Economic developments, such as large industrial plant or civil construction, may have environmental and health consequences. Environmental impact assessment was developed in the United States in the 1970s to control industrial pollution. In European Union countries, through Directives 85/337/EEC and 97/11/EC, environmental impact assessment has been implemented as part of planning control. Health impact assessment, in contrast, has developed during the 1990s. While using approaches similar to environmental impact assessment, it is not regulated by law, and policies and other activities beyond the healthcare sector have been assessed, as well as economic developments. Health impact assessment is developing at international and national levels as well as more locally. Guidelines for health impact assessment have been produced in several countries.

We have investigated how epidemiology can contribute to health impact assessment of environmental developments, using mathematical modelling. The work had three components: defining the relation of environmental assessment to health impact assessment; identifying epidemiological information that links environmental data to morbidity or mortality; and developing a mathematical model to predict the population health impacts.

METHODS AND RESULTS

Environmental assessment

In the United Kingdom, the Department of the Environment has described environmental impact assessment as a “technique and a process by which information about the environmental effects of a ‘project’ is collected, both by the developer and from other sources, and taken into account by the planning authority in forming their judgements on whether the development should go ahead”. The environmental impact assessment process includes screening, scoping, preparing an environmental statement, appraising the statement, negotiation, and risk management.

The United Kingdom Environmental Impact Assessment Regulations require “specified information” within environmental statements including: “a description of the likely significant effects, direct and indirect, on the environment of the development, explained by reference to its possible impact on—human beings; flora; fauna; soil; water; air; climate; the landscape . . . . . .”. The environmental statement may also include “by way of explanation or amplification, further information including ‘an estimate, by type and quantity, of expected residues and emissions (water, air and soil pollution, noise, vibration, light, heat, radiation, etc) resulting from the operation of the proposed development’.

Both the United Kingdom government and industry have produced guidance on good practice. There is also a guide that helps local planning authority decision makers evaluate “environmental information” that is contained in an environmental statement. These guides require investigation of the effects on human beings, but do not indicate the possible impacts on health. Between July 1988 and April 1998, 3103 environmental impact assessments are known to have been submitted in the United Kingdom. The most frequent projects were waste disposal (21%), road building (14%), mining (14%), energy (13%), and urban/retail developments (13%). Environmental impact assessment is undertaken by commercial consultancies on behalf of the developers presenting their application to local planning authorities. However, there is considerable variation in professional practice, in the scope and detail of the review and in the degree of quantification.

Epidemiological approach

The data for our model include epidemiological risk information, population structure and disease characteristics, and an estimate of the exposed population. We reviewed a wide range of literature, including: guidelines for health impact assessment; reviews of the health impact assessment literature; guides to environmental impact assessment; reviews of environmental health and the use epidemiological evidence for environmental health risk assessment; web sites and grey literature reports.

Areas of environmental concern are usually set out in environmental statements within a standard structure. We identified 14 environmental factors/themes relevant to health from...
The Essex Guide to Environmental Impact Assessment, which described environmental topics that may be relevant to consider when carrying out an environmental assessment. Table 1 shows our assessment of environmental health effects for which quantitative risk estimates could be or have been derived for these areas. We included four in our model—outdoor air, chemicals, noise, and transport—where quantitative estimates were strongest. Literature for other health effects of other environmental factors, such as social dimensions or climate change, could not be adequately quantified from the literature search for our model.

Outdoor air

Two reports provide quantitative estimates of the effects of air pollution on health. A national committee in the United Kingdom draws on time series studies that examine the relation between daily levels of air pollution and the risk of adverse health effects, on the same day or subsequent days. A World Health Organisation working group additionally linked evidence of long-term effects of exposure to PM$_{10}$ on total mortality and chronic bronchitis from cohort studies with population data from Austria, France, and Switzerland.

Chemicals

For chemicals classed as carcinogens, dose related estimates of excess lifetime cancer risk have been produced by national bodies such as the United States Environmental Protection Agency, through a process of quantitative risk assessment. These risk assessments mostly rely on data from animal studies as there are less data from epidemiological studies. The lifetime excess cancer risk is an additional risk that the local population might face, and can be converted into a relative risk by calculating the background lifetime cancer risk using Office of National Statistics age specific annual incidence data.

Noise

Reviews indicate that there is some evidence to suggest that community noise may increase blood pressure (the clinical significance of which is unclear) or be a risk factor for coronary heart disease. Noise exposure during sleep may increase blood pressure and heart rate, and noise disturbance may differ across demographic groups of the population; older people, and possibly women may be more affected by noise during sleep. De Hollander et al estimated that noise contributed about a quarter of the health loss (as disability adjusted life years) associated with selected environmental exposures in the Netherlands.

