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Handbook of Sustainable Development Planning

Studies in Modelling and Decision Support

Edited by **M.A. Quaddus and M.A.B. Siddique**

HANDBOOK OF SUSTAINABLE DEVELOPMENT PLANNING

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Preface and acknowledgements

By the time this book went to press the Johannesburg world summit on sustainable development had ended. The main objective of this summit was to reflect on Agenda 21 of the Rio summit ten years ago. The theme of the Johannesburg summit was ‘people, planet, prosperity’ and thus focused on social development, poverty eradication and environmental conservation. While sustainable development has been defined in many different ways, these three major concerns capture the essence of it. On the other hand, sustainable development planning deals with developing plans and supporting decision-making activities to achieve social development, poverty eradication and environmental conservation.

The role of decision-making in sustainable development is also highlighted in Agenda 21. This document lists 38 issues of sustainable development (http://www.un.org/esa/sustdev/issueslist.htm – accessed on 18 November 2002), two of which relate to decision-making. These are ‘Integrated decision-making’ and ‘Information for decision-making and participation’. It is necessary to integrate issues of ‘environment and development at the centre of economic and political decision-making’. However, at the core of the decision-making process is the need for quality information. Information must be collected and disseminated appropriately. One of the most important sources of information is the outcome of the application of model-based decision support systems in sustainable development planning. Modelling brings objectivity to any planning process and supports the corresponding decision-making activities by providing specific and appropriate information.

Thus the primary aim of this book is to disseminate the roles and applications of model-based decision support systems (DSS) in sustainable development planning. Invitations to contribute to this book were sent via special-interest electronic list servers around the globe. Several renowned authors were also specially invited to contribute. Each prospective contributor was initially asked to prepare a two- to three-page proposal on his/her contribution. These proposals were reviewed by the editors and suggestions were made to prepare the full papers. The submitted papers were then reviewed by independent reviewers and the final acceptance/rejection decisions were made by the editors based on the revised papers submitted by the contributors.

The book contains three parts. Part I, Modelling for sustainable development, has four chapters. It deals with the concepts of modelling sustainability from planning and development perspectives and reviews the applications of modelling and decision support in sustainable development planning based on published literature. Part II of the book, Case studies, consists of ten chapters and analyses the applications of various models based on decision support framework for sustainable development planning in the following areas: environmental management, mining, energy management, land and water management, agriculture, aquaculture and infrastructure. Part III of the book, Future directions, proposes future directions for modelling and decision support in the light of the review in Chapter 1 and various other chapters in this book.

We are grateful to the authors of various chapters for their contributions. It had been a long process from the initial outlines to developing the full chapters and then revising them in the light of reviewers' comments. We sincerely acknowledge the authors' willingness to go through this long process. We also acknowledge the work and knowledge of various reviewers of the chapters, many of which had to be done at short notice.

Thanks to all the people at Edward Elgar with whom we corresponded for their advice and facilitation in the production of this book.

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PART I

MODELLING FOR SUSTAINABLE DEVELOPMENT

1 Modelling and decision support in sustainable development planning: a review and analysis

M.A. Quaddus and M.A.B. Siddique

Introduction

The concept of sustainable development gained its currency with the publication of *Our Common Future* by the World Commission on Environment and Development (WECD) in 1987. It emerged from recognition of the need to maintain a balance between economic develeopment and environmental protection and to ensure intra- and intergenerational equity. Before the 1980s, a mono-disciplinary approach was applied to define economic development. Economic development basically meant sustained increase in per capita income. For example, in 1957, Meier and Baldwin defined economic development as 'a process whereby an economy's real national income increases over a long period of time' (Meier and Baldwin, 1957, p. 2). This notion of development was prevalent among many of the third world countries until the end of the 1960s. However, during the last quarter of the twentieth century, a multi-dimensional concept of economic development was developed.

One of the shortcomings of defining economic development in terms of sustained increase in per capita income is that it fails to accommodate the question of distribution of income. It was believed that the distributional aspect would be taken care of by the 'trickle-down effect' of growth. However, by the end of the 1960s, it became clear that economic development over a long period of time in many of the developing countries failed to bring about the 'trickle-down effect'.

A new environmental and social dimension of development, referred to as 'sustainable development', emerged in the 1980s. The first formal definition of sustainable development is found in *Our Common Future*, where it is defined as 'a process that fulfils present human needs without endangering the opportunities of future generations to fulfil their needs' (WECD, 1987, p. 43).

However, since the publication of *Our Common Future*, the concept of sustainable development was further modified and extended by development economists. In *Caring for the Earth* (IUCN/UNEP/WWF, 1991) sustainable development is defined as an improvement in 'the quality of human life while living within the carrying capacity of supporting ecosystems'. It should be noted here that improvement in the quality of human life subject to environmental or ecological constraint is the main focus of this definition.

Although the seminal definition of sustainable development by the WECD has been widely quoted by many, the precise meaning of sustainable development and the ways to achieve it have always been matters of intense debate among researchers and policy-makers. The main criticism directed against the notion of sustainable development perceived by both the WECD and the UNCED (United Nations Conference on Environment and Development) is that it is very broad and general.

The lack of a universally acceptable definition makes the task for sustainable development planners difficult. Moreover, very often the objective of sustainable development is not clear. The implication of this is that the gap between theories (that is, the definition of sustainable development) and the actual application of sustainability to reality becomes particularly significant. This further results in many difficulties in the formulation of policies to plan sustainable development. As a result there is a demand for more precision in order to make sustainable development planning more consistent and efficient.

Our objective in this chapter is to see how modelling and decision support have been applied in sustainable development planning. Modelling brings objectivity to any analysis and supports the decision-making process effectively. To the best of our knowledge such a review in the area of sustainable development is not available in the literature, perhaps with the exception of Nijkamp and van den Bergh (1997). The authors present a review of modelling activities in environmental issues which also cover sustainable development. However, they do not cover decision support activities and present their findings in the form of a literature review. As will be seen later, we present our review in formatted common categories. This reveals a commonality among the articles and makes it easier to identify any gaps for future research. In the next section we present the methodology of our review. The results are given next. Finally, conclusions are drawn.

Research methodology

Sample

Our review is based on published articles/books/monographs in the English language that are available in the public domain. We covered major journals which publish articles in the area of sustainable development. We also searched electronic databases (for example, ABI/Inform, Science direct and so on) using relevant keywords. Finally, we also made use of manual browsing of various journals and conference proceedings in the library for relevant materials.

In selecting relevant articles/documents/chapters in books, we used two important criteria. Besides the fact that the document has to deal with sustainable development of some kind, it also has to (i) address or apply a model of some kind to the problem, and/or (ii) address or deal with some aspects of decision support. Note that if an article addresses (but does not necessarily applies) the need for modelling and/or decision support, we include it in our analysis. However, if an article deals with sustainable development in detail but does not address or apply a modelling tool, we don't include it in our analysis. It must be noted that although our coverage is broad, the review is by no means claimed to be comprehensive. But it provides a good snapshot of the published literature on the use of modelling and decision support in sustainable development.

Research categories

To categorize the articles into various research types we borrowed research categories from the information systems discipline (Alavi and Carlson, 1992; Pervan, 1998; among many others) and adapted them to suit our case. In the end we used the following research categories for our review: frameworks of sustainable development, frameworks of sustainable development and applications, conceptual models, conceptual overview, theory–opinion–example, opinion and personal experience, tools–techniques–methods–model applications, case study.

Model and decision support categories

'Decision making is as old as man' (Eilon, 1972). Whether we walk down the street or deal with a sustainable development planning problem, we need to take the best possible decision under the prevailing circumstances. The process of decision-making involves a number of steps. According to Simon (1960) these steps are: Intelligence, Design and Choice. While 'Intelligence' involves gathering information, it is in the 'Design' step that some kind of model is developed. A model is a representation of reality. While there are many categories and types of models (Klien and Methlie, 1995, p. 160) in our review, we shall use two broad categories of modelling: quantitative and qualitative. Specific quantitative and qualitative model will be further classified for each specific article.

A decision support system (DSS) is a computer-based information system used to support the decision-making activities of managers/planners. Its main components are model base and data base, which are used to develop any specific DSS application. It is highly interactive and user-friendly, and supports a variety of 'what-if' analysis (Sprague and Watson, 1989). In our review we shall assess DSS categorization qualitatively, the degree of which will vary from no mention of DSS to full-blown DSS application.

Results and analysis

Our restricted search resulted in 19 studies on modelling and decision support in sustainable development. In all these studies modelling and decision support constitute a substantial portion of the sustainable research.

Table 1.1 presents the 19 studies in an easy to understand format. These studies are categorized by research type, context of sustainability, modelling type, extent of DSS, and brief outcomes. Next, we describe each category in detail and highlight gaps for possible future research on modelling and decision support in sustainable development planning.

Research type

Distribution of the research categories by frequencies are as follows: frameworks of sustainable development (2), frameworks of sustainable development and applications (4), conceptual models (4), conceptual overview (2), theory–opinion–example (1), opinion and personal experience (0), tools–techniques–methods–model applications (5), case study (1). It is noted that ten studies fall in the category of applications, while the remaining nine are in the non-application category. It is also noted that eight studies fall into the categories of frameworks, conceptual models, and conceptual overview. That is, these eight studies are not of the applied type. One possible area for further study could be to take these frameworks/models/overviews and apply them to some aspects of sustainable development. There is only one case study type application dealing with decision support in sustainable development. This is again a rich area of further study. More case study type applications should be reported in the literature for the benefit of leaders and planners in the area of sustainable development.

Context of sustainability

As shown in Table 1.1, the context of sustainability varies from industrial pollution, grazing management to macro-level planning. It is noted that five applications are in macro-level planning, while the remaining 14 are in a specific problem domain. Both the macro-level and specific models offer opportunities to adapt them to apply in similar contexts.

Modelling type

As mentioned earlier, we have categorized the modelling types broadly into quantitative and qualitative. Fifteen studies used quantitative modelling, with one qualitative and three mixed qualitative–quantitative. Among the

Table 1.1 Modelling and DSS in sustainable development

Source	Research type	Context of sustainability	Modelling type	Extent of DSS	Brief outcomes
Paras (1999)	Tools–techniques–methods–model–applications	Fiscal incentives in the struggle against industrial pollution	Quantitative: ecological optimization method	No mention of computer-based support	Proposes multicriteria taxation model for industrial pollution prevention and control
Madu (1999)	Conceptual models	Environmental planning in developing countries	Quantitative: multicriteria and optimization models	Explicit development and use of DSS	Develops models and DSS to control carbon emission of a country
Quaddus and Siddique (2001)	Frameworks of sustainable development and applications	Macro-level sustainable development planning	Quantitative: multicriteria method in group environment	Explicit development and use of DSS	Develops a framework for sustainable development planning and applies it to a third world country
Van Pelt (1993)	Conceptual models	Ecological sustainability and project appraisal	Quantitative: multicriteria analysis (MCA)	No mention of computer-based support	Applies MCA in sediment control project
McDaniels (1994)	Frameworks of sustainable development and applications	Sustainable development concepts for utility planning	Qualitative/quantitative: multi-party value theory	No mention of computer-based support	Applies the framework for utility decisions in British Columbia
Potier (1996)	Frameworks of sustainable development	Integration of environment and economy	Quantitative: cost–benefit analysis, macroeconomic models	No mention of computer-based support	Addresses the need for using various analytical tools for integrating environment and economy leading to sustainable development

Table 1.1 continued

Source	Research type	Context of sustainability	Modelling type	Extent of DSS	Brief outcomes
Hofkes (1996)	Conceptual models	Macro-level sustainable development	Quantitative: macro-economic growth model	No mention of computer-based support	Derives conditions under which sustainable development is feasible and optimal
Nihoul (1998)	Theory–opinion–example	Macro-level sustainable development	Quantitative: integrating ecological and macroeconomic modelling	No mention of computer-based support	Extends ecosystem models to include macroeconomic processes for sustainable development
Bellami and Lowes (1999)	Tools–techniques–methods–model applications	Sustainable grazing management	Quantitative: model-based consisting of various types of models	Explicit development and use of DSS	Develops and uses the DSS to generate meaningful discussions about grazing management and the concept of sustainability among users
Kelly (1998)	Conceptual overview	Macro-level sustainable development planning	Quantitative: system dynamics (SD)	Suggests development and application of computer-based SD model	Overviews system dynamics modelling advantages and applications, and proposes SD model for sustainable development
Sinclair and Kuluk (1994/95)	Conceptual model	Sustainable solid waste management	Qualitative: macro-level options generator	No mention of computer-based support	Proposes a conceptual model which helps to generate more options for planners for sustainable solid waste management

Marquez and Smith (1999)	Frameworks of sustainable development and applications	Urban form and air quality	Quantitative: a variety of integrated models (based on GIS, spreadsheets etc.)	Explicit use of computer support, but not in full-blown DSS framework	The framework is applied in the city of Melbourne, Australia, and specific benefits are noted
Morrell and Lu (2000)	Case study	Aircraft noise and sustainable development of air transport industry	Quantitative: hedonic price model	No mention of computer-based support	The pricing model is applied in Amsterdam airport, Schiphol, to estimate social cost of aircraft noise, which is found to be much higher than what Dutch govt charges
Jones et al. (2000)	Tools–techniques–methods–model applications	Energy use and emissions for sustainable development	Quantitative: a number of integrated models	GIS-based DSS	Presents the GIS-based energy and environment prediction model(s) in detail
Nijkamp and Vreeker (2000)	Tools–techniques–methods–model applications	Regional sustainability assessment	Qualitative and quantitative: systems model, critical threshold values and multicriteria flag model	Explicit development and use of DSS	The framework is applied in Songkhla/Hat Yai region in Thailand to assess regional development scenarios for sustainability
Pannell and Glenn (2000)	Framework of sustainable development and applications	Sustainability indicators in agriculture	Quantitative: Bayesian decision theory	No mention of computer-based support	Proposes a framework of prioritizing sustainability indicators in agriculture based on Bayesian decision theory. An example is presented to operationalize the framework

Table 1.1 continued

Source	Research type	Context of sustainability	Modelling type	Extent of DSS	Brief outcomes
Prato (1999)	Conceptual overview	Land and water resource management	Quantitative: various multiple attribute decision-making (MADM) methods	Suggests use of MADM type DSS	A stepwise approach is presented to use MADM methods for land and water resource management incorporating sustainability
Zander and Kachele (1999)	Tools–techniques–methods–model applications	Sustainable land use	Quantitative: multiple goal linear program	Explicit development and use of DSS	Modelling framework for multiple objective decision support tool for agroecosystem management is presented and application projects described
Schultink (2000)	Frameworks of sustainable development	Sustainable rural development planning	Quantitative and qualitative: qualitative frameworks and linear programming and input–output analysis	No mention of computer-based support	Proposes a number of frameworks for sustainable performance indices and suggests use of quantitative tools for assessments

quantitative modelling, multicriteria decision-making (MCDM) methods have been used widely. Traditional optimization, cost–benefit analysis and macroeconomic growth models have also been used. One study used the system dynamics method. Mixed modelling and the qualitative approach have not been used as much. These offer rich approaches for further applications in sustainable development planning.

Extent of DSS

This category shows the extent of DSS use in sustainable development planning. Table 1.1 shows that out of 19 studies, nine have used or suggested using DSS-based analysis. Some have of course dealt with full-blown DSS. For example, Bellami and Lowes (1999) dealt with explicit development and use of DSS in sustainable grazing management using a model base consisting of various types of models. However, ten studies, although they dealt with modelling, did not mention the use of DSS- or computer-based support of any kind. For example, Schultink (2000) used linear programming and the input–output approach for sustainable rural development but did not mention the use of computer-based support of any kind. This clearly shows that the future direction of research in sustainable development planning should be towards DSS-based modelling and applications.

Brief outcomes

The last column of Table 1.1 presents brief outcomes of the studies. We only highlight the important outcomes which are self-explanatory. It must be noted that all studies report success of their modelling and/or DSS effort.

Conclusion

This chapter presents a snapshot of modelling and decision support activities in sustainable development planning. Over 70 articles were collected from various printed and electronic sources. Using our criteria of modelling and decision support, only 19 articles have been found to satisfy our sample requirements.

A structured analysis was carried out to review the articles in terms of research type, context of sustainability, modelling type and extent of DSS use. Gaps were identified in all these categories. The future direction of research in sustainable development planning should aim to fill these gaps.

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2 Hierarchical, dynamic modelling and sustainable development

Ian Moffatt

Introduction

The term 'sustainable development' gained international prominence with the publication of *Our Common Future* – the so-called Brundtland Report – in 1987 (WCED, 1987). The term has spawned a long debate over its precise meaning and over one hundred definitions are currently in use (Pezzey, 1992; Moffatt, 1996). A consensus is slowly forming that sustainable development refers to the processes by which sound economic systems can operate well within the biophysical constraints of the ecosystem to provide a good quality of life that is socially just for current and future generations. Whilst the debate on the ways of making this view operational continue at different spatial and temporal scales, for example, globally, nationally, regionally and locally, numerous individuals and groups are involved in trying to make development sustainable. Similarly, policy-makers, having agreed to the idea of sustainable development at the Earth Summit held in Rio de Janeiro, Brazil in 1992 and at the recent World Summit on Sustainable Develoment in Johannesburg in 2002, are now attempting to develop strategies to move societies onto sustainable paths of development. One way of contributing to this goal is to use some of the many different mechanisms described in Local Agenda 21 (UNCED, 1992). As a contribution to making development sustainable several research groups have been attempting to develop models as decision-making aids to assist this ongoing process (Meadows et al., 1972 et seq.; Moffatt 1996). The purpose of this chapter is to describe one attempt to model sustainable development as a dynamic hierarchical approach (Moffatt et al., 2001) drawing upon recently completed research funded by the Economic and Social Research Council (ESRC), United Kingdom.

The chapter has four aims. First, it will briefly describe hierarchical and strategic modelling in the following section. Second, a theoretical framework describing demographic and economic development within ecological limits is presented. This section describes a theory of sustainable corridors and a preliminary dynamic, hierarchical global/national model is also briefly presented. The third aim is to present Scotland as an example of a hierarchical model integrating a nation with the global economy–ecology. A final section notes some of the methodological problems involved in this approach to modelling of sustainable development processes. Some of the ways in which these problems can be solved are suggested in this concluding section.

Hierarchical and strategic modelling

Many complex systems are organized in a hierarchical fashion. Numerous studies of energy flows through ecosystems, for example, illustrate the ways in which upper levels of the system, often predators, rely for their existence on the workings of the system at lower levels. If we damage the primary producers of the food chain in an ecosystem –whether by accident, mismanagement or by design (war) – then we will inevitably bring ruin to the rest of system of which we are a part. The classic study of the human communities on Easter Island bears silent witness to the processes of socioeconomic systems disregarding the limits of the ecological systems of which the Easter Islanders were an integral part (Miller, 2000). At the global scale Toynbee has noted that over the last two hundred years one species (humankind) has acquired enormous power to alter the biosphere. He wrote prophetically that only one prediction can be made with certainty: 'Man, the child of Mother earth, would not be able to survive the crime of matricide if he were to commit it. The penalty would be self-annihilation' (Toynbee, 1976, p. 588).

Obviously, the Brundtland Report and subsequent international meetings have identified the major environmental and economic problems that the earth's communities are facing and are seriously beginning to address some of these issues. The recent meeting in Bonn, Germany to ratify and implement the Kyoto agreement illustrates the difficulties of gaining international agreement. This is especially the case when several major players are also polluters. Some nations (for example the USA) are unwilling to reduce greenhouse gases and hence contribute to maintaining the atmospheric system at about 350 parts per million by volume of CO_2 equivalents, conducive to life on earth (IPCC, 1995, 1996). Yet establishing a secure atmospheric environment with temperature fluctuations within the historical limits is an essential part of maintaining the ecosystems for our support (Moffatt, 1992). As Schneider notes, 'a global temperature change of one degree to two degrees Celsius can have considerable effects. A sustained global increase of more than two degrees Celsius above the present would be unprecedented in the era of human civilization.' (Schneider, 1989, p. 774). More generally agreeing to make development sustainable demands that we understand the complex ways in which economic systems and ecosystems interact, in a hierarchical manner, so that we can have some scenarios to act as guidelines for such vitally important strategic policies.

Whilst there are numerous models of the enhanced greenhouse effect (Moffatt, 1992; IPCC, 1995), there are relatively few models of sustainable development. Arguably the notorious 'Limits to Growth' models of the 1970s and 1990s were early attempts to examine the world as a complex system (Forrester, 1971; Meadows et al., 1972, 1974, 1992). The models linked demographic changes, non-renewable resources, agricultural resources, pollution and capital into a set of positive and negative feedback loops. These early models, like any model, were simplifications of the real world and were severely criticized on methodological grounds but were, at best, one way of alerting decision-makers to the coming problems of attempting to have rapid population and economic growth in a world of finite resources.

Many economists criticized these early models because they had no economic theory underpinning them (Beckerman, 1974; Cole et al., 1973). Many model-builders and scientists criticized the models for disregarding the data for calibrating and testing the models outputs. Only the population sector was calibrated and tested with relevant data. Some political and social scientists did not agree with the neo-Malthusian basis of the models (Cole et al., 1973). Others suggested that the models were too mechanical and that social feedbacks would offer hope for a sustainable future (Oerlemans et al., 1972). Clearly, the early Limits to Growth models caused controversy, and the recent re-run of the model stubbornly refuses to address these issues (Meadows et al., 1992). The recent model offers an appeal to a change in ethics (which is important) but fails to propose new carefully constructed policy recommendations as a way out of the current ecological and economic crises that globalization has brought in its wake.

If we are to make progress in dynamic modelling for contributing to the ongoing processes of sustainable development, then we need to recognize that we are an integral part of ecosystems. Next, we should recognize that ecosystems are organized in a hierarchical fashion and that we must conserve these functioning systems and live within these constraints. Third, we must also acknowledge that despite the growth of multinational companies and supranational organizations (for example the European Union), most important decisions lie with nationally elected politicians. Hence it follows that hierarchical modelling requires that we address global and national (as well as smaller spatial and temporal) scales if we are to develop integrated relevant strategic models. Next, any model must be based on sound theory. This poses a major problem for modelling sustainable development as there are few theoretically sound approaches to integrate economy and ecology into a coherent framework. Fifth, we need to embed useful indicators of sustainable development into dynamic models. This is an essential task if we are to determine whether or not an economic system is on a sustainable trajectory. Finally, we must be able to offer ethically sound policies, based on good science, to ensure the current and future generations have a good quality of life. These prerequisites are not trivial but would appear to be indispensable if we are to make progress in modelling sustainable development.

A theoretical framework

One of the major theoretical difficulties in modelling sustainable development is trying to combine ecological and economic systems within the one conceptual framework. As we enter the new millennium one of the most challenging questions is how to assess, build and maintain sustainable economic and social systems within the carrying capacity of the natural and biological systems of the planet. This section describes one attempt to solve this problem by (a) describing a new theory of sustainable corridors and then (b) developing McMichael's model of the globe into a dynamic hierarchical system model.

A theory of sustainable corridors

It is widely acknowledged that the earth is a set of complex interacting systems (lithosphere, hydrosphere, pedosphere, atmosphere, biosphere and arguably the noosphere). Hence, to portray all these control parameters affecting the ecosphere would be difficult. Fortunately, Gorshkov has shown that only a few critical control parameters are required to gain some understanding of the ecological constraints which determine life in all its manifestations on earth (Gorshkov, 1995; Gorshkov et al., 1994). Unfortunately, it is also recognized belatedly that we are already altering these parameters in such a way as to threaten life on earth. The production of greenhouse gases above the assimilation capacity of the receiving environment is one example from many of the way in which some societies are trying to live beyond the ecologically possible. In effect the irresponsible actions of a few major nations are driving the earth to destruction. Similarly, if we re-examine the level of food production for the earth's ecosystems expressed as net primary production (NPP), we find that human appropriation of NPP is already consuming over 40 per cent of the total. If the human demographic expansion of the globe continues from its current 6 billion people to double, then we will have destroyed most of the NPP for all living organisms (Vitousek et al., 1986). Those people who continue to argue that the earth does not have some real biophysical limits to continued human population growth and resource consumption appear unaware of these biological realities (Lomborg, 2001). Is it then possible to prevent eco-catastrophes from happening? One way of preventing eco-catastrophes is to imagine that we could live in a sustainable corridor well within the ecological constraints of the planet and then try to locate such a corridor to support all life on earth.

A sustainable corridor is a trajectory of populations and resources use which varies through time and space yet remains beneath the maximum value that the global ecology can support and remains above the minimum pattern of consumption of other resources which are prerequisites for life on earth. For human societies a sustainable corridor also has the property that production must be equal to or greater than consumption and that both activities are contained within the upper bounds of the ecologically possible and above the minimum nutritional level required for human survival.

Whilst sustainable corridors are conceptually simple to define, they are very difficult to measure in such a way that they can help strategic decision-makers to ensure that human activities stay well within the bounds of the ecologically imposed constraints. These constraints, over time, are not constants but they do vary within limits, and trying to exceed these limits can only bring universal ruin to human societies. Figure 2.1 shows the lower boundary of a theoretical sustainable corridor. The lower limit represents the minimum consumption of energy, food and water per capita required for human survival for as long as the planet itself survives (estimated at the minimum to be one billion years). Development above this minimum level has been achieved by many, but not all, societies over the last two hundred years. Unfortunately, this pattern of development for the rich nations has put strains on many parts of the ecosphere as well as contributing to the poverty of some nations. In Figure 2.1 the three lines 0–1, 0–2 and 0–3 represent the average global pattern of resource consumption, the consumption pattern of the rich OECD nations and the considerably reduced pattern of consumption of nations comprising the developing world. From this graph it can be observed that the rich nations (0–2) are already above the upper boundary of sustainability, and probably passed this limit some decades ago. The ‘poor South’ nations (0–3) appear to be moving into areas of sustainability although some countries within this group are well below the sustainable level of living (Gray et al., 1993). It should be noted that there is no single path of sustainable development. The actual pathway or trajectory a country pursues depends on internal policy options and individuals’ actions, as well as the influence of external natural and economic forces such as free trade relations and the extent of globalization within a country.

The details of the lower and upper ecological limits within which all economic activity must remain – at least if it is to be sustainable – have been described in detail elsewhere (Moffatt et al., 2001, pp. 153–83). The theory of sustainable development corridors depends heavily upon the detailed

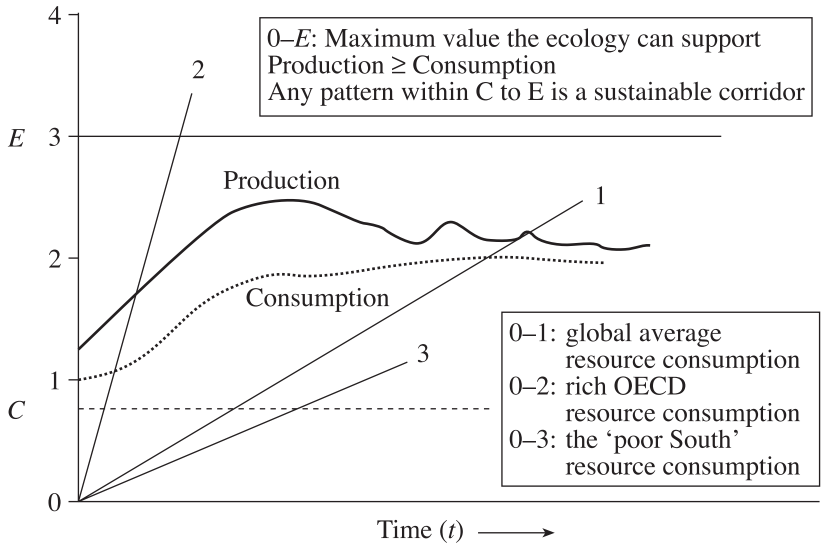

Figure 2.1 Resource consumption and sustainable corridor

calculations provided by Gorshkov and his co-workers (Gorshkov et al., 1994). In brief, Gorshkov has demonstrated that with regard to energy consumption and ecological stability, human activity has already crossed the threshold of ecological stability (Gorshkov, 1995). Human activity is also appropriating net primary production, altering the earth's carbon cycles, reducing the organic stores of the land and sea and altering the world's climate to an extent beyond human historical experience. Continuation of these trends (as seen in Figure 2.1) will result in unsustainable development and ecological collapse of regional and eventually global life support systems. These trends are already perceptible in the data and many people are being made aware of these changes by the mass media.

If we are to be seriously concerned about making development sustainable for current and future generations, then we need to identify possible corridors of sustainability. Such corridors would lie above the minimum levels (*C*, lower level) and stay well within the ecologically possible (*E*, upper level) noted in Figure 2.1. Individuals and nations would, of course, show some variation in preferred lifestyles within these constraints. Similarly, ideas of a just distribution of resource use would also have to be addressed rather than relying solely on market mechanisms. The latter are efficient but they are not necessarily just (Atkinson, 1983). One way of exploring possible sustainable development scenarios is by constructing a simple hierarchical model of the earth's system.

A dynamic hierarchical global/national model

One of the outcomes of the criticism of the Limits to Growth types of model was that if we are to consider sustainability, then we have to model development both globally (to determine the constraints) and locally (that is, at a sub-global scale) simultaneously. Obviously, individual nations can rarely stop major environmental changes, although some nations do contribute much more to the damaging of the world's ecosystems than others. Similarly, as several researchers have noted, it may be possible that one nation can achieve sustainable development but such 'sustainability' may be at the expense of other people (Pezzey, 1996). Clearly, from an ethical perspective, this is unacceptable as it raises issues of a just distribution of resources justly arranged. Allowing 'free trade' to be the sole arbiter of such key resource allocation and ethical questions is like leaving a fox in charge of the chicken coop. It will be immediately apparent that any model of sustainable development will be a very simple structure compared to the complexity of the real world. Hence, if we are to avoid self-delusion by oversimplifying our analysis, then it is vital that any realistic model of the transition to a sustainable world needs to examine the global resource constraints within which all living creatures, including human societies, must operate.

Whilst numerous studies have attempted to model the ecosphere, very few have recognized the differences between the rich and poor countries within their model structure. There are some exceptions to this: the work of the Bariloche group in Latin America has attempted to include social justice into their model. Similarly, the regionally based global model developed by Mesovaric also included a regional dimension to his work (Mesovaric, 1974). Apart from these early studies, generally, however, modellers have failed to see the links between poor and rich nations in the context of modelling. The clearest study of these interrelationships is presented by McMichael in his investigation of global environmental change and the health of the human species. In his study of planetary overload (McMichael, 1993) he suggested a non-operational model of the context, causes and consequences of ecological disruption in the rich and poor countries. The causes and consequences of economic, ecological and social problems in rich and poor countries in the late twentieth century are shown in Figure 2.2. His descriptive model is not operational but represents a point of departure for the current attempt to model global/national interactions to form a model of sustainable development based on the theory of sustainable corridors.

It is possible to develop a global/national hierarchical dynamic model of sustainable development by integrating the ideas of sustainable corridors with a simplified model of planetary overload. In Figure 2.3 the structure of a hierarchical, dynamic global/national model of sustainable develop-

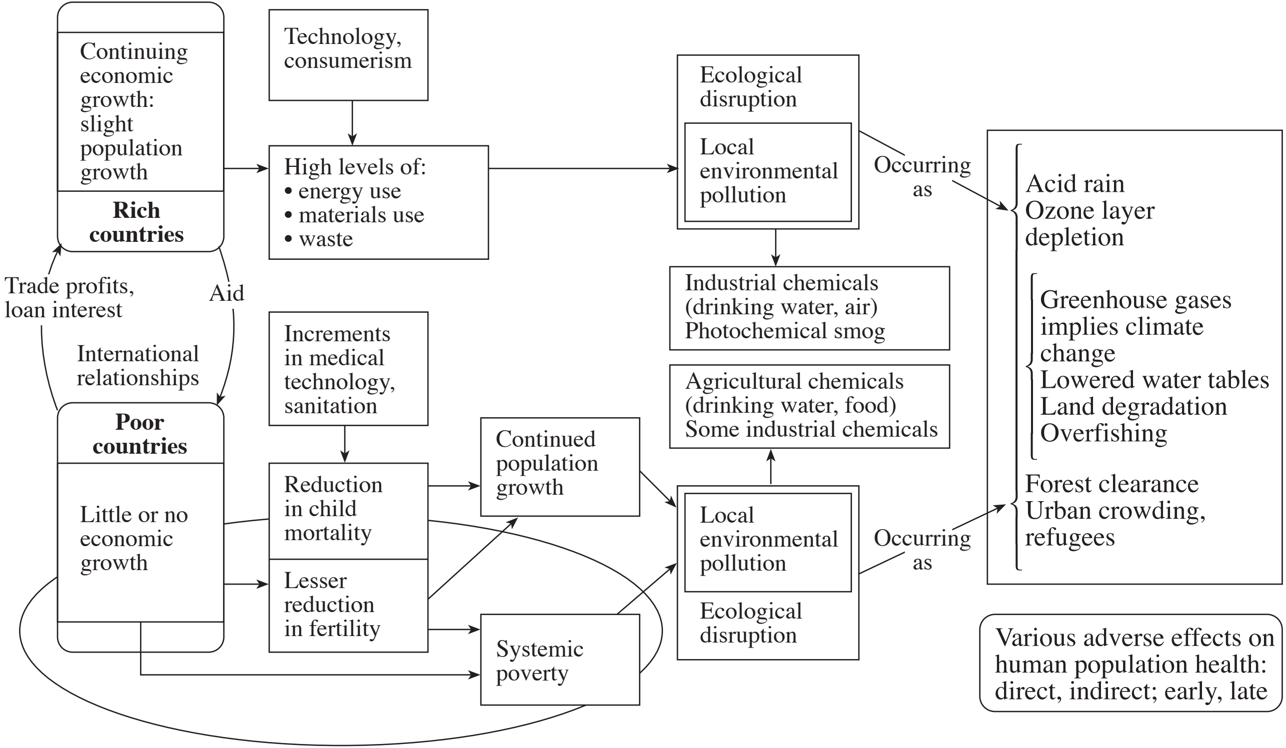

Figure 2.2 Causes and consequences of economic, ecological and social problems

ment is presented. At the upper level of the hierarchy are two feedback loops (one positive and the other negative). The negative feedback loop connects population with net primary production. As the population increases, the NPP declines, resulting, ultimately, in a declining human population. Population also links with non-renewable resources, pollution and NPP as a positive feedback loop. If the positive loop dominates, then an increase in population causes a reduction in non-renewable resources which, in turn, increases pollution which impacts on NPP. The interactions of these two loops can give rise to ecological stability – a condition of ecological dynamic equilibrium.

At the lower level of the hierarchy each nation is modelled in a simple way to represent the interactions within a nation and with the rest of the global economy and ecology. Unlike the global model, two major changes are included in the model's structure. First, the fluctuating pattern of world trade has to be included as all nations are involved in such transactions (at

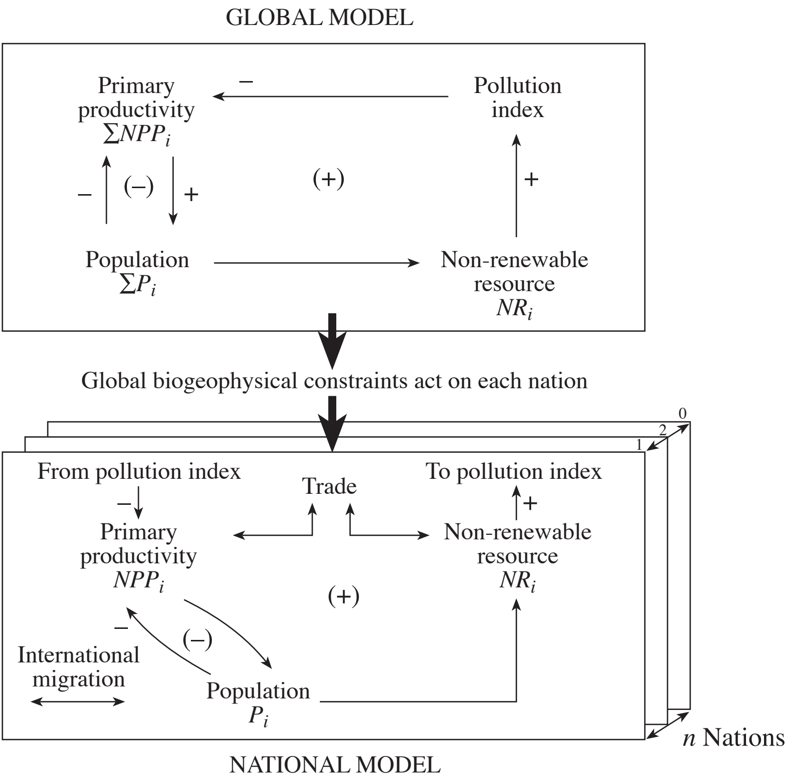

Figure 2.3 Hierarchical model of sustainable development

the global scale there is no trade with other planets!). Next, the pattern of international human migration has also to be included. Again, this is absent from the global model for obvious reasons.

The simple global/national hierarchical model is predicated upon several causal hypotheses. The first hypothesis states that there is an inverse relationship between rising material consumption and falling birth rates. Obviously, many other factors influence birth rates, but in this simple model it is suggested that this hypothesis is a first approximation to real demographic change. Next, the second hypothesis links anthropogenic emissions of carbon dioxide and other greenhouse gases as a non-linear function of material consumption. Third, the rate of consumption or appropriation of the net primary product is increasing and is unsustainable. Empirical work by Vitousek et al. (1986) indicates that some 40 per cent of net primary production is used by human population directly or indirectly. Obviously, as net primary production represents a stock of the basic food supply for all organisms, this cannot exceed 100 per cent.

The base run of the model permits only 50 per cent of NPP to be appropriated by humanity. The fourth hypothesis states that international trade is responsible for the unequal distribution of material goods entering the world market and is observed in the unequal consumption of resources per capita. Currently, disagreements over the role of world trade are important environmentally, socially, economically and politically. In the model a parameter (epsilon) is used as a measure of unequal trade between rich and poor nations. By altering epsilon to 0.5 an equal amount or resources (measured in tonnes) can be used to simulate a more equal allocation of resources across the globe. It should be noted that a more equal distribution of resources can still lead to a massive difference in the per capita consumption patterns which depends on both the wealth and the number of people doing the consuming. The fifth hypothesis assumes that there is a direct relationship between employment opportunities and the pattern of international migration. The sixth hypothesis states that when food resources cannot be met by national agriculture and fishing, then imports of food imports of foodstuffs are essential. This is represented as a change in the 'balance of trade' in the model. Unlike the earlier Limits to Growth models, this model uses a modified Cobb–Douglas production function as a broadly Keynesian mechanism to represent the global economy and national economies.

The entire model was written as a set of difference equations. All the levels or stocks in the model were initialized for the year 1950 and the model was calibrated for the period 1950–90 and run as a business-as-usual scenario for the next 300 simulated years. The solution time for the equations was set at one year. The model was programmed in STELLA and runs on an

IBM PC (full details of the model are described in Moffatt et al., 2001). The results of this preliminary simulation model are described below

A dynamic, hierarchical case study

Any complex, dynamic model has to overcome the problems of calibration and validation. At the global scale this is difficult as we often only have one data set, for example global estimates of CO_2 concentrations or global population. Similarly, in national studies the data for physical parameters are often associated with error bars around the measurement of the data – but, typically, economic data do not come with associated error bars. Given the nature of the data in many studies, then, the practice is to use the best estimates of the state variables to initialize the model and, again, to use the best estimates of the numerical parameters gleaned from the literature. This was undertaken for the model (1950–2000) and then the model was run to simulate 300 years of development from 1950 to 2250. It should be noted that to prevent a circularity of argument it is important that the model reveals some testable predictions (new discoveries) so that it has more content than merely replicating historical patterns.

The problems associated with validation are also daunting. The major problem is that of obtaining a good fit between the actual data for several observed variables and the simulated variables. Often, in complex models, optimum performance, as measured by a goodness-of-fit statistical criterion, do not perform well on all variables. This means that one variable could be a good fit with the relevant data but other variables are not performing well. One solution to this problem is to obtain an overall goodness-of-fit criterion but this may mean that no one simulated variable is statistically close to the real data. The approach adopted here was to combine various estimated parameters and then, by using successive simulations, attempt to capture the best fit between individual state variables rather than adopting an average fit between all variables. It should be noted that calibration can only be used to compare the simulated data with the observed data sets. Once forecasting extends the simulated data into the future, then only different scenarios can be explored. The choice of scenarios depends, in part, on how good a fit the model performs with historical data. It is also obvious that any scenario reflects the implicit value judgements of the model-maker and decision-makers. It should, of course, be realized that each future scenario, if chosen as the basis for policy, has both potentially important positive and negative impacts. Clearly, the methodological problems associated with calibration and validating dynamic, hierarchical models are still in their infancy.

The base run of the dynamic simulation model assumes no major changes to the structure of the world economy or policies to alter world trade so it represents a business-as-usual scenario. The total population continues to rise from 2.5 billion in 1950 to 14.1 billion by 2150. By that time the simulated human population will have consumed all renewable resources as represented by net primary production, and the human race becomes extinct within the year. The rich population grows from 752 million in 1950 to 4.2 billion, whereas the poor population rises from 1.76 billion to 9.9 billion. It should be noted that the earth's population is slightly over 6 billion at present and the model indicates that increasing the population to 14 billion is unsustainable. The CO2 level increase from 275 parts per million by volume (ppmv) and reaches a maximum of 633 ppmv. The environmental index (I) – using the Ehrlich and Holdren equation ($I = P^*A^*T$), where P is population, A is affluence (consumption) and T is technology, rises from 2 in 1950 to a maximum of 3.3 (Ehrlich and Holdren, 1971). Changes in technology are no guarantee of preventing global ecological collapse.

Global world product (GWP) measured in US$ trillions rises from 5.47 through to a maximum of 53.6 before the collapse. Interestingly, the economic value of the world's ecosystem, estimated at $2.52 trillions in 1950, also increases to a level of $55 trillion. Estimates of the latter are notoriously difficult to obtain as the ecological services are essential to the life support of the planet and cannot be simply viewed as market transactions. Nevertheless, Costanza et al. have attempted to provide a dollar estimate of these indispensable ecological services. Their estimate for 1990 is between $16 trillion and $54 trillion and the model forecasts $59 trillion for the same year (Costanza et al., 1997).

The national model is set up to represent potentially any nation. In the study only a highly simplified model of the ecology and economy of Scotland was produced. Again, the levels were initialized for 1950 and the model run for 300 simulated years. By 2160 the global population collapses and, unsurprisingly, so does the Scottish population. The Scottish population does, however, remain more or less stable at 5.3 million people throughout the simulation. Despite the constant population, the Scottish gross domestic product (GDP) grows from approximately £18 billion to £23 billion. Real Scottish wealth (that is, the values of the ecosystems) rises from £25 billion through to £29 billion over the period 1950–2150 before the collapse. The environmental index also rise from 2 to almost 3 over the same period. It should be noted that the preliminary model is a very simplified structure of the real world but does indicate that we can in both theory and practice combine ecological and economic systems within the same dynamic, hierarchical framework. More research needs to be undertaken to develop this approach to modelling. In particular, the need to include every nation in the simulation model is required. A summary of the base run for the globe and a nation (Scotland) is presented in Tables 2.1 and 2.2.

Table 2.1 A summary of the global variable for the hierarchical model

Year	Actual popn (billions)	Predicted popn (billions)	Actual GWP ($ trillions)	Predicted GWP ($ trillions)	Actual CO_2 (ppmv)	Predicted CO_2 (ppmv)
1950	2.55	2.52	3.8	5.5	275	275
1960	3.04	3.53	6.1	9.0	315	335
1970	3.70	4.60	10.1	13.5	335	365
1980	4.46	5.77	14.1	24.6	337	397
1990	5.30	6.96	18.8	20.9	360	430

Table 2.2 National state (Scotland) variable for the hierarchical model

Year	Actual popn (millions)	Predicted popn (millions)	Actual GDP (£ millions)	Predicted GDP (£ millions)	Actual CO_2 (ppmv)	Predicted CO_2 (ppmv)
1950	5.15	5.34	20 000	17 947	275	270
1960	5.15	5.34	21 000	19 107	315	546
1970	5.15	5.34	22 000	20 230	335	546
1980	5.15	5.34	23 240	23 522	337	546
1990	5.10	5.34	30 035	20 435	360	546

It will be observed that on the basis of the data, the global/national model performs reasonably well. The gloomy forecasts are based on a business-as-usual scenario and, as in many simulation models, it is possible to introduce policy options to enquire into the way in which the models of the system may behave if politically and ethically sound environmental policies are pursued. Several simulation experiments were performed with the model and one sustainable corridor for the world and the national economies was located.

The sustainable corridor whereby demographic and economic systems live within the world's ecological carrying capacity was located by a judicious choice of policies and parameter changes. This corridor required several policies to be introduced simultaneously: first, by constraining the world's population to approximately 10 billion people; next, by assuming an equal distribution of material resources, that is, altering the current world trade patterns. Third, by reducing resource consumption and associated CO_2 pollutants; and fourth, by investing heavily in renewable technologies especially with regard to maintaining the natural capital of the earth. It is then possible to achieve a sustainable future. Simultaneously, at the national scale, population migration will have to be controlled and altering taxation by introducing ecotaxation will also aid the national economy and ecology to be sustained. The results of these changes ensure – at least in the model – a sustainable future for both the globe and one nation. Obviously, further research including all nations is required. If the developed model proves its mettle, then the arduous task of moving from a simulated work to activating policies in the real world must begin.

We used Scotland as a case study as part of the global/national simple dynamic hierarchical model integrating global and national economies. It has been demonstrated that if we are to develop a socially just, sound economic system within the ecological carrying capacity of the earth, then some major planning problems will have to be addressed now rather than later. These planning problems include population change; atmospheric alterations of the global climate, especially the carbon dioxide burden; biodiversity; and natural resource use for current and future generations. These problems are part of the process of making development sustainable as identified in the Brundtland Report (WCED, 1987).

At the national level many nations have developed their own strategies for sustainable development. In the UK, for example, successive governments have promoted the idea of sustainable development. Similarly, in Australia the concept of ecologically sustainable development has been taken up. In both countries the need to include local communities, governments and businesses as one way of securing sustainable economic development is being pursued. The current hierarchical model still requires the integration of economic–ecological interactions at a local level. At present, however, it is possible to explore several scenarios of future development and see which are sustainable and which are not. Once the model is further refined and developed, the methodological and political implications of some of the futures need to be examined and discussed. At present it would appear that the vast economic machinery of the global economy has brought untold wealth to a rich minority; it has also improved the living conditions of many people in the developing world. It should be noted that the price of this pattern of economic development has been extracted from both ecology and the rest of society. The current patterns of economic development have been inequitable and a growing number of people are now left in absolute poverty and in squalid living conditions in an impoverished environment. This pattern of exploitation of people and their environment is part of a continuing historical process, but it need not continue (Brandt, 1980). Concerted efforts by many individuals and groups are urgently required so that the global economy can be redirected to improve the lot of all people now and in the future within the constraints of ecological systems. Given sufficient political will and action, the patterns of sustainable development can be achieved, although in the light of recent political negotiations at Kyoto, Bonn and Genoa in 2001 the political will to redirect the global economy is not as strong as it could be.

Concluding comment

This chapter has reported on some of the research findings from an ESRC-funded project into measuring and modelling sustainable development (Moffatt et al., 2001). It has described the way in which it is possible to combine global and national level modelling into a coherent scheme by use of the theory of sustainable corridors and then by developing McMichael's descriptive model into an operational model. By using system dynamics and other techniques such as input–output analysis (not described here), it is feasible to develop a set of models that capture the essence of sustainable development. This means trying to combine ecological and economic systems into a coherent whole while simultaneously permitting different future scenarios to be explored. The latter are based on a planning system which is socially just, transparent and democratically accountable (Daly, 1977). The model described in this chapter integrates global and national economic–ecological interactions and explores, albeit at a crude level of aggregation, Scotland as a nation within a global system of nations.

Obviously, there are several weaknesses in the model. Further theoretical and empirical work is essential so that the model's predictions and the actual data are closer together. This is especially true of the CO_2 burden, which as a concentration should be approximately the same for Scotland as for the rest of the world. Next, including all the world's nations into the model can be undertaken – but this task remains to be completed. The current model integrating Scotland with the global system is not, as yet, connected to the smaller geographical scale commonly referred to as the regional and local levels. It is often at this scale that many policy-makers and environmental mangers actually operate. It is also at this local scale that the lives of individuals are affected by changes in the ecology as well as in the global economy. Current research is ongoing to integrate local with national and global work, but more funding is required. Similarly, ways of integrating different measures of sustainable development into useful indicators of change are described elsewhere and the possibility of using fuzzy set logic, orientors (Moffatt, 2001) and four-dimensional geographical information systems to resolve these problems are being developed.

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3 Modelling long-term sustainability

Kaoru Yamaguchi[1]

Introduction

In the book *Beyond Walras, Keynes and Marx* (Yamaguchi, 1988) I tried to synthesize three economic paradigms in the industrial age: neoclassical, Keynesian and Marxian, under a general equilibrium framework, and presented a new economic paradigm suitable for the information age. Through the work, my interest has gradually shifted toward sustainability of the new economy. This shift of interest resulted in the book *Sustainable Global Communities in the Information Age* (Yamaguchi, 1997), in which I have contributed a chapter entitled 'Sustainability and a MuRatopian Economy'. In the chapter, sustainability is newly defined in terms of physical, social and ecological reproducibility from a general equilibrium point of view developed in Yamaguchi (1988). At that time, I had no tools or software to enable me to model my framework of sustainability for further computational analysis and simulation.

Soon afterwards, I happened to encounter the book *Beyond the Limits* (Meadows et al., 1992), which explores world sustainability by applying simulation results of the World3 model. The model was constructed by computer software called STELLA, which runs on Macintosh. I was amazed by its ability to build complicated models easily, and gradually became interested in the software itself, which can handle complex socioeconomic dynamics without knowing computer languages such as C and C++. The World3 model was an extended version of the World Model, which was originally developed by Jay Forrester in his book *World Dynamics* (Forrester, 1971). The original model was created by computer software called DYNAMO Compiler. The dynamic modelling method, which had been developed by Jay Forrester in the 1960s at the Sloan School of Management, MIT, is now widely known as system dynamics (SD).

Mathematically speaking, system dynamics is a modelling algorithm and method by which dynamical systems of difference and differential equation are numerically solved, and solutions are easily visualized by a computer so that further analytical simulations are made possible. In this sense, SD can cover many dynamic fields such as physics, chemistry, medicine, biology, ecology, business management, economics, environment and so on. So far, several SD softwares have been developed for use with personal computers, such as DYNAMO, STELLA, VENSIM and POWERSIM. Brief summaries of these four softwares are found in the appendices of *Modelling the Environment* (Ford, 1999). The reader can also find more specific software information on the Internet.

Using VENSIM software, this chapter tries to build an SD model of sustainability in terms of physical, social and ecological reproducibilities. To be specific, a macroeconomic growth model is first employed as a starting point. Then the meaning of sustainability is clarified step by step by expanding the model from a simple growth model to a complicated ecological model. As an implementation of the analysis, it is shown that continued economic growth is unsustainable in the long run as long as non-renewable resources are needed. The original draft was mostly written while I was visiting the Hawaii Research Center for Futures Studies, University of Hawaii, at Manoa, in March 2001 at the invitation of its director, Dr James Dator. Hawaii turned out to be a good place for me to consider sustainability. Since Hawaii became the fiftieth US state in 1959, only just less than a half century has passed. Yet its economy, with a rapidly increased population of 1.2 million islanders, needs more than 5 million tourists and their food annually for its survival, while dumping as much garbage in its small islands. Can Hawaii be sustainable for the twenty-first century and beyond? Why did Easter Island in the southern Pacific Ocean suddenly collapse: overpopulation, lack of food, water and natural resources, wars, or epidemics? The following sustainability model is developed with these questions in mind.

A macroeconomic growth model

A step-by-step modelling of sustainability starts with a simple macroeconomic growth model which can be found in macroeconomic textbooks. It consists of the following five equations.

$$K_{t+1} = K_t + I_t \quad \text{(Capital accumulation)} \tag{3.1}$$
$$Y_t = (1/v)K_t \quad \text{(Production function)} \tag{3.2}$$
$$C_t = cY_t \quad \text{(Consumption function)} \tag{3.3}$$
$$S_t = Y_t - C_t \quad \text{(Saving function)} \tag{3.4}$$
$$I_t = S_t \quad \text{(Equilibrium condition)} \tag{3.5}$$

Equation (3.1) represents a capital accumulation process in which capital stock is increased by the amount of investment. Output is assumed to be produced only by capital stock in a macroeconomic production function (3.2). The amount of consumption is assumed to be a portion of output – a well-known macroeconomic consumption function (3.3). Saving is defined as the amount of output less consumption in (3.4). At the equilibrium investment has to be equal to saving, as shown in (3.5); otherwise output would not be sold out completely or in a state of shortage. These five equations are simple enough to describe a macroeconomic growth process. Most of the symbols used in the above equations should be familiar to economics and business researchers. The precise meaning of these variables, however, is usually left unexplained in the textbooks. SD modelling, on the other hand, requires precise specification of their units, as defined in Table 3.1, without which it is impossible to construct a model.[2]

Table 3.1 Unknown variables and constants (1)

Category	Symbol	Notation	Unit
Unknown variables	K_{t+1}	Capital stock	Machine
	Y_t	Output (or income)	Food/year
	C_t	Consumption	Food/year
	S_t	Saving	Food/year
	I_t	Investment	Machine/year
Constants	v	Capital output ratio (= 4)	Machine/(food/year)
	c	Marginal propensity to consume (= 0.8)	Dimensionless
Initial value	K_t	Initial capital stock (= 400)	Machine

A model is said to be at least consistent if it has the same number of equations and unknown variables. The above macroeconomic growth model consists of five equations with five unknowns and two constants. Thus it is consistent. Let us now consider how these equations are computationally solved. Starting with the initial condition of the capital stock K_t, numerical values are assigned from the right-hand variable to the left-hand variables as follows:

$$K_t \to Y_t \to C_t \to S_t \to I_t \to K_{t+1} \tag{3.6}$$

This is how the computer can numerically solve the equations of our dynamic macroeconomic model.

SD modelling and feedback loop

There are two types of equation in our macroeconomic growth model. One type is the equation of stock–flow relation which specifies a dynamic movement. Capital accumulation equation (3.1) is of this type. The other type is the equation of causal relation in which a left-hand variable is caused by right-hand variables (and constants). The remaining four equations in the macroeconomic growth model are of this type.

These two types of equation are clearly distinguished in SD modelling, as illustrated in Figure 3.1. A stock–flow relation is illustrated by a rectangular box that is connected by a double-lined arrow with a flow-regulating faucet, while a causal relation is drawn by a single-lined arrow. We can easily trace a loop of arrows starting from a rectangular box and coming back to the same box. Such a loop is called a 'feedback loop' in system dynamics. A feedback loop thus has to include at least one stock–flow equation. A simultaneous equation system, on the other hand, has only equations of causal relation and, accordingly, cannot have feedback loops. Without a feedback loop, a system cannot be dynamic.

