This paper outlines a new integrated decision-support framework for a more sustainable management of urban pollution, developed within the project ‘Pollutants in the urban environment’ (PUrE). The framework comprises a suite of appropriate models and tools that can be selected by different stakeholders or end-users (such as policy-makers, local authorities, industry, researchers and non-government organisations) to conduct simple screening studies and/or detailed modelling assessments of the effects of pollution in the urban environment. The models and tools enable consideration of individual pollutants and their mixtures released from a wide range of urban sources, as well as evaluation of local and global effects of urban pollution. Examples of the tools and models integrated into the decision-support framework include: life-cycle assessment; substance flow analysis; air and water dispersion and advection modelling; and human health assessment. The important features of the framework are that it is tiered, flexible and modular, allowing the users to choose the appropriate models or tools as well as decision-making paths, depending on their needs and the type of decision-making problem they are addressing. Although the framework is in its early stages of development, its application has already been demonstrated on a number of case studies, as detailed in this paper.

I. INTRODUCTION

Urban environments offer significant benefits to human society in terms of commercial economies of scale, accessibility of services and social cohesion. However, the same characteristics that offer economic and social advantages often also pose significant challenges for environmental management in cities. It has long been recognised that urban environments can pose potentially serious threats to both human health and the environment. The concentration of human activities has an impact on the rate and volume of the flow of materials through the urban environment; the high degree of spatial connectivity increases the complexity associated with mapping urban pollution; and the density of populations has implications for exposure levels from pollutant flows. The complexity in tracking the flow of specific pollutants through the urban environment poses some unique and complex challenges for environmental management. Traditional regulatory approaches are often source- and media-specific, and therefore less effective at dealing with such challenges.

The move towards sustainable urban environmental management will require a framework and approach which can address these types of challenges in an integrated and systematic manner. Such a framework would need to take a systems approach to address all forms of pollution in the urban environment including physical, chemical, biological, thermal, light and noise pollution. It would need to consider the interaction of these different forms of pollution both with each other and across the three environmental media: air, water and soil. It would also need to develop appropriate responses to a number of specific problem areas associated with understanding and managing urban pollution including:

(a) the huge variety of source characteristics associated with pollutants in the urban environment
(b) the complexity inherent in mapping the spatial distribution and the rate of release of pollutants
(c) the uncertainty and spatial variability associated with reactive transport processes
(d) the wide range in physical and chemical properties of urban pollutants and thus of their behaviour in the environment and their impact on human health
(e) the absence of data and the lack of understanding of the long-term behaviour of contaminants in the environment
(f) uncertainties over the effectiveness of natural and anthropogenic remediation methods for environmental contamination.

Developing a framework capable of meeting these various demands would represent a significant improvement on the existing media-specific approaches to urban environmental management.

In an attempt to facilitate development of such a framework, the ‘Pollutants in the urban environment’ (PUrE) project, funded by the Engineering and Physical Sciences Research Council (EPSRC) in the UK, was initiated in 2003. The main aim of the project is to develop an integrated approach and decision support framework that will enable identification of options for a more sustainable management of urban pollution.
The conceptual basis for the framework and the methodological approach to its development are discussed in the rest of this paper.

2. CONCEPTUAL BASIS FOR THE DECISION SUPPORT FRAMEWORK

Taking a systems approach to the urban environment, the PUrE decision-support framework enables integration of the following three steps that are critical for understanding and managing urban pollution

(a) identification and mapping of sources and flows of pollutants
(b) modelling of the fate and transport of pollutants
(c) identification and quantification of the impacts of pollution on the environment and on human and ecological health.

This is shown schematically in Fig. 1, which illustrates the systems approach adopted for integrating these three steps, as represented by the three spheres, into a single framework.

In addition to the sources of pollution, the framework is capable of mapping the stocks and flows of pollutants from different sources and human activities. The methodology for this must be flexible enough to enable consideration of

(a) a range of pollutants released from a single activity or process which may also include multiple sources (point and diffuse)
(b) an array of different activities (or systems), which may be sources of an individual pollutant or mixtures of pollutants.

