Science of the Total Environment xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessment of complex environmental health problems: Framing the structures and structuring the frameworks

Anne B. Knol [a,*], David J. Briggs [b], Erik Lebret [a,c]

[a] National Institute for Public Health and the Environment (RIVM), Centre for Environmental health research, PO Box 1, NL-3720 BA Bilthoven, The Netherlands
[b] Imperial College, London Department of Epidemiology and Public Health, Norfolk Place, London, W2 1PG, United Kingdom
[c] Institute for Risk Assessment Sciences, Utrecht University, P.O. Box 80.178, NL-3508 TD Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 23 September 2009
Received in revised form 10 March 2010
Accepted 12 March 2010
Available online xxxx

Keywords:
Conceptual framework
Causal diagrams
Causality
Assessment
Model
Environment
Health
Systemic risks

ABSTRACT

Many environmental risks are multi-faceted and their health consequences can be far-ranging in both time and space. It can be a challenging task to develop informed policies for such risks. Integrated environmental health impact assessment aims to support policy by assessing environmental health effects in ways that take into account the complexities and uncertainties involved. For such assessment to be successful, a clear and agreed conceptual framework is needed, which defines the issue under consideration and sets out the principles on which the assessment is based. Conceptual frameworks facilitate involvement of stakeholders, support harmonized discussions, help to make assumptions explicit, and provide a framework for data analysis and interpretation.

Various conceptual frameworks have been developed for different purposes, but as yet no clear taxonomy exists. We propose a three-level taxonomy of conceptual frameworks for use in environmental health impact assessment. At the first level of the taxonomy, structural frameworks show the wide context of the issues at hand. At the second level, relational frameworks describe how the assessment variables are causally related. At the third level, this causal structure is translated into an operational model, which serves as a basis for analysis. The different types of frameworks are complementary and all play a role in the assessment process. The taxonomy is illustrated using a hypothetical assessment of urban brownfield development for residential uses.

We suggest that a better understanding of types of conceptual frameworks and their potential roles in the different phases of assessment will contribute to more informed assessments and policies.

1. Introduction

Many of the modern problems that face policy-makers are highly complex in nature and far-reaching in their effects. The most obvious examples are seen at international scale: climate change (Martens and McMichael, 2002; McMichael et al., 2006, 2003), security of resource supplies such as food, water and energy (EEA, 2008; United Nations Environment Programme, 2007; World Water Assessment Programme, 2009), environmental pollution (European Environment Agency, 2005b; Prüss-Ustün and Corvalán, 2007), urban development (European Environment Agency, 2006; UN-Habitat, 2008), population growth (United Nations Population Division, 2009) and — as recent events have made all too clear — the global economy (World Bank, 2008b). They are thus what Klinke and Renn (2006) and the Organisation for Economic Co-operation and Development (OECD) (2000) have termed *systemic risks*: i.e. multi-dimensional problems operating as part of more wide-ranging physical, social, economic and political domains. They often transcend different spatial and administrative scales (from local to trans-national), and may be characterised by long delay periods between cause and effect (Klinke and Renn, 2006). Many-to-one, one-to-many and many-to-many relations are the rule, and not the exception. Many problems at the regional and local level are also systemic in nature. Urban transport policies, for instance, are a response to different influences, including changing lifestyles, technologies, social expectations and urban structure. In addition, they may have a wide variety of impacts — on the environment, economy, social conditions and health. Likewise, indoor air pollution is a product of many different factors: building characteristics, heating and cooking technologies, and the lifestyle and behaviours of the occupants, as well as ambient air pollution levels and the factors — such as urban design — that affect them.

Developing sound policy measures for systemic risks can pose substantial challenges. Full knowledge about health risks, and the consequences of intervention, is often not available. Problems of air pollution have to be addressed, for example, even though the mechanisms by which many components of the air pollution mixture affect

* Corresponding author. Nat Inst Public Health and the Environment (RIVM), Centre for Environmental health research (Postbak 10), PO Box 1, NL-3720 BA Bilthoven, The Netherlands. Tel.: +31 30 2742869; fax +31 30 274 4451.
E-mail address: Anne.knol@rivm.nl (A.B. Knol).

0048-9697/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2010.03.021

health are as yet poorly understood. Likewise, people that live close to power lines express concern about the effects of electromagnetic fields, while science has yet to define the extent to which these actually represents a threat to health. In many cases, policy intervention may even be part of the problem, as much as it is the solution. Many policy measures have a wide range of side-effects, including potential adverse impacts on human health. These side-effects can occur in space (in another place), time (in another year) or policy domain. Introduction of traffic calming measures to reduce risks of traffic accidents, for instance, affects not only traffic speed, but also emissions of air pollutants (in some cases increasing them), noise and choices people make about travel route and mode. The effects of controls on the use of pesticides are not confined to human health, but inevitably affect agricultural production, other farming practices (e.g. crop choice and tillage regime), food prices and consumption behaviour, and ultimately wider aspects of the agricultural and food industry.

Identifying and assessing these side effects is exceedingly difficult, especially under conditions of incomplete scientific knowledge and data. Yet if the full range of potentially important effects is not considered, serious mistakes can be made in policy development, as numerous recent examples illustrate. Policies on biofuels, for instance, were introduced without allowing for the impacts on food production and prices. According to the World Bank, conversion of land to biofuel production has been responsible for a significant increase in world food prices, up to 60% (World Bank, 2008a). In the United Kingdom, the BSE problem (Bovine Spongiform Encephalopathy, commonly known as mad-cow disease) can be traced back, at least in part, to a combination of policy decisions that, on the one hand, encouraged use of animal residues for feedstuff and, on the other, relaxed the regulations on treatment and processing of offal (Millstone and van Zwanenberg, 2000).

The growing recognition of the complexity of many environmental health issues has stimulated the search for more integrated approaches to policy. For many policy-makers, this requires new ways of thinking and operation: ways that are broad in scope, more inclusive in content and more collaborative in nature. This also challenges the science and consultative processes on which policy makers rely for evidence. In response, the International Risk Governance Council (IRGC) has developed a risk governance framework for these systemic risks (Klinke and Renn, 2006; Renn and Graham, 2005). Risk governance can be described as "the identification, assessment, management and communication of risks in a broad context. It includes the totality of actors, rules, conventions, processes and mechanisms concerned with how relevant risk information is collected, analysed and communicated, and how and by whom management decisions are taken" (International Risk Governance Council, 2009). The IRGC governance framework is meant to support the development of comprehensive risk assessment and management strategies (e.g. risk avoidance or risk reduction). The framework stresses the need to consider scientific, economic, social and cultural aspects of risks, the importance of including stakeholders, the need to deal sensibly with uncertainties, and the importance of integrating scientific, economic, social and cultural aspects of risks.

In addition to the risk governance framework, various methods of integrated assessment are being developed, under different guises and names. Assessment refers to assembling, summarising, organising, interpreting, and possibly reconciling pieces of existing knowledge, and communicating them so that they are relevant and helpful to an intelligent but inexpert decision-maker (Parson, 1995). The extension of integrated assessment methods into the field of environmental health has thus far been limited, though concepts of comparative risk assessment (CRA) (Murray et al., 2003) and integrated risk assessment (IRA) (Bridges, 2003; Bridges and Bridges, 2004; Suter et al., 2005) have begun to emerge. In health impact assessment (HIA) (Joffe and Mindell, 2005; Kemm, 2005; Lock, 2000; Mindell and Joffe, 2003; Mindell et al., 2008), also, there is an increasing awareness of the multidisciplinary nature of many environmental health issues and related policies.

