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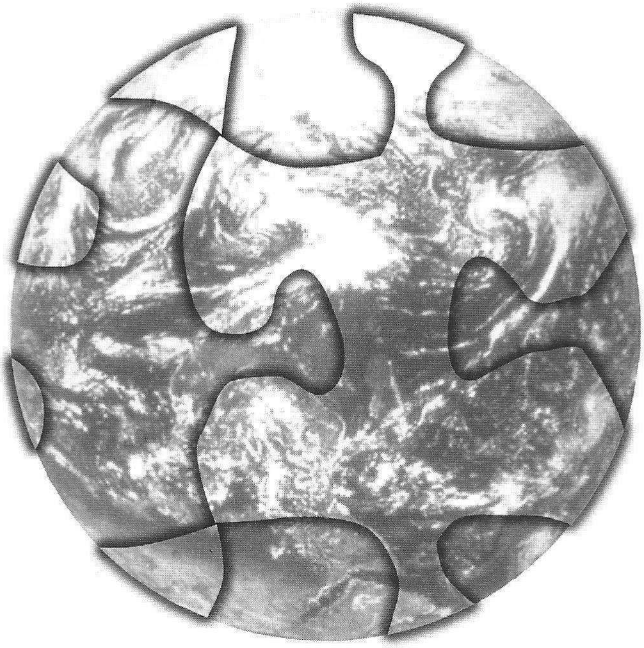
The TARGETS model



"In theory, theory and practice are the same. In practice, they aren't."

3 THE TARGETS MODEL

Jan Rotmans, Marjolein B.A. van Asselt, Bert J.M. de Vries, Arthur H.W. Beusen, Michel G.J. den Elzen, Henk B.M. Hilderink, Arjen Y. Hoekstra, Marco A. Janssen, Heko W. Köster, Louis W. Niessen, and Bart J. Strengers

When tackling a subject as complex as global change and sustainable development, it is essential to be able to 'frame the issues'. This was one of the main reasons for developing the TARGETS model, an integrated model of the global system, consisting of metamodels of important subsystems. In this chapter we introduce TARGETS. Building on the previous chapters, we elaborate on the possibilities and limitations of integrated assessment models. Some of the key issues discussed are aggregation, model calibration and validation, and dealing with uncertainty.

3.1 Introduction

One of the main tools used in integrated assessment of global change issues is the Integrated Assessment (IA) model. This chapter introduces such an integrated model, TARGETS, which builds upon the systems approach and related concepts introduced in Chapter 2. Previous integrated modelling attempts either focused on specific aspects of global change, for instance the climate system (IPCC, 1995), or consisted merely of conceptual descriptions (Shaw *et al.*, 1992). We have tried to go one step further, linking a series of cause-effect chains of global change. Although we realise the shortcomings in our current version of the TARGETS model, we felt there was a need to present our model to a wide audience. We first give some advantages and limitations of IA models. Next, we discuss issues of aggregation, calibration, validation and uncertainty. We proceed with a brief description of the five TARGETS submodels which coincides with the PSIR concept and the vertical integration as introduced in Chapter 2. A more detailed description of these submodels is given in Chapters 4 to 8. Then, we discuss the horizontal integration of the submodels and the cross-linkages between them.

3.2 Integrated assessment modelling

Background

Current projects in IA modelling build on a tradition started in the early 1970s by the Club of Rome (Meadows *et al.*, 1972). This first generation of IA models, the so-called global models, focused on resource depletion, population and pollution. Over the past twenty years, numerous global models have been built (Brecke, 1993; Toth *et al.*, 1989), most of which were rather complicated, highly aggregated and partially integrated. The next generation of IA models addressed specific environmental issues. Examples are the RAINS model developed in the early 1980s (Hordijk, 1991), the IMAGE model (Alcamo, 1994; Rotmans, 1990), the DICE model (Nordhaus, 1992), the PAGE model (Hope and Parker, 1993) and the ICAM1.0 model (Dowlatabadi and Morgan, 1993a; 1993b). The development of a new generation of IA models is now under way. They focus on and benefit from recent findings in such divergent fields as ecosystem dynamics, land-use dynamics and the impacts of climate change on human health and water resources (Rotmans *et al.*, 1996).

It is important to point out that IA models of global change are meant to frame issues and provide a context for debate. They analyse global change phenomena from a broad, synoptic perspective. One of the challenging aspects of building such a model is to find the right balance between simplicity and complexity, aggregation and realism, stochastic and deterministic elements, qualitative depth and quantitative rigour, transparency and adequateness. It is essential to keep in mind the limitations of models like TARGETS and to recognise the kind of issues and questions that can *not* be addressed or are *beyond* the scope of the model.

Value and limitations

Any attempt to fully represent the human and environmental systems and their numerous interlinkages in a quantitative model is doomed to failure. Nevertheless, we maintain that even a simplified but integrated model can provide a useful guide to global change and sustainable development and complement highly detailed models of subsystems that cover only some parts of the phenomena. Among the major advantages of IA models are:

- *exploration of interactions and feedbacks:* explicit inclusion of interactions and feedback mechanisms between subsystems can yield insights that disciplinary studies cannot offer. It can indicate areas of promising new and interdisciplinary research, and also of the potential range and magnitude of global phenomena and of the scale of the interventions needed to counteract or mitigate undesirable aspects;
- *flexible and rapid simulation tools:* the simplified nature and flexible structure of submodels in IA models permit rapid prototyping of new concepts and scientific insights and the indicative simulation and evaluation of long-term scenarios and strategies;
- *coherent framework to structure present knowledge:* by consistently representing and structuring current knowledge, major uncertainties can be identified and ranked. Crucial gaps in current scientific knowledge and weaknesses in discipline-oriented expert models can be identified.
- *tools for communication:* because of their 'umbrella' function these models can be outstanding tools to communicate global change phenomena within the scientific community and between scientists, the public and policy makers and

analysts. Their simplicity enables a transparency which is one of the preconditions for effective communication and debate.