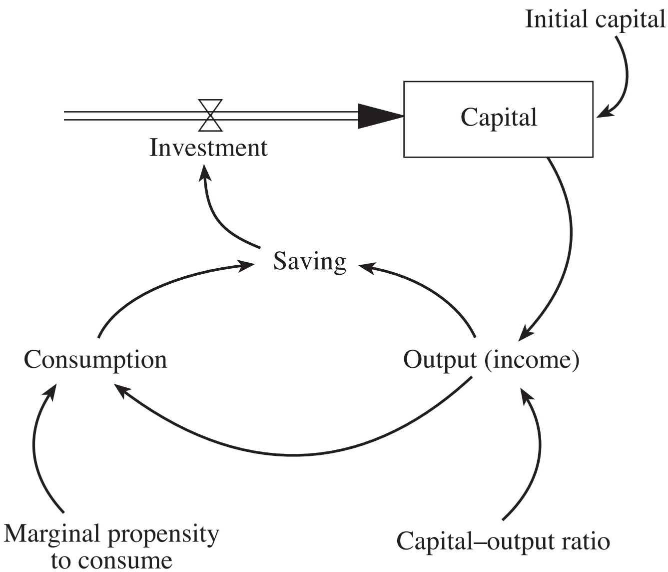

Figure 3.1 Simple macroeconomic growth model

A feedback loop is 'positive' if an increase in stock results in an increase in a returning stock, and 'negative' if a reduced amount of returning stock results. There are two feedback loops starting from the capital stock box in our macroeconomic model, and we can easily show that one loop is positive and the other is negative. Only a negative feedback loop corresponds with a computational trace of equation (3.6). In this sense, an SD diagram can be said to be a more powerful tool than a system of equations for identifying causal loops.

A steady state equilibrium

Since SD modelling is by its nature dynamic, it is very important to find a steady state equilibrium for structural consistency of the model. A steady state implies that all stocks stop changing, which in turn means that the amount of flows (to be precise, net flows) becomes zero. In other words, it is a state of no growth. In our model a steady state equilibrium of capital accumulation is attained for $K_{t+1} = K_t$. To calculate the steady state analytically, five equations of the model have to be first reduced to a single equation of capital accumulation:

$$K_{t+1} = \left(1 + \frac{1-c}{\nu}\right) K_t \tag{3.7}$$

Then, a steady state is easily shown to exist for $c = 1$; that is, the amount of output is all consumed and no saving is made available for investment. In our numerical example, a steady state equilibrium is attained at the values of $K^* = 400,\ Y^* = C^* = 100$, and $S^* = I^* = 0$.

Simulations of economic growth

Let us try to drive the economy out of this steady state equilibrium. A growth path can be easily found by setting 'a marginal propensity to consume' less than one; say, c = 0.8. Then 20 per cent of output (or income) is saved for investment, which in turn increases the capital stock by 20, which then contributes to the increase in output by 5 in the next period, driving the economy toward an indefinite growth. Table 3.2 shows how capital, output, consumption and investment grow at a growth rate of 5 per cent for c = 0.8.

Table 3.2 Macroeconomic growth model

Year	Capital	Output	Consumption	Investment
2001	400.00	100.00	80.00	20.00
2002	420.00	105.00	84.00	21.00
2003	441.00	110.25	88.20	22.04
2004	463.04	115.76	92.61	23.15
2005	468.20	121.55	97.24	24.31
2006	510.51	127.62	102.10	25.52
2007	536.03	134.00	107.20	26.80
2008	562.84	140.71	112.56	28.14
2009	590.98	147.74	118.19	29.54
2010	620.53	155.13	124.10	31.02

Physical reproducibility

Sustainability

In the above macroeconomic growth model, depreciation of capital stock is not considered, or it is regarded as net investment. In reality, capital stocks depreciate, and, to maintain the current level of output, some portion of income has to be saved to replace the depreciation. When the depreciation rate is high, a higher portion of income has to be saved at the cost of consumption. Here arises a sustainability issue of the economy: how to maintain a level of income for sustainable development? In this sense a sustainability issue can be said to be as old as human history.

After the UN Conference on Environment and Development (UNCED), widely known as the Earth Summit, which was held in Rio de Janeiro in 1992, 'sustainable development' became a fashionable phrase in our daily conversations. This might be an indication that our awareness of environmental crises such as global warming, acid rain, depletion of the ozone layer, tropical deforestation, desertification and endangered species has deepened. How, then, should a state of sustainable development be defined? Some proposed definitions are the following:

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (WECD, 1987, p. 63)

> A sustainable society is one that can persist over generations, one that is far-seeing enough, flexible enough, and wise enough not to undermine either its *physical* or its *social* systems of supports. (Emphasis in original) (Meadows et al., 1992, p. 209)

From an economist's point of view, the above definitions lack an interrelated view of production, consumption, society and environment. Sustainability is more comprehensively defined when all activities in the economy, society and nature are interpreted as reproduction processes, that is, in terms of physical, social and ecological reproducibility (Yamaguchi, 1988). A merit of this approach is that an economic structure of reproduction processes such as constructed in the general equilibrium framework (Yamaguchi, 1988) can be applied, since the most basic activity in any society is a reproduction process in which inputs are repeatedly transformed into outputs for consumption and investment each year. Sustainability is similarly presented here as an economic process of physical, social and ecological reproduction step by step. In this way the interrelationship between economic activities and environment will be integrated holistically.

Capital depreciation

Let us now introduce depreciation into the macroeconomic growth model (Table 3.3). The equation of capital accumulation (3.1) is expanded as follows:

$$K_{t+1} = K_t + I_t - D_t \quad \text{(Capital accumulation)} \quad (3.8)$$
$$D_t = \delta K_t \quad \text{(Capital depreciation)} \quad (3.9)$$

As Figure 3.2 shows, this can be easily done in SD modelling by adding an outflow arrow of depreciation from the capital stock. I_t in equation (3.8) is now reinterpreted as gross investment.

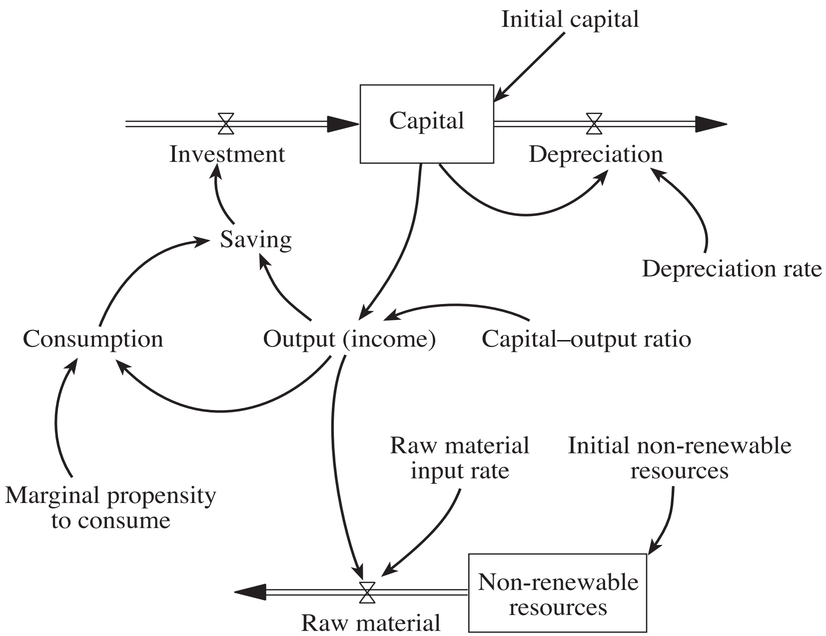

Figure 3.2 Physical reproducibility model

Table 3.3 Unknown variable and constant added (2)

New variable	D_t	Depreciation	Machine/year
New constant	δ	Depreciation rate (= 0.02)	1/year

Physical reproducibility implies that gross investment is greater than or equal to the depreciation.

$$I_t - D_t \geq 0 \qquad \text{(Physical reproducibility)} \quad (3.10)$$

The macroeconomic growth model with depreciation, which is here called the physical reproducibility model, now consists of six equations with six unknown variables: K_{t+1}, Y_t, C_t, S_t, I_t, D_t and three constants: ν, c, δ.

A steady state equilibrium

A steady state equilibrium is attained at $K_{t+1} = K_t$ or $I_t = D_t$, as easily shown by equation (3.8). To obtain the steady state analytically, all equations in the model have to be reduced to a single capital accumulation equation:

$$K_{t+1} = \left(1 + \frac{1-c}{\nu} - \delta\right) K_t \qquad (3.11)$$

A steady state condition is then easily obtained as follows (asterisks are added to the constants that meet this condition):

$$1 + \frac{1-c^*}{\nu^*} = \delta^* \qquad (3.12)$$

At the steady state, the 'marginal propensity to consume' becomes less than unitary; $c = 1 - \delta^* \nu^* < 1$, which implies that a portion of output has to be saved to replace the capital depreciation. One possible combination of numerical values for the steady state is $(\nu^*, c^*, \delta^*) = (4, 0.8, 0.05)$.

Simulations of economic growth

For the economy to grow out of the steady state; that is, $K_{t+1} > K_t$, at least one of the following three actions has to be taken:

1. Increase productivity $((1/\nu) > (1/\nu^*)$ or $\nu < \nu^*$.
2. Reduce consumption (or increase saving and investment) $c < c^*$.
3. Improve capital maintenance $\delta < \delta^*$.

As one such numerical example, let us take case (3) and reset the rate of depreciation at $\delta = 0.02$. In this case, the economic growth rate becomes 3 per cent. As Figure 3.3 illustrates, during the twenty-first century capital stock keeps increasing from $K_{2001} = 400$ to $K_{2101} = 7687$ and so does output, from $Y_{2001} = 100$ to $Y_{2101} = 1921$, more than 19-fold! Can such growth be sustainable?

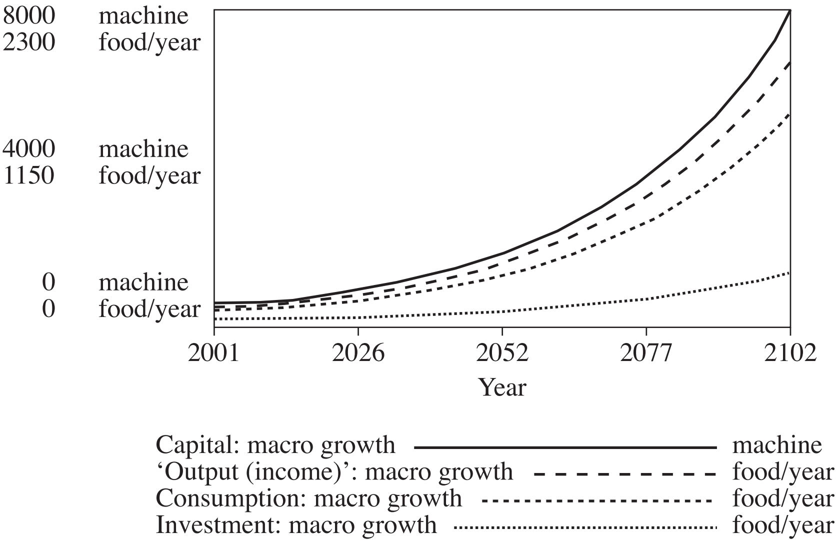

Figure 3.3 *A simulation for economic growth*

Non-renewable resource availability

The physical reproducibility condition (3.10) presupposes an availability of non-renewable natural resources (see Table 3.4) which is represented by the following equations:

$$R_{t+1} \equiv R_t - \Delta R_t \quad \text{(Non-renewable resources depletion)} \quad (3.13)$$

$$\Delta R_t = \lambda Y_t \quad \text{(Non-renewable raw material input)} \quad (3.14)$$

For simplicity, let us assume that non-renewable resources are represented by fossil fuels such as coal, gas and oil whose units are uniformly measured by a ton. Then, λ is interpreted as an input amount of fossil fuels necessary to produce one unit of output.

Table 3.4 *Unknown variable and constant added (3)*

New variable	R_{t+1}	Non-renewable resource	Ton
New constant	λ	Raw material input rate (= 0.05)	Ton/food
Initial value	R_t	Initial non-renewable resource (= 1000)	Ton

Assuming that equations (3.13) and (3.14) are reduced to one equation, we now have seven equations for seven unknown variables and four constants. Hence the model is shown to be consistent.

Let us next consider the existence of a steady state equilibrium. There are two state variables K_{t+1} and R_{t+1} in the model. A steady state of capital accumulation is not affected by the introduction of non-renewable resources, while a steady state of non-renewable resources implies $R_{t+1} = R_t$, which in turn means $\Delta R_t = \lambda Y_t = 0$ or $Y_t = 0$. On the other hand, a steady state equilibrium of capital stock implies a positive amount of output; that is, $Y_t > 0$. A contradiction arises! Hence it is concluded that a macroeconomic growth model with non-renewable resources cannot have a steady state equilibrium by its nature. To make the model feasible, the existence of a steady state equilibrium of non-renewable resources has to be conceptually given up. Or, non-renewable natural resources have to be assumed to be available at any time in the economy so that the earth's limited source of non-renewable resources is not depleted; that is,

$$\sum_{t=2001}^{\infty} \Delta R_t < R_{2001} \qquad \text{(Non-renewable resource availability)} \qquad (3.15)$$

Simulations for sustainability

Non-renewable resources are continuously depleted even at a steady state equilibrium of capital accumulation, contrary to a general belief that they are not in a non-growing economy. At the steady state equilibrium set by the condition (3.12) the initial non-renewable resources $R_{2001} = 1000$ constantly diminish by one half a century later; that is, $R_{2101} = 500$. This can easily be seen by a simple calculation. Since the economy is at the steady state, the output level remains constant at $Y_t = 100$. Hence, $\Delta R_t = \lambda Y_t = 0.05(100) = 5$ and non-renewable resources are depleted by five tons every year. Over a century they will be depleted by 500 tons. It is very important, therefore, to understand that a steady state equilibrium is not sustainable in the long run. In fact, a simple calculation shows that non-renewable resources will be totally exhausted over two centuries; that is, by the year 2201 we will have $R_{2201} = 0$.

To show how fast non-renewable resources deplete in a growing economy, a depreciation rate is reset to $\delta = 0.02$ and the economy starts growing at the rate of 3 per cent. In this case, non-renewable resources will be totally depleted in the year 2066; that is, at the beginning of the next year we will have $R_{2067} = -5.813$.

How can we circumvent such a rapid depletion of non-renewable resources and stay within the limits of resource availability and physical reproducibility? First, an efficient use of non-renewable natural resources has to be invented. For this, an introduction of long-term management of resources will be necessary. Second, substitutes for non-renewable resources have to be discovered or newly invented through technological breakthroughs. For this, research and development of new technology have to be oriented in this direction. The issue of substitutes for non-renewable resources will be more fully analysed in the next section.

Feedback loop for non-renewable resource availability

What will happen if the development of substitutes is delayed or if it fails? To overcome diminishing non-renewable resources, two self-regulating forces might appear in the economy. The first and more direct force is to curb the raw material input rate λ. In a market economy, this might emerge as an increase in prices of non-renewable resources so that their use will be regulated. In SD modelling, this self-regulating force can be easily implemented by drawing an arrow from a stock of non-renewable resources to a constant of the raw material input rate λ and defining a table function as follows:

$$\lambda = \lambda\left(\frac{R_t}{R_{initial}}\right) \tag{3.16}$$

The second and more indirect force might appear as a reduction of productivity as non-renewable resources begin to be exhausted. In other words, a productivity which is defined as $1/\nu$ might begin to decline. In SD modelling, this self-regulating force can be easily implemented by drawing an arrow from non-renewable resources to a capital–output ratio and defining a table function as follows:

$$\nu = \nu\left(\frac{R_t}{R_{initial}}\right) \tag{3.17}$$

The second force of self-regulation is considered here as an example of the effect of diminishing non-renewable resources on the economy. It is assumed that productivity is not affected until non-renewable resources are depleted by up to 40 per cent. Then it begins to decrease as non-renewable resources continue to be depleted. Table 3.5 indicates one such numerical example of diminishing productivity (or an increasing capital–output ratio).

Table 3.5 A table function of capital–output ratio

$R_t/R_{initial}$	0	0.1	0.2	0.3	0.4	0.5	0.6–1
ν	20	16	12	8	6	5	4

Figure 3.4 illustrates the effect of such self-regulating forces. Output level attains its highest peak in the year 2043; $Y_{2043} = 337.53$ then begins to decrease. In the year 2093, the output level becomes less than its initial output level; $Y_{2093} = 98.15 < Y_{2001} = 100$. Apparently, at this lower level of output, the initial number of population would not be sustained. In other words, non-renewable resource availability and population growth become a serious trade-off, and either the preservation of non-renewable resources or population growth has to be sacrificed in the long run. To see this trade-off relation of sustainability more explicitly, the equation of population growth has to be brought into the model.

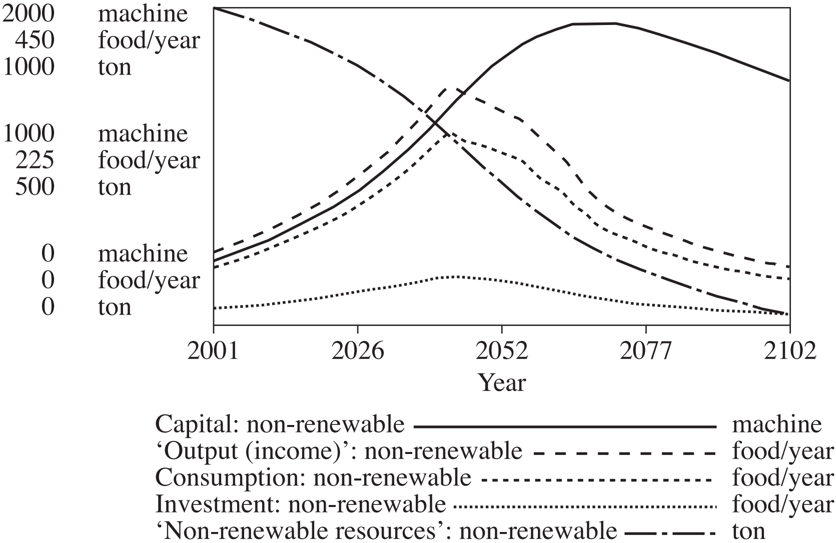

Figure 3.4 Physical reproducibility with non-renewable resources

Social reproducibility

Population growth is now embodied as follows in the model (see Table 3.6) in order to consider social reproducibility:

$$N_{t+1} \equiv N_t + \Delta N_t \qquad \text{(Population growth)} \quad (3.18)$$

$$\Delta N_t = \alpha N_t - \beta N_t \qquad \text{(Net birth = Birth – Death)} \quad (3.19)$$

For the survival of any society a minimum amount of consumption has to be produced in each period to reproduce its population.

Table 3.6 Unknown variables and constants added (4)

New variables	N_{t+1}	Population	Person
	L_t	Workers (labour force)	Person
New constants	α	Birth rate (= 0.03)	1/year
	β	Death rate (= 0.01)	1/year
	θ	Participation ratio of labour force (= 0.6)	Dimensionless
	ℓ	Output–labor ratio (= 0.4)	(Food/year)/person
	$\underline{c}$	Minimum standard of consumption (= 0.16)	(Food/year)/person
Initial value	N_t	Initial population (= 500)	Person

This amount need not be at subsistence level, but has to be enough 'to maintain the minimum standards of wholesome and cultured living' (Article 25, The Constitution of Japan). Let $\underline{c}$ be such a minimum standard of consumption per capita. Then, a total amount of consumption defined in the consumption function (3.3) is now replaced with the following:

$$C_t = \underline{c}N_t \qquad \text{(Minimum standards of consumption)} \quad (3.20)$$

With the introduction of this minimum standard of consumption that is demanded irrespective of the output level, the amount of saving defined in the saving function (3.4) might become negative as population and consumption increase. To warrant a non-negative amount of saving, the saving function has to be technically revised as follows:

$$S_t = max\{Y_t - C_t, 0\} \qquad \text{(Non-negative saving)} \quad (3.21)$$

Social reproducibility is now defined as a reproduction process in which minimum standards of consumption are always secured out of net output;[3] that is,

$$Y_t - D_t - \underline{c}N_t \geq 0 \qquad \text{(Social reproducibility)} \quad (3.22)$$

Note that whenever this social reproducibility condition is met, physical reproducibility (3.10) also holds; that is

$$I_t = S_t = Y_t - C_t = Y_t - \underline{c}N_t \geq D_t \qquad (3.23)$$

With the introduction of population, the number of workers or labor force is easily defined as a portion of the population:

$$L_t = \theta\, N_t \qquad \text{(Workers)} \quad (3.24)$$

Production function (3.2) is now revised with one that allows an inclusion of the labour force explicitly as a new factor of production.[4]

$$Y_t = min\left\{\frac{1}{v}K_t, \ell L_t\right\} \qquad \text{(Production function)} \quad (3.25)$$

Steady state equilibria and neoclassical golden rule

Our macroeconomic growth model is now getting a little bit complex. From the tables of unknown variables and constants (1) through (4) (Tables 3.1, 3.3, 3.4 and 3.6), nine unknown variables and nine constants are enumerated for nine equations. Therefore, the model is shown to be consistent.

Let us now consider a steady state equilibrium. There are three variables of stocks such as capital, population and non-renewable resources: K_{t+1}, N_{t+1}, R_{t+1}. As already mentioned, no steady state equilibrium is possible for non-renewable resources R_{t+1}. To see a steady state of capital and population simultaneously, let us introduce a neoclassical concept of per capita capital stock, which is defined as $k_t = K_t/N_t$. And let $n(= \alpha - \beta)$ be a net growth rate of population. Then the above eight equations, except for the non-renewable resources, are very compactly reduced to a single equation of per capita capital growth. To do so, equation (3.8) is first rewritten as

$$\frac{K_{t+1}}{N_{t+1}}\frac{N_{t+1}}{N_t} = \frac{K_t}{N_t} + \left(\frac{Y_t}{N_t} - \frac{C_t}{N_t}\right) - \delta\frac{K_t}{N_t} \quad (3.26)$$

A simple calculation, then, results in the following per capita capital growth equation:

$$k_{t+1} = k_t + \frac{1}{1+n}\left(min\left\{\frac{1}{\nu}k_{t,\theta\ell}\right\} - \underline{c} - (n+\delta)k_t\right) \quad (3.27)$$

A steady state equilibrium is obtained at $k_{t+1} = k_t$, which in turn yields two equilibrium levels of per capita capital:

1. A case in which per capita output $y_t = Y_t/N_t$ is constrained by per capita capital stock: $y_t = (1/\nu)k_t$. In this case, we have

$$\underline{k} = \frac{\underline{c}}{\frac{1}{\nu} - (\pi + \delta)} \quad (3.28)$$

2. A case in which output is constrained by workers: $Y_t = \ell L_t$. In this case, we have

$$k^* = \frac{\theta\ell - \underline{c}}{\pi + \delta} \tag{3.29}$$

It is easily shown that $\underline{k}$ is an unstable state of equilibrium, since $k_{t+1} < k_t$ for $k_t < \underline{k}$, and $k_{t+1} > k_t$ for $\underline{k} < k_t < k^*$. Thus, per capita capital k_t is, once displaced with the equilibrium, shown to decrease toward zero or converge to k^*. Meanwhile, k^* is a stable state of equilibrium, since $k_{t+1} < k_t$ for $k_t > k^*$.

$$k_t \rightarrow \begin{cases} 0, & \text{if } k_t < \underline{k} \\ k^* & \text{if } k_t > \underline{k} \end{cases} \tag{3.30}$$

Let us examine the stability of per capita capital numerically by allowing the economy to grow out of the initial steady state equilibrium. Depreciation and birth rates are set to $(\delta, \alpha) = (0.02, 0.03)$ and both capital stock and population are allowed to grow. It is then calculated that $\underline{k} = 0.7619$ and $k^* = 2$. Since the initial population is 500, an unstable equilibrium level of initial capital stock is obtained as $K_{2001} = \underline{k}N_{2001} = 380.95$. This means that if the initial capital stock is less than this amount, per capita capital stock tends to diminish toward zero, and the economy will get stuck eventually. For instance, when $K_{2001} = 380$ (and $k_{2001} = 0.76$), per capita capital decreases to $k_{2001} = 0.0296$, and eventually to zero.

On the other hand, if the initial capital stock is greater than this amount, per capita capital tends to converge towards a so-called 'golden rule level of capital' $k^* = 2$ as known in neoclassical growth theory (Blanchard, 1997). For instance, when $K_{2001} = 381$(and $k_{2001} = 0.762$), per capita capital increases to $k_{2001} = 1.898$, and eventually converges to a golden-rule level of capital: $k^* = 2$. It is interesting to note that only one unit difference of capital stock in our numerical example will result in a big difference in its growth path. When the initial capital stock is $K_{2001} = 380$, the economy will be destined to be trapped forever in a stagnant state, while an additional unit of capital stock will drive the economy upwards to its prosperity.

From now on let us reset the initial value of capital stock $K_{2001} = 400$, without losing generality, at the critical value of $K_{2001} = 381$. Figure 3.5 illustrates how capital stock, population, output, consumption and investment continue to grow simultaneously. Population grows at 2 per cent, so does a minimum amount of consumption regardless of the growth of capital stock and output level. Output is first constrained by the availability of capital stock, then from the year 2042, it is constrained by the availability of workers, which is in turn constrained by population growth. Thus the economy continues to grow at an increasing rate as the capital stock grows up to the year 2042 (from 2 per cent to 5 per cent), then it grows at a constant rate of population growth of 2 per cent. This is why there are some bumps on the output and investment growth paths around 2042.

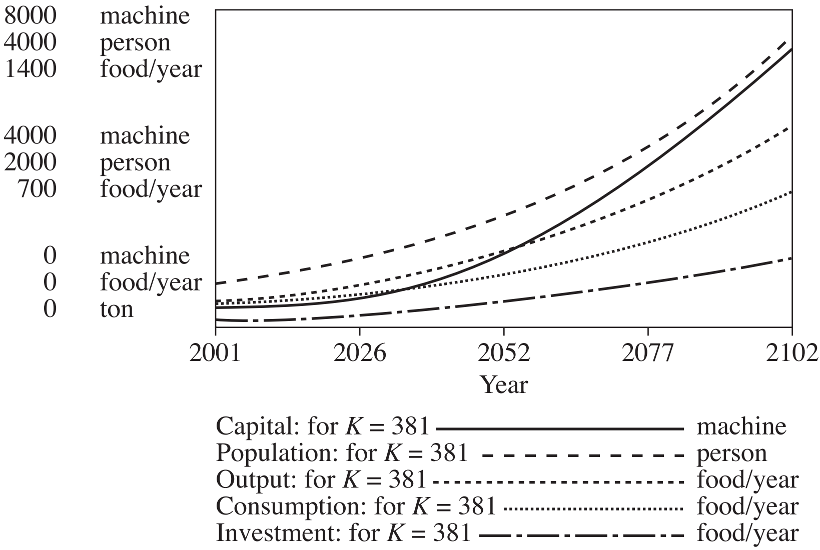

Figure 3.5 Golden rule of economic growth

Even at this growth rate of population, output level is still maintained at a higher level than a minimum amount of consumption so that social reproducibility is constantly sustained. Eventually, per capita capital growth will converge to a steady state of k^*, showing a long-run stability of capital accumulation. This is what is meant by the neoclassical golden rule of economic growth: a very elegant and optimistic theory of economic growth!

Can such growth be sustainable in the long run, indeed? The answer would be yes as long as non-renewable resources were disregarded and left out of the model. Remembering, however, that the neoclassical concept of a steady state allows a constant growth rate of 2 per cent, and the economy still keeps growing, depleting non-renewable resources, the answer would be absolutely no. In fact, non-renewable resources will be totally depleted in the year 2077 in our numerical example and become negative for the next year; that is, $R_{2078} = -13.31$. Even so, neoclassical growth theory keeps silent on this point, giving the impression that our macroeconomy can continue to grow and be stable in the long run.

Feedback loop for non-renewable resource availability

Availability of non-renewable resources is now taken into consideration. To make non-renewable resources available for future generations, let us introduce a similar feedback mechanism as implemented in the previous section for physical reproducibility; that is, as the non-renewable resources continue to be depleted, productivity worsens, and accordingly output is curbed, resulting in preserving non-renewable resources. Two constants in the production function (3.25) could influence productivity separately; that is, the capital–output ratio ν and the output–labour ratio ℓ. Instead of these two constants being affected separately, we introduce a table function that affects output level directly such that

$$Y_t = \text{Productivity}\left(\frac{R_{t+1}}{R_{initial}}\right) Min\left\{\frac{1}{\nu}K_{t,}\ \ell L_t\right\} \text{ (Production feedback)} \quad (3.31)$$

The table function of productivity is defined in Table 3.7. It is assumed that productivity is not affected until non-renewable resources are depleted up to 40 per cent, beyond which it begins to decrease gradually. Figure 3.6 illustrates the social reproducibility model with this feedback loop for non-renewable resources.

Table 3.7 A table function of productivity

$R_{t+1}/R_{initial}$	0	0.1	0.2	0.3	0.4	0.5	0.6–1
Productivity	0	0.1	0.2	0.4	0.6	0.8	1

As expected from the introduction of a productivity feedback loop, Figure 3.7 shows how growth paths of capital stock and net output (output less depreciation) are curved as non-renewable resources continue to be depleted. Non-renewable resources will in this way be preserved.

Feedback loop for social reproducibility

Yet, population can still continue to increase exponentially at a net growth rate of 2 per cent, so does a minimum amount of consumption for maintaining a per capita wholesome and cultured living standard: $C_t = cN_t$. Since net output is curved by a negative feedback loop of non-renewable resources, social reproducibility condition (3.22) will eventually be violated,

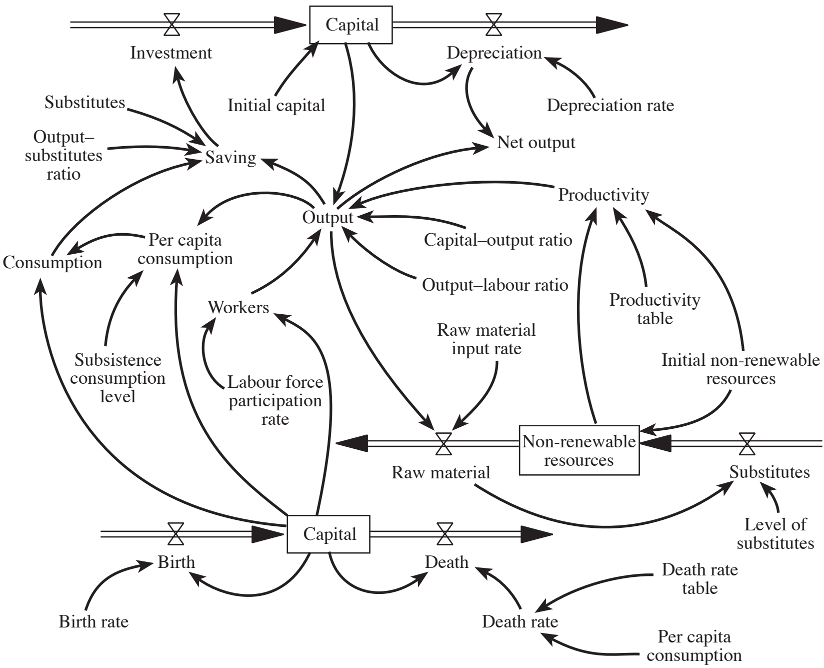

Figure 3.6 Social reproducibility feedback model

and a portion of the population might be forced to be starved to death. The violation of social reproducibility implies

$$Y_t - D_t - \underline{c}N_t < 0 \tag{3.32}$$

In our numerical example, this occurs in the year 2057 when $C_{2057} =$ 242.49 and $Y_{2057} - D_{2057} = 234.33$, so that consumption exceeds net output by the amount of 8.16, as roughly illustrated in Figure 3.7. The violation of social reproducibility implies that a smaller amount of net output has to be shared among people, forcing their level of living standard to be reduced. How far can such a per capita consumption be lowered? To maintain physical reproducibility, it is desirable to keep its level at which per capita consumption is equal to per capita net output. It would be imaginable, however, that starving people would eat everything available out of the output, including the reserved amount of capital stock for depreciation. Reflecting the situation of such a food shortage, per capita consumption has to be recalculated as follows:[5]

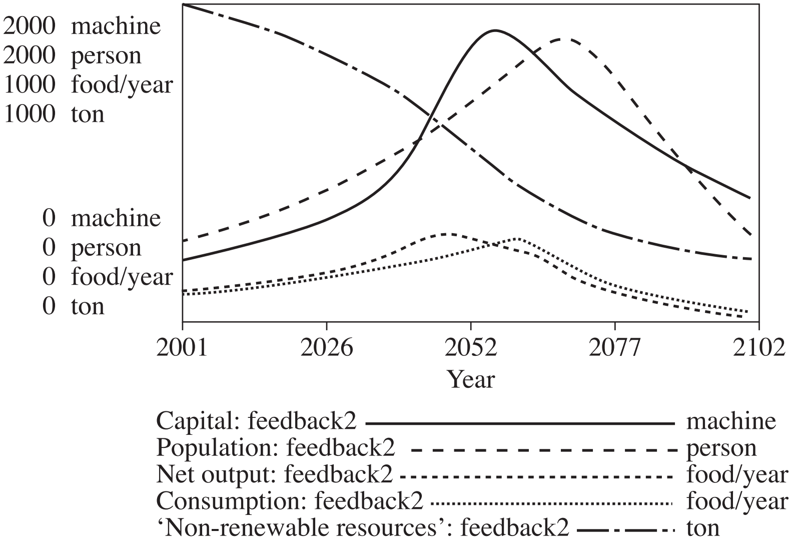

Figure 3.7 Growth paths with social reproducibility feedback

$$\text{Per capita consumption} = \min\left(\underline{c}, \frac{Y_t}{N_t}\right) \tag{3.33}$$

This formula enables per capita consumption to be lowered from the level of $\underline{c} = 0.16$. A decrease in per capita consumption may increase the death rate due to food shortage. This could happen unevenly among weaker people and children, or among countries whose economy is not wealthy enough to buy food, or among countries that are politically weaker and can be neglected. A table function of death rate in Table 3.8 is created to reflect such scenarios. For instance, whenever per capita consumption is reduced by half from the original minimum standard, the death rate is assumed to jump to 5 per cent from 1 per cent. In this way, a negative feedback loop of social reproducibility is completed. Figure 3.6 illustrates a social reproducibility model with this feedback loop of death.

Table 3.8 A table function of death rate

Per capita consumption $\underline{c} = 0.16$	0.14	0.12	0.1	0.08	0.06	0.04
Death rate β 0.01	0.015	0.02	0.03	0.05	0.07	0.1

Figure 3.7 reflects the effect of the feedback loop in relation to the death rate. The amount of consumption exceeds net output during the year 2056, and accordingly capital stock begins to decay. The difference between consumption and net output is the amount of capital depreciation that is allowed to be consumed by hungry people. A century later, the output level becomes only one quarter of its initial level; that is, $Y_{2101} = 25.71$ from $Y_{2001} = 95.25$. Population is almost pulled back to its original level of $N_{2001} = 500$; that is, it increases to its peak at $N_{2069} = 1793$, then begins to decline to $N_{2101} = 541.51$. The per capita consumption level has been maintained at $\underline{c} = 0.16$ until the year 2059, then begins to decline to the level of 0.0474 in the year 2101 (a 70 per cent decrease!), and the death rate jumps up to almost 10 per cent. In this way, all economic activities will be trapped. Is there a way to escape from this economic trap?

Substitutes for non-renewable resources

The economic trap mentioned above is basically caused by a diminishing availability of non-renewable resources. To see the effect, let us modify the equation of non-renewable resource depletion (3.13) so that it allows an inflow of substitutes for non-renewable resources (Table 3.9). Let SU_t

Table 3.9 Unknown variable and constant added (5)

New variable	SU_t	Non-renewable substitutes	ton/year
New constant	ν	Level of substitutes ($0 \le \nu < 1$)	dimensionless
	ρ	Output–substitutes ratio (=1)	food/ton

be an inflow amount of non-renewable substitutes, measured by a unit of ton/year, that can be added to the stock of non-renewable resources, and ν be a level of the substitutes such that ($0 \le \nu < 1$). Then equation (3.13) is replaced by the following:

$$R_{t+1} = R_t + SU_t - \Delta R_t \quad \text{(Non-renewable resource depletion)} \quad (3.34)$$

$$SU_t = \nu \, \Delta R_t \quad \text{(Substitutes for non-renewable input)} \quad (3.35)$$

Or, combining these two, we have

$$R_{t+1} = R_t - (1 - \nu)\Delta R_t \quad \text{(Non-renewable resource depletion)} \quad (3.36)$$

Where do the substitutes come from? For the sake of simplicity, it is assumed that they are converted from the output by a factor of output–substitutes ratio. Saving function (3.4) then has to be revised as follows:

$$S_t = Y_t - C_t - \rho SU_t \tag{3.37}$$

Figure 3.6 illustrates the SD modelling implementation of the substitutes for non-renewable resources.

Several simulations are done under such circumstances to attain the growth paths of the golden rule of capital accumulation illustrated in Figure 3.5. It turns out that at least 400 unit machines of initial capital stock are needed, for a 80 per cent level of substitutes, to drive economic growth initially. So the initial capital stock is reset again to $K_{2001} = 400$. Even so, if a level of substitutes is set higher than 80 per cent, the economy again turns out to be trapped. This is quite a surprising result, because a higher rate of substitutes is supposed to preserve the non-renewable resources. A moment of thought clarifies the reason. A higher level of substitutes subtracts a larger portion of output, and capital accumulation begins to decline with less saving and investment.

On the other hand, a lower level of substitutes depletes non-renewable resources faster, reducing productivity and output. Again, the economy is trapped somewhere in the middle, and cannot attain the golden-rule growth paths over the entire twenty-first century. Only when the level of substitutes is 80 per cent can the economy recover from the economic trap that is caused by a negative feedback loop of non-renewable resources as illustrated in Figure 3.7, and once again begin to attain the golden-rule growth paths for the entire twenty-first century.

However, this is only to postpone the problem of the economic trap to the twenty-second century. Moreover, there will be no way to escape from the economic trap at that time, no matter how much the output–substitutes ratio is reduced and saving and investment is restored. In other words, the economic trap will eventually appear at the beginning of the twenty-second century. This reveals exactly the same structure as in the growth paths with social reproducibility feedback in Figure 3.7, except that a time scale is this time elongated over two centuries. Substitutes for non-renewable resources cannot be an economic saviour in the long run.

Ecological reproducibility

Production and consumption activities as well as capital accumulation as formalized above produce as by-products consumer garbage GC_t, industrial wastes GY_t and capital depreciation dumping GK_t. These by-products are in turn dumped onto the earth or scattered around the atmosphere and ultimately accumulated in the environmental stock called the sink, SK_{t+1}. Some portion of the sink will be naturally regenerated (or recycled) and made available as a renewable resource stock that is called source, SR_{t+1}. As a typical example, we can refer to photosynthesic processes in which tropical forests and trees grow by taking carbon dioxide (industrial wastes) as inputs and producing oxygen as a by-product output.

These three dumping processes together with an extracting process of non-renewable resources now form an entire global environment *Env*, consisting of the earth's sink and source. Hence the formation of the entire global environment might be appropriately considered as an ecological reproduction process which is symbolically illustrated as

$$(\Theta\Delta R_t \oplus GC_t \oplus GY_t \oplus GK_t \Rightarrow Env\,(SK_{t+1} \rightarrow SR_{t+1}) \qquad (3.38)$$

To describe such an ecological reproduction process, we need to add the following seven equations (see Table 3.10).

$$SK_{t+1} \equiv SK_t + \Delta SK_t \qquad \text{(Accumulation of sink)} \qquad (3.39)$$

$$\Delta SK_t = GC_t + GY_t + Gk_t - (\varepsilon + \mu)SK_t \qquad \text{(Net change in sink)} \qquad (3.40)$$

$$GC_t = \gamma_c C_t \qquad \text{(Consumer garbage)} \qquad (3.41)$$

$$GY_t = \gamma_y Y_t \qquad \text{(Industrial wastes)} \qquad (3.42)$$

$$GK_t = \gamma_k D_t \qquad \text{(Depreciation dumping)} \qquad (3.43)$$

$$SR_{t+1} \equiv SR_t + \Delta SK_t \qquad \text{(Accumulation of source)} \qquad (3.44)$$

$$\Delta SR_t = (\varepsilon + \mu)SK_t - \lambda_1 Y_t \qquad \text{(Net change in source)} \qquad (3.45)$$

In order for an ecological reproduction process to continue, the total amount of consumer garbage, industrial wastes and capital depreciation dumping has to be less than the earth's ecological capacity to absorb and dissolve the sink, and those newly regenerated sources have to add enough renewable sources for continued production activities. Otherwise, the amount of sink begins to accumulate, and the accumulated sink will eventually cause the environment to collapse, or renewable sources will be completely depleted. Therefore, for sustainable ecological reproducibility, the following two conditions have to be met:

$$\sum_{t=2001}^{\infty}\left(GC_t + GY_t + GK_t\right) \leq \varepsilon \sum_{t=2001}^{\infty} SK_{t+1} \qquad \text{(Ecological reproducibility)} \qquad (3.46)$$

$$SR_{t+1} > 0,\ t = 2001, \ldots \qquad \text{Renewable source availability)} \qquad (3.47)$$

Fortunately, the ecological reproducibility of recycling the sink into sources and restoring the original ecological shape has been built in the

Table 3.10 Unknown variables and constants added (6)

New variables	SK_{t+1}	Sink	Source
	SR_{t+1}	Source	Source
	CC_t	Consumer garbage	Source/year
	GY_t	Industrial wastes	Source/year
	GK_t	Capital depreciation dumping	Source/year
New constants	ε	Natural rate of regeneration (= 0.15)	1/year
	μ	Recycling rate (= 0.05)	1/year
	λ_1 (= 0.6)	Renewable raw material input rate	Source/food
	γ_c	Garbage rate (= 0.5)	Source/food
	γ_y	Industrial wastes rate (= 0.1)	Source/food
	γ_k	Depreciation dumping rate (= 0.5)	Source/machine
Initial values	SK_t	Initial sink (=300)	Source
	SR_t	Initial source (=3,000)	Source

earth as a self-regulatory mechanism of Gaia (Lovelock, 1988). Consumer garbage, industrial wastes and capital depreciation dumping have been taken care of and disintegrated by a natural reproduction process, and the environment so far seems to have continued to restore itself to a certain degree. Therefore, sustainable development might be possible for the time being so long as the accumulated sink which the ecological reproduction process fails to disintegrate does not reach the environmental capacity of regeneration.

As production and consumption activities expand exponentially, however, such an environmental sink also continues to accumulate exponentially. And the naturally built-in ecological reproducibility of Gaia eventually begins to fail to regenerate the sink so that a portion of the sink will be left unprocessed. Sooner or later, an environmental catastrophe will occur, and the earth might become uninhabitable for many living species, including human beings. In fact, many environment scientists warn us that such a catastrophe has already begun, for instance, see Colborn et al. (1997).

Accordingly, to be able to stay within the limits of ecological reproducibility, first of all, the total amount of environmental sink has to be directly circumscribed within an environmentally regenerating capacity. Second, new development of recycling-oriented products has to be encouraged so that the size of the environmental sink will be reduced at every stage of reproduction and consumption processes. Third, hazardous and toxic wastes which cannot be naturally disposed of must be chemically processed and recycled safely at all costs. Then the equation of ecological reproducibility (3.46) is expanded as follows:

$$\sum_{t=2001}^{\infty}\left(GC_t + GY_t + GK_t\right) \le (\varepsilon + \mu) \sum_{t=2001}^{\infty} SK_{t+1} \quad \text{(Recycling of sink)} \quad (3.48)$$

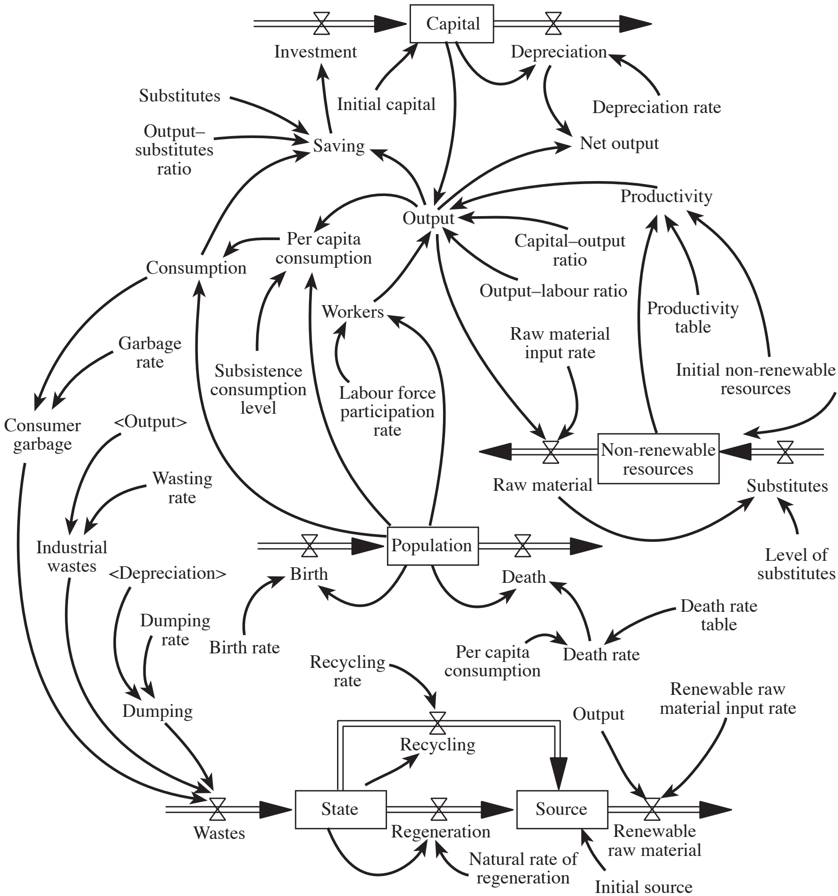

Figure 3.8   Ecological reproducibility model

A steady state equilibrium

A steady state equilibrium of ecological reproducibility is attained at $SK_{t+1} = SK_t$ and $SR_{t+1} = SR_t$, that is, $\Delta SK_t = \Delta SR_t = 0$. From the above equations of ecological reproducibility this implies:

$$GC_t + GY_t + GK_t = (\varepsilon + \mu)\, SK_t = \lambda_1 Y_t \tag{3.49}$$

A steady state of capital accumulation was already achieved in the section on physical reproducibility. Using the same numerical values of that steady state, and constant values assigned in Table 3.10, we have:

$$GC_t + GY_t + GK_t = 0.5 \cdot 80 + 0.1 \cdot 100 + 0.5 \cdot 20 = 60 \tag{3.50}$$
$$(\varepsilon + \mu)SK_t = (0.15 + 0.05)300 = 60 \tag{3.51}$$
$$\lambda_1 Y_t = 0.6 \cdot 100 = 60 \tag{3.52}$$

A steady state of population growth is attained when birth and death rates become equal, as already shown in the section on social reproducibility. Hence, a steady sate of ecological reproducibility is shown to exist and our model of ecological reproducibility becomes consistent. However, this is no longer true if non-renewable resources are considered explicitly. Figure 3.9 illustrates how an ecological steady state equilibrium is almost sustained throughout the twenty-first century until net output starts to decrease in the year 2082.

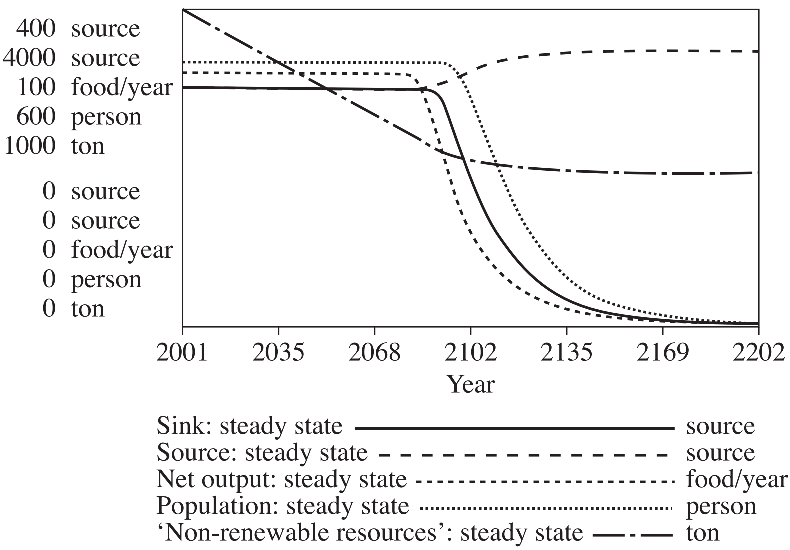

Figure 3.9 A steady state of ecological reproducibility

This decrease in net output is caused by diminishing productivity, which is in turn caused by the depletion of non-renewable resources. Accordingly, per capita consumption decreases and the death rate increases, resulting in a decline of population growth that begins to start in the year 2091, a decade later. Hence, an ecological steady state equilibrium becomes unsustainable in the long run if non-renewable resources are taken into consideration.

Simulations for a sustainable growth

When the depreciation rate and the birth rate are reset to the original values, that is $\delta = 0.02$ and $\alpha = 0.03$, respectively, the economy begins to grow. However, this growth path is eventually curbed by a decrease in net output, and declining population follows, as illustrated in Figure 3.10.

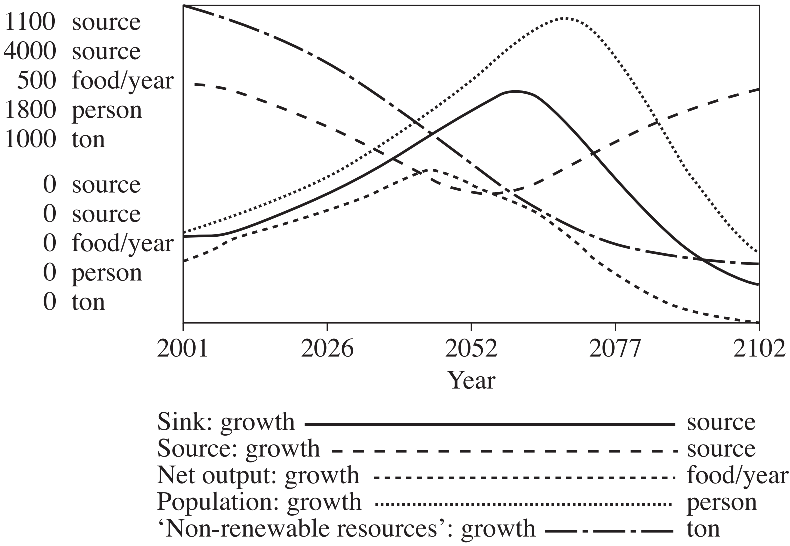

Figure 3.10 Growth paths of ecological reproducibility

To maintain the growth path, a level of substitutes might be again set at 80 per cent, as in the previous section. Then the net output and population start to grow once again for the entire twenty-first century. However, this sustained growth path will begin to cause ecological unsustainability, since the amount of sink continues to accumulate and sources are completely depleted by the year 2090, as illustrated in Figure 3.11.

Eventually some negative feedback loops might emerge to prevent such environmental catastrophes. For instance, the over-accumulation in the sink of chemical wastes will surely affect human health, and as a result the birth rate will be reduced and the death rate will be increased: an emergence of new feedback loops from sink to birth and death rates.

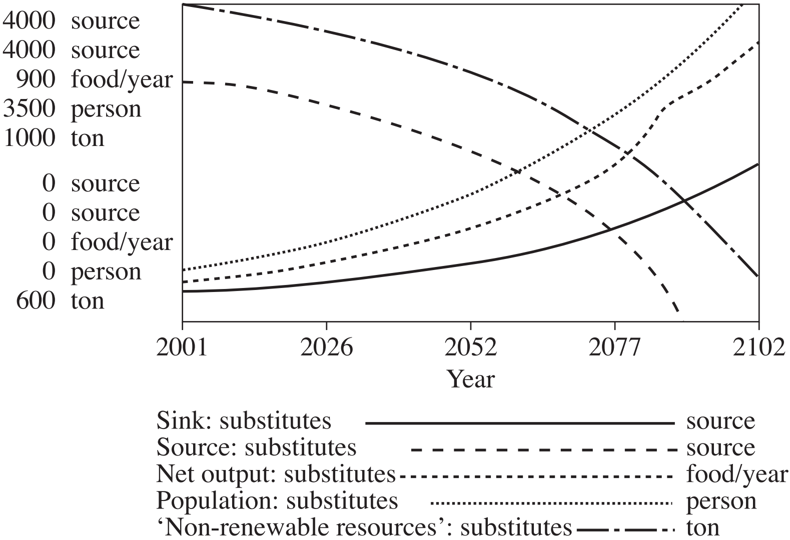

Figure 3.11 Growth paths with non-renewable substitutes

Since a feedback loop of the death rate has already been introduced in Table 3.8, let us consider here only a feedback loop of the birth rate as a table function in Table 3.11.

Table 3.11 A table function of birth rate

$SK_{t+1}/SK_{initial}$	0	0.5	1	2	3	4	5	10
Birth rate α	0.05	0.04	0.03	0.02	0.01	0.008	0.005	0.003

The birth rate is here assumed to decrease from the initial value of 3 per cent as the amount of sink continues to increase. When the amount of sink triples, it is assumed to become the same as the initial death rate of 1 per cent. In this way, a change in population as a whole is assumed to depend on the interplay between the accumulated level of sink and birth rate, and on the interplay between the availability of per capita consumption and death rate.

Meanwhile, as renewable sources continue to be depleted, output will be curbed as in the case of the depletion of non-renewable resources: a feedback loop from source to output. Let us consider such a feedback loop by introducing a second table function of productivity, called an ecological productivity or productivity 2, as defined in Table 3.12.

Table 3.12 A table function of ecological productivity

$SR_{t+1}/SR_{initial}$	0	0.1	0.2	0.3	0.4	0.5	0.6–1	2
Productivity 2	0	0.1	0.2	0.4	0.6	0.8	1	1.2

The table function is assumed similarly as in Table 3.7 such that productivity is not affected until renewable sources are depleted by 40 per cent, beyond which they begin to decrease gradually. Since renewable source could increase beyond the initial amount due to recycling and natural regeneration, productivity is also assumed to increase by 20 per cent in that case.

The equation of the production feedback (3.31) may now be redefined as:

$$Y_t = \text{Productivity}\left(\frac{R_{t+1}}{R_{initial}}\right)\text{Productivity 2}\left(\frac{SR_{t+1}}{SR_{initial}}\right)\min\left\{\frac{1}{\nu}K_t, \ell L_t\right\} \qquad (3.53)$$

This implies that output level is affected by the remaining ratios of both non-renewable resources and renewable sources.