These various approaches to assessment have much in common, but they are based on somewhat different concepts of how environmental factors may affect health, and the information needs of decision makers. It can also be argued that none is yet able to provide assessments of the health effects of complex systemic risks in ways that can fully inform policy decisions. In an attempt to redress this deficiency, Briggs (2008) has proposed the concept of *integrated environmental health impact assessment* (IEHIA). This can be defined as 'a means of assessing the extent, time trends or spatial distribution of health effects related to environmental exposures, and health-related impacts of policies that affect the environment, in ways that take account of the complexities, interdependencies and uncertainties of the real world' Therefore, IEHIA does not only involve the environment and health domains, but also domains such as economy, society, or lifestyle, through which environmental health impacts often propagate. 'Integrated' refers here to different types of integration: along the causal chain from sources to health effects; between different sources, pathways or effects; between scientific disciplines or policy areas; geographically, or temporally (Briggs et al., 2008). IEHIA aims is to unite the various methods of assessment that currently exist, such as HIA and CRA, and provide a more comprehensive framework for assessment in support of policy. Its purpose is to provide a means not only of deciding whether or not risks exist, but also of choosing between different policy options by taking account of their overall impacts — both intended and unintended. The links between IEHIA and other types of assessment are further outlined in (Briggs, 2008).

The process of IEHIA roughly comprises four main stages (Briggs, 2008):

- Issue-framing, during which the problem is defined, and the purpose, scope and limits of the assessment agreed upon;
- Design, during which the methodological approach is specified;
- Execution, in which the relevant data are collected and analysed; and
- Appraisal, in which the results of the assessment are reviewed, communicated and interpreted.

These steps show some similarity to the common steps in other assessment approaches such as HIA and CRA, but there are also some differences. The IEHIA process aims to be inclusive and policy-driven, and focuses more on the first part of assessment (the issue framing phase) than is common in other types of assessments. For a full description of the IEHIA process and the position of IEHIA in relation to other forms of assessment, we refer to (Briggs, 2008).

None of the steps in the assessment process is easy, for the complexities of IEHIA mean that they tend to be used at the limits of existing knowledge. Lack of data and uncertainties in the available models and analytical methods hamper the assessment. These problems are intensified by the large number of stakeholders who might be affected, including policy makers, corporate sectors, NGOs and science communities, as well as representatives of the public, all of whom might justifiably expect to be involved in the policy decisions, and thus party to the assessment (Renn and Graham, 2005). These stakeholders often have different knowledge, values, perceptions and wishes that need to be taken into account. Moreover, the need to involve scientists from different disciplines, and policy-makers from different areas of administration, may breed difficulties of communication and potential conflict emerging from the use of different paradigms.

Underlying these issues, however, is a deeper, conceptual problem. If assessments are to be valid and effective, they have to be structured and designed in a way that both satisfies the many different stakeholders involved and properly reflects the real-world properties and processes of the system under investigation. One means of addressing these challenges is to develop a clear, *a priori* conceptual framework of the system concerned: one that both defines the issue under consideration and sets out the underpinning principles on which the assessment will be based.

Based on work undertaken in two related EU-funded projects, INTARESE (Integrated Assessment of Health Risks from Environmental Stressors in Europe) and HEIMTSA (Health and Environmental Impact Models, Toolbox and Scenario Analysis), this paper examines how conceptual frameworks can be used in support of integrated assessments of environmental health risks. It sets out a typology of conceptual models that can be used in these assessments, and illustrates how they can be applied in the context of a specific example — urban brownfield development for residential uses.

2. Conceptual frameworks

The notion and value of conceptual frameworks, as an aid to thinking and decision-making, gained strength with the development of systems theory during the 1950s and 1960s (Laszlo, 1973; Warren et al., 1979). Their role is to provide an explicit structure within which thinking can take place, and through which to communicate the results of that thinking. In the process of assessment, they should add to and extend the level of understanding of the phenomena being considered, but not act as a strait-jacket for debate. In the words of Judge et al. (1995), conceptual frameworks 'provide a language and frame of reference through which reality can be examined and lead theorists to ask questions that might not otherwise occur'. The use of a conceptual framework can have several potential benefits. It can help to motivate discussion between stakeholders; it can provide a coherent framework within which this debate can take place; it can give a scaffolding on which more detailed definitions of the problem can be built; it can form the basis for planning and organisation of the assessment; and it can offer a structure through which to communicate the results of the assessment, and within which to compare and evaluate the outcomes (Joffe and Mindell, 2006). At the same time, they can form a basis for directing further research and education.

Table 1
Taxonomy of conceptual frameworks and their forms.

Taxonomy of frameworks	Form
LEVEL 1: Structural frameworks	Relatively simple pictorial representation or description of the system under consideration and its important domains.
LEVEL 2: Relational frameworks	Chain- or web-like structures of the key variables within the system and the way these interrelate through logical or functional links
LEVEL 3: Operational models	Detailed operational model of the system under consideration, as a basis for analysis.

Pre-constructed conceptual frameworks, however, may also hinder assessment by obscuring potential other ways to perceive a particular issue. Therefore, it is important to develop these frameworks gradually, involving the views of all stakeholders.

Conceptual frameworks can be represented in many different ways — for example, as narratives, lists, tables or graphics. Several frameworks have been developed in the context of environment and health (Briggs, 2003; Corvalan et al., 1996; Dahlgren and Whitehead, 1991; de Hollander et al., 2007; Diderichsen and Hallqvist, 1998; European Environment Agency, 2005a; Kjellstrom and Corvalan, 1995; Lalonde, 1974; van Kamp et al., 2003), stemming from multiple disciplines and developed for various purposes. For professionals, especially if they come from different disciplines, it can be difficult to determine which of these to use for a specific assessment or how best to apply them.

Somewhat surprisingly, no rigorous taxonomy of frameworks has yet been proposed, and the implications of using different types of framework have rarely been considered. One reason may be that many of the frameworks so far developed defy simple categorisation, but instead cover a spectrum ranging at one extreme from simple, essentially pictorial representations of the world to, at the other, detailed analytical models of the variables and their relationships. In Table 1 we propose a broad three-level subdivision of this spectrum. The hierarchy of these different frameworks is illustrated in Fig. 1.