Obviously, IA models also have limitations and drawbacks. Some of these are just the negative side of the above-mentioned advantages; others have to do with current limitations in computer modelling. In our view, the most important ones are:

- *high level of aggregation:* many processes within the human-environment system occur at a micro level, far below the spatial and temporal aggregation level of current IA models. Parameterisations are used to mimic these processes at the scale and aggregation of the model. This may cause serious errors, as is discussed in the next section;
- *inadequate treatment of and cumulation of uncertainties:* by trying to capture the entire cause-effect chain of a problem, IA models are prone to an accumulation of uncertainties. This, together with the variety of types and sources of uncertainty that IA models comprise, makes an uncertainty analysis for integrated frameworks rather difficult;
- *absence of stochastic behaviour:* most IA models assume that real-world processes can be described in terms of continuous, deterministic mathematical equations. In reality, many processes are stochastic by nature. The resulting extreme conditions may exert significant influence on the overall long-term dynamic behaviour of the system; hence they may play a decisive role even though their occurrence has a low probability;
- *limited calibration and validation:* one of the most vexing aspects of modelling a complex, global system is the absence of real-world observations which allow for rigorous model validation. The high level of aggregation, the dynamic, long-term nature of the model and the high level of complexity of the subsystems and their interactions often implies an inherent lack of empirical variables and parameters. If one can identify relevant data, the available sets are often too small and/or unreliable to apply a thorough calibration and validation procedure. We come back to this in the next section.

In designing, constructing and using a model like TARGETS, there are a number of pitfalls. One of them, on the side of the designers, is that familiarity with particular formalisms, e.g. with optimisation techniques, may lead to an 'availability bias' which imposes restrictions on how the problem is formulated and solved. Another pitfall on the side of the user is to consider the IA model as a 'truth machine' rather than as a tool to understand the issues (Wynne and Schackley, 1994). This easily leads to vigorous but rather pointless debates, as the history of the World3-model has made clear (Freeman, 1973; Peccei, 1982; Meadows *et al.*, 1991).

Integrated models of global change attempt to offer an overall picture of those processes that are causally relevant for understanding global change phenomena.

They are by no means comprehensive. After all, there are no entirely reliable models of the underlying processes, and the integration effort inevitably simplifies such models. In our view, the interpretative and instructive value of an IA model is far more important than its predictive capability.

Model set-up

To describe and model the complex global system, we constructed a set of metamodels which have been linked and integrated. This resulted in the **TARGETS** model: **T**ool to **A**ssess **R**egional and **G**lobal **E**nvironmental and Health **T**argets for **S**ustainability. It consists of five submodels: the population and health, the energy submodel, the land and food, and the water submodel, and the submodel describing the biogeochemical element fluxes ('cycles'). These submodels are interlinked and related to the economic scenario generator. Within each subsystem – and submodel – we distinguish pressure, state, impact and response modules. These represent a vertically integrated cause-effect chain. From the point-of-view of horizontal

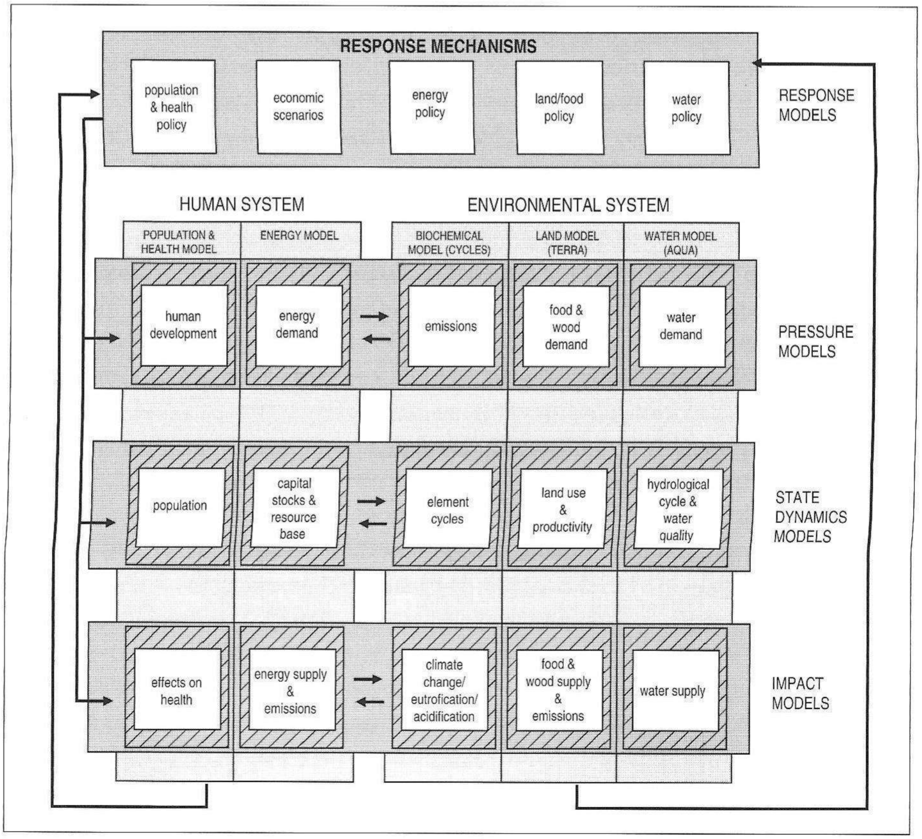


Figure 3.1 Modular set-up of the TARGETS model.

integration, the TARGETS model can be conceived of as pressure, state, impact and response components in each of which the five submodels are linked. Vertical and horizontal integration aspects lead to a representation of the TARGETS model as shown in *Figure 3.1*.

Although the main advantage of the TARGETS model is its integrated character, each submodel has been constructed and can be used independently. Variables which link the submodels are then introduced as exogenous inputs. A first argument for this is that the submodels had to be constructed and implemented in a stand-alone context to allow comparison with other modelling efforts (expert models) in the field. It is also necessary for model calibration and validation and it makes it possible to address submodel-specific issues. A second argument is that the added value of integration can only be evaluated against a background of non-integrated simulation experiments. Moreover, only a thorough understanding of individual submodel behaviour can lead to insight into the consequences of specific links between the various submodels. In Chapter 11 we outline the way in which integrated and non-integrated model experiments have been set up. Detailed simulation experiments with the stand-alone versions of the submodels are presented in Chapter 12 to 16. Before giving a brief description of the various submodels, we deal with a few issues which are relevant to the design, construction and use of a model like TARGETS.

