Global Change and Sustainable Development

a modelling perspective for the next decade

Global Dynamics &
Sustainable Development
Programme

rivm
research for
man and environment

June 1994; RIVM Report no. 461502004

GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT

a modelling perspective for the next decade

J. Rotmans
M.B.A. van Asselt
A.J. de Bruin
M.G.J. den Elzen
J. de Greef
H. Hilderink
A.Y. Hoekstra
M.A. Janssen
H.W. Köster
W.J.M. Martens
L.W. Niessen
H.J.M. de Vries

Global Dynamics & Sustainable Development Programme
GLOBO Report Series no. 4

rivm
research for man and environment
RIJKSINSTITUUT VOOR VOLKSGEZONDHEID EN MILIEUHYGIENE
NATIONAL INSTITUTE OF PUBLIC HEALTH AND ENVIRONMENTAL PROTECTION

Design: Martin Middelburg, studio RIVM
Lay-out, production: Martin Middelburg, studio RIVM
Printing: Rink & van Setten, Holland

National Institute of Public Health and Environmental Protection (RIVM)
P.O. Box 1
3720 BA Bilthoven, The Netherlands
Tel.: 31 -30 - 74 33 23
Fax.: 31 -30 - 25 07 40
E-mail: cwmjan@cwm120.rivm.nl

CONTENTS

SUMMARY OF THE RESEARCH PROGRAMME

General Scope

In the international decision-making community there is a growing need for an operationalisation of the notion of sustainable development. Therefore, in 1992 the National Institute of Public Health and Environmental Protection (RIVM) in The Netherlands launched the research programme 'Global Dynamics and Sustainable Development'. The main objective of this research programme is to operationalise, and to render applicable, the concepts of global change and sustainable development. To this end, a global, integrated assessment model will be developed, by means of which an analysis and assessment can be performed, on a global scale, of the quantitative and qualitative linkages among social and economic processes, biophysical processes and effects on ecosystems and humans. Such a global, integrated assessment model can yield insights into the complex interrelations in time and space between increasing worldwide pressure on the environment, pollution and disruption of essential biogeochemical cycles, and the effects of anthropogenic influences on the environment, human health and society as a whole, in both the short and the longer term. Furthermore, an integrated assessment model can be used to develop concrete strategies for sustainable development, which enables decision makers to select the most promising strategies.

The model should be regarded as an aid to the formulation of possible projections for the future, and not as a means of generating predictions as such. A great deal of attention will be paid to the presentation of the relevant information generated by the model in an insightful manner, which is of crucial importance in the communication process between science and policy-making. This necessitates the 'opening' of models, an exercise which ranges from the construction of a model which can be used interactively, to the creation of strategic planning exercises, whereby models serve to provide guidelines in the background. Because it is becoming increasingly evident that there is no unique definition of sustainable development, and that the interpretation of this concept depends strongly on the perspective of a specific actor, an attempt is to be made to incorporate various scientific and cultural perspectives in the integrated assessment model.

It is therefore expected that the programme will be able to add a new dimension to the use of integrated assessment models: namely, not only the use of such a model as means of communication between scientists and policy makers/analysts, but also between exponents of the natural sciences and the social sciences.

Global change and sustainable development

In this study the totality of changes on planet Earth, including all human interventions and alterations, is considered as constituting global change, a concept which is therefore broader than the concept of global environmental change. The latter only refers to the human-induced biophysical changes in the dynamics of the Earth system, while global change refers to changes in both the biophysical and the human system. In practice, the concept of global environmental change is a general umbrella term for a whole range of mutually dependent global environmental problems. Within the context of this research programme global change is, in contrast to earlier studies, considered from an integrated perspective. This means that the classical way of splitting up environmentally related problems into themes, functions and scales will be abandoned. In this study the starting point is to consider the common causes, mechanisms and impacts of a number of coherent themes, functions and scales, and to translate this in terms of Pressure, State, Impact and Response (P-S-I-R approach). This is more in line with the universal principle of approaching environmentally related problems, which assumes that many of those problems are generic in nature.

Hitherto, the concept of sustainable development has mainly been used as a guide and target for policy making directed towards combatting the threats of global change. The report published by the World Commission on Environment and Development entitled 'Our Common Future' played a key role, with its frequently cited anthropocentric definition of sustainable development: 'a development that fulfils the needs of the present generation without endangering the future needs of future generations'. An alternative definition of sustainable development is presented by IUCN/UNEP/WWF from an ecocentric perspective: 'improving the quality of human life while living within the carrying capacity of supporting ecosystems'. These definitions indicate that there is no unambiguous definition of sustainable development, but that this is strongly dependent on the scientific and cultural perspective chosen. Within the context of this study, instead of putting forward another definition of sustainable development, both the anthropocentric and ecocentric (and maybe a mixed) approach towards the notion of sustainable development will be elaborated. However, as opposed to previous studies dealing with this concept, it will not be considered from a monodisciplinary viewpoint, but it will be a multi- and interdisciplinary effort which allows for an integrated vision of what sustainable development is, and how it can be achieved. The research programme defined here is designed to fill that gap, by bringing different scientific disciplines together, from natural sciences such as physics, chemistry and ecology, as well as social sciences such as sociology and economics.

Global change and sustainable development: *an integrated systems approach*

The justification for adopting a systems approach as a means by which to operationalise the concepts of global change and sustainable development is based on the following chain of argument: sustainable development is closely allied to the natural resilience and buffer capacity of the biosphere in relation to anthropogenic disturbances. On a global scale, this disturbance is denoted as global change and can be represented by a set of interrelated cause-effect chains, here chosen as starting points. The inextricably interconnected cause-effect chains form an organized whole, the properties of which are more than just the sum of its constituent parts. Cause-effect chains may be aggregated into a steering system, pressure subsystems, state dynamics subsystems and impact subsystems. This means that an appropriate methodological approach to the concept of global change is the systems approach, an approach which concentrates on the interactions and feedback mechanisms between the different subsystems of cause-effect chains of global change rather than focusing on each subsystem in isolation. Such a systems approach should be a multi- and interdisciplinary effort based on the integration of knowledge gleaned from a variety of scientific disciplines. Starting at the highest systems aggregation level, the approach followed will consist of the following steps: first, a systems analysis is to be performed, revealing the contours of the whole complex system and its division into various subsystems. In this phase it is essential to investigate what the relations and interactions between the different subsystems are; what the boundaries of the system are, what is exogenous and what endogenous; what the required aggregation level is for the whole system and for the subsystems; and last, but not least, what the limitations of a systems approach for analysing global change and sustainable development are. Next, the different perspectives from which the system can be viewed are to be sketched, as well as the aspect of how to visualize these perspectives. Finally, the concept of uncertainty and the propagation of uncertainty in the whole complex system will be made explicit and clearly visualised, in such a way that it can support the international decision-making process.

An integrated modelling framework for global change and sustainable development

An integrated assessment modelling framework for global change and sustainable development will be developed on the basis of the systems approach described above: **TARGETS:** **T**ool to **A**ssess **R**egional and **G**lobal **E**nvironmental and health **T**argets for **S**ustainability. The justification for developing an integrated assessment model is that it will be one of the first attempts to consider global change and sustainable development from an integrated dynamic perspective. Such an integrated modelling approach will enable the consequences of several types of human influences to be evaluated simultaneously. It is hereby envisaged that synergetic effects, which are currently beyond the horizon of predictive competence, may be brought into view. On the other hand, we must exercise vigilance if we are to avoid building one more large and complex model which produces questionable, misleading or opaque results. We must therefore learn from experiences with global models, which show us that they in particular suffer from: (i) inadequate understanding of the system being modelled; (ii) absence of stochastic behaviour; and (iii) inadequate treatment of the concept of uncertainty. Much attention is therefore to be paid to the issues of uncertainty, stochastic behaviour and how to deal with incomplete knowledge.
The challenging aspect of building such an integrated assessment model is to find the right balance between simplicity and complexity;

aggregation and realistic outcomes; stochastic and deterministic elements; qualitative and quantitative linkages; transparency and uncertainty. Furthermore, it is of major importance to face the limitations of the model to be built and to recognize the type of issues/questions that **cannot** be addressed by and what falls **beyond** the scope of the model.
The approach adopted here will consist of the development of mathematical models to be built for the different subsystems. The mathematical models will be implemented in the form of computer simulation models. These simulation models (modules) will be coupled and ultimately integrated. Finally, the various modules will be validated, as well as the model as a whole.

Indices for sustainable development

One of the possibilities to operationalise the concept of sustainable development is to design sustainability indicators. Indicators can monitor the pressure on, the status of, and the impact on the global environment; they serve as the vehicles for the communication of the model results, on the basis of which sustainable routes can be mapped out. In particular there is a strong need for highly aggregated and composite indicators, here defined as indices, in which condensed information is assembled. The method proposed here attempts to develop a hierarchical framework of indicators which is linked to the integrated modelling framework TARGETS. In the hierarchical indicator framework proposed, different levels of aggregation are distinguished, varying from highly aggregated indices to absolute indicators in the form of observed data or statistics. The main advantage of linking a set of indicators to an integrated modelling framework is that it yields insight into the complex dynamics of the system under concern. This enables the production of coherent information about linkages between causes and effects (vertical integration) and the addressing of cross-linkages between different issues (horizontal integration). This coherent and integrative information can only be generated by an interconnected framework of indicators, and not by separate indicators. The ultimate goal of the hierarchical framework is to create an overall index which captures the key characteristics of the global environment in a single measure, and to demonstrate the dynamic interrelations between this abstract index and the real-world indicators.
The following steps can be distinguished in constructing the hierarchical framework of indicators and indices: experimentation, selection, scaling, weighing and aggregation. The various steps described above can be based upon a combination of expert judgement, delphi-techniques, multi-criteria analysis, public opinion polls, value-based decisions and modelling experiments. This requires frequent and intensive interaction between decision makers and modellers.
The hierarchical framework of indicators and indices will be used to develop and evaluate alternative strategies for sustainable development. First, sustainable states are to be determined by introducing target values which are based on empirical knowledge or on modelling results. Then it will be indicated whether and how these sustainable states could be reached, by calculating the components of the indices in the framework and comparing these values with the target values. Using this method of 'backcasting' to develop coherent and consistent strategies for sustainable development, the technique of optimization might serve as a helpful guide.

Different perspectives

Making the uncertainties in the TARGETS visible and tangible is one of the key issues of this research programme. Although uncertainty due to subjectivity and disagreement plays a key role in integrated assessment modelling, no concrete methods are available for making those uncertainties explicit. Subjective judgement and disagreement can be related to different perspectives people have. The various perspectives considered in this study are based on scientific hypotheses or theories (scientific perspectives), or originate from differences in the values, beliefs and social relations people have (cultural perspectives).
Points of departure for the scientific perspectives are the 'Gaia perspective' and the 'Expectation of the unexpected'. In the biophysics part of TARGETS, these perspectives will be implemented in such a way that, from the 'Gaia' perspective, the negative feedbacks dominate the system (damping effect), while in the 'Expectation of the unexpected' perspective the positive feedbacks dominate (accelerating effect).
Next, the biophysics part of TARGETS will be adjusted to both scientific perspectives by (i) changing the dynamic structure of the system; and (ii) incorporating the natural variability.
With respect to the cultural perspectives, the cultural theory of Thompson *et al.* (1990) will be taken as a

starting point; they consider a cultural perspective as a viable combination of social relationships and cultural bias, based on which five cultural perspectives can be distinguished: hierarchy, egalitarianism, fatalism, individualism and autonomy. In this study four perspectives - we exclude the autonomous perspective, because he is not interested in what happens in the world - will be operationalized. By combing the concept of uncertainty with the concept of cultural perspectives we arrive at the concept of perspective based alternative model routes, as a methodology to make uncertainties explicit within the TARGETS model. Alternative model routes are model interpretations in which the weak parts due to uncertainties in knowledge are colored with the bias and preference of a certain perspective.

Investigation will cover whether the implementation of the scientific and cultural perspectives leads to enhanced insights, and, if so, whether, based on this knowledge, new policies for sustainable development can be formulated and new research priorities can be set.

1. INTRODUCTION

1.1 Global change

Human activities have significantly affected the structure and the functioning of the Earth system. Our use of land, water, minerals and other natural resources has increased more than ten-fold during the past 200 years, and future increases in population and development will only intensify this pressure. Large-scale chemical transformations and natural transfers of energy and materials around the world are involved (IGBP, 1992). During the last few decades we have seen increasing acceptance of the insight that the increase in magnitude and complexity of such large-scale problems causes serious harm, varying from a disruption of local ecosystems up to global disturbance of the biosphere as a whole.
In this study the totality of changes on planet Earth, including all human interventions and alterations, is considered as constituting global change. The concept of global change is broader than the concept of global environmental change, since the latter only refers to the human-induced biophysical changes to the dynamics of the Earth system, while global change refers to changes of both the biophysical and the human system, see *Figure 1.1*.

In practice, the concept of global environmental change is a general umbrella term for a whole range of mutually-dependent global environment problems. One possible way of classifying these global issues is based on the extent of interaction between them (RMNO, 1990; Döös, 1991; UNEP, 1992b; Elzen den and Rotmans, 1993):

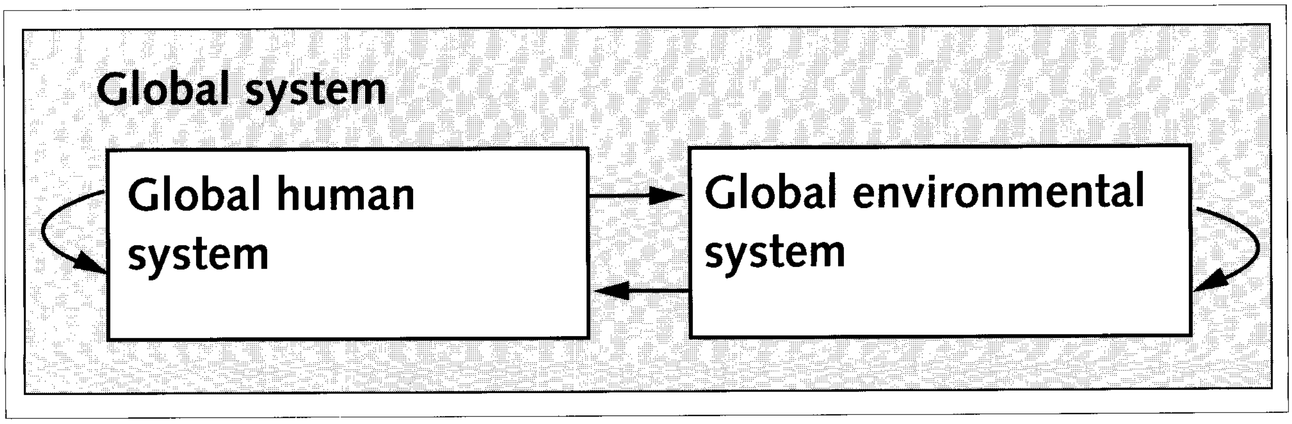
I. climate change, stratospheric ozone depletion, nuclear winter, tropospheric ozone increase, atmospheric deposition (including acidification) and eutrophication.
II. deforestation, erosion, land degradation and desertification
III. dispersion of chemicals: heavy metals and persistent and toxic micropollutants.

Several other typologies are possible, e.g. based on differences in the time scale, scale of alteration and societal response, none of which are satisfying, because they all consider the global phenomena from just one perspective, but not from the integrated viewpoint. Following O'Riordan and Rayner (1991), global environmental change should be considered as a concept with the following characteristics:

* it is caused primarily by human activities superimposed on an underlying organic evolution of biogeochemical processes;
* the effects of these changes have all-encompassing implications, affecting the present and future global social, economic and ecological structures;
* the rate of change is so rapid that it can be identified within a human lifetime;
* the scale of change is potentially irreversible.

One of the major difficulties with respect to global environmental change is to disentangle the natural changes to which the global Earth system is subjected, these being part of a continuous disturbance or variability, from the anthropogenic

Figure 1.1: Global change vis-à-vis global environmental change



changes.
Widespread recognition of global change as a major field of research was not forthcoming until publication of the first Report to the Club of Rome (Meadows *et al.*, 1972). However, their controversial book 'The Limits to Growth' became the target of severe criticism. In 1974, Molina and Rowland (1974) launched their theory on the depletion of the stratospheric ozone layer, which represented a breakthrough in the awareness that human activities have consequences on a global scale (RMNO, 1990). Next on the scene was the problem of acidification, although this is not a global problem but rather one confined to certain continents, followed by the problem of global climate change. Other global phenomena, also closely related to global climate change, entered the research field, such as deforestation, land degradation, erosion, desertification and large-scale chemical pollution.
Milestones in the development of the concept of global change were the appearance of the IIASA study 'Sustainable Development of the Biosphere' in 1986 (Clark and Munn, 1986); the Brundtland report 'Our Common Future', adding the political dimension to the concept of sustainable development (WCED, 1987); the reports of the conferences held in Villach and Bellagio (Jäger, 1988); and the comprehensive overview reports of global climate change by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 1990a; 1990b; 1991; and 1992); the scientific assessments on ozone depletion by WMO/UNEP (e.g. WMO, 1992); and finally, the following extensive research programmes: the World Climate Research Programme (WCRP) initiated in 1979 by the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU); the International Geosphere-Biosphere Programme (IGBP), established in 1986 by ICSU, which aimed to set priorities for global change research (IGBP, 1990; IGBP, 1992); and the Human Dimensions of Global Environmental Change Programme (HDGECP), initiated by the International Social Science Council (ISSC) in 1986, which resulted in the definition of an overall global change research programme for the social sciences in 1990 (Jacobson and Price, 1990).

1.2. Sustainable development

In order to withstand the worldwide threats to the global system, the notion of sustainable development was introduced during the eighties. Since then, the concept of sustainable development has mainly been used as a conceptual guide and target for environmental policy making. However, the operationalisation of sustainable development appears to be extremely difficult, and during recent years, several (competing) definitions of sustainable development have been put forward. The concept of sustainability was first launched in the World Conservation Strategy (IUCN/UNEP/WWF, 1980). It took quite a long time before the concept became more widely known, a process stimulated by the report 'Our Common Future' of the World Commission on Environment and Development (WCED, 1987). The WCED played a key role with their widely-cited anthropocentric definition of sustainable development: 'a development that fulfils the needs of the present generation without endangering the future needs of future generations'. This definition is based on the intergenerational principle that no burdens should be inherited by future generations so that their starting position will be at least no worse than that of past and present generations. An alternative definition of sustainable development is presented by the IUCN/UNEP/WWF (1991) from an ecocentric perspective: 'improving the quality of human life while living within the carrying capacity of supporting ecosystems'. This definition starts from the continuity principle but the concept of 'carrying capacity of ecosystems' has not yet been adequately defined. At a more elaborate level, the concept of sustainable development is dealt with from points of view based on: economics (e.g. Barbier, 1987; Goodland and Ledec, 1987; James, 1989; Klaassen and Opschoor, 1991); ecology (e.g. Nijkamp and Soeteman, 1988; Udo de Haes *et al.*, 1991); culture and society (e.g. Arizpe, 1989); from systems analysis (e.g. Roberts, 1982; De Vries, 1989a and 1989b; Shaw *et al.*, 1991; Van den Bergh, 1991; Meadows *et al.*, 1992); or ethics (e.g. Shearman, 1990). Inventories of the broad range of concepts subsumed by the concept of sustainable development are also available (e.g. Redclift, 1987; Brown *et al.*, 1987; Lélé, 1991; Hoekstra, 1992).

1.3. Global change and sustainable development within the context of this programme

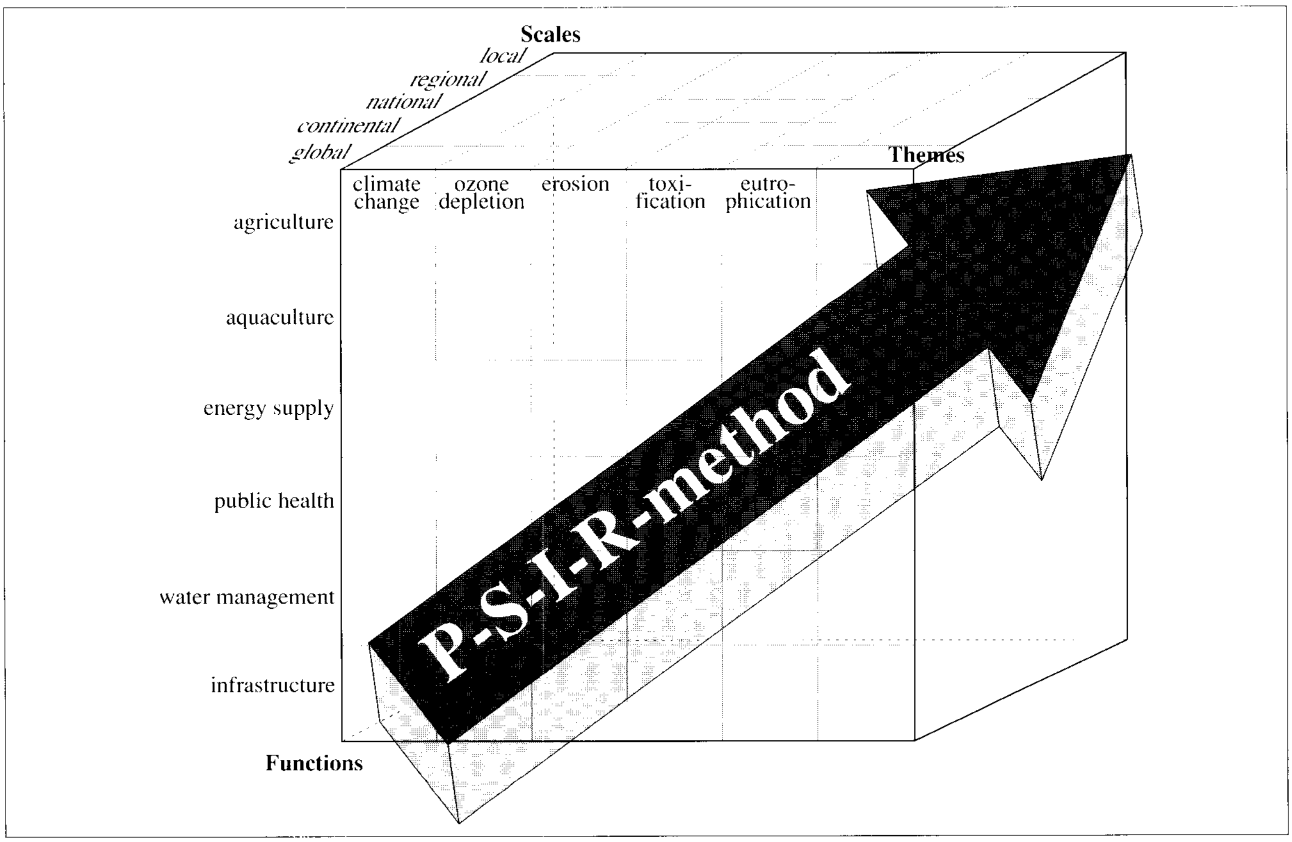
A significant number of the uncertainties within the concept of global change originate from structural misconceptions (scientific uncertainties) and from 'unpredictable' geopolitical, socio-economic and demographic processes (social and economic uncertainties). In this research programme an attempt is made to make these uncertainties explicit. On the one hand scientific uncertainties will be related to different scientific paradigms, and on the other social and economic uncertainties which are not based on scientific theories will be coupled to cultural perspectives.

In this study global change is, in contrast to earlier studies, considered from an integrated perspective. This means that the classical way of splitting up environmentally related problems into themes, functions and scales (Langeweg, 1989) will be abandoned. With respect to global change, this means that the starting point here is to consider the common causes, mechanisms and impacts of a number of coherent themes, functions and scales. Hereafter, in Chapter 3, we shall explain how this integrated approach is translated in terms of Pressure, State, Impact and Response (P-S-I-R approach). The starting point chosen here is more in line with the universal principle of approaching environmentally related problems, which assumes that many of those problems are generic in nature. In this study the integrated (P-S-I-R), universal approach is a *leitmotiv* for analysing global change. In *Figure 1.2* the integrated, universal approach and the classical, theme-, scale-, or function-based approach to environmentally related issues are set alongside each other.

As regards the notion of sustainable development, in view of its normative character, there is no unambiguous definition of sustainable development that can fit with everybody's conception of the notion. A sustainable state for one region or sector at a specific point in time can be unsustainable for another region or sector at the same point in time. It appears that the concept of sustainable development can be understood in many different, subjective ways. The concrete elaboration of the notion seems to depend on the actor's cultural perspective. Therefore, different cultural perspectives will be elaborated, which will be translated into different preferences for the operational definition of sustainable development.

Hence, instead of putting forward another definition of sustainable development, both the anthropocentric and ecocentric (and maybe a mixed) approach towards the notion of sustainable development will be elaborated. However, as opposed to previous studies dealing with this concept, it will not be considered from a monodisciplinary viewpoint, but it will be a multi- and interdisciplinary effort which

Figure 1.2: Integrated, universal (P-S-I-R) approach versus theme-function-scale based approach



allows for an integrated vision of what sustainable development is, and how it can be achieved. The research programme defined here is designed to fill that gap, by bringing different scientific disciplines together, from natural sciences such as physics, chemistry and ecology, as well as social sciences such as sociology and economics.

2. GENERAL SCOPE OF THE STUDY

2.1. Research programme 'Global dynamics and sustainable development'

In 1992 the National Institute of Public Health and Environmental Protection (RIVM) in The Netherlands launched the research programme 'Global Dynamics and Sustainable Development'. The research programme will be performed by a small, multidisciplinary core research team consisting of about ten full-time researchers. The main scientific disciplines involved in the research programme are: mathematics, economics, ecology, hydrology, physics, epidemiology and philosophy/ sociology.

The main objective of this programme is to develop an integrated modelling framework for analysing global change and sustainable development, which will be further explained below. The framework to be developed is referred to as TARGETS, an acronym for **T**ool to **A**ssess **R**egional and **G**lobal **E**nvironmental and health **T**argets for **S**ustainability. A full description of TARGETS at the conceptual level will be presented in the following chapters.

The research is based on a systems based, integrated modelling approach and has a multi- and interdisciplinary character. A top-down approach is chosen, whereby the analysis starts at the highest aggregation (abstraction) level, i.e. the global level, considering the globe as a whole. In the next phase the model will be disaggregated to the level of major world regions, using regional data sets: e.g. Western Europe, Eastern Europe, Northern America, Latin America, Africa and Asia. This implies that case studies will be carried out, which pursue the question of what sustainable development on the regional level means. Alliance has been sought with the IMAGE-project team in regard to data collection, regionalization and aggregation levels.

The modelling framework is to be used by researchers and policy analysts. The primary user groups aimed at include the United Nations Environment Programme (UNEP) and the World Health Organization (WHO). For these user groups the modelling tool should be regarded as an aid in the formulation of global and regional strategies for sustainable development for the next century. The model is not capable of predicting future developments, but should be regarded as an instructive instrument for obtaining insight into the complex dynamic behaviour of the global system. In addition, the model could have a bridging function for the large research programmes: the International Geosphere-Biosphere Programme (IGBP), and the Human Dimensions of Global Environmental Change Programme (HDGECP). This means in practice that the model could serve as a medium for communication between the natural sciences and the social sciences.

Not only the model-building itself, but also the use of the model is one of the focal points of the research programme. Therefore, the concept of strategic planning exercises will be elaborated, which is oriented towards strategies for sustainable development, whereby the model serves to provide support in the background (Vries de *et al.*, 1993).

2.2. Objectives

The main objective of the research programme 'Global Dynamics and Sustainable Development' is to operationalise, and to render applicable, the concepts of global change and sustainable development in such a way, that these notions can be used in the decision making process. This, however, requires an integrated, multi- and interdisciplinary systems-based research approach, whereby the analysis starts at the highest aggregation level. If global change and sustainable development are to be operationalised, it is essential that a systems based, dynamic, integrated modelling approach be adopted, whereby the point of departure chosen is the cause-effect chain. To this end, an integrated assessment model is being developed, by means of which one can identify, on a global scale, quantitative and qualitative linkages among social and economic processes, biophysical processes and effects on ecosystems and humans. Such an integrated assessment model can be used to develop concrete strategies for sustainable development, a process which requires the formulation of sustainability indicators. The referential framework for such sustainability indicators is given by the elements of the causality chain which the model links together. In this manner, the integrated assessment model can yield insights into the complex interrelations in time and space between increasing worldwide pressure on the environment, pollution and disruption of essential biogeochemical cycles, and the effects of anthropogenic influences on the environment, human health and society as a whole, in both the short and the longer term.

The application of integrated assessment modelling, using a purpose-built set of indicators, can increase the policy relevance of global and regional environmental reporting. Advantages of the use of integrated assessment models in environmental reporting and assessment include:

i) the integrated analysis of the interactions between the driving forces, the changing environment, the impacts and the societal response;
ii) the development of forecasts for early warning purposes, which may lead to priority setting;
iii) the improvement of the communication process between decision makers and scientists.

At the same time, building an integrated assessment model will enable knowledge gathered from various scientific fields, ranging from natural to the social sciences, to be integrated in such a way that additional knowledge results. Therefore, the emphasis will lie on the development of a tool that enhances the communication between researchers in the natural sciences on the one hand, and researchers in the social sciences on the other.

We realize that a research programme of this size, scale and complexity is bound to encounter a series of bottlenecks, some of which are foreseeable, but most of which are not. Furthermore, the goals of this research programme may seem rather ambitious in relation to the means available. However, it should be realized that a great deal of experience in this type of large-scale modelling has already been gained with the IMAGE-project. Moreover, where possible existing models, methods and techniques will be used for parts of the modelling framework, rather than developing new tools. Therefore, the goal of the research programme in terms of constructing an integrated assessment model for analysing global change and sustainable development is thought to be attainable.

3. GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT: AN INTEGRATED SYSTEM APPROACH

3.1. Introduction

One of the main experiences in environmental research thus far, is that the reductionistic approach based on aspect-compartment oriented research methods has failed in analysing adequately complex, multidisciplinary, large-scale global phenomena. A more promising way seems to be the holistic, integrated approach, based on a systems-oriented analysis, which concentrates on the interactions and feedback mechanisms between the different subsystems of cause-effect chains rather than focusing on each subsystem in isolation (Dzidonu and Foster, 1993). Therefore, in this research project, a systems approach to global change and sustainable development is advocated. Such an integrated systems approach requires a multi-disciplinary systems analysis, quantification of uncertainties, and visualisation of various system perspectives. These different research aspects of this project will be discussed in succession below.

3.2. Justification of the systems approach

The justification for adopting a systems approach to operationalise the concepts of global change and sustainable development is based on the following line of argument: sustainable development is closely allied to the natural resilience and buffer capacity of the biosphere in relation to anthropogenic disturbances. This disturbance on a global scale is denoted as global change, and can be represented by a set of interrelated cause-effect chains. To operationalise global change and sustainable development the cause-effect chains are chosen as a starting point in this project, which requires an integrated approach. The inextricably interconnected cause-effect chains form an organized whole, a complex system, the properties of which are more than just the sum of its constituent parts, the subsystems. The object of systems analysis is not only to study the particular system structure and to classify and describe the entities (components) of the system, but also to understand the processes, interactions and feedback mechanisms within the system that generate changes in its dynamics and structure. It enables a synoptic approach that addresses the interdependencies between the cause-effect chains. Given the complexity of the system under consideration, and the relative ignorance about the basic processes and interactions that determine its dynamics, the systems approach can help to foster understanding of the causal relationships that are responsible for changes in the structure and dynamics of the system. Therefore, the systems approach seems to be an appropriate method to capture the complexity of the interrelationships between the various subsystems of the complex Earth system. A prerequisite for such a systems approach is inter- and multi-disciplinarity, based on the integration of knowledge gleaned from a variety of scientific disciplines. It then provides the opportunity to conceptualize the issues of global change and sustainable development in a holistic, integrated way.

3.3. Top-down approach

An important feature of the research strategy is the top-down approach which will be chosen, which has implications for several aspects of the research. One major aspect is the degree of generic specificity aimed at, while developing an overall system for the analysis of global change and sustainable development. The subsystems to be built are developed in as generic a form as possible, i.e. irrespective of aggregational, regional or temporal differences. This means that the theories used must be applicable at different levels of spatial aggregation and for different regions in different periods. The approach followed in this research project will consist of the following research steps: first a systems analysis is to be performed, resulting in the contours of the system and the division into various subsystems. Next, the different perspectives from which the system can be viewed are sketched, as well as the aspect of how to visualize these perspectives. Finally, the concept of uncertainty in the broadest sense is treated, which is of major importance in this project.

3.4. Systems analysis

A system is a part of reality that is bounded vis-à-vis its surroundings and consists of a number of entities or elements that are related to each other. An entity is a part of the system that needs further specification by means of defining its properties. The state of a system at a given moment in time is the set of relevant properties which that system has at that time. A process is defined as a time-dependent relation, changing the state of a system (Ackoff, 1971). A subsystem is an element of a larger system which fulfils the conditions of a system in itself, but which also plays a role in the operation of a larger system (Young, 1964). A system is nothing more than a subjective reflection of the researcher's observation, and there are therefore as many interpretations of a system as there are observers (Kramer and Smit de, 1991).