This flexibility has been achieved by linking the life-cycle approach and LCA with substance flow analysis (SFA), as shown in Fig. 2, and detailed by Azapagic and Sinclair.11

In Fig. 2, the foreground system refers to a human activity occurring in the urban environment of interest; the background system comprises all other supporting activities occurring elsewhere. Similarly, direct pollution refers to pollution released in the urban environment and indirect pollution is occurring elsewhere in the life-cycle of the activity of interest. LCA is used to quantify total releases and potential impacts from different human activities in the background and foreground systems, while SFA tracks the flows of pollutants within the urban environment—that is, the foreground system. For example, if car transport is the human activity of interest, then LCA can be used to assess the total (foreground and background) pollution and environmental impacts along the whole life-cycle of that activity, from the extraction of the fuel and its refining (in the background system) to the use of a car in the urban environment (foreground system). SFA is used to assess direct pollution by mapping the flows of pollutants from cars (and any other activities of interest) in the urban environment. The PUrE project...
has already identified a variety of urban activities which are potentially significant sources of pollutants and which will be used as case studies to demonstrate the application of an integrated LCA–SFA approach to mapping the sources and flows of pollutants.

A further interesting aspect of urban pollution, in addition to scientific analysis, is the stakeholders’ perception of the sources of pollution, most common types of pollutants found in the urban areas and their impacts on human health and the environment. It is a well-known fact that decisions are often made on the basis of ‘gut’ feeling rather than a scientific and rational approach so that the decision support framework must be capable of dealing with this issue by providing transparent and unbiased information to stakeholders. In an attempt to explore this aspect a survey of stakeholders, including industry, policy-makers and researchers, was carried out. The stakeholders considered the following human activities to be the main sources of urban pollutants: transport/traffic, industry, domestic activities, sewage, runoff and contaminated land. The survey respondents perceived particulates (PM10), dust, nitrogen oxides (NOx), sulphur oxides (SOx), metals and polycyclic aromatic hydrocarbons (PAH) to be the most common pollutants found in the urban environment. In further development of the framework, a scientific approach will be used to determine if these ‘perceived’ pollutants of concern represent a ‘real’ concern under specific urban scenarios.

2.2. Modelling fate and transport of pollutants

As shown in Fig. 1, once the sources of pollution and flows of pollutants have been identified and quantified, the next step in the PUrE conceptual approach is pollutant fate and transport modelling. Various models enable fate and transport modelling in different environmental media; one of the key challenges is choosing the right type of model for the study of interest. Furthermore, most models are media specific and cannot deal with the complexities of pollutant interactions and transformations as they travel from one environmental medium to another, so that the main challenge here is linking the fate and transport of pollutants in all three environmental media: air, water and land.

These are some of the challenges that will be addressed within the PUrE decision support framework in future work. However, application of some of the fate and transport models has already been demonstrated within the project; for example, the use of a multi-component reactive chemical transport model developed by Cardiff University to model fate and transport of arsenic in the groundwater and the application of a large-scale pollution index method by Queen’s University, Belfast for assessing urban groundwater and surface water pollution potential. While some fate and transport tools will continue to be developed within the project, the main focus will be on the development of an integrated approach to the selection and application of appropriate tools for modelling the sources, fate and transport and effects of a range of pollutants in different environmental media for various urban scenarios. A preliminary checklist of various models and tools used in pollution studies was prepared through a survey of urban stakeholders. Some examples of the tools and models that will be explored for incorporation into the new PUrE framework include air and water dispersion and advection models, surface water and groundwater flow and chemical transport, soil chemistry, multimedia (environmental) fate models and toxicity models (e.g. ADMs, CalTOX, ChemCAN, EcoSense, GREAT-ER and SimpleBOX). The end-user will be able to choose simple or detailed models, depending on the scope and goal of their study.

2.3. Identifying and quantifying the impacts of pollution

The third step in Fig. 1 requires development of a methodology and models for understanding the human health and ecological effects of urban pollution. This is also an integral part of the PUrE framework and it takes, as input, outcomes of the analysis of the previous two steps—that is, human activities, emissions of pollutants, environmental fate, estimated exposures and predicted concentrations—to generate profiles for human health and ecological impacts of urban pollution. Socio-economic aspects of urban pollution will also be evaluated through consideration of associated costs, social issues and urban behaviour, and the decision-makers’ value system, as shown in Fig. 1.