**Table 1** Quantitative risk estimates for a health impact assessment model of urban developments

<table>
<thead>
<tr>
<th>Environmental factors</th>
<th>Health effects for which quantitative risk estimates could be or have been derived given the current evidence base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Acute effects on mortality and hospital admissions, and long term effects on mortality and chronic diseases exist</td>
</tr>
<tr>
<td>Chemicals</td>
<td>Lifetime cancer risk estimates for changes in chemicalcarcinogen concentrations exist</td>
</tr>
<tr>
<td>Noise</td>
<td>Community noise is considered a possible contributor to heart disease, but the noise exposure population and multiple sources of noise (demolition, construction, operation and traffic) must be considered. The physical health effects from short term noise exposure are unclear</td>
</tr>
<tr>
<td>Traffic (trauma/exercise)</td>
<td>Accident statistics are available for local areas, although a proportion of injured people are not locally resident. Modal shifts (between vehicle and walking or cycling) are not usually assessed within environmental statements, so these health effects are difficult to quantify</td>
</tr>
<tr>
<td>Water (tap)</td>
<td>See chemicals, infections short term. Difficult to estimate population exposed</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Not usually relevant to urban developments</td>
</tr>
<tr>
<td>Forestry (fire)</td>
<td>Not usually relevant to urban developments</td>
</tr>
<tr>
<td>Climate</td>
<td>Effects very long-term and international. Small contribution from an individual development to the overall effect</td>
</tr>
<tr>
<td>Hazardous incidents</td>
<td>Not included in the model</td>
</tr>
<tr>
<td>Community severance</td>
<td>Effects on physical health are not quantified</td>
</tr>
<tr>
<td>Changes in employment</td>
<td>Complex effects, both negative and positive. Difficult to quantify the exposed population</td>
</tr>
<tr>
<td>Changes in health and welfare services</td>
<td>The health impacts of health services at national level have been estimated. Environmental statements usually only describe changes in provision</td>
</tr>
<tr>
<td>Sociocultural effects</td>
<td>Relation to health not quantified</td>
</tr>
<tr>
<td>Recreation (leisure)</td>
<td>Changes in population exercise are not usually quantified in environmental statements</td>
</tr>
</tbody>
</table>

The population exposed will differ for each of these environmental factors. Air pollution is usually modelled geographically in the environmental statement. Chemicals may be assessed as air dispersion and also by water. Noise depends on proximity and frequency. Traffic is variable, and may affect both resident and working populations. The smallest geographical areas for these health data are larger than that available for the population from the census. Changes in area boundaries complicate the interpretation of area statistics. The accuracy of statistics at sub-national levels has been discussed.

**Mathematical model**

The model is based on people moving between different health states over their lifetime, as they develop or recover from various health conditions, or die. To describe baseline population health, data are included for the exposed population by age and sex. For the given population, the model calculates baseline age and sex related hazard functions, drawn from mortality and morbidity statistics. The expected effects of exposure (relative risks), of different levels of exposure, to the environmental changes are then incorporated, and the model recalculates estimates for the health status of the population in the presence of the development. The differences between the two sets of estimates are taken as the health impact of the development.

A diagram of the elements of the model is shown in figure 1. The four elements are:

**Environmental factors**

Environmental factors can cause or exacerbate health problems. The health impact of the development will be largely influenced by the level and nature of the environmental changes, which are described in the environmental impact
assessment. Population exposures are indicated, for example, in wind plume models or traffic densities.

Population demographics

A given environmental change will affect different populations in different ways. The age and gender profile of the local population is of particular importance to the overall effect of a set of environmental changes. For example, a pollutant that affects fertility will have a larger impact on a population with a large proportion of women of childbearing age compared with women beyond childbearing age.

Population dynamics

Underlying age related disease and mortality rates influence the impact of environmental changes on the local population. Also, population dynamics within the local area will affect the amount of exposure to environmental changes faced by different sections of the population.

Timescale of project

The duration of the proposed development and hence the length of time that the local population are exposed to the attendant environmental changes will influence the level of health impact on the local population.

Hypothetical example of the model

A hypothetical example shows our approach. A major redevelopment of a chemical plant is planned. The environmental impact assessment of the proposal has predicted that the main environmental impacts will be the pollution of the local water supply with benzidine and a decrease in PM$_{10}$ emissions. Forty per cent of the 50,000 local population will be exposed to benzidine at a level that increases the hazard for developing cancer by 1.04. All of the local population will be subject to PM$_{10}$ levels that are 20 µg/m$^3$ lower than previously. This change is estimated to reduce the hazard for developing bronchitis by 0.83. The redeveloped plant is expected to operate for 15 years.