A particular, plastic technique for describing systems is used in the methodology of system dynamics, described in e.g. Forrester (1961 and 1968) and Goodman (1974), which found its origin in the 1940s. The technique of system dynamics is especially useful for systems composed of interacting entities and feedback loops, and some basic principles of this technique will therefore be used in this study.

A model is defined as a material or formal representation of a system under consideration. The types of model considered here are conceptual models and mathematical models. Conceptual models represent the conception of the essential entities of the system, its boundaries, linkages, interrelationships, and feedbacks in the system. Mathematical models are conceptual models which are formalized in a mathematical way. In a mathematical model, the system, entities and relations can be formally represented by variables and processes, often in the form of a set of differential equations. The following variables and parameters can be distinguished:

- state variables: variables that determine the state of a system at an arbitrary point in time;
- steering variables: quantities that represent the possibilities of decision makers to influence the system under concern in terms of policy options and/or response options.
- empirical quantities: variables or parameters that represent measurable properties of the real-world systems being modelled;
- value quantities: variables or parameters that represent aspects of the preferences of the decision makers, researchers or modellers;
- auxiliary quantities: input parameters or variables; constants; help parameters or variables which are used to calculate state or steering variables.

The classes distinguished are not disjunct in the sense that they overlap. Steering or state variables may be empirical or value quantities as well. The terms 'state' and 'steering' only denote the function the quantities have in the model. Steering variables are used in the steering/response part of the model, while state variables may serve as state-descriptive indicators.

Metamodels are of major importance in integrated modelling approaches. A metamodel is a highly aggregated, simplified and condensed representation of an original model. One of the primary requirements of such a metamodel, besides its flexibility and transparency, is that its structure and outcomes should be validated extensively against the original, expert models and empirical data over the whole range of values to be generated by such a metamodel. If a systems-based approach is adopted as a guiding principle, the biosphere can, in global terms, be considered as a system of reservoirs and processes connecting the reservoirs. Many of these processes are cyclic, nonlinear or otherwise qualitative in nature. Both are influenced, directly and indirectly, by human interventions. Exogenous and endogenous developments perturbing the system, as well as interventions due to human activities, can lead to irreversible changes in the system. Although aggregation is possible at each conceivable level, a plausible division of the cause-effect chains into subsystems on the global scale would be the following, as represented in *Figure 3.1:*

*** STEERING/RESPONSE SYSTEMS:**

- user's possibilities to influence (change) either human activities and/or the environment, which also includes the response to societal and ecological impacts.

*** PRESSURE SUBSYSTEMS:**

- these systems are designed to describe the driving forces underlying the continuously changing pressure on the environment, characterized by three crucial aspects: population, economy / technology and resources.

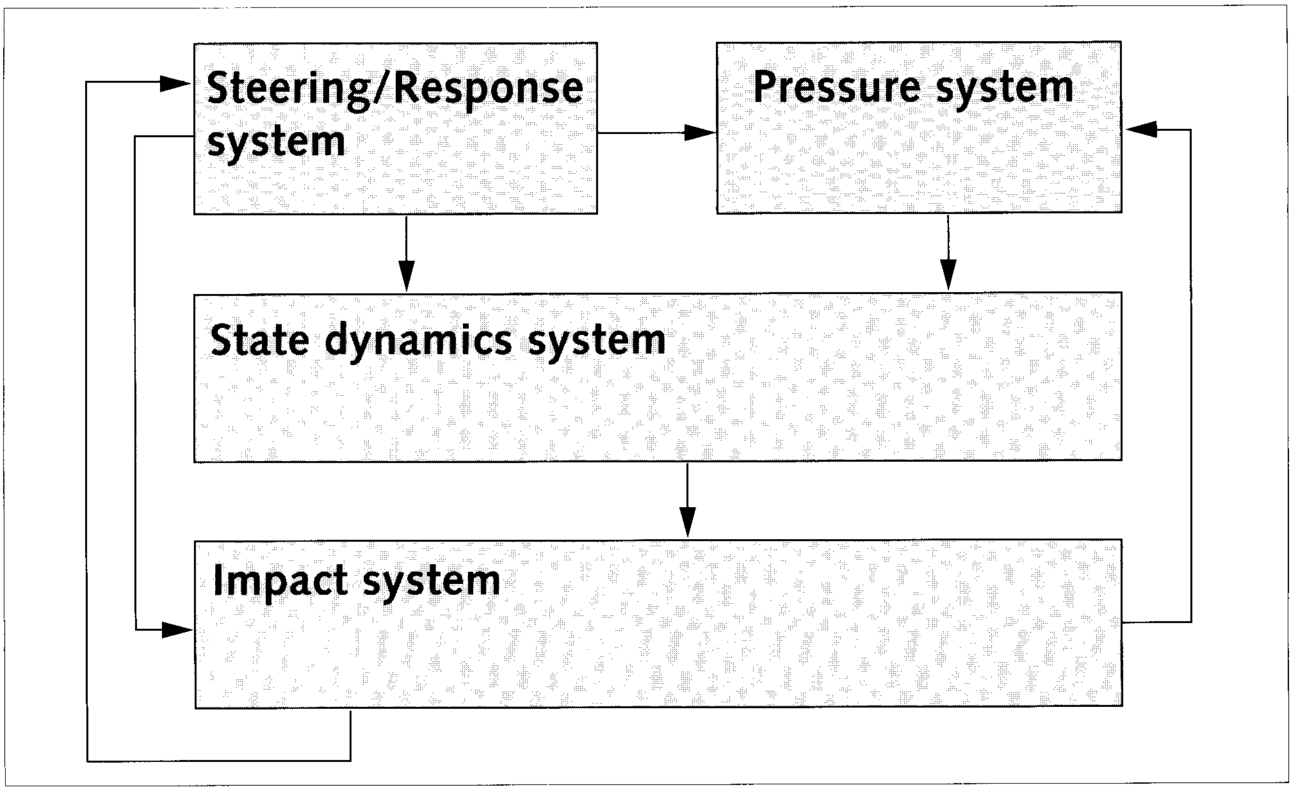


Figure 3.1: Systems diagram of the Pressure-State-Impact-Response (P-S-I-R) chain

*** STATE DYNAMICS SUBSYSTEMS:**

- these systems are designed to describe the changes in the physical, chemical and biological state of the biosphere, as well as the change in human population and resources/capitals. The biogeochemical cycling of elements and the accumulation of chemical agents are major foci of interest.

*** IMPACT SUBSYSTEMS:**

- these systems are designed to describe the effects of human interventions on the global environment (global cycles); the effects of anthropogenic multiple stress on ecosystems; the environmentally related consequences for human health; and finally, the socio-economic effects for various sectors.

All these subsystems have their own characteristics within the four-dimensional space built up from spatial and temporal scales. For the economy/technology subsystem the circulation time may be determined by the useful life of investments or the time required to introduce a new technology; for the biosphere subsystem the response time may be a characteristic which is dependent on biogeochemical cycling; for ecosystems the time scale may be determined by the multiple stress on the ecosystems, varying from several weeks to hundreds of years. The characteristics of the subsystems may change as a result of anthropogenically-induced or evolutionary processes. For each subsystem, and also for the system as a whole, the boundaries and the interactions with the surroundings must be specified. Furthermore, for each subsystem and the whole system, the system structure, aggregation level, uncertainties and sensitivities must be investigated. As stated above, dynamic behaviour can be analysed by means of model experiments, to be performed in a systematic and consistent manner, upon which representative indices can be designed.

It is important to note that a full systems analysis is the only analysis which makes sense. This because a certain development within one or more subsystems can tend towards a sustainable state, but may be unsustainable for the whole system, or even worse, may lead to a shift from a sustainable to an unsustainable state in other subsystems. Using some principles of the system dynamics, the whole system and the various subsystems identified can be analysed in terms of the basic concepts and definitions as defined in the box below.

Reservoir
A reservoir is defined as a cluster of elements that can be considered as reasonably homogeneous.
Flux
A flux is the quantity of elements being transferred from one reservoir to another in unit time. The flux density is defined as the quantity of elements transferred per unit time per unit area.
Source
A source is a reservoir from which the fluxes of elements originate.
Sink
A sink is a storage reservoir, which receives fluxes of elements.
Steady state
If all sources and sinks balance and do not change over the course of time, the reservoir is in a steady state.
Feedbacks
A negative feedback is a process that, after completion of a cycle, suppresses the output signal caused by the original change in the system's state. A positive feedback, however, reinforces the output signal caused by the original change in the system's state.
Circulation time
The circulation time is the ratio between the content of a reservoir and the total flux emerging from it. It can be considered as the time that it takes to empty the reservoir in the absence of a source.
Response time
The response time of a reservoir is the period that it takes to reach a new equilibrium after a sudden change in the system.
Reference state/Target state
The reference state is the undisturbed condition of the system(s), while the target state is the desirable (sustainable) state to be achieved. Changes in the characteristics of the system over time can be quantified by referring to the reference state. Because of the many uncertainties surrounding the notions of 'undisturbed' and 'desirable', the target and/or reference state is often based on risk analysis, and is then expressed in terms of exceeding risks and safety levels. In systems analysis, various possible pathways leading back to or away from the reference state, or to or from the target state, are explored.

In order to investigate the systems concepts and characteristics defined above, a series of experiments are to be performed, using simulation models. For each subsystem, the perturbation of the natural state is to be determined, and the vulnerability, resilience, buffer capacity and recovery capability are to be defined by model experiments. By performing various model experiments in a systematic manner, the behaviour of the subsystems and of the complex system as a whole can be analysed. Similarly, the carrying capacity of the system can be determined.

3.5. System perspective

Each system can be viewed from different perspectives, depending on the type of user involved (natural scientist, social scientist, decision maker, generalist, etc.). Therefore, in order to address the needs of the different user groups, one and the same system should be geared to the users' perception of global change and sustainable development. For instance, the biosphere subsystem can be looked at from the compartment structure perspective, from the environmental problem-oriented perspective, from the chemical substance perspective, or from the mathematical perspective.

In Elzen den (1993), among other perspectives, the compartment structure perspective has been elaborated for an experimental version of the IMAGE model (version 1.6). In this perspective IMAGE 1.6 is considered as a system that couples five compart-ments of the climate system, and integrates the interacting fluxes (transport and transformation processes). The selected five compartments of the climate system are: the atmosphere (troposphere and stratosphere); the ocean (surface waters and deep ocean); the terrestrial biosphere (land biota and soils); the land surface (including human area) and the ice. The following key processes can be distinguished between and within these compartments: fluxes of chemical substances (gases) between reservoirs, atmospheric chemical processes, radiative perturbation, UV-B radiation change, temperature change and sea level change. An advantage of this approach is that it yields greater insight into the fluxes, reservoir

contents and turnover times, and that it can answer questions such as: where does the pollution come from, and where is it going next?
The mathematical perspective of the IMAGE model, version 1.0, has been formulated by Braddock *et al.* (1993), who described IMAGE 1.0 in a schematic way as a dynamic control (nonlinear) system comprising 151 differential and 9 algebraic equations (see also Elzen den, 1993). The advantage of the mathematical perspective is that various mathematical aspects can be investigated in this way, e.g. stability of the model (the model proved to be stable), possible equilibrium points of the system (which were not found), response times of the model to changes in inputs by considering the eigenvalues of the system (response times varied from 1 to 500 years).

3.6. Visualization

In order to comprehend the notion of system perspectives (which can possibly be linked to the cultural perspectives discussed hereafter) it is important to use adequate visualisation tools. Therefore, a modelling and visualisation tool has been developed, which has been called 'M' (Bruin de, *et al.* (1994)). In general, the overall goal of this environment 'M' is to enhance insight into the working and results of global, integrated assessment models. It consists of two basic components: a mathematical modelling language, which makes it possible to specify mathematical equations straightforwardly; and a graphical user interface which enables the user to change parameters, functions, scales and scenarios in an interactive manner. The major goals of the M toolbox, which is under development at RIVM, are:

- to reduce the time needed to implement models and their graphical interfaces;
- to increase the quality of models by opening them up to easy inspection by other researchers;
- to increase the use of models by policy analysts and policy makers by providing easy-to-use interfaces;
- to enable the implementation of multiple views and perspectives;
- to display uncertainties and complexity of the systems behaviour comprehensibly;

The systems to be designed and the models to be built in this project are developed in the M environment. Although the modelling and visualisation environment is still in the development stage, a basic version is already available: 'M' version 2.0 which will be used in this study. In addition, a certain amount of time and effort will have to be devoted to further enhancing version 2.0, and extending and developing the possibilities of this modelling and visualisation tool. However, further development of 'M' will not be a considerable bottleneck within this project, because (i) version 2.0 already satisfies the basic needs, and (ii) the basic software is written in the language 'C', which is one of the widely used languages, and (iii) separate modules can be converted directly into 'C', which enables exportation of models and direct use by other research groups all over the world. A mature version of the modelling and visualisation environment 'M' which will be suited to use on a variety of computer configurations, varying from sophisticated workstations to PCs, will be disseminated among potential users (decision makers and researchers) in the Netherlands and abroad.

3.7. Uncertainties

The concept of uncertainty plays a key role in this research project because forecasting future global change and its consequences for human society is beset with many uncertainties. Uncertainty encompasses a multitude of notions, and various attempts have been made to classify the different types and sources of uncertainty. Morgan and Henrion (1990) distinguish uncertainty about empirical quantities, uncertainty about the functional form of models, and disagreement among experts, which, *inter alia*, may arise from: inherent randomness; subjective judgement; from systematic and random errors; from approximation; and from different perspectives. An alternative classification which might be useful within the context of this study is the distinction between technical uncertainties (concerning observations versus measurements), methodological uncertainties (concerning the right choice of analytical tools) and epistemological uncertainties (concerning the conception of a phenomenon) uncertainties (Funtowitcz and Ravetz, 1989).
For the purposes of this study the various types and sources of uncertainty mentioned above are aggregated to two categories, based on the subdivision of the Earth's system into the human (sub)system and the environmental (sub)system:

1. 'scientific uncertainties': those occurring in the environmental system which arise from the degree of unpredictability of global environmental change processes and may be narrowed as a result of further scientific research or more detailed/appropriate modelling; and

2. 'social and economic uncertainties': those occurring in the human system which arise from the degree of unpredictability of future geopolitical, socio-economic and demographic evolution and which are inherently 'unknowable' or in practice unpredictable.

Note on 1: Scientific uncertainties include, for example, incomplete knowledge of the sources and sinks of chemical substances (gases), caused by lack of measurements, inconsistency of measurements and unknown emission factors. Another source of uncertainty originates from our deficient knowledge of the key physiological, chemical and biological processes. Illustrative of this is the inadequate understanding of the many feedback responses (both geophysical and biogeochemical) which can amplify (positive feedback) or dampen (negative feedback) the response of the biosphere system (Lashof, 1989). The most precarious scientific aspect, however, in assessing the significance of global change, is the estimation of the ecological and socio-economic effects and the effects on human health. There is thus a very high degree of inherent uncertainty in the whole complex system portraying global environmental change and therefore one of the basic issues in this research programme is to estimate uncertainty ranges.

Insofar as 'scientific uncertainties' are concerned, in this study they will be made explicit by coupling them to various scientific paradigms, as described in Chapter 6. In order to quantify or measure these uncertainties, three different methods will be used here:

(i) The probabilistic method, using a subjective probability distribution which will be used for empirical quantities (variables or parameters which are measurable, and are found in both natural and social sciences). (ii) The parametric analysis, in which parameter values are varied for a range of possible values. A parameter often represents uncertainty about the model structure at the metalevel; at this level processes or even models can be represented by parameters. (iii) A weighing method can be applied, based on the opinions of various experts or based on modelling experiments. This weighing method can be used for poorly understood parts of the system and can finally be translated into a semiquantitative or fuzzy form. Alternatively, the weighing method can ultimately be used in a parametric form or probability distribution. To illustrate the latter, an example is given of a method with which to measure uncertainty which was used within the ESCAPE study (Rotmans *et al.*, 1994). The methodology was a combination of a probabilistic and weighing method, and was originally outlined in Santer *et al.* (1990) and further refined and illustrated in Hulme *et al.* (1994). In this study, regional climate change patterns are estimated using the results of seven experiments with General Circulation Models (GCMs). For temperature the outcomes of the model experiments were simply averaged, which produced the best guess temperature estimate. For precipitation a weighing method was introduced to derive the model average, whereby the weight was based on the square of the correlation coefficient between observed values and simulated values for each model experiment. The sample of seven experiments was then assumed to be normally distributed and the standard deviation taken as a measure for inter-model differences, which yields the upper and lower estimates (confidence limits about the best guess). In general terms, when there is a significant disagreement between experts about the underlying scientific issue, the parametric method is to be preferred to the probabilistic method or expert judgement method.

Note on 2: Social and economic uncertainties are related to the set of behavioral rules and human decisions that try to describe the dynamics of the socio-economic system. The information on which these rules and decisions are based is often surrounded with uncertainty. At the same time, because these rules and decisions are loaded with value judgements, they are under continuous change due to changes in cultural value orientations. One of the consequences is that there are no unanimously accepted models to describe the socio-economic system. Morgan and Henrion (1990) advise against the use of probability distributions for decision variables and value parameters. This is mainly because in the case of a probabilistic treatment it is not possible to make alternative decisions or value choices for which the implications may be estimated. It should be noted, however, that the difference between value quantities, steering variables and empirical quantities depends on the context of the model and the perspective of the model user (or builder). The propagation and analysis of uncertainty is discussed in Janssen *et al.* (1990), who give an enumeration of methods and techniques, and in Morgan and Henrion (1990). Because the system concerned is relatively large and complex, and includes many different types of uncertainty, it seems to be legitimate and useful to apply the technique of Latin Hypercube Sampling within the framework of this study. The foregoing means that the results will be both deterministic and stochastic in character. Deterministic outcomes will be represented by best guess estimates, with uncertainty boundaries. The best guess estimates do not per se need to be the average values, but represent choices of parameter values which are based on the best available scientific knowledge. The uncertainty bound (upper and lower value) may be generated by using either the parametric method or the expert judgement approach.

In the stochastic representation, the best guess may correspond to the mean or expected value of the probability distribution. The standard deviation, however, can be used as a measure for the uncertainty of the expected value of parameters or variables. Variations in the standard deviation may therefore reflect an increase or decrease in scientific knowledge. Creating a 'surprise effect' may be relevant because, as Dowlatabadi and Morgan (1993a) argue, an advance in scientific knowledge does not necessarily lead to a decrease in uncertainty, and may even result in the opposite, an increase in uncertainty. Thus, in order to investigate aspects of the dynamics of scientific knowledge, and to what extent they affect the outcomes, the technique of postulating different levels for the mean and standard deviation will be used in this study.

3.8. Calibration and validation

There are many definitions and interpretations of the terms calibration and validation. Moreover, complete calibration and validation of simulation models is impossible, because the underlying systems are never closed (Oreskes et al., 1994).

Within the framework of this study calibration is defined as the procedure for comparing the model results with the results of the real system (historical output, for instance observational data). The question to answer is how close the model output approximates the observational data. In spite of the implied vagueness in the term "as close as possible", statistical techniques can be used to quantify the difference between the model output and measured data.

Validation is defined here as the procedure for testing the adequacy of a given mathematical model. Validation can be divided into two different types. The first type is practical validation, which concerns the validity of the outcomes of the model. In fact, this implies that the outcomes of the model are compared with observational data. The major difference with calibration is that the comparison should be based on a new set of data, which lies outside the calibration pathway. This is often called 'verification' in the literature (Oresker *et al.*, 1994). The second type of validation is conceptual validation, which concerns the test of whether the model represents the real system. This implies that the internal structure of the model is tested, by testing whether the concepts and theoretical laws of the system under consideration are interpreted and represented in a sound way. Conceptual validation is often carried out by applying statistical techniques to test the estimates of parameter values; to test the distribution functions of parameters; and to test the coherence of relations (the latter mainly by regression and correlation analysis). As a matter of fact, conceptual validation is often problem-and domain-dependent. In general, the fundamental difficulty in validation is that, if the validation test is too stringent, the model will never pass the test, or if it is not stringent enough, the model may be an inadequate description of the real system. The difficulties in validating a global, integrated assessment model are discussed in Chapter 4.

4. AN INTEGRATED MODELLING FRAMEWORK FOR GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT

4.1. Introduction

Hitherto, the integrated cause-effect chains approach proposed for the operationalisation of global change and sustainable development has not yet been attempted. Previous attempts to operationalise the notion of sustainable development were limited to parts of the cause-effect chains only, and particularly to their economic facets (Bergh van den, 1991). Shaw et al. (1992), for example, formulated holistic conceptual models of the socio-ecological system in which we live.

There is an increasing interest in the use of integrated assessment models for studying the phenomenon of global change (Jonas *et al.*, 1992; Dowlatabadi and Morgan 1993a and 1993b; Rotmans *et al.*, 1994). This is due to the growing awareness that the various pieces of the global change puzzle can no longer be examined in isolation. To fully comprehend global change, knowledge should be integrated from several disciplines.

4.2. Integrated assessment models: a general description

Within the scope of this study, a global, integrated assessment model is defined as a model that is designed to analyse the phenomenon of global change from an integrated perspective. Integration means capturing as much as possible of the cause-effect relationships (vertical integration = integration of pressure/state/impact modules) although integration here also implies the integration of different modules within one subsystem (horizontal integration = integration of cross-linkages and interactions between various pressures, various state-dynamics descriptions and various impacts).

Integration therefore has two dimensions and the type of global, integrated assessment model proposed here should be integrated in both horizontal and vertical directions. Although there are some serious attempts being made to construct an integrated model of the Earth's atmosphere, hydrosphere and terrestrial biosphere (Fisher, 1988; Krapivin, 1993), it is conceptually and technically not yet (or may never be) possible to link, let alone integrate a variety of complex, detailed and three-dimensional models. Therefore, such integrated assessment models inevitably consist of simpler versions of the more complex models, denoted here as metamodels.

Basic characteristics of metamodels are that they are reformulated, simpler versions of more elaborate and complex aspect-compartment models (expert models) which have previously been constructed and described in the literature (Rotmans, 1990). In this way, state-of-the-art science is captured within such an integrated assessment model. The reformulation and integration aspects require the definition of one single mathematical concept, resulting in a single conceptual framework affording harmonization with respect to aggregation level, temporal and spatial scales, data, etc. The simplicity principle applied to the metamodels within an integrated assessment framework is also justified by the current state of scientific knowledge, which is deficient. However, the primary prerequisite for these metamodels is that they should be tested, verified, calibrated and validated thoroughly against expert models and observational data. Simplification methods that can be applied are: parametrization, rescaling, aggregation, omission of minor contributing factors and linear approximation of nonlinear systems. An example of such a simplification method is the methodology outlined in Santer *et al.* (1990) which describes the projection of regional climate change patterns using the results from GCMs. The method scales the standardised patterns of change in temperature and precipitation generated by GCMs according to the global-mean temperature projections. This methodology has been applied in an integrated climate assessment model for the EC, the ESCAPE model (Rotmans *et al.*, 1994). Another frequently used simplification method is the transfer matrix (source-receptor matrix) which assumes linearity between a country's emissions and its contribution to deposition (Alcamo *et al.*, 1990).

Global, integrated assessment models may not pretend to offer a comprehensive picture of all of the relevant processes of complex reality. In view of the accumulation of uncertainties, which is inevitable in integrated assessment modelling, as already mentioned above, the interpretative and instructive value of global, integrated assessment models is far more important than their predictive capability, which is limited by the incomplete science upon which they are constructed. Therefore, rather than prediction tools, integrated assessment models are interpretative tools, whereby their predictive value is rather low.

Another potential drawback of integrated assessment models is their complexity and potentially unmanageability. These models therefore have to be as transparent as possible, and, if, in addition, they are to be useful to decision makers, they should have a reasonably quick turnaround time (Jonas *et al.*, 1992). A final delicate, disconcerting point which applies to integrated assessment models is the limited possibility of verification and validation of modelling structure and results. Nevertheless, as already mentioned above, a *conditio sine qua non* for integrated assessment models is that they should be validated continuously and fully against expert models and observational data.

In the light of what has been discussed above, one may ask what a global, integrated assessment model is good for. Among the major advantages of such an integrated assessment approach are:

(i) An integrated approach enables the inclusion of systems interactions and feedback mechanisms and can therefore yield insights that scattered information cannot offer. Such a model can provide useful indications of the potential range and magnitude of global phenomena and of the scale of the interventions which are necessary to prevent or mitigate symptoms of global change.

(ii) These models are flexible and rapid simulation tools. The prognostic character of integrated assessment models allows for the indicative calculation and evaluation of long term scenarios and strategies. Therefore, rather than prediction tools, these models are forecasting tools, which, based on the best available current knowledge, are designed to arrive at normative prognoses. The normative element comes into play when the possibility of interference exists, and measures are formulated and implemented to steer the course of future events in a desired direction. In this way, these models are neither more nor less than instruments which can amplify our insights into the present and future driving forces behind our complex social, economic and ecological structures (Rotmans, 1990; Soest van *et al.*, 1988).

(iii) Uncertainties, crucial lacunae in current scientific knowledge and weaknesses in discipline-oriented expert models can be identified and revealed.

(iv) These models are outstanding means of communication between scientists and exponents of all kinds of disciplines; they also foster communication between scientists and decision makers.

Within the context of global change and sustainable development, the justification for developing a global, integrated assessment model is that it will be one the first attempts to appraise global change and sustainable development from an integrated dynamic perspective. Such an integrated modelling approach will enable the consequences of several types of human influences to be evaluated simultaneously. It is hereby envisaged that synergetic effects, which are currently beyond the horizon of predictive competence, may be brought into view

On the other hand, we must exercise vigilance if we are to avoid building one more large and complex model which produces questionable, misleading or opaque results. We must therefore learn from the experiences with global models (Meadows *et al.*, 1982), which show us that they in particular suffer from (i) inadequate understanding of the system being modelled; (ii) absence of stochastic behaviour; and (iii) inadequate treatment of uncertainty (Morgan and Henrion, 1990). A great deal of attention is therefore paid to the issues of uncertainty, stochastic behaviour, and how to deal with incomplete knowledge. The challenging aspect of building such an integrated assessment model is to find the right balance between simplicity and complexity; aggregation and realistic outcomes; stochastic and deterministic elements; qualitative and quantitative linkages; transparency and uncertainty. Furthermore, it is fundamentally important to face the limitations of the model to be built and to recognize the type of issues/questions that **cannot** be addressed by and what falls **beyond** the scope of the model.

4.3. The TARGETS model

4.3.1. Introduction

Based on the various subsystems of the whole system portraying global change, a series of highly-aggregated modules are being built, interlinked and ultimately integrated. This results in an overall integrated assessment framework, **TARGETS**: **T**ool to **A**ssess **R**egional and **G**lobal **E**nvironmental and Health **T**argets for **S**ustainability. The TARGETS model serves to explore long-term, to some extent inherently unknowable, dynamics of global change which may shape the Earth system over the next 100 years. The two-dimensional integration approach sketched out above is incorporated in TARGETS in the following way. The TARGETS integrated framework basically consists of a population and health model, a resources/economy model, a biophysics model, a land model and a water model, which are all interlinked. All types of models comprise a linkage of causative, state-descriptive and impact modules, in this way representing the (vertically) integrated cause-effect chain. All causative or pressure models describe the developments in human population, resources/ economy, land use and water use, respectively, where all developments are fully interlinked (horizontal integration). In a similar way, all models describing the disturbed states of the underlying system are coupled, just as all impact models are. By coupling the various causes, states and impacts for the various subsystems underlying the modules, the horizontal integration comes into play. This enables the representation of TARGETS as a two-dimensional integration matrix, as shown conceptually in *Figure 4.1*.

However, in order to keep the TARGETS framework as flexible as possible, it should comprise autonomously functioning modules, which is in line with the original IMAGE methodological philosophy (Rotmans, 1990).

The time horizon for the TARGETS model will span about two centuries, starting at the beginning of this century, the year 1900, symbolizing the end of the pre-industrial era, until the end of the next century, the year 2100, with time steps varying from one month to one year.

4.3.2. Basic philosphy of the TARGETS model

The TARGETS modelling framework which is to be constructed is not a traditional model that is intended to incorporate all entities, processes and feedbacks that are supposed to be relevant. Over the past 20 years, numerous global models have been built (Brecke, 1993; Meadows *et al.*, 1982) all of which were burdened by an excessive number of processes and feedbacks, and therefore all suffered from the same drawback, namely that their structures were too complex and opaque, and their aggregation level for basic processes and feedbacks was unacceptably high, which resulted in unmanageable tools and the production of sometimes disputable results which should be treated with great care. In addition, they are often difficult to run and poorly documented (Morgan and Henrion, 1990), although there are some exceptions like the WORLD3-model (Meadows *et al.* 1972, and 1992), which is well documented. Thus, in view of the above, the pitfalls of these traditional models should be avoided.

The TARGETS model is also not a traditional model in the sense that it assumes that incremental changes in parts of the global change system will cause gradual and incremental changes in the system as a whole. The real world does not function in such a simple, linear way. Therefore, TARGETS will be a composite framework of simple systems (represented by metamodels) which may show nonlinear and complex, perhaps even chaotic, behaviour. This means that incremental changes in conditions of subsystems may result in considerable changes in the results of the overall system, which may not always be predictable beforehand.

The TARGETS model needs to receive data in an organized fashion, such that the model results can be generated in a consistent and user-friendly way. Therefore, the model will be coupled to a database, which enables the storage, retrieval and display of large amounts of data in a structured environment. Databases make use of quantitative information. In a later phase of the programme, the question of whether it is also possible to structure qualitative information, possibly by developing an information database, as discussed by Shaw *et al.* (1991) will be investigated.

In the light of far from sufficient knowledge in natural and social sciences pertaining to global change, it is absolutely clear that it is impossible to model all entities, processes and feedbacks in a quantitative sense. Therefore, there is a need for a new class of global, integrated assessment models that, on one hand try to capture the essential dynamics of complex discipline-oriented expert models in meta-form (metamodels), but on the other are intended to promote an understanding of the qualitative interactive linkages, which are poorly understood in a quantitative sense. This implies that when it comes to implementation of the insufficiently understood aspects of global change, the use of subjective expert judgement is a prerequisite (Dowlatabadi and Morgan, 1993a and 1993b).

An interesting experiment regarding the role of expert judgement in evaluating global climate change was conducted in the U.S.A. (National Defense University, 1978). The focus of that study was on quantifying perceptions of global climate change up to the year 2000. Based on the subjective probabilities for different aspects of climate change given by an expert panel of 24 climatologists from seven countries, five possible climate scenarios for the year 2000 were constructed, each of which was given with a probability of occurrence. If nothing else, it is interesting to note that the experts under-

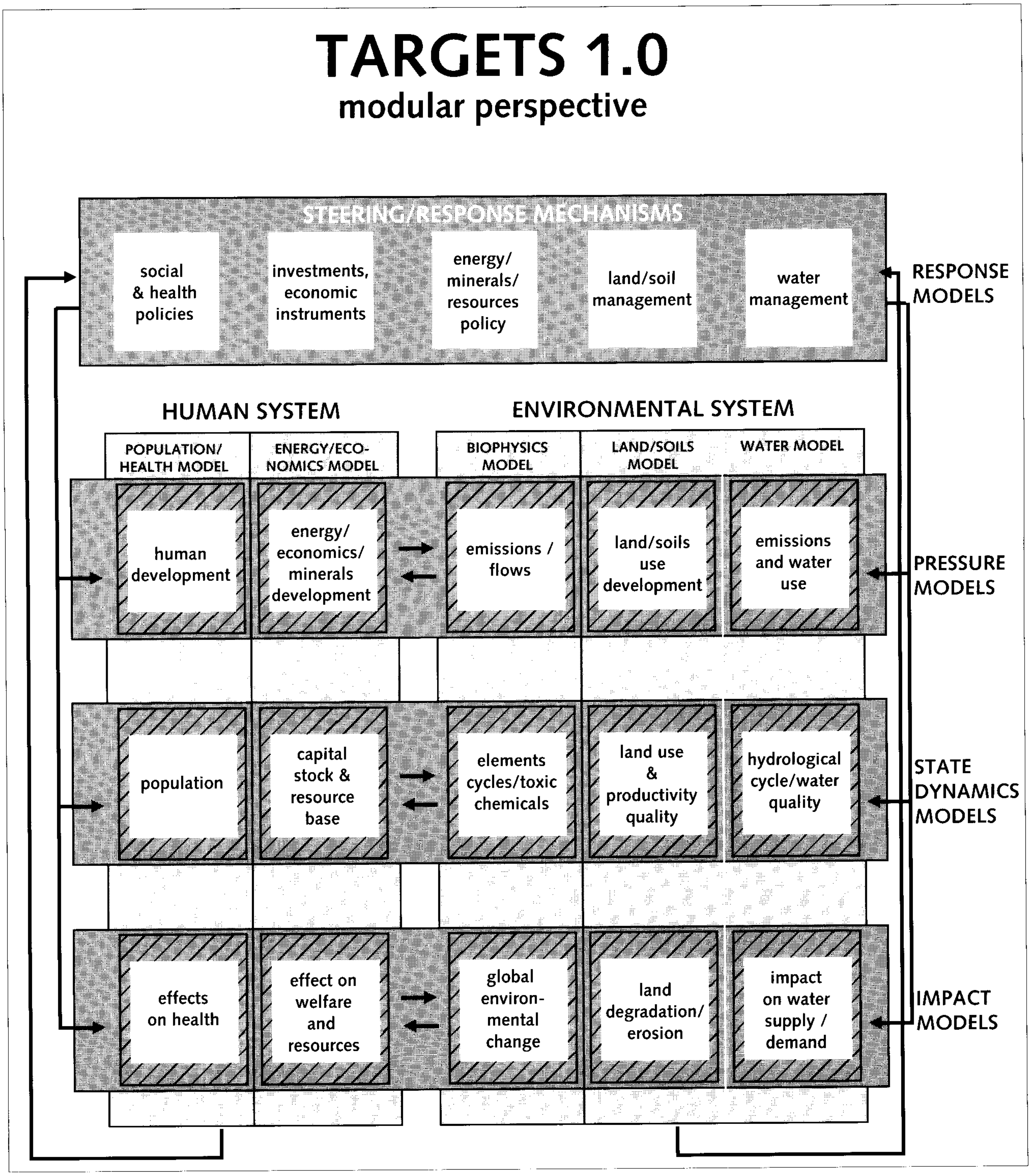


Figure 4.1: Modular perspective of TARGETS, version 1.0

estimated the future global-mean temperature trend for the observable period 1969-1992. In spite of the drawbacks that this method also has, it is one of the challenges of this study to generate methods by which subjective expert judgement can be incorporated in global, integrated assessment models.

