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More Sustainable Management of Pollution:
Integrated Approach, Models and Tools

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ABSTRACT

The PUrE (Pollutants in the Urban Environment) research consortium is developing a new decision-support framework for the integrated assessment of options for more sustainable management of urban pollution. This framework involves three steps: (i) mapping the flow of pollutants associated with human activities; (ii) modelling the fate and transport of pollutants in the environment; and (iii) quantifying the environmental, health and socio-economic impacts of urban pollution. The new decision-support framework provides an integrated approach which will facilitate the comparison of different management options based on their sustainability. The decision-support framework includes a suite of different models and tools, to support the sustainability appraisal of two or more options, for example: life cycle assessment, source (emissions) characterisation, pollutant fate and transport modelling, environmental impact assessment, health impact analysis, ecological impacts assessment, and multi-criteria decision analysis. This paper presents examples of the methodologies used by the project researchers to develop various elements of the framework. The new framework can be used at different levels, for example, to conduct a simple screening study as well as for a more detailed assessment. This paper describes many details of the framework and outlines several case studies developed to demonstrate its application.

Key words: pollution, decision-support, sustainability, models, tools

1. INTRODUCTION

1.1 Background

The Pollutants in the Urban Environment (PUrE) research consortium is developing a new decision-support framework to facilitate the integrated assessment of options for more sustainable management of urban pollution. The new framework comprises a suite of appropriate models and tools that can be selected by different stakeholders or framework users (e.g. policy-makers, local authorities, industry, researchers, NGOs, etc.) to conduct simple screening studies and/or more detailed modelling assessments. The main deliverables from the project are the framework methodology, a software modelling platform incorporating a suite of models and tools, and the framework guidance and user manuals.

1.2 Integrated approach and framework methodology

The conceptual approach for the PUrE framework involves three critical steps defined by the consortium partners:

(i) mapping the flow of pollutants associated with human activities;
(ii) modelling the fate and transport of pollutants in the environment; and
(iii) understanding (*identifying and quantifying*) the environmental, health and socio-economic impacts of urban pollution.

The integrated approach is shown schematically in Figure 1, where the three steps are represented by three linked spheres, set within an urban system. These steps are examined within the context of sustainability, and using a suite of assessment methods, models and tools.

The systems approach to more sustainable management of urban pollution has previously been described in Pettit *et al.* (2005), which provides the background for the development of the framework methodology and outlines the different methods that will be integrated into the overall framework. The multi-disciplinary aspects of the research collaboration, and the integration of methods and models, are described in Pettit *et al.* (2006). This paper provides additional details and examples for the models and tools that are being examined in the PUrE project.

1.3 Stakeholders and users of the PUrE framework

The PUrE framework is being developed for four key groups of stakeholders and potential users, who have been identified as:

i. Regulators, policy-makers/implementers, local authorities and planners;
ii. Industrial and commercial companies, and consultants;
iii. Researchers and students; and,
iv. NGOs, special interest groups or associations.

Tailored guidance will be developed for each of these key groups; however, each will apply the same overall methodology. These stakeholders are being consulted to discuss the urban- pollution related issues of most interest to them, to identify the models and tools currently used to conduct pollution assessments, and to outline potential example applications for the PUrE framework.