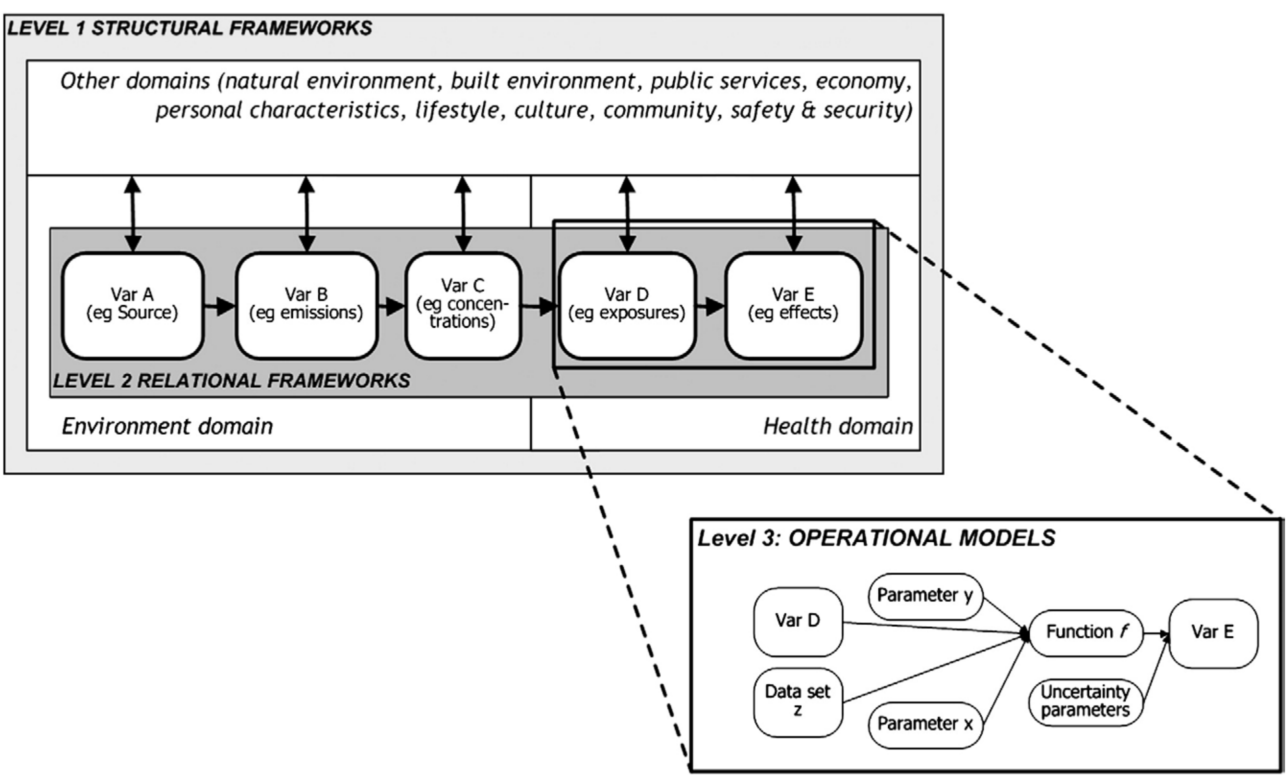


Fig. 1. Hierarchy of three different levels of frameworks: level 1 – structural frameworks; level 2 – relational frameworks; and level 3 – operational models.

Please cite this article as: Knol AB, et al, Assessment of complex environmental health problems: Framing the structures and structuring the frameworks, Sci Total Environ (2010), doi:10.1016/j.scitotenv.2010.03.021

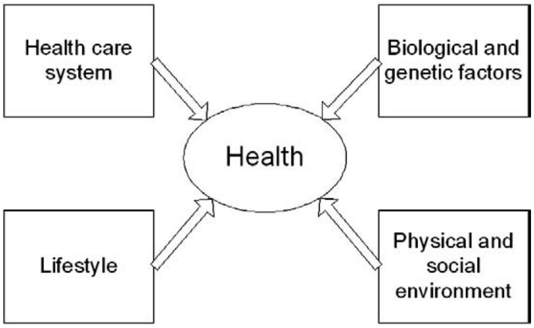


Fig. 2. Lalonde model of determinants of health (Lalonde, 1974).

2.1. Level 1: structural frameworks

At the highest level are the structural frameworks, which describe the general morphology of the system under consideration, often in the form of relatively simple pictorial representations. Typically, they define the *domains* (e.g. economy, biodiversity, health care) into which the world can conveniently be subdivided, and may also show some of the main relationships between them. One of the earliest, yet also most influential, of these frameworks in the area of environmental health was that proposed by Lalonde (1974). It recognises four determinants of health: human biology, environment, life style and health care organization (Fig. 2). This framework was subsequently adopted as the underpinning health model by the Dutch Centre for Public Health Forecasting (de Hollander et al., 2007). Dahlgren and Whitehead (1991) proposed a more complex framework, distinguishing different layers of influence within the health sphere (Fig. 3). The inner core consists of factors which are more or less fixed and immutable (age, sex and hereditary factors), whereas surrounding layers could theoretically be modified (individual lifestyle factors and wider social and community influences). Van Kamp et al. (2003) have presented a model of (human) liveability and (environmental) quality-of-life. It describes the many different domains that might interact with the determinants of environment and health. Various other institutes and research groups have also developed structural frameworks to conceptualise their views on the determinants of health (Arah et al., 2006; Fedoryka, 1997; Kelly et al., 2009; Khassis and Windsor, 1983; Solar and Irwin, 2007; Surjan et al., 2004).

2.2. Level 2: relational frameworks

At level 2 in the hierarchy, relational frameworks focus on the important phenomena within certain domains and the logical or functional links by which these are related. As such, they tend to be chain- or web-like in structure, and to hint at the dynamics of the system. Many of these frameworks have been developed as an aid to indicator construction and selection for policy support. Two of the most widely adopted have been the DPSIR (driving forces-pressures-state-impact-response) framework, used for environmental reporting and assessment in the EU (European Environment Agency, 2005a), and the similar DPSEEA framework (Corvalan et al., 1996; Kjellstrom and Corvalan, 1995), linking Driving forces through Pressures and environmental States to Exposures, health Effects and Actions (Fig. 4). Diderichsen and Hallqvist (1998) devised a somewhat similar framework to represent the social determinants of health. The so-called MEME (Multiple Exposures Multiple Effects) model (Briggs, 2003), developed as a basis for defining indicators of children's environmental health, attempted to break away from the somewhat linear structure inherent in these frameworks. Instead, it regards health effects as the result of exposures to both proximal (i.e. closely related) and more distal (i.e. more indirectly related) risk factors, operating within different environmental settings and wider social, demographic, environmental and policy contexts (Briggs, 2008).

Applied to a specific assessment, relational frameworks represent the individual factors at work within the system, and show their causal relationships. In this assessment-specific form, these frameworks tend to lose the rather structural and often sequential characteristics of their generic counterparts. Instead, they present a comprehensive picture of multiple variables and interactions. While the general principles on which these assessment-specific frameworks are built are more or less fixed, the details of the models will inevitably vary from one issue to another. Briggs (2003), for example, presents a number of models, based on the MEME framework, representing the impact pathways for risks to children's health from vector borne diseases, perinatal diseases, respiratory diseases, physical injuries and diarrhoeal diseases. Kjellstrom et al. (2003)

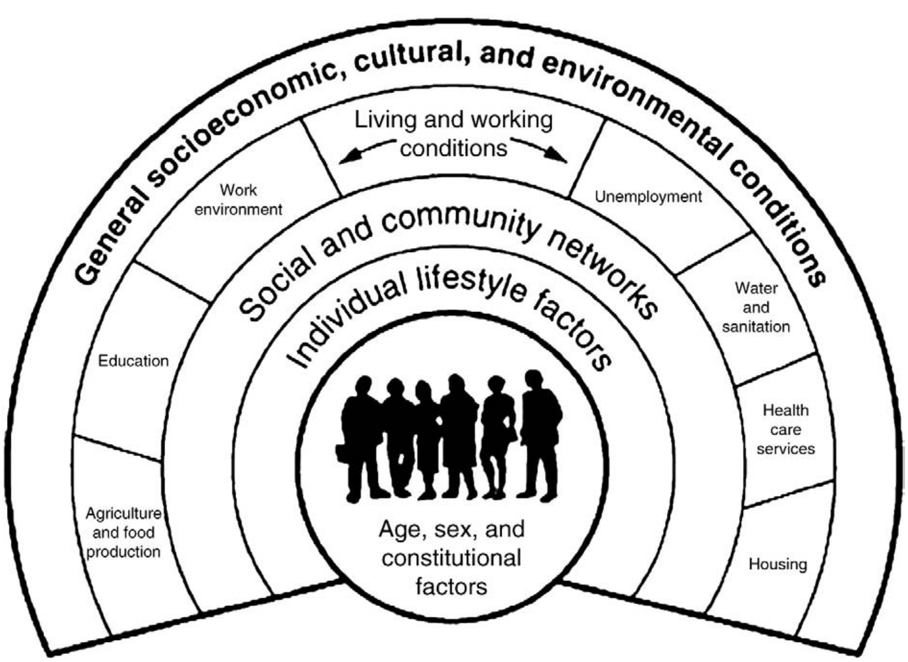


Fig. 3. Dahlgren and Whitehead model of determinants of health (Dahlgren and Whitehead, 1991).