One of the other crucial aspects in which the TARGETS modelling approach distinguishes itself from the modelling attempts which have hitherto been published, is the treatment of uncertainty. This subject has already been discussed above, in Chapter 3.

4.3.3. Top-down approach

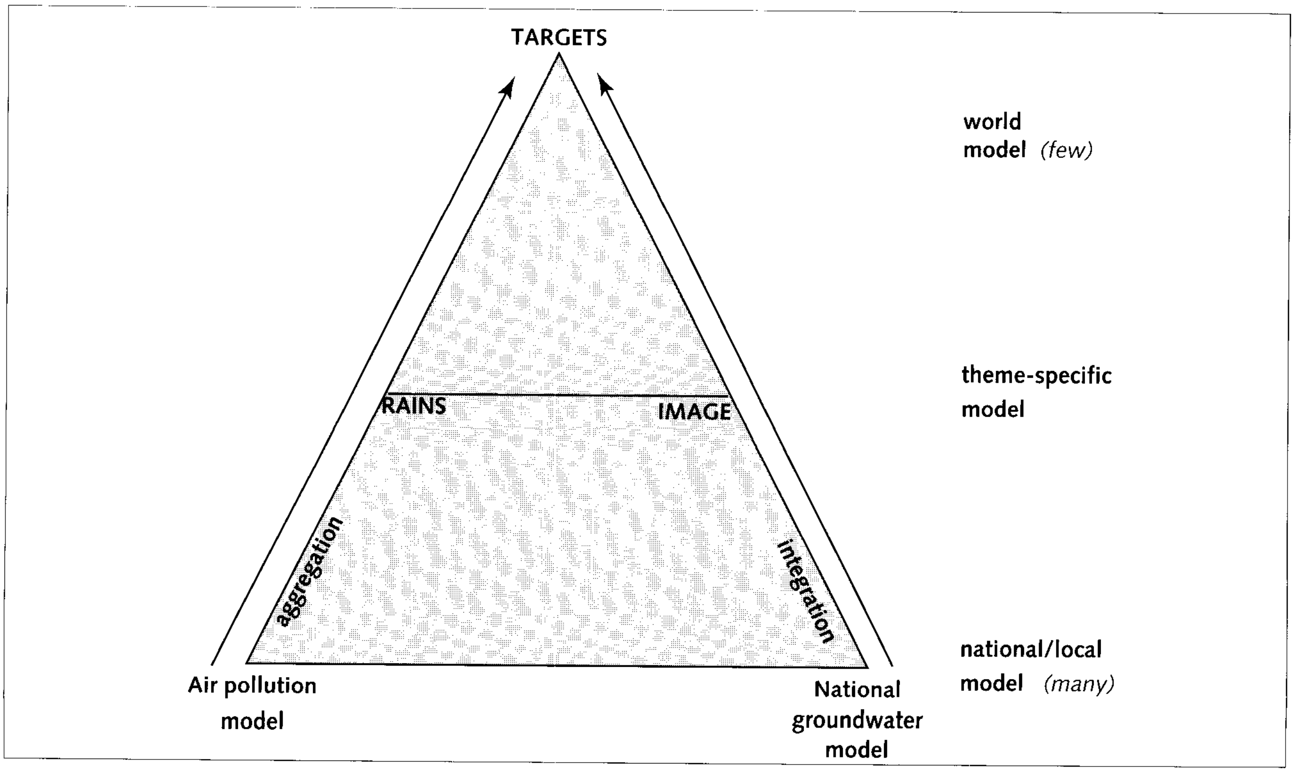
An important aspect of the research is the top-down approach which has been chosen, and which also has

implications for the order in which the simulation model will be implemented. Firstly, a prototype of the TARGETS model will be made operational on a global level, with global data sets. In this global version (version 1.0) of TARGETS, both the distributions on a scale below the temporal resolution in the model and the heterogeneities below the spatial resolution level of the model are taken into account by introducing classes and spatial distribution functions. In *Figure 4.2* different types of models developed by or used at RIVM are set alongside each other pyramidally. As this picture shows the TARGETS model is placed on top of this model pyramid, because it has the highest level of aggregation and integration, which is, as mentioned above, only possible when using the simplicity principle. The TARGETS model utilizes aggregated data and processes which are provided by theme-specific integrated models such as the IMAGE (climate assessment) and the RAINS (acidification assessment) models. Theme-specific integrated models in turn make use of data and processes generated by aspect-compartment models such as air pollution models or groundwater models on the local or national scale. On the other hand, integrated models may reveal weaknesses in aspect-compartment models, which may lead to improvements of these discipline-oriented models.
After operationalisation for the globe as a whole, the model will be disaggregated to the level of major world regions, using regional data sets: Western Europe, Eastern Europe, North America, Latin America, Africa and Asia. For each of the world regions, one representative country or area will be selected for which an integrated assessment study will be carried out. In practice, this means that such case studies pursue the question of what sustainable development on the regional level means. Examples of integrated impact case studies can be found in Grenon and Batisse (1989) for the Mediterranean Basin and in Cohen (1993) for the Mackenzie Basin.

4.3.4. *Calibration and validation*

Each submodel should be scientifically valid in the sense that the model structure, relations, parameters and dynamic behaviour over the period 1900-1990 reflect the prevailing theoretical insights and the key facts pertaining to that part of reality which the model is supposed to represent. In the case of submodels, it will not be easy to collect reliable data sets for the validation period 1900-1990, and failing this, a more recent and briefer period of a few decades will be taken, e.g. 1970-1990. It is of major importance that the various submodels are validated at the regional or country level. Therefore, experts in the field of small-scale, detailed models in a specific region or country will be asked to analyse the model

Figure 4.2: Pyramid of models according to different levels of aggregation and integration.



results and to validate regionalized model results for a specific world region against regional datasubsets. In view of the generic structure of the modules (submodels), which makes them (as far as possible) applicable at different spatial aggregation levels and for different regions in different periods, the experts should indicate the extent to which the generic structure of the module(s) should be adapted to regional conditions and dynamics.

A second way of validating the submodels is by means of the intercomparison with expert models which they are supposed to represent at the meta-level. An example of validating a simple carbon cycle model (based on Goudriaan and Ketner, 1984) against observational data and more complex two- and three-dimensional carbon cycle models is presented in Rotmans and Elzen den (1993) and Wigley (1993). Having validated the submodels, the overall validation of the modelling framework should be performed, whereby special attention should be devoted to the validation of the coherence and internal consistency of the model, as well as to the validation of model results for future explorations outside the original calibration domain.

4.4. Horizontal integrative description of targets

Horizontally, the TARGETS model can be subdivided into steering, pressure, state dynamics and impact submodels, which are described below. All steering models are fully interlinked, just as all pressure, state dynamics and impacts models.

4.4.1. Steering model

The steering model contains those variables by which the user can influence human activities or/and the environment. The steering variables are clustered into financial and legislative measures. Within the cluster of financial measures, one finds 'labelled taxes' and 'labelled investments'. The term 'labelled' means that the taxes and investments are directed towards specific groups in society and meant to result in specific changes in human activities: a tax on the emission of CO_2 is directed at all individuals or groups emitting CO_2 and is meant to reduce the volume of CO_2 emitted. An essential part of the steering model is the allocation model which distributes the total amount of money towards the different sectors, and controls that the entire stream of money forms a closed system, like the physical flows do in the pressure, state dynamics and impact systems. Three types of investments are distinguished: investments in communication and education, investments in infrastructure, and investments in science and technology. The rate of change in technology is one of the major determinants of sustainable development (RMNO, 1992). The impact of a technology varies according to its scale of application. As the scale increases, the marginal benefit of further increments in scale may become negative (Brooks, 1986). The adoption and diffusion of new technologies is often a source of nonlinearity, which can be positive or negative. Highly nonlinear relationships between the rate of improvement of a new technology and its rate of adoption and diffusion may exist (Brooks, 1992). If sustainable development is to be achieved, transfer of technologies among highly industrialized countries and transfer from industrialized countries to developing countries is of vital importance. Therefore, in the steering model, investments in science and technology will steer the development of new technologies and transfer of technologies from developed to developing countries for the energy sector (energy submodel), the winning of resources (minerals submodel), agriculture and food production (agricultural and food submodel), chemical technology and the transportation sector (economy submodel). The steering variables influence variables within the pressure system, but also variables within the state dynamics and impact systems. The reader will have noted that the steering variables are all information variables while the variables within the pressure, the state dynamics and the impact subsystems are physical (material) variables. Various conceptions pertaining to the policy instruments to be taken into account will be elaborated on the basis of various cultural perspectives, as described in Chapter 6: Various Perspectives.

4.4.2. Pressure models

Global pressure models are intended to chart the driving forces behind the increasing worldwide pressure on the environment. Although research on anthropogenic causes of global environmental change is advancing rapidly, there is still a long way to go. A comprehensive, predictive model of humanity's interaction with the natural world still lies far beyond our reach. To understand global change, social scientists must expand the spatial, temporal, and disciplinary scope of their research (Miller and Jacobson, 1992; Edmonds *et al.*, 1993; IFIAS, 1989; Stern *et al.*, 1992).

The pressure models are intended to shed some light on the interdependencies, in terms of their nature and scale, which exist among factors such as growth in population, developments in the stock of capital goods, use of resources, growth in production and technological development. Important intermediary factors are, in the first place, the agricultural and food-provision system, the infrastructure, including health and education provision, rural vis-à-vis urban systems, income distribution and the stocks of natural resources.

In TARGETS, all causative or pressure models describe the developments in human population, resources/economy, land use and water use, respectively, where all developments are fully interlinked. This is demonstrated in the descriptions of the separate modules in section 4.5, which show common pressure systems, in which the pressure system within a specific module is always composed of pressure elements arising from a number of other modules. As a starting point, two separate submodels of Meadow's *et al.* WORLD III model (1992) are used here as a foundation: a conceptually improved model version of the natural resources and the population dynamics model, both described in Vries de, *et al.* (1993). These models are coupled to an economic model, a land use development model and a water use model. In the near future the basic model will be disaggregated whereby the interactions among the various individually-modelled world regions can be examined. Important themes in this context are: the migration of populations related to population and environmental pressure, the movement of trade goods and physical movements of raw materials and (semi-manufactured or intermediate) products, and the dissemination of information/technology/know-how.

4.4.3. State dynamics models

The state dynamics models describe the biogeochemical status of the environmental system and the social and economic status of the human system, which are of course strongly interrelated. The biogeochemical status of the Earth is characterized by an interconnected complex of transport mechanisms and transformation processes, many of which are of a cyclic nature. Biogeochemical cycles describe the transformation and movement of chemical substances in the global environment, and have been studied in great detail during recent decades (Svensson and Söderland, 1975; Frenkel and Goodall, 1978; Likens, 1981; Bolin and Cook, 1983; Gugten, van der, 1988; Schlesinger, 1991; Butcher *et al.*, 1992; Wollast *et al.*, 1993). An integrated model is being developed that delineates the physical, chemical and biological state of the biosphere. An essential part of the model is the integration of the element cycles (C, N, S and P) and the interactions between the cycles in the biosphere. Other cycles implemented are the global hydrological cycle and global cycles of some representative heavy metals, pesticides and organic micropollutants. All these biogeochemical cycles are related to important global and regional issues: climate change, soil degradation, acidification, stratospheric ozone depletion, and dispersion of toxic and persistent micropollutants. The model to be developed is designed to create a comprehensive picture of the global biogeochemical cycles and their interactions with global environmental change. This will be done by coupling the various compartments: the atmosphere, terrestrial biosphere, lithosphere (soils), and the hydrosphere (oceans, coastal seas and rivers); and subsequently integrating the physical, chemical and biological interactions between the diverse compartments.

This global disturbance of the biospheric system interferes with the changing state of the population and resources reservoirs of the human system. The size of the demographic reservoirs subsystem is determined by the fertility rates, and disease and age-specific mortality levels. The mineral and fossil resources reservoirs are determined by human decisions and behavioral rules, such as resource exploitation thorugh investments by private companies or by government planning.

4.4.4. Impact models

The impact models to be designed can be divided into three types of strongly interrelated models.

(i) Models which describe the effect of anthropogenic multiple stress on ecosystems. Generic models will be designed that enable methodological research into the consequences of a number of human interventions for the functioning of ecosystems (ecological succession, structure and resilience).

Among the themes involved are: deforestation, desertification, erosion, etc. Ecological risks will be elucidated by means of illustrative case studies: the consequences of a multiple-stress approach for the sustainability targets which are to be formulated is particularly important. One of the major difficulties in setting sustainability targets for ecosystems is to define the carrying capacity of ecosystems. According to Holling (1986), the carrying capacity is cyclic in nature, whereby gradual changes alternate with rapid changes. Because of this natural variability in the dynamics of ecosystems, the focus should be on the 'undisturbed' development of ecosystems. The undisturbed evolution of ecosystems, however, is difficult to assess, and the only solutions generated so far have been pragmatic, such as the AMOEBE-approach of Brink ten, *et al.* (1991).

(ii) Models which describe the impact of global change on human health. Generic models are developed that enable the estimation of effects of determinants such as socio-economic developments, and changing global environmental conditions. Global environmental change may directly effect the presence of micro-organisms causing diarrhoea and malaria; macro-parasites causing ankylostomiasis; entomological, bacteriological and viral contamination and the presence of vector-borne diseases; suppression of the body's immune system that might lead to increases in non-melanoma and melanoma skin cancer incidences and cataract. Indirectly, global environmental change affects human health via the world food supply and water supply, which may lead to premature death, infectious diseases or certain degenerative diseases. Socio-economic development affects prevention (immunization, water supply and sanitation and vector control) and treatment (therapies) of diseases, and therefore meaningfully changes the palette of determinants. Niessen and Rotmans (1993) describe the coherence between socio-economic and environmental status, which determine changes in the pattern of health determinants which in turn demarcate the changes in the levels of incidence figures for the diseases.

(iii) Models which specify the socio-economic effects for various sectors. Generic models will be developed that enable the quantification of the socio-economic impacts of large-scale environmental problems. Both direct and indirect impacts are to be modelled on a global scale. Direct socio-economic effects may involve the monetary damage that relates environmental stresses to losses; physical damage functions that are meaningful in their natural units but can also be priced; physical damage functions that cannot be priced; and multiple stress damage functions for impacts affected by various stresses that are either independent, or about which there is so little information that the best estimate is multiplicative. Indirect socio-economic impacts include, for instance, the multiplier effects in the economy resulting from direct losses in one or several sectors. This partly depends on the approach chosen, e.g. national income or a socio-economic cost-benefit approach.

Model concepts are under development for the socio-economic impact assessment of changes in or affecting (a) public health: models that estimate the costs of providing water supply and sanitation services, and the costs associated with any given disease; (b) water management: models that describe the demand assessment, water allocation and the assessment of socio-economic impacts; and (c) coastal defence: a vulnerability assessment model, which focuses on people and capital at risk, and on costs of flood protection, based on concepts developed by the IPCC (Delft Hydraulics, 1993). In a later phase conceptual approaches will be developed for the assessment of socio-economic impacts of changes in agriculture and in energy supply and demand. The systems-based methodology underlying these modelling concepts is described in Resource Analysis (1994).

4.5. Vertical integrative description of TARGETS

Vertically, the TARGETS modelling structure can be subdivided into various autonomously functioning models, called modules, each module representing and covering as much as possible of the cause-effect relationship with respect to a particular aspect or theme of global change. The modules describing the human subsystem are the population/health module and the energy/economics/resources module, where as the environmental subsystem is described by the biophysics, toxics, land use and water modules.

4.5.1. The integrated population and health model

Introduction

A comprehensive approach to population, health and environment has to account for population growth and its interrelation with the use of natural and societal resources changing fundamentally global development. During the past two centuries this growth has led to high levels of population densities, now threatening the environment and deteriorating living standards (Ness *et al.*, 1993). Given socio-economic development, the population-environment relationship is dominated by the characteristics of the demographic and epidemiological transition (Omran, 1971), first an accelerated population growth, then, presumably, the achievement of some form of stability. In an indirect manner, economic development largely determines health levels through changes in other socio-economic sectors, which are mostly concomitant and positive in effect. Important sectors outside the public health area that have contributed to improving standards of health include food and drinking water supply, education, communications and income.

Not until the second half of this century did the direct additional effects of health services, both preventive and curative, start making an impact at population level, speeding up the fall of mortality rates (World Bank, 1993). There are still many disparities in fulfilled health potential on the global level and the existence of amendable morbidity and premature mortality continues. Major areas in which health benefits are to be gained are: perinatal conditions, childhood diseases, both water and airborne, other infectious diseases, as well as increasing cardiovascular diseases in developing countries too, often under much more debilitating circumstances.

As a countereffect of economic development, health changes started to occur stemming from changing environmental conditions (Doll, 1992; McMichael, 1993a; 1993b), which is one of the focal points of our research programme. Among the major research areas are:

(i) heat stress: an increase in cardiovascular mortality among the elderly associated with heat exhaustion;
(ii) air pollution: an increase in short and long term respiratory problems associated with air pollution, e.g. chronic bronchitis (Haines and Fuchs, 1991);
(iii) UVB-impact: the influence of UVB-radiation on cataracts and its influence on the immune system response to infections (Elzen den, 1993);
(iv) food production: global climate change will influence health levels in an indirect way by affecting food production (FAO, 1988; Daily and Ehrlich, 1990; Parry and Rosenzweig, 1993; Rosenzweig and Parry, 1994);
(v) water availability and water quality: a changing climate might lead to a reduction in supplies of available water and an increase in the presence of water-borne bacteriological diseases like diarrhoea, cholera and dysentery (WHO, 1990 and 1992; World Bank, 1992 and 1993);
(vi) vector borne diseases: a changing climate may lead to the (re-)introduction of vector-borne diseases like malaria and the presence of hookworm (Martens *et al.*, 1994).

The conceptual model

As said, the complexity of the population-environment relationship urges a broad integrated framework. An integrated population and health model is under development for the global scale, without disaggregating to world regions. The aim of the model is to simulate the changes in morbidity and mortality levels under varying socio-economic and environmental conditions. Epidemiological transitions, determined by social and economic development and environmental change, will be simulated. The global population and health model includes a demographic subsystem, two causal subsystems, i.e. the health services and determinants, and two effect subsystems, i.e. diseases and deaths. *Figure 4.3* shows a diagram of an interpretative model of the population and health subsystem to structure population and health issues according to the pressure (driving forces) - state (population dynamics) - impacts (health status) - response (management) system. The integrated model is driven by outputs generated by four other TARGETS modules: water, food production/availability, economy and climate. The population figures form a major feedback loop to these models. In this way the dynamics of the interplay between population, the environment and development is described instead of using fixed exogenous UN population projections (United Nations Population Division, 1991), like many other models do. The methodology is based on RIVM experience with integrated health modelling and integrated disease-specific modelling (Mosley and Becker, 1991: Niessen and Rotmans, 1993; Ruwaard *et al.*, 1993; Niessen *et al.*, 1993; Bonneux *et al.*, 1994), and with the building up of stocks, human resources and service infrastructure, the delay of effects and effectiveness parameters (Vries de, *et al.*, 1993).

In the TARGETS population and health model diagram, societal responses (e.g. social and health policies) are included in the arrows from the bottom to the top. Policies may lead to interventions in the various sectors, modulating the forces in the pressures (driving forces) compartment. The pressures part consists of forces depending on the state of socio-economic development determining water and food supply, income and literacy level and preventive and curative health services level. Global environmental change influences exposure to health risks.

In the dynamics component, the demographic changes take place under the various environmental and socio-economic pressures that lead to changes in birth and mortality rates. Fertility rates are determined by income expectation, life expectancy/ infant mortality rates, desired family size and contraceptive prevalence. These relations model the general insights

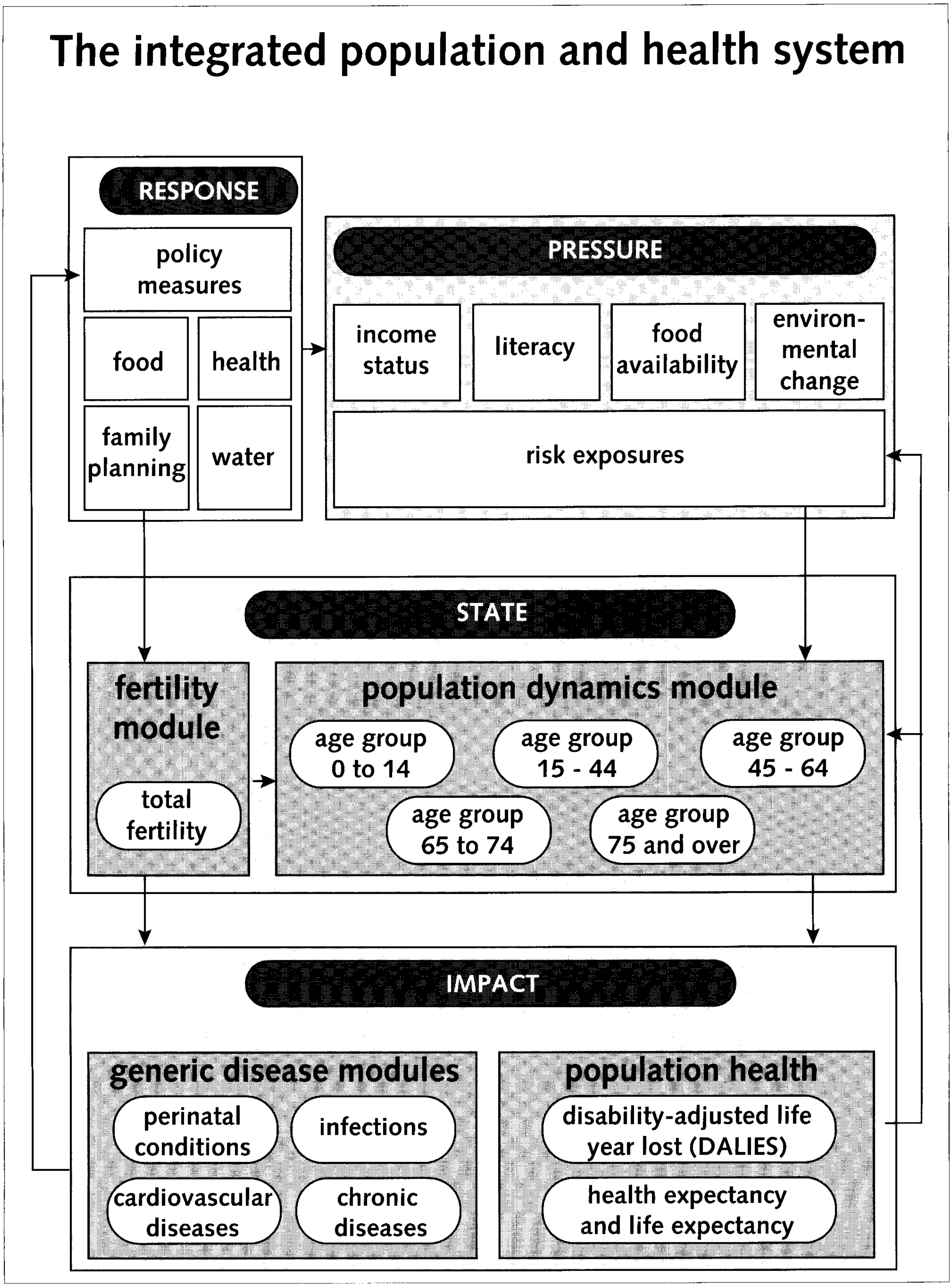


Figure 4.3: The integrated population and health module

into the factors determining fertility rates (UNDP, 1992; 1993).

Mortality rates are determined by age-specific mortality functions which in turn depend on average life expectancy. This, in turn, depends on the levels of food, industrial and service output per capita. The effects are reflected in the health impact part, that distinguishes various disease states and disease-specific mortality rates. All measures combined determine the overall population of health, disease and death, that can be expressed in life expectancy and in the DALIES measure (World Bank, 1993), which is further explained in section 5.5.

The integrated modelling approach aggregates the data regarding the driving health forces as well as regarding the morbidity and mortality levels that are available. At the same time it identifies the gaps in the national information systems. The interpretative mathematical model, subsequently, can identify the specific contributions of social, economic and environmental changes in the number of disability-adjusted life-years for populations.

4.5.2. Energy/economics/minerals model

Introduction

The energy system of the world is based on carbonaceous fuels (about 80%) and biomass (about 15%). Depending on the assumptions and definitions it can be generally said that the energy and industrial sector cause about 75% of the global climate change problem, where within the energy sector transportation, power generation and other combustion processes play about an equal role. Projections show that if global environmental change is not taken into account in energy policy planning, accelerated growth of energy use will take place, based on the same energy system as before. Abundant reserves of natural resources will be used unless technological and financial measures are developed to push energy supply development in a more benevolent direction. On the other hand, in order to limit the risks of global environmental change, a major shift from a fossil fuel-based energy system to a system in which the major part of the energy use is captured by renewable energy sources. This, however, would require major social and economic adaptations. It is a major question whether the global energy system will be able to cope with the social and economic effects of such a shift.

In order to address the above issues an energy/economics/minerals model is under development, which is primarily an improved version of the resources submodel of the World3-model (Meadows *et al.*, 1972; 1992). A key element in this model is its integrated system dynamics perspective.

The conceptual model

The model under development is divided into an energy submodel, an economic submodel and a minerals submodel, as is shown in *Figure 4.4.* The energy submodel simulates the use of fossil fuels and the eventual introduction of renewable and nuclear energy sources, as well as ways to substitute energy end-use for capital ('energy conservation'). Two different types of natural resources can be distinguished: non-renewable resources such as fossil fuels and renewable resources such as forests and soils. Both resources can be represented either in the environmental system or in the human system. Nevertheless, it is usual to define non-renewable resources as economic commodities, so here the non-renewable resources are only represented in the human system.

The energy submodel should be rather detailed because of its crucial role in global change. This submodel will be based on a variety of resource models in literature (Vries de, *et al.*, 1993). The sector is divided into four sections: the solid fuels model, the liquid fuels model, the gaseous fuels model and the electric power model. The three fuel supply models have a similar structure. Depletion is governed by long-run cost-supply curves for the resource base. New investments are based on profitability. Prices are related to costs through a cobweb-like mechanism which reflects the impact of capacity shortages in the production of capital stocks. If an alternative (solid/liquid/gaseous) enters the market, its relative price will determine the degree of market penetration. The data required for the energy submodel are already available.

The minerals submodel simulates the processes of discovering, exploiting and partly recycling a finite resource base of moderately scarce metals. It also simulates the usage patterns of the bulk of relatively abundant metals and their eventual recycling. The representation of the minerals sector much resembles the energy submodel. The model is based on a variety of analyses and models in the literature (Vries de, *et al.*, 1993) and differentiates between metals available in relative abundance and those available on a limited scale during the time period concerned. Although the question of substitution of metals by other metals is an important one, we do no take this into account, except in terms of a price-induced demand reduction. A major problem is that there is insufficient information to implement the

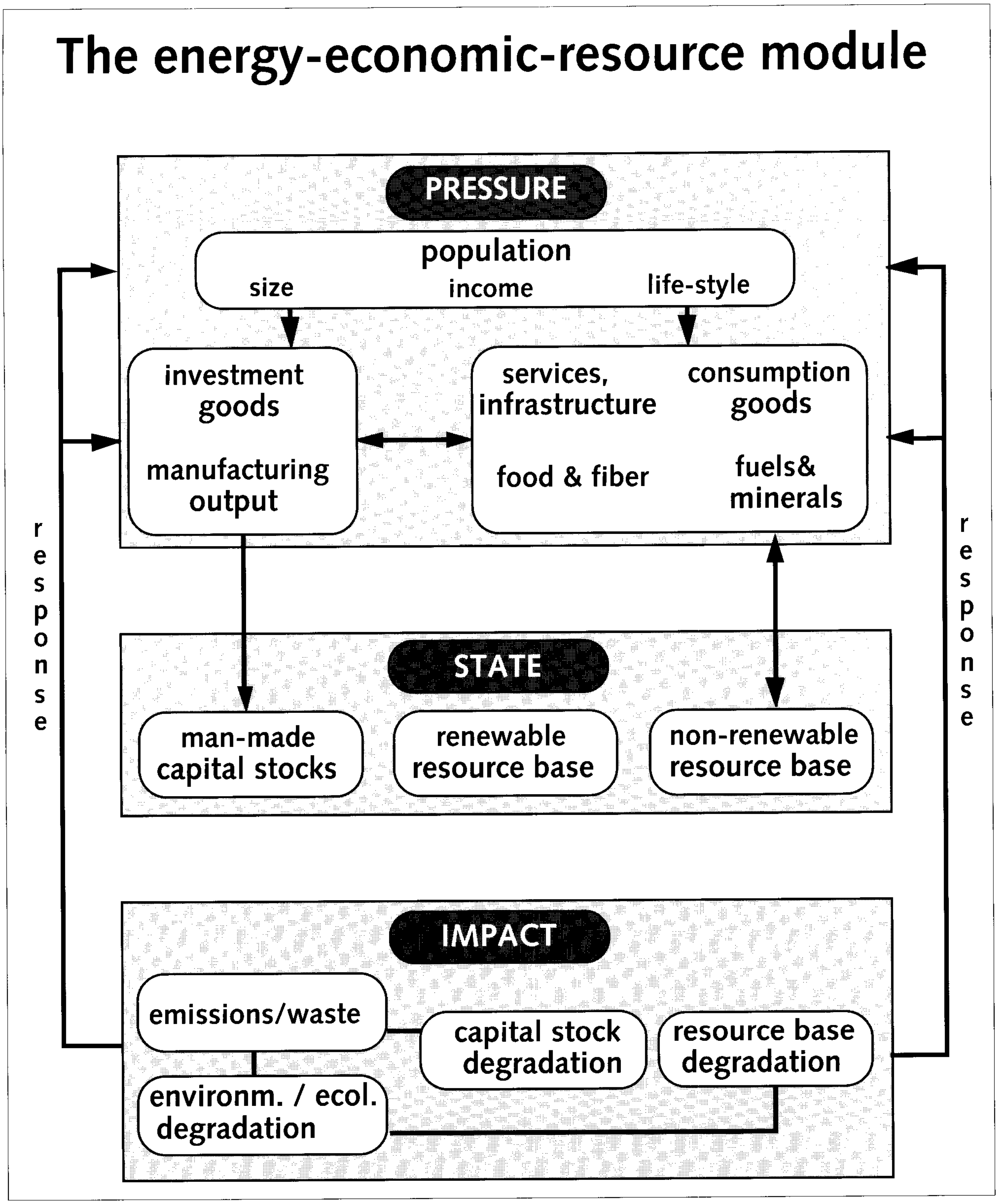


Figure 4.4: The energy-economic-resource module

minerals submodel at the world and regional level.
The very simple economy submodel consists of an industry, services and consumers part. Industrial output is generated at a fixed capital-output ratio; labour is not taken into account; industrial output is allocated to the other modules of TARGETS 1.0. The service sector is expanded on the basis of an assumed relationship between industrial output per capita and desired service output per capita. Consumption is as yet determined by a constant savings rate. For a more elaborate description the reader is referred to Vries de, *et al.* (1993).