3.3 Aggregation, calibration and uncertainty

Aspects of aggregation

The elements of a system usually have a wide variety of characteristics, among them location in space. They are involved in all kinds of dynamic processes, often with quite different time-scales. An additional problem is that these models consist of a variety of submodels, each of which differs with respect to feasible and desirable levels of aggregation, complexity, and spatial and temporal resolution. Hence, aggregation is a crucial issue in model design. Which classes are distinguished and which spatial and temporal resolution are chosen for model variables?

In general, the answer to the above question is – or should be – based on the purpose of the model. The TARGETS model has been set up as a generic framework so that, in principle, it can be applied at different levels of aggregation. Our first objective is to develop a quantitative, transparent tool to explore the long-term dynamics of the world system and present 'the larger picture'. Hence, we have implemented the model in the first instance for the world as a whole. At this high aggregation level one can easily include the more speculative interactions between the human and environmental system and search for their relevance in the context of global change. At lower levels of aggregation, this is often a tedious task.

The different levels of temporal and spatial aggregation give the integrated model an 'hourglass' structure. For example, economy-energy models usually operate in

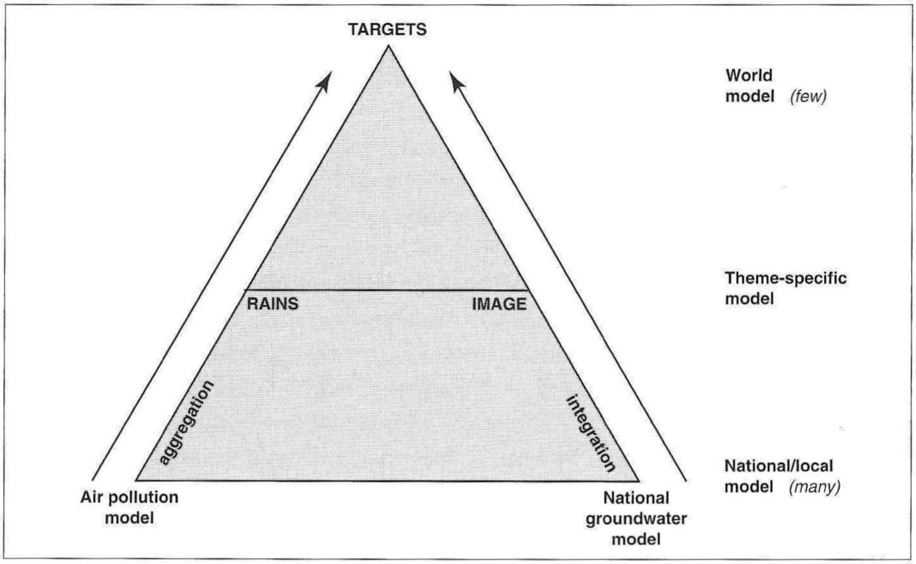


Figure 3.2 Pyramid of models according to different levels of aggregation and integration.

multi-year time steps with national or regional political boundaries. However, atmospheric chemistry models operate in small time steps on a small scale, while climate models have a relatively coarse spatial resolution but run at a fine temporal resolution. Ecological impact models generally require data at fine spatial resolutions but their time resolution varies greatly, from one day to a season or a year. The submodels of the TARGETS model have been set up as generic metamodels which can be calibrated and applied at several levels of temporal and spatial aggregation. Applying them at the global level, as in the TARGETS1.0 model[1], demands a coordinated choice with regard to time-scales, spatial scales and attributes. In the TARGETS1.0 model, both the distributions on a scale below the temporal resolution and the heterogeneities below the spatial resolution level of the model are dealt with by introducing classes and spatial distribution functions.

In *Figure 3.2* different types of models developed by or used at RIVM are categorised along the vertical axis of a pyramid, which indicates the level of aggregation and integration. The TARGETS1.0 model is placed on top of this pyramid, because it has the highest level of aggregation and integration. The high aggregation level makes it an appropriate tool to frame issues regarding global change and sustainable development but it cannot help in formulating what these mean at the regional or local level of a city or a country. Theme-specific integrated

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[1] Henceforth, we refer to the current, global version of the TARGETS model as the TARGETS1.0 model.

Genericity of metamodels

In setting up the metamodels which provide the building blocks for the integrated model, we have attempted to model the subsystems as generic (or universal) as possible. Genericity, here, means that the model represents the subsystem dynamics in such a way that it is a valid description at different levels of spatial and temporal detail. Hence, concepts, hypotheses and theories used should be applicable at different levels of spatial aggregation and for different regions in different periods. Such a genericity is only possible up to a certain point. One limitation is that aggregate global, slow dynamics may be driven by local, fast processes in a way that cannot be covered in a metamodel – and yet may turn out to be crucial. In fact, the question of genericity of certain relationships is one of the key uncertainties we are faced with.

Because a highly aggregated approach like in the TARGETS1.0 model lacks specific regional/ local dynamics, genericity of (sub)models can only partly be realised. This holds for all three levels of complexity shown in *Figure 3.2.* For example, for a commodity like oil in an increasingly free trade context, depletion and technological innovation with regard to exploitation of the resource base can be dealt with adequately at the global level.

However, modelling the import and export flows of oil and their impacts on economic performance requires desaggregation to the level of economically, politically and institutionally relevant actors and dynamics. In our research we have explored the validity domain of several submodels by implementing and parameterising them at lower aggregation levels, e.g. a river basin for water and a country for population and energy. Through these applications we have gained an understanding of the problems one may expect upon aggregating a metamodel derived from local observations to a globally aggregate description.

models such as RAINS and IMAGE, with more spatial and process detail, are better equipped for such questions, but even these models cannot be used to provide detailed spatial descriptions or specific policy proposals. For such purposes, one has to rely on expert models of small populations, environmental compartments and the like which are also the basis for the metamodels. Many of such models are being used for the Dutch National Environmental Outlook (RIVM, 1994). In the process, one may gain scientific quality but lose relevance because the changes in the external variables dominate the dynamics of the modelled system. The actual choices with regard to spatial aggregation in the global TARGETS1.0 model are presented in *Figure 3.3.*

Time

The various subsystems which make up the larger system described by the TARGETS1.0 model are characterised by dynamics with specific time-scales. Economic processes and the related pace of technical change are to a large extent governed by the operational lifetime of the different capital stocks. Within the food and water supply system, similar time-scales are relevant but they are imbedded in the much slower dynamics of processes like soil erosion and groundwater recharge. For the biogeochemical element cycles relevant time-scales range from months for atmospheric processes to hundreds of years for the dynamics of oceans. The time step used within the TARGETS1.0 model is one year, although in some modules a smaller time-step is used. Some physical processes require a time step of one month, such as the hydrological processes in the water submodel (Chapter 6), or of one season, e.g. the biogeochemical processes in the cycles submodel (Chapter 8). The time horizon for the TARGETS1.0 model spans two centuries. All simulation experiments start at the beginning of this century, in the year 1900, which can be thought of as the beginning of the industrial era. The simulations end in the year 2100, which is three to four generations away from people living today. With this time horizon, we look as far ahead as we look back.