Computer software has been written to implement the model. This has been used to estimate the excess mortality and morbidity due to this hypothetical development over the 15 years of its duration. A graphical display of the estimated changes in mortality and morbidity attributable to the proposed development are shown in figure 2.

DISCUSSION

Timeliness

The new public health interest in health impact assessment methodologies provides an opportunity for revisiting environmental impact assessment. The European Office of the World Health Organisation has provided advice on the use of epidemiological evidence for environmental health risk assessment and has established an office to promote health impact assessment. The United Kingdom Royal Commission on Environmental Pollution has suggested the need “to include explicit and formal requirements for assessment of the potential impacts of all developments on health.” Methods for environmental impact assessment have developed within a legal framework, receiving little direct input from public health practitioners. Nevertheless, local planning authorities place more weight on an environmental impact assessment that contains quantified analyses of environmental impact than on one that seems to be based only on qualitative analyses, and this may encourage quantification of health impacts.

Epidemiological studies

The World Health Organisation has recommended that “study reports should describe as precisely as possible the exposure characteristics, shape of the exposure-response function, as well as distinguish between the acute and chronic effects of exposure.” However, at present few epidemiological studies...
provide useable population risk estimates for health impact assessment. We drew on literature reviews in four areas using different approaches.

In the relatively well researched field of air pollution, two recent studies of health impacts gave estimates of short and long term effects respectively.24 The risk of chemicals causing cancer has been assessed through both epidemiological and animal model studies.25 De Hollander et al.26 have considered the implications of aggregating risk estimates, and estimating their interactions, within a single model.

Guideline values, or criteria, for individual maximal exposure are generally used in environmental statements to assess the likelihood of health effects, but it is important to assess the cumulative risk for chronic diseases that develop over a lifetime. Our model is able to incorporate development of both morbidity and mortality. While the epidemiological literature mainly reports mortality and illness episodes, disability adjusted life years27 may provide useful approach in the future.

We have only identified adequate data for a minority of all areas included within environmental statements. Some of these are impacts on ecology rather than human populations: our approach is more applicable to urban developments. Although health may be affected by other factors included in environmental statements, for example, community severance or climate effects, epidemiological estimates in the literature are not sufficiently clear. We have also excluded effects during construction, on workers during production and the impact of hazardous incidents. These are more usually considered in the occupational health literatures. For epidemiological approaches to health impact assessment to develop further, more quantitative environmental information will be needed in environmental statements and more evidence of their health effects required.

Mathematical models

Mathematical modelling has potential for improving the scientific quality of, and tools for, health impact assessment. Models have been developed in other public health fields, such as infectious diseases (for example, predicting development of vCJD28), screening (for example, cervical cancer29), and assessment of medical interventions (for example, cardiac surgery30). The PREVENT model developed by Gunning-Schepers31 was designed to assess the impacts of health promotion policies on population health status of changes in exposure to environmental changes may be estimated. The health of individuals within the public population is represented in the model by a number of “states”, each representing a unique combination of features reflecting health status. For example, a state might be defined in terms of presence or absence of cancer, presence or absence of asthma, and alive or dead. There would be states corresponding to all combinations of these three factors. Such states can also be extended to reflect mortality by different causes, for example, reflecting the possibility of death resulting from a road traffic accident. The model is based on estimating the proportions of the local population in each of the different health states. The model operates by evolving these state proportions over some specified time frame, taking into account expected changes in exposure to environmental factors attributable to a proposed project. Full details of the structure and workings of the model are available from the authors. Here we present how the model would operate for the hypothetical example given in this paper.

In the example given, individuals within the population are considered to be in one of seven health states, namely:

1. Alive with neither cancer nor bronchitis
2. Alive with bronchitis but without cancer
3. Alive with cancer but without bronchitis
4. Alive with both cancer and bronchitis
5. Dead due to bronchitis
6. Dead due to cancer
7. Dead due to a cause other than cancer or bronchitis

For each section of the population, defined by age, sex and risk exposure, the health of that subgroup is separately modelled over sequential five year periods.