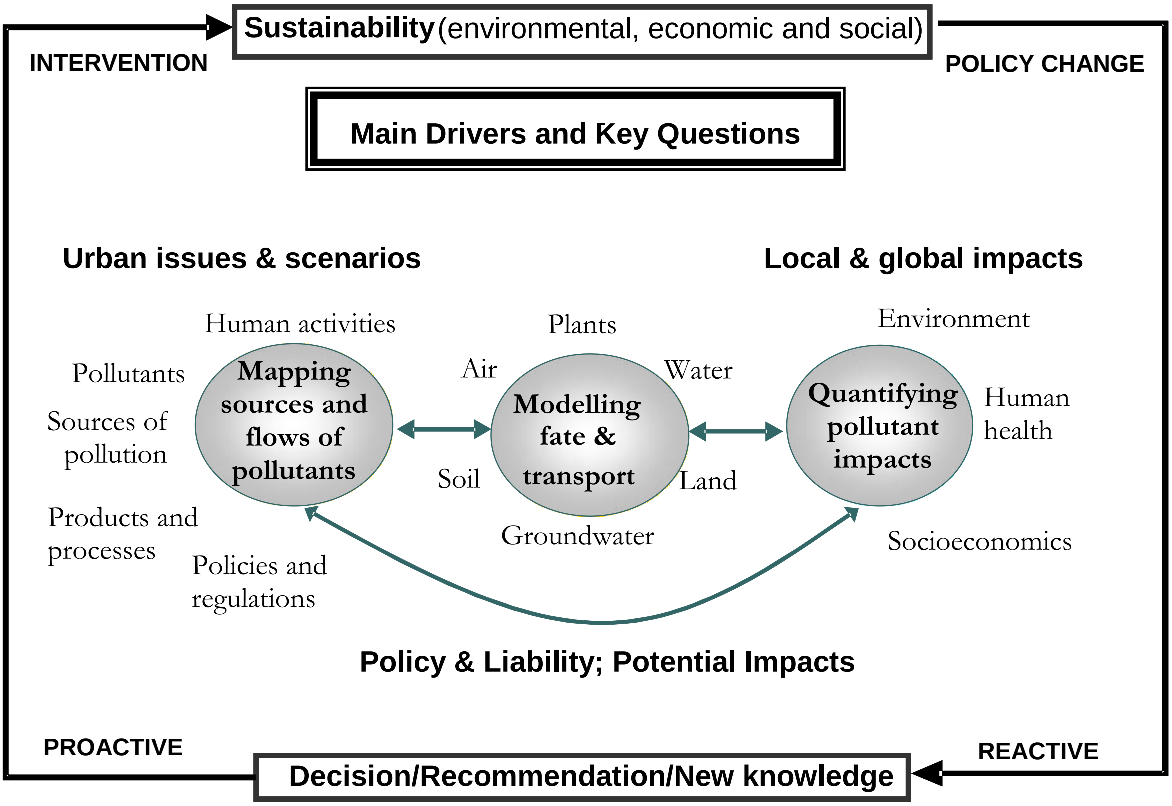

Figure 1. Conceptual basis for the PUrE framework methodology (Pettit *et al*., 2005)

1.4 Software modelling platform

The PUrE software modelling platform will incorporate a suite of methods, models and tools. The platform is being developed as a standalone application for installation on Desktop PCs. The platform itself is being developed using the C# programming language within the .NET Framework using Microsoft Visual Studio. The software platform will implement and mirror the PUrE framework methodology and will allow the user to follow a step by step progression through a framework application. The platform will have an integrated help system that will include the methodology documentation and allow access to on-line information. Also, via a central on-line hub, it will be able to connect to databases developed as part of the PUrE project. Finally, an integrated GIS function will enable the user to view and interrogate spatial data. A range of generic and specific examples will be available for the user to review within the platform. The selection of the models and tools for inclusion in the framework has been based on technical reviews by the researchers and consultations with the key stakeholder groups.

2. DECISION-SUPPORT FRAMEWORK

2.1 Overview

The PUrE decision-support framework consists of three stages: (i) problem structuring, (ii) problem analysis, and (iii) problem resolution. The methodology follows an integrated approach to decision making, as outlined by Belton and Stewart (2002) and described by Azapagic and Perdan (2005a and 2005b). The flowchart for the PUrE decision-support framework is shown in Figure 2. Each application starts with consideration of the stakeholders needs. The users identify the main drivers for the pollution assessment and the key questions they would like to address through a framework application. This will determine the path through the decision framework, and the types of models and tools that should be used.