4.5.3. The biophysics model

Introduction

Biogeochemical cycles describe the transformation and movement of chemical substances in the global environment, and connect with major global issues: climate change, soil degradation, acidification, stratospheric ozone depletion, and dispersion of toxic and persistent micropollutants. Although scientific knowledge of these cycles is growing impressively, it remains inadequate and we even have to accept a certain extent of unpredictable uncertainty due to chaotic behaviour. In spite of this far from sufficient knowledge, an effort has been made to develop an integrated model that delineates the physical, chemical and biological state of the biosphere. This type of highly aggregated and simplified biosphere model might be used to test the potential feasibility of some of the technically based countermeasures proposed during recent years. Some examples of manipulating the atmosphere are presented in Graedel and Crutzen (1993), but these examples lie beyond the scope of the integrated model discussed above. Issues that can be addressed, however, include the idea of depositing iron into the southern ocean to stimulate the atmospheric CO_2-uptake by the oceans, as proposed by Martin *et al.* (1990a and 1990b) and later on rejected by others (Joos *et al.*, 1991a; 1991b; Young *et al.*, 1991). Other ideas concerned the pumping of fertilizer (nitrogen or phosphate) into the ocean, causing enormous populations of algae which could act as a sink for atmospheric carbon. Various other options for the storage of carbon in the ocean have also been suggested, but seem to be ineffective (Baar de, and Stoll, 1989).

The conceptual model

From a model structure perspective, the biophysical part of TARGETS mainly consists of the following parts: a global elements cycles module, a climate assessment module, an ozone assessment module, and an acidification assessment module, which are interlinked, as is shown in the conceptual diagram of *Figure 4.5*.

The global elements cycle model simulates the cycling of carbon, nitrogen, phosphorus, and sulphur between the atmosphere, terrestrial biosphere, lithosphere (soils) and hydrosphere (rivers and oceans) and integrates the interactions between the various compartments. Basically, the model consists of two subsystems: the atmosphere-terrestrial biosphere-soils system and the river-atmosphere-ocean system. In the atmosphere-terrestrial biosphere-soils system the basic entities are ecosystems (land cover types), each of which is further partitioned into carbon/nitrogen/phosphorus reservoirs such as biomass and soils with an inorganic and an organic part, so as to represent the different stages of cycling of carbon, nitrogen and phosphorus through each ecosystem.

In the river-ocean-atmosphere system the ocean is divided into surface layers (a warm and a cold mixed layer), one intermediate layer and two deeper layers, in total up to a depth of about 4000 meters. Each layer consists of an inorganic and organic component, representing the cycling of organic and inorganic carbon, nitrogen and phosphorous through the ocean. The other aspects of the global water system are treated in section 4.5.6, which deals with the AQUA water model.

Prototypes of the global elements cycles of C, N and P have already been developed by Elzen den and Rotmans (1994). In addition, two major aspects of the sulphur cycle will be modelled. First the climate forcing associated with sulphate aerosols, which has only recently been considered seriously (Charlson *et al.*, 1987; Wigley, 1991; Charlson *et al.*, 1992; Kerr, 1992). In this study a simple model developed by Wigley and Raper (1992) will be used to estimate the climate forcing of sulphate aerosols. The second focus will be on the role of dimethylsulphide (DMS) as a potential feedback mechanism within the climate system (Schwartz, 1988; Foley *et al.*, 1991; Ivanov and Freney, 1983; Langner and Rodhe, 1991). A simple modelling approach proposed by Foley *et al.* (1991) will be adopted, which incorporates empirically-based parameterizations for the control of cloud droplet concentration to estimate the magnitude of the DMS-cloud albedo feedback mechanism.

The global elements cycle model triggers, amongst others, the climate assessment model in TARGETS, which comprises an atmospheric chemistry model, a radiation model and a climate model, which are modules of the experimental version 1.6 of IMAGE as described in Elzen den (1993). The atmospheric chemistry model consists of a photochemical tropospheric model, which simulates key processes of the global methane/carbon monoxide/hydroxyl (CH_4-CO-OH) cycle (Rotmans *et al.*, 1992). For nitrous oxide (N_2O) a simple mass balance model has been developed, where the atmospheric disassociation of N_2O is proportional to the atmospheric concentration and inversely proportional to the atmospheric lifetime of N_2O.

Both model approaches are box models that produce

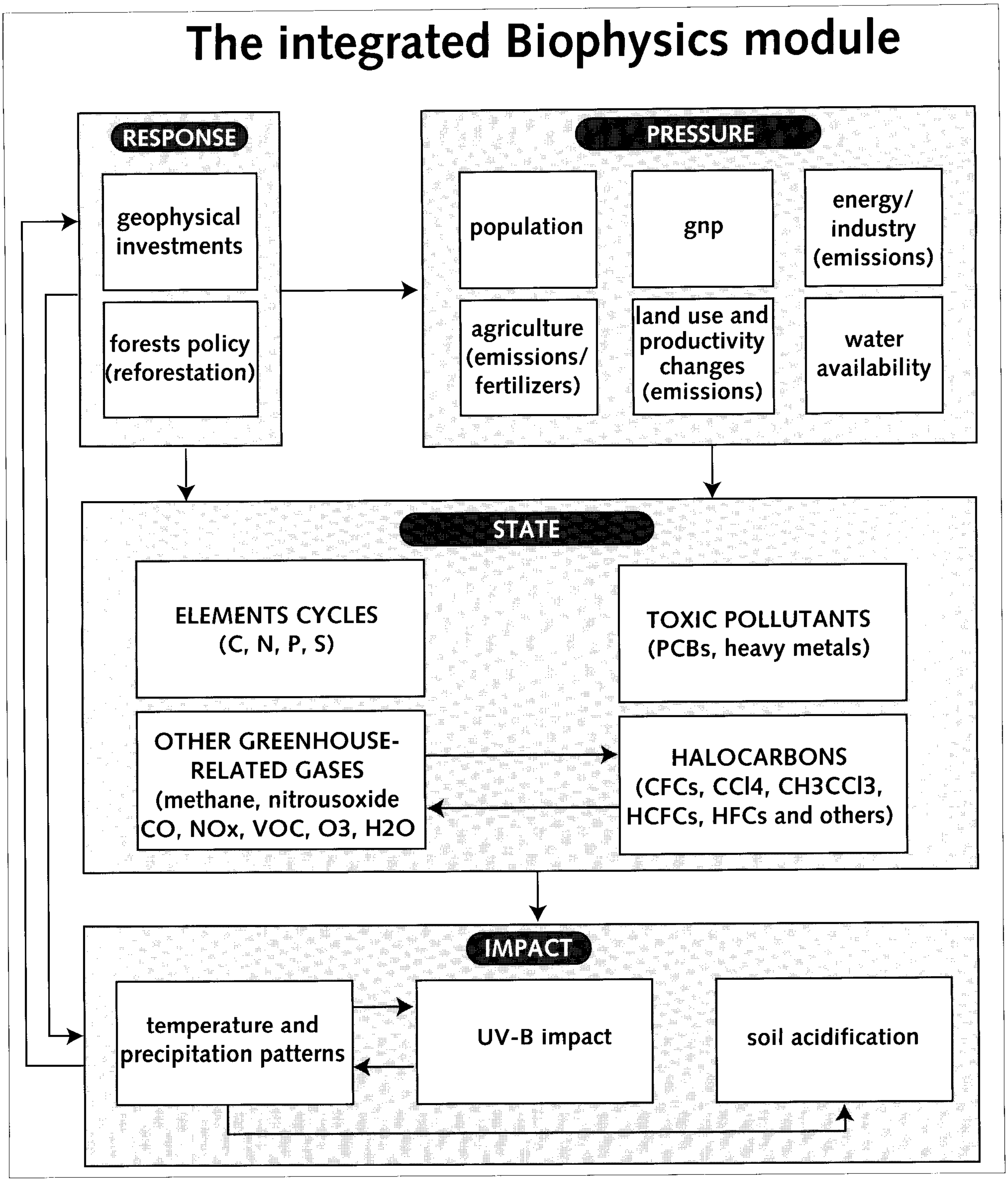


Figure 4.5: The integrated biophysics module

globally averaged values of atmospheric concentrations of gases. The radiation model converts the various greenhouse gas concentrations into radiative forcing changes. The total change in radiative forcing at the tropopause is the sum of the individual contributions of the different gases, as is described in Rotmans (1990). The form used for the radiative forcing functions matches the expressions given by the IPCC (1990). A CO_2-equivalent concentration can be defined, including the combined radiative forcing of all greenhouse gases considered and expressed in terms of CO_2. The total radiative forcing is input for the climate model, which is an energy balanced upwelling box-diffusion model,

based mainly on Wigley and Schlesinger (1985) and described in Rotmans (1990). The climate model determines the time-dependent global-mean temperature change in response to an imposed forcing and includes a land box, an ocean box and atmosphere boxes for atmosphere over land and over oceans. The model fully parameterizes the exchange of heat between the different boxes.
The global-mean temperature projections are then used to generate regional patterns of mean monthly and seasonal changes in future temperature and precipitation for the world. Regional climate change patterns are estimated using results of the coupled-atmosphere GCM transient experiment of the Max Planck Institute (Cubasch *et al.*, 1992) according to the method already described in section 4.2.

The ozone assessment model comprises a halocarbon model and a UV-B impact model. The halocarbon model simulates halocarbon concentrations, and the resulting atmospheric chlorine concentration and the overall radiative forcing, i.e. direct forcing associated with halocarbon concentration changes, and indirect forcing due to stratospheric ozone losses. The latter is a potentially important feedback on the overall radiative forcing due to halocarbons, and is called the stratospheric-ozone-depletion feedback (Wigley and Raper, 1992). At present, the halocarbon model includes five CFCs, methylchloroform, carbon tetrachloride, a number of hydrochlorofluorocarbons and hydrofluorocarbons, two halons, methylbromide and methylchloride. For a detailed description of the model is referred to Elzen den (1993). The UV-B impact model uses as input the atmospheric chlorine concentrations derived from the halocarbon model, and calculates stratospheric ozone depletion (fitted with observed satellite data), increased UV-B radiation (based on regression analysis using an atmospheric UV-transfer model), and non-melanoma and melanoma skin cancer risks (function of life-long cumulative effective UV-B exposure) due to increased UV-B radiation associated with ozone depletion. The UV-B impact model is part of the UV-B chain model, which is described extensively in Elzen den (1993) and Slaper *et al.* (1992).

The acidification assessment model is a meta-version of the RAINS acidification model for Europe, described in Alcamo *et al.* (1990). The model is fed with emissions of SO_2 and NO_x, produced by the energy/economics/minerals module of TARGETS. These emissions provide the input to the atmospheric transport model, which uses a transfer matrix (source receptor matrix) that expresses the relationship between country emissions and local deposition. This transfer matrix is based on the EMEP long-range transport model of sulphur and nitrogen in Europe, and incorporates meteorological and chemical effects on concentration and deposition of the substances mentioned above. Climate change will affect meteorological circumstances, and consequently alter the spatial patterns of long-range transport and deposition of pollutants. Though the magnitude of this climate effect on deposition patterns is still not agreed upon, an attempt has been made to quantify this effect by linking the regionalized climate patterns generated by the climate model to the transfer matrices. The depositions form the input to the soil model, which calculates the soil acidity, taking into account acid load and the soil's buffering capacities. To integrate effects of soil acidification with soil effects of nutrients cycling and climate change, a single integrated soil model has to be developed. It is intended to develop meta-versions of the RAINS acidification model for three specific regions: East Asia, Northern America and Europe.

4.5.4. The global toxics substances model

Introduction

The least understood issue in the discussion of global environmental change is probably the cumulative biogeochemical impact of persistent and toxic micropollutants. These substances, among which are many volatile organic compounds, heavy metals and polychlorinated compounds, can accumulate in an unpredictable (chaotic) manner in the various spheres. Models of global cycles are to be built for some of the heavy metals, the characteristic chemical processes of which are exemplary for the other trace metals. Some examples will be given of the extent to which metals stimulate biological activity: the accumulation and remobilization of persistent chemicals in soils and sediments, under the influence of changing environmental conditions, such as climate change, changing land-use, acidification, etc. Recently this long-known phenomenon has been called the Chemical Time Bombs (CTB) problem (Stigliani, 1988; 1991; Meulen ter, *et al.*, 1993). One example of such a CTB will be worked out in this project, for instance the mercury cycle in the Amazon region (Lacerda and Salomons, 1991).
In the case of the other chemical substances, the extent to which the inconceivably wide range of them can be aggregated up to some representative

chemicals for which cycles can be modelled will be investigated. N.B.: over 11 million chemical substances are known; some 60,000 - 70,000 of which are in regular use, but only about 3,000 of which account for 90% by mass of the total used; whereby between 200 and 1,000 of them are produced annually in quantities in excess of one tonne; data on the environmental and ecotoxicological effects are sparse (UNEP, 1992a).

The conceptual model

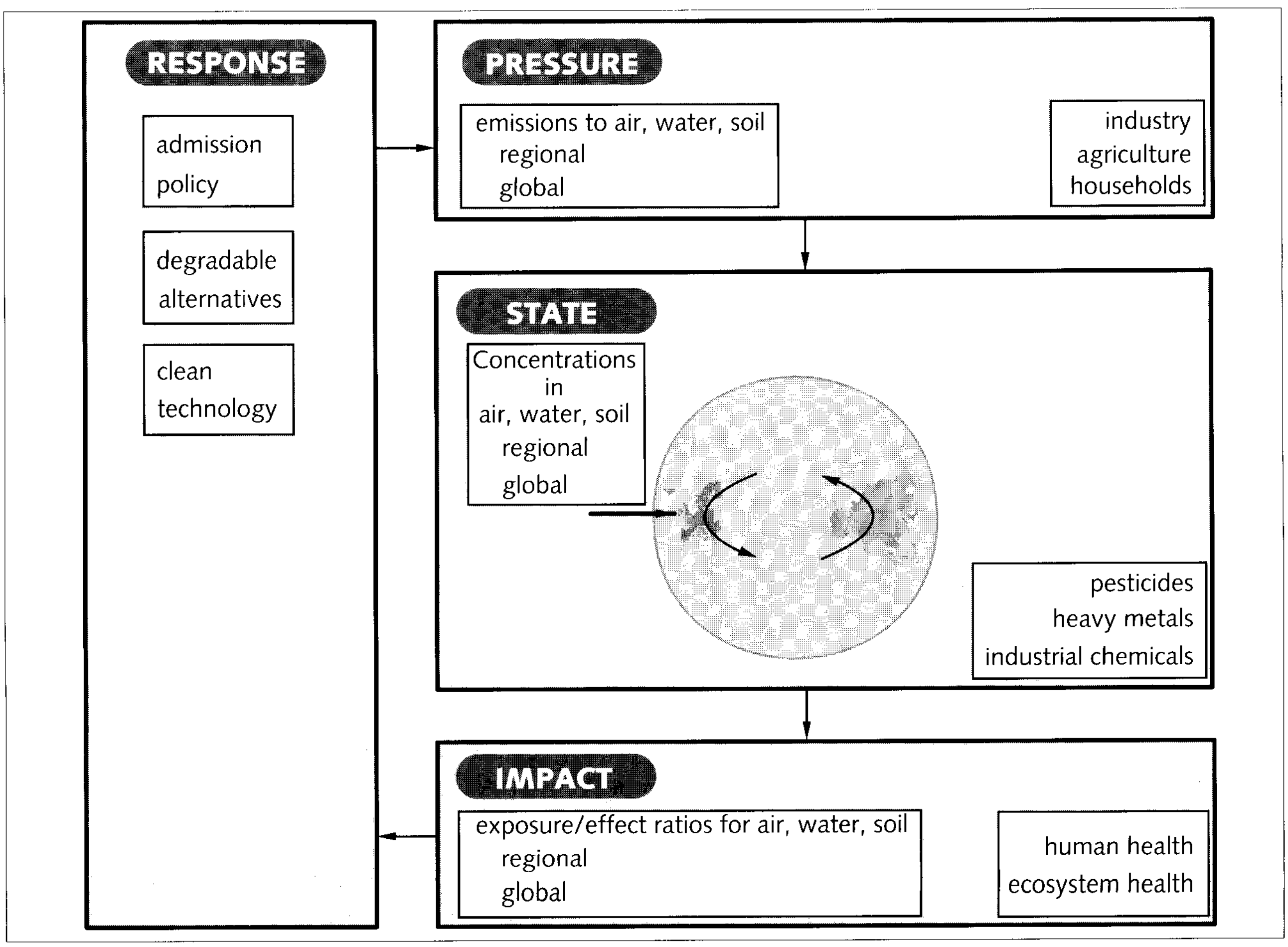
The generic multimedia box modelling spreadsheet SimpleBox (Van de Meent, 1993) is taken as a starting point; transport-and degradation processes will be modelled as in SimpleBox. The global toxic substances model will be based on the nested version of SimpleBox, as used for quantification of 'persistence in the environment' and 'global dispersion potential', which is shown in *Figure 4.6*.

In the overall model diagram of TARGETS the toxics substances model is part of the biophysics model.

In general, the global distribution model for toxic substances focuses on those toxic micropollutants which, on a global and a regional scale, may adversely effect human health and ecosystem functioning, or may adversely affect agricultural production, or may result in a deterioration of drinking water resources. In addition, the extent of global dispersion as well as the availability of data necessary to complete the modelling exercise are criteria for the selection of toxic micropollutants. At most ten different, 'aggregated' toxic chemicals will be selected, which are supposed to represent the major classes of chemical substances. The selected chemicals involve some heavy metals, persistent organic chemicals and some non-persistent chemicals, for which sample outputs in the form of regional and global concentration-time profiles will be produced.

First, a spreadsheet prototype is produced, by which a preliminary sensitivity and uncertainty study is carried out. This shows what output can be generated and to which sort of input the model is most sensitive. Iteratively, the prototype is modified until

Figure 4.6: The integrated toxic substances module



a useful model concept is obtained. Based on these experiments a second prototype will be developed, which will be tested and analysed thoroughly (behaviour with extreme model input, sensitivity to uncertainty in or absence of input data, etc.).

4.5.5. The global land model

Introduction

Land use change is one of the human activities influencing the biogeochemical cycles and thus global change in a drastic way. Presently, the conversion of tropical rainforests is considered to be the most important type of change in this respect. The world's tropical forests presently face tremendous pressures from the increasing demands of increasing populations. More than 10 million hectares of closed tropical rainforests are destroyed annually and an equal amount is severely altered. The results are the extinction of species, increased erosion, threatening of indigenous people, the modification of regional and even global climate, and the destruction of a wide variety of possibly economically important assets.

The integrated land model under development attempts to shed some light on the complex dynamics of the interplay between population growth, economic growth, land management, and food supply on the one hand, and global environmental change (primarily climate change) on the other. The model may provide a better understanding of the human pressure on the global land and food system, and the impacts of changing food supply conditions on human health and economics. In this way the integrated land framework can serve as an aid to formulate land and soil management strategies, which can be evaluated with respect to the goal of sustainable development.

The conceptual model

The global land model deals with the dynamics of the land system (land use and quality) and the food system. The model portrays the complex land dynamics from an integrated perspective, simulating and coupling the various causes (social, demographic and economic processes resulting in food and wood demand, as well as global environmental change), the mechanisms (biophysical land use and fertility processes), the effects (on society in terms of food supply changes, and on ecosystems in terms of deforestation, erosion, degradation and desertification) as well as steering mechanisms (land and soil management practices). The conceptual model is described in Elzen den *et al.* (1994) and is depicted in *Figure 4.7.* It basically consists of a land/soil management and investment module (steering part), a land development module (which forms together with outer pressure factors such as population, economic and energy development the pressure part), a land use and land productivity module (state dynamics part) and a supply/demand module for food, wood and land use (impacts part). First, a prototype of a global land model will be developed, which consists of two submodels: an agricultural model focusing on the main agricultural processes of irrigation, land clearing and intensification, food production (based on agricultural inputs like fertilizer use) and degradation, and a land use change model which focuses on the main driving forces behind the major land clearing processes of deforestation and urbanization. Although the prototype acts on a global scale, spatial heterogeneities are introduced by disaggregation into specific classes for soil, climate and land use. The highly aggregated yield and area data for these classes will be primarily delivered by the IMAGE 2.0 model. For a detailed description of the IMAGE 2.0 model is referred to Alcamo (1994).

In the second phase the model will be made operational for a number of regions, temporarily starting with two: the developing and the developed countries. Also, the modelling of some geographically-explicit processes will be improved, calibrated and validated, using a series of simulation experiments with the IMAGE 2.0 land model. On the other hand, in the near future experiments analysing the endogenously modelled processes of the TARGETS land model might lead to improvements in the IMAGE 2.0 land model.

4.5.6. The global water model AQUA

Introduction

Water is of vital importance to life on Earth because of its function as a medium for regulating heat, supporting aquatic systems, and moving nutrients into plants. Although there is no shortage of water on a global scale, water is very unevenly distributed over the globe, causing extremely low levels of water availability at some places, and overabundances at other places. Water-related problems that are addressed within the global scope of this study are: (i) scarcity of freshwater of proper quality due to human activities in the light of a growing competition between the various user groups; (ii) the impact of a global climate change on

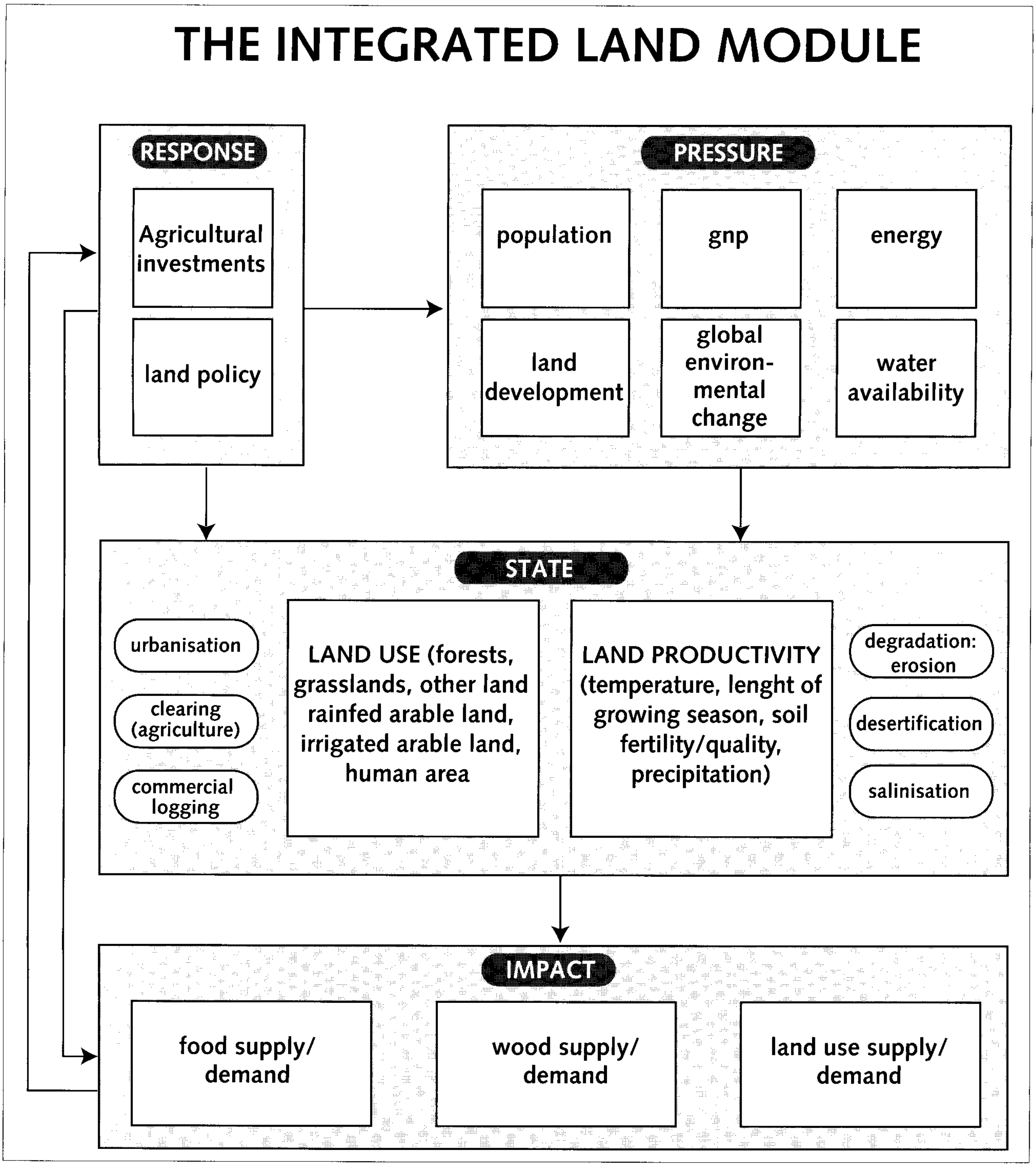


Figure 4.7: The integrated land module

peak river discharges, which may cause flooding of lowlands; (iii) sea level rise, which according to a recent hypothesis launched by Sahagian *et al.* (1994) is caused not only by climate changes, but also by a combination of groundwater withdrawal, surface water diversion and land use changes, resulting in flooding of coastal areas and intrusion of ground water. In order to analyse and evaluate these water-related issues an integrated water model, referred to as AQUA, is being developed. The integrated framework offers the possibility to develop and evaluate water management strategies within the context of sustainable development.

The conceptual model

The global water (river-atmosphere-ocean) model is part of a cross-section of TARGETS that addresses the human influences on the global water system as well as the water system itself and the influences of the global water system on human health, socio-economics and ecosystems. The global water model describes the global water system (both hydrological and qualitative aspects), the human pressure on this system and the effects of changes in the water system on human health, food supply, etc. The integrated water model AQUA contains the following main submodels:

(i) a pressure module describing the quantitative use and the pollution of water;
(ii) a water dynamics module consisting of the hydrological cycle and water quality processes;
(iii) an impact module describing the impacts of the water system on human health and socio-economics, and
(iv) a steering module providing the option to draft and evaluate water management policies.

The main structure of the AQUA model, of which a prototype has already been developed by Hoekstra (1994) is represented in *Figure 4.8*. The AQUA model is in mutual relation with all other modules in TARGETS. Input variables to AQUA are: population (originating from the population and health module); GNP (from the socio-economic module); and temperature (from the climate module). The major output variables of AQUA are: percentage of the population without proper water supply; percentage of population without proper sewerage; percentage of the cropland irrigated; hydropower generation capacity; changes in wetlands, and sea level rise.

The hydrological submodule of AQUA is divided into eleven compartments, where each compartment is considered as a reservoir in which water is stored. The model contains a water balance equation per compartment. The eleven compartments are:
(i) oceans and seas (salt surface water); (ii) atmosphere; (iii) snow and glaciers; (iv) depressions on the land surface; (v) unsaturated soil; (vi) fresh ground water; (vii) salt ground water; (viii) fresh surface water (rivers, lakes, reservoirs, marshes); (ix) ice caps (Antarctica, Greenland, small ice caps); (x) water being used by man; (xi) water in terrestrial biota. *Figure 4.9* shows these compartments and the water fluxes between them, where each arrow represents a water flux that is modelled separately, preferably on a physical basis.

AQUA pretends to be a generic model for an arbitrary river basin. This means that it is a zero-dimensional model, considering the water system as a whole, reckoning with a time step of one month. To test this hypothesis the generic model has to be validated against some of the 20 major river basins or watersheds in the world (Dávid *et al.*, 1988; Kira, 1988; Berner and Berner, 1987). One example of such a watershed is the Rhine basin for which Kwadijk and Rotmans (1994) developed a methodology to estimate the impact of a human-induced climate change on the river Rhine discharge. For this purpose, a climate change assessment model (ESCAPE) was coupled to a water balance model (RHINEFLOW). Their evaluation shows that simple, robust hydrological models are appropriate for the assessment of climate impact on streamflow changes in large rivers in other parts of the world. The same methodology can thus be conveniently applied to larger river basins of the Ganges/Brahmaputra and the Yangtze, which will be done in the next phase. In these case studies we focus on two water-related problems: on the one hand, local and seasonal water scarcity, which comprises both the problems of water absence and inferior water quality, which are strongly interrelated and affect population (domestic water supply), agriculture (irrigation water supply) and industry (industrial water supply) (Falkenmark, 1989; 1992). Although water scarcity mostly emerges regionally, it becomes more and more clear that the problems arising from it will also affect other regions. As for the Middle East, the threat of a future water war seems to be realistic (Gleick, 1993). Undoubtedly, the water scarce regions will become more economically dependent (Falkenmark and Lindh, 1993). And on the other hand, local and seasonal over-abundance of water, which causes regular floodings in the delta area of the Ganges/Brahmaputra and the Yangtze. Both water problems are strongly interrelated with erosion and land degradation.

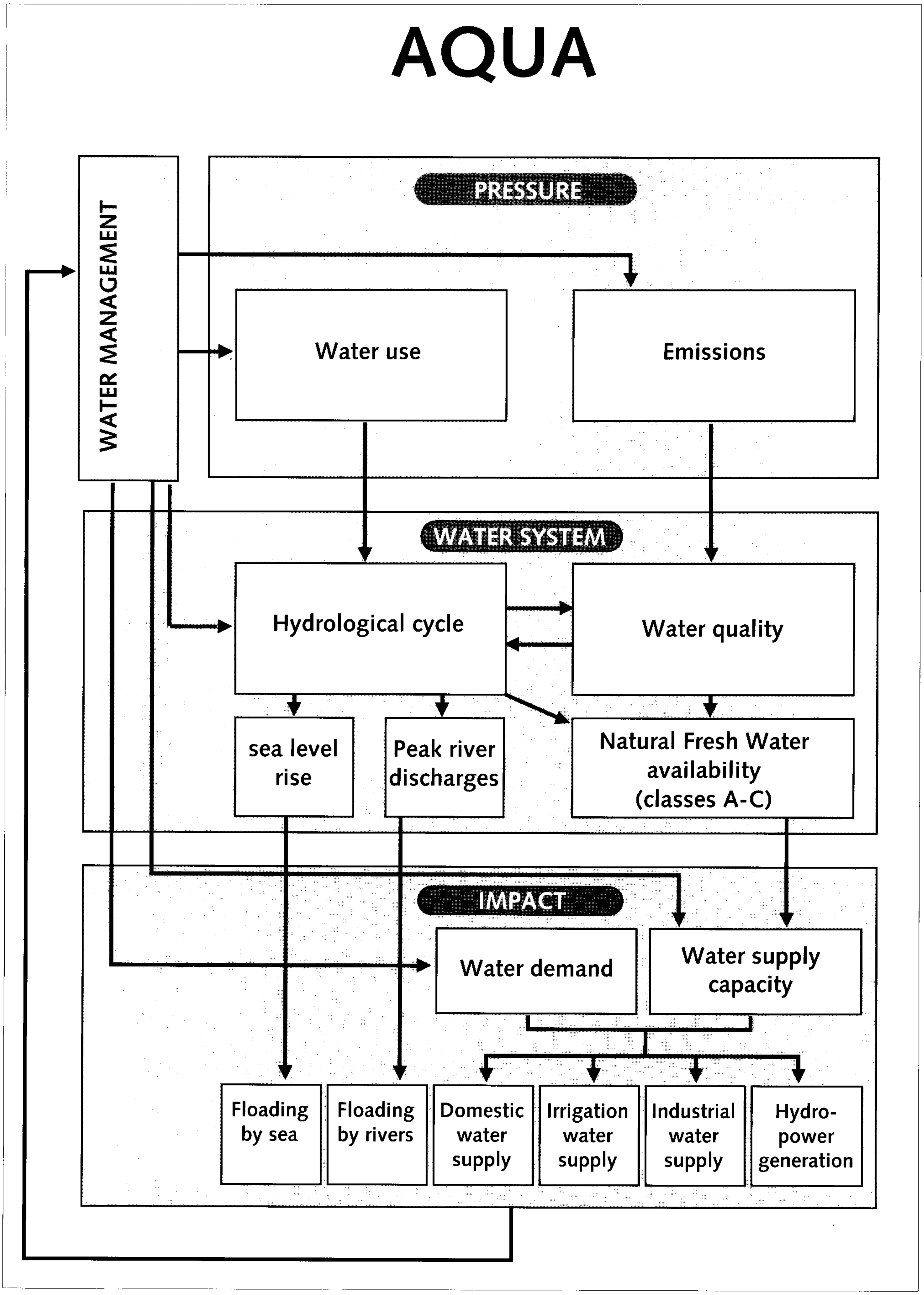


Figure 4.8: The integrated water module AQUA

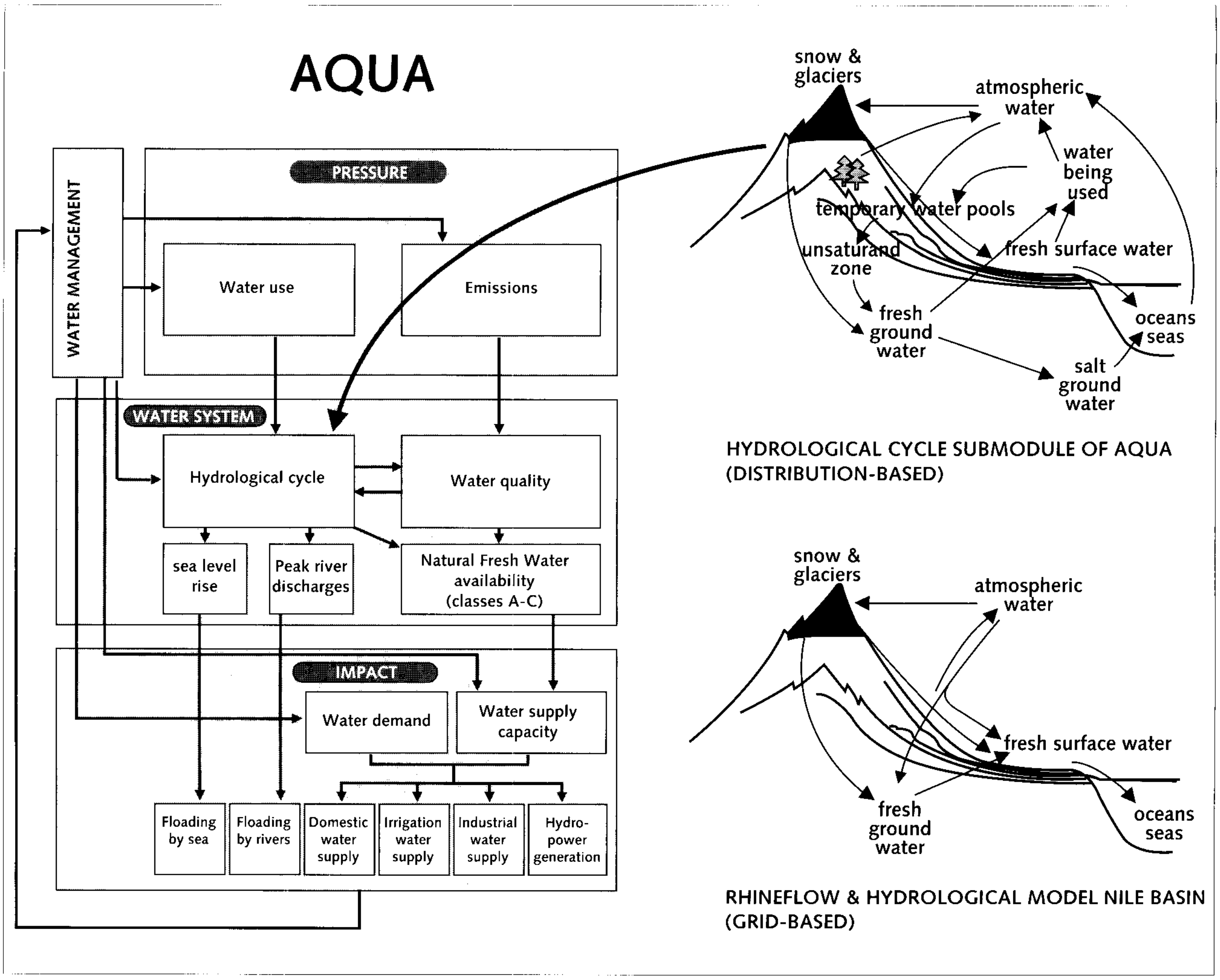


Figure 4.9: Various compartments of the AQUA model

5. HIERARCHICAL FRAMEWORK OF INDICATORS

5.1. Introduction

One of the possibilities to operationalise the concept of sustainable development is to design sustainability indicators. Indicators can monitor the pressure on, the status of, and the impact on the global environment, which enables us to anticipate an impending global change, to establish priorities, to formulate adequate strategies and to test the effectiveness of those strategies. In particular there is a strong need for highly aggregated and composite indicators, here defined as indices, in which condensed information is assembled. So far, compared with an economic index such as GNP and a social index such as HDI (Human Development Index, produced by the United Nations Development Programme) which are recognized worldwide as useful one-dimensional measures, no environmental indices have been developed. Because of the lack of comprehensive, generally accepted measures of the global environment, which can facilitate decision making within the context of sustainable development, there is thus a need for innovative ideas and indicator concepts that are both comprehensive and achievable.