By newly introducing these two feedback loops, ecological reproducibility could be restored by avoiding the problems of the over-accumulation of the sink and the depletion of renewable sources and non-renewable resources. To see this possibility, Monte Carlo or multivariate sensitivity simulations are done over two constants: an output–substitutes ratio and a level of substitutes for non-renewable resources. To be specific, each constant value is randomly chosen between 0 and 1 according to the random uniform distribution, and simulations are repeated 200 times. Figure 3.12 shows the simulation result of confidence bounds by the growth path of population. A line in the middle range of the graph indicates a mean value of the population, which indicates that population growth cannot be sustained as a mean value. In fact, growth paths of population are shown to be unsustainable within at least 75 per cent of confidence bounds. In other words, even with the introduction of ecological feedback loops, it is very hard to find at random a sustainable path over the twenty-second century.

The Monte Carlo simulation shows that if we could find it, we would be very lucky! One such ecologically sustainable growth path over the next two centuries could be, with luck attained at the output–substitutes ratio of 20 per cent and 80 per cent level of substitutes for non-renewable resources, as illustrated in Figure 3.13. Even so, it would be burdensome to achieve such constant values in reality. How can we produce an 80 per cent level of substitutes for non-renewable resources such as oil and other

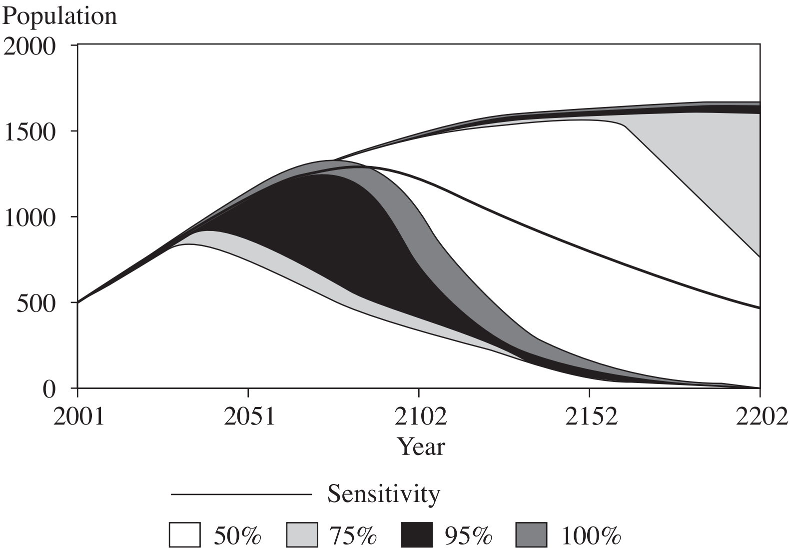

Figure 3.12 *Ecological sensitivity simulation of population*

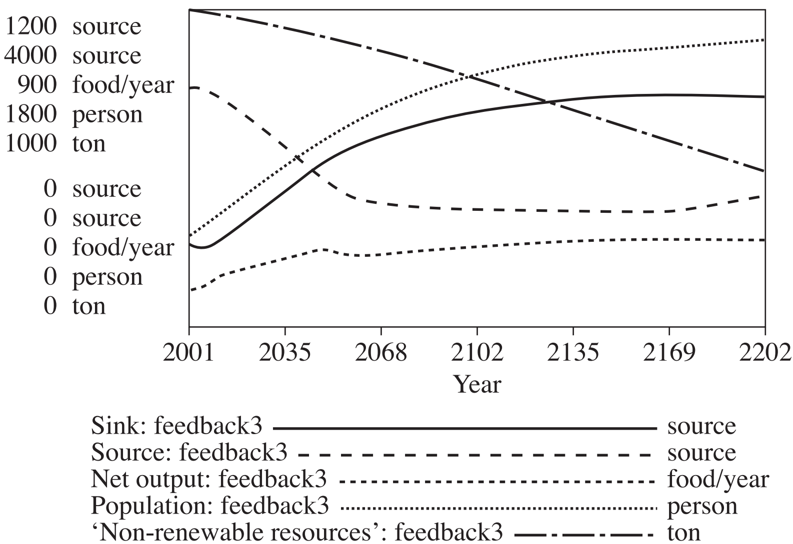

Figure 3.13 *Lucky growth paths with ecological feedback*

fossil fuels? How can we lower the output–substitutes ratio by producing substitutes more efficiently so that the amount of output is not excessively eaten up in the production of substitutes? In our numerical example, in order to attain the above ecological sustainability, the ratio has to be lowered to 0.2 from the initial value of 1 that is assumed in the previous section on social reproducibility. Even if this lucky sustainable path is found, there will be still no way of escaping from the economic trap as illustrated in Figure 3.7. The economic trap will eventually emerge in the twenty-third century so long as non-renewable resources continue to be depleted and production of substitutes continue to eat up the amount of output, leaving less and less amount for consumption, saving and investment. In fact, as soon as our numerical simulation in Figure 3.13 is extended into the twenty-third century, such an economic trap will begin to emerge on the horizon!

Conclusion

We have constructed a system dynamics model of long-term sustainability step by step from a simple macroeconomic growth model. Yet our simulations for sustainability are far from comprehensive, and numerical data used in the model are not the real ones. Hence, there could be many ways to expand or revise the model for further consideration of long-term sustainability of a region, a country, or the world. Whichever sustainability model is constructed, the logic developed in our model will remain the same. In this sense, the system dynamics model developed here would become genetic for sustainability modelling. One of the simulation results of the model is that no long-term sustainability is possible under the continued use of non-renewable resources, and it will remain a challenging issue for any sustainability model yet to be developed.

Notes

1. This chapter is partly based on the author's paper: 'A Step-By-Step System Dynamics Modeling Of Sustainability', submitted at the 19th International Conference of the System Dynamics Society, Atlanta, Georgia, USA, 23–27 July 2001.
2. In order to make the equation (3.5) congruous, a unit conversion factor ε of a unitary value has to be multiplied such that

$$I_t = S_t * \varepsilon$$

   in which ε converts a food unit of saving to a machine unit of capital investment; that is, it has a unit of machine/food dimension. This tedious procedure of unit conversion could be circumvented by replacing machine and food units with a dollar unit, as many macroeconomic textbooks implicitly assume.
3. To be precise, a unit of depreciation (machine/year) has to be converted into a unit of food (food/year) as follows:

$$Y_t - D_t/\varepsilon$$

4. Alternatively, a neoclassical production function such as a Cobb–Douglas production function can be used without any difficulty in SD modelling as follows:

$$Y_t = AK_t^a L_t^{1-a}$$

5. On the other hand, to maintain physical reproducibility, the equation of per capita consumption has to be changed to the following:

$$\text{Per capita consumption} = \min\left(\underline{c}, \frac{Y_t - D_t}{N_t}\right)$$

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4 Sustainability: can it be achieved? Is economics the bottom line?

Clem Tisdell

Introduction

To many, it will seem obvious that economics must be the bottom line in determining whether sustainability will be achieved in practice. There can be little doubt that in our increasingly market-driven and globalizing world, the bulk of individuals and groups act to promote their own economic interest. Economic self-interest is an extremely strong motivator of human actions. When economic self-interest clashes with (social) sustainability goals, these latter goals are unlikely to be met, and some government intervention may be desirable to bring private self-interest into line with the socially perceived interest. Intervention could, for example, take the form of taxes or charges on pollution emissions, or prohibitions on environmental damage backed up by penalties for non-compliance such as might apply to illegal tree-clearing.

But obvious formulation of problems is often deceptive. For example, the economic bottom line for business or an individual may be different to that for a society. Questions may also be raised about the extent to which individuals act in their own selfish economic interest, narrowly conceived, and the extent to which they are influenced by moral dimensions (Etzioni, 1988, 1991; Tisdell, 1997). The basis of human action is quite complex.

However, before giving further attention to this matter, the meaning, desirability and possibility of achieving sustainability is considered and an opinion is given as to whether the goal of sustainability is a useful guide to human action and public policy. Then attention turns to the sense(s) in which economics is the bottom line for sustainability, and how the economic bottom line(s) is (are) related to social and environmental bottom lines. Then relationships between values and sustainability are explored before examining whether sustainability can be achieved and what are the consequences if it cannot be.

Sustainability: an enigma or a clear-cut guide to policy? Weak and strong conditions for sustainability

Many individuals think it is desirable that policies be devised to achieve sustainability. But this objective is meaningless unless one specifies what should be sustained. Is it development that should be sustained, is it biodiversity or something else? In order to have any policy relevance, what is to be sustained must be specified.

Even then, one is not necessarily out of the woods because the object may not be stated in a precise or operational manner. For example, views differ about what constitutes development, so different views can exist about what aspects of development should be sustained. Clearer definitions are possible but these definitions will not satisfy everybody. For example, some economists (for example Tietenberg, 1988, p. 33) define sustainable development as development that ensures the income of future generations is not less than that of current generations. But this will not satisfy individuals who believe that development involves broader considerations. For example, if this aim of achieving non-declining incomes is met at the expense of personal freedom, reduced social cohesion or increasing personal stress and tension, many would not regard it as development at all. So one has to define terms carefully to avoid vagueness and misunderstanding. Some of the varied definitions are outlined in Tisdell (1993).

It has become fashionable to consider 'sustainability' as desirable in some general way. But sustainability of many things is undesirable. Few would want to sustain injustice, poverty and involuntary unemployment. Sustainability in itself is not a virtue, although there are several things that do seem worth sustaining, such as our relatively liberal society.

Having clearly defined the object to be sustained and having obtained agreement about this end, the next matter is to consider whether the purpose can be achieved and, if so, how. It is possible that what one wants to maintain cannot be sustained because of the operation of natural or social principles. For example, given the entropy principle, it may be impossible to sustain global economic growth in material production for ever, even though by careful choices we may sustain it for longer than otherwise.

A further problem is that if sustainability of several attributes is desired, it may be impossible to achieve this simultaneously. Sustainability of one attribute may have to be forgone to achieve sustainability of another. For example, some loss in biodiversity may be needed to sustain incomes. A trade-off between sustainability objectives is often necessary.

A question that has exercised the minds of some economists is how to achieve sustainable development in the relatively narrow economic sense of ensuring that the income of future generations is not less than that of present generations. Orthodox economists and neo-Malthusians give different answers to this question, but all agree that it depends on current generations leaving a suitable bequest for future generations. The difference of opinion is about what constitutes a suitable bequest.

Orthodox economists have generally seen the provision of man-made capital as the most suitable bequest for future generations. This capital is defined as the produced means of future production and consists of such items as factory machinery, tractors, dams, buildings, infrastructure and even education, although the material forms of capital until the 1950s tended to be stressed to the relative neglect of human capital. Karl Marx fervently believed that capital accumulation was the key to improving economic welfare. He was strongly in favour of the accumulation of capital, a message not lost on Stalin and Mao Zedong, but Marx objected to the capitalist market system on moral grounds.

In stark contrast to orthodox economists, neo-Malthusians believe that continued capital accumulation, while it might initially increase material welfare, is an unsustainable strategy because, in the long term, it is likely to impoverish humans. There are several ways this can occur. One is from the pollution generated by the transformation of natural and environmental resources into material commodities, including capital. The second is by the depletion of non-renewable resources used in the transformation process, so production suffers from shortages of natural resource inputs in the future. Third, natural and environmental resources may be damaged or diminished by the economic transformation process to such an extent that they can no longer complement economic production, or do so in a much-reduced way. Therefore economic production or productivity falls. Neo-Malthusians argue that the sustainability of future economic production and welfare depends increasingly on stocks of natural resources and environmental factors being sustained. Consequently, according to neo-Malthusians, it is becoming more important for the welfare of future generations to conserve natural and environmental resources rather than further accumulate man-made capital. This is especially so because the accumulation of man-made capital transforms and depletes natural resources and this capital lasts for a relatively short period, often not for the whole life of one generation of humans but, at most, usually for a few generations. While the relatively unrestrained conversion or transformation of natural resources to man-made capital may have been justified in the past, it is becoming increasingly inappropriate due to the continuing depletion of natural and environmental stocks (cf. Tisdell, 1999a).

The view attributed above to orthodox or conventional economists is sometimes said to be one that involves the imposition of weak conditions for sustainable development. Their view is that sustainable development can be achieved by transforming more natural resources into man-made capital. No particular limit or restriction needs to be imposed on this substitution. Furthermore, many orthodox economists are of the view that further substitution of man-made capital for natural capital is necessary for achieving sustainable economic development.

The view attributed above to neo-Malthusians is sometimes said to be one that involves the imposition of strong conditions for sustainable development. Their view is that further transformation of natural resources into man-made capital *may* endanger the welfare of future generations. This is because natural/environmental capital is to an increasing extent an irreplaceable contributor to economic production and human welfare. Man-made capital is becoming less satisfactory as a substitute for it, and in some cases is incapable of substituting. This means that the existing natural/environmental stock is becoming more precious as a basis for sustaining economic production and human welfare. Therefore, if we wish to sustain the welfare of future generations, we should be wary about irreversibly depleting this stock. We may do more to assist future generations by conserving this stock rather than by converting it into man-made capital.

The contrasting views of economists recommending weak conditions for sustainable development (orthodox economists) and of those claiming that strong conditions must be imposed (neo-Malthusians) in order to achieve sustainable development are summarized in Table 4.1.

Table 4.1 Economic conditions for achieving sustainable development

Weak conditions (orthodox economists)	Strong conditions (neo-Malthusians)
• Accumulation of man-made capital is to be encouraged because it provides a suitable productive bequest for future generations • One can be optimistic about future prospects given the promise of technological progress	• Natural and environmental resources need to be conserved as a suitable bequest to future generations • Conversion of these resources to man-made capital or their use for consumption may diminish the welfare of future generations • Caution is needed

So it can be seen that ‘orthodox’ economists and neo-Malthusians believe that a different economic bottom line applies today from the point of view of achieving sustainable development. But because economic production, consumption and capital accumulation are the life-blood of the capitalist system, the orthodox position prevails rather than the neo-Malthusian. Furthermore, because the employment of labour in the capitalist system depends on the level of economic activity and capital accumulation, and the maintenance of employment usually requires continuing economic growth (to counteract technological or similar sources of unemployment), labour interests also normally reject the neo-Malthusian viewpoint (cf. Tisdell, 1999b, ch. 6). The usually shortsighted nature of politics adds to this lack of support for the neo-Malthusian position. Despite this, the neo-Malthusian position, if not over-interpreted, may well be correct.

What is economics and is it the bottom line for sustainability or just one consideration?

Views about what economics is vary somewhat. But basically economics arises from the fact that human desires exceed the means or resources available to satisfy these and, consequently, relative scarcity exists. This relative scarcity calls for economizing. Dealing with the problem of scarcity involves both private decision-making and social issues. The effectiveness with which societies meet the challenge of scarcity depends on the effectiveness with which individuals make their economic decisions, and the adequacy of the social mechanisms that govern the use of the limited resources available to society. The market mechanism is just one of these social mechanisms.

Economics is a social science. It is more concerned with the social implications of individual decisions and those of businesses than with improving those decisions themselves. Detailed studies of decision-making and administration of businesses tend today to be more the concern of the fields of management and commerce than economics.

Nevertheless, given an economic perspective, economists would argue that any sustainability policies are unlikely to be adopted unless they are in the self-interest of individual consumers and businesses, assuming that implementation of such policies requires supportive action by these economic agents. Economics and finance frequently are the bottom line as far as individual economic agents are concerned. Unless the individual self-interest of economic agents is harnessed to implement sustainability objectives, these objectives are unlikely to be achieved.

Much depends on whether one believes that narrow self-interest or wider dimensions guide individuals. Most economics since Adam Smith (1776) has been developed on the assumption that businesses basically aim to maximize their own profit and consumers their utility or satisfaction. Thus from this point of view, if a sustainability objective is unprofitable for business, it will not be pursued. Although individual businessmen may agree that the objective is morally desirable, they may be unable to pursue it because doing so may threaten the survival of their business. In a highly competitive world, economic agents may have limited scope for pursuing virtuous ends. However, some economists have argued that in a competitive economic system, pursuit of self-interest will promote the collective good. This incidentally is not a view that I share – social intervention is required to ameliorate some of the worst features and failures of the market system.

Traditionally economists have argued that there are four ways to deal with economic scarcity:

1. Increase economic efficiency of resource use;
2. Ensure full employment (that is, the absence of involuntary unemployment);
3. Promote economic growth; and
4. To the extent that the distribution of income and opportunity is considered to be inequitable, alter this to change the burden of scarcity as between individuals, so as to promote social justice.

Today's economic rationalists are particularly keen on objectives (1) and (3) but more muted in relation to considerations (2) and (4). But the blind pursuit of objectives (1) and (3) only can add to social injustice. These objectives (summarized in Table 4.2) should be pursued as a whole package rather than individually, if social justice is to be promoted.

Table 4.2 Summary of traditional economics methods for reducing economic scarcity

1. Increase economic efficiency of resource use
2. Ensure full employment (that is, the absence of involuntary unemployment)
3. Promote economic growth*
4. If the distribution of income or opportunity is inequitable, alter this to change the burden of scarcity as between individuals, in order to promote social justice

* Neo-Malthusians argue that unless care is taken, economic growth can increase scarcity in the long term rather than reduce it.

Note that traditional objective (3) now worries neo-Malthusians. They argue that unless we are careful, the economic growth promoted by present generations is not sustainable. It may become unsustainable if it undermines the natural resource and environmental base on which the maintenance of economic activity depends. Thus today's economic growth could impoverish further generations. It may be incompatible with sustainable development.

Economic systems are embedded in social and natural systems and depend on these. Thus the sustainability of economic development (to the extent that it can be achieved) depends on a suitable degree of sustainability in social and biophysical systems. Government may be regarded as part of the social system and, as Adam Smith observed, law, order and good government are essential for economic progress. They are equally important for the achievement of sustainable economic development. So from this point of view, there are several bottom lines to be fulfilled to achieve sustainable development.

An additional consideration is that individuals might want to sustain attributes other than economic welfare. An enormous range of possibilities exists. Some may want to sustain particular cultures, others may wish to maintain biodiversity, or particular political systems and so on. But there may be no solutions that achieve all these aims simultaneously and intense social conflict may arise about their desirability. Not everyone is agreed that sustainability is good, or possible, and some of those who consider sustainability good cannot agree about what ought to be sustained. There is no escaping the centrality of values in social decision-making.

Values and sustainability

One's approach to valuing sustainability depends on the values to which one subscribes. Economists are anthropocentric in their value systems. In terms of the meaning of 'anthropocentric' given in *The Macquarie Dictionary*, economists view and interpret 'everything in terms of human experience and values'. Economics assumes 'man to be the final aim and end of the universe'.

Furthermore, the English liberal tradition, which dominates modern economics, assumes that the wishes of all individuals (humankind only) should count and that the role of economics is to suggest ways in which these wishes can be most fully satisfied given the limited resources available to satisfy these wishes. It involves humanism in so far as human interests predominate and appears to be based on the ethical doctrine of humanitarianism, 'the doctrine that man's obligations are concerned wholly with the welfare of the human race' (*The Macquarie Dictionary*, 1981, p. 863).

It follows that modern economics only pays attention to the conservation of other species and to maintaining ecological systems and nature inasmuch as individual humans value this. There is no moral obligation independent of human wishes to conserve nature.

This does not mean that economists will take no account of nature in conservation decisions. However, the only weight given to nature is bestowed on it by individual human wishes. Thus if enough individuals want whales to continue to exist and not be harvested, economists would take this into account as an economic value. But whales and other species have no rights to exist independent of human wishes.

Values influencing sustainability are to a large extent culturally determined and this is true in our society. It is also true for economic approaches, although proponents of economic valuation methods often fail to see how culturally influenced their techniques are.

For example, consider a common economic approach to determining whether a natural area or ecosystem should be protected or sustained. Economists might try to find out how much all individuals are willing to pay to conserve it. This is relatively democratic in that everyone counts. However, the playing field is usually not completely level because those who feel strongly in favour of its conservation may have little money and be able to pay little. Future generations are, furthermore, not directly represented. And not all individuals may be well informed about the value of conserving an ecosystem. Money sums are the arbiter in this situation involving willingness to pay.

This anthropocentric approach, however, will be alien to individuals with ecocentric values (sometimes called 'deep ecologists') who believe that there is a case for avoiding the destruction of species and ecosystems independently of human wishes. Such a view is involved in the 'land ethic' of Aldo Leopold (1966) or the view that humankind has a stewardship role in relation to nature (Passmore, 1974). This view rejects democracy as the sole arbiter of values, that is, popular opinions that run counter to these views. In fact, our society rejects popular opinion as an arbiter of social decision-making in a number of circumstances, for example when it is likely to infringe on fundamental human rights. So popular opinion should not be regarded as sacrosanct. Social values are complex and economic valuation fails to capture their full variation and nuances.

In the above cases, deep ecologists will be angry and disillusioned if the ecosystem under consideration for preservation contains unique species but its destruction occurs sanctioned by economic evaluation which indicates that development is the 'best' option because the net economic return from development exceeds the total willingness of individuals to pay for conservation of the ecosystem.

In cases such as this, while economic evaluation may identify the best economic outcome, the economic solution may fail to settle social conflict effectively. When social conflict exists about a sustainability objective (that is, about what ought to be retained), economics is limited in its ability to bring about conflict resolution. The economic input or bottom line will need to be subjugated in such cases to political input, or to arbitration and conciliation in which members of the legal profession are usually skilled.

The relationships between traditional economic values and other social values can be represented to some extent in Figures 4.1 and 4.2. Figure 4.1 indicates that anthropocentric economic values are only a subset of social values. In fact, they are only a subset of anthropocentric or man-centred values. This highlights Pigou's (1932) view that social policy decisions ought not as a rule be made solely on the basis of economic criteria.

Considering the potential for conflict between values of orthodox economists and those of 'deep ecologists', the possibility for a clash in values traditionally held by economists and those of others in society can be seen,

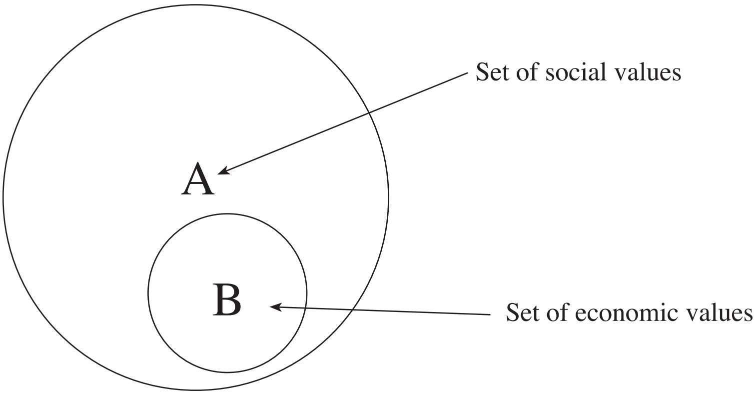


Figure 4.1 *Traditional economic values are anthropocentric and a subset of social values*

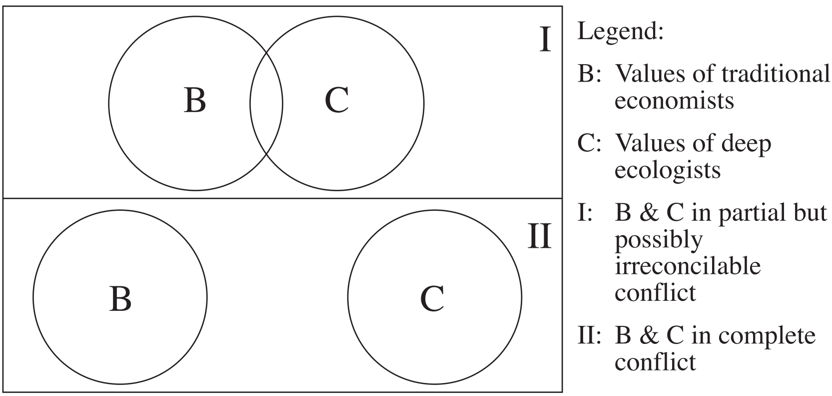
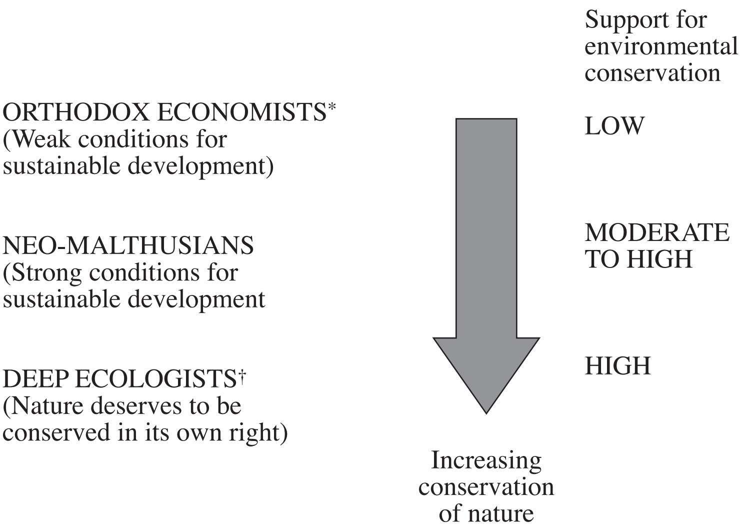


Figure 4.2 *Traditional economic values are likely to be in partial or in total conflict with values of deep ecologists*

as illustrated by Figure 4.2. Deep ecologists believe that all species have an intrinsic right to existence independently of their value to humankind. The worth of their continuing existence is not to be judged solely by their benefit to *Homo sapiens*. Other species and sentient beings should not be assessed or valued solely as instruments for the production of human satisfaction (cf. Sagoff, 1988; Leopold, 1979) as traditional economists are wont to do. Figure 4.2 illustrates two possibilities. If the rectangular set I in Figure 4.2 represents all values, those of traditional economists (set B) may show little overlap with those of deep ecologists (set C). Alternatively, where set II represents all values, there may be no overlap between those of traditional economists and deep ecologists. Either partial or complete conflict of values exists. Consequently, deep ecologists reject most economic techniques, such as social cost–benefit analyses, as instruments for social decision-making and for making policy choices.

Considering Figure 4.3 can highlight the significance of values in relation to the debate about sustainable development. The differences in emphasis of



* Values are anthropocentric.
† Values not purely anthropocentric, include strong ecocentirc values.

Note: Strategies for the objective of ecologically sustainable development (ESD) are likely to be towards the lower portion of the above spectrum.

Figure 4.3 Spectrum of emphasis on natural resource and environmental conservation orthodox economists and neo-Malthusian economists on the conservation of natural as well as environmental resources arise from differences of opinion about what is necessary to sustain the incomes or welfare of human beings. On the other hand, the desire of deep ecologists to conserve natural resources arises because the existence of all species is valued intrinsically. Lack of conservation of such resources may benefit humankind but will drive other species to extinction. Therefore, deep ecologists believe that humans should be prepared to make some economic sacrifice, if necessary, to conserve natural resources and save other species from extinction. They are, therefore, more strongly in favour of environmental conservation than neo-Malthusians, given their value-position.

Can sustainability be achieved?

The question ought to be raised of whether, even with the best intentions and knowledge, it is possible to achieve sustainable economic development or the sustainability of economic subsystems. Furthermore, what is to be done if sustainability cannot be achieved?

Barbier (1987) was probably the first to suggest that the sustainability of systems involving economic activity depended on their being able to satisfy three conditions. In his view, sustainable systems should be:

1. Economically viable;
2. Socially acceptable; and
3. Biophysically sustainable.

Only those systems, for example agricultural systems, that simultaneously satisfy these three conditions would, in his view, be sustainable.

While the above factors are all important considerations in social choice, the possibility exists that no available or possible systems may satisfy all these conditions. If available or possible agricultural systems for a particular region are considered, none may for example, satisfy all the conditions in the above set, or some may do so but only for a limited period of time.

In such circumstances, there may be no agricultural system that ensures long-term sustainability. This actually may be the normal situation. In such circumstances one has no choice but to accept the situation. However, some available systems may show a greater degree of sustainability than others. Consequently, if sustainability (in some sense) is a high priority, the policy-makers or planners can choose the technique or systems that are the most sustainable, even if complete sustainability is a dream. Clearly, many value judgements will be required in making such a choice.

The next difficulty that should be noted has to do with how we measure economic viability, social acceptability and biophysical sustainability. This is not nearly as straightforward as a superficial consideration of the matter might suggest. For example, is profit the appropriate indicator of economic viability? What if it is uncertain or variable? How is social acceptability to be measured? Is an agricultural technique that results in greater income inequality socially less acceptable, for instance? Conway (1985, 1987) assumes that this is so. But income distribution may not be the only indicator of social acceptability. Again biophysical systems have many attributes. Which ones are important for gauging their sustainability? In the case of agricultural systems, for instance, Conway (1985, 1987) uses the ability of the system to return to normal agricultural yields after it has been subject to environmental stress and the stress is removed. But it may not be the only possible measure. We do ourselves little service if we do not recognize the conceptual issues involved in making such concepts operational.

In addition, it should be noted that taking into account the physical entropy issues raised by Georgescu-Roegen (1971), it is only possible to achieve completely sustainable development on a global scale by confining resource use to the flow of flow resources and renewable resources provided by the sun. Use of resources beyond that level will lead to the biophysical 'running down' of resources. This will be slow if dependence on non-renewable resources is slight. Otherwise, it could be at a rapid rate. This implies that in many circumstances, the social choice is about how rapidly to run down the biophysical system. There is still, however, usually some available choice because some economic activities and techniques will run the system down at a faster rate than others. Note that depletion of the non-renewable part of the biophysical system need not imply that economic welfare necessarily continuously declines as this process continues. One can see, however, that the situation is complex, and that it can be very difficult, if not impossible, to achieve long-term biophysical sustainability. In addition, it is not really clear that this condition is absolutely essential for economic sustainability. For instance, within bounds, continuing technological progress can offset the economic consequences of resource depletion.

Concluding comments

From some points of view, economics does provide the bottom line in determining whether policies for achieving sustainability will be adopted. In dealing with sustainability, it is however important to know what one wants to sustain and to decide just how worthwhile it is sustaining. An influential body of economists believes that sustainable development is worth achieving but is divided about the best way of achieving this. Orthodox economists believe that only weak conditions need to be imposed on the conservation of natural and environmental resources whereas neo-Malthusians believe that strong conditions need to be imposed if sustainable development is to be achieved.

While economics is concerned with problems arising from resource scarcity and is a social science, it alone cannot provide solutions to sustainability issues. Economic systems are embedded in social and biophysical systems. Lack of sustainability in social and biophysical systems can imperil the sustainability of economic systems. So from this point of view, economics is just one of several bottom lines for sustainability.

Social values are to a large extent culturally determined. Orthodox economics is anthropocentric and encapsulates a particular set of 'liberal' values. It uses democratic-style methods for the purposes of social evaluation of conservation possibilities and rejects other types of evaluation, such as those favoured by deep ecologists, to justify conservation of biodiversity or ecological sustainability. In such circumstances, economics can only play a limited role in social conflict resolution – a wider perspective is needed which, to some extent, might be provided by members of the legal profession, politicians and social philosophers. As pointed out by the wise British economist, Arthur Pigou, in the early part of the twentieth century, economics is only a part of the process of social assessment. It is not the final arbiter (Pigou, 1932). So from this point of view, it is a part of the social evaluation process but not the bottom line, or just one of many bottom lines.

In summary, it has been pointed out that sustainability as such does not provide a clear-cut guide to policy. First one has to decide what is to be sustained. If this is agreed, it must be in an operational form. However, difficulties may still emerge since opinions may differ about how to achieve sustainability. This was illustrated by differences in the views of economists about how sustainable development is to be achieved. Orthodox economists stress the importance of the accumulation of man-made capital to achieve this end whereas neo-Malthusians stress the importance of conserving natural resources and environmental capital. Both take an anthropocentric point of view. For political reasons the neo-Malthusian has had little support but it may eventually turn out to be correct.

Economics is concerned with reducing economic scarcity and economists have traditionally suggested four main ways of doing this, of which economic growth is one. However, neo-Malthusian economists believe that this may not be a sustainable strategy and that it could result in future poverty.

It should be noted that economic systems are embedded in social and natural systems and depend on these. Economic sustainability depends on the sustainability of these other systems. So from this point of view, it is just one of several bottom lines.

Values must be considered in relation to sustainability. Traditional economics is completely anthropocentric in its approach. Therefore, economic approaches to conservation and sustainability can be at odds with the values of deep ecologists or those willing to accord rights to other sentient beings or ecosystems independent of human wishes, or those who want to make use of value judgements other than those based on the measuring rod of money. Consequently economics evaluation is sometimes ineffective in resolving social conflict, including conflict about what should be sustained. As a rule economics alone should not be the final arbiter of social decisions. It is a part (often an important part) of the social evaluation process but not the bottom line. It is just one of many lines.

Finally, it was suggested that, in some circumstances, no completely sustainable economic system may be available. Thus social choice may be about selecting systems that show more sustainability than others rather than selecting systems that guarantee absolute sustainability.

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PART II

CASE STUDIES

Environmental Management

5 Decision support for environmental disaster planning

Aybüke Aurum, Meliha Handzic and Christine Van Toorn

Introduction

Sustainable development has become one of the major concerns for policy makers and planners in both developed and developing parts of the world (Leman-Stefanovic, 2000). It gained prominence particularly after two important events: the publication of the 1987 WCED (World Commission on Environment and Development) report *Our Common Future* and the 1992 Earth Summit in Rio de Janeiro where many governments pledged to make development sustainable by the beginning of the new millennium (Moffatt and Hanley, 2001).

While sustainability of development is widely recognized as an important goal for international and national policy-makers, the concept still remains difficult to define or measure. WCED views sustainability in terms of meeting the needs of the present without compromising the ability of future generations to meet their needs. Other definitions are more encompassing and emphasize the multidimensional aspects of the concept. For the sake of easier analysis, some researchers have broken down sustainability into ecological – land, water, air, and biodiversity – and human inputs – economical, social, educational and political (Phillis and Andriantiatsaholingiaina, 2001). Others, such as Quaddus and Siddique (2001), have classified it into economic (production, expenditure and income), social (health, nutrition and women) and environmental (floods, forests, wastes, water, fertilizers and air) levels. These components are usually treated individually and then combined into an overall measure.

Given the inherently vague and complex nature of the sustainability concept, it is not surprising that planners and policy-makers are increasingly faced with the problem of finding appropriate approaches and tools for planning (Quaddus and Siddique, 2001). Chapter 40 of the UNSD Agenda 21 (United Nations, 2001) identifies the need to bridge the data gap and improve information availability for decision-making purposes. It calls for the production of usable information, the establishment of standards and methods, the development of documentation and the strengthening of electronic capabilities. It also recommends research into hardware, software and other aspects of information technology as an important means for implementation of these programme areas. Herkert et al. (1996) argue that technological innovations such as knowledge-based decision support tools may play a critical role in the process of sustainable development planning by assisting researchers and policy-makers in structuring and making decisions in the light of sustainable development goals.

Recognizing the fact that technology is a critical ingredient in sustainable development planning, this chapter presents an innovative decision support tool for assisting one particular aspect of sustainable development (natural disaster planning) using a solo-brainstorming technique. Disaster planning is introduced as an important component of sustainable development, and the creative approach needed to support it is discussed. The decision support tool and its underlying design philosophy are presented, and the application of the tool in a bushfire planning exercise is discussed. Concluding arguments are also presented.

Sustainable development and disaster planning

The introduction of the concept of sustainable development sparked numerous environmental debates. Environmentalists became a powerful force in decision-making processes in many countries. As a result, protection of the environment and the preservation of natural resources are receiving increased attention from various agencies. Natural disasters represent a serious threat to the environment and in recent years the world has witnessed some major disasters with tragic environmental and economic consequences (for example earthquake in Turkey, 1999; bushfire in Australia, 1993, 2001). According to UNSD Agenda 21, the overall number of people affected by disasters has been growing by 6 per cent each year since 1960. Due to the increased concentration of people in areas exposed to natural hazards, this trend is expected to continue. Environmental disasters are a particularly serious problem in Australia, where bushfires cause a significant amount of damage every year. The 1993 bushfire in New South Wales, Australia, lasted eight days. During this time a state of emergency was declared and 20 000 fire fighters worked on a rotating basis, several people were injured and four people lost their lives. Eight hundred hectares of bush was lost and the total material cost of damage was estimated to be in the vicinity of A$130–150 million.

In general, there is a recognized high degree of interdependence between sustainable development and vulnerability to natural disasters. Despite this, there are no recommended standards or methods to address this issue (UNSD, Agenda 21). Furthermore, to the best of our knowledge, there has been no prior attempt to develop an adequate decision support tool to aid natural disaster planning. In search of appropriate support approaches in sustainable development, the valuable role of model-based systems such as decision support systems (DSS) and group decision support systems (GDSS) has been widely acknowledged. Such systems aid in providing information for better formulation and selection of development policies in the decision-making process (Robinson, 1993). However, while these systems can address multiple criteria and group issues efficiently and effectively, they have limited application in situations dealing with the unexpected and unknown, such as in the case of a natural disaster. The challenging nature of this issue has prompted us to propose and develop a creative decision support system (CDSS) to assist planning and decision making in the context of environmental disasters. In particular, CDSS is devised as a tool to facilitate planners' generation of creative ideas, identification of relevant issues and evaluation of alternative solutions.

CDSS description

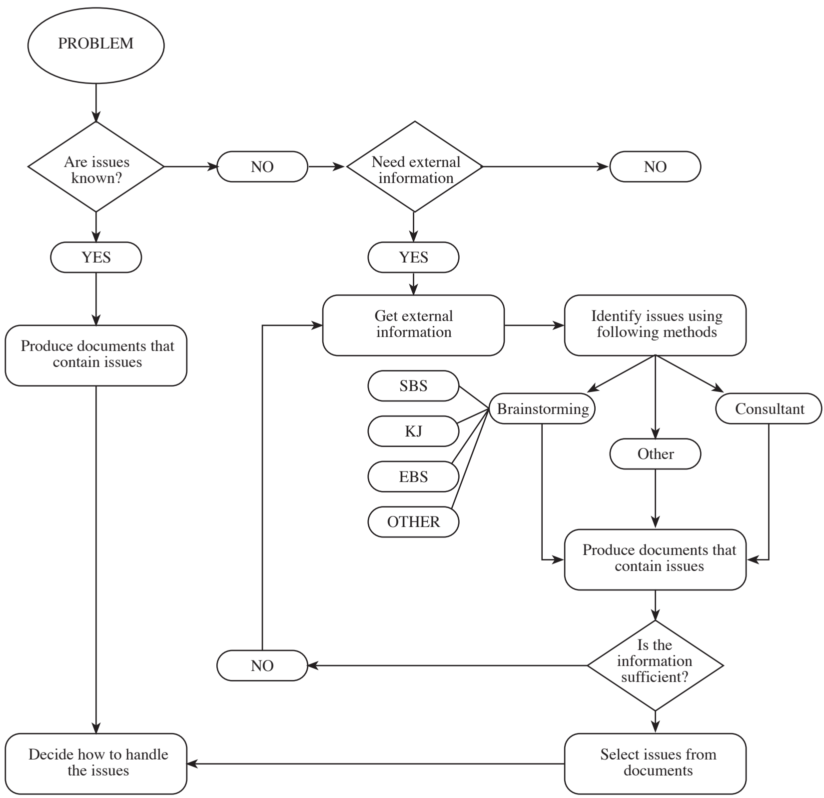
CDSS is a knowledge management tool which supports, facilitates and enhances the outcome of the issue identification stage of decision-making in the planning and operation for an environmental disaster. It guides decision makers to maximize the use of their intellectual assets to promote creative ideas, and make better associations between problem and incoming information to generate awareness of other perspectives. It is an aid for decision-makers and is used to enhance the ability to strategically manage and control regional disaster planning. CDSS has been designed to assist the lateral thinking and triggering processes where ideas are stimulated externally. CDSS incorporates an individual brainstorming technique in which the participant interacts with a set of documents and identifies issues from these. The system was originally developed by Aurum (1997) and has been applied to an investigation into the way decision-makers would design a disaster recovery management plan (Aurum, 1997; Hiller and Aurum, 1996). It has also been used in a study involving the identification of key issues for the development of requirements specification documents in a software engineering environment (Aurum and Martin, 1999). The application of CDSS is relatively simple and does not require a large amount of effort to learn. The tool can also be used to provide feedback to a decision-maker on whether or not incoming information from external sources is consistent with their knowledge and experience.

The following sections describe the underlying framework, the solo brainstorming technique and the design considerations used in developing the system.

Issue identification framework

The issue identification framework was developed by addressing some of the key aspects of the decision-making process. Figure 5.1 shows the role of 'issue identification' in the decision-making process and captures the steps taken to determine needs, develop ideas and assess their merits. In this framework it is assumed that the decision-makers are interested in the issues, needs and possible solutions which may lead to innovative ideas.

In Figure 5.1, the ellipse box at the top labelled 'PROBLEM' represents the type of decision-state that includes issue identification as part of its



SBS = Solo brainstorming session
KJ = KJ method
EBA = Electronic brainstorming systems

Figure 5.1 Issue identification chart

formulation process. The first step in decision-making is to recognize the existence of a problem or to identify the problem (Simon, 1960; Mintzberg et al., 1976; Kleindorfer et al., 1993). The existence of a problem indicates the difference between the environmental facts and the decision-makers' current state and includes elements such as goals and objectives (Lyles and Schwenk, 1992). It identifies the existence of a gap between desired results and actual results and thus leads to a problem-solving activity (Kleindorfer et al., 1993). Having completed the first step, the next step is to frame it in order to improve understanding of the problem and to set objectives by examining needs and opportunities (Nutt, 1984).

Given the above, we must first identify whether the issues are known. If so, the next step will be to produce a set of documents to describe these issues and then decide how to manage them. On the other hand, if the issues are unknown it is the key decision-makers' task to identify them and also to determine whether there is sufficient information in the organization to identify them initially. Each organization has its own knowledge structure in addition to each individual member's personal knowledge. The knowledge is formed and modified continuously by organizational events stored over time and is retrieved as needed. As illustrated in Figure 5.1, if the information (knowledge) is not sufficient, then the key decision-makers may need to seek information from sources external to the organization. In Figure 5.1, external information represents that which is not perceived by key decision-makers at an individual level, this information may be stored in either external or internal sources.

A variety of techniques is available for decision-makers to identify issues. From Figure 5.1, brainstorming can be carried out using either solo brainstorming (Aurum, 1997), electronic brainstorming (Nunamaker et al., 1991), or the KJ method (Ohiwa et al., 1990); there may also be an independent report sought from a third-party consultant, or some other method may be employed. In each case, the outcome of the exercise is a series of documents or statements identifying issues that need to be addressed. Once a series of issues has been identified, there needs to be some assessment of their likely importance (selection). It may not be realistic to expect that every issue can be dealt with equally. This assessment will provide a final set of issues, with brief statements about each one; the follow-up then becomes a straightforward management task. Note that at each stage of the process as outlined in Figure 5.1, an assessment may be made that there is insufficient information to proceed. This in turn could lead to another search being carried out or another consultant being hired.

Solo brainstorming technique

Issue identification and the generation of ideas are cognitive processes. Individuals or groups who engage in these make contributions by using their knowledge and expertise. In this study, we will consider a particular case where the issues need to be identified on an individual basis. We suggest that issues can be identified at an individual level by applying our proposed technique called solo brainstorming. Figure 5.2 illustrates the main elements of an integrated CDSS and the processes involved in system utilization.

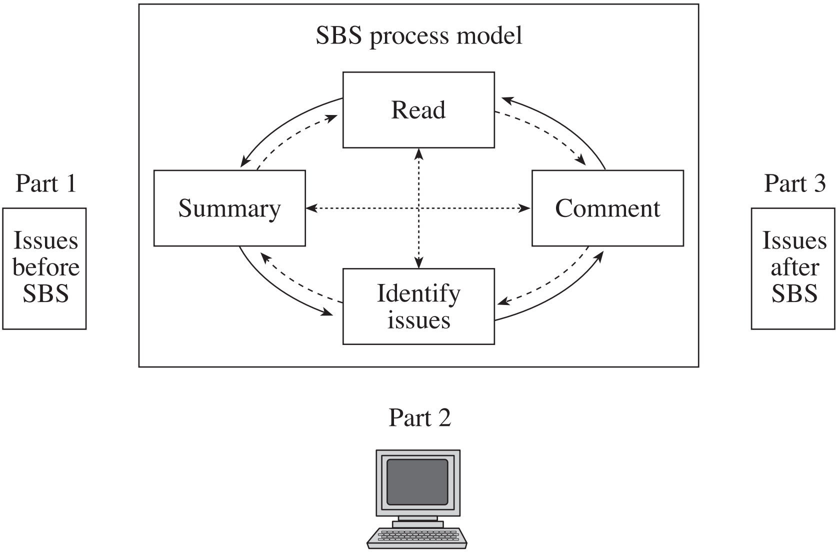


Figure 5.2 Elements of CDSS

Part 1: In order to list issues that they are already aware of before interacting with the incoming information, users first document an initial set of issues they consider relevant to the given problem.

Part 2: Users interact with the incoming information (external information), one at a time, noting issues as they arise and generate ideas by following the solo brainstorming protocol. This study uses abstracts of journal and conference papers as external information. An interactive CDSS session involves 'reading' and 'editing' in a computerized environment by following a protocol which encourages lateral thinking.

The CDSS protocol brings a formal setting to the process of issue identification. The main activities of the session include reading abstracts, typing a summary of the abstracts, making lateral comments and nominating issues from the abstracts to be followed up (Aurum, 1997, 1998). The CDSS protocol also incorporates Osborn's (1957) four basic brainstorming rules: no criticism is allowed while interacting with documents; freewheeling is welcome; quantity is wanted; and combination and improvement are sought. In a CDSS interactive session users, or in other words the decision-makers (DMs), collect information and build ideas while reading the abstracts. Reading and editing help to support learning and the stimulation of ideas. DMs explicitly search for issues in the documents and make their own decision about which issues are significant for their project. Lateral thinking is also utilized in CDSS by encouraging users to make lateral comments. DMs type their comments by combining the incoming information, their knowledge and their prior experience, while addressing the problem at hand. The primary role of the abstracts is to trigger issues and ideas. Responses to abstracts can come from either direct reactions or from stimulated recollections; both are potentially valuable. The aim of this technique is to tease out such reactions to the full; the product of the interaction then becomes a series of issue statements.

Part 3: The output of a CDSS session is a document which includes the CDSS user's ideas, lateral thoughts and issues that are needed to provide a solution to the problem. Finally, users document another set of issues that occurred to them after interacting with the abstracts.

CDSS application

We applied CDSS to a bushfire planning exercise, with the 1993 experience with tragic bushfires in New South Wales, Australia, providing an emergency situation. We carried out a laboratory experiment with 11 volunteer subjects (users). Subjects were mainly postgraduate students from the School of Safety Science at the University of New South Wales, who were also working at different levels of management in various organizations. As part of the planning task, the participants were instructed to identify issues and generate ideas on bushfires. A few days before the experiment, users received detailed written instructions on what would be required of them during the CDSS session. The instructions explained their role in interacting with the data and the protocol which they would need to follow while editing. Users also received an oral explanation and a small demonstration before beginning the task.

Disaster planning scenario

We considered the features that may (or should) have been included in the planning phase that occurred before a natural disaster, such as an earthquake or bushfire. In particular, we were interested in the features that should be included in planning for any future disaster in New South Wales, Australia. It was assumed that a committee had been established to review such planning after the occurrence of a disaster. The scenario envisaged was one where the person involved in the CDSS session was to take a major role in this committee. In part, the committee would look at the way in which the disaster had been managed and determine if it was desirable to alter the method of disaster planning. The committee was to take evidence and receive submissions from those who occupied positions of prominence at the time of the disaster and would also receive submissions from the general public and other concerned parties. Subjects undertaking the proposed exercise were advised that it was important for them to be aware of the range of potential issues before starting to examine submissions and look into ways of handling the evidence. The intention was to review what was in the literature in an isolated way; that is, the identification of potential issues would not be intended to reflect the reality of the Newcastle earthquake (1989) experience, or the New South Wales bushfire (1993) experience in Australia.

Having identified the issues in a general way, it would be possible to consider the specifics of the local case – note the generality of this approach. Issues to be selected were to be those that could apply to a range of situations where earthquakes or bushfires were experienced. For example, experiences from the Los Angeles fires or from the earthquakes in Turkey could be relevant to this analysis, but it was not necessarily expected that they would all be relevant in New South Wales. It might not be appropriate to follow up all issues, but all issues were to be included in the analysis. The scenario of the study assumed that the committee members undertook the CDSS session after a disaster. However, it can also be applied to problems as part of a planning exercise to identify aspects to include and the types of interaction to cover. In the case of planning, the work could be *ab initio*, or part of a review. The intention was to come up with a list of issues and options. As suggested by Churchman (1979), a summary of an issue list can be one of the basic components for planning.

Analysis

To explore what CDSS users could actually accomplish in the disaster planning task, all the issues were listed and studied in detail. The issue list was examined both individually and collectively. The aim was to explore the effectiveness of CDSS in terms of the following factors: the number of issue categories identified by individual users; the productivity of nominal groups, that is, individuals who brainstormed alone and had their non-overlapping issue categories combined; and the minimum number of people required in a group in order to be able to cover the maximum number of issue categories.

To evaluate users' performance, issues that were identified by users were classified by several experts based on their descriptions and/or understanding of the characteristics of 'disaster emergency planning'.

Through this classification, the extent to which users had identified issues both individually and collectively was examined. The experts worked independently but some had long discussions on the classification scheme. Each of the experts developed their own techniques and formed their own classifications. They decided on the heading for each category (including sub-categories) and assigned each issue accordingly. To some extent, the classification schemes from experts who had long discussion sessions did not differ much from each other. In other words, the approach taken when grouping the issues was similar, differing only in detail.

Individual performance

Details of analysis performed indicate that the application of CDSS to a bushfire planning task resulted in several substantial positive effects on user–planners' performance. First, it assisted with the generation of more relevant ideas. More specifically, the average number of generated ideas tripled after interaction with the system (increasing from five to 15). Second, CDSS helped user–planners identify more relevant categories of issues. In numeric terms, the categories addressed expanded on average by 30 per cent (increasing from 17 per cent to 47 per cent).

Users' individual achievements were further evaluated based upon the experts' classification scheme. Some of the preliminary results of this analysis have also been reported at Aurum et al. (2001). Findings show that individual users managed to identify on average around 40 per cent of the issues found by the full group (ranging from a minimum of 19 per cent to a maximum of 63 per cent).

In order to gain a better understanding of the effects of CDSS on the task at hand, we studied – at an individual level – the issues identified 'before' and those identified 'after' the CDSS session. It was found that in both cases issues tended to fall into clusters and that most users wrote down issues as brief phrases rather than long sentences.

Issues identified before the CDSS session – pre-CDSS issues – tended to fall into two clusters:

- common – those identified by the majority of users; and
- unique – those identified by individual users.

After the CDSS session, users were asked to write down another set of issues which had occurred to them while interacting with the system. For the users' convenience, the documents they created during the CDSS session were also supplied for reference purposes. Issues identified after the CDSS session – post-CDSS issues – tended to fall into three clusters:

- directly related to the abstracts provided – identified by the majority of users. These included the following: fitness of the fireman; computer models for fire behaviour; heat-resistant garments; legal issues; psychological effects of bushfire;
- related to the abstracts provided – specific to a user, incorporated the user's own interpretation of the abstracts provided (detailed example provided below);
- unique – identified by individual users.

In the identification of post-CDSS issues, the forming of clusters 'related to the abstracts provided' was most evident in user 2's statements. For example, one such statement was the short, one-word phrase 'onlookers'. This was not obtained directly from the abstracts provided and made us think about this issue more carefully. Another statement from user 2 was 'Considerable resources to counsel fire-fighters seem to be being wasted'. This user made such a statement because there were a few abstracts that made reference to the psychological effects of bushfires on fire-fighters and the arrangements that had been made for counselling. Some users mentioned this subject as an issue that should be considered in planning. On the other hand, user 2 brought another perspective to this issue, a clear example of lateral thinking.

When they were asked to write their post-CDSS issues, users were provided with a copy of their work. It was found, however, that most of them did not consult their documents. When we examined their documents, we found that there were many issues that they identified from the abstracts that were not written in their issue lists. This prompted us to explore the users' documents in more detail (see Aurum, 1997, 1998).

Nominal group performance

Although CDSS is primarily designed for individuals who are aiming to identify issues and generate ideas for possible solutions to a problem, it can potentially be used with geographically dispersed users at any time for the same problem. CDSS can therefore be used by a number of individuals and then the issues identified can be brought together in order to increase the total number of issues generated – that is, CDSS users may become members of a nominal group. To display a comparison between results from individual users working alone, and individual users working collectively, nominal groups were formed from users who had brainstormed individually. From the experts' classifications it was possible to compute several combinations of the users' outcomes.

To explore how individual users would behave collectively in the bushfire planning task, we looked at the behaviour for each combination in these groups of users (that is, two per group, three per group and so on). For our computation, we applied an approach that had been taken by previous researchers in order to calculate the productivity level of brainstorming groups (Diehl and Stroebe, 1987). Using this approach, all the issues were combined and redundant issues were eliminated and counted only once. This process was applied to all the classifications; the target number in the resulting list was the total number of sub-issues generated by the experts. From the resulting lists, we plotted the number of people in nominal groups versus both the maximum and the minimum number of non-overlapping issues that were identified by these users. Results are presented in Figures 5.3 and 5.4.

Figures 5.3 and 5.4 represent comparisons of the experts' classifications. Figure 5.3 shows the maximum number of issues that were identified when the group's best members came together; Figure 5.4 demonstrates the maximum number of issues that were identified when the group's worst members came together. These plots are based on each individual expert's classification.