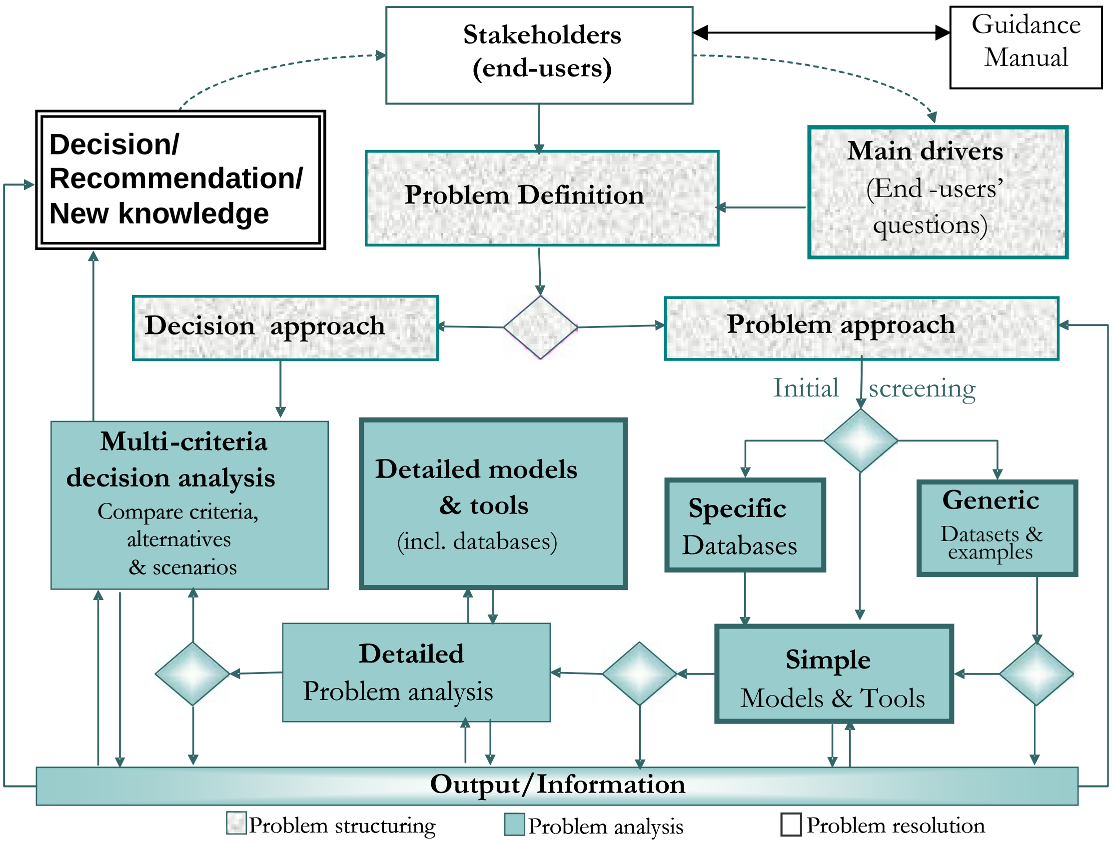

Figure 2. Flowchart for the PUrE decision-support framework (Pettit *et al*., 2005)

The users can choose between two modes of applying the framework: (a) the problem-oriented approach which uses simple models and tools to conduct a screening-level and/or more detailed models and tools for an in-depth assessment; or (b) 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 multi-criteria decision analysis (MCDA) methods. This paper outlines some of the models and tools that can be used in different cases.

2.2 Decision criteria and sustainability issues

The new framework provides an integrated approach for the definition of the urban system, and facilitates the comparison of different management options based on their sustainability. The problem definition step (shown in Figure 2) involves specifying the urban scenario and options, as well as the system boundaries, and the temporal and spatial scales for the assessment (see Table 1). The user selects the decision criteria that will be used to compare the options. In the PUrE approach, the decision criteria represent categories of sustainability issues or sustainability indicators. The decision criteria can be selected from different categories as shown by the examples in Table 1. Users can also include some of their own sustainability issues or specific indicators, however they will have to obtain the data necessary to characterise these criteria, through modelling or from other assessments.

Table 1. Problem definition step; sustainability issues and decision criteria

Problem definition	Sustainability issues and decision criteria		
	Environmental	**Social**	**Economic**
• Name of City • 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)	• Pollutants • Resource depletion • Acidification • Eutrophication • Global warming • Summer smog • Winter smog • Ecotoxicity • etc.	• Health impacts • Land use • Transport • Employment • Local issues • Risks • Environmental justice • National Security • etc.	• Capital costs • Operating costs • Energy costs • Maintenance costs • Waste costs • Government subsidy or grants • etc.

3. CHARACTERISATION OF URBAN POLLUTION

Urban pollution is a complex mixture of substances whose effects may be chemical and/or physical. These primary pollutants may be emitted into a single medium (e.g. air) but can also move through and accumulate in multiple environmental media (e.g. air, water, and soil). Urban dwellers may therefore be exposed via multiple pathways to differing levels and varying compositions of pollutants, with uncertain potential for health impacts. Although average levels can be measured and monitored, and used to estimate possible health-related effects or events, more detailed knowledge of the composition of the pollutant mixtures is required to predict specific human and ecological health impacts from chronic exposures to urban pollutants.

An example of the wider application of the PUrE approach is to provide a framework for the analysis of the effects of mixtures of pollutants. Particulate matter (PM) contains a mixture of pollutants, but the effects have primarily been studied by size rather than by composition; therefore, research on particles could be significantly improved by applying an updated and integrated approach. Particles have both a direct and an indirect impact on the environment. Aerosol particles in the atmosphere can cause light scattering which has a direct effect on climate and visibility; these particles can also indirectly affect the climate by acting as cloud condensation nuclei. Toxic particulates are produced from the absorption and reaction of particles with other pollutants in the atmosphere. Additionally, fine particles may contain inflammatory, carcinogenic and mutagenic compounds; increased exposure to these particles can cause acute or chronic health complications.

Identifying the source of these particles and their composition, and physical and chemical properties, would help to provide a clearer connection between the pollutants and their impact on the environment and the human health. Individual particles have a different chemical morphology; this data could provide information on the formation and reaction mechanism of these particles, as well as the source of the particles and their atmospheric history. Over the years, numerous studies have been conducted to characterise PM_{10} (i.e. particles less than 10 microns in size) but little work has been carried out for smaller particles such as $PM_{2.5}$. However, there is an emerging interest in identifying the effects of very fine particles, including nano-sized particles.