The method proposed here attempts to develop a hierarchical framework of indicators which is linked to the integrated modelling framework TARGETS. While integrated models are important for analysing the phenomenon of global change, indicators serve as the vehicles for the communication of the model results, on the basis of which sustainable routes can be mapped out. In the hierarchical indicator framework proposed, different levels of aggregation are distinguished, varying from highly aggregated indices to absolute indicators in the form of observed data or statistics. The different aggregation levels within the indicator framework enable to build the bridge between the advocates of using highly composite indicators and the traditional statisticians.

The main advantage of linking a set of indicators to an integrated modelling framework is that it yields insight into the complex dynamics of the system under concern. This enables the production of coherent information about linkages between causes and effects (vertical integration) and the addressing of cross-linkages between different issues (horizontal integration). This coherent and integrative information can only be generated by an interconnected framework of indicators, and not by separate indicators.
The ultimate goal of the hierarchical framework is to create an overall index which captures the key characteristics of the global environment in a single measure, and to demonstrate the dynamic interrelations between this abstract index and the real-world indicators.

5.2. Indicators and indices

As early as the 1970s, research was being directed at developing environmental indicators. Ott (1978) puts it as follows: 'Ideally an indicator is a means devised to reduce a large quantity of data to its simplest from, retaining essential meaning for the questions that are being asked of the data.' After having been thwarted by methodological difficulties which caused reduced interest, in the late 1980s the growing attention paid to sustainable development resulted in renewed interest in environmental indicators (Born van den, *et al.*, 1993; Kuik and Verbruggen, 1991). In general, indicators describe complex phenomena in a quantitative way by simplifying them in such a way that communication is possible with specific target groups. This implicates that indicators should have added value vis-à-vis observations or data sets. In this study an indicator is defined as a characteristic of the status and the dynamic behaviour of the system under concern. From the systems-based definition of an indicator, it follows that an indicator is a one-dimensional systems description, which may consist of a single variable (absolute indicator) or of a set of variables (relative indicator).

Single indicators, or combinations of indicators as indices, can be useful tools in assessing an overall situation and evaluating strategic decisions. Indicators or indices can represent the pressure on, the state of, or the effect on a system. Environmental domain indicators representing the pressure on the environment will be of a (socio-) economic character, while those representing the state of the global environment will have a biological/physical/chemical character. When they represent the impact on the environment, they may be either. Originally, the following theoretical requirements were formulated for indicators (Opschoor and Reijnders, 1991; Adriaanse, 1993):

1. they must be observable;
2. they must be predictable;
3. they must be scientifically based;
4. they must be as aggregative as possible;
5. they must be verifiable and reproducible;
6. they must have a definite appeal;
7. they must be sensitive to variations in space and time;
8. they must reflect a trend;
9. they must be subject to human influence;
10. they must be conceptually applicable;
11. the data necessary must be available and easy to collect.

Afterwards, these rather academic criteria were reduced to practicable key conditions for indicators to satisfy (Opschoor and Reijnders, 1991; Adriaanse, 1993):

1. quality of data and data collection;
2. sensitivity to human-induced variations in space and time;
3. policy relevance with a scientific base;
4. recognisability and clarity.

The distinction between indicators and indices is based on a difference in aggregation level. An index is here defined as a multi-dimensional composite made up from a set of indicators. An example of an index composed of several indicators is given in Boer de, *et al.* (1991) who developed an integrated environmental index for application in land use zoning. As a result of their composite, and therefore abstract, character the requirements mentioned above do not necessarily hold for an index. An index is primarily designed to simplify, whereby the inevitable loss of information should be kept to a minimum (Ott, 1978). In practice, indicators and indices are the result of a compromise between scientific accuracy, concise informativeness and usefulness for strategic decision making (Opschoor and Reijnders, 1991).
Following Gilbert and Feenstra (1992) a prerequisite for indices of sustainable development i.e. sustainability indices is that they represent environmental pressure, and the state of, and impact on environmental conditions. In other words, they should capture as much as possible of the cause-effect chains they represent and relate pressure and effects to criteria for sustainable development. This causal chain approach is comparable with the pressure-state-response indicator mechanism proposed by the OECD (1993).
Some of these sustainability indices will be completely new because of the nature of the new sustainability concept that is applied to the systems, while other sustainability indices will make use of (quality) indicators already defined for a particular system (Greef de and Vries de, 1991). If possible, these quality indicators need to be aggregated into a number of overall sustainability indices, which may prove to be useful tools for measuring sustainable development (Liverman *et al.*, 1988). An example of a composite, integrated index is given in Gilbert and Feenstra (1991), who developed a sustainability index for cadmium.

5.3. A model-based conceptual framework of indicators

Generally, indicators that are currently used to report about the global environment are organized and valued without using any integrated modelling framework. This implies that they do not yield information about linkages between causes and effects (vertical integration), nor do they address cross-linkages between various causes and various effects (horizontal integration). In order to fully utilize the prognostic value of the TARGETS model, a hierarchical framework of indicators and indices is created which serves as a communication layer between modellers and decision makers. Similar to the hierarchy of models in TARGETS, the associated set of indicators should also be hierarchical, and consists of a system of pressure, state, impact and response indicators and indices. The indicator framework can be considered as a layer on top of the model layer, see *Figure 5.1*.
Within the hierarchical framework of indicators, four levels of aggregation are distinguished. The first level represents the model-aggregated indices; the second level denotes aggregated indices for the various submodels; the third level denotes relative indicators (absolute indicators per unit); while the fourth layer represents data/statistics. In this way a tree diagram of pressure, state, impact and response indicators and indices is built up (*Figure 5.2*), with at the top-level the overall sustainability index (here called SDI: Sustainable Development Index), capturing the pressure, state, impact and response dynamics for the model as a whole. One level below the sustainability indices for the various submodels can be composed.

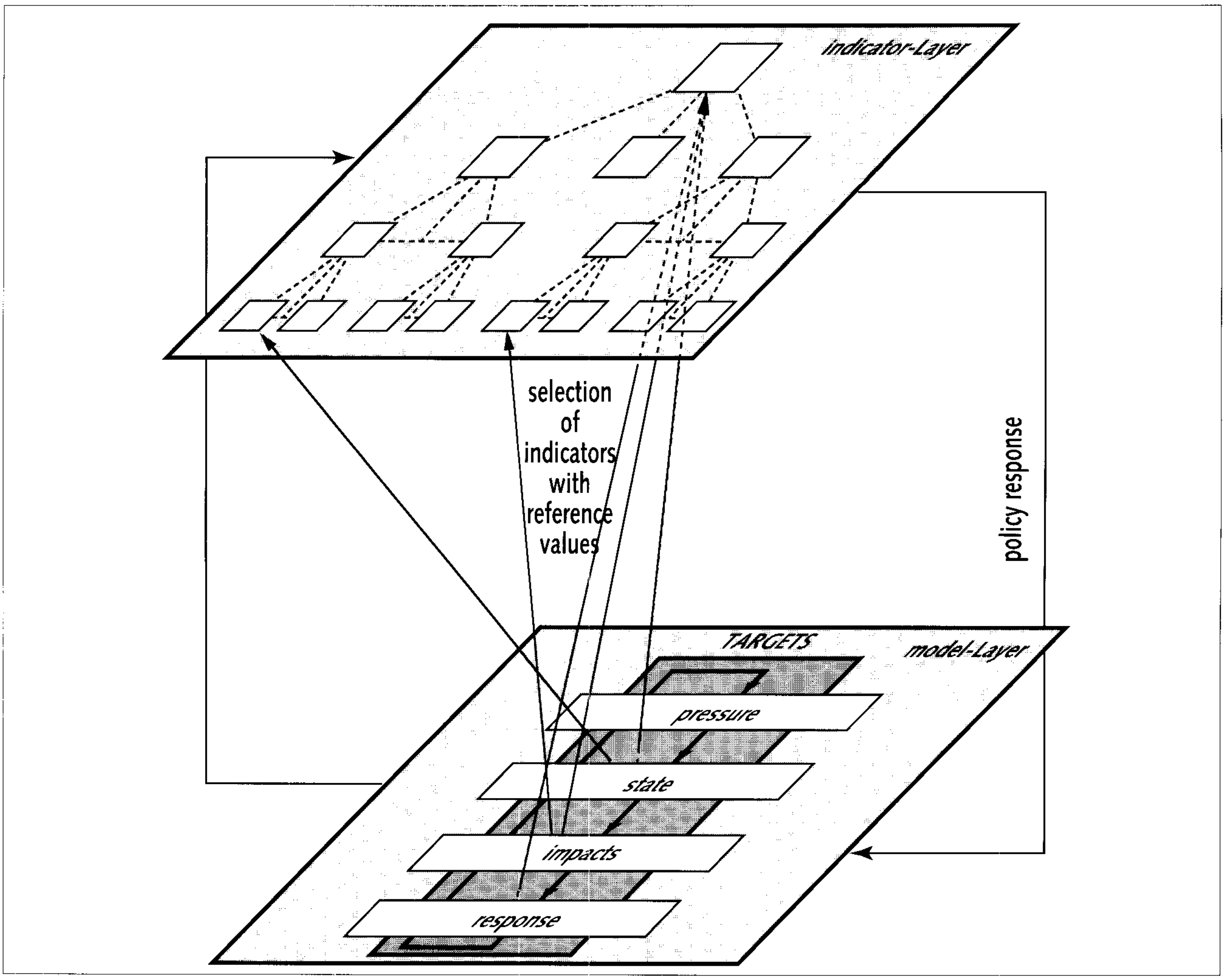


Figure 5.1: Indicator-layer versus model-layer

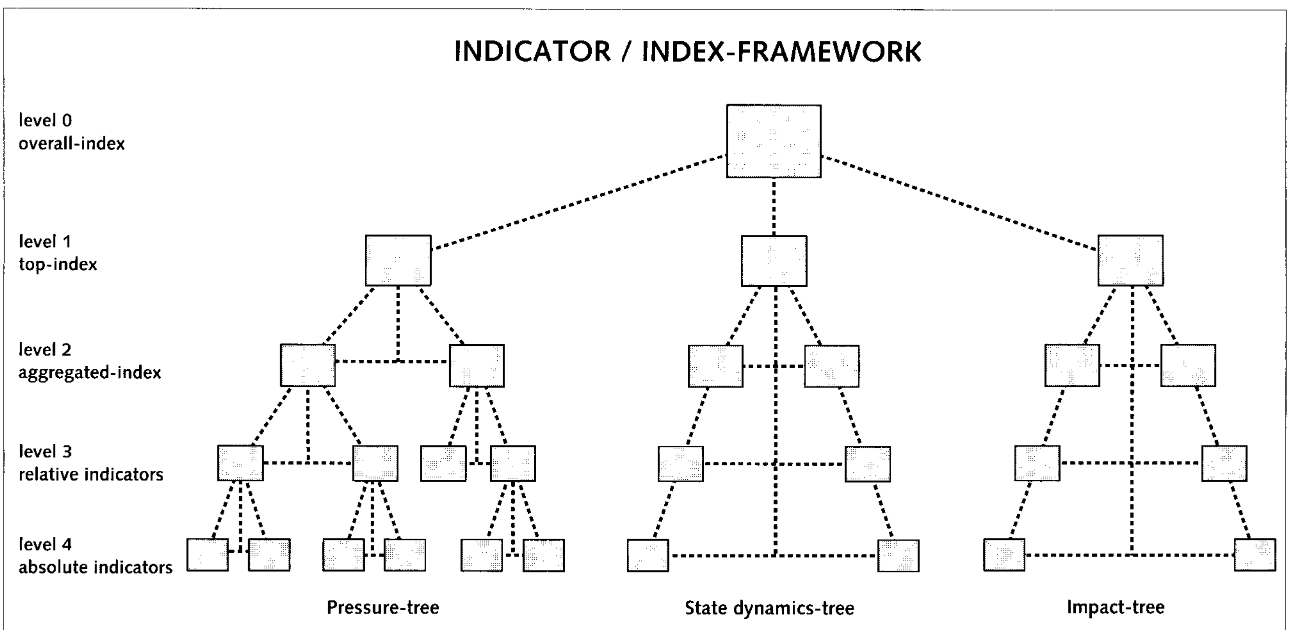


Figure 5.2: Hierarchical framework of indicators

The hierarchical framework of indicators and indices, will be used for two purposes. First, to communicate and translate the insights arising from experiments with the underlying integrated modelling framework in such a way that they can be understood and interpreted by decision makers. Second, to evaluate alternative sustainable development strategies for the complex system as a whole and for the subsystems considered. The hierarchical levels referred to above are basically independent of the geographical scale, which means that the hierarchical framework of indicators can in principle be applied on different scales, varying from the regional to the global. However, because in this study the hierarchical indicator framework is coupled to a global model, the focus will thus be on indicators (and indices) for the global scale, i.e. indicators in terms of global totals/averages. The overall questions to be answered from this global perspective are (i) whether the indicator/index framework can be reduced to a minimum set of indicators/indices which still represents the whole system; and (ii) in what way can the indicator/index framework be used to develop consistent strategies for sustainable development for the globe as a whole?

One of the major advantage of the hierarchical framework of indicators is that it interconnects different indicators at different aggregation levels in such a manner that the linkages between aggregated indices and statistically-based indicators can be made explicit. The flexibility of the indicator framework facilitates a focus on highly aggregated indices which suffice when there is consensus about a specific issue (e.g. economics) or to focus on absolute or relative indicators in case the underlying dynamics are poorly understood. Also, because indicators and indices are directly coupled to dynamic models within the systems-based context, the dynamic behaviour of an aggregated index can, at any point in time, be resolved into time series patterns of statistically-based indicators. Obviously, not all indicators that are relevant for policy purposes can be modelled and taken up in the indicator framework. The spheres of measurable, policy relevant and predictable indicators do not necessarily coincide. Dependent on the requirements of the different users, the indicator framework should in such cases be reconciled with available data and statistics, which are exogenous to the modelling framework used.

The methodology of constructing a hierarchical framework of indicators and indices consists of the following steps:

experimentation: systematically performing experiments using simulation models;

selection: selection of index components based on the experiments performed, and selection of initial, reference and target values;

scaling: transforming index components into dimensionless measures;

weighing: valuation of the dimensionless measures;

aggregation: aggregating results to bring indices up to one integrated index, or up to a smaller number of indices;

visualization: multi-dimensional representation of indicators and indices.

The various steps described above can be based upon a combination of expert judgement, delphi-techniques, multi-criteria analysis, public opinion polls, value-based decisions and modelling experiments. This requires frequent and intensive interaction between decision makers and modellers. In this study, however, two examples will be presented which are mainly based on model experiments and expert judgement (in section 5.4 and 5.5). The indicator framework itself can be viewed as a particular form of a metamodel, with the main difference that the cross-linkages between the indices in the indicator framework are not scientifically or empirically based, but are purely founded on subjective assessment or mathematical manipulations. The steps to be successively taken in the development of a hierarchical framework of indicators and indices are specified in more detail below.

Experimentation

Based on the knowledge gleaned from a range of systematically-performed simulation experiments, representative indices can be selected and formulated for each of the subsystems. Systematically conducted and consistent experiments should investigate the aspects of: (i) perturbation of the natural state; (ii) system behaviour: nonlinearities, stability, feedbacks; (iii) vulnerability and resilience of the system; (iv) sensitivity and uncertainty analysis. In order to investigate these aspects, it is essential that the earlier defined systems concepts, which are partly derived from the system dynamics method, should be applied. This implies that for different points in time, and for different subsystems, the magnitude and content of the reservoirs, the sources and sinks, the circulation time and the response time have to be analysed. This can be done by successively feeding the following scenarios into the model: a reference scenario, various pulse scenarios, a strong growth scenario, a shrink scenario and a trend break scenario. This should yield the information relevant for the development of sustainability indicators and indices with respect to target states, vulnerability, resilience, recovery and buffer capacity of the (sub)system under consideration.

Selection

At each point in time, the indicator framework should have a monitoring function for the current dynamic behaviour of the integrated model and the underlying system as a whole. Likewise, separate indices within the indicator framework are intended to enable monitoring of autonomously functioning modules or subsystems. However, the function of the indicator framework goes beyond the monitoring aspect. Not only modelling information relating to a given moment, but also insights into future intrinsic dynamic behaviour should be provided by the indicator framework. To this end, the following potential, generic index components have been designed:

* pressure on the system
* rate of change of the system
* state of the system
* actual effect or potential risk for the system
* recovery or buffer capacity of the system
* societal (system's) response

This implies that each Sustainable Development Index (SDI) essentially has the following basic structure:
SDI = (pressure, rate of change, state, effect/risk, recovery/buffer capacity, response)

For each of the components, the initial state (referring to the starting point of the simulation), the reference state (representing the undisturbed state of the system), and the target state(s) (desirable state to be achieved by the indicator or index) should be defined. For instance, target values for pressure indicators can be negotiated emissions targets, for the system's state indicators target values can be based on environmental quality norms, while for response indicators target values can be participation in protocols or agreements. However, only a few negotiated emission targets, environmental quality standards, or protocol standards have been established. If these quality standards or criteria are not available, various methods can be used to arrive at these values. One approach is to use the method of risk analysis (Sprent, 1988; Weterings, 1992). It should be realized that this method is highly value-based and therefore greatly dependent on the subjective risk perceptions involved, such as risk aversive, risk accepting, and risk seeking attitudes. Other methods for setting target values make use of the historical 'natural' situation as representative of the undisturbed state; the steady-state situation; threshold values; the recovery or buffering period or purely ethical considerations. In all methods the modelling experiments described above play a key role.

Scaling, Weighing and Aggregating

One of the challenging problems to resolve when setting up a hierarchical indicator framework is to reduce the abstract, multidimensional vector representation of an index to a form of at most three dimensions which can be clearly visualized. In fact this is a classic multi-objective decision making problem (Resource Analysis, 1993). The two problems which then arise are (Shults and Beauchamp, 1972):

(i) scaling (normalisation) the factors or components down to a single scale and rendering the units of measurement dimensionless; and
(ii) weighing the various factors or components of the indices.

Both issues, although unavoidable, should be treated with the greatest care because one should avoid the pitfalls of comparing chalk with cheese, and the value-based decisions that are to be taken will always be subject to criticism.
Various scaling methods exist. One possible method is to determine the ratio of current conditions and the corresponding reference values (Opschoor and Reijnders, 1991). These ratios can be aggregated using mathematical techniques. An alternative method is to transform information into measures of chemical or physical properties, or economic values. The method proposed here is to use a simple mathematical function in order to translate the values of all components of an index to values between 0 and 1.
Weighing provides a method with which to arrive at a ranking order of importance for the index components. Relative weights can be assigned to

each of the index components. The weighing mechanism can be based on expert judgement, delphi techniques, multi-criteria analysis or public opinion polls (Hope *et al.*, 1992; Hope and Parker, 1993). Weighing factors should take account of the relative importance of indices for different time scales, different spatial scales and different sectors or subsystems. In this study, the weighing method will be based on expert judgement and valuation of the index components. Valuation, however, is also determined by cultural perspectives. A method by which these perspectives can be assimilated into valuation procedures will be discussed in the next chapter.

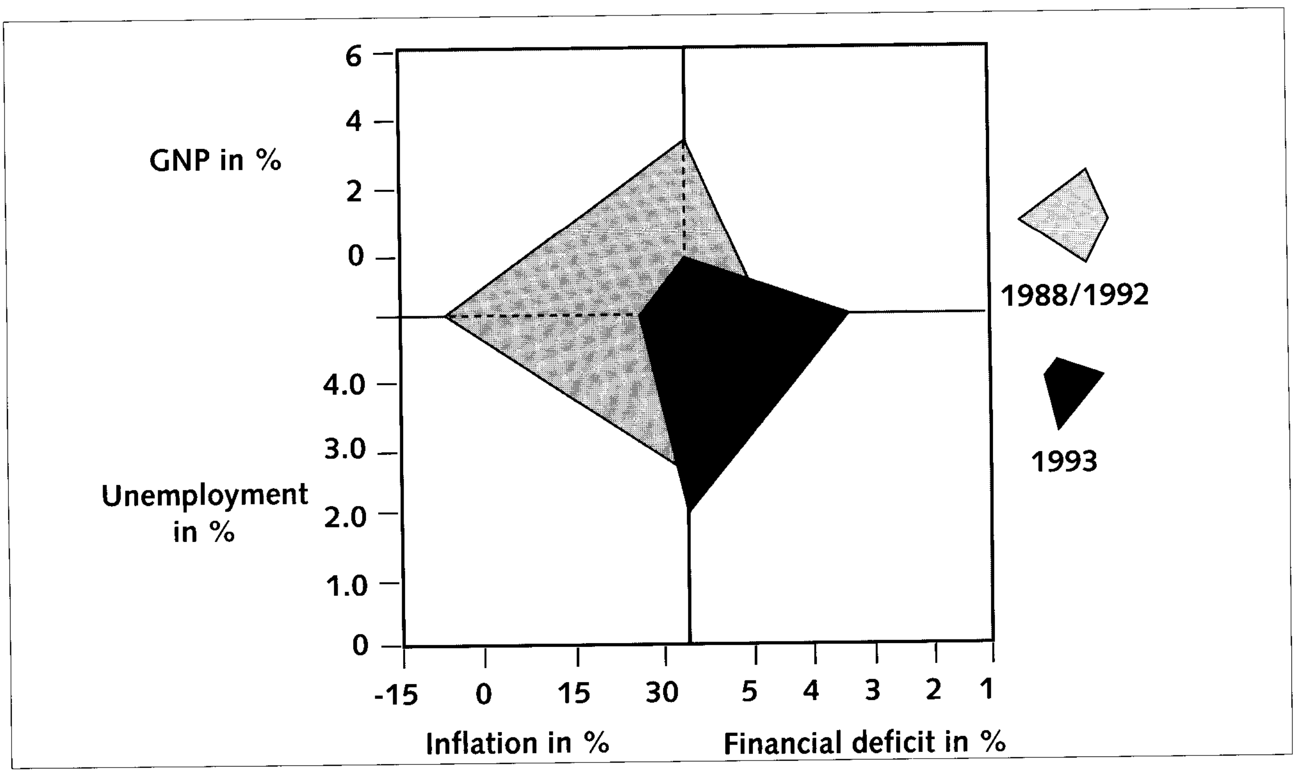
Once the weighing procedure has been completed, the question arises as to how the weighted index components should be aggregated up to a single integrated index, or, if that is not feasible, up to an index with at most three dimensions. Ott (1978) provides a survey of all sorts of aggregation functions, but advocates the use of the nonlinear aggregation root-sum-power function, which may also be of use in this study.

Visualization

Appropriate visualization of the indicator framework is of crucial importance, particularly to bridge the gap between data monitoring at different levels and interrelated indicators and highly aggregated indices useable to support decision making. Taking into account the level of complexity of the messages that will have to be brought across to decision makers, the limited number of dimensions that can be represented in printed form or that can be comprehended by individuals are limiting factors.

Another barrier may be formed by the high degree of abstraction of indices which might hamper the communication with potential user groups. An alternative to the scaling, weighing, and aggregation procedures, resulting in perhaps indigestible aggregation levels, might be to visualize the multi-dimensional components of indices. In developing the indicator framework this means that at all levels of the hierarchical framework the choice can be made between aggregation and visualisation. While aggregation aims at reducing an index to a preferably one-dimensional form, visualization enables us to represent more than three dimensions in one picture. An example of a visualization technique is presented in *Figure 5.3*, which represents four indicators of the Dutch economy (GNP, unemployment, inflation and financial deficit) in a two-dimensional form. The underlying idea is that the more flourishing the state of the Dutch economy is, the larger is the plane spanned by the four economic indicators. The

Figure 5.3: Visualization of the state of the economy in the Netherlands



picture shows that the economic situation in the Netherlands during the period 1988-1992 was better than in the year 1993.
In general, more-dimensional representations include more information about linkages and interactions between different components, but the resulting pictures will be more complex and need more explanation. On the other hand, visualization facilitates the provision of linked information in a concise way, without loss of any information.

5.4. An SDI for stratospheric ozone depletion

The issue of stratospheric ozone depletion can be represented by a sequence of indicators representing the cause-effect chain, beginning with the production of ozone-depleting chemicals and ending with the effects of increased levels of UVB-radiation on human health, see Elzen den (1993). The example of ozone indicators has been worked out for Canada (Environment Canada, 1992). The following indicators reflect the various stages of the cause-effect chain for ozone depletion:

1. world production of ozone-depleting substances;
2. global atmospheric concentrations of CFCs;
3. global stratospheric ozone levels;
4. trends in the intensity of UV-B reaching the Earth's surface;
5. effects of increasing UV-B intensities on human health.

Note on 1: The ozone-depleting substances in this indicator include chlorofluorocarbons, halons, methylchloroform, carbon tetrachloride and hydrochlorofluorocarbons. Individual ozone-depleting substances vary considerably in their capacity to destroy ozone. The combined effect of all ozone-depleting substances is therefore expressed in terms relative to CFC-11, i.e. in CFC-11 equivalents.

Note on 2: This indicator tracks the magnitude and the rate of change of the atmospheric reservoir of the most abundant ozone-depleting substances. Global measurements of atmospheric concentrations of CFC-11 and CFC-12 have been collected since 1977.

Note on 3: This indicator reflects measurements derived from satellite observations. The total column of ozone is measured, including both tropospheric and stratospheric ozone. Stratospheric ozone accounts for about 90% of the total ozone column.

Note on 4: This indicator measures the latitudinal spectral UV-irradiance at the Earth's surface as effected by stratospheric ozone depletion. Only a limited number of measurements of UV-radiation at ground level are available at present.

Note on 5: This indicator represents the increase in the incidence of skin cancer as a result of the increase in exposure to UV-B due to stratospheric ozone depletion. Two types of skin cancer are distinguished: non-melanoma (about 90% of total; mortality rate less than 1%) and melanoma skin cancer (mortality rate of about 25%). The relationship between UV-B exposure and melanoma incidence is not yet clear.

The generic potential SDI which was defined as:

SDI = (pressure, rate of change, state, effect/risk, recovery/buffer capacity)

can now be transformed into a specific SDI for ozone depletion:

SDI_{ozone} = (prod.CFCs, conc.CFCs, strat.O_3 conc., UV-B radiation, % skin canc. inc.)

Because interdependencies exist between the different indicators of the SDI_{ozone}, the SDI_{ozone} can be aggregated to an independent three-dimensional vector. This was performed by using the expert judgement of Elzen den (1993), and resulted in the following ultimate index:

SDI_{ozone} = (prod. CFCs, change in atm. chlorine conc., rel. change in skin canc. inc.)

After scaling the SDI_{ozone} it can be used for steering the integrated ozone assessment model, which represents the cause-effect chain of the global problem of stratospheric ozone depletion (Elzen den, 1993). In addition the SDI_{ozone} can be visualized easily and clearly. For these three independent indicators of SDI_{ozone} the reference values and threshold values (beyond which an unsustainable state is arrived at) are well-known or can readily be estimated. Strategies can now be formulated for managing the global problem of stratospheric ozone depletion. Whether these strategies are sustainable or not, can be determined using the SDI_{ozone}.

5.5. A hierarchical framework of indicators and indices for population and health

It is proposed that for population and health three levels of aggregation are to be distinguished. In *Figure 5.4*, the indicators that are derived from the population sub-modules are depicted as an index-tree as described above. The actual choice of the aggregation level, weighing and selection of the indices to be used will, again, have to take place according to local and regional priorities. Most of all, they will depend on the stage of socio-economic development.

At the least aggregated level the regular model output figures are depicted. These model output figures are based on the various stocks and flows of the model. Routine pressure and impact statistics in relation to the transition level of the population and the level and nature of the epidemiological transition are collected from routine data registries. Presented in time series, these are to be used for the purpose of historical validation simultaneously.
At the second level indices can be defined for the three Pressure-State-Impact-components as a whole of the health system. Most of these indices are used in international reporting. At the highest aggregated level an overall human system index can be defined comparable to the UNDP human development index (UNDP, 1993). Similarly, policy could be evaluated through the use of indices, taking the various policy areas into account, including distribution and access issues.

N.B. In *Figure 5.4* the socio-economic index is the equivalent of the UNDP Human Development Index. This index combines pressure parameters (GNP, literacy) with an impact parameter (life expectancy) without accounting for the "input-output" relationship. For this reason it is included in the depiction at a lower level of aggregation for comparison.

Pressure level

Risk levels at the population level have been expressed in terms of people exposed and danger threshold have defined based on research results found in, usually, experimental settings. Using the population-attributive risk, derived from the relative risk associated with a particular exposure, one can calculate which proportion of disease incidence in time is explained by the level of exposure. At the pressure level, a overall "health risk" index is proposed which adds up the risks related to all exposure categories while weighing for their contribution to the incidence of diseases. The use of a discount rate is possible to correct for the moment in time disease incidence occurs. No weighing takes place for the age at which disease incidence is occurring. Because of the delays involved, this overall pressure index will provide an early warning signal for potential future health changes.

State level

Two state indices are proposed: one related to fertility and one related to population. The fertility index expressed the percentage of children born that have been planned: the "planned births ratio". This ratio depends on actual effective contraceptive use and desired family size. There are quite a number of related empirical data sources available from census, demographical surveys and family planning programmes. This fertility index demonstrates the potential for fertility change and the momentum of population growth.