Mathematical modelling can play an important role in quantifying the health impacts of urban pollution and in evaluating health consequences of alternatives in industrial development, as well as comparing alternative mitigation or reduction options. The health impact analysis (HIA) approach developed by the London School of Hygiene and Tropical Medicine (LSHTM) and tested within the PUrE project has several advantages over health impact assessment approaches. Most of the health models used in health impact assessment (including LCA) use static relationships to estimate the elevated
lifetime risks of diseases (e.g. cancers) or cause-specific deaths due to exposure. A dynamic model which simulates the health profile of a cohort population over a specified period as individuals age and are subjected to time-varying exposures captures more extensively the health impact on a population than a static model, which gives elevated lifetime risks for individuals subject to an assumed average exposure. Furthermore, the HIA framework is based on an analytical approach in which mathematical analysis is used to estimate and compare health consequences of different alternatives and options.\textsuperscript{14,16}

Exposure assessment combines environmental information, such as the spatial and temporal concentration of pollutants, with behavioural information (such as life styles, activity, etc.) in order to estimate the actual doses which people receive. Most models used in health impact assessment assume time-invariant exposures. However, the HIA framework developed by LSHTM,\textsuperscript{14} uses dynamic health models to simulate the impact of time-varying exposures on the population. Spatial variations in exposure for the detailed HIA models will need to be defined using geographic information systems (GIS), in order to map local scenarios.

This HIA framework is capable of addressing a multiplicity of sources of pollution, such as diffuse or point sources, and can be used for a mixture of pollutants or chemicals. Furthermore, it can simulate both primary health effects associated with primary pollutants and secondary effects which can be induced by options that are introduced primarily to mitigate the impact of the primary pollutants. One of the main advantages of the HIA framework is that it defines a wider system boundary than that which is often used in health impact assessment.\textsuperscript{14,16}

In addition to human health, urban ecology is an essential component of sustainable urban environments. Urban green space, which includes waterbodies, recreational parks, amenity trees and gardens, is under continual pressure from human activities, including pollution and redevelopment. Terrestrial flora and fauna can exhibit signs of environmental stress both on an individual and community basis, which may be toxicological effects or the inability to colonise a particular habitat; also, they can provide a pathway through which pollutants may expand the sphere of their influence to ‘higher’ organisms or additional locations.\textsuperscript{17,18} Urban green spaces can be designed to support more sustainable management options for urban pollution, for example sustainable drainage systems (SUDs). As far as the authors are aware, no other decision frameworks or tools are available at the urban scale for assessing specifically the impacts of urban pollution on ecosystem health. Although it is recognised that tools currently exist which may contribute to a risk assessment process, the assessment of ecosystem health in the urban environment presents many unique challenges that require bespoke consideration.\textsuperscript{6}

Therefore, one of the aims of the project is to develop an assessment method for the PUrE framework that will integrate a suite of appropriate models and tools to help urban stakeholders understand the potential ecological impacts of pollution in the urban environment. Examples of existing models and tool kits that will be evaluated for these purposes include the Environmental Agency (EA) tiered ecological risk assessment approach, the United States Environmental Protection Agency (USEPA), total risk integrated methodology (TRIM) model and models produced under the Urban regeneration and the environment (URGENT) research programme (funded by the Natural Environment Research Council (NERC)).\textsuperscript{6,11} A tiered risk assessment approach and toolkits for ecological risk in the urban environment will also be developed to provide environmental impact assessment (EIA) predictions of future urban development, whether as a pollutant source, receptor or pathway manipulator.\textsuperscript{6} Examples might include introduction of traffic congestion charging zones, establishment or decline of industry, or planning of new green space. This approach would help to inform decision-makers of the environmental impacts of development.

2.4. Integrative aspects of the framework

In addition to the three critical steps in evaluating and managing urban pollution, Fig. 1 shows a number of other steps and elements that affect urban pollution and must be integrated within the decision support framework. For example, a special feature of the PUrE framework is the feedback loop which encourages the users to use the new knowledge and understanding gained by applying the framework to improve the management of the sources of urban pollution and prevent further impacts. This special feature can be applied in two directions: as the forward bypass, it can be used to perform a screening level evaluation of the potential effects (impacts) of certain sources of pollution (i.e. bypassing the detailed modelling of the fate and transport). The PUrE framework can also be applied in reverse to identify a possible source or cause of an observed impact, for example as in environmental forensics. Thus the feedback loop can be used to examine liability or a new policy measure introduced to prevent pollution impacts.