Appendix B: Brief Description of the Operation of the Mathematical Model

The mathematical model has a generic structure such that the impact on many dimensions of the health of a population of a range of environmental changes may be estimated. The health of individuals within the public population is represented in the model by a number of “states”, each representing a unique combination of features reflecting health status. For example, a state might be defined in terms of presence or absence of cancer, presence or absence of asthma, and alive or dead. There would be states corresponding to all combinations of these three factors. Such states can also be extended to reflect mortality by different causes, for example, reflecting the possibility of death resulting from a road traffic accident. The model is based on estimating the proportions of the local population in each of the different health states. The model operates by evolving these state proportions over some specified time frame, taking into account expected changes in exposure to environmental factors attributable to a proposed project. Full details of the structure and workings of the model are available from the authors. Here we present how the model would operate for the hypothetical example given in this paper.

In the example given, individuals within the population are considered to be in one of seven health states, namely:

1. Alive without disease
2. Alive with bronchitis
3. Alive with cancer
4. Alive with both cancer and bronchitis
5. Dead due to bronchitis
6. Dead due to cancer
7. Dead due to a cause other than cancer or bronchitis

For each section of the population, defined by age, sex and risk exposure, the health of that subgroup is separately modelled over sequential five year periods.

Consider the subgroup of the population composed of men aged 40-44 that are not exposed to any of the environmental changes associated with a project. Let \( p_i(t) \) be the probability that an individual that is a member of this subgroup is in health state \( i \) at a time \( t \) into the modelled period, where the index variable \( i \) corresponds to the health state defined above.

The probabilities \( p_i(t) \) are linked by the differential equations

\[
\begin{align*}
p_1(t) &= -\left(\alpha_{12} + \alpha_{13} + \alpha_{14}\right)p_1(t) \\
p_2(t) &= \alpha_{12}p_1(t) - \left(\alpha_{24} + \alpha_{25} + \alpha_{26}\right)p_2(t) \\
p_3(t) &= \alpha_{13}p_1(t) - \left(\alpha_{34} + \alpha_{36} + \alpha_{37}\right)p_3(t) \\
p_4(t) &= \alpha_{24}p_2(t) + \alpha_{25}p_5(t) - \left(\alpha_{45} + \alpha_{46} + \alpha_{47}\right)p_4(t) \\
p_5(t) &= \alpha_{36}p_3(t) + \alpha_{37}p_4(t) \\
p_6(t) &= \alpha_{46}p_4(t) + \alpha_{48}p_4(t) \\
p_7(t) &= \alpha_{57}p_4(t) + \alpha_{58}p_4(t) + \alpha_{59}p_4(t) + \alpha_{510}p_4(t)
\end{align*}
\]

Where \( \alpha_i \) is the hazard for a man of age 40-44 who is not exposed to the environmental changes of the proposed project, moving from...
health state i to health state j. Note that it is assumed that a set of constant hazards applies to a subgroup of the population over a five year period.

The mathematical model sets up and solves these differential equations for each subgroup of the population. The effect of exposure to environmental factors is modelled by adjusting the hazards that apply to the exposed sections of the population. For example, the equations that apply to men aged 40–44 exposed to both the benzidine pollution and lower PM10 emissions associated with the proposed project discussed in the text are:

\[
\begin{align*}
  p_1(t) &= -(0.83\alpha_{12} + 1.04\alpha_{13} + \alpha_{14})p_1(t) \\
  p_2(t) &= 0.83\alpha_{12}p_1(t) - (0.25 + 0.27\alpha_{13})p_2(t) \\
  p_3(t) &= 1.04\alpha_{13}p_1(t) - (0.18 + 0.46\alpha_{14} + \alpha_{15})p_3(t) \\
  p_4(t) &= 0.83\alpha_{12}p_1(t) + 0.83\alpha_{13}p_2(t) - (\alpha_{23} + \alpha_{24} + \alpha_{25})p_4(t) \\
  p_5(t) &= \alpha_{23}p_2(t) + \alpha_{24}p_3(t) \\
  p_6(t) &= \alpha_{33}p_3(t) + \alpha_{34}p_4(t) \\
  p_7(t) &= \alpha_{43}p_3(t) + \alpha_{45}p_5(t) + \alpha_{46}p_6(t) \\
  p_8(t) &= \alpha_{53}p_3(t) + \alpha_{54}p_5(t) + \alpha_{56}p_6(t) + \alpha_{57}p_7(t) + \alpha_{58}p_8(t)
\end{align*}
\]

In the example given, exposure to each of the two factors considered is viewed as all or nothing with no dose-response relationship. The generic structure of the model allows more complicated exposure effects with different sections of the population being exposed to differing levels of each environmental factor considered. This simply increases the number of subgroups within the population and hence the number of sets of differential equations that the model constructs and solves.

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