Please cite this article as: Knol AB, et al, Assessment of complex environmental health problems: Framing the structures and structuring the frameworks, Sci Total Environ (2010), doi:10.1016/j.scitotenv.2010.03.021

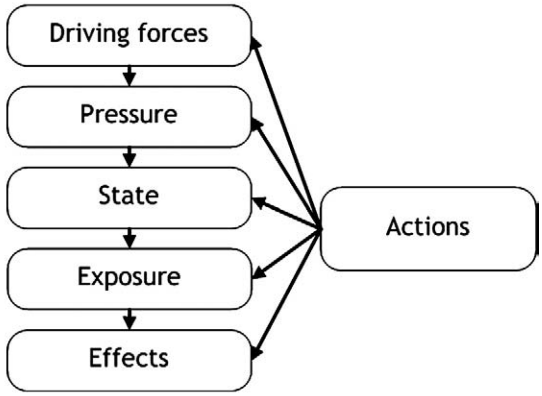


Fig. 4. DPSEEA framework (Corvalan et al., 1996; Kjellstrom and Corvalan, 1995).

developed a detailed impact pathway for health effects of road transport, based on the DPSEEA framework. In addition, many relational frameworks that are not based on a specific generic framework have been developed for particular research areas (e.g. (Bagge and Sher, 2008; DeBaun and Gurney, 2001; Goutard et al., 2007; Huynen et al., 2005; Price and Hawkins, 2007)).

2.3. Level 3: operational models

More detailed models are often needed as a basis for analysis. These operational (level 3) models tend to be complex, and may defy expression in the form of a single diagram. Instead, they are often specified as a set of analytical equations, or as a series of graphs, representing the sub-systems, variables and processes that need to be quantified.

By their very nature, operational models have to be flexible, in order to meet the needs and constraints of individual applications. Explicit rules for model building are nevertheless needed, in order to ensure that the models are transparent, unambiguous and valid. Heuristics of this type have been widely discussed and developed in relation to environmental health indicators (Briggs, 2003; Corvalan et al., 1996; Ezzati et al., 2005), and many of these are more widely pertinent. Two criteria tend to be emphasised: relevance and validity. According to the first of these, all variables and relationships must play a significant role in the system being analysed, such that excluding them would materially affect the outcome of the assessment. This principle thus helps to avoid redundancy in the assessment. Under the second criterion, variables and their relationships must be based on known (or at least credible) causal associations or processes. This is important not only to avoid biasing the assessment by including spurious variables and relationships, but also to make sure that the results of the assessment are interpretable — and that actions taken as a consequence will have the desired effect.

A range of tools and methods for constructing and representing operational models have been developed in recent years, differing in terms of their underlying concepts of causality, level of detail as well as their functionality (Greenland and Brumback, 2002; Vineis and Kriebel, 2006). Amongst these, directed acyclic graphs (DAGs) and associated Bayesian networks have attracted particular attention as a tool for developing analytical strategies in epidemiological research (Greenland et al., 1999; Pearl, 2000; VanderWeele and Robins, 2007). Most proprietary analytical software programs, such as SAS (SAS, 2009), Stata (Baum, 2009) or Analytica (Lumina Decision Systems, 2008), incorporate functions and formats for defining variables and relationships. The last of these also provides a framework for structuring hierarchical models and defining variables, for example by distinguishing between decision, chance and outcome variables.

2.4. Using conceptual frameworks in IEHIA

The different levels of conceptual modelling set out above are not in contradiction with each other. They are clearly complementary. Each represents the system that is being assessed at different levels of detail, and for different purposes in the four different phases of the IEHIA process. Naturally, conceptual frameworks can also fulfil an important role in other types of assessments, such as HIA and CRA, or assessments that are not specifically related to health impacts. In this paper, however, we describe their roles and functions in relation to the process of IEHIA.

In this process, all three framework levels have a role to play, for the assessment almost inevitably involves a gradual progression along the spectrum, from an initial, broad picture of the system under consideration to a detailed model that can serve as a basis for analysis (Fig. 5). In the *issue-framing phase*, a general, yet comprehensible

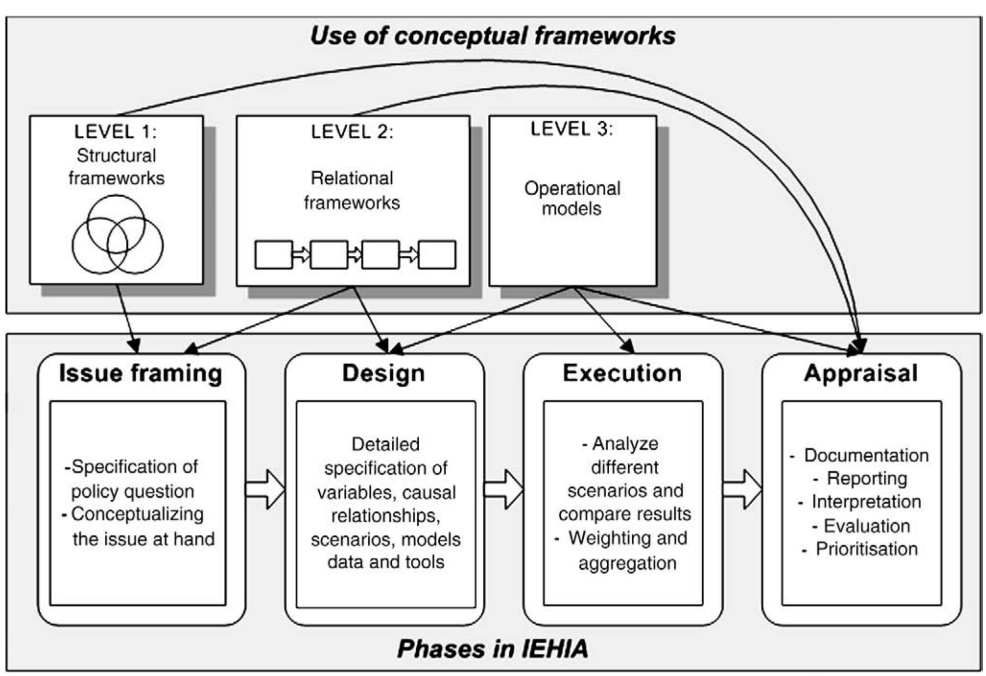


Fig. 5. Phases in the process of integrated assessment (adapted from (Briggs, 2008)) and associated use of conceptual frameworks. In practise, processes are iterative and not necessarily chronological.

Please cite this article as: Knol AB, et al, Assessment of complex environmental health problems: Framing the structures and structuring the frameworks, Sci Total Environ (2010), doi:10.1016/j.scitotenv.2010.03.021

model is needed which stimulates thinking and discussion among stakeholders. At this stage, practical implementation and operation is not necessary. This level 1 framework subsequently needs to be given more specificity in the form of a relational model characterising the causal structure of the system. In the *design* and *execution phase*, this then needs to be translated into a detailed operational model, based on a clear set of heuristics. Finally, in the *appraisal phase*, it may be appropriate to return to a simpler model, focusing on the relevant measures of impact, in order to summarise the results of the assessment and help compare, or choose between, the different options available. All of the frameworks are highly interrelated. The core elements of the assessment that come up during the issue framing phase will also be included in the operational model. In addition, if new insights come up when the operational model is being made, these might necessitate adaptations in the level 1 and 2 frameworks. This emphasizes the iterative nature of assessment.