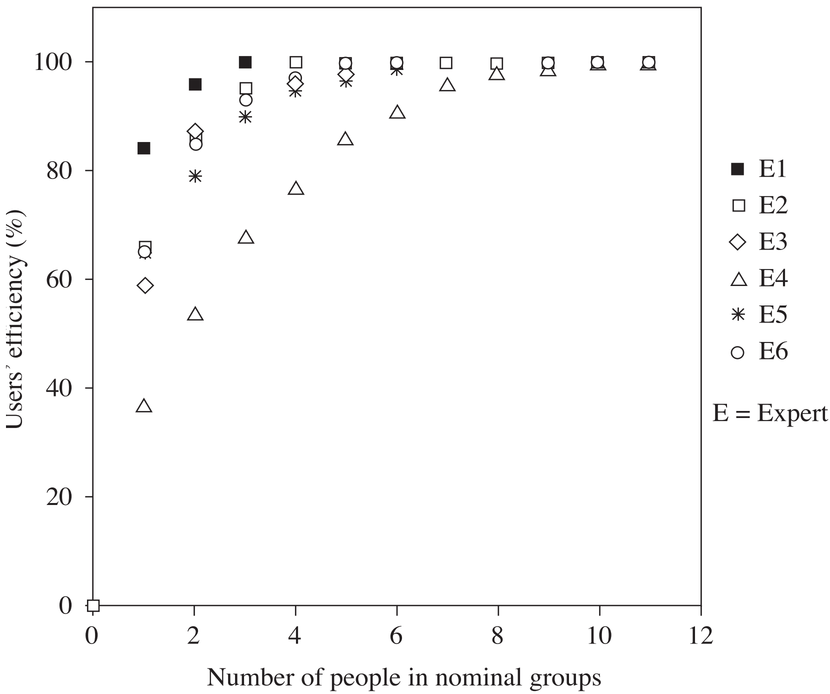


Figure 5.3 Optimum number of people needed in groups – with the best performers

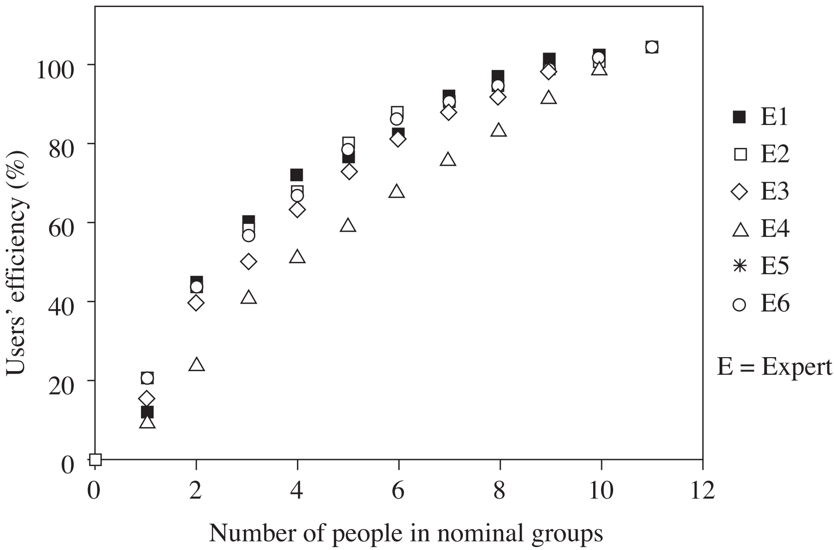


Figure 5.4 Optimum number of people needed in groups – with the worst performers

Based upon the result of these classifications, the logarithmic distributions of the maximum and minimum productivity levels are calculated and presented in Figures 5.5 and 5.6. These curves show that for the maximum productivity level shown in Figure 5.5, four people can cover 95 per cent of the issues, and five people can cover 97 per cent of the issues. However, we cannot always expect the participants to demonstrate their best performance in a CDSS session, as some users may not be very productive. In the minimum productivity level, Figure 5.6, our findings suggest that with four people, 63 per cent of the issues can be covered, and with five people, 69.7 per cent of the issues can be covered.

As previously mentioned, these results were based upon the experts' classifications. One might question what the results might have looked like with another group of experts or whether the experts' approach to the classification scheme plays a significant role in the results. We studied each expert's classification scheme in order to investigate any possible effect on our findings, and discovered that experts may approach the task of issue classification from different points of view.

For instance, one may classify issues on bushfires as issues relating to communication, or issues relating to emergency equipment and so on, whilst another may classify them as issues to be taken care of in the different phases of management – as part of strategic planning, implementation and so on. However, we concluded that what was important was how much detail the experts put into the classification and not so much what approach the experts took when classifying issues.

Experts reported that when they examined the issues, they found that users' short statements or phrases were sometimes ambiguous. A precise unambiguous description of what was meant would lead to only one issue being able to be identified. However, these statements or phrases can suggest a multiplicity of issues to other members of the team carrying out a CDSS session, or to a decision-maker using someone else's CDSS session output. This was actually seen by experts as an additional advantage of using the CDSS protocol for issue identification, provided that the CDSS session was followed by a second person reviewing the documents to pick out the issues. Experts also reported that the more time they spent on the classification, the more categories they came up with. This was primarily because issue statements made by users were not always unambiguous; for example, a phrase like 'communication', has several possible interpretations. The fact that meaning was not clear tended to force the person to think widely to interpret it and consequently come up with more issues. This was also found by the experts to be another advantage of CDSS because, in this way, the second person could usually identify additional issues.

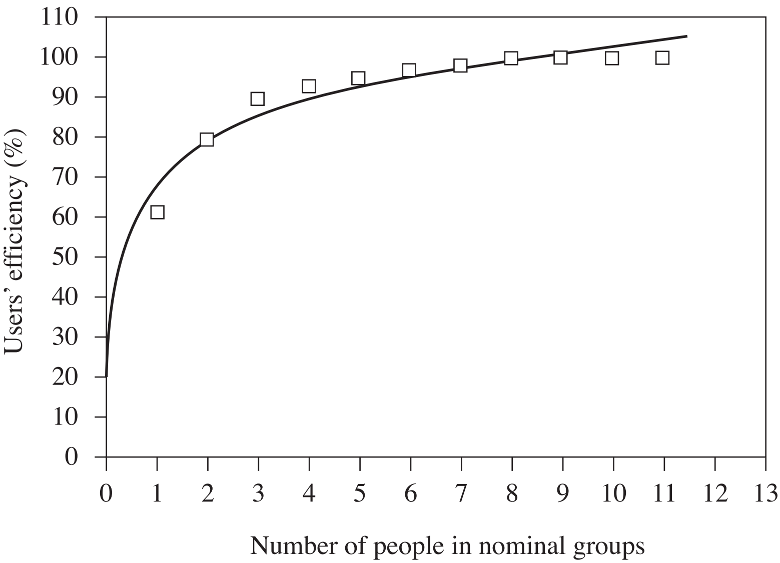


Figure 5.5 Maximum productivity level

Whilst the current study applied a brainstorming-based CDSS to a natural disaster planning situation, other research by Aurum and Martin (1999) and Aurum and Handzic (2001) used a similar system in a software engineering context to provide a way of discovering and recording what 'really matters' when determining user requirements. The outcomes of these studies complemented each other and confirmed that CDSS may be a valuable aid in creative problem-solving tasks. In addition, the results of this study are consistent with the findings of other researchers in group settings. The results support the notion of the usefulness of developing ideas in an individual session and then having ideas discussed in a group session (Aurum and Martin, 1999; Diehl and Stroebe, 1987; Dillon et al., 1972; Bouchard, 1969).

The emphasis here is not a comparison of the real group work with the nominal group work, but more the size of the knowledge base that can be formed by individuals at the end of the CDSS session. Furthermore, if these individuals are exposed to group discussions after the CDSS session, they can also expand this knowledge pool by adding new comments and ideas. Note also that many of the common problems seen in traditional brainstorming sessions, for example production blocking and evaluation apprehension (Diehl and Stroebe, 1987) can be avoided by individual CDSS sessions before the group meeting. This can enable group members

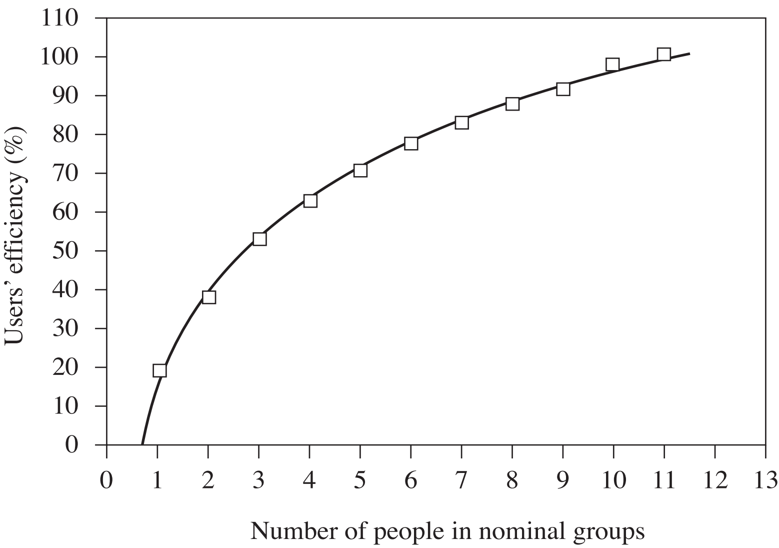


Figure 5.6 Minimum productivity level

to express their ideas freely and with more confidence, they can also develop their ideas or thoughts with no interruption or social pressure. In addition, the 'housekeeping process' (that is, removing redundant ideas), which is often seen in electronic brainstorming sessions, does not apply to our CDSS. This is because (as previously explained), in the third part of the CDSS session the participant filters out the issues (that occurred to them during the interaction) from the document that they generated during the second part of the session.

Implications for theory and practice

The research conducted in this study makes some important contributions to the theory and practice of sustainable development planning in general, and, in particular, to environmental disaster planning. Most importantly, the study contributes a new and successful computer technology-based approach to support environmental disaster management. It also illustrates that nominal groups of people are likely to perform better than individuals on the task of critical issue identification for planning purposes.

The improvement of the natural disaster planning process through the application of CDSS could provide a new foundation for the management of response to catastrophic natural events. CDSS is capable of aiding planners in improving the quality of natural disaster planning within their region. The CDSS system provides the area with an innovative and creative lateral thinking process. Empirical results support the notion that creativity and innovation are extremely important factors for success in a rapidly changing environment.

For practitioners, this study raises awareness of the importance of issue identification for environment management and informs them of a potential approach which is available. CDSS aids planners by enhancing the ability to strategically manage and control regional emergency networks in an efficient and effective manner, and also provides a step-by-step model as a guide. It suggests a simple and effective system that can be used in a variety of environmental management situations.

Recommendations for future study

Whilst the current study provides some interesting findings, caution is necessary regarding their generalizability due to a number of limiting factors. These results were obtained from a controlled laboratory experiment; it would be interesting to see the effects of the system in an unconstrained field study environment. In addition, the performance of users in a CDSS session could have been affected by their state of mind. In some cases, the user may have already been 'aware' of the issues and had the desire to look for some particular aspects, rather than identifying issues in general. This suggests the need to examine the tool effectiveness among different groups of users.

We believe CDSS to be a valuable tool which could be applied to a wide range of sustainable development aspects. Further research may address these and other issues in the future in order to determine whether the application of CDSS in other task, environment and people contexts would produce comparable results.

Conclusions

Disaster planning represents an important component of sustainable development planning. Despite this, the literature is lacking in providing adequate methods and tools to support this activity. In this study, we propose a creative decision support system (CDSS) as a tool to assist and enhance disaster planning task performance. Our underlying assumption is that 'thinking' applications can be developed, learnt, practised and used in order to generate ideas. In turn, they can enable an individual to think better about the problem at hand. The technique of 'solo brainstorming' was used as a foundation for designing a computer-based CDSS. Essentially, the system was developed to provide support to individual users in identifying relevant issues, generating innovative ideas and evaluating possible solutions to a given planning problem.

An application of the system is presented in a specific bushfire planning scenario. The productivity level of CDSS users, both individually and collectively – as though the users worked together – is illustrated. The results indicate that CDSS made a positive contribution to enhancing the individual planners' creative performance. They were found to generate a substantially greater number of relevant ideas, as well as address a greater number of relevant categories of issues after interacting with CDSS.

Another important finding from our study is the identification of the number of people needed to participate in nominal groups in order to achieve optimal performance. Basically, the productivity of CDSS users working in a nominal group appeared to be relatively static given a group size of around four to six.

The results of this study provide strong support for the view that planners' creative thinking can be enhanced by appropriate stimulation, as suggested by some theorists (Marakas, 1998). The system proposed here was found to contribute to improvement in both the quality and quantity of planners' ideas in the bushfire planning context. These results also agree with our earlier findings from similar studies in a software engineering context (Aurum and Handzic, 2001).

CDSS can help planners process stimulating documents while identifying issues for a variety of sustainability variables. However, it is also important that the planning environment be conducive to the creative decision-making process.

The findings suggest that CDSS may become a very useful aid to policy- and decision-makers in sustainable development planning, particularly in situations where the problems are unstructured, goals indistinct, and the outcome of an action cannot always be clearly identified.

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6 Using data envelopment analysis for ecoefficiency evaluation

Joseph Sarkis and Srinivas Talluri

Introduction

Ecoefficiency is the evaluation of an organization's ecological (or environmental) efficiency. This topic has come under increasing scrutiny by a variety of stakeholders, of which the organization itself is one. Ecoefficiency is meant to determine how well an organization uses its resources. Not only is this important from an economic basis, but also from an environmental and social basis. Sustainability measures for organizational ecoefficiency measurement are currently under investigation and development. To help evaluate these measures data envelopment analysis (DEA) can be used. DEA is a quantitative multifactor productivity measurement tool that has gained much attention in the operations research and application literature. DEA has proven quite useful for a number of managerial decision problems and research questions, but it has been rarely applied within the realm of corporate environmental management. The limited application of DEA for environmental issues provides fertile ground for its use as both a research and practical tool. In this chapter, we shall identify the various applications from both a practical and research perspective. We illustrate DEA's suitability as a tool to help evaluate the ecoefficiency of organizations, address research questions pertaining to environment ecoperformance of organizations, and help managers make decisions. The DEA models, and extensions, that are evaluated in this chapter are from a family of deterministic (rather than stochastic) models.

DEA and the environment: a literature review

DEA has been applied to a number of organizational (public and private) performance evaluations. There has been a limited evaluation of corporate environmental issues whether external (industry level) or internal (corporate level), using DEA. DEA can prove to be an effective tool for the management of ecoefficiency in organizations or institutions.

DEA is a multifactor productivity measure that uses linear programming optimization to determine the relative efficiencies of various units in a set. These units may be companies, plants, industries, or other comparable sets. Since the introduction of DEA, from the seminal article by Charnes et al. (1978), its application and developments have grown.

DEA-based modeling and research that have incorporated environmental factors do exist. Examples of macroeconomic DEA-based works that incorporate some form of environmental factors evaluation include: efficiencies of energy (Criswell and Thompson, 1996); use for forest management (Kao et al., 1993), industrial regional development (Karkazis and Boffey, 1997); country productivity evaluations (Lovell et al., 1995); site location (Thompson et al., 1986); industrial productivity and emissions (Yaisawarng and Klein, 1994); and opportunities for environmental improvements in the agricultural industry (Ball et al., 1994; Poit-Lepetit et al., 1997). Some researchers have also applied DEA to evaluation of pollution efficiency for individual plants and/or firms using emission data (Haynes et al., 1993, 1994; Sarkis and Cordeiro, 2001; Tyteca, 1996). These works focus on a policy perspective, rather than corporate managerial and competitive dimensions.

DEA models

A number of models are now summarized. Included among the models will be the basic multifactor models introduced by Charnes et al. (CCR) (1978) and Banker et al. (BCC) (1984). The CCR and BCC models provide an opportunity to evaluate technical and scale efficiencies of various units under investigation. But their limitations for research and practical purposes include truncation difficulties that do not allow for effective non-parametric statistical evaluation or ranking of alternatives. To overcome some of these difficulties, three additional variations on these approaches are included. These techniques include models by Andersen and Petersen (1993), Doyle and Green (1994), and Rousseau and Semple (1995). These series of models provide the core elements of deterministic DEA models that allow for a more effective set of tools for evaluating ecoefficiency within organizations. The next few sections will focus on the underlying models that are used by DEA; decision support software is available to support these decisions such as Banxia's Frontier Analyst (http://www.banxia.com/). Additional DEA software, both for-profit and free, is referenced at http://www.uq.edu.au/financesite/.

Basic ratio-based technical and scale efficiency DEA models

Traditionally, productivity models have been used to measure the efficiency of systems. Typically DEA productivity models for a given decision-making unit (DMU) use ratios based on the amount of outputs per given set of inputs. The definition of a DMU can vary greatly from individuals to countries as long as the unit can be modeled with input and output values. DEA allows for the simultaneous analysis of multiple inputs to multiple outputs, a multifactor productivity approach. Using the notation of Doyle and Green (1994), the general efficiency measure used by DEA is best summarized by equation (6.1):

$$E_{ks} = \frac{\sum_y O_{sy} v_{ky}}{\sum_x I_{sx} u_{kx}} \tag{6.1}$$

where:

E_{ks} is the efficiency or productivity measure of DMU *s*, using the weights of test DMU *k*;
O_{sy} is the value of output *y* for DMU *s*;
I_{sx} is the value for input *x* of DMU *s*;
v_{ky} is the weight assigned to DMU *k* for output *y*; and
u_{kx} is the weight assigned to DMU *k* for input *x*.

In the CCR model, the objective is to maximize the efficiency value of a test DMU *k* from among a reference set of DMUs *s*, by selecting the optimal weights associated with the input and output measures. The maximum efficiencies are constrained to 1. The formulation is represented in expression (6.2):

$$\text{maximize } E_{kk} = \frac{\sum_y O_{ky} v_{ky}}{\sum_x I_{kx} u_{kx}} \tag{6.2}$$

$$\text{subject to: } E_{ks} \leq 1 \quad \forall \text{ DMUs } s$$

$$u_{kx}, v_{ky} \geq 0$$

This nonlinear programming formulation (6.2) is equivalent to formuation (6.3):

$$\text{maximize } E_{kk} = \sum_y O_{ky} v_{ky} \tag{6.3}$$

$$\text{subject to: } E_{ks} \leq 1 \quad \forall \text{ DMUs } s$$

$$\sum_x I_{kx} u_{kx} = 1$$

$$u_{kx}, v_{ky} \geq 0$$

The result of formulation (6.3) is an optimal simple or technical efficiency value (E_{kk}^*) that is at most equal to 1 (this formulation has also been defined as the constant returns to scale formulation). If $E_{kk}^* = 1$, then no other DMU is more efficient than DMU k for its selected weights. That is, $E_{kk}^* = 1$ has DMU k on the optimal frontier and is not dominated by any other DMU. If $E_{kk}^* < 1$, then DMU k does not lie on the optimal frontier and there is at least one other DMU that is more efficient for the optimal set of weights determined by (6.3). The formulation (6.3) is executed s times, once for each DMU.

The dual of the CCR formulation (also defined as the envelopment side) is represented by formulation (6.4):

$$\begin{aligned} &\text{minimize} \quad \theta \\ &\text{subject to:} \sum_s \lambda_s I_{sx} - \theta I_{sx} \leq 0 \quad \forall \quad \text{Inputs } I \\ &\sum_s \lambda_s O_{sy} - O_{ky} \geq 0 \quad \forall \quad \text{Outputs } O \\ &\lambda_s \geq 0 \quad \forall \quad \text{DMUs } s \end{aligned} \tag{6.4}$$

The CCR model has an assumption of constant returns to scale for the inputs and outputs. To take into consideration variable returns to scale, BCC is utilized. The BCC model aids in determining the scale efficiency of a set of units (which is a technically efficient unit for the variable returns to scale model). This new model has an additional convexity constraint defined by limiting the summation of the multiplier weights (λ) equal to one, or:

$$\sum_s \lambda_s = 1 \tag{6.5}$$

The use of the CCR and BCC models together helps determine the overall technical and scale efficiencies of the DMUs and whether the data exhibit varying returns to scale.

Cross-efficiency models

One of the difficulties with simple efficiency scores is a resulting set of 'mavericks.' A maverick DMU score weighs heavily on a single input or output, thus making that DMU more efficient than any other DMU. A procedure for discriminating between true efficient DMUs and false positive DMUs is to analyze the cross-efficiencies. Sexton et al. (1986) introduced the concept of cross-efficiencies and the cross-efficiency matrix (CEM).

The CEM provides information on the efficiency of a specific DMU with the optimal weighting schemes determined for other DMUs. Each of the columns of the CEM is then averaged to get a mean cross-efficiency measure (defined as the simple cross-efficiency (SXEF) measure when the optimal weights used for the CEM are from the basic CCR model) for each DMU (e_s). A false positive DMU score may be associated with an efficient DMU that has a relatively small cross-efficiency value or a value that is less than that of an initially inefficient DMU.

A pitfall in determining a cross-efficiency score is that the weights, derived from the CCR model, used to calculate the optimal simple efficiencies (and eventually used in cross-efficiency measures) may not be unique. To overcome this difficulty, a formulation (6.6) developed by Doyle and Green (1994), one that will help generate a less ambiguous set of optimal weights, may be used for cross-efficiency calculation and development of a CEM.

$$
\begin{aligned}
&\text{minimize} \sum_y \left(v_{ky} \sum_{s \neq k} O_{sy} \right), \\
&\text{subject to: } \sum_x \left(u_{kx} \sum_{s \neq k} I_{sx} \right) = 1, \\
&\sum_y O_{ky} v_{ky} - E_{kk}^* \sum_x I_{kx} u_{kx} = 0 \\
&E_{ks} \leq 1 \quad \forall \quad \text{DMU} \quad s \neq k \\
&u_{kx}, v_{ky} \geq 0
\end{aligned}
\tag{6.6}
$$

The Doyle and Green formulation as presented in (6.6) has a primary goal of obtaining a maximum simple efficiency score for DMU k (the test unit) and a secondary goal of determining a set of weights that minimize the other DMUs' aggregate output, as defined by the objective function. The test unit k is defined as an average unit whose efficiency is minimized. This model has been defined as an aggressive formulation (AXEF). The data required in (6.6) include the optimal efficiency scores (E_{kk}^*) from the CCR model, as shown by the second constraint set. This procedure for cross-efficiency calculation requires a two-phased approach to determine the optimal weights.

Discriminatory DEA models

There are two sets of DEA models, which we have defined as 'discriminatory' because they allow for discrimination of efficient units as well as inefficient units. The first model is a variation of the CCR model and has been proposed by Andersen and Petersen (1993), among others. In their model, they simply eliminate the test unit from the constraint set. The new formulation is represented by (6.7):

$$
\begin{aligned}
&\text{maximize } E_{kk} = \sum_y O_{ky} v_{ky}, \\
&\text{subject to: } E_{ks} \le 1 \quad \forall \quad \text{DMUs } s \neq k \\
&\sum_x I_{kx} u_{kx} = 1 \\
&u_{kx}, v_{ky} \ge 0
\end{aligned}
\tag{6.7}
$$

We call this the reduced CCR (RCCR) formulation.

Rousseau and Semple's (1995) model focuses on the preservation of a unit's classification (for example, changes required to input and output values to maintain a unit's classification as efficient or inefficient). This approach is based on determining a unit's sensitivity to changes in the data values. The formulation used here to evaluate the data set is the generalized Tchebycheff radius of classification preservation (GTR) model (6.8):

$$
\begin{aligned}
&\text{minimize } \alpha^{+} - \alpha^{-} \\
&\text{subject to: } \sum_{s \neq k} \lambda_s I_{sx} - \alpha^{+} I_{kx} + \alpha^{-} I_{kx} - I_{kx} \le 0 \qquad \forall \text{ Inputs } I \\
&\sum_{s \neq k} \lambda_s O_{sy} + \alpha^{+} O_{ky} - \alpha^{-} O_{ky} - O_{ky} \ge 0 \qquad \forall \text{ Outputs } O \\
&\sum_{s \neq k} \lambda_s = 1 \\
&\lambda_s, \alpha^{+}, \alpha^{-} \ge 0
\end{aligned}
\tag{6.8}
$$

where α^{+} is the distance of an efficient unit from the Pareto frontier and α^{-} is the distance of an inefficient unit from the Pareto frontier.

Unlike the other DEA models discussed above, the optimal value for this formulation can be either negative (inefficient unit) or positive (efficient unit). The magnitude of the objective value is also significant because it defines the robustness of the unit's score. Magnitudes of objective values can serve as good measures to discriminate among units with similar classifications, and thus to rank the various units either efficient or inefficient. Whereas the RCCR model is based on the CCR formulation, the GTR model is underpinned by the BCC formulation.

Environmental input and output factors

The papers that have considered the application of DEA for environmental efficiency analysis have used a variety of environmental factors (Haynes et al., 1993, 1994; Sarkis and Cordeiro, 2001; Tyteca, 1998). Many of the possible measures for environmental efficiency can be derived from environmental performance indicators (EPI) or sustainability indicators. There are many levels of indicators available; they may cover individual, plant, company, industry, community or nation. A difficulty arises in trying to decipher which indicators are the most important ones to include. The DEA model is very sensitive to the data that are selected.

There are measures that are more aggregated, community measures and macroeconomic measures are examples. The indicators for organizational studies will have to be at the corporate, plant, shop or even individual level for adequate analysis. A number of recent activities have allowed information that can be used for corporate-level sustainability analysis, such as ISO 14000 performance guidelines, environmental reporting, and corporate sustainability indicator research. For research and recommendations on environmental performance indicators and environmental databases see Azzone and Manzini (1994) and Gerde and Logdon (1999).

Potential inputs and outputs for the DEA models are summarized in Table 6.1. Included among the factors are emissions data, environmental expenditures, number of environmental programs and penalties.

Table 6.1 Environmental indicators as input and output factors for DEA

Inputs	Outputs
Raw material intake	Water emissions
Energy	Air emissions
Materials used	Solid wastes
Employees	Toxic wastes
General budget	Employee health and safety
Environmental budget	Products
Recycled material	Recycled products
	Penalties
	Permits denied

Sources: Azzone and Manzini (1994), Gerde and London (1999) and Tyteca (1998).

We begin with an illustrative example using data from Tyteca (1998). The results of each of the various models are then presented with some analysis. How these data can be used from a research perspective is also explained; we then detail how these results can be used for managerial decision-making.

Data and model

The original source of this environmental data for 48 electric utility plants in the USA was from the Energy Information Administration of the United States Department of Energy (EIA). The inputs and outputs for the example are summarized in Figure 6.1.

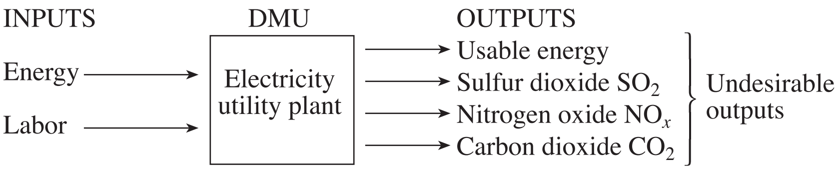

Figure 6.1 Inputs, DMU and outputs for illustrative example

Notice that there are two major inputs, energy (or raw materials) and labor, and four outputs, sulfur dioxide (SO_2), nitrogen oxides (NO), and carbon dioxide (CO_2), and usable energy. Of the outputs only usable energy is considered a desirable output, where a larger value is viewed as more acceptable. The other outputs are defined as undesirable outputs. An undesirable output is one that you wish to minimize, that is, larger values are less desirable. In this situation, sulfur dioxide, nitrogen oxides and carbon dioxide are considered to be undesirable outputs because they are major sources of acid rain and global warming, two relatively important environmental issues that are regional and global in effect and scope, whereas usable energy would be the electricity actually used by consumers.

To effectively model the undesirable outputs in the various DEA models, they will effectively serve as inputs (where smaller values are preferable to larger values). Thus, the multifactor productivity ratio to be evaluated is:

$$K_k = \frac{v_{k1}UE_k}{u_{k1}EN_k + u_{k2}L_k + u_{k3}SO_k + u_{k4}NO_k + u_{k5}CO_k} \tag{6.9}$$

where:

E_k is the efficiency score for plant k;
UE_k is the usable energy for plant k;
EN_k is the input energy (raw material) for plant k;
L_k is the input labor for plant k;
SO_k is the sulfur dioxide emissions for plant k;
NO_k is the nitrogen oxides emissions for plant k; and
CO_k is the carbon dioxide emissions for plant k.

The total energy input is an aggregated value of total coal, oil and gas used. To aggregate these values, the original amounts were converted into BTUs. The transformations were 21 287 BTUs for every short ton of coal, 5 800 000 BTUs for every barrel of oil, and 1026 BTUs for every cubic foot of gas (EIA, 1999). The labor input relates to the size of the company. Raw material costs may have been used as an input as well since various types of energy-producing raw materials may have been used. Revenue may capture more expensive and/or less polluting material and incorporate the economic factors more effectively. At this stage let us only focus on the current model, which is based on real data.

Results and discussion

In the evaluation of the 48 electric utility plants we have utilized a variety of DEA models in a sequential manner, each providing increasing insights into the efficiency of the electric utility plants. Initially, the CCR model computations are performed and the results are shown in Table 6.2 under the heading 'CCR'. The CCR model identified plants 2, 6, 15, 17, 20, 25, 26, 36, 37, 39, 44, 46 and 48 as efficient, with a relative efficiency score of 1.000. The remaining plants are considered to be inefficient, with scores of less than 1.000. According to the CCR model the inefficient plants must either reduce their inputs for the same level of outputs or increase their outputs for the same level of inputs in order to become efficient. A benchmarking analysis can also be performed here in order to identify the optimal targets for each of the inefficient plants to use as sources of improvement. Some of the limitations with the CCR model are that it assumes constant returns to scale and also fails to differentiate among efficient units.

The BCC model overcomes the constant returns to scale limitation of the CCR model. In manufacturing situations it is sometimes practical to assume that as input increases the output increases at a decreasing rate, which is the variable returns to scale assumption. The BCC model basically works under this assumption. The model results for the analysis of power plants is shown under the heading 'BCC' in Table 6.2. Based on these results, one can conclude that plants 1, 2, 4, 6, 10, 11, 15, 17, 19, 20, 23, 25, 26, 35, 36, 37, 39, 40, 43, 44, 45, 46 and 48 are efficient, with a relative efficiency score of 1.000. Although the BCC model incorporates the variable returns to scale assumption into the evaluation process, it does not provide a means for differentiating an even greater set of efficient units.

The cross-efficiency models (SXEF and AXEF) and the ranking model (RCCR) allow for discriminating the efficient units and thereby provide a means for ranking the decision-making units or more effectively making statistical inferences for research purposes. Although the simple cross-efficiency model (SXEF) evaluations allow for ranking decision-making

Table 6.2 Results of illustrative example for various DEA models

DMU	CCR	BCC	SXEF	AXEF	RCCR	GTR
1	0.950	1.000	0.867	0.827	0.950	0.052
2	1.000	1.000	0.954	0.921	1.228	0.115
3	0.896	0.919	0.775	0.688	0.896	–0.031
4	0.995	1.000	0.865	0.754	0.995	0.050
5	0.945	0.953	0.842	0.801	0.945	–0.026
6	1.000	1.000	0.929	0.885	1.136	0.261
7	0.947	0.989	0.861	0.789	0.947	–0.011
8	0.978	0.980	0.806	0.739	0.978	–0.010
9	0.898	0.978	0.728	0.657	0.898	–0.022
10	0.969	1.000	0.804	0.704	0.969	0.034
11	0.958	1.000	0.795	0.756	0.958	0.000
12	0.894	0.895	0.660	0.561	0.894	–0.054
13	0.939	0.950	0.801	0.717	0.939	–0.025
14	0.875	0.917	0.777	0.721	0.875	–0.026
15	1.000	1.000	0.881	0.840	1.026	0.136
16	0.861	0.866	0.727	0.699	0.861	–0.075
17	1.000	1.000	0.665	0.573	1.008	0.004
18	0.946	0.947	0.791	0.699	0.946	–0.028
19	0.975	1.000	0.871	0.772	0.975	0.055
20	1.000	1.000	0.851	0.804	1.051	0.143
21	0.909	0.910	0.706	0.607	0.909	–0.046
22	0.821	0.821	0.614	0.530	0.821	–0.097
23	0.986	1.000	0.765	0.669	0.986	0.001
24	0.935	0.940	0.830	0.728	0.935	–0.031
25	1.000	1.000	0.940	0.849	1.110	0.097
26	1.000	1.000	0.918	0.814	1.134	0.132
27	0.933	0.942	0.744	0.652	0.933	–0.031
28	0.918	0.927	0.827	0.755	0.918	–0.038
29	0.922	0.929	0.789	0.703	0.922	–0.036
30	0.945	0.950	0.745	0.662	0.945	–0.025
31	0.955	0.960	0.861	0.778	0.955	–0.020
32	0.984	0.995	0.806	0.713	0.984	–0.003
33	0.935	0.936	0.784	0.681	0.935	–0.033
34	0.960	0.964	0.786	0.675	0.960	–0.019
35	0.972	1.000	0.857	0.824	0.972	0.060
36	1.000	1.000	0.868	0.816	1.022	0.011
37	1.000	1.000	0.946	0.903	1.158	0.141
38	0.944	0.948	0.695	0.610	0.944	–0.027

Table 6.2 continued

DMU	CCR	BCC	SXEF	AXEF	RCCR	GTR
39	1.000	1.000	0.667	0.586	1.025	0.119
40	0.907	1.000	0.784	0.699	0.907	0.032
41	0.850	0.874	0.741	0.663	0.850	–0.038
42	0.835	0.839	0.697	0.608	0.835	–0.087
43	0.843	1.000	0.611	0.529	0.843	3.343
44	1.000	1.000	0.903	0.859	1.839	1.041
45	0.994	1.000	0.934	0.897	0.994	0.072
46	1.000	1.000	0.864	0.831	1.280	0.123
47	0.929	0.935	0.785	0.687	0.929	–0.033
48	1.000	1.000	0.841	0.776	1.542	0.242

units, they do not address the problem of multiple optimum solutions in DEA. A more comprehensive method for performing ranking is by using the aggressive cross-efficiency model (AXEF). Based on these model results, shown under the heading 'AXEF', it is evident that plant 2 is the best overall performer, with a score of 0.921, followed by plant 37, which achieved a score of 0.903. This analysis can be utilized to rank all the plants, including the efficient ones, in determining the best performers. It is interesting to note that CCR efficient plants 17 and 39 are ranked very low with respect to the 'AXEF' evaluations with mean scores of 0.573 and 0.586, respectively. In fact some of the CCR inefficient units are better overall performers than plants 17 and 39, which is only evident from the cross-efficiency model evaluations.

An alternative method that can be utilized for ranking and discriminatory evaluation purposes is the RCCR model. The RCCR model is different from the AXEF model in that it does not base its calculations on how a unit performs with respect to the strengths of other units in the comparison set. It bases its calculations solely on how large a score a unit can achieve without violating the efficiency constraints of the other units in the set. The results of these evaluations are shown under the heading 'RCCR'. The GTR results are more continuous than the remainder of the models since they do not truncate at zero. DMUs with negative numbers in the GTR column (last column of Table 6.2) represent inefficient units.

Research and application of the DEA results

We shall now briefly define how these results may be used to evaluate organizations and their environmental efficiency from both a research and practitioner or applied perspective.

Research and DEA ecoefficiency results From a research perspective, DEA results may be statistically evaluated. The major difficulty with DEA data is that they do not necessarily fall within some of the distribution requirements assumed by various statistical inferential tools. Thus there is a reliance on non-parametric statistical inferential techniques. As we have seen, the results in Table 6.2 are relative efficiencies for organizations or units within organizations. These efficiency scores can then be used to evaluate theory using non-parametric statistical techniques. The major non-parametric tools that have been identified in the literature are based on ranking statistics. The two models that are specifically recommended for this purpose are the Mann–Whitney U-test and the Kruskal–Wallis rank test (see Conover, 1980).

To apply these non-parametric techniques, there needs to be a classification of the data. For the above data set, a number of possible classifications may be incorporated. For example, there may be differences in ecoefficiency performance based on size, geographic location, company ownership, or managerial characteristics of the organizations.

Another theory-testing approach (as well as for practical application) is the use of DEA performance metrics as a dependent variable for multiple regression. Various regression models such as ordinary least squares, Logistic, and Tobit regression techniques have been applied in building this relationship. The difficulties with applying multiple regression are normality assumptions associated with the data, and truncation of data sets. DEA techniques (for example cross-efficiency and GTR approaches) that allow for better discriminatory power may alleviate the truncation problem.

Practice and application In practice and application, DEA can be used to help organizations carry out benchmarking and performance evaluation. DEA, as a benchmarking tool, can help organizations identify where they are weak in terms of environmental performance and ecoefficiency and address those issues. This is one way that managers can continuously improve their operations using DEA as a performance measurement tool. External benchmarking using DEA has typically been on financial or marketing performance and measures, for example with the banking industry. Internal benchmarking has also been developed. Benchmarking using DEA has been used with respect to the 'envelopment' side of the linear programming formulation. That is, the units that have a positive score ($\lambda > 0$) form the facet set and are regarded as the benchmark DMUs. In other words, it is these DMUs that should be benchmark partners for the organization that wishes to improve its operations.

The advances in benchmarking include using DEA with various clustering approaches to help in benchmarking comparable units from cross-efficiency weights. Once again, the use of environmental factors will show how this can be used. External environmental measures (benchmarks) would include total emissions, expenditures, and so on, while internal measures could include recycling amounts and toxic chemicals generated by processes.

From a managerial perspective, recent applications have shown DEA can be used as a multiple criteria decision-making tool (Sarkis, 1999). The evaluation of environmental projects or programs is one application of the various DEA models. Since environmental technology and programs are typically strategic, the use of multiple factors is usually pursued. These multiple factors may include tangible and intangible characteristics. DEA is suitable for these. With the DEA ranking approaches available, the decision-making for these programs become clear. As well, managerial information can be integrated with these approaches by introducing weight limitation constraints, also defined as cone ratios and assurance regions. This flexibility in DEA allows for a number of ways that ranking and multiple criteria techniques can be used. Clearly, one of the limitations of this set of models is that only deterministic and discrete alternatives can initially be considered.

We can use the results from the illustrative problem to show how DEA can be used as a managerial decision tool. Instead of electric utility plants, DMUs can be redefined to be various environmental technologies (48 in total) that an organization needs to investigate for potential adoption. The technologies are to be evaluated on six criteria. The six criteria characteristics are such that five of the criteria improve as the value decreases (for example cost, emissions), and one of the criteria improves as their values increase (for example energy delivered). The results can then be analyzed from a technology-ranking perspective. DEA techniques that are good discriminators are more valuable for selection decisions. Thus the use of RCCR, SXEF, AXEF and GTR approaches could be considered as preferable techniques. Unfortunately, in the illustrative example, the models provide different solutions for the best DMU. RCCR would recommend DMU 44, AXEF and SXEF approaches would recommend DMU 2, while GTR would recommend DMU 33. A portfolio selection approach (where sets of technology are to be selected) may also give different groupings of best choices depending on the technique. To overcome these discrepancies, additional decision tools or other factors can be considered.

Issues in expanding ecoefficiency to sustain efficiency

The evaluation of ecological efficiency of systems is only one step and one dimension of the more fully encompassing topic of sustainability. To help evaluate sustainable efficiency of systems, the use of DEA is most practicable. The issue is to determine what exactly is meant by the term sustainability. There are many definitions to the term, as shown in the article by Gladwin et al. (1995), who present almost a dozen definitions. Essentially, a common definition that can be applied within the context of efficiency is that sustainability has at least three major dimensions of measures: economic, social and environmental. This three-dimension perspective of measuring sustainability is especially suited to corporations and organizations (or industry in general) and has been defined as the 'triple bottom line.' Whereas, traditionally, organizations are concerned about the economic bottom line, those that are environmentally conscious add the second bottom line of environmental performance and the third bottom line of social performance, which arise from issues related to corporate social responsibility and corporate social responsiveness.

Similar to ecoefficiency determination, the appropriate selection and evaluation of inputs and outputs that will measure this triple bottom line must be determined. A difficulty in accomplishing this task is that quantitative measures of social responsibility may be more difficult to ascertain. For example, how will community involvement, supporting the culture of indigenous groups, and schooling in poverty-stricken areas, be integrated into an efficiency model as DEA? Some form of categorical measures could be used, assigning yes/no or some level of participation measure as either inputs or outputs. Monetizing the contribution to charitable sources or percentage of employees involved in social programs may also be used. Health and safety performance (which may be a proxy of caring for people) may be a measure, albeit imperfect. Tyteca (1998) has introduced such measures to more effectively incorporate the 'social' dimensions of sustainability, but these measures do not necessarily provide a clear and complete picture of true social responsibility in organizations. That is why a tool that can evaluate a number of dimensions, especially those as diverse as social, environmental and economic measures, may be something that can better evaluate corporate sustainability.

Finding sources of triple bottom line data to help evaluate organizations and industries has and will continue to become less difficult as more organizations adopt voluntary corporate reporting standards that have evolved from environmental reporting measures. The global reporting initiative led by the non-governmental organization (NGO) called CERES is attempting to standardize reporting of this type to make it easier to audit and compare organizational social performance. Information on the global reporting initiative can be found at http://www.globalreporting.org/.

Summary and conclusion

In summary, we view DEA as a valuable tool for both academics and practitioners. This chapter is meant to enlighten the environmental management and research community on the utility of this tool for ecoefficiency measurement. Basic, cross-efficiency and ranking DEA-based models were all introduced in this review. Their basic assumptions and purposes were presented. Their usefulness was further exemplified by an illustrative example from published environmentally based data. How the results could be evaluated for research and managerial purposes was also explained. Supporting statistical and managerial decision-making tools and how they could be used with the results were detailed.

The researcher can investigate ecoefficiency issues by looking at industry- or corporate-level analyses. If ecoefficiency is the dependent variable, investigation into what makes some units efficient and others not can be completed. Both non-parametric and regression tools can be applied in these types of investigations. Managers will have at their disposal the efficiency scores to determine how well they are doing with respect to other comparable units (benchmarking) or to help decide on various projects or programs. Integrating managerial preference into the DEA models and their sensitivity to this inclusion is a possible area of further investigation.

The review we have presented here does not cover all the DEA literature. There is a whole class of stochastic DEA models that could be evaluated and implemented for ecoefficiency. In addition, there are models that consider qualitative factors and game-theoretic approaches. Testing the utility of each of the DEA models in various settings can further enhance the selection process. More research into the strengths and weaknesses of the various DEA models is still needed. How DEA compares to other economic productive efficiency models and their usefulness from an environmental perspective is a potential direction for research and investigation.

As well, the application of DEA to sustainable issues is another and more complete step. In this chapter we have outlined how this application can be integrated. The level of analysis for sustainability with DEA can range from individual evaluation to corporate, industry or even national levels. The identification, adjustment and further development of data for sustainability analysis is one of the first steps in applying DEA for sustainability and going beyond ecoefficiency.

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Mining

7 Hierarchical framework for evaluating mine projects for sustainability: a case study from India

M.A. Quaddus and Kampan Mukherjee

Introduction

Sustainability and sustainable development had been the most sought-after policy objective for planners at the regional, national and international level in the last decade. Although there are several hundred definitions of sustainable development (Sun, 2000), the most common definition portrays it as the process of development which meets the needs of the present without compromising the ability to meet those of the future (WCED, 1987; Sun, 2000). Literature suggests that sustainable planning is typically undertaken by the top-level planners at the macro level. However, at the micro level (the project level and so on), sustainable planning is viewed as the process of interrelated decision-making which explicitly considers the sustainability decision criteria (van Pelt, 1993; McDaniels, 1994; Milne, 1996; Madu, 1999; Quaddus and Siddique, 2001). Various approaches are available to model micro-level sustainable planning such as project appraisal.

In this chapter we develop a hierarchical framework for evaluating mine projects for sustainability. Borrowing the concepts from Quaddus and Siddique (2001), Madu (1999) and various literature on sustainablility, we first develop a generic framework and then present a specific application of the framework in the context of mine projects evaluation in India. The chapter is organized as follows. In the next section we present the background literature with respect to sustainable planning approaches at macro and micro level. An introduction to the Indian mining industry is also presented in this section. The integrated hierarchical framework for mine project evaluation is then developed based on the background literature. The framework is then applied to a specific mine project evaluation in India and detailed results are presented and discussed. Finally, conclusions are presented in the last section.

Background

Sustainable development at the macro level

The WCED (1987) definition of sustainable development takes a very long-term view. Van Pelt (1993) mentions that a major condition of sustainable development is the availability of sufficient environmental resources. This notion is also supported by Duncan (1992), who gave a macro-level operational definition of sustainable development that involves appropriate allocation of resources between environmental maintenance, consumption and investment. Therefore an important aspect of sustainable development is the proper management of environmental resources, that is, striking a balance in the allocation of environmental resources between various economic activities.

In Quaddus and Siddique (2001) the authors identify three underpinning concepts of sustainable development at the macro level. First, indefinite population growth in a limited resources environment is a major hindrance to sustainable development. It is more so in many of the developing countries which are completely dependent on natural resources for social and economic development (Madu, 1999). Second, macro-level sustainable development must achieve intergenerational equity. How this can be achieved is subject to debate, but every nation must conserve its non-renewable resources and make optimal use of renewable resources. Third, sustainable development must eliminate poverty and deprivation. This may lead to the dependence of the underdeveloped countries on the developed countries for better technologies and know-how in various economic sectors. This, however, has been criticized as perpetual dependence of the underdeveloped nations on the industrialized nations and may ultimately not work as intended (Singer, 1992). A delicate balance is therefore needed.

For macro-level environmental planning leading to sustainable development, Madu (1999) proposes a decision support framework. The author proposes a number of multicriteria and optimization methods in his decision support framework. Nijkamp and Van der Bergh (1997) present an overview of different modelling approaches for environmental policy analysis and propose the use of scenario experiments for sustainable development. The authors note that scenario experiments handle uncertainty and fuzzy outcomes better than other traditional approaches. Van Berkel (2000) notes the need for sustainable technology in support of sustainable development. He argues that developed nations should invest in these technologies, in particular cleaner production and practices.

Sustainable development at the micro level

Micro-level planning for sustainable development starts at the projects level, which has been identified as essential for macro-level planning. Project appraisal, management and implementation require interrelated decision-making activities which must be carried out with respect to a number of sustainability criteria.

Van Pelt (1993) emphasizes the need for appropriate project appraisal tool to deal with sustainability criteria. He promotes the use of a multicriteria analysis (MCA) tool compared to the traditional cost–benefit analysis tool, because MCA does not require outcomes to be converted into monetary terms. Van Pelt mentions that a clear sustainability policy must be determined for the projects to be evaluated and a number of sustainability criteria and their weights must first be determined. These criteria must deal with a host of environmental concerns and their project-level targets. McDaniels (1994) argues that holistic judgements are inadequate in implementing sustainable development concepts. One needs to identify the key groups and obtain value trade-offs in their social and environmental objectives, which will then result in better chances of implementing the sustainable development plans. The author illustrates this concept in the context of a Canadian utility planning problem. Milne (1996) discusses the concept of sustainability and develops its relationship with decision-making. He also formalizes the need for management accounting for externalities and sustainability, which will capture non-market impacts of projects. Lesser and Zerbe (1995) discuss the need for 'value'-based cost–benefit analysis at the project level 'that can delineate more clearly the trade-offs that decision makers and citizens face, and can assess the different risks inherent in alternative policies'.

The mining industry in India

India is endowed with vast reserves of mineral resources, and coal, being one of the four fuel minerals, plays an important role in the national economy as the prime source of energy generation. Its reserve base is approximately 213 billion tonnes and is expected to last for the next 250 years, much longer than petroleum. With more than 43 per cent annual growth in coal production during the last 25 years, India now ranks third among the coal-producing countries of the world, behind China and the USA (Boparai, 1999). The challenges of global competitiveness and the ever-increasing needs of the economy have been admirably met by the phenomenal increase in production levels, mainly from opencast mines (Verma, 1998).

Coal-mining activities in India started nearly 200 years ago. By 1900 almost 80 per cent of national coal production was shared between two important coalfields – Raniganj and Jharia. Later on other coalfields were discovered and explored. During the 1950s and 1960s (the post-independence period) coal production could not grow beyond 2–3 per cent per annum due to poor infrastructure facilities. Until 1970 coal production was mostly in the hands of privately owned mining companies. Selective mining of easily accessible high-quality deposits and inexpensive labour attracted a large number of small investors (World Bank, 1997). However, until now the Indian coal sector has experienced three distinct periods of sectoral management – pre-nationalization, post-nationalization and post-reform. To deal with the deteriorating situation, the government of India took over all coking coalmines in 1970 and in 1973 all mines producing thermal coal. The coal industry was formally nationalized during the next two years. The main objectives of nationalization included consolidation and creation of an organized system of management, increase of production capacity through implementation of a higher level of technology and improvement of the quality of work life. Ninety-eight per cent of national coal production is now contributed by two public sector undertakings.

The impact of nationalization became quite marked. Annual coal production increased at 5.7 per cent compound rate during 1971 to 1994, which is about a three-fold production increment after nationalization (Ministry of Coal, 1999). But the result did not meet expectations. Later on in the early 1990s the government of India proposed a drastic change in its economic policy, which up until then was more inclined towards a socialistic and closed-door system. Globalization and the competitive market economy replaced protectionism and subsidy-based management policy. It was realized that the Indian coal sector had been suffering from poor efficiency and profitability, which were compensated by government subsidies. New reform policies of price deregulation, lowering of import duties, encouragement of private investments, withdrawal of subsidies and so on are the main features of the post-reform era. This has compelled the coal sector to prepare itself for the new challenges (Lall, 1994). In the context of the above and the fact that demand for coal exceeds supply (demand for 354 million tonnes against production of 324 million tonnes as estimated for 2001–2002), the industry envisages a threat from imported coal, which is of better quality (Sarkar, 2000). This calls for emphasis on improved performance and establishment of a comprehensive framework for performance evaluation and analysis applicable to the Indian coal sector (Mukherjee and Sarkar, 2002).

Sustainability in the Indian coal sector

The need for inclusion of the sustainability phenomenon in mining activities is beyond any doubt or question, once we look at the effect on nature and the environment of exploiting non-renewable mineral resources. Intensification of mining activities inevitably leads to deforestation, degradation of land, emission of pollutants in air and water and so on. Sustainable development came into existence as a serious issue in the Indian mining industry almost two decades ago. A collaborative approach, in fact, is essential in developing economic, environmental and societal policies that affect the mining industry (Sen, 2000).

So far, Indian attempts in this regard have been expressed in creating legislation to take care of environmental issues. The Water (Prevention and Control of Pollution) Act 1974, the Water (Prevention and Control of Pollution) Cess Act 1977, and the Air (Prevention and Control of Pollution) Act 1981 include the legislative obligations and directives to be complied with as per the standards and policies of the State Pollution Control Board (SPCB) relating to the emission of pollutants to water and air. The Environment (Protection) Act 1986 seems to be a more comprehensive legislative measure, empowering central government to close or prohibit any industry, operation or process and also to stop or regulate the supply of electricity, water or other services. Any industrial concern must submit an 'Environment Statement' every year and obtain prior clearance from the Ministry of Environment and Forests (MoEF) in the case of new projects or modernization/expansion of an existing project. The National Environment Tribunal Act 1991 exists to make expeditious decisions on all environment-related cases and also those regarding relief in the case of accidents or damages due to handling of hazardous substance as per the Public Liability Insurance Act 1991. There is a separate act in force for getting approval from the MoEF for diversion of any forest land for non-forest purposes, clearing trees and so on, known as the Forest (Conservation) Act 1980. The amendment of the Mines and Minerals (Regulations and Development) Act in 1987 has incorporated environmental protection issues in granting or extending mining leases and on disposal of tailings. The policy of economic reforms came into existence in 1991 and accordingly the new 'Statement of Industrial Policy' was issued which recognized the need to include environmental factors in the developmental process to meet the objectives of sustainable development. Maintenance of sustainable growth in productivity, gainful employment, preservation of the environment and efficient use of available resources are the primary objectives of the new industrial policy package (Sinha, 2001).

Thus coal-mining companies in India prepare environmental management plans (EMPs) before opening a new mine, or modernizing or expanding an existing mine project in order to obtain clearance from MoEF and other statutory authorities such as SPCB. EMPs include the possible impacts on the environment through an environmental impact assessment (EIA) and the planned courses of action to prevent and control the impacts. EIAs integrate all possible impacts on the environment due to mining activities by some quantitative measures (Sinha, 2001; Kumar, 1997). Further, each opencast coalmine prepares the reclamation plan for landfilling of the quarries by efficient solid waste management procedures. The societal impact of mining activities is managed by well-accepted rehabilitation and resettlement programmes.

The above shows that the sustainability concept has already become an inbuilt phenomenon in decisions about mine development and investment in the Indian coal sector. Unfortunately, there is hardly any literature that reflects the inherent conflict between economic and environmental issues. Perhaps this trade-off between financial gain and contribution to sustainable development demands the immediate attention of management scientists. It should be emphasized that the economic reform policy compels the coal industry to intensify its production with high efficiency and judicious resource utilization and also to enhance profitability as the government is withdrawing funds and subsidies. So success in implementing the sustainable development concept lies in creating a comprehensive framework by an effective mix of cost–benefit factors on the one hand and environmental and societal factors on the other. The next section develops such a framework for micro-level analysis of mining projects for sustainable development.

A hierarchical framework for evaluating mining projects

However sustainability is defined, it requires a symmetric treatment of the present and the future, with explicit recognition of the life-preserving value of environmental assets (Heal, 1997). Sustainability may be located at three different points on the sustainability spectrum (Pearce et al., 1993; Moll, 1991) – weak, strong and very strong sustainability.

In this chapter we intend to build up a framework of sustainable development based on the weak sustainability concept that permits constrained economic growth. Further, the focus of this study is the development of a decision support tool at the company level (that is, micro-level sustainability), so that national-level parameters relating to sustainable development are excluded from this analysis. The proposed framework includes both the financial cost–benefit factors along with all the relevant issues of sustainable development. This calls for a trade-off among the criteria regarding their importance, applying the well-established principles of analytic hierarchy process (AHP) (Saaty, 1980).

Comprehensive framework

The proposed framework is an attempt to capture the various viewpoints of social/management scientists in defining and formulating sustainable development relevant to the minerals industry.

Figure 7.1 shows a hierarchical framework for a mine project evaluation keeping in view both the financial cost–benefit and the relevant sustainable development issues. Adopting the idea proposed in technology impact assessment by Minns (1994), the mine projects are primarily to be assessed by internal and external impacts (level 2). The internal impacts are measured by the standard evaluation indices, for example net present value (NPV), return on investment (ROI), investment cost, financial risk and so on, whereas the external impacts primarily reflect the sustainable development factors. However, the external issues, which are governed by governmental regulations on the environment, mine safety and so on, are to be considered in a feasibility study before initiating this evaluation process.