Space

In all subsystems but especially in those which deal with the reservoirs and flows of elements and the dynamics of land and water use, there is a distinct spatial heterogeneity. We utilise aggregated data and processes derived from models such as

Spatial categories in the TARGETS submodels

In the land and food submodel (TERRA) spatial heterogeneities are introduced by disaggregation into specific classes for soil, climate and land use. Seven land-cover types have been distinguished. 'Degraded land' is not shown in *Figure 3.3,* because it is negligible in 1900. Next, the land-cover types have been disaggregated further into the following classes (Chapter 7):

- two economic or temperature zone classes (developed and developing);
- three length of growing period (LGP) classes;
- three inherent soil productivity (Q) classes.

In the water submodel (AQUA), a total of ten water reservoirs are distinguished, three of which are groundwater stocks (for more details, see Figure 6.5). The water reservoirs which are most important for the biosphere: fresh surface water, soil moisture, biological water and renewable fresh groundwater, are a small proportion of the total. In the element cycles submodel (CYCLES), we use the same classes as in the TERRA submodel for the terrestrial biosphere. The oceans are modelled as seven separate layers. The atmosphere is represented as a single, uniformly mixed reservoir.

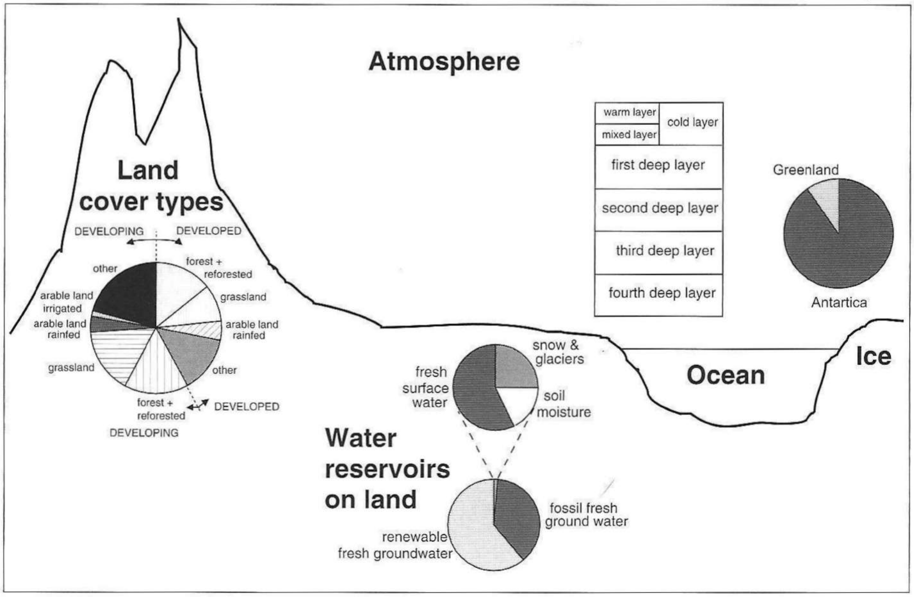

Figure 3.3 Schematic overview of the initial disaggregations used in the TARGETS1.0 model.

the IMAGE2.0 model (Alcamo. 1994) and from the HYDE data base (Klein Goldewijk and Battjes. 1995). Details are given in *Figure 3.3* and Chapters 4 to 8.

Other attributes

One also has to aggregate with respect to reservoir attributes other than location in time and space. Ideally, this should be based on an understanding of the system at the micro-level. For example, if the diet or provision of clean water is below the level of people's aspiration, this induces behaviour to improve the situation. The resulting actions are inherently non-equilibrium processes, which influence the state of the local system and thereby lead to impacts and responses. The crucial question here is how to scale up and down between the macro and micro levels. For example, with regard to demographic developments, there is extensive knowledge of the determinants of fertility and diseases at the individual level. What is usually done is to combine this knowledge in clusters (such as disease clusters and population cohorts) and in aggregated indicators (such as the total fertility rate and disability-adjusted-life-years), which can be used at the level of populations.

In practice, the choice to disaggregate will depend on the model objectives and the kind of questions the model should be able to address. In the TARGETS1.0 model, the human population is disaggregated into five age cohorts and a corresponding number of disease burden classes. Fuel producing capital is represented by four distinct capital stocks, based on the distinction between solid, liquid and gaseous fuels. For water quality, four classes have been formulated. Other causative factors, like food availability, access to safe water and income distribution for the human population, are not related to subclasses. More details are given in Chapters 4 to 8.

Calibration and validation

There are many definitions and interpretations of the terms calibration and validation. Complete calibration and validation of models for a system as large and complex as the Earth is impossible, because the underlying systems are never fully closed (Oreskes *et al.*, 1994). Within the TARGETS1.0 model calibration is defined as a procedure which gauges the most important parameters in such a way that the model simulations come close to the observations.

Validation is defined here as a procedure for testing the adequacy of a mathematical model. There are two types of validation. The first is practical validation. It is done by comparing model outcomes with other model-based research or simulating a period different from the one used for calibration. All submodels have been calibrated for the period 1900-1990 and have, in a limited way, been practically validated using parameter sensitivity analyses (Chapters 4 to 8).