3. An example

The role of the different types of frameworks in the assessment process can best be illustrated by an example. Here, we use a hypothetical case: the use of brownfield sites for housing development. Brownfields are abandoned or underused industrial or commercial facilities. They might contain contaminated soil or other despoiled land. Demographic changes in Europe are greatly increasing the demand for housing, and are leading, in turn, to major pressures on the peri-urban environment. The consequences are not only loss of prime agricultural land and semi-natural habitats, but also reduced access to green space for the urban population, and increasing land prices. At the same time, there are substantial brownfields, such as old industrial and military land in Europe (including many areas in the former Soviet territories), which have so far often been ignored or avoided for development purposes (Grimski and Ferber, 2001; International Economic Development Council, 2001). In the face of the conflicting pressures, however, several countries have begun to encourage residential development on these brownfield sites, often with support from the European Union (Franz et al., 2006). The United Kingdom, The Netherlands and Germany are examples of countries which are prominent ‘recyclers’ of older industrial areas (International Economic Development Council, 2008). The imperative for brownfield development in these countries is evident: they have limited remaining undeveloped land and a strong desire to preserve their remaining green space. The potential health impacts of such redevelopment policies have, however, so far been given little attention. Below, we will outline the different types of frameworks that could be developed at each stage of this hypothetical assessment.

3.1. Issue framing

As Fig. 5 indicates, the initial step in the assessment process is issue-framing. This phase should ideally involve representatives from all the main stakeholder groups with interests in the policy — including individuals or organisations with responsibility for its implementation and management or those who might be affected in some way by its introduction (National Research Council, 1996). Key stakeholders in this context would thus include regional and local authorities (e.g. housing, planning, environment, social services), elected representatives (e.g. councillors), health authorities (e.g. health trusts, medical services), industry (including building companies, architects, investment companies), land-owners and the public. Scientists and professional impact assessors are also likely to be important players, by contributing to the assessment, while the media will have an important role in disseminating information to, and reflecting the opinions of, the public.

During the issue framing phase, these stakeholders define the problem to be assessed, and set out the scope of the assessment — i.e. agree on what is important and why. This provides an opportunity to

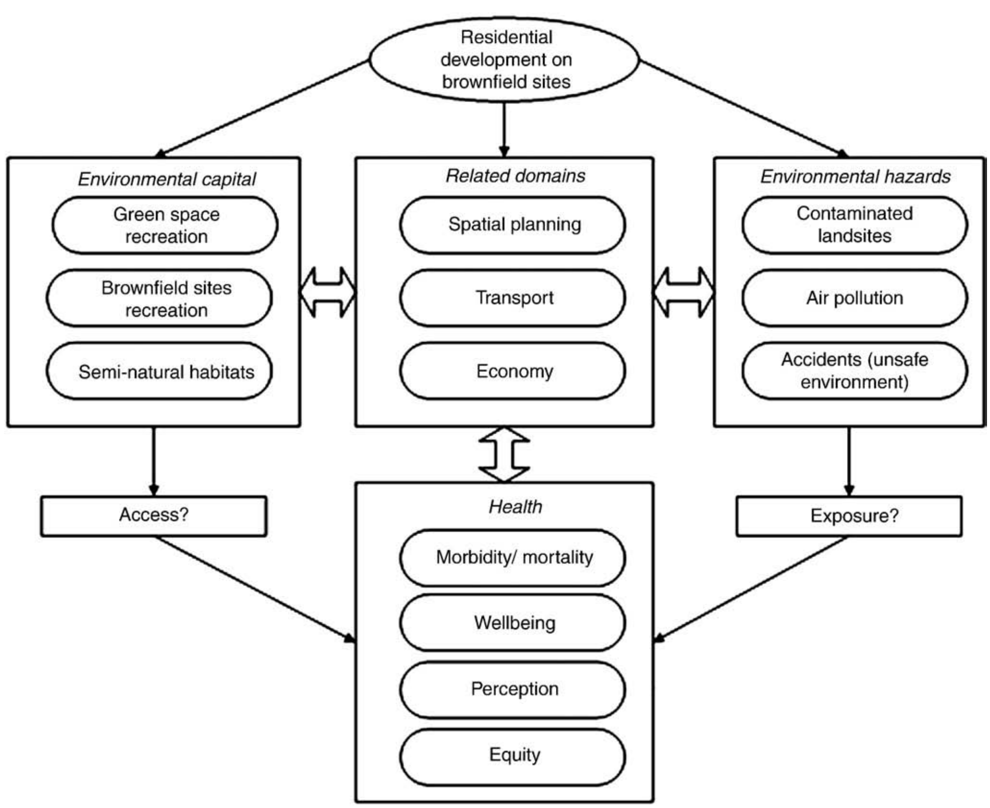


Fig. 6. Level 1 — structural framework applied to the assessment of residential development of brownfield sites.

Please cite this article as: Knol AB, et al, Assessment of complex environmental health problems: Framing the structures and structuring the frameworks, Sci Total Environ (2010), doi:10.1016/j.scitotenv.2010.03.021

explore in more detail the different facets of the issue, and to compare and communicate the different options that exist, before selecting the most appropriate approach (Joffe and Mindell, 2006). How this is done, and by whom, is likely to vary according to circumstance. It may involve both face-to-face meetings (e.g. focus groups, public meetings, expert committees) and remote consultation (e.g. via questionnaires, internet surveys, letters to the newspapers or councillors). In some cases the process may be strongly directed by the lead agency, such as the regional housing or planning authority, that commissions the assessment, or by the scientists acting on their behalf. In other cases, it may be a more haphazard process, emerging in response, for example, to public or business concerns and without any statutory authority.

In this phase, a conceptual framework can facilitate involvement of stakeholders, help to make assumptions explicit, and harmonize discussions (Joffe and Mindell, 2006). A clear conceptual framework will rarely be developed immediately or in one step. Instead, at least two stages of framework development are needed in the issue framing phase: one to set out the underlying logic of 'how the world works' (Level 1 framework) and the next to construct an initial relational model of the issue on the basis of this world-view (Level 2 framework). Figs. 6 and 7 give examples for the case of brownfield site development. First, a relatively simple and iconic level 1 structural framework is used, in order to ensure that it can readily be understood by experts and non-experts alike. The aim of this is to define the broad domains of interest (housing, economic, social, environmental, health) and show how these inter-relate. The model is rather loose in format, for discussion with stakeholders tends to demand the use of flexible devices for discussion and visualisation, similar to mind-maps (Edelenbos and Klijn, 2006; Kloprogge and van der Sluijs, 2006; Tolman, 1948).

The level 2 relational framework (Fig. 7), which may be expected to emerge more slowly, comprises the 'first pass' conceptualisation of the system. It shows the major sources, pathways and impacts that are considered relevant in relation to brownfield development. In our example, important elements to emerge include the identification of the various potential adverse health effects that may occur due to exposures to contaminants, such as hydrocarbon spillages, solvents, pesticides, heavy metals, etc. Adverse impacts on wellbeing also arise through loss of amenities within the urban area, for many brownfield sites provide some form of wildlife habitat and — albeit poor quality — recreational space. Also, residential development may affect transport and associated pollution from the increased residential population in the city. On the other hand, potential health gains arise due to protection of the greenfield areas that would otherwise have been developed, and the housing provision that the development provides. Additionally, the redevelopment of brownfield sites can reduce the risk of physical accidents in children using these sites as playing fields, caused by uncovered holes, unsafe structures, or sharp objects. The potential health effects that might occur as a result of the redevelopment process itself — site cleaning, preparation, building — are not included in the frameworks shown here, but might in reality also be subjected to assessment.

In Fig. 7, an elementary indication of the causal direction of each link is specified with directional arrows. Furthermore, "+" indicates what is assumed to be a positive function (an increase in the source variable leads to an increase in the dependent variable), "–" indicates a negative function, and "?" indicates a relation is mixed or unknown (Joffe and Mindell, 2006). This also means that one variable may indicate both positive as well as negative effects, depending on its sign. For example, the variable indicating the costs can also be regarded as the potential benefits, if the final result of the variable has a negative value.

3.2. Design and execution

Once a broad overview of the issue at hand is available and the main variables and relationships have been identified and agreed upon by the various stakeholders, a more specific operational model is constructed in the design phase. Simultaneously, the methods, models, data and tools necessary to execute the assessment have to be identified. As part of this process, the provisional and somewhat intuitive models used to frame the issue need to be converted into a more detailed description of the system that can be used as the template for analysis. The level 3 operational models that thus emerge are inevitably complex and detailed.