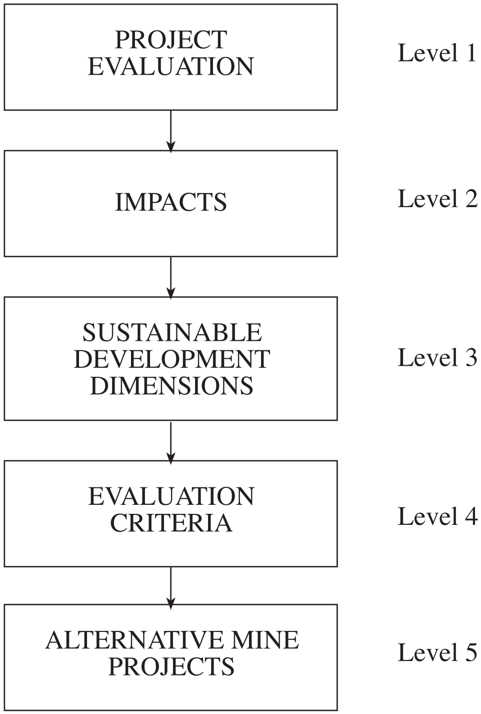


Figure 7.1 A hierarchical framework for mine project evaluation

Level 3 further classifies the sustainable development factors (that is, the external impacts) in the three major dimensions: physical and environmental, economic, and social (Eggert, 2000; Kelly, 1998; Milne, 1996). The physical and environmental dimension represents the sustainability of the natural environment and the preservation of natural resources. All the potential environmental hazard factors due to mining and the need for preservation of mineral reserves are included in this dimension. Economic sustainability reflects improvement of human standards of living. In macro analysis it may be measured by GDP per capita, the Human Development Index of the UNDP and so on. However, at the micro level it may be explained as the generation of man-made capital which is offset by depletion of mineral resources, and this growth of man-made capital in turn leads to higher living standards. The social dimension of sustainability reflects social justice through equitable distribution; that is, the society, particularly the local community, should not share the burden of different social costs due to mining activities, on the same lines of growth and equity as in the Brundtland Report (1987).

The specific evaluation criteria are identified in level 4, the detailed list being shown in Figure 7.2. The indices under internal impacts are financial parameters, for example NPV, ROI, investment cost and financial risk (perhaps estimated statistically), which can simply be computed from the estimated cash flow streams.

The conservation issue of the physical dimension is represented by the fact that the amount of mineral deposit exposed by exploration and mine development activities compensates the depletion of minerals by regular production activities (Eggert, 1995, 2000). This maintains the availability of mineral reserves for future generations. On the other hand, mining activities are often responsible for environmental hazards and subsequently these are associated with environmental repair costs (Warhurst, 1994). Although there is no significant environmental impact during the exploration and mine development stages, major impacts have been experienced during mine extraction/production and mineral beneficiation stages (Eggert, 1994). These environmental criteria also include the loss of farmland for mining, and cost of reclamation of the damaged land. Deterioration of the landscape and aesthetic issues may further be considered as sustainable development parameters. Moreover, environmental hazards include deterioration of air and water quality and acid-mine drainage.

The economic dimension of sustainable development in mining activities may be reflected in the generation of employment opportunities for individuals and the scope for enhancement of productivity and the knowledge level through training, which, in fact, develops human capital at the cost of depletion of mineral reserves. Further, the more advanced technology adopted by the mining company improves the competitive advantage for other mine units through technology diffusion. This may also lead to the opening up new business opportunities in transport, construction and spare parts manufacturing sectors.

The social dimension includes the parameters involving the cost and benefit impacts on society, and the mine projects should be evaluated both in terms of the possible positive impacts, for example the creation of new facilities such as public health centres, schools and so on, and the negative impacts, such as increased alcoholism and crime and so on and social and cultural disruption. Accident proneness and unsafety of mines may also be included as evaluation measures under the social dimension of sustainable development. For a similar model at the national level see Quaddus and Siddique (2001).

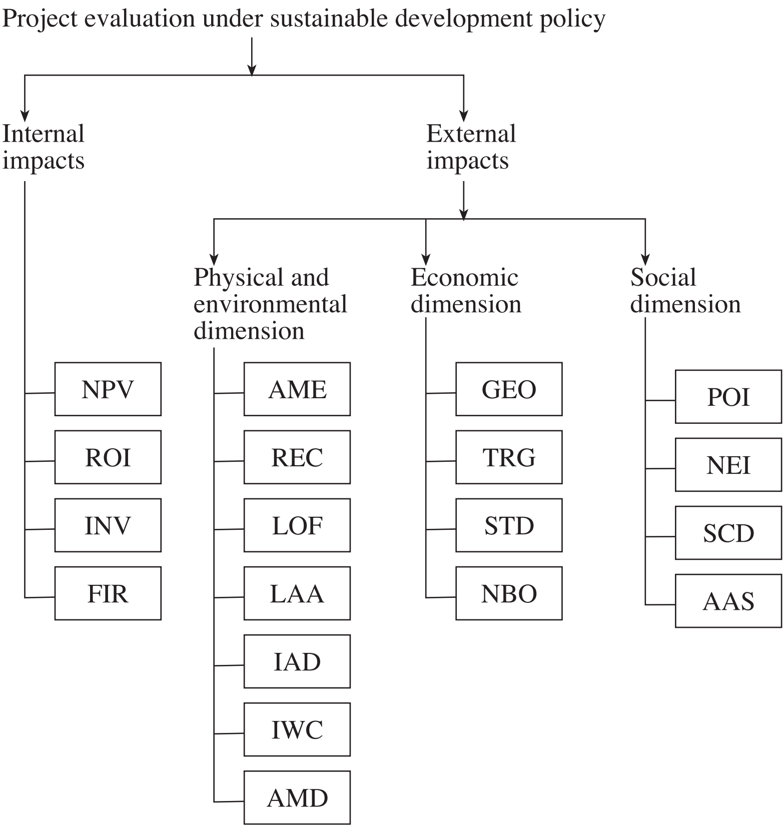
The case application

The proposed methodology (Figure 7.2) is applied to evaluate two coalmine projects under the largest coal company of India, Coal India Limited (CIL). CIL is a holding company, formed as a public sector undertaking in the early 1970s after the nationalization of the coal sector. It contributes 88 per cent of national coal production and controls eight subsidiary coal companies. Seven of these subsidiary companies are engaged in coal production and beneficiation, namely Eastern Coalfields Ltd (ECL), Bharat Coking Coal Ltd (BCCL), Central Coalfields Ltd (CCL), Western Coalfields Ltd (WCL), South Eastern Coalfields Ltd (SECL), Northern Coalfields Ltd (NCL) and Mahanadi Coalfields Ltd (MCL). It is quite evident that geographically it covers almost all regions of India and geologically all coalfields. Among the above companies, SECL, NCL and MCL are consistently more profitable compared to the others. The eighth subsidiary coal company is responsible for the planning and design activities of all subsidiaries and it plays an advisory and consulting role.

CIL produces coal of various grades, both coking and non-coking types. The coking variety of coal is required for steel production, whereas non-coking coal is mainly consumed by thermal power plants. CIL operates 500 coalmines, including both underground and opencast (quarry) with a 0.6 million workforce. With turnover exceeding Rs (rupees) 200 billion, CIL's annual production has recently been estimated at around 300 million tonnes. Due to easier working and higher intensity of production, the share of production from opencast mines is 80 per cent, whereas that of underground ones is only 20 per cent. Most of the customers of CIL are other public sector undertakings in India, the thermal power sector taking the largest share.

The corporate body of CIL is primarily responsible for formulating strategic plans in consultation with the Ministry of Coal and for closely monitoring the performance of the subsidiary companies. The strategic plans of CIL meet the demand of Five-Year Plan of the government of India. Subsequently each subsidiary coal company formulates its own plan and is a multi-tier phenomenon as per the organizational hierarchy. Evaluation of mine projects seems to be one of the key decisions at CIL level.

The proposed methodology involving the sustainability concept is applied to evaluate two mine projects of CIL – code-named project A and project B. Two corporate executives of the coal company, having sufficient knowledge



Key: NPV: net present value; ROI: retum on investment; INV: cost of investment; FIR: financial risk in investment; AME: amount of mineral deposit exposed through exploration and mine development; REC: reclamation of damaged lands; LOF: loss of farmland/agricultural land; LAA: deterioration of landscape and aesthetic values; IAD: impact of air deterioration; IWC: impact of water contamination; AMD: acid mine drainage; GEO: generation of employment opportunity; TRG: providing training facilities to unskilled workers; STD: Sectoral improvement through technology diffusion; NBO: opening up new business opportunities, such as transport, construction, spare parts manufacturing etc.; POI: positive impacts, such as creation of public health centres, schools etc.; NEI: negative impacts, such as increase of alcoholism, crime etc.; SCD: social and cultural disruption; AAS: accident and mine safety.

Figure 7.2 A model for mine project evaluation for sustainability about the projects and corporate policies of the company, took part in the study to provide needed data, many of which have been collected via structured questionnaires.

Mine projects under evaluation

Both projects A and B are opencast mines with a target production capacity of 10 million tonnes per annum, but they are from different subsidiary companies. Mine A is in Korba coalfield, belonging to SECL, whereas project B is a mine in Singrauli coalfield, under NCL. Due to variations in geo-mining and geo-technical conditions, the capacities of production equipment earmarked for the mines are also different. For mine A both the overburden removal and coal extraction are to be performed by the system of shovel – dumper combination, whereas draglines are to be used for overburden removal along with shovel and dumpers for mine B. Detailed information is shown in Table 7.1.

Model formulation

Model formulation involves adaptation of the comprehensive model of Figure 7.2 to the specific application. Most of the features of Figure 7.2 were applicable to the specific application; however, there were some changes in some of the specific criteria. For example, under ‘Internal impacts’ the criteria used were ‘Profitability’, ‘Internal rate of return’, ‘Capital investment requirements’, and ‘Output per man shift’. Similar changes took place in other dimensions of the model.

As indicated earlier, Saaty’s AHP modelling tool (Saaty, 1980) was used for the analyses. A corresponding decision support system (DSS) which implements the AHP is widely known as ‘expert choice’. We have used expert choice all the way through from model development and calibration to detailed sensitivity analysis.

Figure 7.3 shows the expert-choice-based hierarchical model for the mine projects evaluation as adapted from Figure 7.2. As shown in Figure 7.3, the ‘Goal’ (level 1) of the model is ‘mine project evaluation’. Level 2 of the model shows the ‘internal’ and ‘external’ impacts, similar to Figure 7.2. Level 3 shows the ‘physical–environmental’, ‘economic’ and ‘social’ dimensions under ‘External impacts’ (see Figure 7.3). Level 4 shows the criteria under various dimensions of level 3. Note that criteria under ‘Internal impacts’ are not shown in the figure. It is noted that these criteria will vary depending on specific applications. As mentioned earlier, two alternatives under evaluation are mine projects A and B of Coal India Limited (CIL) (not shown in Figure 7.3).

Table 7.1 Facts about the mines

Items	Mine A	Mine B
Mineable reserve and overburden volume	278 mill. tonnes and 252 mill. tonnes	464 mill. tonnes and 1737 mill. tonnes
Quality of coal	Grade F	Grade C and F
Main consumers	Captive thermal power plants of an aluminium producing company and state electricity board	Super-thermal power plant
Capacity of production equipment for overburden removal:	Electric shovels (10 m^3, 3 m^3) and dumpers (120 t, 85 t, 35 t)	Draglines (24 m^3, 20 m^3), Electric shovels (20 m^3, 12.5 m^3, 10 m^3) and dumpers (170 t, 120 t,85 t)
For coal extraction:	Electric shovels (5 m^3, 3 m^3) and dumpers (50 t, 35 t)	Electric shovels (10m3, 8m3) and dumpers (85t)
Maximum depth (metres)	140	240
Capital expenditure (million Rs)[1]	5340	18 480
Labour productivity (tonnes per manshift)	18	141
Manpower	2104	2800
Cost of production (Rs per tonne) at target production capacity	200	397
Profitability (Rs per tonne) at target production capacity	157	331

Sources: Figures in the table are estimated by relevant authority.

Data collection

Data for AHP model are the importance and preference weights of various elements of the hierarchy, which are collected via a process of pairwise comparisons in a top-down fashion. It first starts with the pairwise comparison of the level 2 elements with respect to level 1 element. For

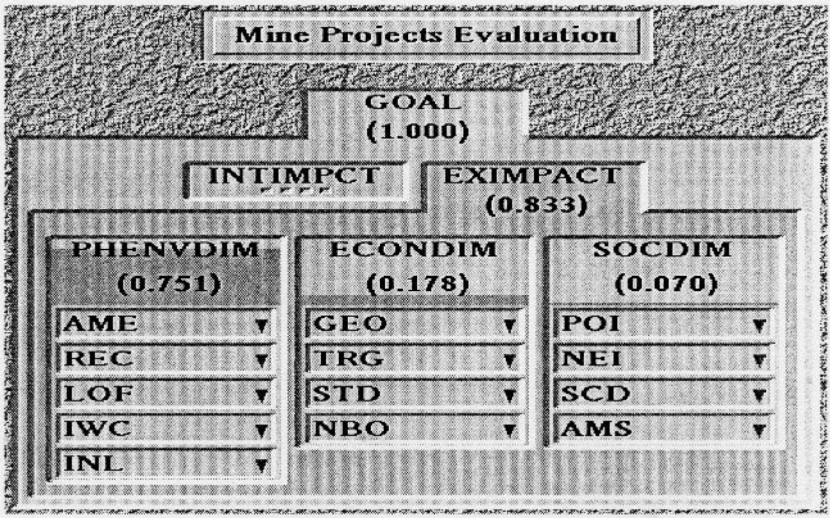


Figure 7.3 Hierarchical model of mining project evaluation incorporating sustainable factors

example, to find the importance weights of the level 2 elements of Figure 7.3 the following question will be put to an expert: *between internal and external impacts, which one is more important to evaluate the mines in question?* This elicitation process continues down the hierarchy until the preference weights for the mine projects are obtained.

As mentioned earlier, two corporate executives took part in the study. The required data were collected via two sets of structured questionnaires. Some example calibrations were included in the questionnaire, which made filling in the questionnaire easier.

Results and analyses

Figures 7.4 and 7.5 show the composite priority weights of the mine projects for executives 1 and 2. It is observed that for corporate executive 1 project B has the highest priority weight of 0.655. Figure 7.5 reveals that project B is also preferred by executive 2 with a priority weight of 0.546.

We then performed the analysis based on the geometric mean of the assessments of the two executives (Saaty, 1980). It resulted in priority weights of 0.569 for project B and 0.431 for project A. It is therefore observed that for overall sustainability mine project B is preferable.

A range of sensitivity analyses was then performed to explain the possible impacts of various criteria on the final results. These analyses were performed based on the geometric mean assessments of the two executives.

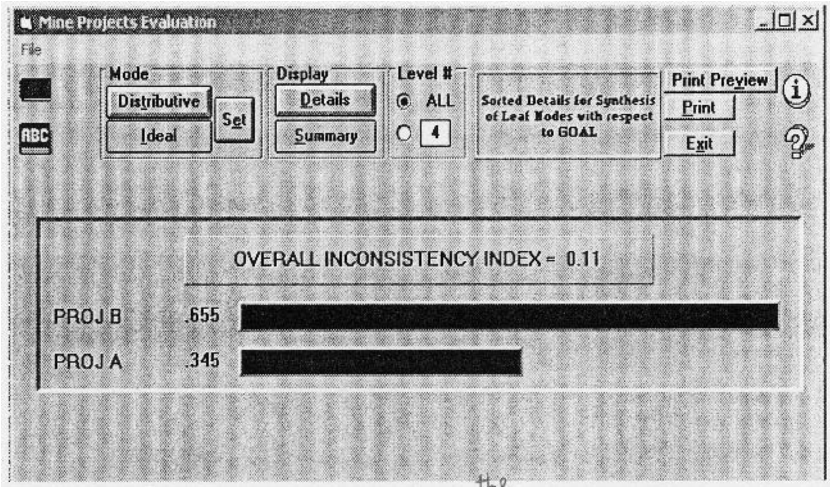


Figure 7.4 Composite priority weights of mining projects as per corporate executive 1

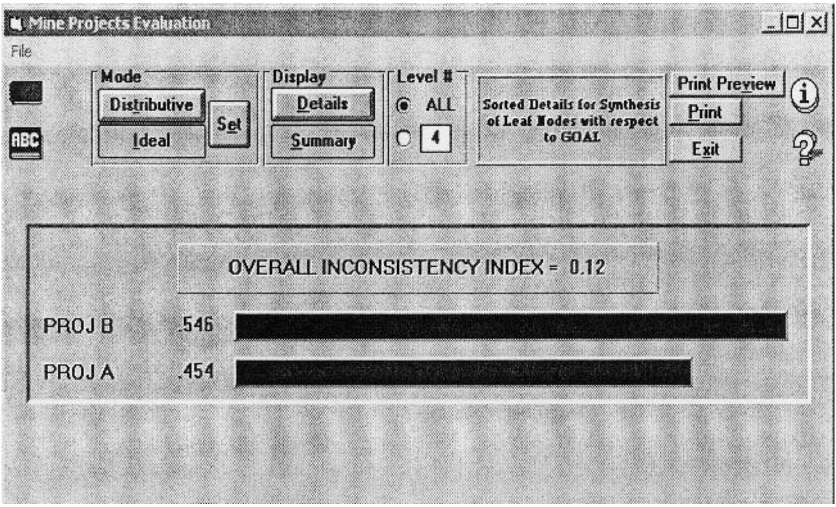


Figure 7.5 Composite priority weights of mining projects as per corporate executive 2

It was observed that the final result is not sensitive to the 'internal impacting' criteria of profitability, IRR, investment requirements and output per man-shift. That is, whatever priorities are assigned to these criteria, project B is always preferred to project A. Similarly, criteria under the 'economic' and 'social' dimensions are also not sensitive to the final results.

However, a number of criteria under the 'physical and environmental' dimension have been found to be sensitive to the final result. These include: LOF (loss of farmland), IWC (impact of water contamination), and INL (impact of high noise level).

Figure 7.6 shows the sensitivity of 'LOF'. The current weight of LOF is 0.171, at which project B is preferred. However, if this weight is increased to about 0.7 or above, project A becomes the most preferred alternative. It acts as food for thought for the executives. Is the priority of LOF likely to increase to such a high level?

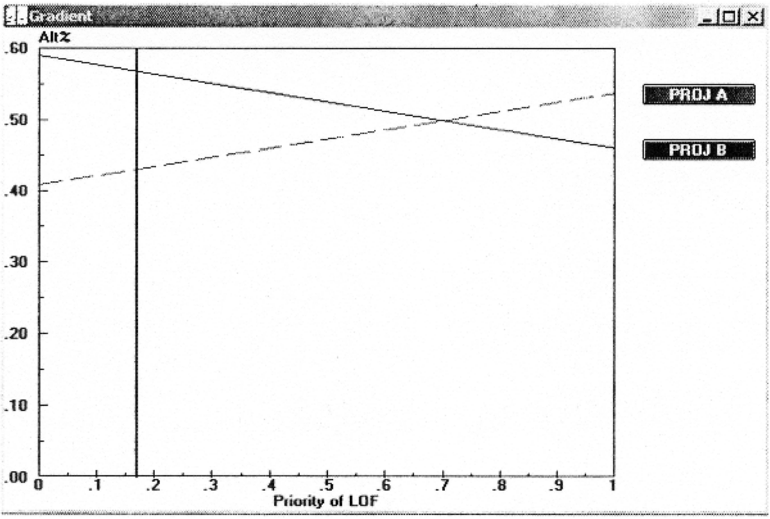


Figure 7.6 Sensitivity graph of LOF (loss of farmland)

It was also observed that the sensitivities of IWC and INL are similar. That is, their current weights need to increase substantially to alter the preference from project B to project A. It can therefore be claimed with some degree of certainty that mine project B is the most sustainable project for Coal India Limited.

Conclusions

Sustainable development planning is a complex process. Both macro- and micro-level approaches are needed. This chapter presents a hierarchical methodology to evaluate mine projects based on a range of sustainability criteria, which is a micro-level planning problem. The comprehensive model is developed and justified based on various literature.

The model is then applied to a real-world mine projects evaluation problem in India. The model is calibrated by collecting data from two corporate executives. Saaty's analytical hierarchy process (AHP) (Saaty, 1980) is used to analyse the model. After running a range of sensitivity analyses, mine B is proposed as the most preferred sustainable mine for the company. It is observed that sensitivity analyses play a major role for this kind of decision selection problem.

Note

1. Rs stands for rupees, the currency of India. Rs 50 is approximately equal to US$1.

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Energy Management

8 Resources, pollution and sustainable energy policies: the case of Pakistan

Hassan Qudrat-Ullah

Introduction

The development of sustainable policies for the energy sector is a complex task that poses serious dilemmas for the economies of many developing countries. Pakistan, a developing country with a rapidly growing energy consumer economy, faces a similar situation. According to some recent demand projections, there is a 12 per cent annual growth rate in demand for electricity over the foreseeable future (HDIP, 1990). To meet such a high demand, in 1991–92 the government of Pakistan introduced reforms that provide incentives for private (including foreign) sector investments, particularly in the electric power industry. In response to these lucrative incentives, many independent power producers (IPPs) signed agreements with the government. Most of the IPPs' offers included oil-, coal- and/or gas-fired electricity generation. Hydroelectric generation, despite its rich resource base in the country, did not hold much attraction for the IPPs, perhaps because it involved very large capital investment.

Pakistan depends significantly (40 per cent) on oil imports to meet domestic oil demand. On the other hand oil, coal and/or gas power plants pose serious challenges to the environment in the form of CO_2 emissions. Moreover, recent global developments[1] in the need for limitation and reduction of greenhouse gases puts a high demand on environmental considerations when making energy and electricity policies. This necessitates the assessment of the existing electricity policy and eventually a decision by policy-makers either to reinforce it or possibly introduce a shift.

Moreover, recent development thinking is that to achieve sustainable development the natural resource base must sustain livelihoods. On the other hand, energy production, which is fundamental to any development initiative, is mostly dependent upon available resources. Therefore, the link between the energy strategies and sustainable development is very intimate. The goal of energy strategies for a country should not be confined to meeting the increasing demand for energy but also to promoting the sustainable use of available natural resources. Do the current energy policies of Pakistan subscribe to these concepts of sustainable development?

In this context, this chapter describes the development, validation and application of a dynamic simulation model to better understand and improve, within the environmental and resource constraints, the energy policy design for the electricity supply system of Pakistan. It begins by describing the context and relevance of the underlying modelling approach (that is, system dynamics) for model development. Then the main structural features of the model, including the empirical validation that made the model useful, are described. Next, utility of the model is demonstrated through evaluation of the base case energy policy, followed by the alternative energy policy design in three different contexts: electricity supply, resource import dependence and evolution of CO_2 emissions. Energy strategies for sustainable development are also discussed in this section. The chapter concludes with a description of the theoretical contributions made and of the major insights gained.

System dynamics modelling for energy analysis

In recent times, the issue of energy planning in the context of environmental protection has turned out to be of vital importance for sustainable development. The analysis of economy-wide energy decisions requires in the first place an integrated modelling approach, which allows an adequate representation of the interplay between energy, the economy and the environment. By and large, non-linear general equilibrium economic approaches have been used to serve the planning needs of energy policy decision-makers. Although these approaches intend to provide a picture of long-term trends in energy–economy development, as equilibrium calculations are made on a term-by-term basis, they do not address short-term effects or transitional policy issues (Dyner and Bunn, 1997). Moreover, with ongoing restructuring and liberalization of economies, as is the case with many developing countries including Pakistan, the use of empirical modelling and economic approaches is relatively limited in their practical implications.

Researchers, especially from the system dynamics community, have found system dynamics (SD) modelling to be useful in providing some broad insights into the dynamics of energy, economy and environment. For instance, SD models have been developed and applied to national energy policy evaluation (Ford, 1983; Nail, 1992); investments and uncertainty (Ford, 1985), conservation policy analysis (Ford and Bull, 1989); effects of agents on utility performance (Geraphty and Lyneis, 1985); inter-fuel substitution in OECD–European electricity production (Moxnes, 1990); privatization of the electricity industry (Bunn and Larsen, 1992; Bunn et al.

(1997); energy efficiency and electricity substitution by gas in the residential and industrial sectors (Dyner et al., 1995). In the current work, where the objective is first to evaluate existing energy policy in terms of economic and environmental criteria and then to provide some useful insights through alternative policy mix analyses, the development of a system dynamics model seemed an appropriate choice. The next section further elaborates on the system dynamics modelling approach and the model development.

The model and its development

MDESRAP (model for dynamics of electricity supply, resources and pollution), was originally developed in 1998 and has been applied to energy policy assessment exercises, both in academic and practitioners' settings (Qudrat-Ullah, 1999). It is a dynamic simulation model based on system dynamics (SD) methodology (Forrester, 1961) and is implemented in POWERSIM^{TM2} (Constructor, version 2.5d). The mathematical equations of the model are available from the author.

Modelling approach

At the heart of MDESRAP is a system dynamics approach. System dynamics is particularly good at studying complex, dynamic phenomena. To study 'the dynamics of electricity supply, resources and pollution', a complex, dynamic problem, we have employed a system dynamics approach. In particular, this unique methodology offers the following features:

- Interaction (and feedback) between the system variables, over time, in and across various sectors such as demand, investment, production capital, resource, production, environment and finances; allows the structural assumptions to be made explicit.
- A disequilibrium framework for modelling, where the adjustments, say, in the need for electricity-generating technologies in response to adjustments in resource price to new equilibria typically create imbalances and transient behaviour.
- Variability in the elasticity of substitution between competing electricity-generating technologies.
- Delays and other distortions in perceiving the true value of the variables (for example, the difference in the price of the 'substitute' to that of electricity have to be maintained before the actual decision to adopt the 'substitute' is made).
- Desired and actual variables' magnitudes (for example, rate of production of electricity and cost-efficiency).
- Non-linear responses to actions (for example, the effect of import dependence on the investment share of the technologies).

This simulation methodology then takes cause–effect relationships, time delays, non-linearities and decision rules and combines them in feedback loops that describe how the system works. Once the phenomenon under study is adequately modelled and specified, simulation is used to perform a wide range of 'what-if?' scenarios, often benchmarked against the base case scenario. These departures from the base case explore alternative strategies, under a wide range of alternative economic, environmental and competitive scenarios.

Model structure

MDESRAP is an integrated dynamic simulation model that represents, at a strategic level, the interactions among:

- patterns of energy intensity and energy demand;
- market-based substitution between electricity and its competitive alternative;
- investments in competing electricity-generating technologies (coal-, oil-, hydro- and gas-based power plants);
- construction of new power plants and depreciation of older ones;
- capacity constraints (for example, the cheaper option is exploited first);
- CO_2 emission levels (only electricity generation related);
- resource availability (through both indigenous and imported supplies);
- the financial structure (including the realization of the environment premium, the import dependence premium and the investment incentive premium);
- the regulatory process.

As illustrated in Figure 8.1, the model is organized into seven sectors:

1. The electricity demand sector describes how the electricity demand (MWh/year) is generated, based on GDP and the electricity intensity of GDP. GDP is exogenous to the model and the average electricity intensity is dependent on the endogenously computed average price of electricity.
2. The investment sector describes how investments in electricity capital are made across the generating technologies (coal, oil, gas and hydro power plants), based on the capital costs of these technologies, the environment premium (due to the CO_2 tax), the investment incentive premium and the resource import dependence premium.
3. The capital sector describes how electricity capital (production capacity

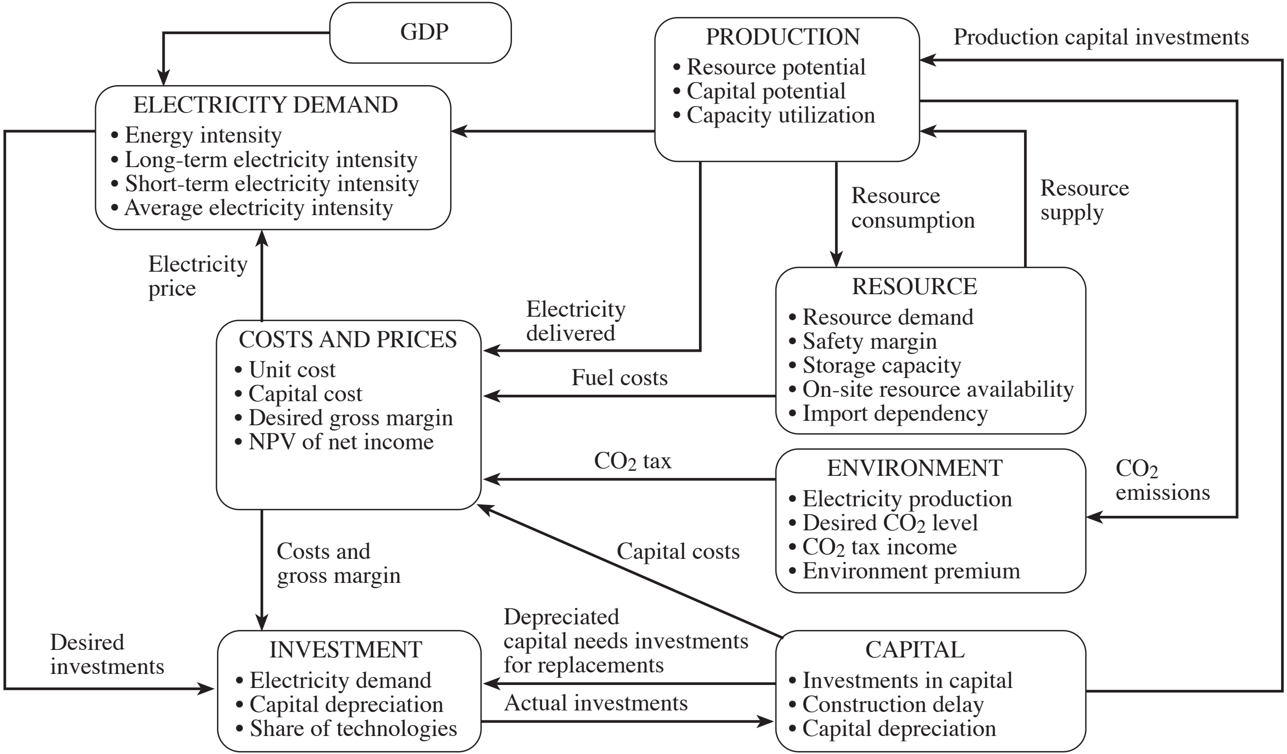

Figure 8.1 MDESRAP's architecture

(MW)) is acquired, based on capital demand and supply (investments being realized) for each of the technologies. The delays involved in the construction of new power plants are explicitly modelled in this sector.
4. The resource sector models the dynamics of resource demand and supply; a safety margin is included in resource demand. On-site resource availability constraints (for example, storage capacity) are explicitly modelled. The import dependence premium, based on how much resource is imported for each of the electricity generation technologies, is also computed in this sector.
5. The production sector describes the electricity production that is dependent on resource potential and production capacity capital. The capacity utilization of each of the power plants is modelled as a function of the ratio of demand for electricity to capacity to produce it.
6. The environment sector describes how the environment premium ($MWh) is determined for each of the electricity-generating technologies, based on the amount of electricity produced, CO_2 emission intensity of fuel, and CO_2 tax rates, while taking into account the reference CO_2 emission limit.
7. The costs and pricing sector describes financial conditions, such as costs, price and net income as they develop as a result of investments.

Figure 8.1 also illustrates the important interactions among the sectors of the model, for example, changes in demand from the electricity demand sector, when matched against (i) the available capacity from the production sector, (ii) the variations in electricity intensity from the cost and pricing sector, and scale of IPPs' investment in the investment sector.

The capital depreciation from the capital sector also affects IPPs' investments. The investment sector allocates the share of IPPs' investments in each case of electricity, generating capital based on the costs and investment incentive premium of these technologies coming from the cost and pricing sector. IPPs' investments, after capital construction delays, add to the production capital units of the respective technologies in the capital sector. The production capital from the capital sector and the resource units from the resource sector provide electricity production potential to the production sector. Electricity production in the production sector influences both the resources sector via 'resource depletion' and the environment sector via 'CO_2 emissions'.

The CO_2 tax information from the environment sector, the resource costs from the resource sector, the capital costs from the capital sector and the amount of electricity produced from the production sector affect the price of electricity. These changes in the electricity price from the costs and pricing sector then 'feed back' into electricity demand and potentially cause further changes in demand for electricity. Figure 8.1 depicts other such feedback relationships.

Model validation

Validation is the process of building confidence in the usefulness of a model (Forrester and Senge, 1980). To establish such validity, a system dynamics model must generate the 'right output behaviour for the right reasons' (Barlas, 1996, p. 186). In system dynamics models, model structure can be compared to descriptive knowledge of real-system structure; and model behaviour may be compared to observed real-system behaviour (Forrester and Senge, 1980). MDESRAP was exposed to such tests for its structural as well as behavioural validity. In addition, the mean-square error and Theil's inequality statistics were used to evaluate the historical fit of our model. Before the scenario analysis, the model was calibrated to the case-specific data.

The following sections describe these methods of model validation and calibration.

Structural validity of the model Since SD models are causal models, the structural validity of a system dynamics model becomes of fundamental importance in the overall validation process (Barlas, 1989a). We have applied a two-pronged approach to the structural validation of MDESRAP. First, during the construction of the model, we utilized (i) the specific case (Pakistan) data and (ii) the sub-models/structures of the existing models of the domain. The relationships developed in the model, which were based on the specific case data, provided a sort of 'empirical' structural validation. The adopted sub-models of the existing models of the domain served as a 'theoretical' structural validation (Forrester and Senge, 1980). Table 8.1 provides the sources of information used during the model's sub-structures development.

Second, we applied the structurally oriented behaviour tests (extreme condition test and behaviour sensitivity test) to validate the structure of the model. The results of the tests were positive and increased our confidence in the model structure.

Behaviour validity of the model Validation of model behaviour is an important part of simulation validation in general and system dynamics model validation in particular (Barlas, 1989). The main purpose of behaviour validation is to compare the model-generated behaviour to the observed behaviour of the real system. The behaviour pattern of the electricity supply

Table 8.1 Model structures adopted from the existing work

Sub-structure / Concepts	Reference	Remarks
Investment incentives dynamics	Dyner and Bunn (1997)	Causal structure was adopted
Substitution mechanism between electricity and competitor (oil)	Davidsen (1989), Section 3.1.9	Structural formulation was adopted
Substitution mechanism among the competing electricity-generating technologies	Moxnes (1990)	Structural formulation was adopted
Production capital structure	Moxnes (1990)	Structural formulation was adopted
Gross margin	Sterman (1980)	Structural formulation was adopted

is assumed to be indicative of model behaviour. Barlas has suggested a set of pattern-oriented tests appropriate for SD model's behaviour validation:

- Trend comparison and removal
- Autocorrelation function test for period comparison
- Cross-correlation function test for phase lag detection
- Comparing the means
- Comparing the amplitude variations.

MDESRAP was exposed to all these tests and strong support was found for its validity. The details of all these tests are listed in Qudrat-Ullah (1999). Here, as an example, we show the results of only one test: comparing the amplitude variations.

To compare the variations in the simulated output, Barlas has suggested the 'percentage error in variations (E_2)' as:

$$E_2 = |S_S - S_A| / S_A,$$

where S_S and S_A are the standard deviations of the simulated and reference time patterns respectively. The values of the standard deviations of the simulated and the reference time series are 21347.3 and 20725.5 respectively. The percentage error in the variations turns out to be 3 per cent. This small percentage error in the variations, E_2 implies that model revision/

modification is not called for and the behaviour pattern validity of the model is further reinforced.

Theil's inequality statistics The mean-square error and Theil's inequality statistics have been used to evaluate the historical fit of our model. These statistics convey a measure of overall behaviour discrepancy. The model is a dynamic general disequilibrium representation of Pakistan's electricity supply sector, excluding nuclear generation. Starting the model simulation in 1980 provides 16 years of simulated data to compare to the actual behaviour of the electricity supply sector of Pakistan. As indicated in Figures 8.2 to 8.4, the results of the simulation reproduce Pakistan's experience with regard to (i) energy intensity, (ii) electricity production (supply) and (iii) CO_2 intensity, relatively accurately. These variables are endogenously generated in the model and adequately serve the purpose of our investigation: 'to assess the impact of investment incentives on electricity-generating technology mix and emissions level, over the long term'. Energy intensity provides us with the overall behaviour of the economy, while the other two, electricity production and CO_2 intensity, exhibit the scenarios of electricity supply and related CO_2 emissions in the environment.

Table 8.2 presents the error analysis in terms of the mean-squared error (MSE), the root mean squared percentage error (RMSPE) and Theil's inequality statistics for these three variables.

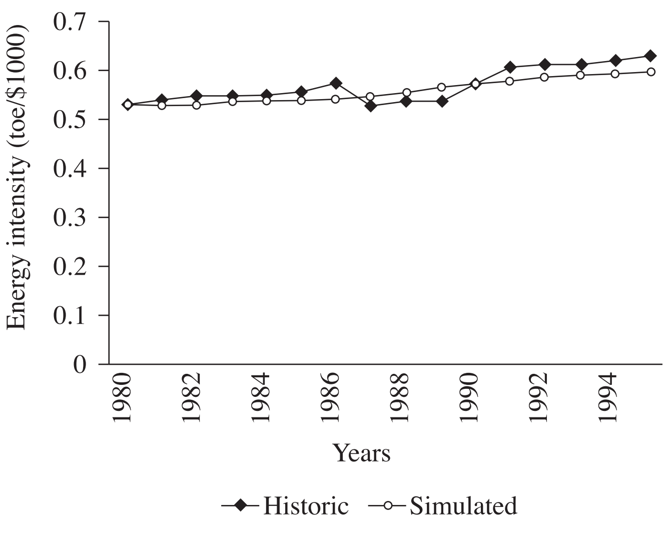

Figure 8.2 Simulated and historic energy intensity

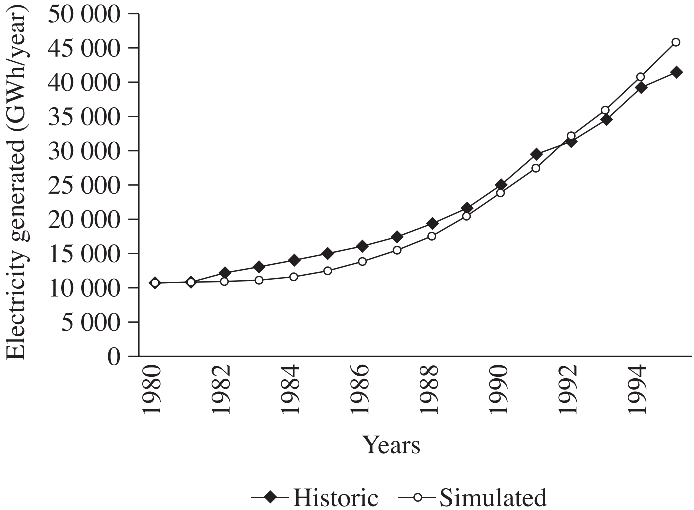

Figure 8.3 Simulated and historic electricity generation

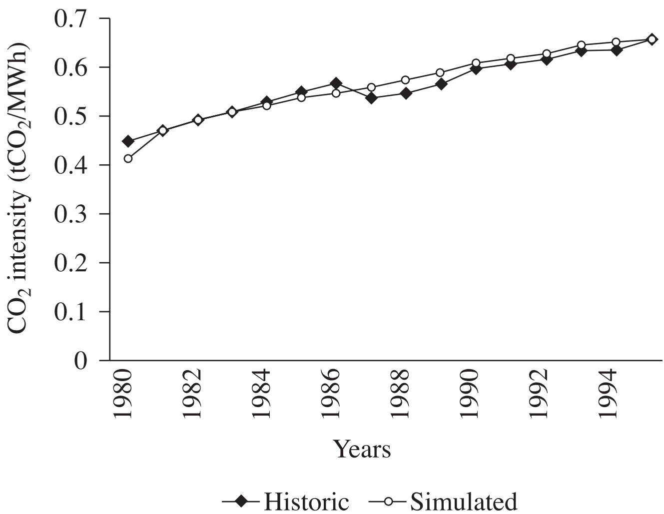

Figure 8.4 Simulated and historic CO_2 intensity

The RMSPE provides a normalized measure of the magnitude of the error. The MSE and inequality statistics provide a measure of the total error and how it breaks down into bias, unequal variation and unequal co-variations components (Sterman, 1984). While the small total errors in the variables provide confidence in the model, large errors might suggest the presence of internal inconsistency of the model or the particular structure controlling the variables with large errors.

Table 8.2 Error analysis of the model

Variable	MSE (units^2)	RMSPE (%)	U^M	U^S	U^C
Energy intensity	0.00040144	4	0.08	0.17	0.75
Electricity production	3842542.62	10	0.13	0.54	0.35
CO_2 intensity	0.00026138	3	0.10	0.46	0.44

Theil's inequality statistics provide us with an excellent error decomposition to resolve such doubts. Consider energy intensity. The RMSPE is 4 per cent. This means that the variable replicates the behaviour quite accurately. Of this small magnitude error, the major portion (nearly 75 per cent) is due to unequal co-variation. This indicates that the simulated energy intensity tracks the underlying trend in the historical energy intensity almost perfectly, but diverges point by point.

Electricity production is characterized by an RMSPE of 10 per cent. The error decomposition reveals that 13 per cent of MSE is due to bias, with 35 per cent due to unequal co-variation and 54 per cent due to unequal variation. The error plot is presented in Figure 8.5 and reveals that electricity production, after beginning with a shortfall of over 8 per cent in 1980, experienced an improvement with a rise of 2 per cent in 1983. After 1984, production again fell about 4 per cent up until 1987, when it again surpassed actual production on a scale of 2–4 per cent for the rest of the period.

This behaviour can be explained with the aid of an assumption about the size of power plants. In our model, we have assumed the size of power plants to be 100 MWe. However, the model could easily be 'tuned' (by selecting the appropriate variable values for power plant sizes) to replicate the historic production of electricity.

If the purpose of the model were point prediction or short-term forecasting, such tuning would be appropriate and would help build confidence in the utility of the model. But since the purpose is assessment of long-term impacts and policy analysis, relying on such *ad hoc* adjustments to parameter and exogenous variables would not enhance the validity of the model and might actually reduce confidence by obscuring the model's ability to endogenously generate the behaviour of interest.

Figure 8.5 Error in electricity production

As a final illustration of error decomposition, consider the RMSPE in CO_2 intensity. Only 10 per cent of MSE is due to bias and the rest is (almost) equally shared by unequal variance and unequal covariance. Again, a simplifying assumption is responsible. A plot of the error is presented in Figure 8.6. We have assumed that initial accumulation of CO_2 corresponds to the current electricity generation. But in reality, this stock could be of higher magnitude. In the model, it would be an easy matter to 'tune' this value to generate the matching value for CO_2 intensity. Also, another assumption (about fuel intensity) causes overestimation of CO_2 intensity generated by the model during the period 1983–95. We have assumed constant fuel intensity (consumption/unit of electricity produced) throughout the whole period. However, by simple adjustments of the fuel intensity parameter, the model would replicate the actual CO_2 intensity. Since the model is not intended for forecasting but rather for policy analysis, the error in CO_2 intensity is of little concern, as it will not affect the relative efficacy of policies.

In summary, we applied these *multiple tests* (trend comparison and removal, autocorrelation function test for period comparison, cross-correlation function test for phase lag detection, comparing the means and comparing the amplitude variations) and Theil's inequality statistics to our model's behaviour evaluation. Each test focused on a specific pattern component. The model passed all the tests quite convincingly. Therefore, given that the model had already passed the structural validity phase, the

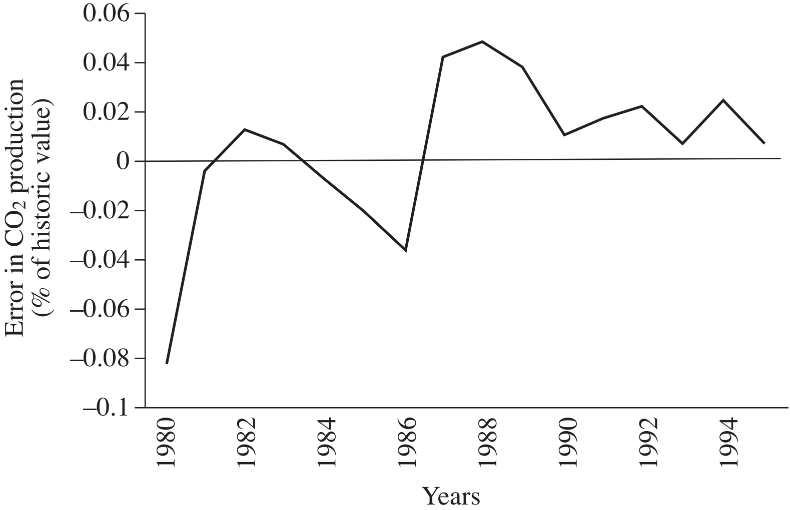

Figure 8.6 Error in CO_2 intensity

favourable outcome of the multiple tests and Theil's inequality statistics contributes significantly to the credibility of the model.

MDESRAP has been calibrated to represent the electricity generation history (from 1980 to 2000) of Pakistan. This time span is considered mainly because the IPPs' investments in the electricity generation sector started in the late 1980s. The model is initialized so as to be in a steady state under the influence of the exogenous economic conditions (that is, the GDP of Pakistan), with the base year 1980.

Policy analysis

Having described the conceptual building blocks and the validity procedures for the MDESRAP model, we can begin to apply the model to assess the base case policy and generate alternative scenarios. The key to effective scenario modelling is to unfold several alternative futures in order to challenge conventional wisdom and to encourage users to think how they would act if this future were to unfold. It is important and timely to remind the interested readers and users of this product that such simulated futures are not predictions of electricity price, supply and demand; nor do they represent official government forecasts. In the following, in addition to the base case scenario, three alternative policy mix scenarios – environment-oriented, market-oriented and self-oriented – are developed.

Base case policy

Policy description Pakistan's electric power demand is growing rapidly (by as much as 12 per cent per year) and is projected to continue to do so for the foreseeable future (HDIP, 1990). To attract the huge investments required in the energy sector, in 1990–91 the government of Pakistan introduced reforms that provided incentives for private (including foreign) sector investments, particularly in the electric power industry. The main features of the promulgated policy are:

- the government's guarantee for payment of WAPDA and KESC[3] power purchase obligations;
- the government's guarantee of fuel supply from public sector entities;
- reduced local currency investment requirements;
- simplified procedures;
- attractive bulk power tariffs (6.5 cents per kWh).

Policy evaluation We assess the long-term impact of this policy (base case) in a three-dimensional context: (i) how does it affect electricity supply (generation capacity mix); (ii) how does it affect resource import dependence; (iii) and how does it contribute to the evolution of (electricity-related) CO_2 emissions?

Electricity supply The simulation results shown in Table 8.3 illustrate the impact of the policy mix on capacity (electricity-generating technology) mix.

We can observe in Table 8.3 a major shift from coal and hydro power plants to oil and gas power plants. Both the unit cost (required price) and the premium for employability and flexibility seem to drive this shift in the capacity mix. Though the unit cost for coal-based technology is relatively small, it is the relatively large (penalty) premium that causes the shift in coal-based capacity: a reduction of coal-based capacity of 33 per cent relative to the pre-policy scenario.

Table 8.3 Comparison of cumulative capacity (GW) mix

Scenario	Coal-based	Hydro-based	Oil-based	Gas-based
Pre-policy scenario (in GW)	0.09	24.54	0.45	16.40
Post-policy scenario[a] (in GW)	0.06	18.34	0.76	25.18
% change	–33	–25	+ 69	+ 54

[a] These results relate to 1990.

In the case of hydro-based generation, there is a (reward) premium that favours the choice of technology. But the unit cost seems to surmount the effect of this premium. In hydro development, also, capacity constraints cause an exponential increase in the marginal costs of investments. Consequently, this additional cost-increasing factor brings a further rise in the unit cost of hydro generation through an increase in the gross margin. Note that the gross margin includes the per unit cost of capital depreciation, a charge to cover the target rate of return and the increased marginal cost due to the capacity constraints. Thus the increased marginal costs are reflected as an increased gross margin. Therefore, the technology becomes less attractive for investments. In the case of thermal capacity development, we have assumed that the effect of the capacity constraints is insignificant. However, here too, the gross margin experiences a modest increase. The delays involved in the process of capacity refurbishing seem to cause this increase in the gross margin.

Also, we can see the economic pressure behind the so-called 'dash for gas' and the fast income generator 'oil' which characterized the capacity building intentions[4] of all generators (IPPs) during the early years of policy promulgation.

Resource import dependence The effect of policy incentives on fuel imports is shown in Table 8.4. With abundant (at least for the current time horizon) local gas resources, only the resource requirement of oil-based generation is met through imports. The cumulative oil imports for electricity generation reach a level of 6287 million barrels, 40 per cent above the pre-policy imports level. The less capital-intensive technology and an earlier income stream generation potential drives the increased IPPs' investment in the oil-based power plants. Consequently, more oil is imported. This scenario explains how the substantial amount of hard-earned foreign exchange of the economy of Pakistan is being spent (and will be spent) to keep the oil-based power plants running.

Table 8.4 Comparison of cumulative oil imports

Scenario	Cumulative oil imports
Pre-policy scenario (in million barrels)	4486.48
Post-policy scenario (in million barrels)	6287.02
% change	+ 40

CO_2 emissions The base case represents a scenario of unconstrained CO_2 emissions because policy incentives do not include any environmental constraints or limits. The cumulative CO_2 emissions reflect a mix of coal, oil, gas and renewable (hydro) production capacities (Table 8.5). After the policy incentives have been introduced, the increasing trend in CO_2 emissions is further reinforced. This corresponds to the intention of IPPs to preferably invest in thermal generation. Under the influence of policy incentives, the cumulative CO_2 emissions (inside the national boundaries of the country) attain a level that is 48 per cent above the pre-policy case.

Table 8.5 Comparison of CO_2 emissions

Scenario	Cumulative CO_2	Escaped CO_2
Pre-policy scenario (in million tons of CO_2)	217.88	1211.64
Post-policy scenario (in million tons of CO_2)	322.28	1543.91
% change	+ 48	+ 27

Similarly, there is a substantial increase of 27 per cent in the amount of escaped CO_2 (outside the national boundary of the country). Thus the overall impact of the policy incentives on the environment is not friendly.

The alternative policy design

The model developed is used to carry out comparative policy impact assessments, with the objective of identifying alternative policies which have environmental and economic benefits under the constraint of available indigenous resources. The base case model is modified to include the structure responsible for the computation of endogenous CO_2 tax systems, the environment premium and the import dependence premium. Three alternative scenarios: environment-oriented scenario, market-oriented scenario and self-oriented scenario are developed, each covering a 31-year period from 2000 to 2030.

Environment-oriented policy mix

Scenario description This scenario is mainly based on the existing policy incentives (guaranteed bulk power purchase at 6.5 cents/kWh for 30 years and guaranteed fuel supply), besides the following conditions:

- restricting CO_2 emissions to 1990 level;
- more efficient power generation (5 per cent improvement).

Scenario evaluation There is a significant impact of this scenario on electricity price. Table 8.6 shows that the electricity price increases steadily during the initial years of the environment-oriented scenario, followed by a large increase in the price during the period 2005–2025 and finally it settles at a value of $62.68/MWh for the remainder of the time horizon.

Table 8.6 Comparison of price (base scenario vs. environment-oriented scenario)

Year	Electricity price ($/MWh)		% change (compared to base case level)
	Base scenario	Environment scenario	
2000	21.91	21.91	0
2005	19.79	24.10	+ 22
2010	18.54	36.04	+ 95
2015	18.31	47.81	+ 161
2020	18.51	56.50	+ 205
2025	18.96	63.92	+ 237
2030	19.69	62.68	+ 218

This increase in the electricity price is explained by the following facts:

- Hydro-based generation, which is used as a substitute under the influence of the environment-friendly scenario, is the most capital-intensive technology. The electricity price that includes the capital costs therefore experiences a large increase after it has been written down.
- During the earlier phase (2000–2010) of the substitution process, oil imports (though with a decreasing trend) cause the increase in the fuel costs that eventually leads to a further increase in the electricity price.
- The internally determined CO_2 tax is added to the operating costs of electricity production. Therefore, the price of electricity that is cost-based experiences an additional increase.

Thus it seems quite impossible to keep the emissions at 1990 levels without adding an extra burden to the consumers: they have to spend more to live in a cleaner environment.

During the first decade of the scenario, electricity intensity remains almost unchanged. The responses to the price changes are delayed by an average of about four years. Afterwards, with a small increase in 2015, electricity intensity follows a linearly decreasing trend (Table 8.7). This trend reflects the electricity price increase and is due to the delays in reaction to the price changes.

Table 8.7 Comparison of electricity intensity (base scenario vs. environment-oriented scenario)

Year	Electricity price ($/MWh)		% change (compared to base case level)
	Base scenario	Environment scenario	
2000	1.68	1.68	0
2005	1.72	1.72	0
2010	1.77	1.77	0
2015	1.85	1.82	–2
2020	1.95	1.86	–5
2025	2.07	1.84	–11
2030	2.21	1.78	–19

Examination of the results presented in Table 8.8 shows that with the imposition of control on CO_2 emissions, the economy adjusts itself to slower growth with relatively smaller capacity investments, electricity supply and electricity demand values.

The reduction of 5 per cent in the total electricity demand is indicative of the costs to the economy in terms the lost electricity intensity resulting from the increase in the costs of electricity due to emission constraints. The increased costs lead to a relatively higher price. The higher the electricity price, the lower consumption: a slowdown of the economy.

Table 8.8 Results of environment-oriented scenario

Scenario	Capacity investments (GW)	Electricity supply (GWh)	Electricity intensity (kWh/$)	Electricity demand (TWh)
Reference scenario	44.34	699 817	2.21	6496.45
Environment-oriented scenario	41.26	764 088	1.78	6194.45
% change	–7	–20	–19	–5

Due to the imposition of CO_2 control, future investments into the hydro power plants become competitive (Table 8.9). The costs of electricity are relatively increased due to CO_2 tax and the capital-intensive technology substitution; relatively less generation capacity of hydro power plants is added after the construction delay that eventually causes loss in the demand for electricity. Table 8.9 shows a shift in the capacity mix.

Table 8.9 Comparison of capacity mix (reference scenario vs. environment-oriented scenario)

Scenario	Coal-based	Hydro-based	Oil-based	Gas-based
Reference scenario (GW)	0.0644	18.34	0.755	25.18
Environment-oriented scenario (GW)	0.0263	33.12	0.278	7.83
% change	–59	+ 81	–63	–69

Before the implementation of the environment-oriented policy mix, thermal capacity is steadily substituted being the least expensive technology. Consequently, CO_2 emissions experience a linearly increasing accumulation into the environment. In the year 2000, CO_2 emissions control policy is invoked. The imposition of control reduces the CO_2 emissions. Also, the CO_2 tax income is spent over a period of time to treat the accumulated CO_2 emissions. Eventually, we see that CO_2 emissions are under the binding constraint in 2009. After 2009, CO_2 emissions remain under the environmental constraint except for the last couple of years of the remaining time horizon (Table 8.10).

Table 8.10 Comparison of emissions (environment-oriented scenario)

Year	CO_2 emissions (million tons/year)		% change (compared to base case level)
	Base scenario	Environment scenario	
2000	70.98	70.98	0
2005	108.54	62.04	–43
2010	147.18	17.01	–88
2015	185.19	16.69	–91
2020	224.72	16.08	–93
2025	269.36	16.41	–94
2030	322.28	40.56	–87

The delays involved in both tax spending and CO_2 emissions mitigation capacity building cause a slight increase in the level of CO_2 emissions for the later years of the time horizon. The variations in electricity intensity cause changes in the electricity demand pattern. In response to this price–demand feedback, the economy adjusts accordingly.