A second type of validation is conceptual validation, which tests whether the concepts and laws used to represent the system under consideration are interpreted and formulated correctly. Conceptual validation of the TARGETS1.0 model requires that each submodel should be scientifically valid in the sense that the model structure and dynamic behaviour over the period 1900-1990, or for a shorter period if there are data limitations, reflect prevailing insights about the modelled subsystems. One way of conceptually validating the submodels is by comparing them with expert models which they are supposed to represent at the metalevel. 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 den Elzen (1993b). The CYCLES submodel has been validated by comparing it with the Terrestrial Ecosystem Model (Melillo *et al.*, 1993), the GLOCO model (Hudson *et al.*, 1994), and a general nitrogen and carbon cycle model (den Elzen *et al.*, 1997; Rastetter *et al.*, 1991). The health module of the population and health submodel has been compared with the Harvard incidence-prevalence model (Murray and Lopez, 1994; World Bank, 1993) and the disease module with a similar model for the Netherlands (Barendregt and Bonneux, 1992). For the other submodels, expert models have also been used for comparison and validation.

A second conceptual validation approach is the so-called Strategic Cyclical Scaling (SCS) method proposed by Root and Schneider (1995). This involves continuous cycling between large and small-scale assessments. Such an iterative scaling procedure implies that for a specific submodel the global version is disaggregated and adjusted for a specific region, country or river basin. The new insights are then used to improve the global version, after which implementation for another region, country or river basin follows. Applying the SCS approach at the level of submodels of TARGETS, case-studies have been carried out in order to validate the claim that the generic metamodels cover the crucial processes. With regard to energy, a developing country has been chosen (India) as well as a country which portrays the transition pathway in developed countries (USA). With the population and health submodel, case-studies with parts of the submodel have been done for India (Hutter *et al.*, 1996), China, Mexico (van Vianen *et al.*, 1997) and the Netherlands. For the water submodel, the Ganges-Brahmaputra (Hoekstra, 1995) and the Zambezi (Vis, 1996) basins have been chosen.

Conceptual validation can also be performed by involving experts. First, submodels and their modules have been developed in cooperation with other research institutions and universities. Besides, experts in small-scale, detailed models in a specific region or country have been asked to analyse the model results and to validate regionalised model results for a specific world region against regional data subsets. This has, for example, been done for the fertility component of the population and health submodel in a three-day workshop organised by the Population Research Centres of the University of Kerala (India) and the University of Groningen, in which leading Indian demographers participated (Hutter *et al.*, 1996). In cooperation with the Dutch Ministry of Housing, Physical Planning and Environment (VROM), a workshop was held in which energy experts and policy analysts were asked to give feedback on the energy submodel (de Vries and Janssen, 1996). In the last stage of the project, the submodels and the TARGETS1.0 model as a whole were reviewed by a total of over fifty national and international experts. The TARGETS1.0 model as a whole has been calibrated against historical time-series for major outcomes and in interaction with the stand-alone experiments with the submodels (Chapter 11). There has not yet been a systematic and rigorous conceptual validation.

Uncertainty analysis

Exploring future global change and its consequences for human society is beset with many uncertainties. These may be scientific in nature, arising from incomplete knowledge of key physiological, chemical and biological processes and related to the first level of complexity (Section 2.4). Many are of a socio-economic nature – related to people's behaviour – and reflect inadequate knowledge with respect to the second level of complexity. Finally, uncertainties also enter at the third level of complexity: the level at which norms and values are shaped and reinforced.

Uncertainty analysis should not be confused with sensitivity analysis, although both are essential if one wishes to gain insight into the reliability of models. We adopt the definitions given by Janssen *et al.* (1990). Sensitivity analysis is the study of the influence of variations in model parameters and initial values on model outcomes. Uncertainty analysis is the study of the uncertain aspects of a model and the influence of these uncertainties on model outcomes. Sensitivity analyses are useful to indicate which parameters represent crucial assumptions in the model. In order to indicate reliable confidence bounds, the uncertainty analysis should be comprehensive, which means that as many different sources of uncertainty as possible need to be considered. To this end we use classical uncertainty analysis but we also introduce the idea of model routes to deal with uncertainties arising from disagreement among experts. A perspective-based (or multiple) model route is a chain of biased interpretations of the crucial uncertainties in a model. To invest the model routes with coherence, we use cultural perspectives in order to make choices with regard to controversial model parameters and relations (Chapter 10). This methodology encourages us to make subjective judgements explicit and to consider at least more than one perspective. In this way, differences in future projections can be understood as the outcome of divergent views and valuations, instead of merely low, high and medium values. This approach also facilitates the interpretation of fundamental uncertainties in terms of risk.

3.4 Description of the TARGETS1.0 submodels

Vertical integration

One distinction within the TARGETS framework is between the human system and the environmental – or natural – system. The former mainly focuses on demographic and health aspects of the human population and the provision of food, water and energy. The latter comprises a variety of flows of natural and man-made substances between the atmosphere, the ocean and the terrestrial biosphere. Of course, the distinction is not sharp. A difficulty is to disentangle the anthropogenic changes from the changes which are part of the natural evolution of environmental (sub)systems. We conceptualise human interventions as superimposed on a 'steady state' of environmental subsystems, ignoring for example long-term evolutionary changes in ecosystems. Ecosystem-related processes only feature in the TARGETS1.0 model as part of a highly aggregated description of aquatic and terrestrial ecosystems, with indicators such as water quality and land-use and land-cover distributions. We now proceed with a description of the TARGETS1.0 model. In our terminology, a model consists of submodels, while submodels in turn have modules as building blocks. Vertically, the TARGETS1.0 model consists of five submodels, each representing the cause-effect relationship for a particular theme of global change, and an economic scenario generator. *Figure 3.4* in section 3.5 shows the different submodels and their interactions.

The Population and Health submodel (Chapter 4)

The objective of the population and health submodel is to simulate changes in morbidity and mortality levels under varying social, economic and environmental conditions. Based on a number of socio-economic and environmental determinants, it simulates the population size and the health of the population in terms of both life expectancy and healthy life expectancy. The submodel consists of three modules: a fertility module, a disease module and a population state module.