Characterisation of particles is essential for the purpose of assessing their impacts on the environment and health. This can be done by collecting detailed information on the shape, size and chemical composition of individual particles. Many different tools are available for collecting this information. In collaboration with the PUrE researchers, the researchers at the University of Sheffield are carrying out an extensive programme of experimental research and modelling as part of a PUrE Plus project looking at mixtures of pollutants. The main objective is to produce a comprehensive characterisation of particles in the urban environment. Six urban sampling locations have been selected to study the effects of particulate from mainly combustion sources, such as traffic. Particulate samples are being collected from kerb-side and at elevated levels, and at several sites monitored by the Local Authority.

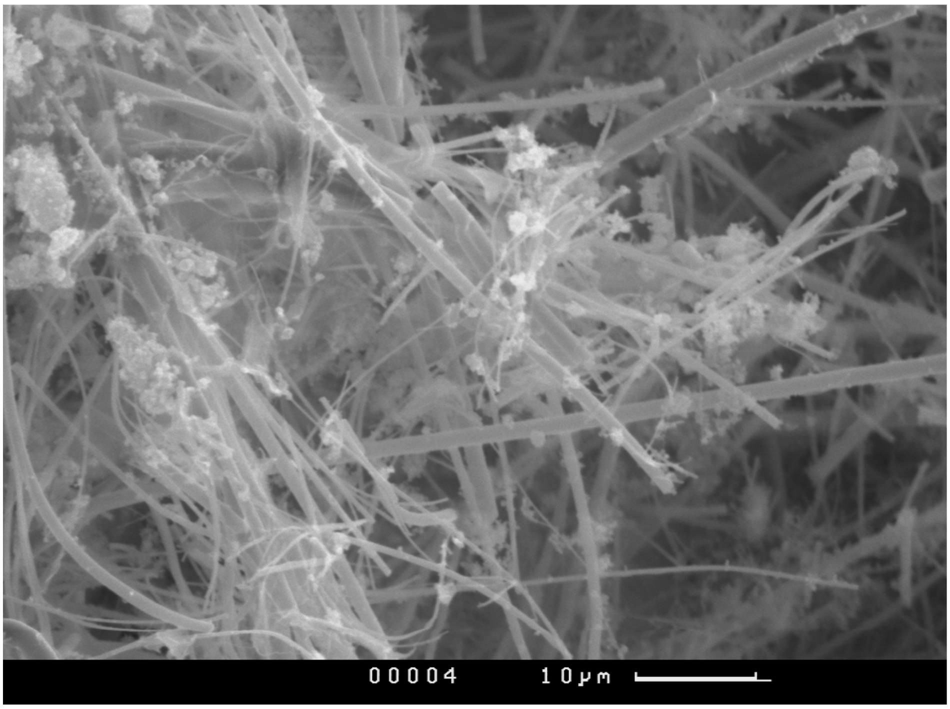

Figure 3. Picture of pollutant particles: $PM_{2.5}$ sample (SEM at 10 um)

Initial examination of urban particles has been conducted using several different tools: SEM (scanning electron microscopy), TEM (transmission electron microscopy) and ESEM (Environmental Scanning Electron Microscopy). This has provided some visual images of individual particles and information on the shape of substances present in the particulate. Figure 3 shows the results obtained for very small ($PM_{2.5}$) particles. The image consists mainly of filter fibres, decorated with very fine particles.

The preliminary results of the analyses show that the particulate matter samples have significantly different compositions. The Plus project research is examining how other models and tools included in the PUrE framework can be applied or adapted to examine the sources, behaviour, and impacts of mixtures of pollutants, such as particulate matter. Several of these models and tools are described in the next section.

4. MODELS AND TOOLS

4.1 Overview

Applying the new framework involves the selection of different models and tools to support the sustainability appraisal of the management options, for example: life cycle assessment modelling, source (emissions) characterisation, pollutant fate and transport modelling, environmental impact assessment, health impact analysis, ecological impact assessment, and multi-criteria decision analysis. This is a multifaceted and iterative process; and the following sections present examples of the tools and methodologies used by the project researchers to develop various elements of the framework.

4.2 Life cycle assessment modelling

Life Cycle Assessment (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 the 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 is used to define the urban system, and to map the sources and flows of pollutants, as described in Azapagic *et al.* (2007). The LCA approach to defining an urban system comprised of multiple sources of pollution is shown in Figure 4.

