatment facilities. This provides profiles of the predicted pollutant concentrations in the local area (arising from these activities). The associated health effects on the local community are then estimated using the HIA models. These results show that although it is possible to distinguish between the options, the relative health effects are found to be relatively low for both scenarios.

The background levels of the particulates in the city centre are relatively high; therefore a green intervention is proposed which involves planting more trees in the city parks to intercept the PM. This is investigated using an ecological model that considers the number and types of trees.[19] The sustainability of each option is then compared in terms of the predicted life cycle environmental impacts (e.g. global warming, acidification, eutrophication, summer smog, etc.); the estimated health effects on the local community; the potential economic costs associated with the construction and operation of the two types of MSW treatment facilities; and social aspects such as attitudes towards incineration and energy recovery, and impacts on recycling behaviour. The user can then use MCDA, with these sustainability issues defined as decision criteria. The user can observe the influence on the final outcome of their own preferences for different decision criteria, as part of the sensitivity analysis.

4.1.2 Test bed 2

This test bed looks at identifying more sustainable options for electricity generation and compares building a new biomass facility *versus* expanding an existing coal power plant. The assessment begins by looking at the differences in the technologies and the emissions datasets. An initial factor is the selection of the type and source of the biomass, in this case miscanthus from local farms and wood waste from local industries. Coal is supplied from overseas and transported by rail from the port; whilst the biomass is transported by road. LCA modelling of the two scenarios provides a range of environmental burdens and potential environmental impacts for both options.[20] The next step is air dispersion modelling which considers the emissions from the facilities as well as the transport emissions and provides predicted pollutant levels in the surrounding areas.

The health impact analysis looks at primary health impacts (e.g. pollution); secondary health impacts (e.g. traffic injuries); and summed health outcomes across the exposed populations. The predicted average levels of pollutants (PM_{10}, SO_2 and NOx) are found unlikely to cause adverse toxicological effects on the local ecology; therefore the EIA focuses on cumulative deposition of metal emissions to the soils at a green space located near the biomass energy plant.

All the findings from the assessment modelling (i.e. environmental impacts, health impacts, ecological effects) are then presented alongside the information on the economic costs and social issues. These can then be used in MCDA to identify a more sustainable option. This test bed in particular illustrates how the choice of the 'sustainable' option varies depending on the choice of decision criteria, the user preferences for these as well as the MCDA method used.[19,20] This enables the user to gauge the sensitivity of their decision with respect to different influencing factors.[19]

4.2 Real case studies

The real case studies are more detailed than the test beds described above. Also, whereas the test beds are not necessarily based on real locations and can be comprised of mixed datasets and hypothetical situations, the real case studies use real datasets and represent an application of the PUrE framework to real-life situations. Two case studies have been developed, one based in Sheffield and one in London. They examine several local sources of pollution and the associated effects on ecology and human health, as well as the interactions with the local and wider environment.

4.2.1 Sheffield case study

The Sheffield case study has been developed in collaboration with the Sheffield City Council who provided the air quality monitoring data,[21] samples of PM, emissions data for the sources included in the modelling as well as the air dispersion modelling results. These data and the air dispersion modelling results have been used along with other models and tools including LCA, SFA and HIA to predict the impacts of key pollutants (NO_2, SO_2 and PM10) in Sheffield from Part A type processes, which are those subject to the EU Directive on Integrated Pollution Prevention and Control.

Two scenarios are considered: one with the Part A processes included in the model and another with these processes excluded from the model.[22] The main findings for the first scenario are that the major contributors to the environmental pollution in the city are motorway transport, steel production and city transport, respectively. For the second scenario, the modelling results show that the absence (or closure) of the Part A type processes would lead to a 90% and 70% reduction in the SO_2 and NO_2 concentrations in the city, preventing 27 premature deaths. However, socio-economic factors would also need to be considered to assess the overall sustainability of such a scenario. The case study also looks in some detail at the composition and shapes of PM10 as a means of identifying the possible sources of particulates and understanding the behaviour of mixtures of pollutants in an urban environment. It has been found that the particles collected near the motorway have more salt and carbonaceous materials whilst those sampled closer to industrial activities have a high content of heavy metals. This enables tracing back the main sources contributing to these emissions, in this case transport and steel production, respectively.

This case study is useful as it shows the cumulative impact of a large number of processes within an urban area rather than a single facility, which is often the case in other studies. It also presents the human HIA results at the ward level, as opposed to the city scale; the use of ward level data also allows for further evaluation of other socio-economic factors in relation to air quality.

4.2.2 London case study

The London case study[17] examines the role of urban green space as a means for reducing the local levels of particulate (PM10) pollution and providing health benefits. The focus is on the Green Grid as a potential 'technological intervention' scenario for reducing pollution in East London (although it is noted that this is not the primary intention of the Green Grid plan). The expected benefits of the Green Grid plan include flood protection, leisure activity, aesthetics, health and better quality of life. The main findings from the London case study are that the Green Grid (as proposed) can reduce levels of particulate (PM10) by up to 10%, and this could lead to quantifiable health benefits. There may be further health benefits from the uptake of other air pollutants. However, the ecological impacts of establishing the Green Grid, and therefore creating pathways to ecological receptors, should also be considered.

4.2.3 Further case studies

A further real case study has examined legacy hydrocarbon pollution in an industrial harbour area of Siracusa in Sicily. It illustrates how the PUrE framework methodology can be applied to compare different remediation technologies and options proposed for more sustainable management of the contaminated groundwater. Another case study also related to legacy pollution in an industrial area is set in Avonmouth in the UK. This study illustrates the effectiveness of the regulatory and policy-related changes as well as technical interventions carried out on a historic smelting facility. It also looks at the potential human health effects under the different operating scenarios as a result of these interventions and the potential risk to ecological receptors from metal deposition to soil (e.g. arsenic, cadmium, zinc, lead). The outcomes from this case study show that the impact of policy and technological interventions is significant – this learning could be applied to similar current and future industrial installations.

5 Conclusions

Sustainable management of urban pollution requires an integrated approach to enable consideration of the huge variety of pollution sources in the urban environment; the wide range of urban pollutants and their interactions with each other and across the environmental media; and various impacts of pollution on human health and the environment. This paper has presented one such framework, known as PUrE, which meets these demands and arguably represents a significant improvement on the existing media-specific or issue-specific approaches to urban environmental management. The PUrE framework comprises a suite of different models and tools, including LCA, SFA, source and pollutants characterisation, fate and transport modelling, HIA, EIA, and MCDA. It is also supported by its own databases and a number of examples, test beds and case studies to illustrate the application of the framework.

The PUrE software is available free of charge; a demo-version can be downloaded at www.pureframework.org. Whilst the PUrE framework is related to outdoor pollution, future developments will be related to pollution in the indoor environment. This study is carried out by the research consortium PUrE Intrawise and further information is available at www.pureintrawise.org.

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