The operational model for our hypothetical assessment of brownfields would consist of a large set of interlinked equations, datasets and models. Exposure–response relationships would need to be established

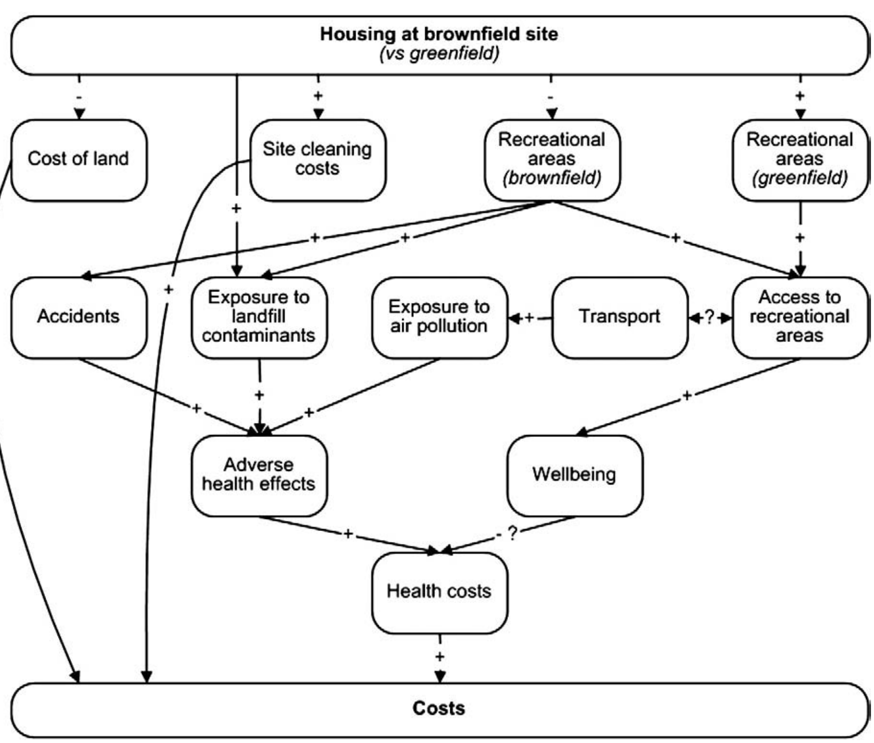


Fig. 7. Level 2 — relational framework applied to the assessment of residential development of brownfield sites.

Please cite this article as: Knol AB, et al, Assessment of complex environmental health problems: Framing the structures and structuring the frameworks, Sci Total Environ (2010), doi:10.1016/j.scitotenv.2010.03.021

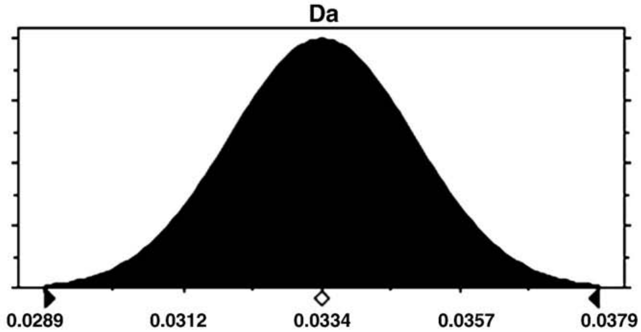
for each of the pollutants and health effects, while the resulting impacts may need to be combined into aggregate measures through some form of weighting and summation. Each of these steps may pose important methodological challenges, because of gaps in the available data and knowledge, and limitations of existing models. Even greater problems may be envisaged in assessing the yet more intangible effects (both negative and positive) likely to be felt in areas which were saved from development. The operational model developed at this stage, therefore, not only acts as a basis for analysis but also helps to draw further attention to potential uncertainties that may be encountered. If these are to be made explicit, it is important that the model is not trimmed to what is possible and plausible, but shows also those elements of the system that cannot be reliably quantified and might — in a later stage — be excluded from the quantitative part of the analysis.

It is beyond the scope of this paper to present a full operational model for the assessment of residential development of brownfield sites. However, various operational models on related topics exist in the literature, and may serve as an illustration. For example, the UK Contaminated Land Exposure Assessment (CLEA) project has developed software to estimate the risks of long-term exposure to contaminants in soil (Environment Agency, 2009). The software is based on a set of linked conceptual models of exposure, which are defined by a series of parameters, algorithms and data sets. Similarly, the Dutch National Institute for Public Health and the Environment (RIVM) has developed the VOLASOIL model, which estimates the indoor air concentration originating from volatile compounds of soil contamination (Bakker et al., 2008). This model also includes sensitivity and uncertainty analyses that can be used to compare different conceptual models of the system. As a final example, Dawidowski et al. (2002) describe the use of geographic information systems (GIS) to show the distribution of heavy metal concentrations in different environmental media such as air and water, based on a set

A

Parameter	Symbol	Unit
Measured concentration in groundwater	Csw	m
Depth of groundwater table	dgw	m
Measured concentration in soil air at dp	Csa	$mol.dm^{-3}$ or $g.m^{-3}$
Measured concentration in soil at dp	Cs	$mol.kg^{-1}$ or $mg.kgdry\ soil^{-1}$
Average depth of contaminant	dp	m

B



C

$$VF = \frac{\rho_s}{\frac{1}{10} \times Q/C_{wind}} \sqrt{\frac{4D_{eff}}{\pi\tau \times 31536000\, s\, yr^{-1}} \times \frac{K_{aw}}{K_{sw}\,\rho_s}}$$

Where: VF is the volation factor from surface soil to ambient air, g cm^{-3}
ρ_s is the dry bulk soil density, g cm-3
Q/C_{wind} is the air dispersion factor, g m^{-2} s^{-1} per kg m^{-3}
D_{eff} is the effective diffusion coefficient for unsaturated soils, cm^2 s^{-1}
τ is the averaging time for surface emission vapour flux, year
K_{aw} is the averaging air-water partition coefficient at ambient temperature, cm^3 cm^{-3}
K_{sw} is the total soil-water partition coefficient, cm^3 g^{-1}

D

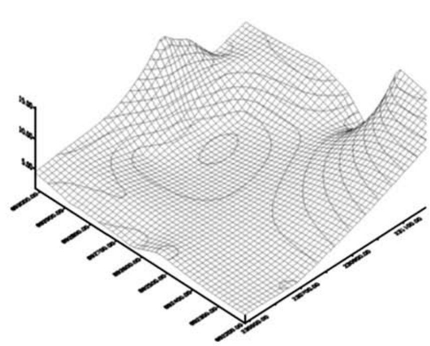


Fig. 8. Examples of parts of level 3 — operational models related to the assessment of residential development of brownfield sites: A) input data; B) parameter distributions; C) equations; D) output.

of mathematical and logic relations. Some illustrations of the in- and output of these operational models are shown in Fig. 8.

3.3. Appraisal

In the final appraisal phase, decision makers (and other stakeholders) need to evaluate the results of the analysis and prioritise the policy options on the basis of the indicators selected as a basis for assessment. In addition, stakeholders may want to look back upon the initial conceptualisation of the issue in order to check that the assessment has been faithful to the principles established at that point, and to understand how any changes have arisen. For this latter reason, results of the assessment should, as far as possible, be fitted to the original conceptual frameworks, and any adaptations from those need to be highlighted and explained. At the same time, it is likely to be helpful to express the results in terms of the more detailed, operational model used in the design and execution stage, both to give further insight into the issue and its complexity, and to help justify any changes in the analysis. Such reference to each of the frameworks provides valuable information about the conceptual basis and the proper interpretation of the indicators chosen to communicate the assessment results.