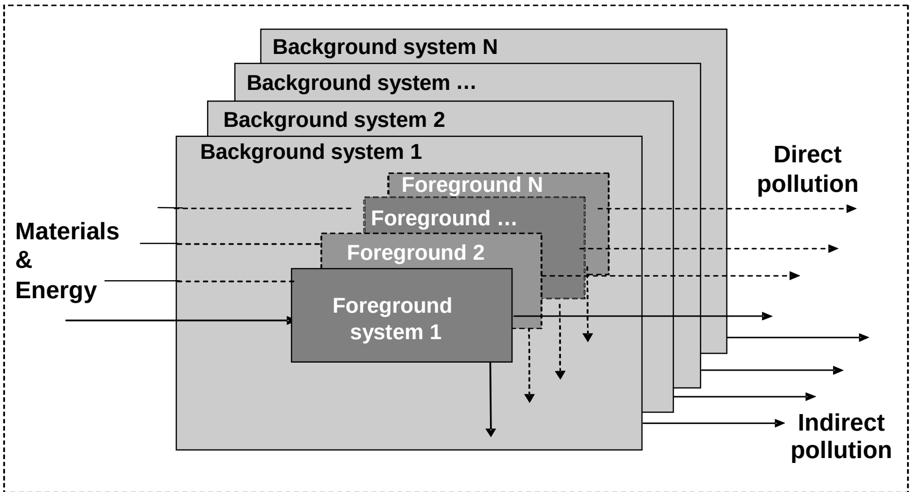

Figure 4. LCA approach to mapping sources of pollution (Azapagic *et al.*, 2007)

The main objective of applying LCA is to assess the critical environmental burdens and impacts contributing to the adverse effects on human and ecological health, both in the immediate vicinity of the urban activities (called the “Foreground system”) and in the wider environment or globally (referred to as the “Background system”).

LCA modelling is used within the PUrE decision-support framework to characterise the anthropogenic activities occurring within an urban system, and to quantify the environmental impacts (or sustainability indicators). Several LCA examples have been prepared for inclusion into the framework. These include a number of hypothetical urban activities characterised using generic data, and real case studies based on actual data obtained from two large cities in the United Kingdom.

Within the framework, LCA is linked with substance flow analysis (SFA) to facilitate mapping of the flows of pollutants in the urban environment on a life cycle basis. SFA has been successfully applied in a number of recent studies (e.g. Krook *et al.,* 2006; Tukker *et al*., 2006) to track toxic pollution arising from anthropogenic activities within urban systems. As neither of the two tools, LCA or SFA, is well-suited for a direct use within the PUrE framework, an adaptation of the necessary features of the two has been developed, as detailed in Azapagic *et al.* (2007). This linking of LCA and SFA has been examined further in the PUrE project studies being conducted by The University of Manchester.

More detailed and site-specific assessments of the impacts of the release and dispersal of pollutants from industrial and traffic sources have also been performed to associate the predicted results with real scenarios. This has been achieved by setting up air dispersion models which use detailed information on industrial/traffic sources, local terrain, and meteorology for different times of the year, mainly to simulate the winter and summer scenarios of human exposure to toxic pollution within a contained urban canopy. As part of the integrated approach, the output profiles of key pollutants (e.g. SO_x, NO_x and PM_{10}) from detailed pollution dispersion models are being used in the next step of the framework, which involves application of the human health and ecological models to forecast the related effects to the respective populations.

4.3 Pollutant fate and transport modelling

Cardiff University has been conducting a review of fate and transport models for incorporation into the PUrE framework. To allow various scenarios to be considered it is necessary to be able to undertake the modelling of fate and transport of a range of pollutants in the urban environment. 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. 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 geochemical interactions can be considered by using finite element models such as COMPASS (Cleall *et al.,* 2007); whilst complex air dispersion problems can be addressed by models such as AERMOD (Cimorelli *et al.*, 2004). 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 the interactions between the media, for example deposition of airborne particulates to the ground or a surface water body, require consideration. This can be achieved by using a multi-media model, or by linking several models together.

Two of the case study examples (referred to as the Test beds) have focused on the fate and transport of airborne pollutants. This has required the undertaking of detailed air dispersion modelling which has considered a number of pollutant sources (e.g. road and rail transport emissions in addition to incinerator stack emissions) and a number of different pollutants (e.g. PM_{10}, SOx, NOx). This has allowed for assessment of the increases in pollutant level related to the various choices considered in these examples (e.g. comparing different waste treatment technologies, or alternative fuels for power generation).