The percentage losses in GDP under the influence of the scenario are significant (Figure 8.7). We can observe that the percentage loss in GDP is exponentially increasing until the year 2030, when it appears to taper off. Thus, based on the simulation results, we may conclude that it is difficult to keep the CO_2 emissions at their base case (1990) levels without significantly affecting the growth of the economy.

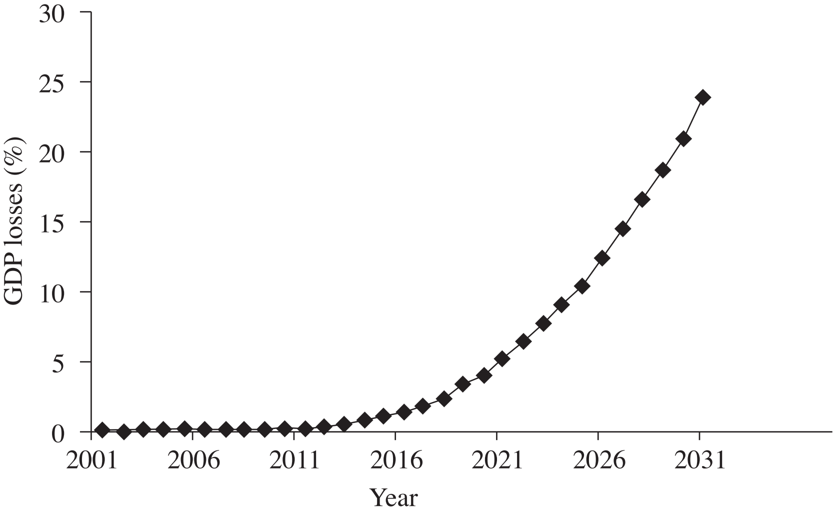

Figure 8.7 Percentage losses in GDP

The effect of the environment-oriented policy mix on oil imports for electricity generation is shown in Table 8.11. Cumulative oil imports reach a level of 2839 million barrels, a reduction of 55 per cent compared to the base case levels. This development is a consequence of the shift of investments to the least emitting technologies (Table 8.9). Only a small portion of total production capacity is oil-based and requires fuel (oil) imports. The rest of production capacity is shared by hydro-based and gas-based power plants with projected market shares of 80 per cent and 19 per cent, respectively. The fuel requirement for gas-based power plants is met through indigenous resources. Thus we see that under the environmental constraints it is possible to significantly reduce oil import dependence without setting additional constraints.

Table 8.11 Comparison of cumulative oil imports

Scenario	Cumulative oil imports (million barrels)
Reference scenario	6287
Environment-oriented scenario	2839
% change	–55

Market-oriented policy mix

Scenario description This scenario is basically the same as the base case scenario, but it applies the market price rate (instead of 6.5 cents/kWh) as the government purchase rate. The policies included in this scenario are:

- more efficient power generation (5 per cent improvement);
- guaranteed bulk power purchase at market price for 30 years;
- guaranteed fuel supply from local resources.

Scenario evaluation There is a significant impact of market-oriented policy mix on electricity price (Table 8.12). The electricity price increases, relative to the base case, steadily during the initial years (2000–2010). During this period the hydro-base capacity is under construction and may cause a corresponding increase in the price of electricity. Thereafter, it experiences a constant increase, compared to the base case, of about 5 per cent during the period 2010–25 before settling at a value of $20.28/MWh for the remaining time of the scenario. Thus the market conditions, as conventional wisdom suggests, in the long term may provide relief to the consumers in terms of relatively cheaper electricity.

The simulation results do not show a significant impact of the current scenario on the electricity intensity of GDP. Actually, the price of electricity does not increase that significantly during the earlier half of the scenario time period. In the later half of time horizon, when the price does increase slightly, the responses to the price changes are delayed. Therefore, the electricity intensity remains almost unchanged.

The results, under the influence of the market-oriented scenario, exhibit a relatively insignificant change in the capacity investments, electricity supply, electricity intensity and demand for electricity, compared to the base case results. However, there is a slight shift in the capacity mix, as shown in Table

8.13. The hydro-based and the gas-based power plants dominate the market with shares of 45 per cent and 54 per cent, respectively.

Table 8.12 Comparison of electricity price (base scenario vs. market-oriented scenario)

Year	Electricity price ($/MWh)		% change (compared to base case level)
	Base scenario	Current scenario	
2000	21.91	21.95	+ 0.2
2005	19.79	20.36	+ 2.9
2010	18.54	19.51	+ 5.2
2015	18.31	19.27	+ 5.2
2020	18.51	19.44	+ 5.0
2025	18.96	20.01	+ 5.5
2030	19.69	20.28	+ 3.0

Table 8.13 Comparison of capacity mix (base scenario vs. market-oriented scenario)

Scenario	Coal-based	Hydro-based	Oil-based	Gas-based
Reference scenario (GW)	0.0644	18.34	0.755	25.18
Market-oriented scenario (GW)	0.0614	19.23	0.728	23.88
% change	–5	+ 5	–4	–5

Under the assumed perfect market conditions, the relatively higher share of hydro-based capacity in the investments is a reflection of the IPPs' long-term perspective on investments.

In the market-oriented scenario, CO_2 emissions are significantly reduced, relative to the base case, during the last decade (2020–30). There appear to be two mechanisms operating to cause this overall emission reduction: substitution of hydro-based technology and the improved efficiency of power plants. However, compared with the base case, the CO_2 emissions trajectory exhibits a slower growth pattern and results in a decrease of the cumulative CO_2 emissions. Upon realization of relatively more hydro-based substitution, the largest decrease of emissions occurs in 2030 (Table 8.14). Consequently, the market-oriented policy possibly leads to a relatively cleaner environment without adding significant charges to the end users.

Table 8.14 Comparison of emissions (market-oriented scenario)

Year	CO_2 emissions (million tons)		% change (compared to base case level)
	Base scenario	Current scenario	
2000	70.98	70.98	0
2005	108.54	108.49	–0.05
2010	147.18	146.50	–0.45
2015	185.19	182.86	–1.26
2020	224.72	219.78	–2.20
2025	269.36	260.67	–3.23
2030	322.28	308.33	–4.33

The percentage losses in GDP, relative to the base case, under the influence of the market-oriented scenario are portrayed in Figure 8.8. We can observe that the percentage losses in GDP follow roughly an exponentially increasing pattern until the year 2030, when they appear to attenuate. Thus it seems quite possible to attract IPP investments at levels similar to the base case (1990) levels with power purchase price as the market price and without significantly reducing the growth of the economy.

Cumulative oil imports reach a level of 6159 million barrels, a reduction of 2 per cent compared to the base case level of 6287 million barrels (Table 8.15). This development is a consequence of the shift of investments to hydro-based capacity (Table 8.13). Thus we see that under market constraints oil imports experience a slight reduction without necessarily setting the additional measures.

Table 8.15 Comparison of cumulative oil imports (base scenario vs. current scenario)

Scenario	Cumulative oil imports (million barrels)
Reference scenario	6287
Market-oriented scenario	6159
% change	–2

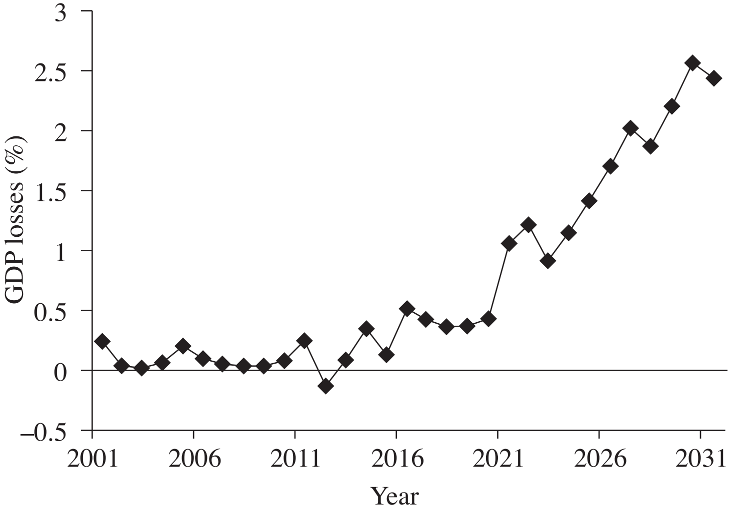

Figure 8.8 Percentage losses in GDP under the market-oriented scenario

Self-oriented policy mix

Scenario description This scenario is mainly a reaction to the reduced dependence on domestic resources for electricity generation. The policies included in this scenario are:

- reduced dependence on fuel imports (not more than 5 per cent of the total generation);
- efficient power generation (5 per cent improvement);
- guaranteed bulk power purchase at 6.5 cents/kWh for 30 years;
- guaranteed fuel supply from local resources.

Scenario evaluation The simulation results show no significant impact of the self-oriented scenario on electricity price. Also, there is relatively little change either in cumulative capacity investments or in electricity supply, and virtually no change in the electricity intensity of GDP. That is to say, with the imposition of import controls in 2000, we do not observe any significant change in the consumption pattern of electricity. This implies that the import dependence restriction does not necessarily result in an increase in the price of electricity. Neither does it reduce the electricity intensity of GDP. The economy appears to continue to grow at the pace of the base case scenario. However, there is a slight shift in the generation capacity mix (Table 8.16).

Oil-based production capacity experiences a significant decrease of 8 per cent of the base case level, while coal-based production capacity remains unchanged. Neither the hydro-based nor gas-based capacities experience significant change. Overall, hydro-based and gas-based production capacities become dominant and gain a market share 41.4 per cent and 56.9 per cent, respectively. In this way, the reduction in the import-based production capacity (that is, of oil-based power plants) is compensated by the corresponding increase in the indigenous resource-based production (that is, of hydro-based and gas-based power plants). Thus the indigenous-resource-based electricity generation constraint does not necessarily add a burden either for the consumers or for the overall economy of the country.

Table 8.16 Comparison of capacity mix (reference vs. self-oriented scenario)

Scenario	Coal-based	Hydro-based	Oil-based	Gas-based
Reference scenario (GW)	0.0644	18.34	0.755	25.18
Self-oriented scenario (GW)	0.0644	18.36	0.694	25.21
% change	0	+ 0.1	–8.1	+ 0.1

In the self-oriented scenario, there is no significant change in CO_2 emission levels compared to the base case scenario. The capacity mix substitution process explains this; under the constraint of fuel imports, the oil-based capacity is substituted by hydro-based generation capacity that brings down the emissions to the level of the base case scenario. Thus the indigenous-resource-based electricity generation policy appears to be an environment-friendly policy.

As under the influence of the self-oriented policy mix, we did not see any significant change in the electricity price scenario, GDP losses, therefore, are negligible. Thus it seems quite possible to keep the pace of the economy at a level similar to the base case level but with a significant reduction in fuel import dependence.

Furthermore, under the influence of this scenario, the level of cumulative oil imports reaches 5992 million barrels, a reduction of 5 per cent compared to the base case level (Table 8.17). The shift of investments to the indigenous-resource-based production technologies seems to cause this reduction in the import dependence level without compromising the growth of the economy.

Table 8.17 Comparison of cumulative oil imports (reference scenario vs. current scenario)

Scenario	Cumulative oil imports (million barrels)
Reference scenario	6287
Self-oriented scenario	5992
% change	–2

Energy strategies for sustainable development The alternative policy mix analysis presented in the previous section demonstrates some of the potential direct impacts of energy policies on the two broader aspects of sustainability – economic growth and environmental emissions. Table 8.18 presents a comparison of the solutions obtained with the model, in the context of (i) losses in GDP (relative to base case), (ii) import dependence levels and (iii) CO_2 emissions, based on the following scenarios:

A A base case scenario
B An environment-oriented scenario
C A market-oriented scenario
D A self-oriented scenario.

Energy policies and economic growth Examination of the third column values of Table 8.18 shows that with the imposition of control on CO_2 emissions (scenario B), the economy adjusts itself to slower growth with smaller GDP values. In fact, the same effect on GDP is observable to varying degrees in all other scenarios. The losses in GDP in each case are indicative of the costs to the economy in terms of lost output resulting from the corresponding decrease in the electricity intensity of GDP. The electricity intensity is mainly dependent upon the price of electricity consumers have to pay. The higher the electricity price, the lower the consumption, causing a slowdown of the economy. From Table 8.16 it can be seen that the highest losses in the projected GDP occur in scenario B, followed by the moderate GDP losses in scenario C and almost no losses (electricity intensity related) to the economy in scenario D.

The investments in capital-intensive technology and the realization of endogenous CO_2 tax under the environment controls regime may cause the increase in the required price of electricity. On the other hand, the long-term perspective on investments (that is, to invest in technologies with low operating costs) by the IPPs appears to influence the increase in electricity prices under the market-oriented scenario. Thus current scenario analysis suggests no conclusive scenario for energy policy to support sustainable development. Perhaps a combination of above-mentioned strategies might better support the sustainable development programme.

Table 8.18 Summary solutions: alternative policy mix scenarios

Year	Scenario	Losses in GDP (%)	Imports (10 million barrels)	CO_2 emission (10 million tons)
2000	A	–	770.7	70.98
	B	0.25	762.1	70.98
	C	0.25	762.1	70.98
	D	0.25	762.1	70.98
2005	A	–	1289.0	108.54
	B	0.11	1194.6	62.04
	C	0.11	1273.1	108.49
	D	0.11	1265.5	108.55
2010	A	–	1965.1	147.18
	B	0.26	1564.0	17.01
	C	0.26	1940.0	146.50
	D	0.26	1921.3	185.12
2015	A	–	2793.1	185.19
	B	1.62	1854.5	16.69
	C	0.52	2758.4	182.86
	D	–0.02	2718.8	
2020	A	–	3780.2	224.72
	B	5.45	2138.8	16.08
	C	1.08	3725.0	219.78
	D	0.04	3655.0	224.07
2025	A	–	4914.1	269.36
	B	12.78	2478.7	16.41
	C	1.72	4858.4	260.67
	D	0.25	4747.4	269.09
2030	A	–	6287.0	322.28
	B	24.32	2839.1	40.56
	C	2.45	6158.6	308.33
	D	0.13	5992.0	321.86

When we look at the oil import dependence level, the analysis suggests an almost similar conclusion, but in reverse order. Contrary to the case of electricity intensity, scenario B is highly successful in achieving the desired level of import dependence. The largest cumulative reduction in oil imports of 55 per cent, compared to the base case levels, occurs under the environment-oriented scenario, B (see Table 8.18, column 4, scenarios A and B for the year 2030). This development is a consequence of the shift of investments towards the least emitting technologies. In the extreme case of scenario C, when oil-based production capacity becomes the preferred choice of IPPs, a risk-aversive behaviour, electricity production becomes vulnerable to supply disruption.

However, the results of scenario D present an interesting case. In scenario D, the self-oriented scenario, the government sets restrictions on oil imports for electricity generation. The controls induce a modest decrease in oil imports. Also, GDP losses under scenario D are insignificant. Thus it seems quite possible to keep the pace of the economy at levels similar to the base case levels but with a significant reduction in fuel import dependence.

Energy policies and environmental emissions The emissions of CO_2 are displayed in Figure 8.9 and in the fifth column of Table 8.18.

Although there is in general a reduction in CO_2 emissions for all scenarios relative to the base case, the reduction in scenario B is more prominent than in C and D. It is understandable that, in scenario B, when the emissions control is invoked, a significant shift occurs between the thermal-based production capacity and the hydro-based production capacity, resulting in the greatest overall reduction of CO_2 emissions.

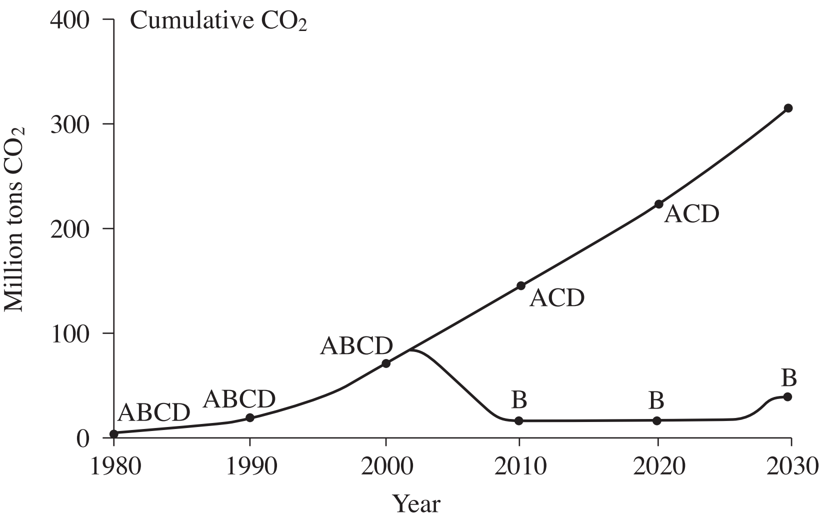

Figure 8.9 Evolution of CO_2 emissions under alternative scenarios

A simultaneous look at the results given in Tables 8.3, 8.8, 8.13 and 8.16 reveals the tendency to change in the composition of production capacity from the base case of 'business as usual' to the alternative policy mix scenarios B, C and D. The shift away from thermal capacity is very pronounced in scenario B. This is mainly compensated by the development of hydro-based capacity at a greater level, as a result of emissions-constraining policy incentives. Under these incentives, depending on its emissions levels, a technology is either rewarded or penalized in the form of a premium. It is understood that employing this environment premium, hydro-based capacity becomes less costly in the overall picture. The gas-based production capacity experiences the largest expansion in the market-oriented scenario, C. This development in the gas-based capacity seems to be the consequence of the relatively lower capital and operating costs. The self-oriented policy mix scenario, D, however, does not exhibit any significant change in the overall capacity mix. This explains how the regulatory structures, as in scenario B, might help to carve environment-friendly energy policies and simultaneously support sustainable use of available, but limited, indigenous resources of nations.

In summary, looking at the results of various energy policy scenarios, it becomes clear that a crucial strategic element for a sustainable energy programme relies both on strengthening market forces in the energy sector and provision of conducive framework conditions by the governments. Neither party appears to be successful in shifting to a sustainable energy regime by itself. For example, increased energy efficiency may be achieved by fostering market forces. On the contrary, sustainable development in the energy sector needs a legal framework for environmental protection and public funding. In this regard, setting up market forces and establishing a legal framework provides a complementary mechanism (Glatzel, 2001) for supporting sustainable development.

Conclusion

By having an empirical component – the direct comparison of a theory with the specific real-world setting that it is attempting to describe – this chapter makes contributions in both the theoretical and the practical domains.

First, the model is a coherent and internally consistent theory of the dynamics of electricity supply, resources and pollution that provides an endogenous explanation of *risk-averse* behaviour of the independent power producers (IPPs) and the resulting increase in the investments for oil- and gas-based power plants and decline in hydro-based power plant investments. The presence of significant political uncertainty together with ongoing structural reforms often causes IPPs' risk-averse behaviour. A risk-averse attitude, in turn, encourages IPPs to take a short-term perspective on investments. As such, the model contributes to the understanding of the dynamics of electricity supply, resources and environment – crucial to any sustainable development initiative.

Second, by being the enactment of a theory, that is, a simplification of the real world, the model permits the isolation of the most significant determinants of system behaviour. The ability to isolate dominant factors allows us to use the model to explore alternative strategies and design policy recommendations for a sustainable energy programme. An explicit set of policy recommendations for a sustainable energy programme within the environmental and indigenous resource constraints has been developed in this chapter. Some useful insights obtained are:

- The government's purchase rate signal, by itself, will not provide a stable signal for investments; rather, it may promote risk averse behaviour.
- The unchanged prolongation of existing policy, or the business-as-usual case, seems to attract IPP investments in the electricity supply sector, but not without the adverse consequences for the environment and the economy. In response to the policy incentives, the IPPs demonstrate a short-term perspective on investments often caused by a risk-averse attitude. There is a huge shift in the capacity mix. Oil- and gas-based (electricity) generation experiences increases of 68 and 51 per cent, respectively, while hydro-based generation faces a decrease of 27 per cent (compared to the pre-policy case). The environment is exposed to an additional 167 million tons of CO_2. The economy endures the increased (additional 1919 million barrels) oil import dependence. Thus, the more stringent the CO_2 emissions control limits, the slower is the growth of investments.
- The model results show that the high CO_2 reduction targets for the electricity sector of Pakistan are achievable but with significant economic effects based on policy interventions. On one hand, the analysis is based on autonomous efficiency improvement (of 5 per cent) assumptions; on the other, a significant CO_2 tax proposal is assumed. It seems quite impossible to keep the emissions at 1990 levels without putting an extra burden on consumers and forcing a significant reduction in the growth of the economy.
- Contrary to the end-of-pipe measures for emission reductions, the programme involving efficiency improvement and competitive substitution for the least emitting technology may, in the long run, cause the economy to evolve with reduced CO_2 emissions and the least import dependence. Therefore, both the efficiency improvement and

the progressive investments in the least (or non-) emitting technologies should be stressed in the government's electricity policies.

- Encouraging investments in the indigenous-resource-based electricity-generating technologies seems, in the long term, to offset the initial burden on consumers (in terms of the relative lower price) and the economy (in terms of the relative increased intensity and reduced import dependence).
- The results of the model also suggest that a market may fail to allocate resources to exploit the rich hydro-based generation potential. An active government promotion of hydro-based electricity-generating technology policy implemented through fiscal instruments can substantially increase the market share of hydro-based generation.
- The simulation results indicate that the increased share of hydro-based production in the total production (of electricity), in the long term, causes environmental as well as economic benefits. The notable benefits include a significant reduction in CO_2 emissions, a drastic decrease in the import dependence level and the relative lower price of electricity for consumers.

Furthermore, energy strategies for sustainable development are discussed. The likely impacts of energy policies on some of the indicators of sustainable development are delineated. The complementary role of public–private partnership in the energy sector is argued.

Finally, this chapter has contributed an empirically validated tool for future research and a tool for improving the understanding of energy policy planners and practitioners, especially in the context of energy–economy–environment interactions.

Notes

1. Kyoto Protocol, agreed in 1998.
2. POWERSIM™ is a trademark of Modelldata AS, Norway.
3. Both WAPDA and KESC are public sector utilities.
4. By the end of 1996, the government of Pakistan had received investment offers from IPPs of about 4 GW capacity, of which 2.5 GW was for gas-fired power plants, 1.2 GW for oil-fired power plants, and the rest (0.3 GW) for coal-fired power plants.

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Land and Water Management

9 On the edge of policy failure: an evaluation of New York City's watershed protection plan from a system dynamics perspective

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Introduction

The City of New York's upstate watershed furnishes the daily water needs of the City's nearly 8 million inhabitants. In its varying forms, this watershed has provided tasteful, healthy and abundant water for decades, although it is geographically quite distant from its urban consumers. In an interesting role reversal, the historically rural, upstate communities within the watershed have begun to yearn for the benefits gained through development and growth, while New York City, having abandoned the explosive growth of youth, struggles to protect its water as a vital natural resource. The problem of water for New York offers academics and practitioners the opportunity to explore why collaborative understanding is so rare, and collective problem solving so elusive. Moreover, this analysis offers guidance, both in our efforts to develop reasoned responses to vital natural resources questions, and, even more importantly, in our struggle to envision a world shaped by sustainable development.

This chapter offers a qualitative and analytical approach to evaluate the New York City watershed problem as the dynamic interplay of two feedback-rich and interdependent subsystems. Achieving the delicate balance of environmental well-being and economic health is a dilemma that spans regions and localities and is better assessed through an analysis that acknowledges the fragile interconnectedness of regions and their problems. Donella Meadows, coauthor of the *Limits to Growth* studies, prolific writer and teacher, spoke often and eloquently about our perceptions of complex systems. In a chapter originally published in *CoEvolution Quarterly* in 1982, and later included in her analysis of the first decade of computer modeling, *Groping in the Dark*, she pondered the seeming contradiction between what we know intuitively with regard to our global systems, and what is often reflected in our public policy: 'The world is a complex, interconnected, finite and ecological–social–psychological–economic system. We treat it as if it were not, as if it were divisible, separable, simple and infinite. Our persistent, intractable, global problems arise directly from this mismatch.[1] Without a clear understanding of the nature of a complex system, its relationships and factors that limit and deplete growth, its boundaries and feedback loops, our capacity to develop alternative paradigms is hopelessly constrained.

Herman Daly, noted advocate of a 'steady-state economy', offers additional insights. Keenly aware of the implications of pursuing the current growth paradigm, Daly also argues in favor of complex systems, and acknowledgement of their limiting factors. Aspiring to a different worldview, he disputes the assumption that the economy is something other than another subsystem of our global system. Indeed, he argues that we are quickly moving from a world characterized by its limiting manmade capital, to one where natural capital is the limiting agent. We must respond to this new pattern of scarcity.[2]

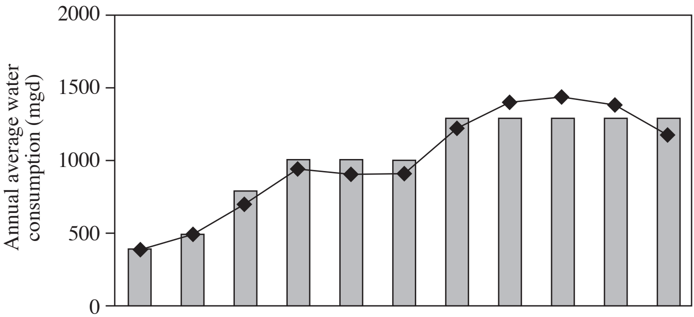
This chapter will provide a concise analysis of the New York City watershed problem against the backdrop of complex systems and sustainable development. First, a brief introduction to the history of the New York City watershed will be provided, from the perspective of the City's burgeoning demand, and from the perspective of the upstate rural communities as they transition from farming communities to more developed enclaves, supported by either tourism or industry. Next, the model will be introduced, and the structural and behavioral insights it affords will be explored. Finally, different policy scenarios will be assessed, exploring the ways in which the environmental and economic subsystems may complement each other and lend more hope to a sustainable worldview. In light of the model analysis, this chapter will conclude with a discussion of the alternatives for the City and its watershed communities.

Brief history

History of water supply and consumption

The controversy surrounding New York City's water supply has a rich and quite extensive history.[3] As far back as 1835, the City abandoned the use of private wells and, specifically, the increasingly polluted Bronx River, in favor of the abundant Croton River supply. Within a decade, however, consumption had exceeded readily available supply, and plans were made to substantially increase the Croton system. By 1911, the Croton Reservoir system had grown impressively, including some 12 reservoirs and three controlled lakes. Soon, however, the metropolis threatened to exceed its water supply, and the Catskill system was completed in 1926. Including the Ashokan, Schoharie and Kensico Reservoirs, construction of the water system supplied some of the best water in the nation, often at the expense of displaced families whose homes were now at the bottom of reservoirs. By the 1960s, as the philosophy of environmental protection grew in influence, another water system was added: the Delaware system was completed in 1965. Including the Cannonsville, Pepacton, Neversink and Rondout reservoirs, it would (and continues to) supply 50 percent of the City's water. Not only did this era deal with one of the worst droughts the City would face; it would welcome a new era in drinking water safety. In 1974, the Safe Drinking Water Act was passed, and New York's water reached even greater prominence, renowned as safe and superior in taste and quality.

It would be reasonable to hypothesize that the plan of action for water provision to the City up until this point was to increase supply until it became more cost-effective to address the issue of water efficiency. During the late 1980s and early 1990s, water consumption and conservation became the overriding concern of the City's water bureaucracy with some degree of success. Recent New York City demand projections indicate that water consumption will continue to remain stable for the next 40 years.[4] As is shown in Figure 9.1, early concern regarding supply initiated the implementation of an extensive metering program, leak detection, and programs to encourage water-saving devices, with a notable effect on per capita consumption.



Year	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990
Safe yield	400	500	800	1000	1000	1000	1290	1290	1290	1290	1290
Total consumption	380	500	700	950	900	900	1200	1400	1444	1403	1185

Figure 9.1 New York City water consumption

History of water quality and watershed development

Paralleling issues of water consumption, the concern regarding future water quality began to appear on policy agendas with increasing regularity. The

Croton Reservoir system, consisting of 375 square miles of watershed with 12 reservoirs, has received increasing attention in the last ten years, culminating in an EPA mandated filtration requirement by 2007.[5] Croton's Kensico Reservoir was also the focus of a Natural Resources Defense Council chapter, which cited development as the most damaging factor affecting water quality in the Croton system.[6] In addition, this is not a situation of pollution in an isolated reservoir: Kensico acts as the final stop for about 1.3 billion gallons of water per day from the Catskill and Delaware reservoirs.

Development pressures within the other areas of the watershed were perceived as mostly irrelevant until recently. As concern over potentially expensive filtration of the Catskill and Delaware systems became a serious threat, more attention was paid to land use patterns in the Catskills, and the potential for increased pollution in the future. As is shown by Figure 9.2, development pressure is indeed something that should be given much more attention.

Urban areas located along the Hudson River have been sprawling outward for years, though at a rate which has not caused a great deal of alarm. The

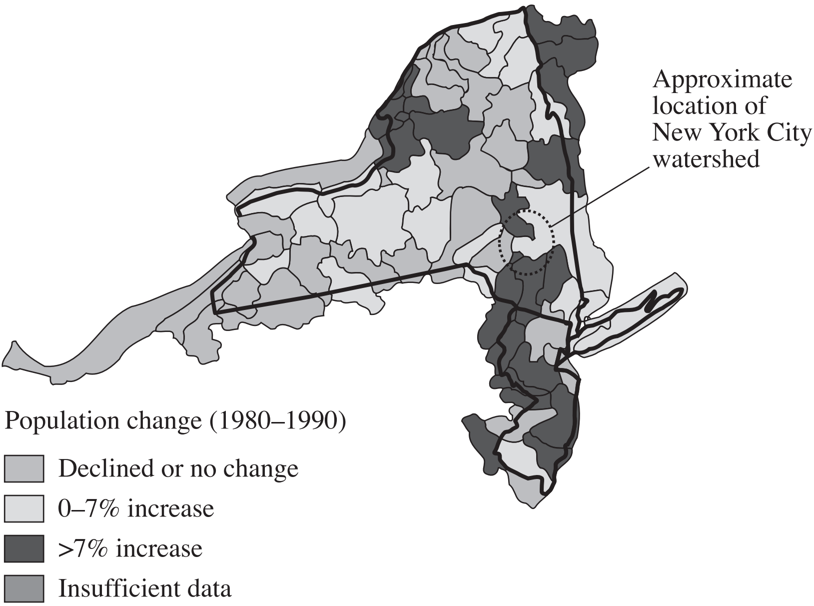


Figure 9.2 Map of New York State population growth, 1980–90

Source: United States Census Data, 1990.

pattern indicated by Figure 9.2 can be interpreted in different ways. To err on the side of caution, though, it would be prudent to note that some of the areas in the map, with greater than 7 percent increase in population, are also within the watershed area.

Furthermore, various urban sprawl studies conducted in the past several years indicate that population is not necessarily the most appropriate indicator.[7] In the upstate New York Capital District region, a recent report prepared by the Capital District Regional Planning Commission notes that while the region's population grew at 5 percent between 1986 and 1997, the amount of developed land grew 10 percent in the same period.[8] It seems the trend is to spread out, shown by a decline in inner-city populations, and intensive suburban and fringe development. And, as populations spread outward, population and building structure density declines.

As an example of this trend, Greene and Delaware Counties, the counties that make up most of the Catskill/Delaware watershed, have undergone development without significant population increases (see Table 9.1). Ulster County, much closer to highly developed urban areas, shows a somewhat different trend, having already occupied much of its land. Its growth has slowed somewhat, and its vacancy rate has declined. One could hypothesize that these counties exhibit different stages of development – as a county becomes more occupied, and the most desirable land has been consumed, in-migrating residents begin to occupy the less desirable remaining land. Those individuals that can afford to move further out to the country and endure the longer commutes, do; older suburbs experience in-fill development; and newly discovered rural communities experience a rise in building.

Table 9.1 Housing stock changes, 1980–90

County	Housing units, total, 1990	Housing units, percentage change, 1980–90	Housing units, percentage vacant, 1990	Housing units, percentage built between 1980–1990
Delaware	27 361	20.3	35.5	17.5
Greene	25 000	17.1	33.6	18.8
Ulster	71 716	3.5	15.2	14.7

Source: United States Census Data, 1990.

According to the economic development study commissioned by the City as part of their watershed protection measures, there are approximately 78 000 people living within the watershed, which encompasses more than

50 towns. Almost two-thirds of the land in the watershed (about 700 000 acres) is considered parkland, although only 250 000 acres is designated as 'forever wild.'[9] The West of Hudson Economic Development Study did not indicate what the population predictions were for the region, noting that the region was 'clearly rural'. In contrast, the Greene County Economic Development home page begins with a reference to the mythical Rip Van Winkle, 'The Sleep is Over!',[10] indicating that the Greene County portion of the watershed will be undergoing very visible development changes in the next decade.

While the rest of New York State experienced prosperity through the 1990s, the watershed counties encountered a drop in employment, and incomes in the county are substantially lower than the statewide average.[11] Additionally, real wages in the region have declined, while statewide, the reverse it true. The City's economic development study pointed to two trends: simple wage reduction for full-time workers, and an increase in part-time workers. Without a new economic stimulus, the report acknowledges that little improvement in the standard of living is likely to take place. The state of economic indicators further encourages an attitude towards economic development (typically with little acknowledgement of the form it takes), and away from conservation. In a region that is suffering from high unemployment and a declining standard of living, local governments are not sympathetic to outside parties preaching sustainability and environmental protection.[12]

Cognizant of the increasing criticism of environmentalists concerned with the protection of the watershed, and with the necessity of meeting the regulations imposed by the United States Environmental Protection Agency, the City created a comprehensive long-range plan that detailed, among other things, watershed protection measures. Perhaps the most important element of this 1989 plan was that it enabled the City to receive a long-term waiver from the obligation to filter the Catskill and Delaware water supply.

Regardless of the City's reputation for superior quality drinking water, the EPA insisted on consistency across states. In 1989, it promulgated the Surface Water Treatment Rule pursuant to the 1986 Safe Drinking Water Act Amendments, and required that all surface drinking water sources meet specific requirements by June of 1993, or the supply must be filtered. The cost of filtration of the Catskill and Delaware water supply would exceed, by some accounts, $8 billion.

In September of 1990, the City released a specific watershed protection plan, which included revised watershed rules and regulations to replace those that had not been altered since 1953, and a plan to acquire land around the reservoirs upstate. Land acquisition was necessary in order to create a suitable 'buffer zone' along the shoreline and essential wetland areas around the reservoirs. Release of this original document initiated fierce opposition among the watershed communities, who accused the City of threatening the economic development potential of the region. The communities responded by organizing into the Coalition of Watershed Towns, and continued to represent a large segment of the watershed community.

In January of 1993, EPA granted a one-year waiver to the City; in December of 1993, a second waiver was granted, providing an additional three years of avoidances as long as various conditions were met. This included a final revision of the Watershed Rules and Regulations, and a firm program of land acquisition. In April of 1995, Governor George Pataki entered the stalled negotiations, provided additional counsel, and guided the controversy towards a seemingly peaceful end. By November of 1995, an Agreement in Principle had been defined.

On 21 January 1997, the Watershed Memorandum of Agreement was signed by representatives from the non-profit, governmental and citizen sectors, and is the legally binding document that ensures avoidance of filtration of the Catskill and Delaware water supplies, and guides the implementation of the watershed protection program.

New York City watershed agreement

As is typical of public policy, the final watershed agreement included only some of what the City had originally requested. The final agreement stipulated that the City could purchase land in order to create an adequate buffer zone around the reservoirs and important tributaries. Over the next several years, the City will solicit owners of 355 050 fragile acres of watershed land, about 30 percent of the watershed. There can be no lands acquired through eminent domain, and there is room for exemptions within various townships to allow for 'reasonable opportunities for development ...'[13] The City has allocated $250 000 000 for the purposes of land acquisition.

Additionally, the new watershed rules have been enhanced to better control sources of pollution. Upgrades have already been completed on most of the original seven designated wastewater treatment plants; unfortunately, project funds are no longer available to complete the remaining studies on an additional 15 sites. The City must approve all new, repaired or replaced septic systems. Funds were allocated to help homeowners with the cost of replacement.

Finally, in order to ensure economic and social prosperity, various programs have been instituted with City dollars. In addition to the previously mentioned wastewater treatment activities, the $60 million Catskill Fund for the Future was enacted to distribute funds and grants to promote environmentally sensitive economic development projects. This program, and a number of others which focus on such issues as road salt containment and storm water runoff, will be administered by the Catskill Watershed Corporation, the City-designated non-profit organization.

A socio-economic model of watershed land use and development

The following model analysis is the result of an independent research project undertaken during the author's tenure as a Master's student in Public Policy at the University at Albany. At the time of its original completion, the watershed communities, and their various support organizations, were beginning to develop projects and timetables to meet their obligations, the City had begun its construction of wastewater treatment systems in several watershed communities, and, in general, the policy environment was tense.

Because the problem of water for New York City was both a dynamic one, as its components and variables change over time, and a problem that involves issues of feedback, it was analyzed using system dynamics. As a methodology for understanding complex systems, system dynamics includes the construction of formal models, based on assumptions derived from historical evidence, investigation and intuition, allowing users to engage in simulation and experimentation. For the purpose of creating the models shown here, Vensim modeling software was used.[14]

Model overview

The following system dynamics model attempts to integrate the policy choices adopted by the City of New York to address their need for unfiltered water, and thus continued environmental preservation in the Catskills, and the social and economic developments of the watershed region. It will illustrate the interacting relationships and the feedback mechanisms that shape the behavior of the various components of this policy problem. The system dynamics model shown here draws from Forrester's urban model,[15] and Simonovic's analysis of water resources policy modeling.[16]

It is necessary to first consider which feedback relationships, or 'loops,' are a necessary component of the system, and provide insight into the policy issue. As stated earlier, the water policy planning for New York City grew incrementally, responding directly to the needs of a growing urban population in two ways. Figure 9.3 offers a conceptual view of the model's assumptions.

Figure 9.3 illustrates the various feedback mechanisms at work in this simplified model of behavior in the New York City watershed. It illustrates the two balancing ('B' in the figure) loops working to control water use and watershed size in New York City. The watershed expansion loop indicates New York City's original preferred policy to address growing water demand. Population growth leads to heightened awareness of potential scarcity, which

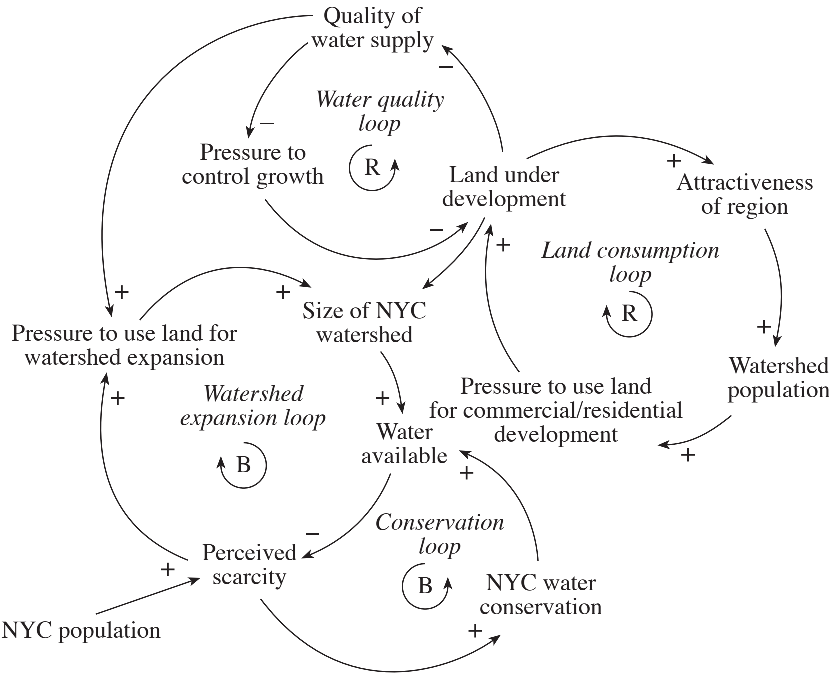


Figure 9.3 Conceptual view of the watershed model

encouraged growth in the size of the watershed region. As the size of the watershed grew, so did water availability, which alleviated the pressures of scarcity, at least until the population grew again.

The conservation loop illustrates the more recent policy adopted by the City. In this case, the pressures of population and water scarcity, and the fact that additional watershed construction is not economically feasible or politically appealing, led the City to choose to implement water conservation measures. By eliminating wasteful use and promoting more water-saving devices, the City is able to make better use of the current supply, thus increasing effective capacity and addressing concerns about scarcity. As the population becomes comfortable with perceived abundance, though, one wonders if per capita consumption will remain low.

In another sector of the model, the watershed itself is examined in detail, including the various issues related to land use, economic development and population pressures. Drawn from Forrester's work with the urban model, some necessary alterations have been made to make this model more compatible with a rural village scenario.

The behavior implied in the land consumption loop portrays a familiar dilemma in planning and management literature. As population increases, and where there are few limiting factors, there is a greater desire for development. If there is a suitable amount of housing available, it is likely that more people will enter the region. In a region where there is a tremendous shortage of housing, there are likely to be fewer people willing to move to a region, as housing prices and land restrictions would present obstacles.

Similarly, as the population grows, there is a greater need for employment, which tends to stimulate business, which will historically grow in the face of a large and inexpensive labor pool. The large labor pool also represents a large stock of potential consumers, who would encourage business health and expansion. As the stock of business increases, additional people are likely to enter the region as it is perceived prosperous and growing, and the job outlook seems optimistic.

In an environment where people, business and housing could grow, these two loops would continue unabatedly. In a region where there are limits (and one could argue that there are always limits), the availability of the land will limit the continued outward expansion of business and housing stocks.

Figure 9.3 begins to illustrate the competing priorities of the watershed communities and New York City. As watershed businesses housing grow in size, they consume land. The 'plus' signs on the arrows indicate the positive relationship between business and housing stocks and the land under development. As shown in the final loop, the water quality loop, such increases in development have detrimental effects on water quality, and there is an increased pressure to mitigate such growth, either through effecting change in the way land is developed or through outright purchase of land within the watershed. That protection, either by severe regulation of development or by purchase, should act to limit how quickly the stocks of housing and business expand.

Base run

The base run will act as the benchmark with which to compare subsequent policy runs. It has been parameterized to fit most closely with reality in 1900. The model runs over a long period of time, 150 years, which best supports this type of long-range policy problem.

The preliminary graphs (Figures 9.4–9.6) identify the most important variable at work on the New York City water supply sector of the model, and illustrate the most interesting and relevant behavior. The following graphs (Figures 9.7–9.10) illustrate behavior and variables in the Catskill watershed sector, also showing noteworthy behavior and an analysis of how this behavior can be interpreted.

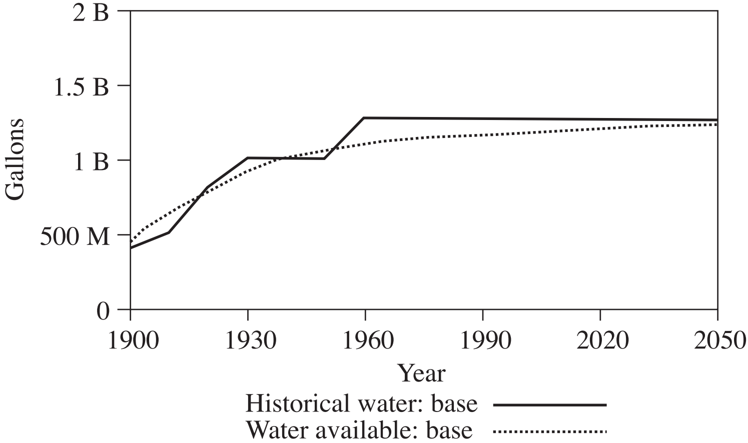


Figure 9.4 *Historical watershed size compared to model watershed size*

The figures offer a graphical explanation of model behavior. Population in the city, and the growing per capita water consumption among that population, initiated surges in watershed growth, shown in Figure 9.4. The model-generated data constitute an average of acres added to the watershed over time, while watershed projects that added reservoirs are shown by the solid line on the graph.

Indicated per capita water use, shown in Figure 9.5, grows over time. Curiously, as this has not been studied extensively, the City population seems to 'adjust' to having more water by consuming more.

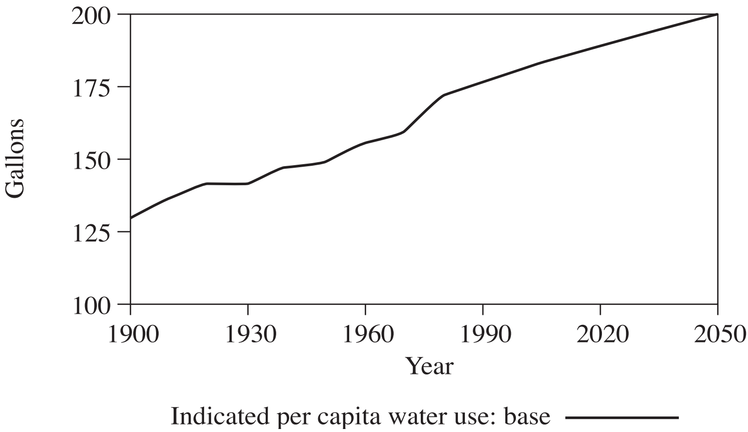


Figure 9.5 *Model-indicated per capita water use over time*

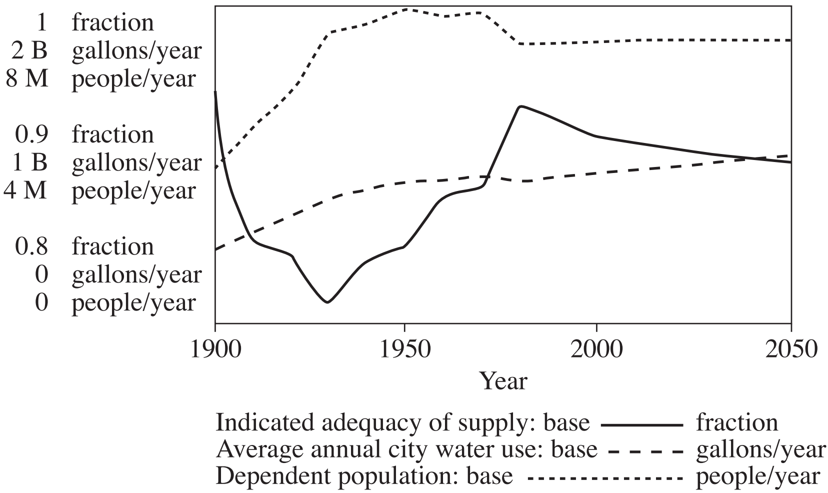


Figure 9.6 Comparison of three sector variables: adequacy, consumption and population

As illustrated in Figure 9.6, the City has been unable to keep pace with the need for water, for the greater part of this century. This fact is due primarily to a population growth rate that was increasing in tandem with frantic water supply expansion. Essentially, the City was in a constant struggle to 'catch up'. If the city population had not declined before becoming somewhat static, the alternative scenario may have spelled disaster for a region with little room to continue expansion and few funds to embark on new watershed projects.

Starting with Figure 9.9, it becomes clear why New York City has historically not demonstrated a great deal of enthusiasm for watershed protection before the Watershed Agreement of 1997. Very little of the watershed has been covered with structures, until fairly recently. This does not, of course, preclude pollution from a number of other sources, including agricultural runoff, impervious surfaces, such as roads, and various recreational activities, including golf courses. Watershed protection has not been perceived as an immediate need because, as shown by this graph, the need has appeared as a sudden threat.

The underlying or true need, however, becomes much more obvious as one examines the trends of business, housing and population in the Catskills. Shown in Figure 9.7, these stocks illustrate extensive growth, which threatens to bring the issue of land protection quickly to the forefront. Although this graph tends to magnify the problem somewhat, the behavior is reasonably

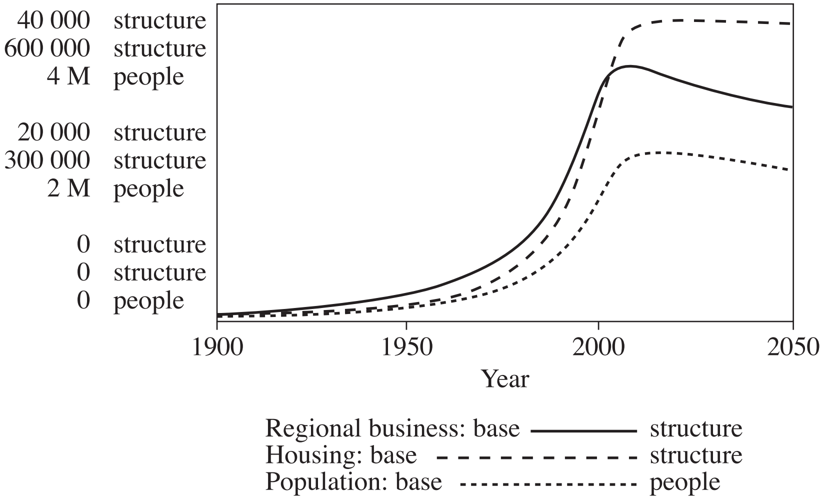


Figure 9.7 Business, housing and population within the watershed

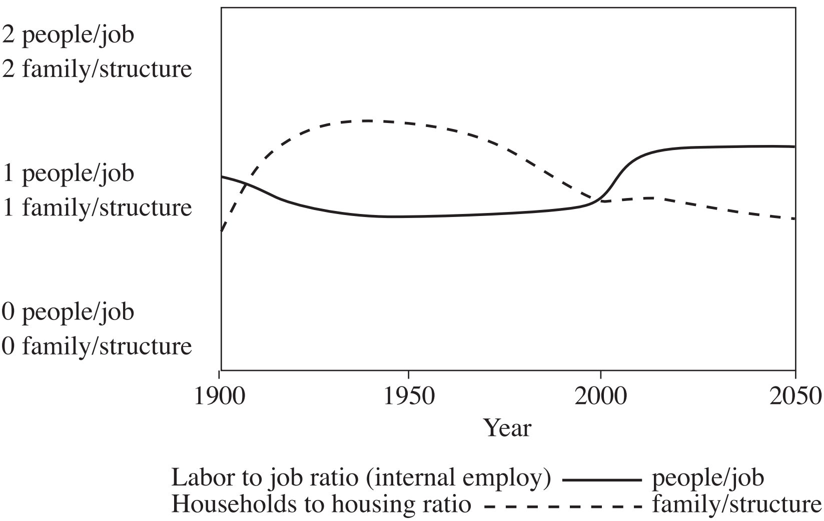


Figure 9.8 Employment and housing in the watershed

accurate. Dwellings in Greene County, for example, doubled between 1970 and 1990. The population is forecast to rise from approximately 50 000 to more than 60 000 in the next ten years.

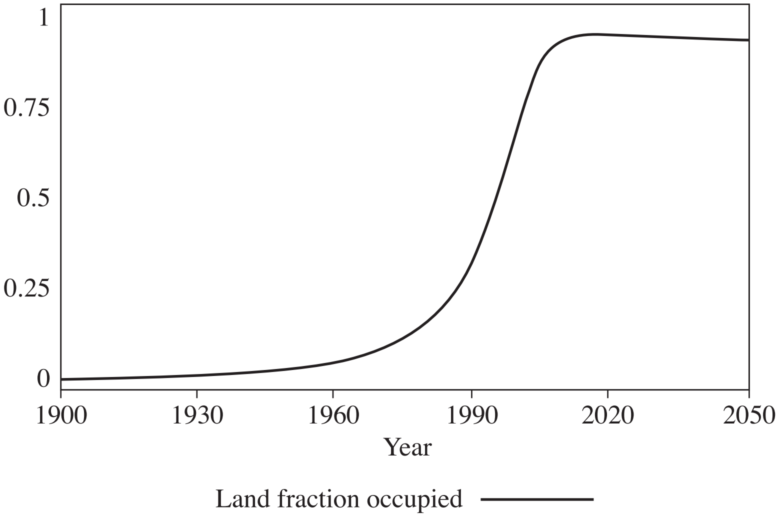


Figure 9.9 Fraction of developed land in the Catskill region

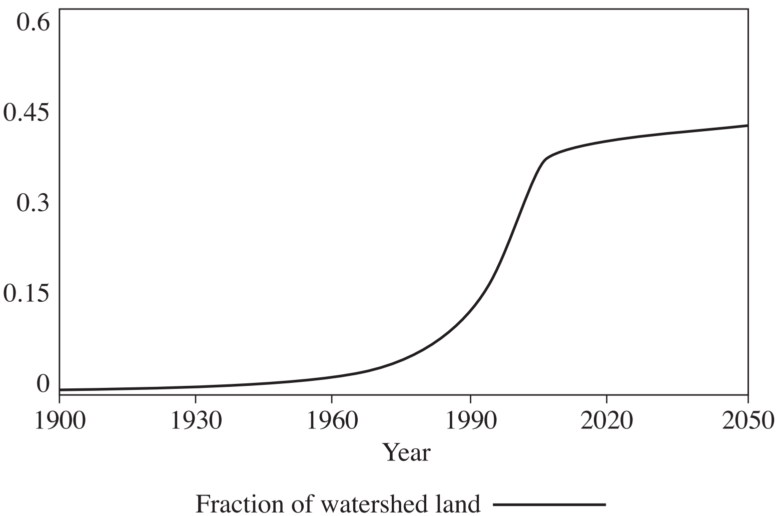


Figure 9.10 The overlap function: amount of developed Catskill land that falls within the watershed region

Of even greater concern is the model behavior shown in Figure 9.8. As the area becomes increasingly attractive, more people relocate to the region in search of the appealing housing conditions and the opportunity for employment. Although the job market is favorable for businesses, commercial enterprises can no longer expand as land availability restricts their growth. In the face of additional people and slowing employment growth, the unemployment rate rises. More housing is built in response to a housing crisis, which then results in a growing rate of abandoned housing.

As shown in Figure 9.10, simply monitoring the traditional indicators, such as building and population, does not present a complete picture for watershed planners. Development is taking place throughout the Catskill region, only part of which makes up the watershed region. Perhaps even more importantly, because development occurs more often than not in spurts, with little consistency, monitoring over ten-year increments does not allow for a complete analysis of the situation. In the case of the model-formulated data, there is little growth from 1920 to 1930, and still relatively little from 1960 to 1970. Yet, if seen as a more complete trend over time, there is growth, and growth that should have been considered much earlier in order for protective measures to have any past and current effect.

Model-tested Policies

The policies outlined here attempt to offer some insight into why the City has proceeded in the manner it has, what the typical responses are (and have been) to the problems of water quality and development, and what alternatives may offer a better scenario for long-term protection.