4. Discussion and conclusions

Conceptual frameworks are very useful tools in the process of integrated environmental health impact assessment. They can help to stimulate thinking outside the channels within which different experts from different disciplines usually work; facilitate involvement of stakeholders; help to make assumptions explicit; provide a framework for data analysis, generate testable predictions and projections; explore the effects of interventions; identify data gaps or weak links; and provide a context for interpretation of results (Joffe and Mindell, 2006). Several generic conceptual frameworks have been developed for use in IEHIA, each from a different perspective and with a different purpose. In some ways, this plethora of frameworks represents a problem, for it can confuse those involved and add to the lack of consistency in the way assessments are designed and executed. On the other hand, it also reflects the reality that different issues and assessments need to be conceived differently. This thus emphasises the importance of flexibility in issue-framing, rather than the imposition of a rigid (and not always appropriate) preconceived framework. In other words: conceptual frameworks need to be developed from the subject matter rather than the subject matter being squeezed into pre-existing categories. Indeed, one of the most important benefits of building frameworks from scratch is that they force those concerned to think about the underlying principles, and how best to represent them. Often, the process of developing conceptual models is at least as valuable as the model itself.

In selecting and developing frameworks for the purpose of assessment, however, there is a need for clear understanding of the different types of frameworks that may be devised, and their potential role in assessment. In this paper, we have therefore proposed a simple taxonomy of frameworks and shown how these can be applied to the example of urban brownfield development. At the first level, structural frameworks show the wide context of environmental health issues, set within the domains of for example economy, culture, and psychology. At the second level, relational frameworks describe how environmental health variables are commonly causally related. At the third level, operational models serve as a basis for analysis.

The frameworks at levels 1 and 2 deliberately simplify the complexities that characterise the real world, for the very purpose of enabling assessments to come to terms with these complexities. As a consequence, these generic frameworks cannot make explicit all the processes and interconnections that exist, and may be relevant, in many situations.

They are thus essentially supportive tools, which should be elaborated in discussions with stakeholders. The operational models developed at level 3, in contrast, are usually an attempt to capture the details of the complete system under study, as a basis for analysis. Constructing those is inevitably a largely scientific exercise, in which stakeholders are often much less involved. However, in order to represent the ideas put forward by these stakeholders, the operational models should stay as close as possible to the more general models that they intend to represent, and any deviations from the principles underlying those models should be explained.

The motive for this paper was the somewhat surprising lack of discussion to date on the nature of conceptual frameworks, and how best to apply them in the field of environmental health. The need for these frameworks is nevertheless increasing, as environmental health policies, and the sciences that support them, attempt to break away from their traditional, essentially reductionist approaches, and instead deal with risks to health in a more integrated way. The concept of risk governance has increased the awareness of the need for integrating knowledge from different disciplines and involving stakeholders in all phases of assessment. This process has confronted risk assessors and policy-makers with a new challenge: how to order their thoughts, and conduct debates with stakeholders, in an organised and efficient way, and in the face of huge complexity and ambiguity. Conceptual frameworks are an important tool in this respect, but if they are to be applied effectively then the current gaps in understanding need to be addressed.

Further research into the issues raised here is therefore needed. Examples should be developed, using real-life situations, to demonstrate the utility of conceptual frameworks in assessment and policy-making. There is a need also to understand more clearly how different conceptualisations of the world may affect the perception and prioritisation of what needs to be assessed, and the results (and ultimate use) of the assessments. From this, it might be possible to devise more detailed rules for framework design and development. Likewise, methods and tools are needed to help construct conceptual models effectively, especially amongst different stakeholders who may vary in their expertise and knowledge. In the 1990s, Antunes and Camara (1986) presented suggestions for the development of a computerized system for selecting variables and defining causal relationships, based on expert knowledge and heuristics. However, to our knowledge, no such tool which is suitable for IEHIA yet exists. In addition, further work is required to help devise ways of seamlessly making the step from simple, qualitative descriptions of the systems under consideration, devised during the issue-framing stage, into more quantitative and rigorous analytical models that can be used to carry out the assessment. These are challenges that deserve attention, for it is increasingly evident that the solution to the environmental health problems that face the modern world will not come from a collection or piecemeal approaches, but demand more integrated and collective action. This will only be achieved if all those concerned can readily share their knowledge and communicate their concerns in an equal and open environment. Integrated assessments have a key role to play in this context, but the science (and art) of structuring complex problems in ways that enable assessment still needs to advance.

Acknowledgements

We would like to thank Irene van Kamp and Bert Brunekreef for their useful comments to earlier versions of this manuscript. In addition, we thank the reviewer for the very helpful comments and suggestions.

References

Antunes P, Cámara A. A new approach to environmental impact assessment. Conference proceedings, The 1986 international conference of the systems dynamics society, Sevilla, October 1986.