- A *pressure* module represents the socio-economic and environmental factors that determine the fertility level, the health risks and the causes of illness and death. The socio-economic pressures are socio-economic status and female literacy level, while the environmental pressures are food and water availability, global climate change and changes in UV-B radiation;
- The *state* module consists of a number of reservoirs, which differ with respect to age, sex and health. Births are determined in the fertility module. The disease module calculates disease-specific morbidity and mortality. In the population state module, the calculated birth and death figures are used to simulate the population size distributed over five age groups and between males and females;
- An *impact* module represents the quantitative and qualitative aspects of demographic developments. The quantitative aspect reflects the size and structure of the total population. We consider the disease-adjusted life expectancy as one of the impacts representing the quality of the population;
- A *response* module includes policy responses regarding fertility behaviour, investments in health care and some other broad policy options. Health services can be allocated among primary and secondary prevention and curative care.

The energy submodel TIME (Chapter 5)

The role of the energy submodel is to simulate the demand and supply of commercial fuels and electricity, given levels of economic activity, and the associated emissions. It consists of five modules: Energy Demand, Electric Power Generation, and three Fuel Supply modules (Solid, Liquid, Gaseous).

- The *pressure* module simulates demand for commercial fuels in five separate economic sectors: residential, commercial/services, industrial, transport and other. Heat and electricity end-use demand are calculated from economic activity levels.
- The *state* module consists of the Fuel Supply modules and the Electric Power Generation module. The key state variables are the capital stocks used to produce energy and the fossil fuel resources. Important features in the Fuel Supply modules are resource depletion, penetration of commercial biofuels and learning-by-doing. The Electric Power Generation Model simulates the generation of electricity by utilising thermal, non-thermal and hydropower generating capital stocks.
- An *impact* module generates yearly emissions of six energy-related gases, CO_2 being the most important one. Land requirements for biofuel production are calculated.
- A *response* module makes it possible to include policy measures which influence energy efficiency and fuel substitution. Among them are the hydropower expansion path and research, development and demostration (RD&D) programmes with respect to biofuel, and non-thermal electricity generation.

The water submodel AQUA (Chapter 6)

AQUA takes into account the functions of the water system that are considered most relevant in the context of global change. Human-related functions considered are the supply of water for the domestic, agricultural and industrial sectors, hydroelectric power generation and coastal defences. Ecological functions taken into account are natural water supply to terrestrial ecosystems and the quality of aquatic ecosystems.

- A *pressure* module describes both socio-economic and environmental pressures on the water system. Total water demand is calculated as a function of population size, economic activity levels, demand for irrigated cropland and water supply efficiencies. The model includes the option of treatment of waste water before discharge;
- The *state* module simulates hydrological fluxes and changes in fresh water quality. The hydrological cycle is modelled by distinguishing ten water reservoirs, some of which are fresh surface and ground water, atmospheric water and oceans (*Figure 3.3*). The water flows between these reservoirs are simulated. Water quality, distinguished in four classes, is described in terms of nutrient concentrations;

- An *impact* module describes the impacts of water system changes on the environment and human society. It describes the performance of the various functions of the water system. The actual water supplies to households, agriculture and industry are calculated, as are the generation of hydroelectric power and the impact of a sea-level rise on the world's coast lines;
- A *response* module enables the user to model human response to negative impacts in the form of water policy measures comprising financial (e.g. water pricing), legislative and managerial measures.

The land and food submodel TERRA (Chapter 7)

The land and food submodel TERRA simulates food supply and demand, and land-use changes in relation to the element fluxes modelled in the CYCLES submodel. It is designed to offer understanding of human pressures on the global land and food system, and of potential impacts of changing food supply conditions on human health.

- A *pressure* module describes the demand for food resulting from the demand for vegetable and animal products, for tropical wood (excluding fuelwood). Demand is calculated as a function of economic activity and population size. Environmental pressures considered in the TERRA submodel are water availability for irrigation and climate change;
- The *state* module simulates changes in the physical state of the Earth's land surface in terms of changing land use and changes in the inputs and outputs of food production as a function of environmental and socio-economic pressures and land policies. The three main modules in the state system are: land-use/land-cover dynamics, erosion and climate change, and food and feed supply. Several land classes are distinguished (*Figure 3.3*);
- The *impact* module describes the impacts of food shortages which are a pressure in the Population and Health submodel. It also calculates changes in the forested and natural grassland areas – which are crude proxies for the loss of natural ecosystems – and loss of arable land through degradation;
- A *response* module gives various policy options: land clearing, expansion of the area of irrigated arable land, increased use of fertilisers and other inputs on rainfed arable land, land or soil conservation, and reforestation.

The element submodel CYCLES (Chapter 8)

The CYCLES submodel describes the cause-effect chain of the global biogeochemical element cycles. It links the anthropogenic pressures in the form of emissions and land and water use to the flows of elements within and between the various compartments. The basic elements C (carbon), N (nitrogen), P (phosphorus) and S (sulphur) are simulated because of their important role in global change phenomena. Some other chemical substances are also explicitly modelled. There is no separate *response* module. The anthropogenic pressures can be counteracted by measures incorporated in the energy, water and land response modules.

- The *pressure* module describes the driving forces underlying anthropogenic interference with the element cycles: emissions and flows of compounds of C, N, P and S from the energy and industrial sector, land-use changes, biomass burning, erosion, fertiliser use, harvesting, and water flow changes;
- A *state* module models the physical, chemical and biological fluxes of the basic elements and other chemicals within and between the atmosphere, terrestrial biosphere, lithosphere (soils), and hydrosphere (fresh surface waters and oceans). The atmosphere, the oceans and the terrestrial biosphere have been disaggregated into specific classes (*Figure* 3.3);
- The *impact* module describes the impacts of the changes in the fluxes of basic elements and other chemical substances on the global environment. It has two modules: for climate and ozone. The most important one, the climate assessment module, simulates the radiative forcing and global-mean temperature changes due to changes in concentrations of greenhouse gases and sulphate aerosols.

The economic scenario generator

Apart from these five submodels, we use a model of the economy. It is merely a transparent mechanism to reproduce exogenous Gross World Product (GWP) trajectories. It is referred to as the 'economic scenario generator'. GWP is taken to be the sum of consumption, value added in industry and services, and the monetary value of food production. Part of industrial output is used to satisfy the investment requirements for the provision of food, water and energy. In this way the scenario generator provides us with a simple money accounting framework.