The second index proposed is the dependence ratio describing the number of dependants within a population i.e. those under 15 and those above 65 years of age as a proportion of the whole population. This index describes the position of the involved population within the fertility transition and it's proximity to a steady state.

Impact level

Health status assessment at the population level implies a quality-of-life measure. It is expressed in the health expectancy measure. Until the past decade, the population health has been measured in its overall life expectancy, stressing the gains in mortality reduction and, hence, gain in absolute life years. Recently (World Bank, 1993), composite quality measures, including those life years spent with disease, have been made operational, making use of the international available health statistics. Weighing the total years lived for the time spent with and without disease lead to disability-adjusted-life-years per 1000 persons (the DALY measure). Calculating this measure one weighs the severity of the disease according to a disability scale that

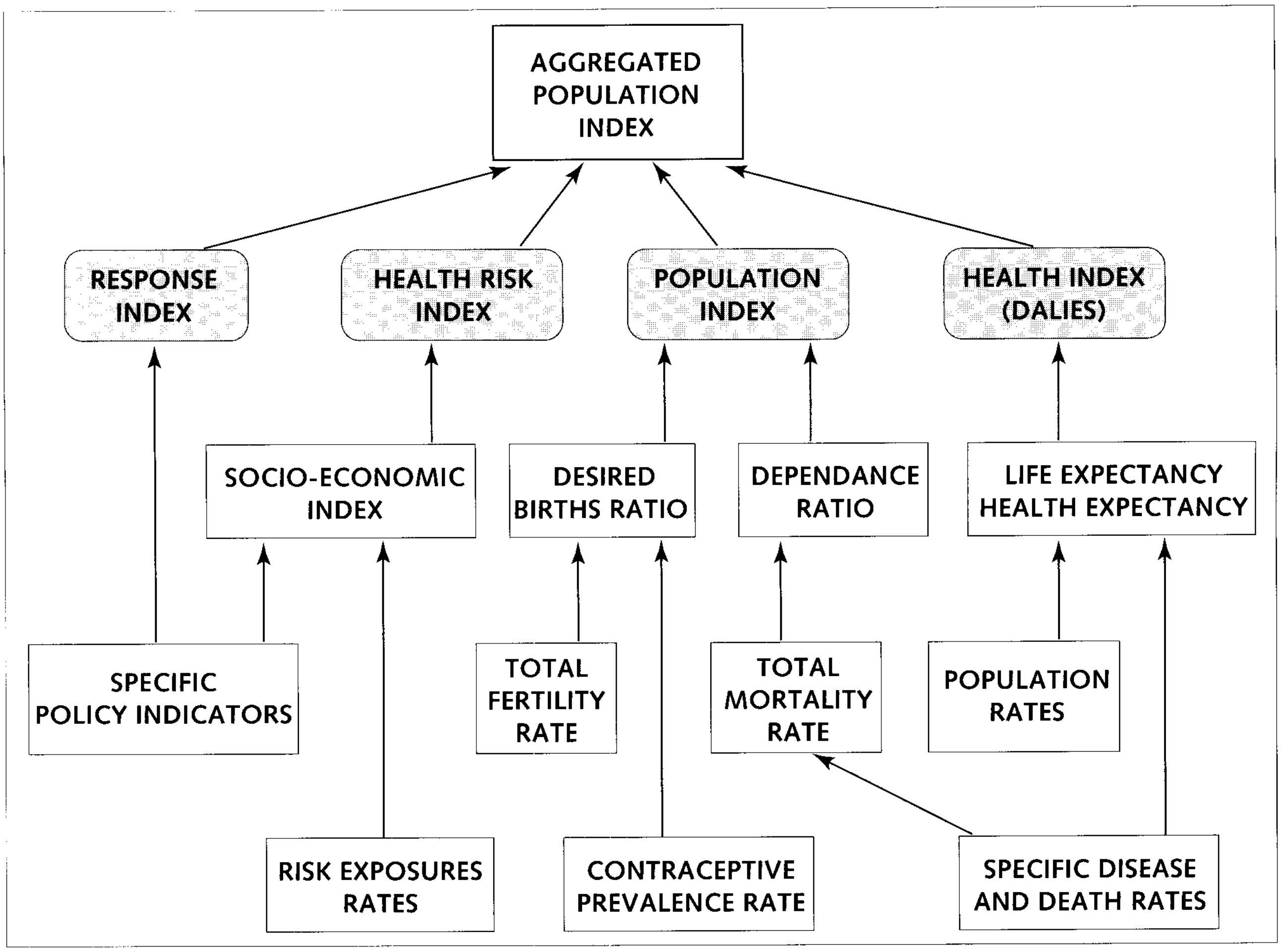


Figure 5.4: Hierarchical indicator-framework for the integrated population and health system

consists of six categories. In this way, time lived with a disability is made comparable with time lost due to premature mortality. The value of time lived at different age is captured using an exponential function reflecting the dependence of the young and the elderly on adults. A 3% discount rate is used in the calculation of total lost life years.

In most areas of the world, data are still insufficient to monitor trends in this index based on disability-adjusted-life-years on an empirical science basis. Efforts are made to do through central offices for population statistics. The available data on dalies are based, again, on modelling i.e. life-table extrapolations and a Delphi-like method (World Bank, 1993).

One aggregated population and health index

None of the important single indices outlined above describes the population and health situation as whole. Choosing a higher level of aggregation, the above indices again can be weighted, scaled and aggregated. Weighing of health risk versus actual health loss will depend on the level of risk one desires to accept. Weighing fertility and population indices versus the pressure and impact indices will depend on the kind of population policy chosen. Next, scaling and aggregation as delineated above will lead to one overall index describing population and health in time.

5.6. Stategies for sustainable development

A common and useful distinction is drawn here between 'scenarios' and 'strategies'. Scenarios reflect both various exogenous developments, i.e. 'uncontrollable' or autonomous developments outside the system considered, and various endogenous developments, i.e. developments within the system considered that cannot be steered or influenced. Various strategies (to be decided upon by decision makers) are analysed under various scenarios which are not controlled by decision makers. The combination of a strategy and a scenario is generally referred to as a 'case'.

The development of the state of the system can be monitored by measuring the values of the sustainability indices. To evaluate the consequences of strategies or scenarios the desirable state of the system can also be simulated through modelling efforts resulting in calculated values for the sustainability indices. Evaluation of a simulated state of the system with respect to the objectives can take place through comparison with the target values. The impacts of a certain strategy or scenario can be calculated by comparing the simulated values of the indicators with the values obtained for a reference scenario or case.

As mentioned above, the hierarchical framework of indicators and indices can be used to evaluate alternative strategies or scenarios for sustainable development and to monitor the state of the system. For a specific strategy or scenario the components of the SDI's have to be calculated and compared with the target values and reference values. Because extrapolation of current trends and conditions is an inadequate method for making long-term projections, it will not be used here in developing strategies for sustainable development. Instead, we first determine sustainable states and then indicate whether and how these sustainable states could be reached. Such a pathway may include surprises, and we are aware that no methodology has yet been developed which enables the systematic incorporation of surprises into scenarios and strategies. Using this method of 'backcasting' to develop coherent and consistent response strategies for globale change and sustainable development, the techniques of optimization (search strategies) and fuzzy logic might serve as a helpful guide. Although there is no optimal solution possible for global change and sustainable development, optimization techniques can be used to explore the solution space in search of specific strategies for sustainable development. However, while integrated assessment simulation models cannot be used for optimization goals in the usual way (apart from simple climate assessment models like that of Nordhaus (1992)), it is possible to make use of heuristic methods which employ metamodels and optimization techniques in an attempt to find local optima by starting the search in several reference scenarios. A heuristic method is described in Janssen *et al.* (1992) and Janssen *et al.* (1994).

The concept of fuzzy programming is introduced to reflect the uncertainty and vagueness associated with the optimization of global change and sustainable development. The reason for using fuzzy logic programming is that we wish to satisfy all kinds of imprecisely known constraints as well as possible, without achieving a maximum performance. By using fuzzy approaches, decision makers are exposed to a broader range of solutions, which appear to be better than those generated using ordinary optimization techniques (Bare and Mendoza, 1993).

6. VARIOUS PERSPECTIVES

6.1. Introduction

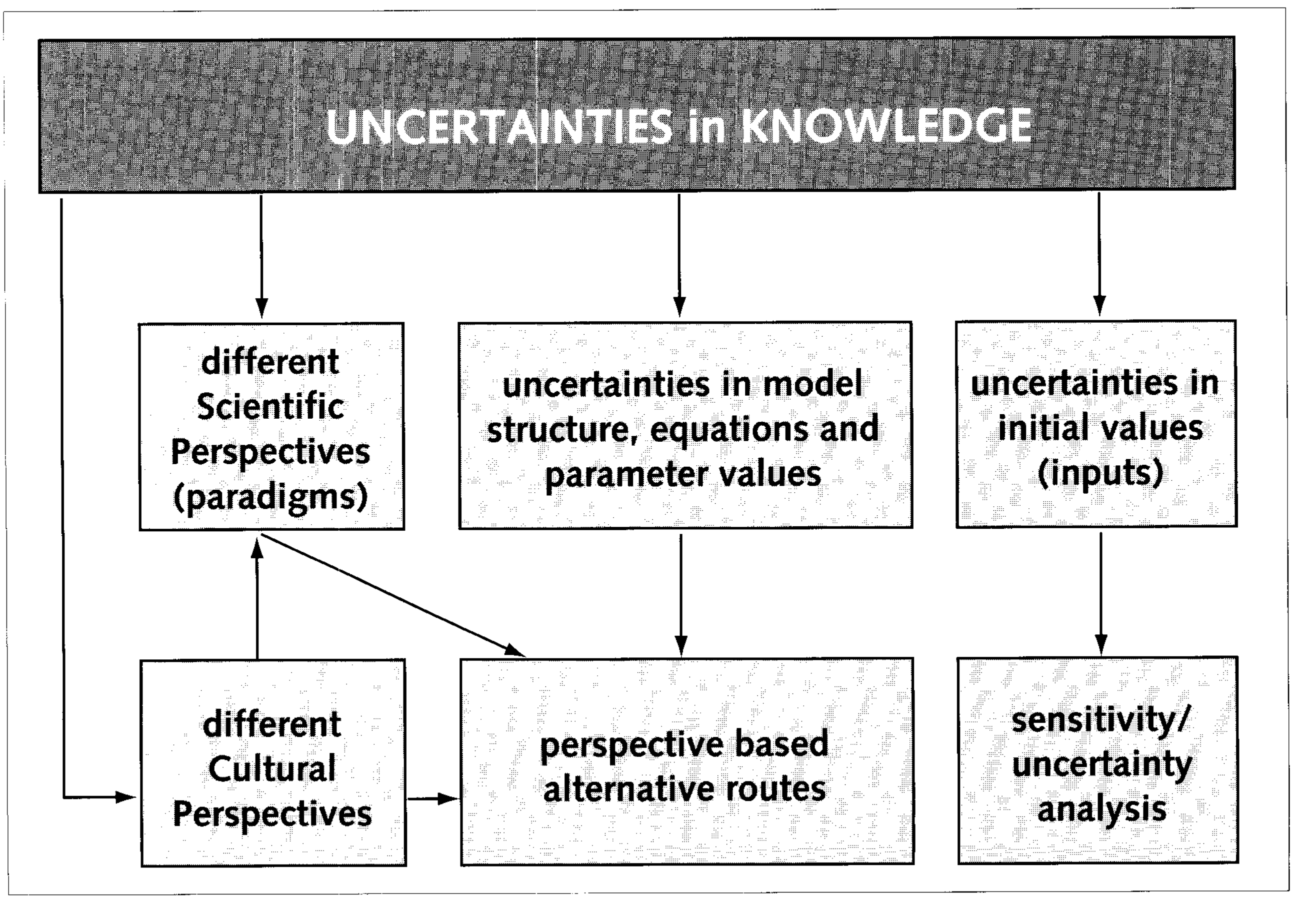
No unique and correct description of the real world exists. The problem is not that there are no consistent descriptions of the world, but rather that there are too many (Wallace and Norton, 1992). Because of the complexity of global change, here considered as the totality of changes on planet Earth, including all human interventions and alterations, there are numerous valid perspectives from which to describe and evaluate the phenomenon of global change. Choosing a perspective or paradigm for global change automatically implies a specific way of describing global change, so that each scientific description of global change is value-based. This means that the integrated systems approach to global change and sustainable development, chosen in this study as starting point for analysing the phenomenon of global change, is just one of the many possible representations.

The various perspectives considered in this study are based on scientific hypotheses or theories (scientific perspectives), or originate from differences in cultural perspectives (cultural perspectives). In this study an approach is introduced by which uncertainties in models can be made explicit by relating different types of uncertainty to different types of perspectives, as is shown in *Figure 6.1*. This is done by creating perspective-based alternative modelling routes, some examples of which will be discussed below.

6.2. Scientific perspectives

Scientific perspectives, some examples of which will be given below, relate to the appreciation of the interacting biological, physical, chemical and social

Figure 6.1: Perspectives related to different types of uncertainties



processes.
Vernadsky was the founder of the scientific perspective which has it that the biosphere acts as an interacting, organic-geologic physiological whole (Vernadsky, 1945). Vernadsky introduced the term 'noosphere', which represents the amalgamation of the biosphere and the technosphere (UNEP, 1992b). If you are a 'Vernadskyite' you assume that the wholeness of all physical and socio-economic processes on Earth cannot be modelled in an adequate way. In fact, the modern viewpoint of interacting socio-economic and ecological systems is based on Vernadsky's perspective.
One of the most inspiring, but also controversial theories in recent environmental science has been the 'Gaia-hypothesis' developed by James Lovelock (Lovelock, 1979 and 1988). The Gaia theory can be considered as a new scientific paradigm, which looks upon the Earth system as a cybernetic whole, as a coherent system of life which is self-regulating and self-changing. If you are a 'Gaian' you consider that the complex interactions among biogeochemical processes constitute a self-correcting global organism on different temporal and spatial scales. Lovelock has illustrated his ideas with a simple model, Daisyworld, a planet in which the environment is represented by the temperature and the biota by a single species, namely daisies.

Gaia-adherents consider the Gaia theory to be a major scientific revolution of our time, but sceptical researchers refer to the counterexamples which have been postulated, and more generally regard the Gaia theory as an untestable hypothesis. A basic issue in a vivid scientific discussion was the question of whether the Gaia theory should be interpreted literally or as a metaphor (Wallace and Norton, 1992).
A third new scientific perspective deals with the 'expectation of the unexpected' (Timmerman, 1986). This perspective is very topical and focuses on the concepts of chaos, risk, discontinuity, disequilibrium and surprise. This scientific referential framework fits in well with the concepts of the carrying capacity of ecosystems, which is of a cyclic nature, as well as resilience of ecosystems, introduced by Holling (1973; 1986). Not until the past couple of years has the idea gained acceptance that the concept of chaos, which is a measure of the sensitivity of a system to initial conditions, not only works in physical systems but also in human systems. A counterpart of the 'expectation of the unexpected' perspective is the evolutionary perspective, which supposes a gradual, incremental development of the world system that can be described by surprise-free models (Brooks, 1986).

6.3. Cultural perspectives

Human attitudes towards the environment have evolved during history and are determined by, among other things, cultural perspectives, which have been classified in various ways. During the last couple of years there has been an increasing recognition of the usefulness of the various cultural perspectives within the context of sustainable development, but, alas, only in a qualitative sense. An interesting contribution has been made by Schwartz and Thompson (1990) and Thompson *et al.* (1990). In their cultural theory they combine anthropological insights from e.g. Douglas (1982) with recent ecological knowledge developed by e.g. Holling (1973; 1986). The crux of their theory is that societies can be characterized along two axes: groups and grids. The group axis measures the degree to which individuals consider themselves part of a group of individuals with whom they share values and beliefs. The grid axis indicates the extent to which individuals are subjected to role prescriptions within a larger structural entity. The group-grid characterization yields different perspectives from which people perceive the world and behave in it. Thompson *et al.* (1990) argue that the viability of a perspective depends upon a mutually supportive relationship between a particular cultural bias and a particular pattern of social relations. They claim that five and only five perspectives - hierarchy, egalitarianism, fatalism, individualism and autonomy - meet the conditions of viability. These perspectives are in competition for adherents, but, on the other hand, are interdependent. In this study the autonomous perspective will not be elaborated, because the 'hermit' according to Thompson *et al.* (1990) is not interested in what happens in the world, but only wants to dislodge himself from the world.
Thompson *et al.* (1990) claim that the notions of human and physical nature are socially constructed, and that the four myths of nature, derived from ecologists (Holling, 1986; Timmerman, 1986) closely coincide with the ideas of nature. The different characteristics concerning nature, myth of nature and human nature of the four perspectives are summarized in *Table 6.1*.

Table 6.1: Characteristics of the various cultural perspectives

Perspective / Notion	egalitarian	individualist	hierarchist	fatalist
nature	accountable	skill controlled cornucopia	isomorphic	lottery
myth of nature	ephemeral	benign	perverse	capricious
attitude towards nature	great care	laissez-faire	regulate	just cope
human nature	born good	self-seeking	evil	unpredictable
attitude towards humans	construct egalitarian society	channel rather than change	restrict	distrust

Table 6.2: Cultural biased preferences in terms of strategies

Perspective / Strategy	egalitarian	individualist	hierarchist	fatalist
needs and resources	can manage needs but not resources	can manage needs and resources	can manage resources but not needs	can manage neither resources nor needs
economic growth	not preferred	preferred: create personal wealth	preferred: create coll. wealth	preferred: chance may bring it
attitude towards risk	risk-aversive	risk-seeking	risk-accepting	risk-avoiding

As a matter of fact, the four perspectives sketched above are merely indicative and theoretical constructions. In reality, perspectives consist of combinations of the perspectives stated above, and will develop dynamically, shifting from one perspective to another, in a process of mutual competition and addition. In spite of the caricatural character of the perspectives sketched above, they can serve as a useful framework with which to make more explicit the role of such perspectives in the complex problem of global change. For example, by creating a sequence of culturally biased preferences with respect to how to make a living, different strategies can be developed for different perspectives. Thompson *et al.* (1990) deduced four strategies for 'making ends meet', of which some basic features are shown in *Table 6.2*. In general, each of these strategies aims at upholding the corresponding perspective.

6.4. Implementation of perspectives in the TARGETS model

6.4.1. Implementation of scientific perspectives

Points of departure are on the one hand the rival scientific perspectives, i.e. the 'Gaia perspective' and the 'Expectation of the unexpected', and on the other the global integrated assessment model, TARGETS. The numerous 'scientific uncertainties' within the TARGETS modelling framework will be investigated from the viewpoints of the two apparently antithetical scientific perspectives. In the first step of the approach, these uncertainties need to be related to the 'Gaia' perspective and the 'Expectation of the unexpected' perspective. To this end, the probabilistic method will be used. This implies that subjective probability distributions will be selected or designed for the major scientific uncertainties. This can be done in such a way that, from the 'Gaia' perspective, the negative feedbacks dominate the system (dampening effect), while in the 'Expectation of the unexpected' perspective the positive feedbacks dominate (accumulative effect).
To avoid obtaining unrealistic results from these approaches, the outcomes have to be validated. Therefore, in the next step a limited number of simulation experiments will be performed, after which the results of the simulation experiments will be tested against experimental data sets. Extensive data records are already available, at least for atmospheric carbon and global-mean temperature.
More realistic experiments, however, would imply the reformulation of subsystems of the TARGETS framework. This is because representative Gaia-systems can only be realized by adding or omitting certain entities, processes, interactions and feedbacks to the system. In Schneider and Boston (1992) examples are presented of Gaia- model representations of the global carbon cycle, which differ in dynamic structure from conventional global carbon cycle models. Similarly, Westbroek (1991) offers an interesting prototype of a world model in which a Gaia-system is incorporated. It is therefore proposed to start such a relatively sophisticated analysis with a detached part of the TARGETS model, namely the coupled carbon cycle/climate model.
The coupled carbon cycle/climate model will thus be adjusted to both scientific perspectives by (i) changing the dynamic structure of the underlying system; and (ii) including the natural variability into the coupled carbon cycle/model, to test the sensitivity of the system to fluctuating inputs. After having performed a limited number of experiments using experimental designs, the outcomes can again be validated against the data records for atmospheric carbon and global mean temperature. If this restructuring and reformulation of the coupled carbon cycle/climate model yields satisfactory results, such an approach can be extended to other parts of the TARGETS framework.

6.4.2. Implementation of cultural perspectives

In a manner analogous to that used for the scientific perspectives, the cultural perspectives will be related to the concept of uncertainty. Social and economic uncertainties, which are often due to subjectivity and disagreement, can be made explicit by filling them in differently for the various cultural perspectives. To this end, a consistent mode of conduct or strategy is to be developed for each perspective, based on its biases and preferences, some of which are given in Table 6.2; others can be found in the literature (Thompson *et al.*, 1990; Schwartz and Thompson, 1990; Vries de, 1989a, 1989b; Zweers, 1989; Achterberg, 1986; Sprent, 1988; Weterings, 1992). For each module, a limited number of crucial uncertainties will be selected, each of which will be modelled according to the biases and preferences of the perspective-based strategy under concern. Levers for alternative modelling routes can be derived from the perspective-based strategies. An alternative modelling route can be considered as a model interpretation in which a sequence of crucial uncertainties is 'opened' and modelled explicitly in accordance with the biases and preferences of a particular perspective. Thus, a separate modelling route or pathway will be generated for each perspective. This implies that the fatalistic perspective is of no use to us, because from this perspective everything is a lottery, thus the appropriate model would consist of random relations and parameters. Therefore, although fatalists are an essential element of the total system -Thompson *et al.* (1990) consider them as the cultural equivalent of compost- this 'passive perspective' will not be implemented in the TARGETS model.
Regarding the 'active perspectives' generally, hierarchists reduce the methodological and epistemological uncertainties to technical uncertainties, which can be managed by decision making (reductionist). They accept risk up to a certain level and under the condition that it is based on expert judgement (risk accepting behaviour, see *Table 6.2*). Individualists approach all kinds of uncertainty as if they are methodological issues,

Table 6.3: An example of alternative routes

Perspective	Description	Submodel
Egalitarian	* All resources are scarce	Energy
	* Anthropogenic climate change may be disastrous	Biophysics
	* Desired fertility depends on the social norm	Health
	* Population growth can be lowered by education	Health
Hierarchist	* Some resources are scarce	Energy
	* Anthropogenic climate change is a problem	Biophysics
	* Desired fertility depends on education	Health
	* Population growth can be lowered by family planning and legislation	Health
Individualist	* Resources are abundant	Energy
	* Anthropogenic climate change may be advantageous	Biophysics
	* Desired fertility is only an individual choice	Health
	* Population growth is determined by economic development	Health

requiring expert judgement, leading to best solutions (pragmatic approach). They consider risk as essential condition for new developments (risk seeking behaviour). Egalitarians are concerned with the ethical aspects of uncertainty, and they recognize epistemological uncertainty. They consider risk as dangerous and undesirable (risk aversive).

An example of alternative modelling routes for three different perspectives will be presented below. The example focuses on a cross-section of the TARGETS model, which consists of the energy -, biophysics -, and population and health modules. Furthermore, only one or two uncertainties are analysed per module, and only in a qualitative manner, just to illustrate the concept. The various themes considered are: resources reserves, climate change, fertility and population growth, and the perceptions of the various perspectives concerning the above-mentioned themes are summarized in *Table 6.3*. With respect to present and future reserves of resources, egalitarians consider these small, because of their premise of scarcity, while for individualists most resources have not yet been discovered, but can be exploited by development of new technologies. Regarding a human-induced climate change, hierarchists consider it a serious problem and want to mitigate it by regulating climate protocols and conventions, whereas individualists push the Gaia-theory to demonstrate the self-regulating mechanism of the climate system. Finally, population growth can be steered by education and fertility rate is dependent on the social norm in the egalitarian viewpoint, where individualists claim that population growth is determined by economic growth and human behaviour with respect to desired fertility cannot be influenced, because desired fertility is assumed to be an individual choice. After having framed alternative modelling routes in a qualitative sense, the perspective-based sequence of uncertainties needs to be mathematically translated and quantified. To this end, various mathematical techniques are available: parametric analysis, probability distribution functions, fuzzy programming, delphi-techniques, multi-criteria analysis and expert judgement, each method with its own pros and cons.

N.B.: The allocation of responsibility in reducing fossil CO_2-emissions is one of the major problems of global change. The allocation of carbon dioxide emissions can be based on intergenerational and intertemporal equity (Elzen den, *et al.*, 1992; Grübler and Fujii, 1991; Krause *et al.*, 1989). Janssen and Rotmans (1994) have tried to quantify the influence of cultural perspectives on the allocation of fossil CO_2 emission rights. Although this is not to be recommended, and was only intended as an exercise, in this preliminary analysis they used perspective-based parameter distributions.

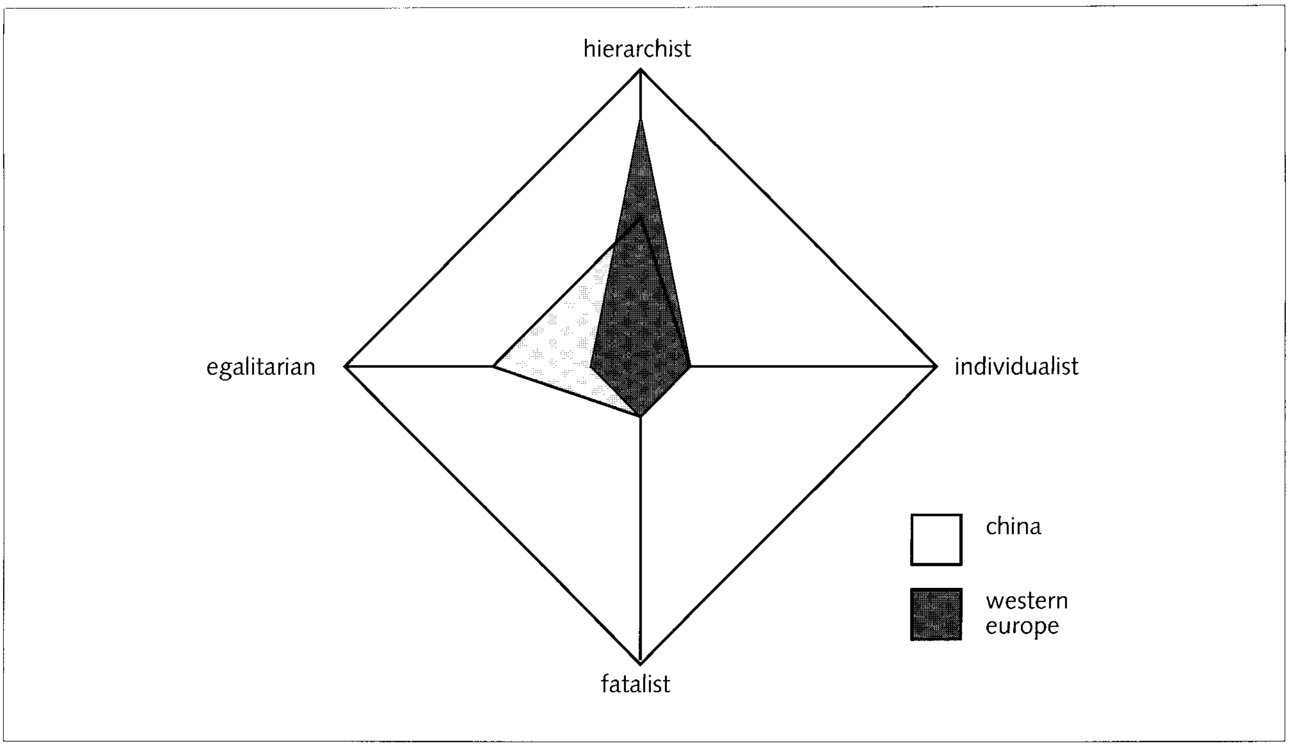


Figure 6.2: Visualization of cultural differences between China and Western Europe

6.5. Future developments

Thompson *et al.* (1990) claim that their cultural theory is universal. They argue that distinctive sets of values, beliefs and habits (in nations, neighbourhoods, tribes and races) are reducible to only a few cultural biases and preferences. Following this claim each country can be characterized as a mixture of the four cultural perspectives distinguished. Thompson *et al.* (1990) show for several countries some examples of how such a mixture would look like. In the near future the global TARGETS model version 1.0 will be regionalized. When developing model versions for specific regions it is of crucial importance to take into account cultural differences between nations or regions, in stead of building another highly sophisticated model that only reflects the 'western' way of thinking. A simple reflection of how this complicated issue can be addressed is presented in Figure 6.2, which shows a visualization of an example from Thompson *et al.* (1990).

7. EXPECTED RESULTS

7.1. Integrated communication tool

The integrated systems and modelling approach proposed here will enable the consequences of several types of human influences to be evaluated simultaneously. It is hereby envisaged that synergetic effects, which are currently beyond the horizon of predictive competence, may be brought into view. Such a global, integrated assessment model should be regarded as an aid to the formulation of possible projections for the future, and not as a means of generating predictions as such. As mentioned before, the interpretative and illustrative value of such a modelling framework is therefore much more important than its predictive potency.

A great deal of attention will be paid to the presentation of the relevant information generated by the model in an insightful manner. This necessitates the 'opening' of models, an exercise which ranges from the construction of a user-friendly model which can be used interactively, to the creation of strategic planning exercises oriented towards strategies for sustainable development, whereby models serve to provide guidelines in the background (Vries de *et al.*, 1993). It is therefore expected that it will become possible to add a new dimension to the use of integrated assessment models: namely, the use of a model as a medium for communication between exponents of the natural sciences and the social sciences. Although this overall goal may seem rather ambitious, the experience gained within the IMAGE-project may be useful in avoiding major pitfalls, in order to realise the objectives stated above as far as possible.

7.2. Potential user groups

In this section an overview is presented of user groups that could possibly profit from the integrated assessment framework TARGETS. They include researchers as well as policy analysts and policy makers. Even though each different user requires a different functionality from TARGETS, the choice made here is nevertheless to reckon with all potential users. A prerequisite for the usage by dissimilar user groups is that the model should be flexible and transparent, and lend itself to tailoring to the particular needs of a user group. Therefore the basic functionalities will be developed first, ones which are relevant to all potential user groups. During the subsequent phases of development of TARGETS, more specific functionalities will be added, stemming from user-specific demands. The development of TARGETS is thus directed by the demands of the targeted user groups, albeit anticipated, rather than revealed demands.

Three important user groups are distinguished:

(i) Policy analysts. Additional interest: developing strategies that lead to a sustainable development. Additional functionality of TARGETS: setting policy options, analysing their results and evaluation of the options. TARGETS should become a policy analytical model.

(ii) Policy makers. Additional interest: basic understanding of the complexity of global change and its driving forces. Additional functionality of TARGETS: it should become a decision support system.

(iii) Researchers. Main interest: understanding the interrelation between social processes and biophysical changes of the global environment. Additional functionality of TARGETS: Simulation of human activities affecting the biophysical system and biophysical processes influencing socio-economics, human health and ecosystems.

Following Hordijk (1991) an integrated assessment model will be used by the last two groups in policy analysis if the following conditions are fulfilled:

* the model should cover many, if not all, of the relevant aspects of the environmental problem(s) considered;
* the model should be scientifically credible;
* as far as possible, existing data and models should be used;
* the model should be easily accessible to non-specialists;
* the model should be politically acceptable to the electorates concerned.