Arah OA, Westert GP, Hurst J, Klazinga NS. A conceptual framework for the OECD Health Care Quality Indicators Project. Int J Qual Health Care 2006;18(Suppl 1):5-13.
Bagge CL, Sher KJ. Adolescent alcohol involvement and suicide attempts: toward the development of a conceptual framework. Clin Psychol Rev 2008;28:1283–96.
Bakker J, Lijzen J, van Wijnen H. Site-specific human risk assessment of soil contamination with volatile compounds [Locatiespecifieke humane risicobeoordeling van bodemverontreiniging met vluchtige verbindingen]. RIVM report 711701049 RIVM, Bilthoven, the Netherlands; 2008.
Baum C. An Introduction to Stata Programming. Stata Press; 2009.
Bridges J. Human health and environmental risk assessment: the need for a more harmonised and integrated approach. Chemosphere 2003;52:1347–51.
Bridges JW, Bridges O. Integrated risk assessment and endocrine disrupters. Toxicology 2004;205:11–5.
Briggs DJ. Making a difference. Indicators to improve children's environmental health. Geneva: World Health Organisation; 2003.
Briggs DJ. A framework for integrated environmental health impact assessment of systemic risks. Environ Health 2008:7.
Briggs DJ, Sabel CE, Lee K. Uncertainty in epidemiology and health risk and impact assessment. Environ Geochem Health 2008;31:189–203.
Corvalan C, Briggs DJ, Kjellstrom T. Development of environmental health indicators. Linkage methods for environment and health analysis. General guidelines. UNEP, USEPA and WHO, Geneva, 1996.
Dahlgren G, Whitehead M. Policies strategies to promote social equity in health. Stockholm, Sweden: Institute for Future Studies; 1991.
Dawidowski A, Bzowski Z, Konopa W. Application of geographic information system (GIS) to the assessment of soil contamination. International Carpathian Control Conference ICCC' 2002, Malenovice, Czech Republic; 2002.
de Hollander AEM, Hoeymans N, Melse JM, van Oers J, Polder J. Care for health. The 2006 Dutch Public Health Status and Forecasts Report. RIVM report 270061003 RIVM, Bilthoven; 2007.
DeBaun MR, Gurney JG. Environmental exposure and cancer in children. A conceptual framework for the pediatrician. Pediatr Clin North Am 2001;48:1215–21.
Diderichsen F, Hallqvist J. Social inequalities in health: some methodological considerations for the study of social position and social context. Inequality in health — a Swedish perspective. Stockholm: Swedish Council for Social Research; 1998.
Edelenbos J, Klijn E. Managing stakeholder involvement in decision-making: a comparative analysis of six interactive processes in The Netherlands. J Public Adm Res Theory 2006;16:417–46.
EEA. Energy and environment report 2008. EEA Report No 6/2008; 2008.
Environment Agency. CLEA software (version 1.4) Handbook. Science report — SC050021/SR4 Bristol, UK; 2009.
European Environment Agency. The European envionment — state and outlook. Luxembourg: Office for Official Publications of the European Communities; 2005a.
European Environment Agency. The European environment — state and outlook. Luxembourg: Office for Official Publications of the European Communities; 2005b.
European Environment Agency. Urban sprawl in Europe — the ignored challenge. EEA Report No 10/2006; 2006.
Ezzati M, Utzinger J, Cairncross S, Cohen AJ, Singer BH. Environmental risks in the developing world: exposure indicators for evaluating interventions, programmes, and policies. J Epidemiol Community Health 2005;59:15–22.
Fedoryka K. Health as a normative concept: towards a new conceptual framework. J Med Philos 1997;22:143–60.
Franz M, Pahlen G, Nathanail P, Okuniek N, Koj A. Sustainable development and brownfield regeneration. What defines the quality of derelict land recycling? Environ Sci 2006;3:135–51.
Goutard F, Roger F, Guitian FJ, Balanca G, Argaw K, Demissie A, et al. Conceptual framework for avian influenza risk assessment in Africa: the case of Ethiopia. Avian Dis 2007;51:504–6.
Greenland S, Brumback B. An overview of relations among causal modelling methods. Int J Epidemiol 2002;31:1030–7.
Greenland S, Pearl J, Robins JM. Causal diagrams for epidemiologic research. Epidemiology 1999;10:37–48.
Grimski D, Ferber U. Urban brownfields in Europe. Land Contam Reclam 2001;9:143–8.
Huynen MM, Martens P, Hilderink HB. The health impacts of globalization: a conceptual framework. Global Health 2005;1:14.
International Economic Development Council. Converting Brownfields to Green Space. Washington, DC: International Economic Development Council; 2001.
International Economic Development Council. International Brownfields Redevelopment. Washington, DC: International Economic Development Council; 2008.
International Risk Governance Council. Risk governance deficits: an analysis and illustration of the most common deficits in risk governance. Geneva: International Risk Governance Council; 2009.
Joffe M, Mindell J. Health impact assessment. Occup Environ Med 2005;62:907–12.
Joffe M, Mindell J. Complex causal process diagrams for analyzing the health impacts of policy interventions. Am J Public Health 2006;96:473–9.
Judge D, Stoker G, Wolman H. Urban politics and theory: an introduction. In: Judge D, Stoker G, Wolman H, editors. Theories of Urban Politics. London: Sage; 1995. p. 1-13.
Kelly MP, Stewart E, Morgan A, Killoran A, Fischer A, Threlfall A, et al. A conceptual framework for public health: NICE's emerging approach. Public Health 2009;123: e14–20.
Kemm J. The future challenges for HIA. Environ Impact Assess Rev 2005;25:799–807.
Khassis U, Windsor RA. Building an infrastructure for health: a conceptual framework and application. Hygie 1983;2:27–32.
Kjellstrom T, Corvalan C. Frameworks for the development of environmental health indicators. World Health Stat Q 1995;48:144–54.
Kjellstrom T, van Kerkhoff L, Bammer G, McMichael T. Comparative assessment of transport risks - how it can contribute to health impact assessment of transport policies. Bull World Health Organ 2003;81:451–7.
Klinke A, Renn O. Systemic risks as challenge for policy making in risk governance. Forum: Qualitative Social Research; 2006. p. 7.
Kloprogge P, van der Sluijs JP. The inclusion of stakeholder knowledge and perspectives in integrated assessment of climate change. Clim Change 2006;75:359–89.
Lalonde M. A conceptual framework for health. RNAO News 1974;30:5–6.
Laszlo E. The rise of general systems theories in contemporary science. Zeitschfift ftlr allgemeine Wissenschaftstheorie, IW2. 1973. p. 335–44.
Lock K. Health impact assessment. BMJ 2000;320:1395–8.
Lumina Decision Systems. Analytica. Lumina Decision Systems; 2008.
Martens P, McMichael AJ. Environmental change, climate and health: issues and research methods. Cambridge: Cambridge University Press; 2002.
McMichael A, Campbell-Lendrum D, Ebi K, Githeko A, Scheraga J, Woodward A. Climate change and human health: risks and responses. Geneva: World Health Organization; 2003.
McMichael AJ, Woodruff RE, Hales S. Climate change and human health: present and future risks. Lancet 2006;367:859–69.
Millstone E, van Zwanenberg P. A crisis of trust: for science, scientists or for institutions? Nat Med 2000;6:1307–8.
Mindell J, Joffe M. Health impact assessment in relation to other forms of impact assessment. J. Public Health Med 2003;25:107–12.
Mindell JS, Boltong A, Forde I. A review of health impact assessment frameworks. Public Health 2008;122:1177–87.
Murray CJ, Ezzati M, Lopez AD, Rodgers A, van der Hoorn S. Comparative quantification of health risks conceptual framework and methodological issues. Popul Health Metr 2003;1:1.
National Research Council. Understanding Risk: Informing Decisions in a Democratic Society. Washington, DC: National Academy Press; 1996.
Parson E. Integrated assessment and environmental policy making, in pursuit of usefulness. Energy Policy 1995;23:463–75.
Pearl J. Causality. Cambridge University Press; 2000.
Price NL, Hawkins K. A conceptual framework for the social analysis of reproductive health. J Health Popul Nutr 2007;25:24–36.
Prüss-Ustün A, Corvalán C. How much disease burden can be prevented by environmental interventions? Epidemiology 2007;18:167–78.
Renn O, Graham P. White paper on risk governance towards an integrative approach. International Risk Governance Council; 2005.
SAS. SAS Language Reference: Concepts. SAS Variables — Variable Attributes. http://www.sfu.ca/sasdoc/sashtml/lrcon/z1103996.htm.
Solar O, Irwin A. Towards a conceptual framework for analysis and action on the social determinants of health. Geneva: WHO Commission on Social Determinants of Health; 2007.
Surjan G, Szilagyi E, Kovacs T, Kincses G. Conceptual framework of health indicators: the IDA model. Stud Health Technol Inform 2004;107:1230–4.
Suter GW, Vermeire T, Munns Jr WR, Sekizawa J. An integrated framework for health and ecological risk assessment. Toxicol Appl Pharmacol 2005;207:611–6.
Tolman E. Cognitive maps in rats and men. Psychol Rev 1948;55:189–208.
UN-Habitat. State of the World's Cities 2008/2009: Harmonious Cities. Nairobi, Kenya: United Nations Human Settlement Program; 2008.
United Nations Environment Programme. Global Environment Outlook GEO4 — environment for development; 2007.
United Nations Population Division. World Population Prospects, 2008 Revision. United Nations Population Division; 2009.
van Kamp I, Leidelmeijer K, Marsman G, de Hollander AEM. Urban environmental quality and human well-being. Towards a conceptual framework and demarcation of concepts; a literature study. Landscape Urban Plann 2003;65:5-18.
VanderWeele TJ, Robins JM. Directed acyclic graphs, sufficient causes, and the properties of conditioning on a common effect. Am J Epidemiol 2007;166:1096–104.
Vineis P, Kriebel D. Causal models in epidemiology: past inheritance and genetic future. Environ Health 2006;5:21.
Warren CE, Allen M, Haefner JW. Conceptual frameworks and the philosophical foundations of general living systems theory. Behav Sci 1979;24:296–310.
World Bank. Biofuels: the promise and the risks. World Development Report 2008. Agriculture for Development; 2008a.
World Bank. Global Economic Prospects 2009: Commodities at the Crossroads; 2008b.
World Water Assessment Programme. The 3rd United Nations World Water Development Report: Water in a Changing World (WWDR-3). Earthscan, Paris, London: Unesco; 2009.

Please cite this article as: Knol AB, et al, Assessment of complex environmental health problems: Framing the structures and structuring the frameworks, Sci Total Environ (2010), doi:10.1016/j.scitotenv.2010.03.021