The water supply crisis

To address additional demands for water, the City continued to build infrastructure and gain more water. However, as shown in the previous figures, the consumption of water has always presented as important a problem as the development of additional reservoirs and delivery systems. If, for example, the City were able to harness greater water per acre, from the beginning, consumption issues would have impeded steps to maintain an adequate supply. This scenario is illustrated graphically in Figure 9.11

The logic is equally predictable under the assumption that there will be many more people needing the NYC water supply in the next 50 years. A legitimate concern remains due to the possibility that more upstate counties will want to tap into NYC's delivery system as their suburbs grow beyond their capacity to serve. As illustrated in Figure 9.12, more people using the same supply will allow for less per capita use. Greater conservation will probably be implemented through governmental intervention and regulation, as has previously been done.

Interestingly, if greater conservation strategies had been planned very early on in New York City water planning, the outcome might have been noticeably different. Figure 9.13 indicates the different scenario that might

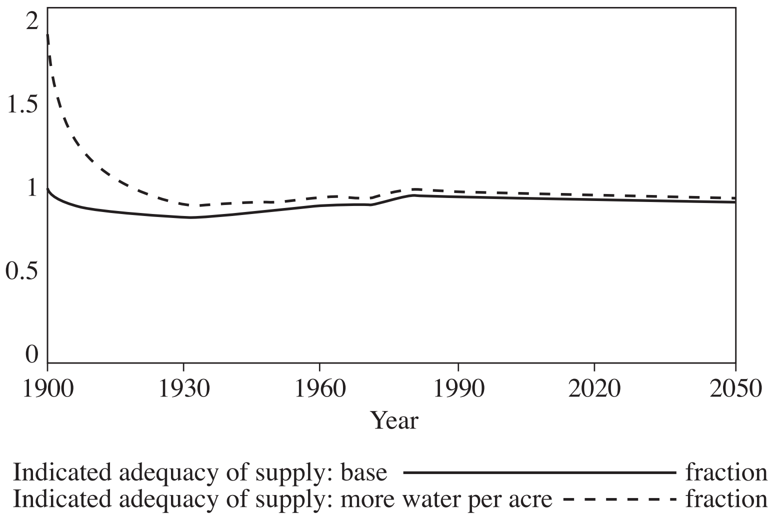


Figure 9.11 Adequacy of the water supply (base = 1000 and more water per acre = 2000)

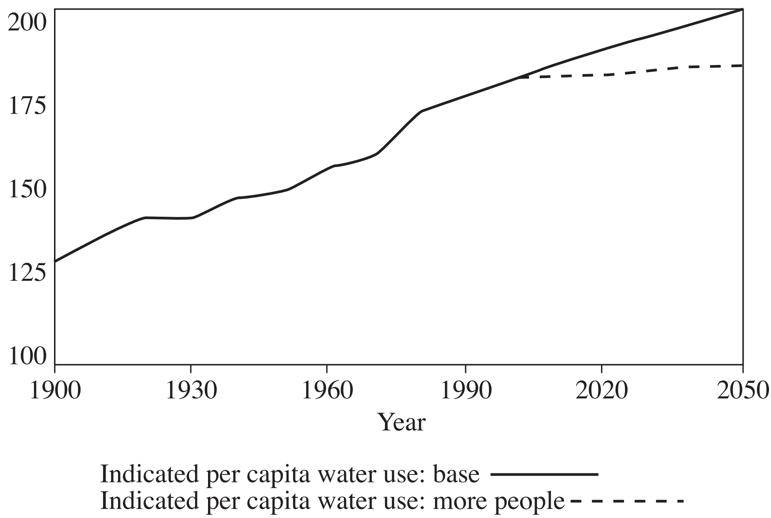


Figure 9.12 Per capita water use, base vs. larger population

have taken place if water authorities had imposed strict conservation on residents and made use of water saving technology as it became available.

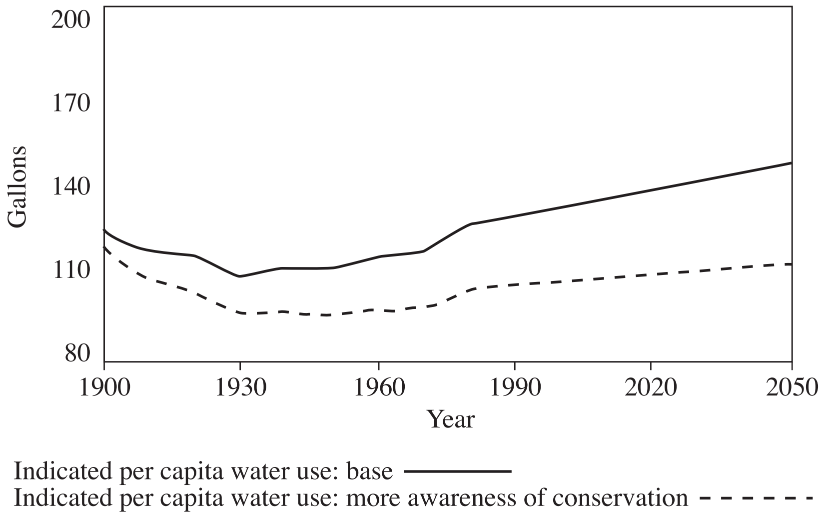


Figure 9.13 Per capita water use with strict conservation

The dilemma of watershed pollution

There are several obvious responses to watershed pollution that could have been taken by the City, which would have represented viable options for the future. One policy tactic focuses on more careful monitoring of the watershed development in order to allow more timely protection strategies.

In this model, a trend function has been used to explore the relationship between the rate of protection and the careful monitoring and evaluation of development over time. New York City has not been overtly interested in the growth of the watershed until faced with a crisis. If the City had been more sensitive to the trend data, it might have been able to respond quickly and effectively to threats to water quality. In the example shown in Figure 9.14, the City continuously updated its analysis of the watershed situation, monitoring the land fraction developed in the Catskills on a yearly basis.

Figure 9.14 illustrates this extreme example of watershed protection, where developable land has been severely restricted. The likelihood of the City implementing such a scheme in past years, when water quality and watershed development was not an issue, was minimal. Today, when water quality has made it to the top of policy agendas, it is too late to engage in a monitoring scheme as the only avenue. And although the City has started to buy up land and to implement conservation easements in an attempt to

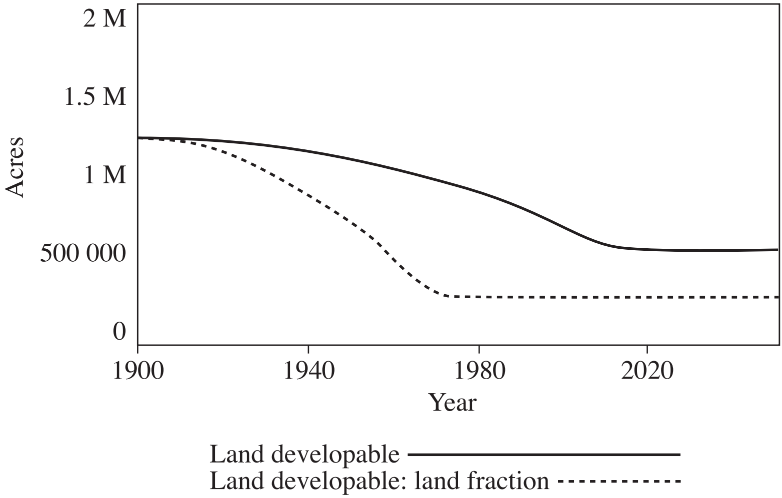


Figure 9.14 Hypothetically, a rigorous monitoring and protection scheme

protect more land, this strategy, even in conjunction with trend analysis and monitoring, is insufficient. Furthermore, protection of the watershed in the form of land acquisition does not bode well for the growing population of uncooperative watershed residents.

Additional protection would have arguably resulted in a disruption in the already fragile watershed economy, as there would have been significantly less land to grow into. As is common in urban areas, when the land becomes crowded, regional business growth begins to slow, even as the need for jobs is growing. The unemployment rate rises, as shown in Figure 9.15. One typical method of effecting a rising unemployment rate is to consider the type of employment in a region. Large industrial complexes will offer more jobs per structure than small village businesses will. Currently, the Hudson Valley region of upstate New York, which has reportedly lost out during the recent economic boom, is being touted by the governor as either the site for a recently released plan for re-industrialization, or an East Coast 'Silicon Valley.'[17] This type of economic growth will not provide a sustainable answer to unemployment; indeed it may make matters worse.

As shown in Figure 9.16, providing additional jobs in a region does not offer a long-term solution to unemployment. A positive employment rate will entice more residents, who will quickly return the unemployment rate back to an equilibrium rate. And it aggravates the housing situation as shown in Figure 9.17.

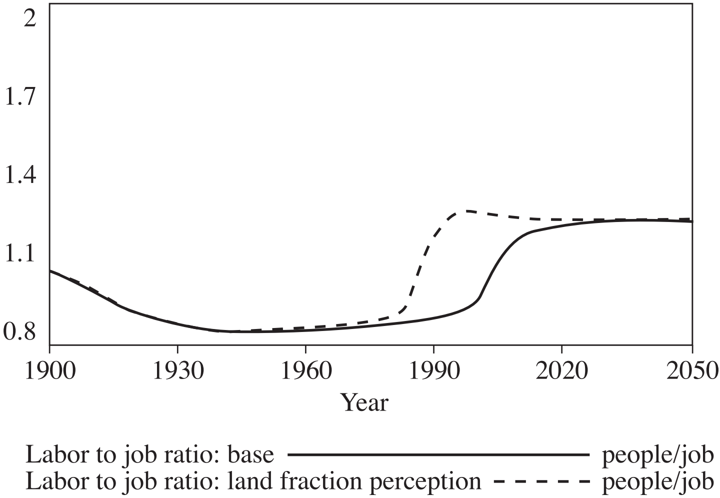


Figure 9.15 Less land, fewer jobs

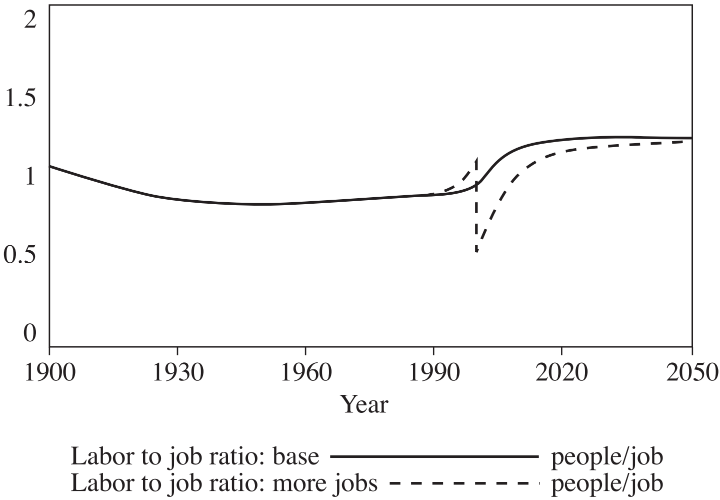


Figure 9.16 Silicon Valley scenario

Unfortunately, there are no easy answers to New York's dilemma of watershed protection. A committed land use and protection plan must be able to balance water quality concerns with the economic issues of watershed

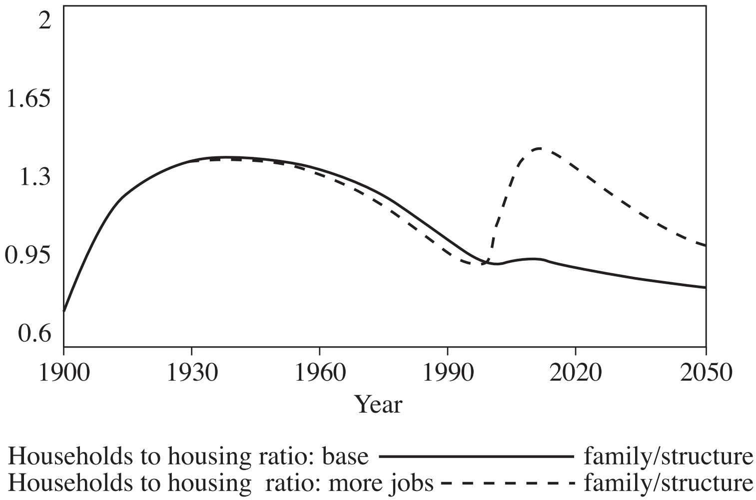


Figure 9.17 *More jobs, then more people, then less capacity to house residents*

residents. Farmland protection, although not modeled specifically here, may represent one strategy, as it maintains the employment of the farming population while maintaining the open space necessary for water quality.

Insights and conclusions

The insights drawn from the model data and the process of model construction are useful. There must be a comprehensive strategy that promotes sustainable industry within the villages and hamlets of the Catskill region. Simply purchasing land within the region will not help the City politically, and may hurt the economy of the Catskills.

Much can be learned from the experience of New York City. If thoughtful purchases of wild lands in the Catskill Mountains had been conducted in conjunction with reservoir construction, concerns regarding sustainable watershed development would not have quickly risen to the top of the policy agenda. If the City had carefully and tactfully managed their water resource in conjunction with residents in watershed areas, as a consumer and not an authority, the relationship today might have been more workable. And if the City had considered allowing the state to take over the water supply as an uninvolved mediator, early in the State's water supply history, the problem of water quality might not have risen to its current level of prominence. There are a number of other conclusions that can be drawn from this analysis that address not only the value of using system dynamics modeling as a tool for policy analysis, but also pertain to the usefulness of considering policy within the paradigm of sustainable development.

Due to the onslaught of urban regions spreading outward (most recently noted in the case of the Albany–Schenectady–Troy metropolitan area), population pressures within the rural region will continue unabated. Although there are burgeoning efforts to address growth issues, in particular New York City's funding of village and town comprehensive plans, there is still too little awareness of the futility of simply encouraging rampant 'job creation'. Concurrent with the watershed's interest in economic growth, the City has begun to enforce regulations with more zeal. However, it is unclear what effect these measures will have on the standard of living in the watershed; and thus far they have not succeeded in producing a more amiable working relationship between involved parties.

The Memorandum of Agreement provided for land acquisition and waste management facilities, and attempted to shape the coming development with funds to establish environmentally safe industry. Considering the deteriorating working relationship, the inability of New York City to live up to the tenets of the original agreement and the staggering potential for growth in the watershed, additional EPA waivers seem unlikely.

From a policy perspective, it is likely that no matter what the City attempts to do in the watershed, it will be met with strong opposition from landowners and residents of the Catskills. The EPA will perceive any successes as suboptimal, and the City will have little reason to continue to pursue strong watershed protection programs. In other words, if a Delaware/Catskills water filtration system seems inevitable, the incentive for New York City to protect the watershed disintegrates.

On a more positive note, the watershed communities are in a unique position to experiment with sustainable development. As the Zeitgeist of the nation shifts more to a tenor of environmentalism and community well-being, the watershed may act as a model for the rest of the country – embracing needed economic supports and rural protection with an ethic of environmental awareness to build workable, sustainable communities. As was shown in the model, developing better methods of monitoring water quality, with a shorter feedback time, may assist with this goal. Additionally, developing indicators that the upstate communities will embrace, measures that allow them to monitor their own environmental, economic and social health, may provide the necessary information infrastructure for future prosperity. It is hoped that greater awareness of the complexity of their shared environment may yield to a new era of collaboration between the City of New York and the upstate watershed communities.

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10 Modelling sustainable water prices

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Introduction

Establishing a rational price for water is very important for both the water companies and consumers. The price should be based on the cost of supply to achieve a more reasonable use of water. Following the end of the Second World War, domestic consumers in Central European countries normally paid a small percentage of the cost of drinking water while the state subsidized the rest.

After 1990 water charges suddenly increased and constituted a significant proportion of the household's average income. This led to a significant decrease in water consumption and underutilization of existing plant capacity. One of the decisive factors in water consumption decrease was the installation of meters. Whether this observed tendency for water consumption to decrease can be stopped and when this might happen has been unknown until now. There is relatively little knowledge of the impact of price changes on water demand. Moreover, there is no satisfactory model to explain this phenomenon. In this chapter, basic principles for setting water prices will be presented by providing incentives for efficient water use, distributing cost equitably, considering social issues and keeping the tariff rate structure simple for easy implementation. It proposes a method for assessing the impact of economic incentives such as charges on water consumption. This method is applied to the specific conditions of Central European countries. Finally, conclusions and hints for correct systems prices which aim at more sustainable consumption will be suggested.

Sustainable development

Many cultures in the past have recognized the need for harmony between the environment, society and economy without referring to it as sustainability. In the current literature, no agreed definition of sustainable development has emerged, however this concept most frequently refers to the definition given by the report *Our Common Future* (known as the Brundtland Report) that delivers this term as the activity which meets present needs without compromising the ability of future generations to meet their future needs (WCED, 1987; Greiner, 1999).

Peet, cited by Somlody (1994), rightly observes that the definition of Brundtland is too general; however, nothing better has been proposed so far. Peet is of the view that sustainability is a rather ethical guiding principle. Many sustainable programmes, including the European Community programme, summarize rather general guidelines. Others indicate that despite growing concern about environmental issues there is a wide gap between awareness and action (Greiner, 1999). Without state intervention, and incentives such as prices, sustainable development is unlikely to become a reality. For such a development to occur, a stable economy is an important, although difficult to reach precondition for most developing countries.

Ring et al. (1999) claim that sustainable development is not a fixed state but rather a process of change towards a more environmentally sound and socially equitable way of life. Helm (2000) suggests that sustainability recognizes that without intervention the global environment will not be able to provide a reasonable standard of living for future generations. Nevertheless, delivering all the goals of sustainable development such as economic development, a better environment and concern for the poor simultaneously is probably beyond the capabilities of policy-makers (Atkinson, 2000). Some opponents of sustainable development argue that its cost is high and instead propose weak sustainability, while ecologists and ecological economists advocate strong sustainability. Pearce et al., cited by Atkinson (2000), claims that very few supporters of strong sustainability endorse the idea that all natural assets must be preserved at any cost.

Sustainable development of water resources

To fully understand the term 'sustainable consumption of water' is extremely difficult. There is no really global or unified strategy on how to handle the variety of water problems existing in the world. This is probably one reason why the Brundtland Report and the 1992 United Nations Conference overlooked the water issue (Somlody, 1994). According to the OECD (1998), water consumption 'should meet basic needs for water servicing without jeopardizing the ability of future generations to meet their water needs and while protecting the water need of the environment'.

Although water resources are renewable, water systems can be so degraded that resources can be lost, and the ecosystem can be dependent on a minimum quantity and quality of water to the threshold below which they are damaged. For many countries the availability of water is the main determinant of economic growth, industrial structure and national trade. Water is a limited and valuable resource essential to life (freshwater resources form less than 1 per cent of total global water, out of which 85 per cent is used for irrigation) which behaves rather differently from other elements of the biosphere. Since the beginning of the twentieth century global water withdrawals have increased by over six times, while world population has only doubled in the same period. Seckler (1996) put the number of people living in water-scarce countries as 13–20 per cent of the global population by the year 2050.

As water increasingly becomes a scarce resource, the need to control the deterioration of water quality is translated into demanding legislation. Countries state the purposes and objectives of their water policies in water legislation. Water regulation systems and laws vary among different countries. For example, the Canadian Water Act encourages optimum use of water resources for the benefit of the people. German law requires that water be managed in a manner that serves the common interest, benefiting individual users while preventing avoidable harmful impacts. Taken together, these statements indicate that water management forms one of the biggest challenges of the coming decades. Therefore, suppliers and regulators who charge for water use, metering and educating by increasing the awareness of the user about water conservation, must reduce their demand toward a more sustainable level (EEA, 2000).

The largest consumer of water in Europe is industry, unlike other continents where it is agriculture (Cowan, 2000). According to the European Environment Agency (EEA 2000), 38 per cent of water in Europe is used for public water supply, 30 per cent is used for agriculture – mainly irrigation – and the remainder is used for industry and power. The main consumers of public water utilities are households and small businesses (Gorczyca, 1998). Household consumption of water was on the rise until the 1990s in many countries. The prognoses then, which were made with the assumption of low price, were for a further increase in consumption due to a prediction of higher demand (Somlody, 1994). The increasing trend of consumption was reversed with the application of higher market charges and it depended largely on the cost of water supply. A number of industrial enterprises also reduced water consumption and it was clear that the existing providers had excessive capacity. The current use of water in Central Europe is, on average, at the European level and much lower than predicted in the past. For example, the average consumption of water in Polish households calculated per inhabitant was 136 litres per day using the water network in 1999 (GUS, 2000). In Western countries (for example in Austria and Italy), the use of water is more than 200 litres per capita per day. In Japan and Canada this value is more than 250 litres per capita per day, in the USA it is more than 380 litres per capita per day.

Water charges

Currently, water is overconsumed worldwide and wasted in large part because consumers do not receive appropriate education about the value of this resource (OECD, 1998). The literature emphasizes concern about improving pricing signals in order to move towards sustainable consumption. A reform of pricing regimes and tariff systems is important, not only for the incentives this would give to commercial and residential consumers to rationalize their consumption, but also for the revenues of water companies. It is largely accepted that water has an economic value in all competing uses and should be treated as an economic good. The amount of money paid for water, therefore, not only reflects the environmental cost of water, but also the economic cost (OECD, 1999). There is a great deal of concern about how much, if anything, low-income consumers should pay for this basic commodity (Constance, 1999). Proponents of low prices argue that the impact of economic instruments – applied to public water supply – on health, together with the affordability of water to poorer consumers, needs to be considered. Additionally, there are technical complications regarding how to set charges that would best reflect water value (Gonzalez et al., 1999).

A tariff is a system of procedures and elements that determine the customer's total water bill. Any part of that bill can be called a charge, measured in money per time or money units alone. And any units can be called a rate, usually measured in money/volume units. Later in this chapter the rate will be called price. Most tariffs are a combination of elements dependent on consumption or other factors. A connection charge is put on a customer who joins the public water supply system. A fixed charge is equal for each customer or it might depend on some other factors (for example, number of water meters, geographic location and customer group). If a metering system is in place, the following elements occur: a volumetric rate, block charge, or minimum charge. A volumetric rate, when multiplied by the volume of water consumed in a charging period, gives rise to the volumetric charge for that period.

According to the criterion of economic efficiency, the volumetric charge components of the pricing structure could cover any cost that varies with demand on a system (short and long term) or peak demands made on it, while the fixed element should be left to cover only the costs that do not vary with consumption or cannot be accommodated in the variable element. The variable part of the tariff gives consumers incentives to use water efficiently, and the fixed part allows the covering of overhead expenses by water companies. For metered customers the water charge can be influenced by the ratio between the fixed and variable charge. Based on the actual cost of supplying the water, the standing charge should be more than 80 per cent of the total charge, with the remainder as variable charge, since the fixed assets are prevailing (EEA, 1999). In practice the percentage of volume-related charge is higher, the standing one reaching more than 75 per cent. This system is an incentive to save water and is attractive to users who consume low levels of water. The huge variation between countries and sectors in the fixed element of pricing schemes reflects the varying objectives that countries have for their schemes. Different volumetric rates are frequently attached to different blocks. Thus if rates rise or fall as a consequence of increased water consumption, the schedules are referred to increasing or decreasing block tariffs. Block charges are defined by lower and upper volumes of consumption per charging level. In general, two parts, a rising and a declining block, are widespread (EEA, 1999).

Charges are generally not related to the true cost of water and are not the same for different categories of consumers. Water charges vary according to the capital and social cost of operating the water supply (OECD, 1999). A tariff structure is generally fixed at the municipal level and can vary widely within a country.

According to OECD (1999), the presence of minimum charges or a significant fixed element in tariff reduces the conservation message and lowers the potential strength of the signal to reduce consumption. The flat fee tariffs diminish the impact of pricing on consumption patterns (Table 10.1). One example of this is the considerably high percentage of service fees in the tariffs of some countries, with some fees being as high as 90 per cent of water bills. Such a percentage provides the scope for introducing a tariff schedule with very low volumetric rates. In some countries social or conservation tariffs are present (Table 10.1). A tariff can be specified and it can include a basic allowance (charged at zero or a very low rate). The term 'tariff specification' alludes to the justification that describes increasing block tariffs as social tariffs. It is claimed that such a system of tariffs grants poor customers the opportunity to use a small amount of water and pay prices from the range of low blocks of tariffs, or sometimes zero prices. Certainly, a small first-block range may force the poor to pay the price from higher blocks. It can be particularly difficult for large families because they need more water than smaller, high-income families. Conversely, it may occur that the quantity of water to which the lowest price is applied is so large that few users face the higher charges associated with larger consumption levels. Nevertheless, there exists a whole range of income redistribution possibilities via such an increasing block tariff system, provided that the width of such blocks is appropriately set.

An example of social or conservation-oriented tariff structure exists in Belgium. The first 15 cubic metres per annum per person (41 litres) in each household is provided free. This water pricing system was introduced for several reasons: first, this amount of water is small enough so that very few households will face a zero price for their water consumption; second, it is socially correct since it covers a certain amount of water as an essential

Table 10.1 Categories of prices applied in various OECD countries

Category[a]	Countries included	Conservation signal	No. of countries
'Cutting-edge' conservation pricing[b]	Korea	Very strong	1
Conservation or social pricing[c]	Belgium, Greece, Japan, Italy, Mexico, Spain, Portugal, Turkey	Very strong	8
Price times quantity volumetric[d]	Czech Rep., Hungary, Poland	Stronger	3
Traditional volumetric[e]	Austria, Denmark, Finland, France, Germany, Netherlands, Sweden, Switzerland	Stronger	8
Mixed volumetric[f]	Australia, Luxembourg, USA	Weak	3
Mixed (general)[g]	Canada	Weak	1
Predominantly flat fee	Iceland, New Zealand, Norway, UK	None	4
Domestic water charges in general taxation	Ireland	None	1

Notes:

a In this table no explanation is given of the extent to which subsidization may be preventing all economic and environmental costs being reflected in charges.

b Increasing-block schedule with usual number of blocks, 6–10.

c Typically including increasing-block system with two or more blocks. In some countries fixed rate is also added.

d Constant volumetric rate, no fixed charge is included.

e Constant volumetric rate plus fixed charge (in Austria and Japan an increasing-block schedule occurs in some companies).

f Constant volumetric rate or increasing-block schedule, or decreasing one.

g In Canada 56 per cent of public water supplies apply flat fee structures.

Source: adapted from (OECD, 1999, pp. 21 and 24).

good; third, it is equitable among households of different sizes. In Asia most utilities use a large number of blocks in their increasing-block structures. A minimum consumption charge, which usually covers the first 10 cubic metres per month per household, is applied as a fixed charge. However, many companies in Korea have recently abandoned the basic rate and increased the price of water in order to persuade people to use water more carefully and as a step toward encouraging conservation prices.

A volumetric rate multiplied by the volume of water consumed in a charging period gives rise to the volumetric charge for a given period. In this system the charge for water is calculated by multiplying the unit rate for 1 cubic metre of water by the consumption in a given period. A pure volumetric system gives a strong potential signal about the desirability of not wasting water supplies, hence conserving resources. Such a system can be seen to occur in previous communist countries (Table 10.1). Lively discussions about a possible shift towards simplistic volumetric prices are taking place in many other countries. The observed shift toward an increase in the use of volumetric prices can be interpreted as a shift toward a more equitable allocation of costs since it better reflects actual consumption by individual users. Moreover, a transfer toward a greater use of increasing block pricing within the variable component can be interpreted as an effort to place more burden on the highest-income users. These moves can be seen as steps toward both social and conservation prices.

The strong tradition of low tariffs for households and increasing block rates are present in Belgium, Italy, Greece, Portugal, Spain and the USA. In Spain, there is a large diversity of tariff structures, with block tariffs increasing the most. It is observed that there are countries without fixed charge (non-volumetric) shares of average water such as Austria, the Czech Republic, Hungary and Poland, and also countries with a high percentage of fixed part tariffs, reaching 49 per cent of fixed parts in prices, such as Japan (OECD, 1999).

Although Germany applies only a traditional volumetric system, its prices are set at a level allowing the full cost of supply to be recovered. Their conservation signal may be stronger than that in countries with stronger conservation-oriented tariffs, but with lower prices. Conversely, water in the USA and Canada is perceived as very cheap because of previous subsidies and the slow recognition of emerging environmental problems. Only one-quarter of US utilities have switched from decreasing-block schedules to increasing-block ones.

In recent years, water prices have increased significantly in OECD countries. According to some American data cited by Dinar and Subramanian (1998), this price increase in many countries was greater than the rate of inflation. For example, residential water prices have increased almost 10 per cent above the inflation rate. About 37 per cent of the utilities charged fixed prices, 22 per cent used rising block increases and 38 per cent used declining prices. The remaining 3 per cent used a mixture of schemes.

Annual expenditures for water in different countries in Europe vary from 53 euro (per family per year) in Rome to 287 euro per year in Brussels and 350 euro in Germany (see Table 10.2). In Central Europe, prices vary from 20 euro to 59 euro (EEA, 2000; Strosser, 2001). In relation to GDP per capita, the annual expenditure for water varies from 0.2 per cent of the household's income in Oslo to 3.5 per cent in Bucharest, close to the affordable level, which is 5 per cent, according to the World Bank.

In Central and Eastern Europe water prices have risen sharply, at a much higher rate than inflation, since 1989. In Hungary, there were large real price increases (18.7 per cent over the period 1986–96), mainly due to increasing restrictions on the use of central government subsidies in recent years and big increases in real charges. The results of analyses of the influence of water price on consumption, conducted in Hungary, showed that a price increase might have a much greater impact in countries where the price of water had previously been kept very low (EEA, 1999). In Hungary the expenditures for water and sewage have reached 10 per cent of the net income of an individual on the average wage (Karaszi et al., 2000). In order to bring about more accurate water charge payments, domestic end measuring was introduced. In just seven years a total of 800 000 domestic end-user water meters were installed in huge numbers, 373 000 of which were in Budapest (Hungary).

The EEA Report (1999) also states that very low prices in international terms are often associated with a relatively high percentage of income per capita. However, some of the countries with the highest water supply charges in international terms do not have water charges that are high in proportion to income per capita (Table 10.3). Many experts disagree with the controversial threshold of 4 per cent as the maximum share of water service costs in total households' income proposed and used by some organizations (Speck and Stosser, 2001). The affordability figures are average ones for the population of a given city. However, the use of average figures is not adequate, due to the existence of the wide diversity of household income, particularly in areas of Central and Eastern Europe. The use of direct financial compensation is viewed as an effective means of addressing social issues and protecting low-income families from higher water prices.

Domestic metering

According to OECD (1998), measuring the volume of used water is the only means of showing the value of water to the consumer. It creates strong incentives for consumers to use water more efficiently and is a precondition

Table 10.2 Prices and annual expenditures for water in some European countries

Country	Water price (per 1 m^3 in euro)	Cities and expenditures in Euro[a]
	Central and Eastern Europe	
Bulgaria	0.06–0.31[d]	
Croatia	0.40–1.10	
Czech Republic		Prague 59[c]
Estonia	0.13–0.45[d]	Tallinn 100[c]
Hungary	0.26–0.77	
Poland	0.05–0.44[j,k]	Warsaw 44
Romania	0.21[d, e]	Bucharest 20[c]
Slovakia	0.20	
Slovenia	0.42[d, e]	Lubljana 35[c]
	Western Europe	
Belgium		Brussels 287[c]
Denmark	0.25–1.65[f,h]	Copenhagen 250, Aarhus 148[b]
Finland	0.52[d]	Helsinki 214, Turku 312[b]
France	0.12–3.63[f,i]	Paris 182, Lyon 338[b]
Germany	1.81–3.96[f]	350[d]
Italy	0.20–1.31[f, g]	Rome 53[c]
Netherlands	0.80–2.55[f,j]	Amsterdam 186, The Hague 294[b]
Norway		84.8
Portugal		Lisbon 72, Porto 121[b]
Spain	0.01–2.50[f]	Seville 65, Barcelona 150[b]
Sweden		591, country average
Switzerland		Berne 195
United Kingdom	1.00–2.80[f,j]	414 454 (when unmetered consumption)[b]

Notes:

a The calculations were made based on a four-person family living in a house using 200 cubic meters of water per year, i.e. 136 litres per capita per day.
b Data from end 1995, source: Klarer et al. (1999).
c 1996, source: EEA (1999), p. 70.
d End 1997, source: Klarer et al. (1999).
e Country average.
f Kramer and Piotrowski (1998).
g 1992.
h 1993.
i 1994.
j 1995.
k Data from Chamber of Commerce, Polish Waterworks.

Table 10.3 Annual water charge in some European cities in relation to GDP per capita

City	Water charge in relation to GDP per capita (%)
Bucharest*	3.5
Vilnius*	2.6
Prague*	2.4
Lisbon	2.4
Budapest*	2.1
Brussels	1.4
Madrid	1.2
London	0.8
Paris	0.7
Rome	0.3
Oslo	0.2

Note: * Central and Eastern Europe.

Source: European Environment Agency (2000).

for the proper application of tariff policies. Despite water scarcity, domestic metering is not very popular in OECD countries, and even some European cities do not use meters. The water supplied to individual houses is metered in nearly every OECD country, but not in all apartment blocks, where most of the population live. The owner of the block receives a volumetrically based water bill. These charges are recovered from tenants (or individual owners) on such criteria as floor space, the number of people in the household and so on. The presence of a single master meter may have no effect on total demand (the owner allocates the increase in the aggregate bill, and each resident decides that the increase is not his fault, but pays the bill anyway).

The decision about whether to adopt a metering approach is based on perceptions of the optimal pricing structure, and is taken after conducting analyses to determine whether the costs of installing and administering the water measuring system are larger than the benefits anticipated in terms of reduced water consumption, induced infrastructure cost, and reduced variability in demand. There is also some risk associated with the possibility of illegal connection; and the risk that reduced water flow in water pipes may reduce their ability to function in accordance with the original design (OECD, 1999). The immediate savings expected to follow from the introduction of metering are estimated to amount to about 20 per cent of consumption (OECD, 1999). Research conducted in the UK shows that the use of water in metered households is 10 per cent lower than in unmetered ones (EEA, 1999). The decrease in water consumption in Poland after installation of water meters is estimated to be 30 per cent (Gorczyca, 1998).

Similar results were obtained in Hungary even though water meters were not installed everywhere (EEA, 1999). Other data show that the metered households in Canada use 50 per cent less water than those that have no meters, even without price increases (Environment Waterworks Canada, 1997). Similarly, the Czech Republic experienced a reduction in consumption of about 18 per cent over the period 1992–97. In Luxembourg, over the period 1990–94, consumption decreased by about 12 litres per capita, reaching a level of 169 litres per capita per day while water charges rose by 6 per cent. Grossman et al. (1993) discovered that collectively metered households in Australia consumed 17 per cent more water than those with individualized metering.

The research conducted in Australia shows that water consumption is a significant function of the number of households serviced by meter (Grossman et al., 1993). Collectively provided water encourages free-rider behaviour; for example, in Perth, two or more houses are billed jointly. Although implementation of individual metering for all dwelling units would eliminate free-rider behaviour, the cost of maintaining a greater number of meters would be very high.

Introduction of the metering system and changing the pricing system to three consumption bands in Barcelona led to a decrease of consumption by almost 17 per cent in most cases (Myers, 1996). In Athens raising the price of water on an increasing-block basis resulted in a monthly decline in water consumption of 17–25 per cent in some months following the introduction of the new pricing (Briassoulis, 1994).

Customers often opt for meters and expect that their measured charges will be lower than their previous ones based on the value of their houses. But installation of a meter is a very expensive option for them. The non-volumetric charging systems promote subsidizing the high water users by the low ones within an apartment building. But putting the charges on a fairer basis inevitably has implications for charges paid by other customers, such as big families or consumers remaining on a 'traditional' rate.

It is true that metering can enhance environmental goals, such as the efficiency of the water service, and make households responsible only for their own consumption. But this may lead to a price increase that affects low-income consumers, which is not socially acceptable. Therefore, low-income consumers should be protected against excessive increases in water prices.

One option for increasing common water metering is to select customers and install meters primarily in households which use large amounts of water.

OFWAT, the economic regulator of privatized companies in England and Wales, is opposed to universal domestic metering, but supports metering where water is a scarce resource or is consumed in large amounts. The obligatory measured charging in these countries relies on the compulsory metering of all new houses, of water used for garden sprinklers and of swimming pools. Anglian Water expects to have 60 per cent of households linked to volumetric charging early in the next decade (DETR, 1998). Currently about 3 per cent of households are switching to measured charges each year in England and in Wales.

Modelling water prices

The method presented below allows the assessment in some countries of the impact of an observed increase in charges for drinking water consumption. To realize this goal, the relationships among factors influencing water prices, such as the average cost of water treatment in municipalities and production and sale of water by the waterworks companies, are needed.

Demand for a product, including water, generally reacts to a change in price. When the price goes up, consumption falls as people conserve water to avoid paying higher bills. The leaks are repaired and water-saving measures are introduced.

It is difficult to assess the effect of water prices on consumption on a more global level since sufficient information is not available on prices charged locally and their effect on consumption in different countries. Until now, it has generally been accepted that water demand by households is not usually amenable to price. Elasticity of demand is a measure of how much demand changes in response to a change in price. Many researchers have investigated the relationship between the price of water and its consumption level. Babbit, Donald and Cleasby (cited by Qdais and Nassay, 2001) have posited the following relationship:

$$C = 21 - 10\log Q, \tag{10.1}$$

where:
C = cost of water production (in US dollars per 1000 cubic feet)
Q = rate of water used in thousands of gallons per year.

Walski et al. (1985) developed a model for evaluating the effectiveness of water conservation measures. They calculated a reduction factor in water use as a function of water price elasticity as follows:

$$R_t = 1.0 - (P_1/P_2)^e, \tag{10.2}$$

where:
R = reduction factor,
P_1 = initial price,
P_2 = final price,
e = elasticity of demand, which is a measure of how strongly the quantity demanded responds to change in price.

Crowley et al. (1994) remark that an increase in price will tend to reduce demand; consequently the sale of water will also decrease. They proposed a polynomial relationship between the consumption of water and its price. This relationship will be applied to the present relationship between the sale of waterworks and the price of water. This mathematical formula was chosen for a number of reasons: first, the graphical representation of this relationship is a convex curve, which does not cross either the vertical or horizontal axis; second, it is in agreement with economic theory, according to which consumption of water falls as its price increases. The model is shown as:

$$y_t = a_1 x_t^{a_2}, \tag{10.3}$$

where:
y_t = sale of water in period t,
x_t = price per unit of consumption in period t,
a_1 = constant,
a_2 = a coefficient which measures the elasticity of demand.

Since y is proportional to the inverse of x, a_2 must be negative. When a_2 equals zero, changes in price have no effect on demand. This means that as the price of water increases, its consumption decreases in an asymptotic way, with the reverse also being true. A big inelasticity of demand in households occurs when coefficient a_2 is between –1 and 0. When a_2 =–1, y is proportional to inverse of x_t, and small changes of x_t cause almost proportionate changes in y_t. A low a_2 value indicates a high degree of inelasticity. Several cases of the water price increase have shown a fall in consumption. When a_2 equals –0.2, a 29 per cent price increase is required to reduce demand by 5 per cent (Crowley et al., 1994). In a number of developed countries (for example Israel, Canada, the USA, Australia and the UK) empirical analysis has shown that the price elasticity of demand for water in households is between –0.3 and –0.7. Most studies record price

Table 10.4 Studies and values of price elasticity of water demand for domestic consumers

Studies and years	Elasticity (range)	Places reported	Notes
Agthee and Billings (1974)	–0.18 –2.23	Arizona, USA	OLS, 45 obs.
Agthee and Billings (1980)	–0.61 –0.27	Tucson, AZ, USA	OLS, oth., 45 obs.
Boistard (1985)	–0.17	France	
Carver and Boland (1969)	–0.10	Washington, USA	OLS, 373 obs.
Danielson (1979)	–1.38 –0.31	Raleigh, NC, USA	Oth.
Deller et al. (1986)	–1.12		OLS
Döckel (1973)	–0.69	South Africa	
Gallagher et al. (1972, 1979)	–0.36	Toowoonba, Queensland, USA	Calculated for two periods, pooled cross-section and time-series
Gallagher et al. (1981)	–0.26	Queensland, USA	Pooled cross-section
Grima (1972)	–0.75 –1.07	Croatia	Cross-section
Hanke and de Mare (1971)	–0.15	Malmo, Sweden	OLS, 959 obs.
Hewitt and Hanemann (1995)	–1.59	USA	Oth. D/C choice model, 1703 obs.
Howe and Linaweaver (1967)	–0.21 –0.23	USA	OLS, 197 obs.
Howe (1982)	–0.06 –0.43 –0.57	Eastern and Western parts of USA	Cross-section
Laukkanen (1981)	–0.11	Helsinki, Finland	Time-series 1970–78
Martin et al. (1976)	–0.26	Tucson, Arizona, 2159 households in Arizona, USA	Pooled cross-section and time-series data
Moncur (1987)	–0.68 –0.03	Honolulu, USA	OLS, 46 116–53 802 obs.
Nieswiadomy (1989)	–0.30 –0.90	USA	OLS, panel data
Qdais and Nassay (2001)	–0.10	Abu Dhabi, Jordan	Oth., calculated after introducing metering and new prices for water
Renzetti and Dupont (1997)	–0.50		
Thomas and Syme (1979)	0.18	Perth, Australia	Oth., a contingent valuation approach
Thomas et al. (1983)	–0.30 –0.90	USA	Cross-section
Veck and Bill (1998)	–0.17	Alberton and Thokoza, South Africa	Oth.

Notes: OLS – ordinary least squares, Oth. – other estimation method, D/C – discrete choice, obs. – observations.

Sources: Dalhuisen et al. (no date), pp. 34–7; Dalhuisen and Nijkamp (2001), p. 94, Qdais and Nassay (2001).

elasticity around zero, but some found price elasticity to be below –1.5 (Table 10.4).

A second relationship described is that between water production and the sale of water. Production refers to water extraction and treatment, while sale refers to the amount of water delivered to inhabitants. Not all water is sold to customers; there are leakages and some water is used for technological purposes. The problem associated with leakages is related to both the quality of water transported and the state of the network (EEA, 2001). Losses of water in the distribution network can reach high percentages of the volume introduced.

Dalhuisen and Nijkamp (2001) remark that due to market failures, the percentage of leakages is very high and in Europe it varies between 10 and 70 per cent. Nevertheless, there are countries, such as Germany, Austria and Denmark, where leakages are below 10 per cent of water taken from the source (Table 10.5). In France, Spain, Sweden and the UK losses amount to 30 per cent. In Croatia, the Czech Republic, Portugal and Switzerland, this amount is bigger than 30 per cent, while in Albania it amounts to as much as 75 per cent.

Table 10.5 Leakages of water in Europe

Country	Estimated loses (%) of water supply	Notes
Albania, Bulgaria	More than 60	Except Sofia
Armenia, Croatia, Moldova, Ukraine	40–60	
Hungary, Romania, Bulgaria	30–40	
Czech Republic, France, Italy, Finland	10–30	
Austria, Germany (West), Denmark	Below 10	

Source: European Environment Agency (2000).

Leakages refer to different areas such as networks, user installations and before meters, and varies between 30 and 60 per cent of the total amount of water from the source. It needs to be emphasized that tracing and repairing leakages can be very expensive. Therefore a linear relationship is proposed to exist between the production of water and the sale of water:

$$p_t = b_1{}^* y_t + b_2, \tag{10.4}$$

where:
y_t = demand for water in period t,
p_t = production of water in period t,
b_1 = constant,
b_2 = constant,

In what follows, we will be concerned with the relationship between the average cost of water and its production. Water delivery service has a high fixed cost and a low variable cost. The total fixed cost can amount to 80–90 per cent of the total cost while the remainder equals the total variable cost which depends on water production. Total cost strongly depends on fixed cost due to the high proportion of total fixed cost in the total cost. While the average variable cost is constant, it strongly depends on the production of water. The following relationship is proposed on the basis of empirical data:

$$k_t = c_1 \, p^{c_2}{}_t, \tag{10.5}$$

where:
k_t = average cost of water production, demand for water in period t,
p_t = production of water in period t,
$c_1,\ c_2$ = constants.

And finally, we look at the relationship between cost and rate. This relationship is dependent on the way in which water consumption rates are set, that is, the relation between the price of water and water with a tariff applied. Municipal water utilities set prices in relation to average cost and do not exploit their monopoly position by charging prices that generate significant accounting profits. Moncur and Pollock (1996) remark that most water utilities adhere to policies ignoring scarcity rents, and base that price on average, instead of marginal costs, due to the 'non-profit' character of publicly owned enterprises. Water utilities also operate under strong political incentives to hold prices down using various accounting practices. The absence of a market allows them to accommodate political constraints on price levels and ignore some costs, such as scarcity rents. Moreover, countries set prices that are relatively free from constraining market forces and in this way the accounting convention serves primarily to determine costs, which in turn are the basis for setting prices (Moncur and Pollock, 1996).

Many approaches to tariff setting for water in previously communist countries do not allow the operator to charge fully for water (Waughray et al., 2001). In Central and Eastern Europe the total anticipated cost of supplying water for the forthcoming year is divided by the projected volume of water to be supplied. The tariffs are calculated on the basis of an agreed cost setting, plus an allowance for profits. The profit is set as a percentage of costs. This methodology is used in government-owned companies where the profit margin is set between 10 and 40 per cent or more. This means that there is no incentive for the operator to improve efficiency since revenues would be reduced if costs were reduced. The municipality usually decides what costs can be included in tariff calculation. Bad debt is not included in calculations and depreciation charges are set at a very low rate, while inflation is rarely factored into the equation. Furthermore, the operator is obliged to discount these losses.

We do not show any mathematical formula of the relationship (10.6), as setting prices involves complicated procedures:

$$x_{t+1} = g(k_t), \tag{10.6}$$

where:
x_{t+1} = price of water in the next period,
k_t = average cost of water production, demand for water in period t.

The price is set on the basis of the planned annual cost of water production. If the real consumption of water in the next period is lower than planned, water utilities will bear financial losses. Local government, which is not interested in increasing burdens for inhabitants, must approve it. By understating prices, companies generate high consumption rates.

Let us consider the numeral x_0 belonging to the domain of the function $F(x)$, that is, by assuming the water price in a current year (set on the basis of average cost of water production). By substituting $t = 0$ for price x_0 we get the price in the next period $t = 1$ $F(x_0) = x_1$. Then for $t = 1$ we get the price in the period $F(x_2) = x_3$, and so on until we receive the price x^*. The sequence $x_{t+1} = F(x_t)$ is convergent to that price and its boundary is the value x^*, for which $F(x^*) = x^*$. Price x_2 is higher than price x_1 (if process (10.6) is an increasing one), and consequently it leads to the decrease of water sales due to a general decline in water consumption by households. This occurs because an increase in water production cost is caused mainly by a decrease in water production (Figure 10.1).

Empirical evidence of water prices

With a few exceptions, data on water conservation effectiveness in Central Europe are not collected or stored in one place and the utilities do not usually make them available to the public, thus making it very difficult to

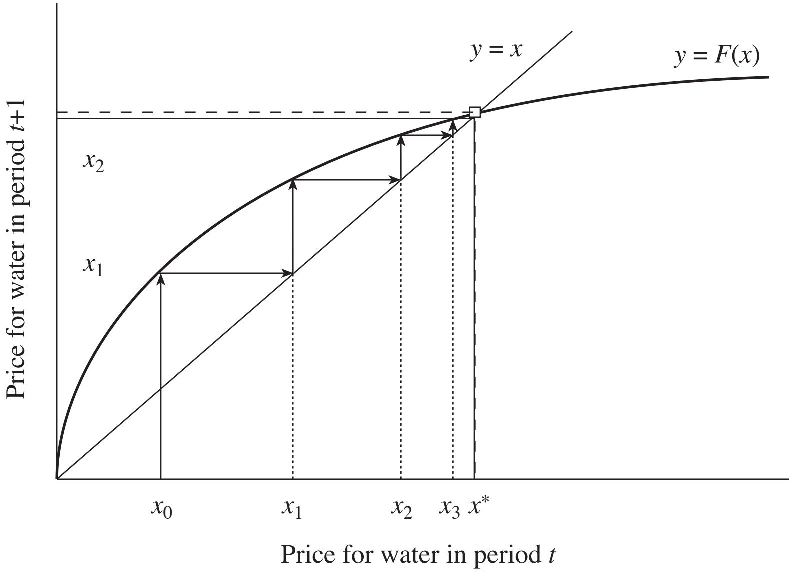

Figure 10.1 Process of creating successive values of water prices

obtain a great deal of data, particularly on the current values of the cost of production. The parameters for the formulae were obtained from the data collected from 30 water companies in 45 of the bigger towns in one of the countries of Central Europe, that is, Poland. The collected data enabled us to develop the model. The average sale of water by the companies analysed was equal to 30 million cubic metres per year in the 1990s. Only in three cases involving companies in the biggest cities were the sales of water considerably higher.

The coefficients of the first relationship are as follows: a_1 is equal to 78.829, while coefficient a_2, (elasticity of demand) equals –0.59. Thus there is inelasticity in the demand for water. The value of the water demand elasticity coefficient is confirmed by the data from the literature presented in the previous section.

Coefficients b_1 and b_2 are equal to 1.133 and 1.884, respectively (10.4). By comparing the values of variables representing the production and sales of water we can see the average water losses observed in the existing companies, which equal 20–30 per cent of the extracted water. This figure corresponds very well with the existing literature concerning water losses in the networks. The formulae show that there are still possibilities available for reducing water leakages and making the consumption of water more sustainable.

Coefficients c_1 and c_2 of the relation (10.5) are equal to 699.3 and –1.24, respectively. This relationship shows a strong inverse correlation between the average cost of water and its production. In this way a decrease in water production may significantly influence water company revenues provided that prices do not reflect water cost. This relationship can be verified by the theory previously outlined. The following mathematical formula of function $g(x)$ was found:

$$g(x_t) = 1.60^{*}k^{0.70} \tag{10.7}$$

where $t \; \varepsilon \; \{1,2,3 \ldots \}$,

Further, we will find a bounded price below which consumption of water will not go. To simplify the calculations, variables such as sales of water, production of water and average cost (y_t, p_t, k_t) were eliminated (model equations 10.1–10.4) and a recurrent process was obtained whereby water price in a period $t + 1$ is a function of price in the period t:

$$x_{t+1} = 3.18^{*}x_t^{0.48} \tag{10.8}$$

where$t \; \varepsilon \; \{1,2,3 \ldots \}$.

As an example we take an initial price of 4.86 in national currency in one of the towns with a population of 100 000. The recurrent process (10.6) with this initial price is convergent to the price $x^* = 9.25$. The number x^* is a boundary of sequence (10.6). For this price the sale of water obtained is 21.2 million cubic metres per year. From the calculations we notice that a significant increase in water price leads to a decrease in water sales which accounts for about 30 per cent. These calculations are valid for the domain for which the model is still valid.

The results of this model show that a decrease in water consumption by households leads to a significant increase in water price. Water saved by domestic consumers leads to a decrease in water production by water companies and the declining utilization of the waterworks capacity. Nevertheless, the relationships presented concern only the circumstances in which a volumetric tariff system is applied. In reality, the authorities provide subsidies and do not allow the introduction of prices that are too high.

The results obtained are in agreement with results reported by other authors. Myers (1996) claims that using pricing policy to reduce demand means making water too expensive for people on low incomes to continue their present patterns of use. As low-income families are less likely to have gardens, they are forced to economize water for hygiene use. He also argues that the money spent on installing water meters and maintaining them would be better invested in things such as preventing pipe leakage and producing efficient appliances. However, there are several other ways to reduce water consumption. One of them is to apply low-flush toilets. These toilets, in conjunction with other water-saving devices, could lead to about a 40 per cent increase in water saving, according to Myers (1996). Investment in stopping leakage and using water-efficient devices such as low-volume flush toilets or efficient dishwashers would result in a considerable reduction in the main areas of domestic water consumption without forcing users to cut back on essential water consumption.

Karaszi et al. (2000) discovered that other factors besides the installation of end-user meters and water price lead to a decrease in consumption. In the buildings examined, along with user meters, consumers also made renovations such as replacing over-exploited pipes. He also found that the fall in water consumption after the installation of water meters is followed by an increase in consumption, but only to a small extent.

Speck and Strosser (2001) found that, on average, there is a wide diversity of water prices in Central and Eastern Europe and the European Union, in terms of both price structure and its levels. Full recovery of cost exists in some large cities as opposed to smaller ones or rural areas. In cases where water services are tightly controlled by state authorities, prices are very often understated to reduce inflation or set before elections. The change in water price is not the only factor that explains the decrease in consumption. In fact, little is known about the marginal impact of price changes on water demand. The overall economic recession and changes in incomes are, among others, the main reasons for a decrease in water demand.

Conclusions

The goal of this chapter was to present a method of assessing the impact of increases in water prices on the consumption of water. The research presented shows that more sustainable water consumption can only be reached by proper water pricing. The development of appropriate water pricing systems aimed at promoting sustainability of water management is badly required. In the absence of economic water pricing, users have no incentives to conserve a scarce good such as water. This leads to the need for additional capital to expand the supply and sewerage systems. This state of the water market was found to be present in the countries of Central Europe.

A full cost pricing can lead to the elimination of the need for new waterworks or expansion of old ones, but it also implies a higher cost for producers and higher prices for consumers. Nevertheless, the long-term benefits in terms of more sustainable growth outweigh these short-term costs, although some aid to low-income consumers may be needed in the foreseeable future. Transparent water prices can also have an impact on water demand through the information that the consumer receives.

These prices have a psychological effect on consumers and thus modify their behaviour.

Water pricing needs to act as an incentive for achieving environmental objectives and also as an adequate recovery of water services costs. In Central European countries consumers were asked to pay more and reduce consumption in this way. However, they should play a key role in water pricing policies, for example by consultation. More research is required to better understand the factors influencing water demand and pollution, and to assess the impact of price changes on water demand under a variety of conditions. Information on the environmental impact of water prices is indeed very rare in the existing literature. Although controversies may remain regarding the role of meters in the reduction of water demand, metering is the key to building the information base necessary for setting management policies effectively. The pricing of water will continue to play a key role in both economic and environmental terms.

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Agriculture

11 Assessing the sustainability of Mediterranean intensive agricultural systems through the combined use of dynamic system models, environmental modelling and geographical information systems

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Introduction

The transformation of ecosystems to produce food or fibre has made agriculture the main driving force behind landscape modification. During the last several decades the relationships between agricultural activities and the environment have changed, giving rise to a broad set of environmental problems (Comisión de las Comunidades Europeas, 1992; Agencia Europea de Medio Ambiente, 1998). These include the reduction of flora, fauna and natural habitats; the pollution of freshwaters, aquifers and marine ecosystems, atmospheric pollution, the exhaustion of aquifers and surface waters; the salinization of soil and subterranean waters; soil degradation; and landscape deterioration in rural areas. Clearly the intensity or importance of these problems depends on the predominant type of agricultural system and is highest in so-called industrial agriculture, which is very dependent on the availability of new lands, infrastructures and on the intensive input of water, fertilizers, energy and capital.