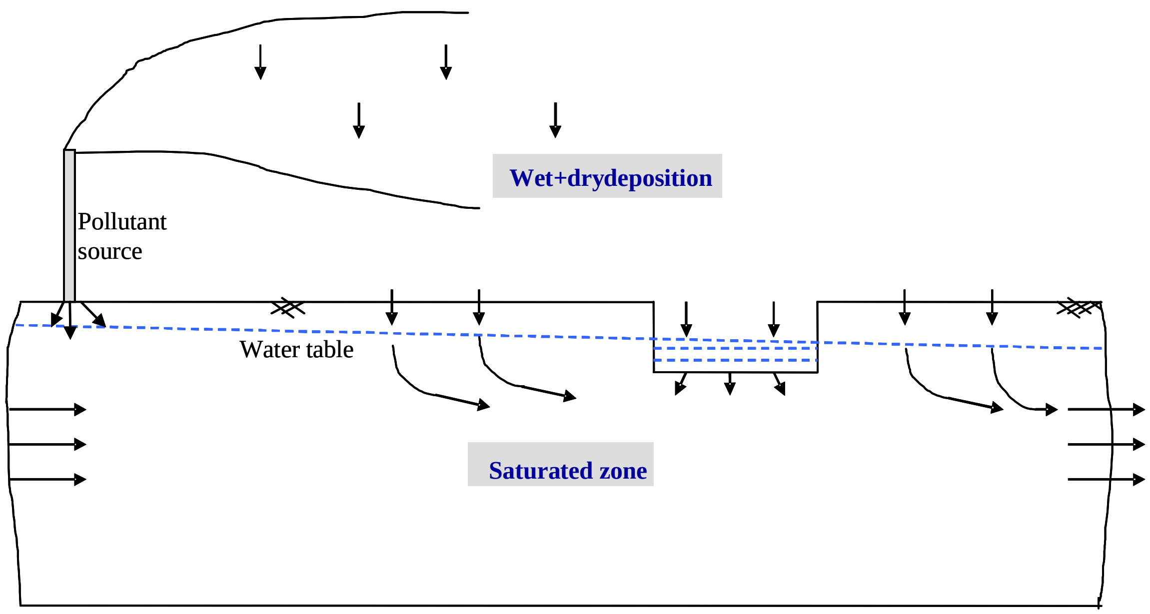

Figure 5. A typical multi-media pollutant fate and transport problem

4.4 Health impacts analysis

The London School of Hygiene and Tropical Medicine are developing the Health Impacts Analysis (HIA) component of the PUrE framework. 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. 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 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 nonlinear (Steenland and Deddens, 2004). The population health model determines the excess number of disease-specific deaths using life table methods (Golboham *et al*., 2006). For multiple exposure pathways, different methods for aggregating the health impacts will be used and compared (Price and Chaisson, 2005).

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 (Cullen and Frey, 1999; Babendreir and Castleton, 2005). Dealing with model uncertainty is a key aspect of the health modelling framework and methods for characterising and propagating the uncertainties in the various sub-models to the health outcome are being developed.

4.5 Ecological impact assessment

Forest Research is developing the Ecological Impact Assessment (EIA) component of the PUrE framework, to enable users to quantify the influence of pollutants in the urban environment on terrestrial ecosystem health and function. The impacts of site development, both past and future, on urban and peri-urban ecosystems must be considered during the planning process. An examination of the effects on habitat destruction and fragmentation and the potential loss of biodiversity is an integral part of this process. However, the detrimental effect of the pollutants arising from some activities on ecosystems is difficult to ascertain, particularly where the pollutant loading on an area is already high from an accumulation of a number of sources or an industrial legacy.

The EIA component of the PUrE framework will consist of the three levels: Generic, Simple and Detailed. The full EIA process is shown in Figure 6. These levels will align with the proposed Environment Agency Ecological Risk Assessment Guidance for Contaminated Land (Environment Agency, 2003). The EIA will use a combination of: (i) a database containing toxic concentrations from the literature (for the eco-toxicological tests as recommended by the Environment Agency (2003)); (ii) modelling; and, where necessary, (iii) ecotoxicological testing.

At the Simple Level the user will be able to compare measured, ‘typical’ or predicted soil concentrations with Soil Screening Values or equivalent, where available, or NOEC, LOEC, EC and LC (No Observed Effect Concentration, Lowest Observed Effect Concentration, Effect Concentration and Lethal Concentration, respectively) values from the literature. For example, when assessing the risks of particulate deposition from an industrial process the user can calculate the predicted pollutant soil concentrations at a greenspace after increasing time periods. These values will then be inputted into the software and a table produced giving the Soil Screening Value and ranges of toxic concentrations from the literature for each indicator species. Depending on the outcome of such analysis and the objectives of the user, they 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 into vegetation. If the level of uncertainty or risk is still unacceptable the user may wish to carry out some ecotoxicological testing.