Integrating the spatial and temporal considerations into the PUrE framework is also an important factor for better management of urban pollution. The project has examined a range of spatial factors and dynamic processes that must be taken into account.\textsuperscript{6} As the spatial scale for the PUrE framework is ‘urban’, there is a need for some flexibility in defining the scale of an assessment. For example, preliminary screening may be carried out over a larger urban scale, which could be followed by more detailed modelling of a smaller defined zone. McKinley and Yang\textsuperscript{15} have shown that the choice regarding the scale (e.g. grid size and dimension) can significantly influence the predictions (i.e. pollution potential hazard rating), as well as any decisions that could be based on the modelling. The linked LCA and SFA approach (as shown in Fig. 2) supports consideration of local and global effects. The scoping research has identified several important dynamic processes (e.g. dispersion, advection, retention, accumulation, reaction), which can also involve complex interactions. Future work will involve full integration of LCA, SFA, GIS and fate and transport modelling. Risk and uncertainty will also be an integral part of the framework.

The desired outcome of applying the PUrE integrated assessment framework is to reach a decision, or to make recommendations for a solution, or to determine a need for further investigations, and to gain new knowledge about pollution in the urban environment. It is important that decision-makers act on this new knowledge, and reassess the sustainability of their particular urban scenario. This is depicted by the ‘proactive’ arrow in Fig. 1,
which directs the end-user to consider possible 'intervention' strategies that could be used to manage urban pollution more effectively. Future events such as 'policy change' place the end-user into a more 'reactive' position in assessing urban pollution. The 'proactive/intervention' and 'policy change/reactive' arrows create an external loop which shows that the application of the PUrE framework is intended to be iterative and is also a learning process for the urban stakeholders.

The next section explains how this conceptual basis has been used for the development of the PUrE decision support framework.

3. DECISION SUPPORT FRAMEWORK

The PUrE decision support framework consists of three parts (see Fig. 3): problem structuring; problem analysis; and problem resolution. This methodology follows an integrated approach to decision making¹⁹ and builds on the previous work by Azapagic and Perdan.¹³,²⁰

Problem structuring enables end-users to define the decision problem by examining the main 'drivers' or posing a series of relevant questions, and to take either the decision- or problem-oriented (modelling) route. The guidance manual will be developed to cover a wide range of possible questions and applications and aid decision-makers in structuring their problem. This stage is followed by problem analysis, where end-users can choose either simple models and tools or complex models to analyse sources of pollutants as well as their fate and impacts on receptors. As already discussed, examples of the tools that will be included in the framework include life-cycle assessment, substance flow analysis, air and water and soil pollution models, health impact models, index methods and sustainability indicators. Problem resolution involves application of multi-attribute decision analysis to help end-users reach a decision, make appropriate recommendations or gain new knowledge. The user will be able to choose a suitable multiple criteria decision analysis (MCDA) technique, such as multi-objective optimisation, goal programming, value-based or outranking approaches.¹³,²⁰

The important features of the framework are that it is tiered, flexible and modular, allowing the user to choose the appropriate models or tools as well as decision-making paths, depending on their needs and the type of decision-making problem they are addressing. It can also be applied in an iterative manner which will support further learning through progression from simple treatments to more detailed modelling, as well as comparative evaluations of various options and optimisation-oriented assessments.

3.1. Stakeholders, drivers and questions

The potential users of the PUrE framework come from a wide range of sectors, such as environmental regulation, urban policy-making and planning, national policy-making, industry and commerce, environmental and waste management, as well as academia, government and non-government organisations (NGOs). The type and scope of assessment that they may want to carry out will be determined by their main drivers or questions and the specific problems that they would like to address by applying the framework. Therefore, the key to successful application of the decision support framework is identification of these drivers and/or questions that the end-users intend to explore.

Some examples of the typical drivers for urban pollution studies include: new policies or regulations; urban renewal or changes in urban planning; redevelopment of industrial estates or contaminated lands; and introduction of new products or materials into the urban environment. Some examples of the regulatory drivers include the EU Directives on water, environmental liability, strategic environmental assessment (SEA), integrated pollution prevention and control (IPPC), registration, evaluation and authorisation of chemicals (REACH); legislation in the UK on control of major accident hazards (COMAH); and environmental statements for major urban renewal, planning issues.