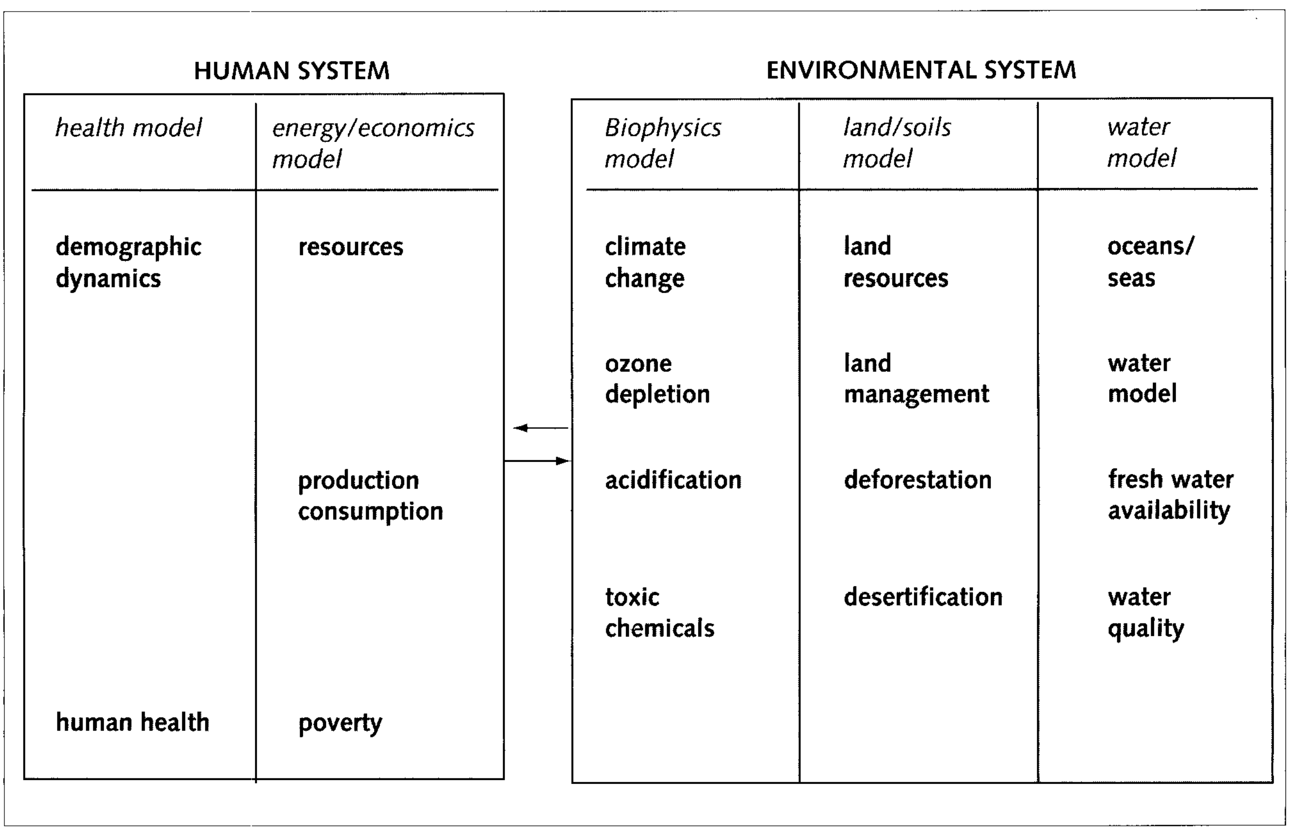
At the institutional level, the three user groups can be connected via the following institutions, in decreasing order of priority:

(i) United Nations Environment Programme (UNEP). The TARGETS model could be used within the Earthwatch Programme, initiated by the UNEP to provide integrated environmental assessments as support for environmental policy. In addition, the TARGETS model can serve as a conceptual 'thinking' framework to structure the discussion concerning global change and to demonstrate the coherence between the various items of the Agenda 21. *Figure 7.1* shows which items of the Agenda 21 are, in a highly aggregated way, covered by the TARGETS framework.

(ii) World Health Organization (WHO) and the World Bank. The TARGETS model could be used to give a quantitative demonstration of the numerous interrelations between the economy, environment and population.

(iii) International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDGECP). The TARGETS model could prove especially worthwhile for establishing a link between IGBP and HDGECP.

Figure 7.1: TARGETS framework versus Agenda 21 issues



8. ORGANIZATIONAL EMBEDMENT

8.1. Project management

The project is directed by Jan Rotmans, who will coordinate all research activities and is responsible for the financial project management. The base research work will be conducted by a core project team, which consists of about 15 researchers, among which are mathematicians, an econometrist, an energy specialist, a hydrologist, an environmental health specialist, a physicist, a toxicologist, an ecologist, and a sociologist. A conditio sine qua non for setting up a multi-and interdisciplinary research team is that all these researchers speak, think, model and operate in the same language. Therefore, during the process of building an integrated assessment framework, all team members make use of the modelling and visualization language 'M'. As will be elucidated below the research programme spans a number of interrelated subprojects. To integrate all bits and pieces from the various projects an integration team, consisting of Michel den Elzen, Henk Hilderink and Arjen Hoekstra, takes care of the fact all project activities are geared for one another, by coordinating all day-to-day activities and remaining in frequent contact with all project members and the project leader.

It is the intention of this research programme to be connected to the potential user groups from the start on. In order to guarantee this, all intermediate products generated by the programme will be discussed and critically reviewed by potential user groups. It is planned to establish an Advisory Board, consisting of persons with broad scientific experience, who will advise on the overall direction of the project and provide linkages with relevant persons, institutions and organizations. The Advisory Board will be informed about all aspects of the project, and their advice will be sought at annual meetings. Each year a meeting of the Advisory Board will be held, featuring presentations by members of the project team on the annual progress made. Furthermore, an annual progress report will appear which will be judged and evaluated by the Advisory Board.

8.2. Various subprojects

As mentioned above the research programme consists of a number of strongly interrelated subprojects, which all have one coordinator who organizes the research activities of the subproject under concern, and which mostly consists of a small research team. For each subproject the overall objectives, methodology and research topics are briefly described, as well as the coordinator and the research team involved.

8.2.1. Integrated land modelling

Coordinator	Michel den Elzen
Other researchers	Heko Köster, Jodi de Greef, Pim Martens, Mark Heil (trainee)

Objective
The main objective of this study is the development of an integrated model to assess changes in land use and quality (land fertility) under various agriculture and forestry policies as well as in global food supply and, to a lesser extent wood supply. This global land framework can be used to quantify relations between the effects of population and economic growth, investments in land and soil improvement practices and global environmental change on the land use and quality changes and future food supply under concern. In this way the framework can serve as an aid in the formulation of sustainable land and soil management strategies.

Methodology
The model describes the causes (social, demographic and economic processes as well as global environmental change like climate change and land and soil management practices), mechanisms (biophysical land use and fertility processes), and effects on society (food supply) and ecosystems (deforestation, erosion, degradation, and desertification). In the first phase a global model will be developed, which will be fed with highly aggregated data of different soil, climate and land use classes using the geographically-explicit data generated by the IMAGE 2.0 land model. The TARGETS land model consists of an agricultural module (focusing on irrigation, land clearing, intensification, food production and degradation) and a land use change module (which deals with deforestation and urbanisation). In the second phase the model will be made operational for two regions: the developing and the developed countries. In the final step the model will be implemented for individual world regions.

Research Topics

The land model concentrates on the following main interactions. *Agriculture:* ongoing population growth requires an increasing demand for food, which leads to investments in clearing of forests for agricultural land (grasslands and arable land), intensification of the existing arable land (fertilizer use, improved agricultural practices) and irrigation of arable land and finally to a change in the global food supply. *Land use changes:* besides the demand for agricultural land (land clearing), population growth requires wood, leading to the demand for forest lands (forest harvesting), and also to a demand for human land (urbanisation). *Degradation:* different forms of degradation (water and wind soil erosion, desertification, salinization, acidification) of existing arable land due to a lack of soil and land conservation management practices, or other physical and chemical causes lead to losses of land fertility, and finally to land yield losses. *Global climate change:* finally, climate change affects the land yield, although it is at present uncertain whether this is positive or negative.

8.2.2. Energy/economics/resources modelling

Coordinator	Bert de Vries
Other researchers	Ruud van den Wijngaart, Marco Janssen, Hessel van de Berg (trainee)

Introduction

This project focuses on the development of an integrated model for the representation of the economic-resource system. Although modelling the economic-resource system at the aggregated world level has only limited relevance, because the dynamics of this system is to a large extent governed by human decisions and behavioral rules, which are value-based, an attempt has been made to model this system on a global scale. The main goal of this model to increase the insight into the long-term dynamics of the interplay between the industrial -, electric power-, consumer - and service sector in relation to population and environmental developments.

Methodology

The model under development is divided into an energy submodel and a minerals submodel. The energy submodel simulates the use of fossil fuels and the eventual introduction of renewable and nuclear energy sources, as well as ways to conserve energy. The energy model consists of four model sections: the solid fuels model, the liquid fuels model, the gaseous fuels model and the electric power model. If an alternative (solid/liquid/gaseous) enters the market, its relative price will determine the degree of market penetration. The minerals submodel simulates the processes of discovering, exploiting and partly recycling a finite resource base of moderately-scarce metals. It also simulates the usage patterns of the bulk of relatively abundant metals and their eventual recycling. The very simple economy submodel consists of an industry, services and consumers part. Industrial output is generated at a fixed capital-output ratio; labour is not taken into account. The service sector is expanded on the basis of an assumed relationship between industrial output per capita and desired service output per capita. Consumption is at the moment determined by a constant savings rate. Each submodel governs a set of investment decisions which are based on relative costs/prices. Alternatively, they can be overruled by setting an exogenous target for certain variables, e.g. the market share of biofuels in the light liquid fuel market. On top of this, there are a number of steering variables which influence the autonomous dynamics, e.g. a carbon tax on fossil fuels.

Research Topics

This model will focus on the issue of how to deal with economic developments in relation to the use and availability of natural resources. The world energy system is heavily based on carbonaceous fuels. Projections show that if a continuation of the current growth of energy use were to take place, abundant reserves of natural resources will be used, unless technological and financial measures are adopted. On the other hand, there is a major question about the extent to which the future energy demand can be satisfied with renewable energy sources, taking account of the currently formulated long-term environmental goals.

8.2.3. Modelling biogeochemical cycles

Coordinator	Michel den Elzen
Other researchers	Jan Rotmans, Michel Bakkenes (trainee)

Introduction

This research project aims at the development of an integrated model which tries to give a comprehensive picture of the global biogeochemical cycles. An essential part of the model is the integration of the element cycles (C, N, S and P) and the interactions between the cycles in the biosphere. The model to be developed is designed to create an integrated picture of the global element cycles and their interactions with global environmental change.

Methodology
In order to construct a global elements cycle model, the various compartments (atmosphere, terrestrial biosphere, lithosphere, and hydrosphere) are coupled, and the interactions (physical, chemical, and biological processes) between these compartments are modelled. The elements cycle model basically consists of the following models: a carbon cycle model, a phosphorus cycle model, a nitrogen cycle model and a sulphur cycle model, which are highly interlinked. The underlying biospheric system consists of two subsystems: the atmosphere-terrestrial biosphere-soil system and the river-atmosphere ocean system. The atmosphere-terrestrial biosphere-soil system is categorized into a number of land cover types, each of which is further partitioned into carbon/nitrogen reservoirs and soils with an inorganic and organic part. In the river-atmosphere-ocean system the ocean is divided into seven layers, each of which consists of an organic and an inorganic component. For the modelling of river systems the reader is referred to the global water dynamics (AQUA) project.

Research Topics
This type of highly aggregated biosphere model will focus on the testing of the potential feasibility of some of the technically based countermeasures proposed during recent years. Issues that can be addressed include the idea of depositing iron into the southern ocean to stimulate the atmospheric CO_2-uptake by the oceans. Other ideas concerned the pumping of fertilizer (nitrogen or phosphate) into the ocean, causing enormous populations of algae which could act as a sink for atmospheric carbon, and the large scale storage of CO_2 in the ocean.

8.2.4. modelling global toxic substances

Coordinator	Dick van de Meent
Other researchers	Eric Verbruggen,
	Michel den Elzen
	Martijn Root (trainee)

Introduction
This research project aims at the development of a global distribution model for toxic substances. With the help of such a model possibilities for reporting global fate and effects of a limited number, but illustrative toxic substances (via aggregation representative for categories of persistent and non-persistent organic chemicals and trace metals) can be demonstrated.

Methodology
The generic multimedia box modelling spreadsheet SimpleBox (Van de Meent, 1993) is the starting point; transport-and degradation processes will be modelled as in SimpleBox. The global toxic substances model will be based on the nested version of SimpleBox, as used for quantification of 'persistence in the environment' and 'global dispersion potential'. First, a spreadsheet prototype is produced, which is used for a preliminary sensitivity- and uncertainty study. This shows what output can be generated and to which sort of input the model is most sensitive. Iteratively, the prototype is modified until a useful model concept is obtained. A second prototype will be developed on the basis of these experiments, and this will be tested and analysed thoroughly (behaviour with extreme model input, sensitivity to uncertainty in or absence of input data, etc.).

Research Topics
In general, the global distribution model for toxic substances focuses on those toxic micropollutants which, on a global and a regional scale, may adversely effect human health and ecosystem functioning, or may adversely affect agricultural production, or may result in a deterioration of drinking water resources. In addition, the extent of global dispersion as well as the availability of data necessary to complete the modelling exercise are criteria for the selection of toxic micropollutants. At most ten different, 'aggregated' toxic chemicals will be selected, which are supposed to represent the major classes of chemical substances. The selected chemicals involve some heavy metals, persistent organic chemicals and some non-persistent chemicals, for which sample outputs will be produced in the form of regional and global concentration-time profiles. Some examples will be given of the extent to which the accumulation and remobilization of persistent chemicals in soils and sediments may stimulate biological activity, under the influence of changing environmental conditions.

8.2.5. Modelling global water dynamics

Coordinator	Arjen Hoekstra
Other researchers	Frijda Zuydhof (trainee)

Introduction
This research project aims at the development of an

integrated tool for global policy analysis in the field of water management. A separate part of this integrated tool is the AQUA model, which forms a cross-section of TARGETS that addresses the human influences on the global water system and the influences of the global water system on human health, socio-economics and ecosystems. The AQUA model provides the user a better understanding of the dynamics of the global water system, the interrelations between the processes within regional water systems, and the effects of global change on regional water-related dynamics. In this way the AQUA model can serve as an aid in the formulation of global water management strategies, which can be evaluated with respect to the goal of sustainable development.

Methodology

AQUA deals with both the dynamics of the hydrological cycle (water quantity) and the dynamics of the water quality. The most important relations that will be addressed within AQUA are the relations between the global water system and: (i) human health; (ii) ecosystems; (iii) agriculture; and (iv) aquaculture.

In the first phase a global model will be developed, which will be fed with global data. After having developed the model for the globe as a whole, in the second phase the model will be made operational for clusters of large river basins. Finally, the model will be disaggregated to the level of individual river basins.

Research Topics

In general, the AQUA model will focus on both direct human-water interactions (e.g. human activities-water pollution-water quality-human health) and indirect human-water interactions (e.g. human-climate-water interactions). More specifically, the AQUA model will address two important water-related problems: at the one hand local and seasonal water scarcity, which is characterized by the demand for water and the available amount of usable water and comprises both the problem of water absence and the problem of inferior water quality. On the other hand local and seasonal water excess causes regular inundations of delta areas. These water problems are strongly interrelated with erosion and land degradation.

8.2.6. Integrated modelling of population and health

Coordinator	Louis Niessen
Other researchers	Henk Hilderink

Introduction

This research project aims at the development of an integrated population and health model to assess changes in population health under various environmental conditions as well as in various stages of the epidemiological and demographical transitions. Using this global health framework relations can be quantified between the effects of investments in health services and the incidence/prevalence of the diseases under concern. Furthermore, the global health framework can serve as an aid in the formulation of strategies, which can be evaluated with respect of the goal of sustainable development.

Methodology

The research will imply the development of a hitherto untried systems approach to the description of the occurrence of disease in populations (Niessen and Rotmans, 1993) using methodologies from the fields of epidemiology, health economics, health services and public health. The integrated analysis will lead to a description of the driving forces of the health system, its causal components, including health resources, the pathways that determine health outcomes, and the health effects themselves within populations. The positioning as an impact model within the overall TARGETS model will facilitate an adequate formulation of the parameters that compose the interfaces with the other modules. The integrated approach will lead to the development of sustainability indicators describing the health system as a whole, including resources and effects.

Research Topics

In the first phase the systems approach will be explored and a mature population and health model will be designed during the course of 1994. During the second phase the model will be improved and refined further, calibrated, validated and uncertainty analysis will be systematically performed. The following sequence of topics is planned. In the first two years model exercises on (i) water-related diseases; (ii) health loss through malnutrition; (iii) atherosclerotic diseases; (iv) vector-borne diseases; and cardio-vascular diseases. During the second two years an integrated output analysis of (v) the integrated health system and use of indicators;

(vi) health gain through health services vis-à-vis health gain through socio-economic services.

8.2.7. *Socio-economic impact analysis*

Coordinator	Henk Hilderink
Other researchers	Arjen Hoekstra, Mark Fraters

Introduction

The objective of this study is to develop a conceptual, systems-based methodology to quantify socio-economic impacts of large scale environmental problems. The final objective is to model global socio-economic impacts dynamically at the level of five to ten regions. The products generated by the project can be considered as stand-alone socio-economic impact components which can be inserted into the TARGETS modelling framework.

Methodology

The heart of the approach developed is to structure possibly relevant impacts into impact categories for which generic response mechanisms can be used. Both direct and indirect impacts are to be modelled on a global scale. Direct socio-economic effects may involve the monetary damage that relates environmental stresses to losses; physical damage functions that are meaningful in their natural units but can also be priced; physical damage functions that cannot be priced; and multiple stress damage functions for impacts affected by various stresses that are either independent, or about which there is so little information that the best estimate is multiplicative. Indirect socio-economic impacts include, for instance, the multiplier effects in the economy resulting from direct losses in one or several sectors. This partly depends on the approach chosen, e.g. national income or a socio-economic cost-benefit approach.

Research Topics

Prototype impact-assessment models are to be developed for public health, water management, and coastal defence. For public health a generic model will be developed for the estimation of costs associated with any given disease, as well as a costs model for providing water-supply and sanitation services. For the water management sector a demand assessment, water allocation and impacts (public water supply, domestic and agricultural self-supply and irrigated agriculture) model are wholly included in the water cycle model of AQUA. With respect to coastal defence a vulnerability assessment model is to be developed which calculates people at risk, capital at risk and expected capital damage, driven by a future sea level rise.

Socio-economic impact models for the agricultural and energy sector will be developed in the near future.

8.2.8. *Meeting TARGETS*

Coordinator	Marco Janssen
Other researchers	Anco van Duyvenboden (trainee)

Introduction

Besides scanning the future by scenario analysis there is another perspective for looking at global change and sustainable development. Instead of estimating the consequences of possible future scenarios, strategies can be developed which meet certain (policy) targets. In this subproject an optimization approach for the TARGETS model will be developed in order to find response strategies for global change and sustainable development, starting with climate change as an illustrative example.

Methodology

Although there is no unique optimal strategy for the notion of sustainable development, optimization techniques might serve as a helpful tool for the search for response strategies for sustainable development. During the last few years a number of studies have appeared which have used an optimization approach to climate change. In order to find 'optimal' solutions they used simplified, highly parameterized, analytical models. Because such quasi-static models do not describe the dynamics of the system adequately, optimization might lead to invalid solutions. Janssen *et al.* (1994) have developed a heuristic method which combines optimization techniques and dynamic models. This heuristic method is used as a starting point for an optimization approach for global change and sustainable development. Using methodologies from different disciplines, such as nonlinear optimization, fuzzy programming, game theory and multicriteria analysis, a tool will be developed to analyse the TARGETS model from an optimization perspective and to derive strategies to meet certain targets.

Research Topics

The research consists of three phases. The first phase deals with the development and testing of the heuristic method, the development of an optimization approach under uncertainty, and some experiments to be performed for climate change. The second phase focuses on the use of the heuristic method for global change from a global perspective. In this phase, attention will be paid to the use of the sustainability indicator approach and the inclusion of different perspectives in optimization problems. In the third phase the optimization approach will be used for deriving regional strategies and analysing international (cooperation) strategies.

8.2.9. Modelling perspectives

Coordinator Marjolein van Asselt

Introduction

Uncertainties play a key role in the TARGETS philosophy, because forecasting future global change and its consequences for society is beset with many uncertainties. Addressing the issue of uncertainty is important to enable decision makers to identify the major uncertainties as well as to distinguish between the various sources of uncertainty. In most integrated assessment models, however, the uncertainties are hidden. This research project aims at the development of a methodology which provides the basis for making those uncertainties explicit.

Methodology

A lot of uncertainty is caused by subjective judgement and disagreement, which notions can be related to different perspectives people have. Therefore, in this study a methodology is to be developed which is based on the implementation of cultural perspectives following the cultural theory as postulated by Thompson *et al.* (1990).

First, a dichotomy between weak and strong knowledge is introduced. While strong knowledge is based on empirical facts, weak knowledge contains a great deal of uncertainty, and is based on subjective judgement and is a potential source of disagreement. Therefore, in the second step the quantities and relations in the modules which are based on weak knowledge are to be traced, which is the result of a continuous dialogue between the modellers and the model analyst. This leads to a meta representation of a specific module, which includes crucial uncertainties due to subjectivity and disagreement per module. In the quantitative part of the analysis the model entities are divided into state variables, steering variables, empirical quantities, value quantities and auxiliary quantities. In this study the focus will be on the empirical and value quantities which are representations of subjective knowledge and disagreement. Mathematical techniques as sensitivity and uncertainty analyses are then used to reduce the quantities to at most ten crucial model elements per module. These crucial model uncertainties are then made explicit by relating them to different cultural perspectives. The model uncertainties are filled in differently, dependent on the biases and preferences of the different cultural perspectives. In this way alternative, perspective-based model routes can be generated.

Research Topics

The alternative model routes created can be viewed as model interpretations, in which not only parameters but also relationships are varied, resulting in alternative model structures. In this respect alternative model routes differ significantly from scenarios or strategies as used in the traditional way. Alternative model routes may ultimately serve as interpretative strategies for sustainable development. For the four perspectives considered - egalitarianism, individualism, fatalism and hierarchy- alternative model routes will be generated, resulting in different interpretations of the ideograph of sustainable development.

8.2.10. Visualization

Coordinator Jos de Bruin
Other researchers Pascal de Vink, Michel Bakkenes

Introduction

The TARGETS model will be implemented in the M environment. This environment supports the development, execution and visualization of mathematical dynamical models. Although the modelling and visualization environment M is still in the development stage, a basic version, namely 2.0 is already available, and will be used in this research project. In addition, time and effort will have to be devoted to further enhancing version 2.0, and extending and developing the possibilities of this modelling and visualisation tool.

Methodology

An M model is specified using a notation very similar to the standard mathematical formulation of ordinary differential equations, difference equations and algebraic equations. Apart from offering a very compact notation, M takes care of the translation of a set of equations into a numerical recipe, i.e. into a C program that can be compiled and run. The resulting simulator will have been linked automatically with all the routines necessary to interface with the outside world, freeing the model builder from all worries about input and output. A graphical user interface is included that uses these routines to generate the appropriate 'widgets' for the model variables and to draw the dependency graphs reflecting the relations between the variables. Using the GUI in design mode, any number of hierarchical diagrams can be drawn to provide different perspectives on the underlying model. In use mode, these views can be explored and used interactively to run the model on different scenarios and input values.

Research Topics

The major goals of the M toolbox, which is under development at RIVM, are:

- to reduce the time needed to implement models and their graphical interfaces;
- to increase the quality of implementations by standardizing the translation of a set of equations into a runnable model;
- to increase the quality of models by opening them up to easy inspection by other researchers (and easy debugging by the modelbuilders themselves);
- to increase the use of models by policy analysts and policy makers by providing easy-to-use interfaces;
- to increase the impact of model presentations by making use of the latest technology in interactive information systems and use these model presentations to provide as much context and background information as needed to support the structure of the model and the choice of scenarios used.

8.3. National position of the research programme

During the execution of the research programme 'Global Dynamics and Sustainable Development' an intensive cooperation with several institutes in the Netherlands, which are mentioned below in arbitrary order, will exist:

* The Delft University of Technology, School of Engineering and Policy Analysis, Prof.dr.ir. W.A.H. Thissen. The cooperation concerns the development of the a integrative tool for global policy analysis in the field of water management, the AQUA model.

* The University of Limburg, Faculty of General Sciences, Prof.dr.ir. O.J. Vrieze and the Faculty of Environmental Health, Prof.dr. J.C.S. Kleinjans. The cooperation concerns the modelling of human health effects due to global environmental change.

* The University of Utrecht, The Research Institute of Toxicology, Prof. dr. J. Hermens and drs. E. Verbruggen. The cooperation concerns the development of an integrated modelling tool for analysing toxic substances.

* The University of Utrecht, Department of Physical Geography, dr. J. Kwadijk. This cooperation involves the application of a methodology to estimate the impact of a human-induced climate change on streamflow changes in the large rivers basins of the Ganges/ Brahmaputra and the Yangtze.

* The Agricultural University of Wageningen, dr. T. Jetten. The cooperation concerns the large-scale modelling of vector-borne diseases.

* The Agricultural University of Wageningen, Prof.dr. de Haan which aims at the analysis and modelling aspects of global cycles of heavy metals.

* The University of Groningen, Prof.dr. F. Willekens, which focuses on the further development and improvement of the population dynamics model, being a part of the integrated population and health model of TARGETS.

* The Technological University of Twente, Faculty of Science and Society, Prof.dr. A. Rip. The cooperation aims at the incorporation of knowledge and expertise from the social sciences in integrated assessment models.

* The Institute for Environmental Studies (IVM) of the Free University of Amsterdam, Prof.dr.ir. P. Vellinga. The cooperation concerns an assessment of the impacts of changes in the biogeochemical cycli on environment and society, based on which C-, S-, N- and P-emissions quota are to be allocated

* The Catholic University of Tilburg, Prof.dr. J.P.C. Kleijnen, which aims at the performance of sensitivity - and uncertainty analyses with the TARGETS model.

* Erasmus University of Rotterdam, Department of Public Health and Social Medicine, Prof. P.J. van der Maas. The cooperation involves scientific advice regarding the health aspects of the integrated population and health model of TARGETS.

8.4. International position of the research programme

At the international scale official collaboration has been established with the following institutes:

* The World Resource Institute (WRI) in Washington, U.S.A. From 1 July 1994 dr. R. Zapert will act as a liaison between the '2050 Sustainability' project of WRI (WRI, 1993) and the 'Global Dynamics and Sustainable Development' project of RIVM. One of his main activities will be the development of a PC-version of TARGETS which can be used within the 2050 project.

* Max-Planck Institut für Meteorologie (MPI) in Hamburg, Germany. The collaboration involves the use of GCM-results for calibrating parts of the TARGETS model, in exhange for which the TARGETS model can be used by MPI.

* Potsdam Institut für Klimafolgenforschung (PIK) in Potsdam, Germany. The PIK-Institut is involved in the complex systems analysis of the TARGETS model and in the intercomparison with other global models.

* London School of Hygiene & Tropical Medicine in London, U.K. The Department of Epidemiology & Population Sciences will be involved in the further development of the integrated population and health model.

* The University of South Australia in Adelaide, Australia. The School of Mathematics will develop a mathematical system of the TARGETS model, which enables the performance of a thorough mathematical analysis of the model.

* The Academy of Sciences in Geneva, Switzerland. Via the collaboration with M. Thompson it will be investigated whether, based on the knowledge arising from the implementation of the cultural perspectives in integrated assessment models, new research strategies can be formulated and new research priorities can be set.

* In the near future collaboration will be set up with a number of institutes in developing countries (especially in Latin America and Asia), in order to involve these institutes into the modelling process in a more active way.

Furthermore, opportunities for cooperation will be sought among the larger international research programmes. Via Dr. Leemans, who is a member of the Dutch Committee of the International Geosphere-Biosphere Programme (IGBP), members of the IGBP Task Force on Global Analysis, Interpretation and Modelling (GAIM) have already been informed about the potential research plans set out in this research proposal. In addition, contacts will be established with Dr. Jacobson from the University of Michigan, who is one of the key persons in the research programme entitled Human Dimensions of Global Environmental Change (HDGEC).

At the end of 1992, J. Rotmans (RIVM), K. Hasselmann (MPI) and H.J. Schellnhuber (PIK) have founded a network of 'global change modellers'. This network provides a platform for natural and social scientists from all over the world, who are involved in global modelling, to exchange state-of-the art scientific information. Within the referential framework of this network, already two workshops have already been organized: in Potsdam (November 1992) and in Zeist (June 1993). The network encompasses numerous institutes and universities with which useful informal contacts have been built up. If appropriate within the scope of the research programme 'Global Dynamics and Sustainable Development', such contacts could readily be formalized and upgraded to official collaborations.

8.5. Time schedule

A provisional working schedule for the research programme, for the period 1994-1998 would be:

TIME PERIOD	INTERMEDIATE PRODUCT
July 1994	- First prototype of TARGETS, version 1.0.
July - October 1994	- Calibration and validation of TARGETS, version 1.0; first systematic series of experiments. - Case studies for river basins Ganges/Brahmaputra and Yangze. - Case-studies for India and China.
November 1994	- Expert review of TARGETS 1.0.
December 1994	- Fully calibrated, validated and documented version of TARGETS 1.0. - Global integrative analysis, based on systems analysis and experiments with TARGETS 1.0. - Book of TARGETS 1.0. - Formulation of sustainable strategies, based on series of experiments with the indicator framework and TARGETS 1.0.
January 1995	- Advisory Board Meeting.
April 1995	- Conceptual model version of TARGETS 2.0.
July 1995	- PC-version of TARGETS 1.0. - Prototype of TARGETS 2.0, disaggregated for a number of world regions.
December 1995	- Version 2.0 of TARGETS, regionalized for a number of major world regions.
January 1996 - July 1996	- Calibration and validation of TARGETS, version 2.0; first systematic series of experiments.
September 1996	- Expert review of TARGETS 2.0.
October 1996 - December 1996	- Fully documented, calibrated and validated version of TARGETS 2.0. - Regionalized integrative analysis, based on systematically performed series of experiments.
July 1997	- Operational form of the framework of indicators and indices at the regional level. - Formulation of sustainable strategies at the regional level, based on series of experiments with the indicator framework and TARGETS 2.0. - Book of TARGETS 2.0
December 1997	- Full integrative analysis. - Full operationalisation of Global Change and Sustainable Development for the selected world regions in form of case studies, based on various perspectives.
January 1998	- Final Advisory Board Meeting.

ACKNOWLEDGEMENTS

Although being the only author of this booklet, I could never have written it without the help of all team members of the research project 'Global Dynamics and Sustainable Development'. The author thanks them all for their indispensable contributions to this manuscript. Furthermore, I would like to thank Anton van der Giessen of the Centre for Mathematical Methods (CWM) and Rob Swart of the Environmental Forecasting Bureau (MTV) of RIVM for their many helpful comments and contributions. Special thanks are due to Martin Middelburg who was responsible for the graphics and lay-out of this pamphlet. Finally, I would like to thank Allan Miller and Ian Priestnall for their efforts in correcting and improving the English text.

9. REFERENCES

- Achterberg, W. (1986), *'Partners in de natuur: een onderzoek naar de aard en de fundamenten van een ecologische ethiek'*, Utrecht, The Netherlands.
- Ackoff, R.L. (1971), *'Towards a system of systems concepts'*, Management Science July 1971, no. 17.
- Adriaanse, A. (1993), *'Environmental policy performance indicators'*, A study on the development of indicators for environmental policy in the Netherlands, SDU Publishers, The Hague, The Netherlands.
- Alcamo, J., Shaw, R. and Hordijk, L. (eds.) (1990), *'The RAINS model of acidification: science and strategies in Europe'*, Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Alcamo, J. (ed.) (1994), *'Integrated modelling of global climate change IMAGE 2.0'*, , Special Issue of the Journal of Water, Air and Soil Pollution, April 1994.
- Arizpe, L. (1989), *'On cultural and social sustainability'*, In: Emmerij, L. (ed.), 'One world or several?' Development Centre of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- Baar, H.J.W. de, and Stoll, M.H.C. (1989), *'Storage of carbon dioxide in the oceans'*, In: Okken, P.A., Swart, R.J. and Zwerver, S. (eds.), 'Climate and Energy, Kluwer, Dordrecht, The Netherlands, 143-177.
- Barbier, E.B. (1987), *'The concept of sustainable economic development'*, Environmental Conservation 14, no. 2, 101-110.
- Bare, B.B. and Mendoza, G.A. (1993), *'A fuzzy approach to natural resource management from a regional perspective'*, Paper presented at the European Conference of Operations Research, July 1993, Lisbon, Portugal.
- Bergh, J.C.J.M. van den (1991), *'Dynamic models for sustainable development'*, PhD Thesis, Tinbergen Institute, Amsterdam, The Netherlands.
- Berner, E.K. and Berner, R.A. (1987), *'The global water cycle'*, Prentice-Hall, Englewood Cliffs, NJ., USA.
- Boer, J. de, Aiking, H., Lammers, E., Sol, V. and Feenstra, J. (1991), *'Contours of an integrated environmental index for application in land-use zo'*, In: Kuik, O. and Verbruggen, H. (eds.), 'In search of indicators of sustainable development', Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Bolin, B. and Cook, R.B. (eds.) (1983), *'The major biogeochemical cycles and their interactions'*, SCOPE 21, John Wiley & Sons, New York, U.S.A.
- Bonneux, L., Barendregt, J.J., Meeter, K., Bonsel, G.J. and Maas, P.J. van der (1994), *'Estimating clinical morbidity due to ischemic heart disease and congestive heart failure'*, American Journal of Public Health (in press).
- Born, G.J. van den, Bakkes, J.A., Helder, J.C., Swart, R.J., Hope, C.W. and Parker, J.D.E. (1993), *'An overview of environmental indicators-state of the art and perspectives'*, Draft UNEP-Report, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven, The Netherlands and University of Cambridge, Cambridge, U.K., December 1993.
- Braddock, R., Filar, J., Rotmans, J. and Elzen, M.G.J. den (1993), *'The IMAGE greenhouse model as a mathematical system'*, University of Adelaide Technical Report 93-no 1, Adelaide, Australia.
- Brecke, P. (1993), *'Integrated global models that run on personal computers'*, SIMULATION 60, no. 2, February 1993.
- Brink, B.J.E. ten, Hosper, S.H. and Colijn, F. (1991), *'A quantitative method for description and assessment of ecosystems: the AMOEBE approach*, Marine Pollution Bulletin 23, 265-270.
- Brooks, H. (1986), *'The typology of surprises in technology, institutions, and development'*, In: Clark and Munn (eds.) , *'Sustainable development of the biosphere'*, IIASA-Book, Cambridge University Press, London, U.K.
- Brooks, H. (1992), *'Sustainability and technology'*, In: 'Science and sustainability: selected papers on IIASA's 20th anniversary', International Institute for Applied Systems Analysis (IIASA), 1992, Laxenburg, Austria.
- Bruin, J. de, Rotmans, J., Vink, P. de and Wijk, J. van (1994), *'The modelling and visualisation environment 'M''*, RIVM-Report in preparation.
- Butcher, S.S., Charlson, R.J., Orians, G.H. and Wolfe, G.V. (1992), *'Global biogeochemical cycles'*, Academic Press, London.
- Buttel, F.H., Hawkins, A.P. and Power, A.G. (1990), *'From limits to growth to global change: constraints and contradictions in the evolution of environmental science and ideology'*, Global Environmental Change, December 1990, 57-66.
- Charlson, R.J., Lovelock, J.E., M.O. Andrae, Warren, S.G. (1987), *'Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate'*, Nature 326, 655-661.
- Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, R.D., Coakley, J.A., Hansen, J.E. and Hofmann, D.J. (1992), *'Climate forcing by anthropogenic aerosols'*, Science 255, 423-429.