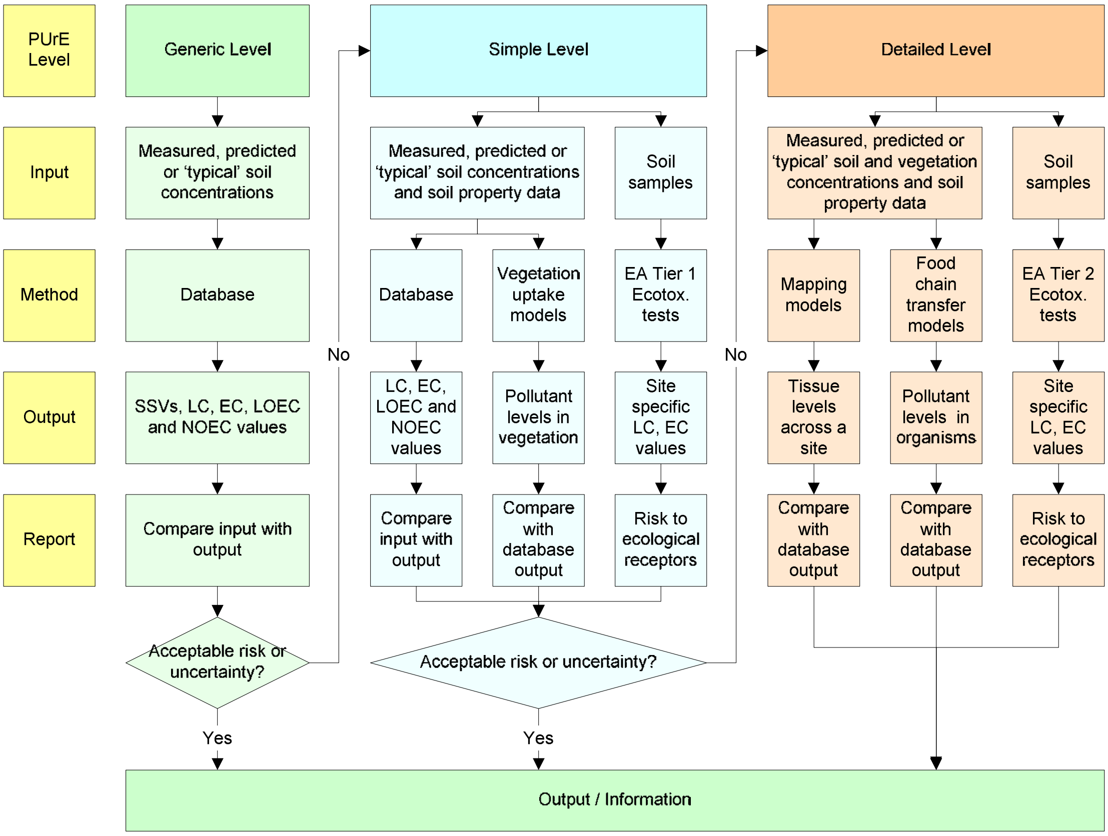

Figure 6: The Ecological Impacts Assessment (EIA) process

Finally, at the Detailed Level, the user will be able to examine the potential for food-chain transfer of pollutants from a combination of models and, where necessary ecotoxicological 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 of pollutants, the user will also be able to assess the potential for the mitigation of particulate pollution by vegetation establishment. They will be able to 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 will enable particulate interception and air quality to be taken into account alongside those factors more commonly associated with urban greenspace design. Furthermore, the user can assess the particulate interception at different time periods, for different age classes of tree, and between broadleaves and conifers or other species.

4.7 Multi-criteria decision analysis

The decision-making steps of the PUrE framework will be supported by the use of Multi-Criteria Decision Analysis (MCDA) methods. A range of MCDA methods and techniques are being examined, including value-based and outranking approaches.

Several MCDA methods are being explored in conjunction with the PUrE consortium partners, as many of these techniques are participatory in nature, and therefore benefit from a group discussion and a wide range of stakeholder views. The aims are to examine how easy or difficult it is to reach a consensus between different stakeholders on the choice of sustainability (i.e. decision) criteria and on their relative importance; and to examine if and how the choice of the sustainability (decision) criteria can be affected by the results of problem analysis compared to choosing these *a priori.* The examples conducted so far have used qualitative approaches such as ranking of criteria by group discussion, and quantitative approaches involving weighting and ranking of the decision criteria (calculated values) obtained from a modelling assessment.

5. CASE STUDY EXAMPLES

5.1 Overview

The PUrE researchers are developing a range of examples to illustrate the integrated framework and the suite of models and tools. The new framework can be used at different levels, for example, to conduct a simple screening study as well as for a more detailed assessment. The modelling platform will provide generic examples to illustrate the features of the individual models or tools. The Guidance developed for the framework will provide several detailed case study examples that illustrate the integrated methodology and the application of different combinations of models and tools. The next sections outline several examples which highlight the integrated approach and the selections of models and tools employed in each case.

5.1 Test beds

To date, two test beds have been developed to demonstrate a full application of the PUrE decision-support framework. These are briefly outlined below.