We discriminate between two capital stocks: industrial capital and service capital. Industrial capital generates industrial output, which is partly reinvested in new industrial capital. The remainder is invested into various sectors: food, water, energy, and health and other services. The investment categories are: irrigation, agricultural inputs (fertiliser in particular), land clearing and conservation, domestic and industrial water supply, waste-water treatment, fossil fuel supply, electricity supply and energy efficiency. Health services investments are taken from service output and subdivided into preventive and curative services. Investments required to satisfy the derived demands for food, water and energy are fully met. Given a presumed relationship between the growth of industrial output and of service output, the remainder is assumed to be for consumption. We use the resulting – and 'maximum allowable' – growth rate in the per capita consumption as one of the indicators of welfare and sustainable development.

There are two reasons why we have opted for such a simple approach towards the economic system. The first is that we wish to avoid major controversies in the field of economic modelling dominating the results of the TARGETS1.0 simulation experiments. The second reason is more mundane: we lacked the expertise and resources to incorporate an economic model which would simulate at least the key factors in long-term economic growth in a satisfactory way. However, the first steps towards cooperation with economic researchers have been made (CPB, 1992; Duchin and Lange, 1994).

Limitations

After this brief description of the submodels, some of the limitations of the TARGETS1.0 model can be seen more clearly. Because economic developments are very important factors in assessing global change, the simple representation of economic processes is a serious limitation. The part of the investment goods, for example, which is dealt with in explicit detail (food, water, energy) is at most one quarter to one third of total world economic output. Important response mechanisms within the human system which determine the overall pattern of economic activities, such as changes in capital and labour productivity and in interest rates, are absent. Another omission is that the impacts of global change on the functioning of the world economy are not modelled explicitly. Feedbacks from for instance climate change on the productivity level in the industrial and service sector may have significant consequences for the overall behaviour of the system. With regard to ecosystems, the model gives at best a rough impression of ecosystem health in the form of indicators such as water quality and the size of the area covered by original vegetation. Ecological processes which may occur in response to changing element fluxes, for example, are not modelled. Hence, the issue of biodiversity is beyond the scope of the present model version. Due to the chosen aggregation level, the causes and impacts of such processes as immigration, urbanisation, wars and refugee movements are implicitly dealt with.

Horizontal integration

One can also focus on the horizontal integration. From that point-of-view, the TARGETS1.0 model can be subdivided into linked pressure, state, impacts and response components. The *pressure* modules are intended to chart the driving forces behind the increasing worldwide pressure on the environment and human society. The *state* modules describe the biogeochemical status of the environmental system and the social and economic status of the human system. The *impact* modules can be divided into three types of interrelated impacts. First, there are the effects of anthropogenic stresses on the environment which affect water availability, water quality, erosivity and climate conditions. A second type of impact is the influence of global change on human health, both direct and indirect. Direct effects relate to changes in disease determinants; indirect effects occur through deterioration of the world food and water supply. A third type of impact are the socio-economic effects of large-scale environmental problems. These show up in rising costs for food, water and energy. They can also take the form of direct losses of land or capital.

goods, which are however not simulated in the present version. Although only partly implemented, there is also an assessment of vulnerability in the form of people and capital at risk and the costs of flood protection for the coastal defence sector.

With regard to the *response* modules, it should be noted that there are many endogenous responses within the model, for instance the decision to invest in electric power plants if electricity demand grows or to increase agricultural inputs if food demand grows. This shows up as a change in costs or prices, which can be viewed as a model-endogenous response which in turn affects the system's behaviour. In a more narrow sense, the response components contain model variables which can be used to simulate exogenous interference with the way in which the system develops in a model experiment. These variables are information variables, unlike the largely physical stock and flow variables within the pressure, state and impact components. The response variables cover a variety of policy-related actions, among them financial incentives, regulation, information programmes and RD&D programmes (Rayner, 1991). Financial incentives are only implicitly included. Regulation encompasses legislation and rules, designed to control the activities of citizens and/or institutions. Important in the TARGETS1.0 model are the abortion legislation, water pricing and imposition of a carbon tax. Public information programmes are designed to alter the behaviour of citizens. Three important response variables relate to the representation of programmes to improve education, especially of women, of mass communication programmes for population policy, and of information campaigns devoted to the efficient use of water. The fourth one, RD&D programmes, involve policy incentives with regard to energy and water efficiency, biomass, and non-thermal electricity production.

3.5 Submodel linkages in the TARGETS1.0 model

Many integrated models use outputs from one submodel in the form of complete time-series as inputs for another submodel. This is a quite limited type of integration. In a model simulation experiment with the TARGETS1.0 model, data flow between the different submodels in each time step, which allows instantaneous simulation of interactions between submodels. The interactions between the submodels are shown in *Figure 3.4*. We briefly describe these interactions here; a more detailed description is given in the Chapters 4 to 8.

Gross World Product (GWP) is exported by the economic scenario generator to all submodels, except CYCLES. Sectoral GWP, or GWP per capita if combined with population size as exported by the Population and Health submodel to all other submodels, determines energy, food and water demand in the Energy, TERRA and AQUA submodel, respectively. In the Energy submodel, two components of GWP, i.e. value added services and value-added industry, are the drivers for energy demand in the five sectors. In AQUA, industrial output is used to determine industrial water demand. In the Population and Health submodel, GWP per capita has an effect on health and life expectancy. The required investments from the Energy, TERRA and AQUA submodel, and the health services demand from the Population and Health submodel, are accounted for in the economic scenario generator.

There are a number of outputs from the Energy submodel to the other submodels. The combustion of fossil fuels generates emissions of CO_2, SO_2, NO_x, N_2O and CH_4 which are inputs for the CYCLES submodel. The land requirements for biofuels are supplied to the TERRA submodel and allocated to grassland and arable land. The