The PUrE framework enables both proactive and reactive approaches (see Fig. 1) to managing urban pollution, as well as consideration of the effects of policy change and intervention strategies. The framework must be flexible enough to address the current, as well as future requirements imposed by different regulatory drivers and must be adaptable for use by the many different stakeholder groups.
who are affected by these policies. To address these requirements, some of the specific types of questions that the end-users will be able to explore within the PUrE framework include the following.

(a) What are the major sources of pollutant(s) x, y, z in my urban area?
(b) How would changes to a process x affect the local environment and population?
(c) How could product x affect the urban environment and urban society?
(d) Would activity x have any negative effects on the health of urban dwellers?
(e) What are the implications of policy x?

3.2. Sustainability as the context for urban pollution studies

Conventional pollution assessments may only consider sustainability factors near the end of the assessment, for example when looking at possible pollution treatment or management options. However, in the PUrE framework sustainability is the primary focus so that sustainability issues important to the stakeholders are identified at the start of the decision process, in the problem structuring step. These issues and the related sustainability indicators are then used to assess the outcome of the problem analysis stage. However, the users’ choice of sustainability issues and indicators prior to the assessment can influence the outcome of the analysis. A unique feature of the PUrE framework is that it can be applied iteratively, using different sets of indicators but without changing the datasets or models, which allows the user to observe how their individual choice of issues and indicators affects the decision outcome. The PUrE framework also allows the user to evaluate the trade-offs between different aspects of sustainability; for example, by comparing different pollutants and impacts that could be associated with the choice of alternative processes, products, technologies or services.

3.3. Tailoring the framework for the user needs

To facilitate the uptake of the methodology and tools, different versions of the framework will be developed for the main end-user groups—that is, regulators/policy-makers, industry, researchers and NGOs. However, these versions will all be based on a common generic methodology that will ensure that different versions remain mutually consistent. For example, if the user wishes to explore a question related to a pollutant (see the list of possible questions in section 3.1), this would trigger the provision of some useful background information on that pollutant to help structure and define the problem. The selection of a process- or product-related question would give the end-user a possibility to explore a generic LCA example which could highlight potential life-cycle impacts of this process or product. This would help the user to identify the scope (‘size’) of the problem and set the appropriate initial boundary conditions.

The selection of an urban activity as a problem to be explored would be treated differently from a process (e.g. industrial practice) and would have a societal viewpoint. This route would involve a human behaviour oriented route for problem analysis. The accompanying guidance manual would need to explore why people carry out this activity and possible alternative actions. The examples of possible effects and impacts could highlight the socio-economic context of sustainability and ‘quality of life’ issues. Asking the policy-related question would necessitate further steps to elaborate the scope and identify specific issues and concerns, in order to focus the assessment. This represents the broadest application for the framework and the corresponding guidance would need to cover many possibilities for the development of the alternative options and scenarios.

4. CONCLUSIONS

The aim of the PUrE project is to develop a decision support framework that will provide a useful suite of models and tools, linked to a variety of GIS-enabled datasets, to help end-users (regulators, industry, researchers and other urban stakeholders) to conduct assessments ranging from simple screening studies to detailed modelling of different urban scenarios and prediction of possible impacts of urban pollution. Among other uses, this new framework would provide a more effective means to

(a) examine the effects of diffuse as well as point sources of pollution
(b) assess the implications of new policy measures
(c) explore sustainability issues for changes to products, processes or services
(d) understand the behaviour of key pollutants in the urban environment.

Sustainability is a primary focus of the PUrE framework: sustainability issues determine the context for problem structuring; sustainability criteria are used to judge the outcome of problem analysis; and sustainable solutions are the objective of problem resolution. Different versions of the methodology and guidance will be tailored to the needs of the main end-user groups.

The important features of the framework are that it is tiered, flexible and modular, allowing the users to choose the appropriate models or tools as well as decision-making paths, depending on their needs and the type of decision-making problem they are addressing. A suite of appropriate models and tools and associated guidance will support simple as well as detailed modelling assessments of urban pollution. The overall systems approach and life-cycle thinking provide a robust underpinning for the further development of the decision support framework within the PUrE project.

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REFERENCES


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