Test bed # 1 was aimed at identifying more sustainable options for the thermal treatment of municipal solid waste (MSW). Two options were compared: one large-scale incinerator versus four smaller pyrolysis-gasification units situated at different locations in a (hypothetical) city. Following the problem structuring stage and the problem-oriented approach to problem analysis (see Figure 2), LCA modelling was conducted at a generic screening level to characterise the sources and pollutants of interest, and to predict a range of potential environmental impacts. A screening of typical emissions and releases to environmental media (air and water) showed the water pathway could be neglected for this assessment. The next step was air dispersion modelling of emissions from the incinerator, the pyrolysis units and the trucks transporting MSW which provided profiles of the predicted pollutant concentrations in the local area (arising due to these facilities). The associated health effects on the local community were calculated using the HIA models. Although it was possible to distinguish between the options, the relative health effects were found to be relatively low for both scenarios. The background levels of particulates in the city centre were relatively high; therefore a green intervention was proposed which involved planting more trees in the city parks to intercept the PM. This was investigated using an ecological model that considers the number and types of trees (based on Broadmeadow *et al*., 1998). The sustainability of each option was then compared in terms of: the predicted 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 operating phases for the two options; and social aspects such as attitudes towards incineration and energy recovery, and waste recycling behaviour. The decision-making process was shown to consider a range of issues, in addition to the treatment technology, which will ideally lead to a more sustainable outcome (Pettit *et al.,* 2006).

Test bed # 2 looked at identifying more sustainable options for electricity generation, and compared building a new biomass facility versus expanding an existing power plant firing coal. This assessment began by looking at the differences in the technologies and the emissions datasets. An initial factor was the selection of the type and source of the biomass (e.g. miscanthus from local farms, wood wastes from local industries). Coal was supplied from overseas and transported by rail from the port; while the biomass was transported by road. LCA modelling of the two scenarios provided a range of potential environmental impacts. The next step was air dispersion modelling which considered the emissions from the facilities as well as the transport emissions, and provided predicted pollutant levels in the surrounding areas. The health assessment looked at: primary health impacts (e.g. pollution); secondary health impacts (e.g. traffic injuries); and summed the health outcomes across the exposed populations. The predicted average levels of pollutants (e.g. PM_{10}, SO_2 and NOx) were considered unlikely to cause adverse toxicological effects on the local ecology; therefore the EIA focussed on cumulative deposition of metal emissions to the soils at a hypothetical greenspace located near the biomass energy plant. All of the findings from the assessment modelling (i.e. environmental impacts, health impacts, ecological effects) were summarised alongside information gathered on the economic costs and social issues. The summary matrix of the decision criteria (sustainability issues) was then used by the consortium partners to explore different MCDA methods (as noted in Section 4.7). The choice of the most sustainable energy source was found to be sensitive to the selection of the decision criteria and their perceived importance to decision-makers. In addition to demonstrating the application of the decision-support integrated framework, this test bed showed the importance of the decision-makers and their value system on the problem resolution stage (the final stage of the PUrE framework as shown in Figure 2).

5.2 Real Case studies

The PUrE project has several Plus component projects that are focusing on the further development of specific features of the integrated framework. These Plus projects are using real locations to develop detailed case studies that will demonstrate an integrated approach to: (a) the assessment of mixtures of pollutants; (b) detailed problem analysis using advanced models; and (c) consideration of risk and uncertainty elements of the decision-support framework.

The case studies selected for the PUrE Plus projects are therefore more detailed than the Test beds described above. Also, whereas the Test beds do not need to be real locations and can be comprised of mixed datasets and hypothetical situations, the Plus project case studies require real datasets and represent an application of the PUrE framework to real life situations.

Two case study sites are being used in Plus project A (Mixtures of Pollutants) to compare and contrast the sources, movement and effects of pollutants, in two different UK cities: Sheffield and London. These studies 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. Plus project A includes the application of: LCA and air dispersion modelling (as described in Section 4.2); analytical techniques for characterisation of pollutants in air (i.e. PM as noted in Section 3); measurement of airborne metals deposited to soil and plants; eco-toxicological tests; and human health impacts modelling.

Plus project B involves the development of: detailed models for characterising pollutants produced from combustion sources; integrated approaches for linking fate and transport of pollutants for air, soil, water and groundwater media; detailed models for ecological impacts assessment; and dynamic models for human health impacts analysis.

The researchers for the Plus B and Plus C projects are in the process of selecting appropriate case study locations. This choice will depend on the availability of datasets for characterising the extent of pollution and observed impacts in the urban study areas. These new case study examples will demonstrate how an integrated approach and appropriate models and tools can be used to identify more sustainable options for management of urban pollution.

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