- Clark, W.C. and Munn, R.E. (eds.) (1986), *'Sustainable development of the biosphere'*, IIASA-Book, Cambridge University Press, London, U.K.

- Cohen, S.J. (ed.) (1993), *'Mackenzie Basin Impact Study: Interim Report I'*, Canadian Climate Center, Downsview, Ontario, Environment Canada, Canada.

- Consortium for International Earth Science Information Network (CIESIN) (1992), *'Pathways of understanding: the interactions of humanity and global environmental change'*, University Center, MI 48710, USA.

- Cubasch, U., Hasselmann, K., Höck, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B.D. and Sausen, R. (1992), *'Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model'*, Climate Dynamics 8, 55-69.

- Daily, G.C. and Ehrlich, P.R. (1990), *'An exploratory model of the impact of rapid climate change on the world food situation'*, Proc. R. Soc. London B 241, 232-244.

- Dávid, L.J., Golubev, G.N. and Nakayama, M. (1988), *'The environmental management of large international basins, the EMINWA programme of UNEP'*, International Journal of Water Resources Development 4, no. 2, 103-107.

- Delft Hydraulics (1993), *'Sea level rise: a global vulnerability assessment: vulnerability assessment for population, coastal wetlands and rice production on a global scale'*. Second revised edition. Prepared for: Tidal Waters Division, Rijkswaterstaat, Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands.

- Doll, R. (1992), *'Health and the environment in the 1990s'*, American Journal of Public Health 82, no. 7, 933-941.

- Döös, B., R. (1991), *'Environmental issues requiring international action'*, IIASA-Report no. RR-91-16, International Institute for Applied Systems Analysis, Laxenburg, Austria.

- Douglas, M. (ed.) (1982), *'Essays in the sociology of perception'*, Routledge and Kegan Paul, London, U.K.

- Dovers, S.R. and Handmer, J.W. (1992), *'Uncertainty, sustainability and change'*, Global Environmental Change, December 1992, 262-276

- Dowlatabadi, H. and Morgan, G.M. (1993a), *'Integrated Assessment of climate change'*, Science 259, 1813-1814.

- Dowlatabadi, H. and Morgan, G.M. (1993b), *'A model framework for integrated studies of the climate problem'*, Energy Policy March 1993, 209-221.

- Dzidonu, C.K. and Foster, F.G. (1993), *'Prolegomena to OR modelling of the global environment-development problem'*, Journal of the Operational Research Society 44, no. 4, 321-331.

- Edmonds, J.A., Ashton, W.B., Cooper, C.L., Longstreth, J., Rayner, J. and Rosenberg, N.J. (1993), *'Global climate change and the social sciences: an international assessment'*, Draft Report, Batelle, Pacific Northwest Laboratories, Washington, D.C., USA.

- Elzen, M.G.J. den, Janssen, M.A., Rotmans, J., Swart, R.J. and Vries, H.J.M. de (1992), *'Allocating constrained global carbon budgets: interregional and intergenerational equity for a sustainable world'*, International Journal of Global Energy Issues 4, no. 4, 287-301.

- Elzen, M.G.J. den (1993), *'Global environmental change: an integrated modelling approach'*, PhD.Thesis, University of Maastricht, The Netherlands.

- Elzen, M.G.J. den and Rotmans, J. (1994), *'Modelling global biogeochemical cycles: an integrated modelling approach'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-report no. 461502007, in preparation, Bilthoven, The Netherlands.

- Elzen, M.G.J. den, Köster, H.W., Martens, W.J.M., Heil, M. (1994), *'The global land model of TARGETS'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-report no. 461502005, in preparation, Bilthoven, The Netherlands.

- Environment Canada (1992), *stratospheric ozone depletion'*, Environmental Indicator Bulletin no. 92, 1-4, Ottawa, Canada.

- Falkenmark, M. (1989), 'The massive water scarcity now threatening Africa: Why isn't it being addressed?', Ambio 18, no. 2, 112-118.

- Falkenmark, M. (1992), *'A water perspective on population, environment, and development'*, In: Imhoff, E. van, Themmen, E., Willekens, F. (eds.), 'Population, environment and development', Swets & Zeitlinger.

- Falkenmark, M. and Lindh, G. (1993), *'Water and economic development'*, In: Gleick, P.H. (ed.), 'Water in crisis, a guide to the world's fresh water resources', Oxford University Press, New York, U.S.A.

- Fisher, A. (1988), *'One model to fit all'*, MOSAIC 19, no. 34, 53-59.

- Foley, J.A., Taylor, K.E. and Ghan, S.J. (1991), *'Plankton dimethylsulfide and cloud albedo: an estimate of the feedback response'*, Climatic Change January 1991.

- Food and Agriculture Organization of the United Nations (FAO) (1988), *'World Agriculture: Toward 2000'*, Nikos Alexandratos (ed.), Belhaven Press, London, U.K.

- Forrester, J.W. (1961), *'Industrial dynamics'*, the M.I.T. Press, Cambridge, Massachusetts, U.S.A.

- Forrester, J.W. (1968), *'Principles of systems'*, Wright-Allen Press Inc., Cambridge, Massachusetts, U.S.A.

- Frenkel, F.N. and Goodall, D.W. (1978), *'Simulation modelling of environmental problems'*, SCOPE 9, John Wiley & Sons, New York, U.S.A.

- Funtowitcz, S.O. and Ravetz, J.R. (1989), *'Managing uncertainty in policy-related research'*, paper presented at the International Colloquium 'Les experts sont formels: Controverses Scientifiques et Décisions Politiques dans le Domaine de l'Environment', Arc et Sanans, France, 11-13 September 1989.

- Gilbert, A.J. and Feenstra, J.F. (1992), *'An indicator of sustainable development: diffusion of cadmium'*, Institute for Environmental Studies, Report no. 92/06, Amsterdam, The Netherlands.

- Gleick, P.H. (ed.) (1993), *'Water in crisis, a guide to the world's fresh water resources'*, Oxford University Press, New York, U.S.A.

- Goodland, R. and Ledec, G. (1987), *'Neoclassical economics and principles of sustainable development'*, Ecological Modelling 38, 19-46.

- Goodman, M.R. (1974), *'Study notes in system dynamics'*, Wright-Allen Press Inc., Cambridge, Massachusetts, U.S.A.

- Goudriaan, J. and Ketner, P. (1984), *'A simulation study for the global carbon cycle including man's impact on the biosphere'*, Climatic Change 6, 167-192.

- Graedel, T.E. and Crutzen, P.J. (1993), *'Atmospheric change: an earth system perspective'*, Freeman and Company, New York, USA.

- Greef, J. de and De Vries, H.J.M. (1991), *'Sustainable development as guiding principle for environmental policy'* (in Dutch), RIVM Report no. 481501001, Bilthoven, The Netherlands.

- Grenon, M. and Batisse, M. (1989), *'Futures for the Mediterranean basin: the blue plan'*, Oxford University Press, U.K.

- Grübler, A. and Fujii, Y. (1991), *'Intergenerational and spatial equity issues of carbon accounts'*, Energy 16 (11/12), 1397-1416.

- Gugten, D. van der (1988), *'The global phosphorus cycle: anthropogenic disturbance and its effect'* (in Dutch), TNO SCMO Report R 88/08, Delft, The Netherlands.

- Haines, A. and Fuchs, C. (1991), *'Potential impacts on health of atmospheric change'*, Journal of Public Health Medicine 13, no. 2, 69-80.

- Hoekstra, A.Y. (1992), *'Quantifying ecological quality'* (in Dutch), Research Report T720, Delft Hydraulics, Delft, The Netherlands.

- Hoekstra, A.Y. (1994), *'AQUA: an integrated tool for global water policy making'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-report no. 461502006, in preparation, Bilthoven, The Netherlands.

- Holling, C.S. (1973), *'Resilience and stability of ecological ecosystems'*, Ann. Rev. Ecology and Systematics 4, 1-23.

- Holling, C.S. (1986), *'The resilience of terrestrial ecosystems: local surprise and global change'*, in Clark, W.C. and Munn, R.E. (eds.), 'Sustainable development of the biosphere', International Institute for Applied Systems Analysis (IIASA), Cambridge University Press, London, U.K.

- Hope, C., Parker, J. and Peake, S. (1992), *A pilot environmental index for the U.K. in the 1980s'*, Energy Policy 20, no. 4, April 1992, 335-343.

- Hope, C. and Parker, J. (1993), *'Forum: sharpening the environmental debate'*, Energy Policy November 1993, 1075-1076.

- Hordijk, L. (1991), *'An integrated assessment model for acidification in Europe'*, PhD.Thesis, Free University of Amsterdam, The Netherlands.

- Hulme, M., Zhao, Z-C and Jiang, T. (1994), *'Recent and future climate change in East Asia'*, International Journal of Climatology (in press).

- International Federation of Institutes for Advanced Study (IFIAS) (1989), *'The human dimensions of global change: an international programme on human interactions with the earth'*, Toronto, Canada.

- International Geosphere-Biosphere Programme (IGBP) (1990), *'A study of global change: the initial core programmes'*, The Royal Swedish Academy of Sciences, Stockholm, Sweden.

- International Geosphere-Biosphere Programme (IGBP) (1992), *'Global change: reducing uncertainties'*, The Royal Swedish Academy of Sciences, Stockholm, Sweden.

- Intergovernmental Panel on Climate Change (IPCC) (1990a), *'Climate Change: The IPCC Scientific Assessment'*, Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (eds.), Cambridge University Press, Cambridge, U.K.

- Intergovernmental Panel on Climate Change (IPCC) (1990b), *'Climate Change: The IPCC Impacts Assessment'*, Australian Government Publishing Service, Australia.

- Intergovernmental Panel on Climate Change (IPCC) (1991), 'Climate Change: the IPCC Response Strategies', Island Press.

- Intergovernmental Panel on Climate Change (IPCC) (1992), *'Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment'*, Houghton, J.T., Callander, B.A. and Varney, S.K. (eds.), Cambridge University Press, Cambridge, U.K.

- IUCN/UNEP/WWF (1980), *'World conservation strategy, Living resource conservation for sustainable development'*, International Union for Conservation of Nature and Natural Resources (IUCN), United Nations Environment Programme (UNEP) and World Wildlife Fund (WWF), Gland, Switzerland.

- IUCN/UNEP/WWF (1991), *'Caring for the earth: a strategy for sustainable living'*, International Union for Conservation of Nature and Natural Resources (IUCN), United Nations Environment Programme (UNEP) and World Wildlife Fund (WWF), October 1991, Gland, Switzerland.

- Ivanov, M.V. and Freney, J.R. (1983), *'The global biogeochemical sulphur cycle'*, SCOPE 19, John Wiley & Sons, New York, U.S.A.

- Jacobson, H.K. and Price, M.F. (1990), *'A framework for research on the human dimensions of global environmental changes'*, The International Social Science Council, 1 Rue Miollis, 75015 Paris, France.

- Jäger, J. (ed.) (1988), *'Developing policies for responding to climatic change. A summary of discussions and recommendations of the workshops in Villach and Bellagio in 1987*, Report WCIP-1; WMO/TD no. 225.

- James, D.E. (1989), *'Achieving sustainable development: applications of economic techniques'*, Milieu 4, 129-133.

- Janssen, P.H.M., Slob, W. and Rotmans, J. (1990), *'Uncertainty analysis and sensitivity analysis: an inventory of ideas, methods and techniques from the literature'*, (in Dutch), National Institute of Public Health and Environmental Protection (RIVM), RIVM-Report no. 958805001, Bilthoven, The Netherlands.

- Janssen, M.A., Elzen, M.G.J. den and Rotmans, J. (1992), *'Allocating CO_2-emissions by using equity rules and optimization'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-Report no. 222901012, Bilthoven, The Netherlands.

- Janssen, M.A., Rotmans, J. and Vrieze, O.J. (1994), *'Climate change: optimization of response strategies'*, Reports in Operations Research and Systems Theory, Report M 94-01, University of Limburg, Maastricht, The Netherlands.

- Janssen, M.A. and Rotmans, J. (1994), *'Allocation of fossil CO_2 emission rights: quantifying cultural perspectives'*, Reports in Operations Research and Systems Theory, Report M 94-02, University of Limburg, Maastricht, The Netherlands.

- Jonas, M., Olendrzynski, K., Krabec, J. and Shaw, R. (1992), *'IIASA's work on climate change: assessing environmental impacts'*, IIASA-Report no. SR-92-9, International Institute on Applied Systems Analysis, Laxenburg, Austria.

- Joos, F., Siegenthaler, U. and Sarmiento, J.L. (1991a), *'Possible effects of iron fertilization in the southern ocean on atmospheric CO_2 concentration'*, Global Biogeochemical Cycles 5, no. 2, 135-150.

- Joos, F., Sarmiento, J.L. and Siegenthaler, U. (1991b), *'Estimates of the effect of southern ocean iron fertilization on atmospheric CO_2 concentrations'*, Nature 349, 772-775.

- Kerr, R.A. (1992), *'Pollutant haze cools the greenhouse'*, Science 255, 682-683.

- Kira, T. (1988), *'Towards the environmentally sound management of lake/watershed systems, the aims and activities of ILEC'*, International Journal of Water Resources Development 4, no. 2, 124-126.

- Klaassen, G.A.J. and Opschoor, J.B. (1991), *'Economics of sustainability or the sustainability of economics: different paradigms'*, Ecological economics 115, 93-115.

- Kramer, N.J.T.A. and Smit, J. de (1991), *'Systeemdenken'*, Stenfert Kroese Uitgevers, Leiden, The Netherlands.

- Krapivin, V.F. (1993), *'Mathematical model for global ecological investigations'*, Ecological Modelling 67, 103-127.

- Krause, F., Bach, W. and Koomey, J. (1989), *'Energy policy in the greenhouse, Vol. I: from warming fate to warming limit: benchmarks for a global climate convention'*, International Programme for Sustainable Energy Paths, El cerrito (IPSEP).

- Kuik, O.J. and Verbruggen, H. (eds.) (1991), *'In Search of indicators of sustainable development'*, Kluwer Academic Publishers, Dordrecht, The Netherlands.

- Kwadijk, J. and Rotmans, J. (1994), *'The impact of climate change on the River Rhine: a scenario study'*, Climatic Change, in press.

- Lacerda, L.C. and Salomons, W. (1991), *'Mercury in the Amazon: a chemical time bomb?'*, Foundation for Ecodevelopment, Hoofddorp, The Netherlands.

- Langeweg, F. (1989), *'Concern for tomorrow: a National environmental survey 1985-2010'*, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven, The Netherlands.

- Langner, J. and Rodhe, H. (1991), *'A global three-dimensional model of the tropospheric sulphur cycle'*, Journal of Atmospheric Chemistry 13, 225-263.

- Lashof, D.A. (1989), *'The dynamic greenhouse: feedback processes that may influence future concentrations of atmospheric trace gases and climate change'*, Climatic Change 14, 213-242.

- Lélé, S.M. (1991), *'Sustainable development: a critical review'*, World Development 19, no. 6, 607-621.

- Likens, G.E. (1981), *'Some perspectives of the major biogeochemical cycles'*, SCOPE 17, John Wiley & Sons, New York, U.S.A.

- Liverman, D.M., Hanson, Brown, B. and Merideth, R.W. (1988), *'Global sustainability: toward measurement'*, Environmental Management 12, no. 2, 133-143.

- Lovelock, J.E. (1979), *'Gaia: a new look at life on earth'*, Oxford University Press, Oxford.

- Lovelock, J.E. (1988), *'The ages of Gaia: a biography of our living earth'*, Norton and Company, New York, U.S.A.

- Martens, W.J.M., Rotmans, J. and Niessen, L.W. (1994), *'Climate change and malaria risk: an integrated modelling approach'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-report no. 461502003, March 1994.

- Martin, J.H., Fitzwater, S.E. and Gordon, R.M. (1990a), *'Iron deficiency limits phytoplankton growth in Antarctic waters'*, Global Biogeochemical Cycles 4, 5-12.

- Martin, J.H., Gordon, R.M. and Fitzwater, S.E. (1990b), *'Iron in Antarctic waters'*, Nature 345, 156-158.

- McMichael, A.J. (1993a), *'Global environmental change and human population health: a conceptual and scientific challenge for epidemiology'*, International Journal of Epidemiology 22, 1-8.

- McMichael, A.J. (1993b), *'Planetary overload: global environmental change and the health of the human species'*, Cambridge University Press, Cambridge, U.K.

- Meadows, D.H., Meadows, D.L., Randers, J. and Behrens, W.W. (1972), *'The limits to growth'*, Universe Books, New York, U.S.A.

- Meadows, D., Richardson, J. and Bruckmann, G. (1982), *'Groping in the dark: the first decade of global modelling'*, John Wiley & Sons, New York, U.S.A.

- Meadows, D.H., Meadows, D.L. and Randers, J. (1992), *'Beyond the limits: a a worldwide catastrophe or a sustainable world'*. Spectrum/Aula, Utrecht.

- Meent, D. van de (1993), *'SIMPLEBOX: a generic multimedia fate evaluation model'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-Report 672720001, Bilthoven, The Netherlands.

- Meulen, G.R.B. ter, Stigliani, W.M., Salomons, W., Bridges, E.M. and Imeson, A.C. (1993), *'Chemical time bombs'*. Proceedings of the European State-of-the-art Conference on delayed effects of chemicals in soils and sediments, 2-5 September 1992, Veldhoven, The Netherlands. Published by The Foundation for Ecodevelopment "Stichting Mondiaal Alternatief", Hoofddorp, The Netherlands.

- Miller, R.B. and Jacobson, H.K. (1992), *'Research on the human components of global change: next steps'*, Working Paper presented at the 1992 Annual Meeting of the American Association for the Advancement of Science, Chicago, 6-11 February 1992.

- Molina, M.J. and Rowland, F.S. (1974), *'Stratospheric sink for chlorofluoromethanes: chlorine atomic catalysed destruction of ozone'*, Nature 249, 810-814.

- Morgan, G.M. and Henrion, M. (1990), *'Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis'*, Cambridge University Press, New York, U.S.A.

- Mosley, W.H. and Becker, S. (1991), *'Demographic models for child survival and implications for health intervention programmes'*, Health Policy Planning 6, no. 3, 218-233.

- National Defense University (NDU) (1978), *'Climate change to the year 2000: a survey of expert opinion'*, NDU-Report, 1-16, 59-77, Washington, D.C. U.S.A.

- Ness, G.D., Drake, W.D. and Brechin, S.R. (eds.) (1993), *'Population-environment dynamics - ideas and observations'*, The University of Michigan Press.

- Niessen, L.W., Barendregt, J.J., Bonneux, L. and Koudstaal, P.J. (1993), *'Stroke trends in an aging population'*, Stroke Journal of Cerebro-vascular Circulation 24, 931-939.

- Niessen, L.W. and Rotmans, J. (1993), *'Sustaining Health: towards an integrated Global Health Model'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-report no. 461502001, May 1993.

- Nijkamp, P. and Soeteman, F.J. (1988), *'Ecologically sustainable economic development: key issues for strategic environmental management'*, International Journal of Social Economics 15, no. 3/4, 88-102.

- Nordhaus, W.D. (1992), *'An optimal transition path for controlling greenhouse gases'*, Science 258, 1315-1319.

- OECD (Organization for Economic Development) (1993), *'Environmental indicators: basic concepts and terminology'*, Background Paper no. 1, by Group on the State of the Environment. In: Proceedings of the Workshop on Indicators for use in environmental performance reviews, 1/2 February 1993, Paris.

- Omran, A.R. (1971), *'The epidemiological transition: a theory of the epidemiology of population change'*, Milbank Memorial Fund 49, 509-538.

- Opschoor, J.B. and Reijnders, L. (1991), *'Towards sustainable development indicators'*, Hoofdstuk 2 in: Kuik, O. en Verbruggen, H. (eds.) 'In search of indicators of sustainable development'. Kluwer Academic Publishers, Dordrecht/Boston/London.

- Oreskes, N., Shrader-Frechette, K. and Belitz, K. (1994), *'Verification, validation, and confirmation of numerical models in the Earth sciences'*, Science 263, 641-646.

- O'Riordan, T. and Rayner, S. (1991), *'Risk management for global environmental change'*, Global Environmental Change March 1991, 91-108.

- Ott, W. (1978), *'Environmental indices: theory and practice'*, Ann Arbor, Michigan, U.S.A.

- Parry, M. and Rosenzweig, C. (1993), *'Food supply and risk of hunger'*, The Lancet 342, November 27, 1345-1347.

- RMNO: Raad voor het Milieu-en Natuuronderzoek (1990), *'Research on global change in the Netherlands: opportunities for research in the Netherlands in an international framework'*, RMNO-Publication no. 42, Rijswijk, The Netherlands.

- RMNO: Raad voor het Milieu- en Natuuronderzoek (1992a), *'Meerjarenvisie 1992: Programma van milieu- en natuuronderzoek ten behoeve van een duurzame ontwikkeling'*, RMNO-Publication no. 70, Rijswijk, The Netherlands.

- RMNO: Raad voor het Milieu-en Natuuronderzoek (1992b), *'De milieugebruiksruimte als uitdaging voor technologie-ontwikkeling'*, RMNO-Publication no. 74, Rijswijk, The Netherlands.

- Redclift, M. (1987), *'Sustainable development: exploring the contradictions'*, London, Routledge, U.K.

- Resource Analysis (1993), *'Indicators of sustainability of current and future use of the North Sea'*, February 1993, Delft, The Netherlands.

- Resource Analysis (1994), *'Socio-economic impacts study of international environmental problems (SEIS): feasibility study'*, Phase 2 Report, January 1994, Resource Analysis, Delft, The Netherlands.

- Roberts, P.C. (1982), *'Resilience, transience and sustainablity'*, In: Bruckmann, G. (ed.), Environmental aspects in global modelling', Proceedings of the 7th IIASA Symposium on Global Modelling, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

- Rosenzweig, C. and Parry, M.L. (1994), *'Potential impact of climate change on world food supply'*, Nature 367, 133-138.

- Rotmans, J. (1990), *'IMAGE: an Integrated Model to Assess the Greenhouse Effect'*, Kluwer, Dordrecht/Boston/London.

- Rotmans, J., Elzen, M.G.J. den, Krol, M.S., Swart, R.J. and Woerd, H.J. van der (1992), *'Stabilizing atmospheric concentrations: towards international methane control'*, AMBIO 21 no. 6, 404-413.

- Rotmans, J. and Elzen, M.G.J. den (1993), *'Modelling feedback processes in the carbon cycle: balancing the carbon budget'*, Tellus 45B.

- Rotmans, J., Hulme, M. and Downing, T. (1994), *'Climate change implications for Europe: an application of the ESCAPE model'*, Global Environmental Change, in press.

- Ruwaard, D., Hoogenveen, R.T, Verkleij, H., Kromhout, D., Casparie, A.F. and Veen van der, E.A. (1993), *'Forecasting the number of diabetic patients in the Netherlands in 2005'*, American Journal of Public Health 83, 989-995.

- Sahagian, D.L., Schwartz, F.W. and Jacobs, D.K. (1994), *'Direct anthropogenic contributions to sea level rise in the twentieth century'*, Nature 367, 54-57.

- Santer, B.D., Wigley, T.M.L., Schlesinger, M.E. and Mitchell, J.F.B. (1990), *'Developing climate scenarios from equilibrium GCM results'*, Max Planck Institute für Meteorologie, Report no. 47, Hamburg, Germany.

- Schlesinger, W.H. (1991), *'Biogeochemistry: an analysis of global change'*, Academic Press, London.

- Schneider, S.H. and Boston, P.J. (eds.) (1992), *'Scientists on Gaia'*, MIT Press, Cambridge, MA, USA.

- Schwartz, S.E. (1988), *'Are global cloud albedo and climate controlled by marine phytoplankton?'*, Nature 336, 441-445.

- Schwartz, M. and Thompson, M. (1990), *'Divided we stand: redefining politics, technology and social choice'*, Harvester Wheatsheaf, New York, USA.

- Shaw, R., Gallopin, G., Weaver, P. and Öberg, S. (1991), *'Sustainable Development: A Systems Approach'*, Final Report submitted to the Secretariat of the United Nations Conference on Environment and Development, Conches/Geneva, Switzerland and to the Department of External Affairs and International Trade, Ottawa, Ontaria, Canada, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

- Shaw, R., Gallopin, G., Weaver, P. and Öberg, S. (1992), *'Sustainable Development: A Systems Approach'*, IIASA-Report SR-92-06, International Institute for Applied Systems Analysis, Laxenburg, Austria.

- Shearman, R. (1990), *'The meaning and ethics of sustainability'*, Environmental Management 14, no. 1, 1-8.

- Shults, W.D. and Beauchamp, J.J. (1972), *'Statistically based air-quality indices'*, In: Thomas, W.A. (ed.), 'Indicators of Environmental Quality', Plenum Press, London, U.K.

- Slaper, H., Elzen, M.G.J. den, Woerd, H.J. van der, and Greef, J. de (1992), *'Ozone depletion and skin cancer incidence: an integrated modelling approach'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM-Report no. 749202001, Bilthoven, The Netherlands.

- Soest, J.P. van, Kasteren, J. van, Jansen, F., Groen, A., Hartman, B. and Bakker, J. (1988), *'Reality of the model'* (In Dutch), Aramith Uitgevers, Amsterdam, The Netherlands.

- Sprent, P. (1988), *'Taking risks: the science of uncertainty'*, Penguin, London.

- Stern, P.C. Young, O.R. and Druckman, D. (eds.) (1992), *'Global environmental change: understanding the human dimensions'*, National Academy Press, Washington, D.C., U.S.A.

- Stigliani, W.M. (1988), *'Changes in valued "capacities" of soils and sediments as indicators of nonlinear and time-delayed environmental effects'*, Environmental Monitoring and Assessment 10, 245-307.

- Stigliani, W.M. (ed.) (1991), *'Chemical time bombs: definition, concepts, and examples'*, Executive Report no. 16, International Institute for Applied Systems Analysis, Laxenburg, Austria.

- Svensson, B.H. and Söderlund, R. (eds.) (1975), *'Nitrogen, phosphorus and sulphur - global cycles'*, SCOPE 7, John Wiley & Sons, New York, U.S.A.

- Thompson, M., Ellis, R. and Wildavsky, A. (1990), *'Cultural theory'*, Westview Press, Boulder, Colorado, U.S.A.

- Timmerman, P. (1986), *'Mythology and surprise in the sustainable development of the biosphere'*, In: Clark and Munn (eds.) , 'Sustainable development of the biosphere', IIASA-Book, Cambridge University Press, London, U.K.

- Turner, B.L., Kasperson, R.E., Meyer, W.B., Dow, K.M., Golding, D., Kasperson, J.X., Mitchell, R.C. and Ratick, S.J. (1990), *'Two types of global environmental change: definition and spatial-scale issues in their human dimensions'*, Global Environmental Change, December 1990, 14-22.

- Udo de Haes, H.A., Nip, M.I. and Klijn, F. (1991), *'Towards sustainability: indicators of environmental quality'*, In: Kuik, O.J. and Verbruggen, H. (eds.), In search of indicators of sustainable development, Kluwer Academic Publishers, Dordrecht, The Netherlands.

- United Nations Environment Programme (UNEP) (1992a), *'Chemical pollution: a global overview'*, Geneva, Switzerland.

- United Nations Environment Programme (UNEP) (1992b), *'The world environment 1972-1992: two decades of challenge'*, Tolba, M.K. and El-Kholy, O.A. (eds.), Chapman & Hall, London, U.K.

- United Nations Development Programme (UNDP) (1992), *'Human Development Report 1992'*, Oxford University Press, New York, USA.

- United Nations Development Programme (UNDP) (1993), *'Human Development Report 1993'*, Oxford University Press, New York, USA.

- United Nations Population Division (1991), *'Long Range World Projections: Two Centuries of Population Growth, 1950-2150'*, United Nations, New York, USA.

- Vernadsky, V. (1945), *'The biosphere and the noosphere'*, American Scientist 33, no. 1, 1-12.

- Vries, H.J.M. de (1989a), *'Sustainable resource use: an inquiry into modelling and planning'*, University Press, Groningen, The Netherlands.

- Vries, H.J.M. de (1989b), *'Perspectieven op duurzame ontwikkeling'*, Lucht en Omgeving, December 1989, 168-171.

- Vries, H.J.M. de, Fiddaman, T. and Janssen, R. (1993), *'Outline for a Global Environmental Strategic Planning Exercise (GESPE-project)'*, National Institute of Public Health and Environmental Protection (RIVM), RIVM Report no. 461502002, Bilthoven, The Netherlands.

- Wallace, R.R. and Norton, B.G. (1992), *'Policy implications of Gaian theory'*, Ecological economics 6, 103-118.

- Westbroek, P. (1991), *'Life as a geological force: dynamics of the earth'*, Norton, New York.

- Weterings, R. (1992), *'Strategic use of risk information'*, PhD.Thesis, Utrecht, The Netherlands.

- Wigley, T.M.L. and Schlesinger, M.E. (1985), *'Analytical solution for the effect on increasing CO_2 on global mean temperature'*, Nature 315, 649-652.

- Wigley, T.M.L. (1991), *'Could reducing fossil-fuel emissions cause global warming?'*, Nature 349, 503-506.

- Wigley, T.M.L. and Raper, S.C.B. (1992), 'Implications for climate and sea level of revised IPCC emissions scenarios', Nature 357, 293-300.

- Wigley, T.M.L. (1993), *'Balancing the carbon budget: implications for projections of future carbon dioxide concentration changes'*, Tellus 45B.

- Wollast, R., Mackenzie, F.T. and Chou, L. (1993), *'Interactions of C, N, P and S biogeochemical cycles and global change'*, NATO ASI Series I, vol. 4, Springer Verlag, Berlin, Germany.

- World Bank (1992), *'Development and the environment'*, World Development Report 1992, Oxford University Press, Oxford, U.K./Washington, U.S.A.

- World Bank (1993), *'Investing in health'*, World Development Report 1993, Oxford University Report, Oxford, U.K./Washington, U.S.A.

- World Commission on Environment and Development (WCED) (1987), *'Our Common Future'*, Oxford University Press, Oxford, U.K.

- World Health Organization (WHO) (1990), *'Potential health effects of climatic change'*, WHO/PEP/90.10, Geneva, Switzerland.

- World Health Organization (WHO) (1992), *'Our planet, our health: report of the WHO commission on health and environment'*, WHO, Geneva, Switzerland.

- World Meteorological Organization (WMO) (1992), *'Scientific Assessment of Ozone Depletion: 1991'*, WMO/UNEP, WMO Global Ozone Research and Monitoring Programme, Report no. 25.

- World Resources Institute (WRI) (1993), *'The 2050 project: transition to sustainability in the next century'*, WRI and Santa Fe Institute, Washington D.C., USA.

- Young, O.R. (1964), *'A survey of general systems theory'*, General Systems IX.

- Young, R.W., Carder, K.L., Betzer, P.R., Costello, D.K., Duce, R.A., DiTullio, G.R., Tindale, N.W., Laws, E.A., Uematsu, M., Merrill, J.T. and Feely, R.A. (1991), *'Atmospheric iron inputs and primary productivity: phytoplankton responses in the north Pacific'*, Global Biogeochemical Cycles 5, no. 2, 119-134.

- Zweers, W. (1989), *'Grondhoudingen ten opzichte van de natuur'*, Heidemijtijdschrift, Juni 1989, 74-80.