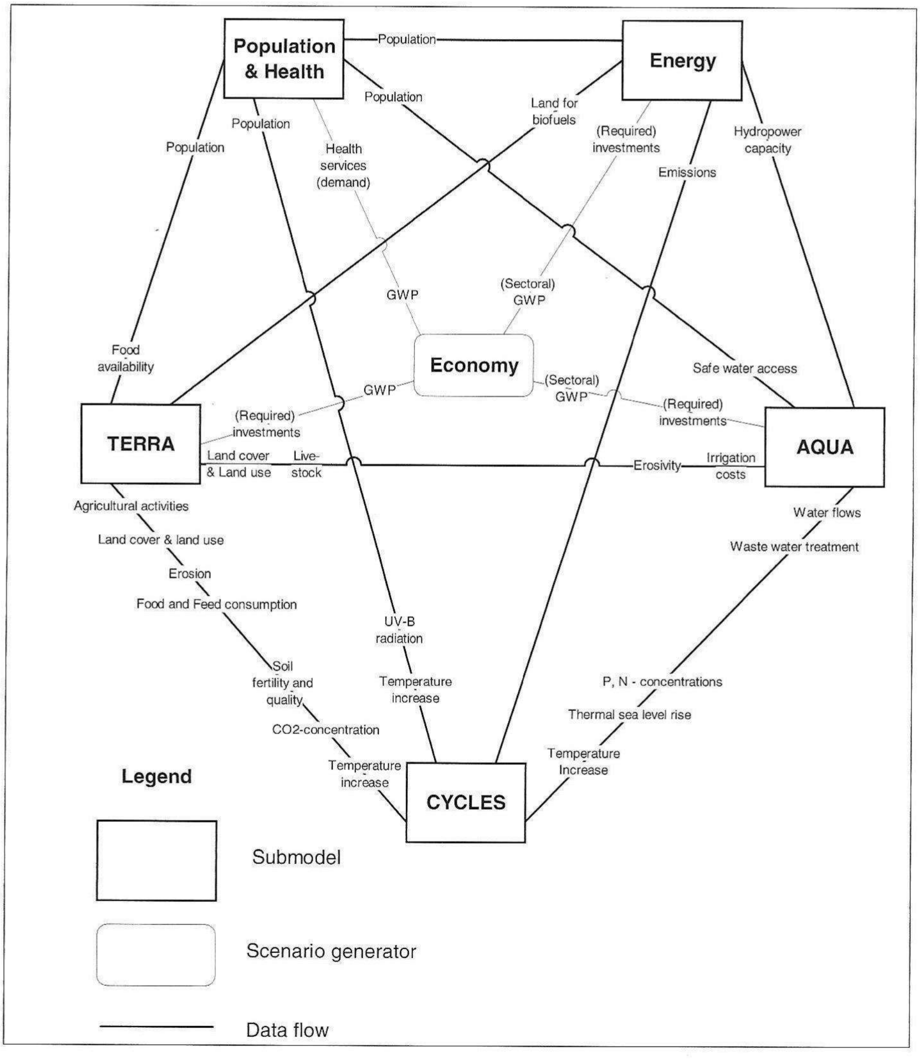

Figure 3.4 Interactions between the submodels.

expansion of hydropower is exported to the AQUA submodel and determines the demand for new water reservoirs in AQUA.

Access to safe drinking water and proper sanitation, which are exported from the AQUA submodel, affect the demographic and health dynamics in the Population and Health submodel. The hydrological cycle influences the element cycles in the CYCLES submodel: the outflows of elements from groundwater and surface water are driven by the water outflows from these water reservoirs. Also, AQUA simulates domestic and industrial wastewater treatment which determines the fate of nutrients. One of the factors determining erosion, the rain erosivity factor, is calculated in AQUA on the basis of the rainfall distribution throughout the year and exported to the TERRA submodel. Finally, the costs of irrigation are influenced by water availability and quality.

The available food per capita, exported by the TERRA submodel, affects people's nutritional status and thereby human mortality simulated in the Population and Health submodel. Land-cover changes affect the processes of evaporation, infiltration, percolation and river runoff simulated in AQUA. The area of irrigated cropland determines the irrigation water demand in AQUA, which is the main component of total water demand. Another (small) component is determined by the size of livestock in TERRA. Changes in land-cover patterns, erosion, emissions as a result of agricultural activities (fertiliser use, biomass burning and domestic animals) and food and feed consumption are exported to the CYCLES submodel. They affect the global flows of basic elements and related compounds within and between the major reservoirs in CYCLES. A global temperature increase simulated in the CYCLES submodel has an effect on malaria risk, schistosomiases and cardiovascular diseases in the Population and Health submodel. Changes in the level of UV-B radiation affects the risk of skin cancer. In TERRA, higher CO_2 concentrations can affect the potential yield of arable land positively (CO_2 fertilisation) and temperature increase negatively (heat stress). The flow of organic matter and inorganic compounds has an effect on soil fertility and quality and thus on food production in the TERRA submodel. The concentrations of various substances in fresh groundwater and surface water, calculated in CYCLES, are exported to AQUA to determine fresh-water quality classes. Another link concerns the effects of a temperature change on the hydrological processes in AQUA. Finally, sea-level rise due to thermal expansion is exported, which is an important component of total sea-level rise simulated in AQUA.

3.6 Future work

As has been said before, we view the TARGETS model primarily as a toolbox which allows for experimentation with new concepts, methods and techniques. A model version is then a material manifestation of successful ideas, which invites testing and critical review. The model should not place scientists in a straitjacket, but rather function as a means of stimulating creative thinking. Often when a model is launched, a great deal of effort is devoted to refining the model by including more details. Such a strategy may actually not lead to a model which is more useful or scientific. On the contrary, it may result in a less transparent and rather unmanageable model, thereby losing its role as an exploratory and instructive tool. Moreover, the additional detail requires more data which are often unreliable or only partly available. Hence, future work on the TARGETS model will take another direction.

Some submodels are presently being implemented for regions, in connection with the IMAGE2.0 model. This broadens the experience with the model and refines the genericity. It also necessitates the inclusion of regional interactions, as for instance with fuel trade. A second step is to improve the dynamic representation of human actions, among them consumer behaviour (Jager *et al.*, 1997) and farming. A third step is to explore the role of the TARGETS framework as a tool to communicate issues of global change and sustainable development to a larger audience of policy makers and analysts and of scientists and interested lay people. The TARGETS1.0 model with its interactive visualisation shell is already being used in the context of the ULYSSES project (Jaeger, 1995) it will also be made available on CD-ROM. Some exploratory steps for the design of a policy exercise have been formulated (de Vries *et al.*, 1993).

From a modelling perspective, we intend to continue the application of novel approaches in the emerging field of complex systems modelling. Some case studies have been worked out to illustrate the potential benefits of an evolutionary modelling approach, among them the application of genetic algorithms to search for optimal and suboptimal trajectories (Janssen, 1996).