Most of the above problems have been considered as environmental indicators for the evaluation of the sustainability of socioeconomic development. The Sustainable Development Commission has promoted the elaboration of an initial set of 134 indicators of sustainable development classified into four categories (social, economic, environmental and institutional). In the case of environmental indicators, some are directly related to problems generated by agriculture. In particular, indicators regarding the protection of water quality, the protection of coastal zones, natural resources, land planning and biodiversity conservation and others are related to the promotion of sustainable agriculture and sustainable rural development. All these indicators can be classified into pressure indicators, which reflect direct or indirect pressures on the environment (such as natural resources consumption or waste production); state indicators, which describe the quality of environment or natural resources; or response or reaction indicators, which show the social or political effort applied to solve the environmental problems (Ministerio de Medio Ambiente, 2000). These indicators, whose specific methodological issues are under discussion, may be helpful in evaluating the sustainability of some of the most emblematic agricultural systems, including Mediterranean irrigated lands.

Irrigated lands have traditionally constituted one of the most characteristic agro-landscapes in the Mediterranean. In addition to their socioeconomic importance, irrigation systems have also played a major ecological and environmental role. Traditional Mediterranean irrigated lands are located in river valleys and lowlands, areas with a high natural aptitude for irrigation due to the natural availability of renewable resources, particularly water and fertile soils, and also due to the suitable topography. Such conditions have enabled not only the attainment of a high socioeconomic value but also the maintenance of a set of environmental conditions like many shown by natural riparian systems. However, these valuable agro-landscapes are progressively decaying and disappearing (González, 1993; Martínez Fernández et al., 2000) due to recent socioeconomic changes, which are simultaneously promoting the development of new irrigated lands with very different environmental social and economic characteristics outside the river valleys. These new irrigated lands constitute complex systems of rapid evolution and have a major effect on land, water resources, landscape, biodiversity and the ecological value of extensive tracts of the Mediterranean area, especially in arid and semi-arid environments like those of south-eastern Spain.

The irrigated lands of Mazarrón and Aguilas in the south-east of Spain constitute a good example of new intensive Mediterranean agriculture. They are located close to the coast and are naturally arid (260 mm mean annual rainfall) and exposed to high temperatures (17°C average). These conditions constitute one of the main reasons for the expansion of irrigated lands in arid and semi-arid Mediterranean environments, where the profitability of irrigated lands may be between ten and twenty times greater than that of drylands. These irrigate lands initially opened up in the 1960s due to a growing demand for fresh vegetables in Europe, a market which has shown no sign of saturation. This new agriculture is based on groundwater exploitation and makes full use of technological advances, implying a degree of autonomy from actual agronomic quality of the soil since only two natural resources are basic for its maintenance: water and available space. The intensive use of groundwater resources has led to the over-exploitation of local aquifers and to seawater intrusion, water salinization and the falling of water tables. Moreover, the continued expansion of irrigated lands has meant taking over areas of high ecological value, threatening part of the habitat of endangered protected species. Some of these effects constitute full environmental externalities while others negatively influence the profitability of irrigated lands because of decreasing available space, scarce water resources and in particular low water quality due to salinization. All these factors establish complex relationships which condition the general behaviour of the system. Spatial and temporal dynamics, the expansion of irrigated lands, water availability and competition for space with other uses such as nature conservation, are interdependent processes which must be analysed in an integrated framework by means of dynamic system models, environmental modelling and geographical information systems (GIS).

Agricultural systems and their environmental externalities, like many other environmental problems, constitute complex systems, whose study requires systemic approaches capable of explicitly managing the temporal dimension, sustainability conditions, uncertainty and externalities (Bergh, 1996). Although several studies deal with agricultural systems from systemic perspectives, comparatively few focus on irrigated lands and their environmental externalities. The speed and intensity of the changes undergone by these agricultural systems, especially in the Mediterranean, require greater attention and an overview which incorporates the environmental dimension.

Several papers investigate the modelling of intensive agricultural systems from environmental perspectives. These papers (for example Folmer and Thijssen, 1996, Giupponi and Rosato, 1999) mainly consider two relatively independent models: an economic model and an environmental model or sub-model. The main model is centred on the economic factors of the agricultural systems, while a pre or post-model focuses on the environmental indicators of interest, usually those related to emissions and pollution due to fertilizers and pesticides (Bergh, 1996).

Recent research has approached the economic and environmental modelling of intensive agricultural systems in the Mediterranean by means of a dynamic system model. Saysel (1999) developed the Gapsim model, which tackles the close socioeconomic and environmental relationships linked to a large hydraulic project in semi-arid Mediterranean systems, particularly in the region of Anatolia (Turkey). Dynamic system models have also been applied to the study of other Mediterranean irrigated lands in relation to the scarcity of water resources, desertification problems (Muñoz, 1991; Martínez Vicente et al., 2000), non-point agricultural pollution (Martínez Fernández et al., 2000) and the progressive loss of traditional irrigated lands (Martínez Fernández and Esteve Selma 2000a).

In general the environmental modelling of agricultural systems in the European context focuses on pollution problems such as those generated by fertilizers and pesticides, while the consumption of resources such as water or space has received relatively little attention (Madsen et al., 1996). This is probably explained by the relative abundance of water in most parts of Europe and by the absence of important active processes of land transformation for agricultural use in areas with a high ecological value. In contrast, water consumption is a key factor in evaluating the environmental effects of agriculture in the Mediterranean area. Agriculture in this area also generates problems related to land occupation and transformation, which for socioeconomic and environmental reasons contains well-conserved natural habitats whose continuity is now under threat with the intensive dynamics of land use changes and the expansion of irrigated lands.

It is necessary to give greater attention to issues regarding natural resource consumption in the economic–environmental modelling of intensive agricultural systems, especially in the Mediterranean area. Recent research has shown that managing the spatial dimension usually requires the use of GIS, preferably in combination with other methodologies capable of tackling the different environmental and socioeconomic factors and their relevant spatial and temporal dynamics (Reyes et al., 1996; Westervelt et al., 1997; Apeldoorn et al., 1998; and Meyer-Aurich et al., 1998).

The aim of this chapter is to contribute to an overall understanding of the complex environmental and socioeconomic system of intensive agriculture, particularly in new Mediterranean irrigated lands with their environmental externalities, using a systemic approach. In this way we hope to obtain information that will be useful in the decision-making process in assessing the overall sustainability of such intensive agricultural systems, the key driving factors influencing these systems, the available management options for these systems and the relative effectiveness of different policies.

This will be done through a study of the temporal and spatial dynamics of new irrigated lands in Mazarrón and Aguilas (Province of Murcia, south-eastern Spain), which may be considered representative of the most intensive agricultural systems in the Mediterranean area. A combination of dynamic system models, environmental modelling and GIS will be used to analyse the current spatial distribution of irrigated lands, the land use changes during the last decades and the key socioeconomic and environmental factors driving the whole system. This approach will allow us to study the temporal evolution of several sustainability indicators and state indicators of agricultural systems. Sustainability indicators include particular pressure indicators such as the area occupied by irrigated lands, pollution flows or water consumption, and state indicators include the habitat loss of several endangered species and the water level of aquifers. Response indicators of sustainability will be explored in the context of several scenarios in order to assess the long-term sustainability of current trends and other available measures and policies. These scenarios include control of the expansion of irrigated lands and specific nature conservation policies.

General methodological approach

Recent land use changes in the Mazarrón–Aguilas study area were analysed through an extensive and detailed systematic sampling of land use. The sample includes 1211 units covering the whole study area with a total extension of 72 500 hectares at two different times: 1981 (via aerial photographs) and 1999 (via direct fieldwork). The land uses that were considered include forests, natural scrubland, horticultural and tree crop drylands, open-air horticultural irrigated crops, irrigated tree crops and greenhouses. The data gathered were combined with a geo-referenced environmental database, which includes around forty ecological, topographic and lithological variables. This allowed the environmental characterization of each type of irrigated land both in 1981 and 1999, the construction of a land use transition matrix to detect the environmental characteristics of the main land use changes, and the elaboration of environmental response models for the different types of irrigated land.

These models were obtained using generalized linear models (McCullagh and Nelder, 1989) and forward stepwise procedures to select descriptive variables (Nicholls, 1989). The environmental models of irrigated lands allow analysis of the chosen landscape characteristics for irrigated land both in 1981 and 1999, and of the main trends in landscape change. Finally the environmental models and the geo-referenced database were combined with a GIS to generate potential distribution maps on different dates by using the probability of the presence of irrigated land in each UTM cell (Universal Transversal Mercator) of the study area. These maps can be used to analyse past, current and potential conflicts due to spatial competition between irrigated lands and alternatives such as nature conservation. Finally the above analyses enabled a detailed and realistic description of one of the main sectors of the dynamic system model, the irrigated lands sector.

In addition, a dynamic system model was developed to include the main socioeconomic and environmental factors in relation to irrigated lands, water resources, available space, profitability and pollution. Dynamic system models (Forrester, 1975; Roberts et al., 1983; Vennix, 1996) are of special interest in the study of problems related to sustainability and the elaboration of models of sustainable development (Meadows et al., 1992; Jorgensen, 1994; Bergh, 1996; Reyes et al., 1996). This is because they require a dynamic and long-term perspective and the integration of social, economic and environmental factors. Dynamic system models have proved to be useful in management, planning and decision-taking processes (Vennix, 1996; Henderson and Lord, 1995).

The dynamic system model describes the structure of the system by referring to the main factors, interactions and feedback processes which simulate its dynamic behaviour. The structure is defined by a set of variables, basically levels and rates, and the relationships and feedback loops they establish. Levels provide information about the system's state, while rates are control variables which determine the changes in levels with time. Feedback loops, a central concept in the structure of dynamic system models, constitute closed cause–effect relationships inducing exponential processes (positive loops) or tendencies to some type of equilibrium (negative loops). Non-linear relationships and delays are other elements which add complexity to the system.

The dynamic model was developed using the software VENSIM® (Ventana Systems, 1994). The modelling process involved several stages: conceptualization, data acquisition, formulation of the model equations and calibration. In the final stage of the modelling process, the model was iteratively improved through calibration against the historical data for the main variables. The model was then validated using different structural tests (Barlas, 1996), including dimensional consistence tests, sensitive analysis and extreme condition tests.

Finally the dynamic model was used to define and explore the possible effects of several management scenarios on the whole system. The results, in particular the expected total area of irrigated lands, were analysed in combination with the environmental models of irrigated lands and a GIS to generate a spatial projection of each scenario and to analyse the environmental externalities in relation to the occupation of areas of a high ecological value.

Environmental and spatial modelling of the new irrigated lands

During the last two decades the area of irrigated lands in the study area has increased from 10 000 ha in 1981 to 17 000 ha in 1999, which represents about 24 per cent of the study area of 72 500 ha. This increase of 70 per cent in irrigated land has occurred at the expense of areas previously occupied by dryland and natural vegetation, in particular scrubland. Of particular relevance is the growth area covered by greenhouses, which in less than 20 years has increased to 6000 ha, an area eight times greater than its initial extension. Analysis of the land using a transition matrix shows the intense dynamics of land use changes affecting dryland, 43 per cent of which has become scrubland (due to land abandonment and natural succession) or changed to become new irrigated lands. This trend may be interpreted as a reduction of the most characteristic rural space, probably associated with a loss of functionality, to favour two ecologically extreme landscapes: the natural one and the one characterized by the agriculturally intensive use of space and natural resources.

On the other hand irrigated lands, too, exhibit an important internal dynamic of land use change. There are two main changes: the transformation of tree crops into open-air horticultural crops and the transformation of open-air horticultural crops into greenhouses. Figure 11.1 shows the main land use transitions which have occurred during the study period.

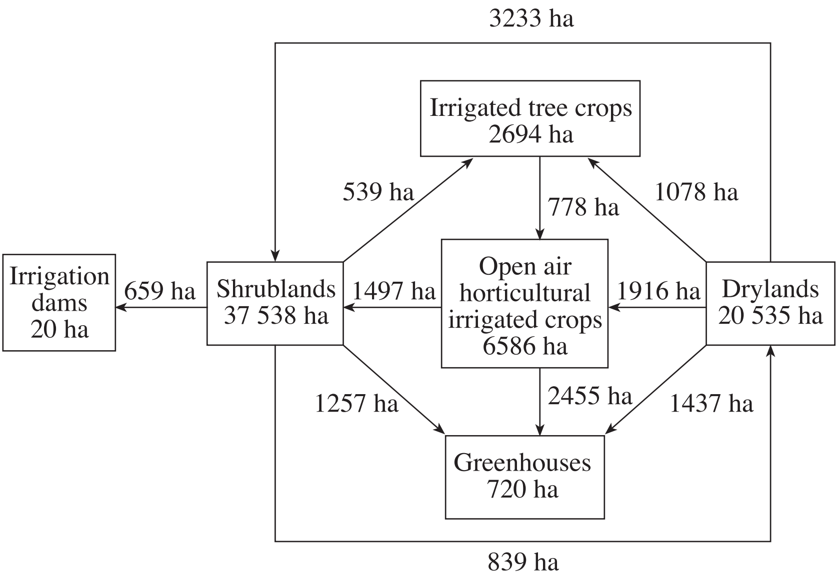


Figure 11.1 *Main land use transitions between 1981 and 1999 in the study area, indicating the area occupied by each land use in 1981 and the area involved in each land use change. The total study area covers 72 500 ha*

The general pattern in all these land use transitions represents a clear tendency of change to the most intensive uses, following the gradient: natural vegetation–dryland–irrigated land–urban use. Within the irrigated land sector, there is another gradient: tree crops–open air horticultural crops–greenhouses. The degree of reversibility of agricultural uses is also related to the intensity of such agricultural use: drylands show a high rate of change in the two opposite directions (natural vegetation and irrigated land), while irrigated tree crops and open air horticultural crops usually move to more intensive uses. Finally, greenhouses show a degree of irreversibility similar to that of urban use, at least in the time span considered in this study. The expansion of greenhouses implies a more intense and qualitatively different transformation of territory and landscape. This is a distinctive characteristic, which in conjunction with other factors makes greenhouse-based agriculture more similar to some industrial activities. On the other hand the environmental characterization of land uses in 1981 and 1999 reveals that a significant part of the new irrigated lands, especially greenhouses, is located in areas of little agricultural value and naturally occupied by scrublands. These areas include pronounced slopes where the new agriculture generates greater potential risks of erosion processes and of occupation of areas of special ecological value.

Land use data have been used in combination with the geo-referenced database to develop an environmental response model of the different types of irrigated lands in 1981 and 1999. The current model of irrigated land incorporates topographical (slope), climatic (winter rainfall) and lithological (presence of siliceous materials) variables. Figure 11.2 shows the increased tendency of the current irrigated lands to occupy steep slopes in comparison to 1981. This increase in the use of sloping land might be a possible cause of greater environmental problems due to the greater risk of erosion processes and the greater occupation of non-perturbed areas of high ecological value. Figure 11.3 shows the two variable models as a function of slope and winter rainfall. The combination of the environmental model and the GIS enables a spatial projection of the potential distribution of irrigated lands in the study area (Figure 11.4).

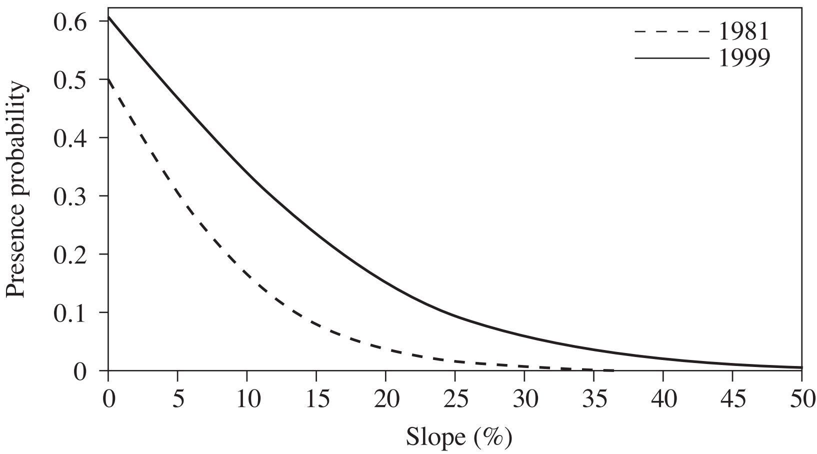


Figure 11.2 Probability of the presence of total irrigated lands in 1981 and 1999 as a function of slope

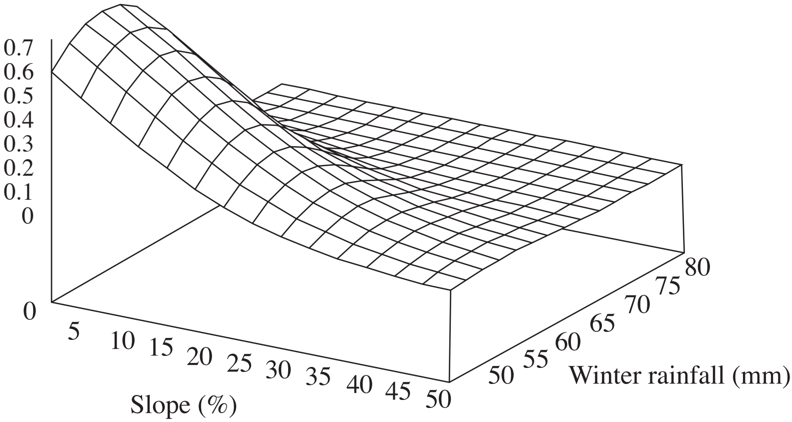


Figure 11.3 *Probability of the presence of current total irrigated lands as a function of slope and winter rainfall*

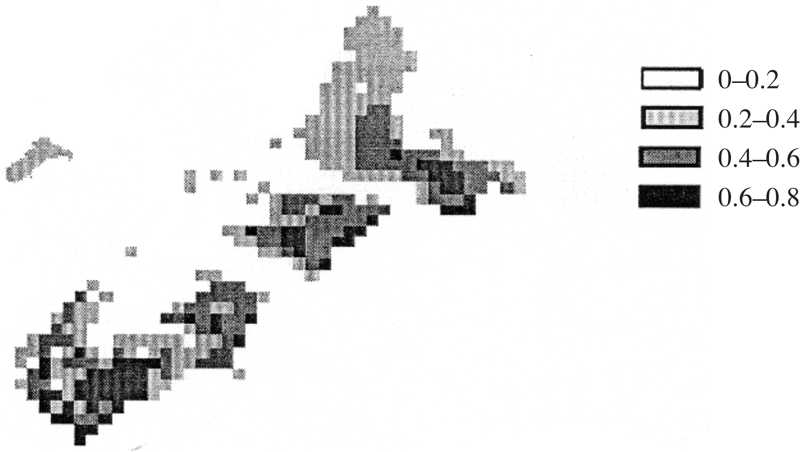


Figure 11.4 *Potential distribution of irrigated land in the study area indicating the probability of the presence in each cell unit*

The information and results obtained with the spatial analysis are the basis of the dynamic model, particularly the conceptualization and parameter definition of the irrigated land sector. The environmental model allows us to determine the potential distribution of irrigated land in terms of its environmental requirements and restrictions. The model also enables us to quantify the maximum expected area of irrigated lands in the study area, one of the most important model parameters.

Finally the environmental model and the GIS can be used to generate the spatial models of irrigated lands associated with each scenario defined and explored by the dynamic model.

The dynamic model: new irrigated lands

The main purpose of the new irrigated lands dynamic model is to assess the current and long-term sustainability of the intensive irrigated lands of Mazarrón and Aguilas using several pressure and state indicators which form part of the model variables. The pressure indicators considered include the area occupied by irrigated land, water consumption, nitrate and phosphate leaching and the production of plastic wastes. The state indicators of sustainability include the water level of aquifers, water conductivity, soil conductivity and several indicators concerning the environmental quality of the areas occupied by new irrigated lands, in particular the habitat loss of *Testudo graeca*, the habitat loss of *Periploca angustifolia*, the occupation of Protected Areas and the occupation of Special Conservation Areas, as proposed at the European level.

The final version of the new irrigated lands dynamic model includes 251 variables and parameters in five sectors: irrigated land, profitability, available area, water resources and pollution. The model has 12 level variables, 32 rate variables, 5 exogenous variables, 113 auxiliary variables and 89 parameters interconnected through a large number of feedback loops. The model starts in 1960 and follows a monthly temporal resolution. Figure 11.5 presents a simplified diagram showing the main factors and relationships.

The increase in irrigated land generates several environmental effects, some of which imply greater economic costs and lower profitability, which eventually may slow down the expansion of irrigated lands. All these effects are included in several feedback loops and integrated into an aggregated profitability index. As an example, we describe one of the negative feedback loops: the greater the area of irrigated lands, the higher the water demand, so aquifer exploitation increases and piezometric levels go down. This increases water extraction costs, which affects profitability and slows down the irrigated land expansion. The exploitation of aquifers also induces their salinization. Irrigation with this low-quality water immediately affects the quantity and quality of production and hence the relative profitability of the affected irrigated lands. This promotes a search for external water resources from alternative sources such as water transfers from other surface and subterranean water systems and marine desalinization. Other environmental effects, such as the available area remaining for new irrigated lands, are also included in the aggregated costs index through other feedback loops. Two

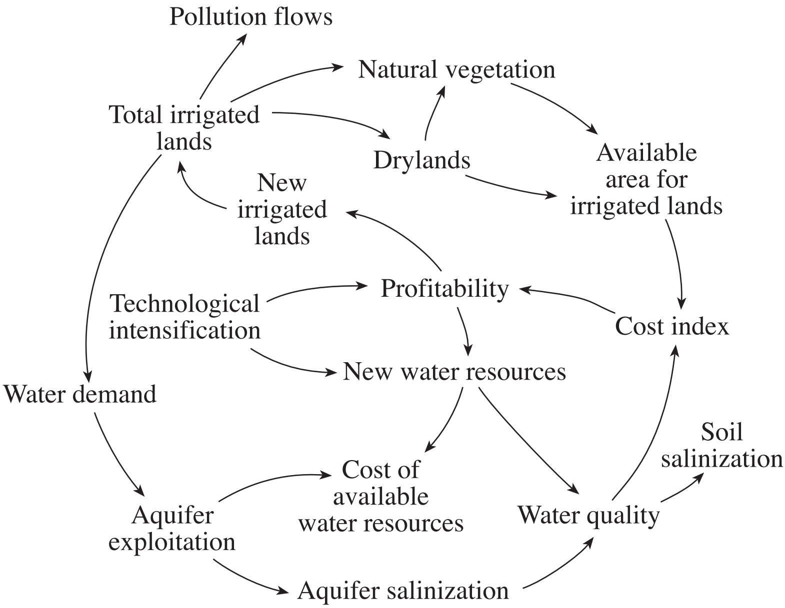
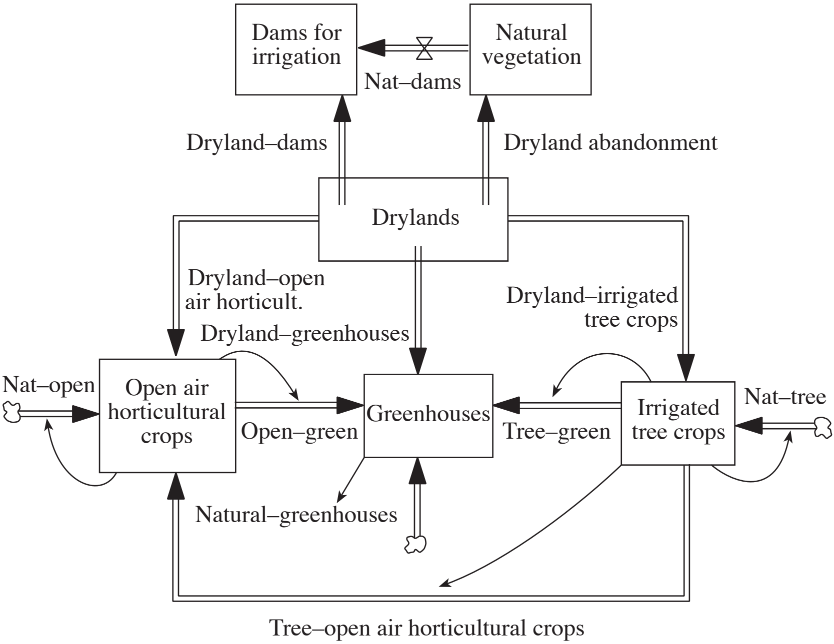


Figure 11.5 *Simplified diagram of the new irrigated lands model*

of the five model sectors (irrigated lands and available water resources) are briefly described.

Figure 11.6 shows a simplified diagram of the irrigated land sector with the area of irrigated tree crops, open air horticultural crops, greenhouses, dryland, natural vegetation (scrublands) and dams for irrigation. The whole set of variables and parameter was determined using data obtained from fieldwork and the environmental and spatial modelling. The area occupied by each one of the three types of irrigated land varies with time through a total of 12 rate variables representing land use changes. The rate of change of each land use depends on a profitability index, calculated as the differences of profitability between each land use and the aggregated costs index.

The water resources sector includes two variables indicating level: the water level in the Mazarrón and Aguilas aquifers and available external resources from alternative water sources (Figure 11.7). The level in the aquifers varies as a function of two inflows: natural recharge from rainfall and drainage and percolation from irrigation. It also varies as a function of two outflows: springs and pumping. The rate of pumping depends on water demand, the quality of irrigation water and the availability of water



Note: Nat–dams: natural vegetation to dams; Nat–open: natural vegetation to open air irrigated horticultural crops; Open–green: open air irrigated horticultural crops to greenhouses; tree–green: irrigated tree crops to greenhouses; nat–tree; natural vegetation to irrigated tree crops.

Figure 11.6 Simplified diagram of the irrigated land sector showing the level (boxes) and rate (flow arrows) variables representing the main uses and land use changes

resources from other sources. On the other hand, the aquifer water level determines the piezometric level and the irrigation water quality, one of the factors that has a major effect on the relative profitability of irrigated land and its rate of growth.

The profitability sector includes the specific index of technological intensification of each type of irrigated land and its relative profitability ratio (which have a major effect on land use changes), and the aggregated costs index, which summarizes the combined effects on costs induced by the quality of the irrigation water, the cost of pumping water, the water deficit and the remaining available area for new irrigated lands. Because of the past and current behaviour of these irrigated land systems, which show

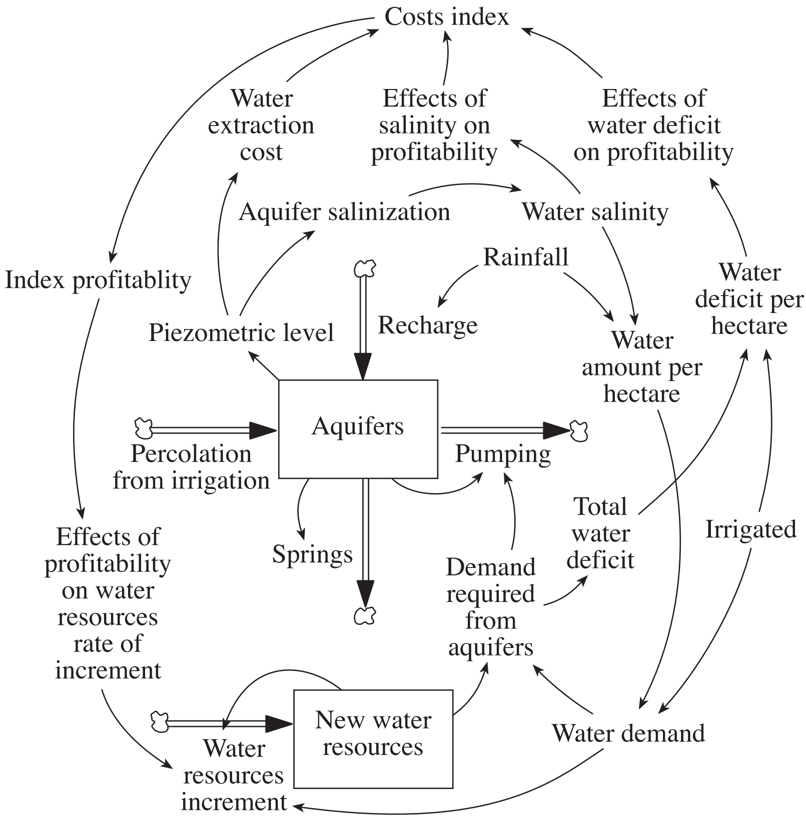


Figure 11.7 Simplified diagram of the water resources sector

no market-related problems, exogenous restrictions on the expansion of irrigated lands are not considered.

With regard to the available space sector, the main variables included are dryland, high-quality natural vegetation (scrublands), low-quality natural vegetation (generated through succession processes after dryland abandonment) and the fraction of drylands and natural vegetation environmentally susceptible to being transformed into new irrigated lands. The environmental model of irrigated lands, or potential distribution model, allowed the determination of several important variables and parameters of this sector, including the maximum area of irrigated lands. This is based on the presence probability of irrigated lands in each cell unit of the study area. This maximum area reaches around 28 000 ha in the whole study area, of which 17 000 ha are already irrigated lands.

Finally, the pollution sector includes several processes, in particular soil salinization, non-point agricultural pollution due to nitrate and phosphate leaching and the production of plastic wastes. These environmental effects do not constitute direct costs to the irrigated land sector, and therefore can be considered as pure environmental externalities generated by the system.

The dynamic model simulation from 1960 to the present gives results similar to the corresponding real data series, showing the increment of irrigated lands from 1200 ha in 1960 to 17 000 ha in 1999 (Figure 11.8) and the exponential growth of greenhouses. The relative profitability index exhibits a notable fall between 1980 and 1990, mainly due to the deterioration in irrigation water quality generated by the over-exploitation of aquifers, and consequent salinization (Figure 11.9).

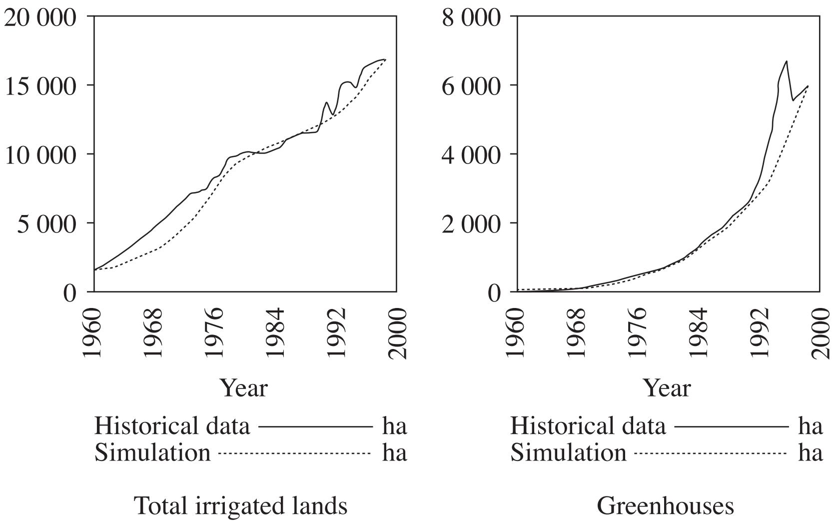


Figure 11.8 Temporal evolution of total irrigated lands and greenhouses from 1960 to 1999: historic data and simulation results

With reference to pollution flows, during the last few years, the level of nitrate and phosphate leaching has doubled due to the greater extension and intensification of irrigated land. Finally, the production of plastic wastes from greenhouses shows a pronounced increase, reaching around 6600 tons per year.

In synthesis, the model shows a shift from the initial prevalence of positive feedback loops promoting exponential growth to the dominance of negative

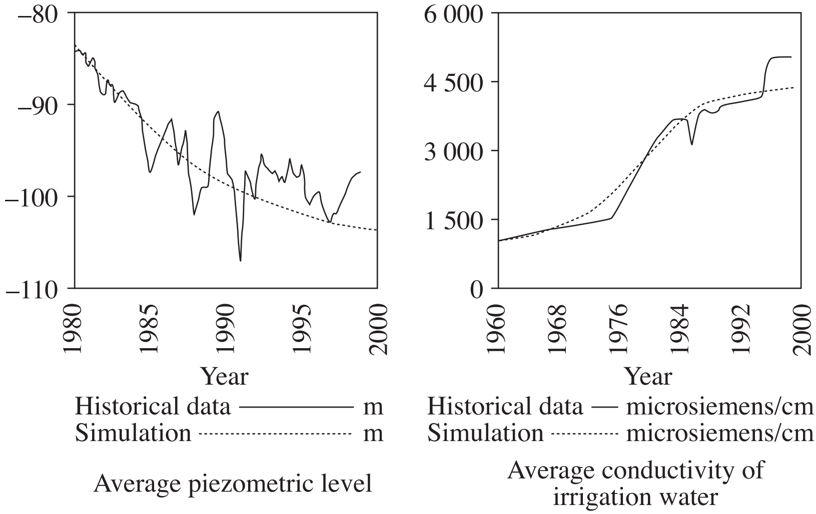


Figure 11.9 *Temporal evolution of the average piezometric level of aquifers and the average conductivity of irrigation water: historical data and simulation results*

feedback loops, when the system begins to perceive its own local restrictions due to key factors such as the quantity and quality of water resources.

Several current initiatives and administrative policies are attempting to overcome the main perceived local restriction on current irrigated land, water scarcity (which eventually might keep the whole system within certain overall sustainable limits), through a significant increase in external water resources. The idea is to transfer large quantities of water from the Ebro basin to the irrigated lands bordering the Mediterranean in Spain, as described in the Spanish National Hydrologic Plan. This will be analysed later in the base trend scenario.

Application of validation procedures to the new irrigated lands model

The validation process tries to establish the model's degree of confidence as a function of the objectives for which it was developed. In the case of dynamic system models these objectives usually deal with a general understanding of the system and the main patterns and trends of its dynamic behaviour.

Validation was a fundamental issue during the whole model development process. A period of 25 years was chosen, since this was considered relevant for the main dynamic assumptions of the dynamic model. Structural validation tests, the basic approach in the validation of dynamic system models (Barlas, 1996), were applied to validate the new irrigated lands model, including the extension of the time horizon, the analysis of dimensional consistency, extreme condition tests, sensitivity analysis and a comparison with historical data series. Some of the validation results are presented below.

The aim of the *extreme condition tests* is to verify the realistic behaviour of the model far beyond the conditions under which the model was developed. The new irrigated lands model showed a satisfactory response to several extreme condition tests, such as the absence of profitability or the extreme salinization of irrigation water, cases in which, as might be expected, the irrigated land area is drastically reduced (Figure 11.10).

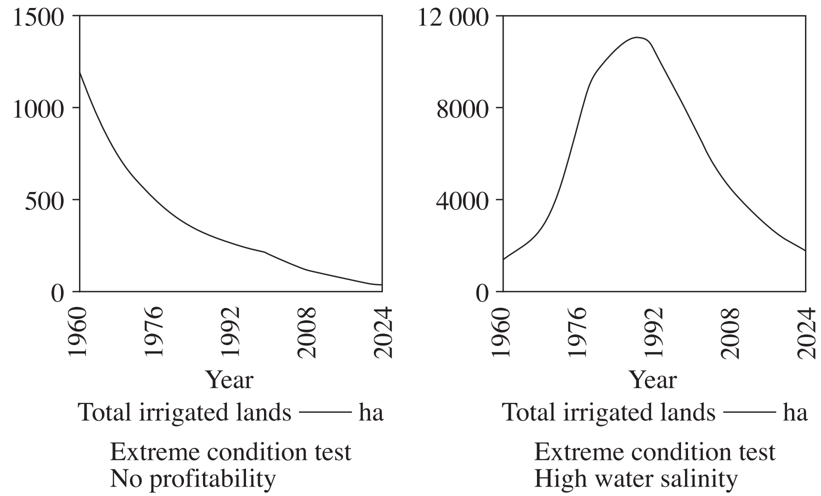
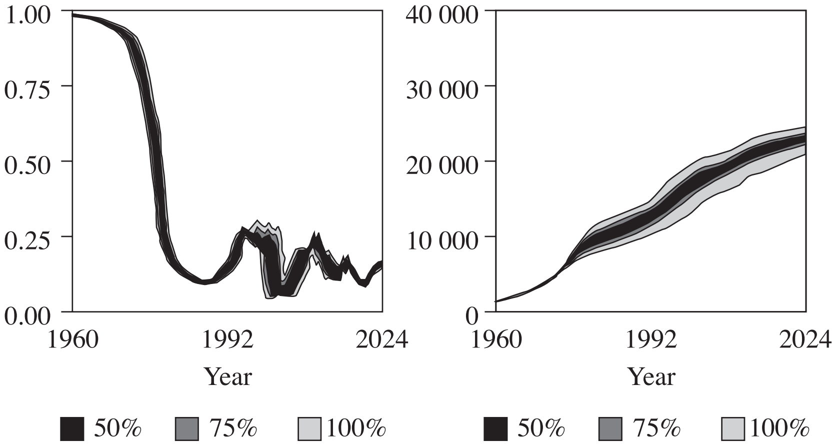


Figure 11.10 *Extreme condition tests. If profitability is very low (left) or water salinity is very high (right), the area of irrigated lands quickly decreases*

The sensitivity analysis evaluates the model's robustness to changes in the values of the different parameters. Robust models should show smooth, generally quantitative but not qualitative changes in the general patterns of dynamic behaviour.

The sensitivity analysis requires a large number of simulations in which the value of one selected parameter changes within a specified range. The sensitivity analysis of a broad set of model parameters, like the initial value of aquifer water level and the Montecarlo simulation, in which all tested parameters are simultaneously varied, confirmed the robustness of the new irrigated lands model (Figure 11.11).



Note: Confidence intervals of 50, 75, and 100% are shown. No dimensional units

Figure 11.11 *Sensitivity analysis (variation range of the aggregated cost index in response to changes in the value of the initial aquifer water level (left) and variation range of total irrigated land under the Montecarlo simulation (right)*

Environmental externalities of the new irrigated lands

The main environmental externalities associated with the system under study are linked to the two main natural resources consumed by the new irrigated lands of Mazarrón and Aguilas: space and water. The evolution of such externalities was analysed with reference to several state indicators of sustainability related to space (protected open space, special conservation areas and habitats of *Testudo graeca* and *Periploca angustifolia*) and water (level of aquifers, aquifer water salinity and natural discharge through springs). Some of the main results are described below.

Around 10 500 ha (14.5 per cent) of the study area is included in a protected open space, a sign of the generally high ecological value and good conservation state of many coastal areas in south-eastern Spain. Despite this, 17.6 per cent of the protected areas is occupied by irrigated land. In addition, 22 per cent of the areas susceptible to being transformed into new irrigated land (unit cells of drylands or natural vegetation with a presence probability of irrigated lands higher than 0.5, as expressed by the potential distribution model) is also located inside a protected open space. This high susceptibility to land use change constitutes a threat to the protected areas and their ecological value.

Furthermore, the study area falls within the distribution area of *Testudo graeca*, a singular terrestrial tortoise with a very restricted European distribution. About 57 per cent (41 500 ha) of the study area corresponds to the optimum habitat of this endangered species (Figure 11.12), that is, to areas where the probability of its presence is equal to or greater than 0.7, as expressed by the environmental model of the species (Giménez et al., 2001). This value has been interpreted as the threshold value for a high-quality habitat for this species. As revealed by the fieldwork and spatial analysis, irrigated lands occupied around 3900 ha of this optimum habitat in 1981, which means a loss of 9.4 per cent of the original total in the study area. During the last two decades the increase in irrigated lands has led to a significant increase in the loss of habitat. The 9150 ha of optimum habitat currently occupied means that 22 per cent of the optimum habitat of *Testudo graeca* in the study area has been lost due to irrigated lands.

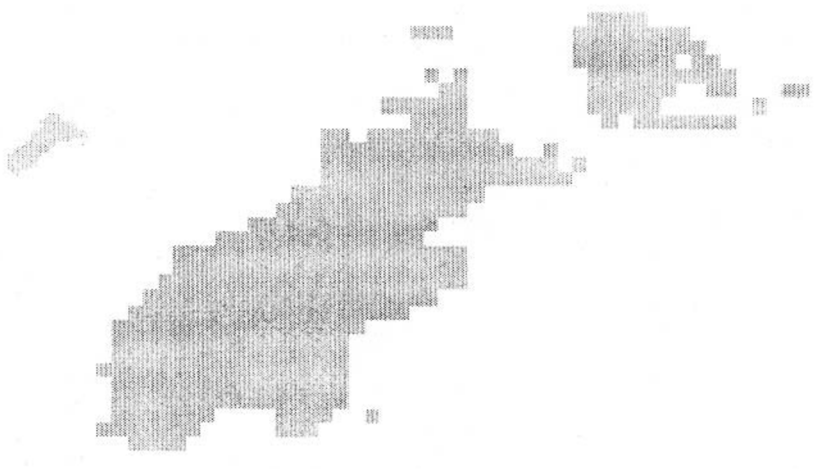


Figure 11.12 Optimum habitat of Testudo graeca *in the study area*

This loss is due to both greater extension of irrigated lands and the higher habitat quality of the areas being transformed: the average habitat quality of the areas occupied by irrigated lands increased from 0.51 in 1981 to 0.66 in 1999. Greenhouses have contributed most to this loss of optimum habitat (around 40 per cent of total loss). In total, 1137 ha (43 per cent) of the areas highly susceptible to being transformed into irrigated lands, as expressed by the potential distribution model, constitute optimum habitat of *Testudo graeca*. This means that any scenario which considers an increase in irrigated lands will negatively affect the conservation of this species.

Finally, the study area contains habitats of *Periploca angustifolia*, one of the most singular and scarce species of European Mediterranean shrubs. It is a Priority Habitat as described in the 92/43 Habitats Directive of the European Union.

Recent research (López, 2000) has established the potential distribution of this species in the Province of Murcia as well as the study area (Figure 11.13), and it suggests that the Province of Murcia contains more than half of the total existing habitat in the Iberian Peninsula. Around 12 200 ha (64 per cent) of the total habitat in the province is located inside the study area, so it is a key factor for the conservation of this species.

Figure 11.13 Potential distribution of Periploca angustifolia *in the study area*

Land use changes, in particular the increase in irrigated lands, constitute one of the main factors threatening the conservation of this species. Spatial analysis revealed that the irrigated lands created during the last two decades have brought about considerable habitat loss. This loss is not only due to the greater extension of irrigated lands but also to the higher average quality of the habitat of *Periploca* being occupied. Current irrigated land has consumed 3250 ha of such habitat, which constitutes approximately 28.8 per cent of the total habitat in the study area. This is a very high percentage, taking into account the restricted distribution of *Periploca*. The erection of greenhouses has been the highest contributing factor to this habitat loss, in both absolute and relative terms, because the average habitat probability of the areas occupied by greenhouses is 0.32, double that of open air horticultural crops. The areas with a high probability of transformation represent another 600 ha of this optimum habitat. These areas might disappear, depending on the scenarios considered.

Water is the other important natural resource supporting the irrigated lands of Mazarrón and Aguilas. Water was initially exclusively obtained from local aquifers, but they soon showed symptoms of over-exploitation, with decaying piezometric levels and progressive water salinization. The dynamic model simulated the negative temporal evolution of aquifers during recent decades by reference to aquifer levels, natural outflows through springs, piezometric levels and aquifer water salinity (Figure 11.9).

The fall in piezometric levels, the exhaustion of aquifer water reserves and progressive salinization have direct and indirect effects on the irrigated land system in the form of growing costs, as explained with the new irrigated lands model. However, the fall in the piezometric levels generates another effect, which may be considered as a pure environmental externality: the loss of springs and other natural outflows from aquifers along with associated wetlands and biodiversity. This constitutes a very important state indicator of sustainability both for agricultural systems and the management of aquifers in Mediterranean environments. The model shows a considerable reduction of natural outflows through springs since the 1960s (Figure 11.14).

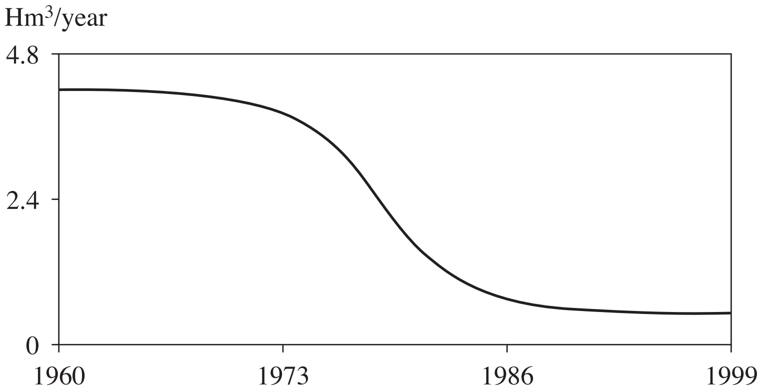


Figure 11.14 Evolution of annual discharge of Mazarrón and Aguilas aquifers through springs: simulation results

Simulation results and historical data indicate that the over-exploitation of aquifers has led to an 86 per cent loss of initial natural outflows. This drastic reduction in water flows is probably responsible for the elimination of a great number of wetlands and a reduction in biodiversity. This is an important ecological loss in the context of Mediterranean arid systems, like those existing in south-eastern Spain, and a clear sign of the unsustainability of these intensive irrigated lands.

In addition, the consumption of aquifer water reserves implies the loss of non-renewable natural resources of considerable strategic, social, environmental and economic importance. In fact, aquifer over-use and the exhaustion of water reserves constitute the clearest example of desertification in the European context and a real paradigm of environmental and economic unsustainability (Martínez Fernández and Esteve Selma, 1996; 2000b).

Finally, the pollution flows have increased due to the greater extension and intensification of irrigation. There is a clear gradient in the intensity of pollution flows from irrigated tree crops to open air horticultural crops to greenhouses, the last responsible for the highest fertilizer inputs and generating the most plastic wastes. Results show a negative temporal evolution of the pressure indicators of unsustainability considered in the model in relation to pollution. Nitrogen and phosphorous leaching reaches around 1700 and 50 tons per year respectively (Figure 11.15), while heavy storms may generate exceptionally high leaching episodes. The effect of this agricultural non-point pollution is beginning to manifest itself both in the water quality of the aquifers and in the first symptoms of eutrophication processes in the ephemeral channels of the study area and in the closest coastal marine environments. Current production of plastic wastes has reached 6600 tons per year (Figure 11.15).

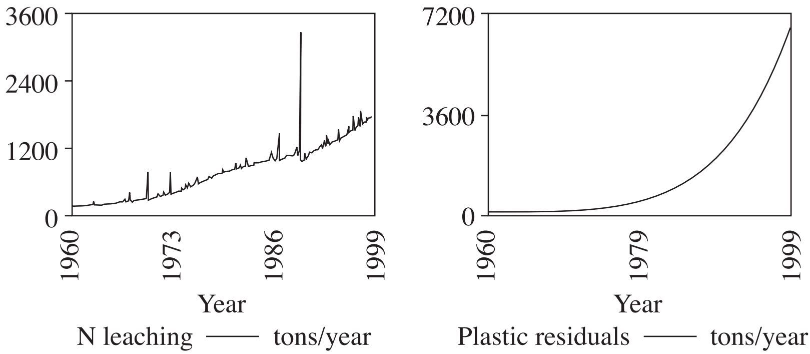


Figure 11.15 Temporal evolution of N leaching (left) and plastic wastes (right) generated by the irrigated lands

Development and exploration of scenarios

Several scenarios concerning the availability of space and water resources have been proposed in order to explore the possible dynamic evolution of the whole system and to analyse, among other issues, the occupation of areas of high ecological value. Scenarios associated with models of the potential habitat distribution of endangered species have been shown to be useful for evaluating the impact of agricultural policies and other land use changes in relation to the conservation of such species (Pearlstine et al., 1995; White et al., 1997; Apeldoorn et al., 1998). The main scenarios considered are:

1. *Base trend.* All model parameters remain unchanged, assuming the continuation of current trends over the next 25 years. This means maintaining the current increasing rate of increment of water usage, as may be expected from recently approved current initiatives, in particular the Spanish National Hydrological Plan and the transfer of water from the Ebro basin to the irrigated lands in south-eastern Spain. This scenario, according to current expectations, attempts to overcome water scarcity, the main restricting local factor for current irrigated lands. On the other hand, no special environmental policies are adopted.
2. *No external water resources*. This represents a pessimistic scenario in which the availability of water resources does not increase.
3. *Technological intensification and partial increment of water resources.* This assumes a reduced rate of increase in the external water supply. On the other hand it considers an increase in the technological innovation for use in irrigated lands, which partially counterbalances the increased costs due to scarce water resources.
4. *Weak nature conservation policy*. A weak nature conservation policy is added to the characteristics of scenario 3, which excludes the transformation into irrigated lands of protected areas except in zones with quaternary materials, indicating a more natural aptitude for agricultural uses.
5. *Strong nature conservation policy*. A broad nature conservation policy is added to the characteristics of scenario 3, which excludes new irrigated lands in entire protected areas and in the high-quality habitat of *Testudo graeca* (areas with a probability of presence greater than 70 per cent) and *Periploca angustifolia* (areas with a probability of presence greater than 25 per cent).

All these scenarios were projected over the time horizon for which the model was validated, covering the period 1999–2024. The main results are as follows. Under the base trend scenario, the current trend for increases in irrigated land continues during the next 25 years to reach 23 500 ha by the end of the simulation period. Total irrigated land occupies 80 per cent of the available area at the expense of dryland and natural vegetation. This expansion is exclusively generated by an increase in greenhouses, while tree crops and open air horticultural crops suffer a slight reduction (Figure 11.16). At the end of the simulation period the reduction of available area has a clear effect on the aggregated costs index and on the profitability index.

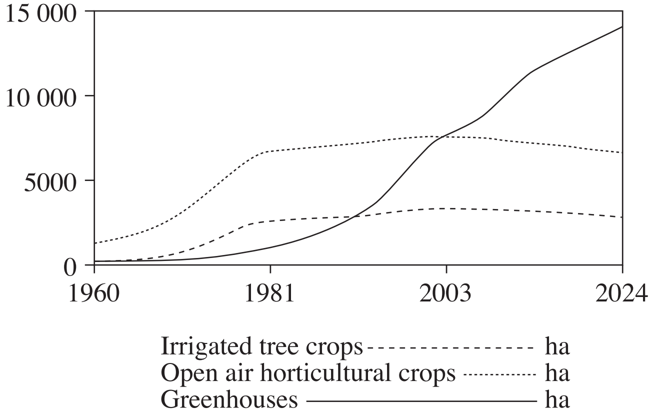


Figure 11.16 *Base trend scenario: temporal evolution of different types of irrigated lands*

On the other hand, aquifer over-exploitation leads to the rapid exhaustion of available water reserves and pumping is reduced to a minimum. Although the high rate of increase in external water resources is maintained, such resources are not enough to counterbalance the aquifer exhaustion, so an important water deficit appears which affects the profitability index and slows down but does not stop the increase of irrigated lands. This optimistic scenario of increased water resources cannot eliminate the water deficit because it depends not only on the available water but also on other endogenous factors and feedback loops of the system, so any increase in the supply of water induces a further expansion of irrigated lands and a greater demand for water. These results support the hypothesis that the water deficit problem cannot be solved exclusively by current policies based on increasing available water resources. This hypothesis is also emerging from analyses of the same problem on a greater spatial scale involving the whole Province of Murcia.

Indeed, this province constitutes a good example of the serious environmental consequences generated by the permanent growth of irrigated lands, a process which can be summarized as follows (Figure 11.17).

First, the perceived scarcity and fluctuation of water resources leads to plans to increase the water supply, eliminating the water deficit and allowing an increase in irrigated lands. However, the expectations generated by the

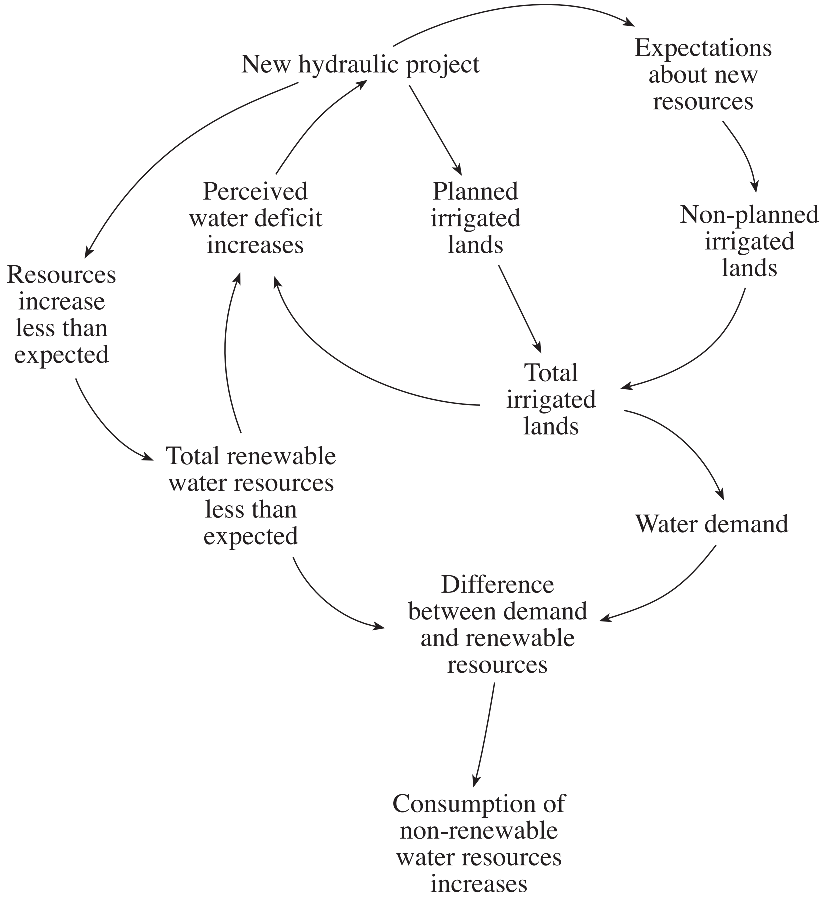


Figure 11.17 Simplified diagram of the unsustainable process promoted by expectations of new water resources

project promote additional, non-planned increases of irrigated lands, so after some years the total area of irrigated land considerably exceeds the area considered in the planning process.

On the other hand, the new hydraulic infrastructure does not, for several reasons, provide the expected amount of additional water resources. The imbalance between available water resources and agricultural water demand after the hydraulic project is greater than the initial imbalance. This increased imbalance is generated both by the increased water demand induced by expectations concerning the hydraulic project and less-than-expected water resources obtained with such a project. This water imbalance leads to a greater use of aquifers and an increased consumption in reserves or non-renewable water resources. At the same time, through a well-known process of eroding objectives, existing but non-planned irrigated lands are fully integrated in the next planning process. Thus the total amount of irrigated lands considered in such a process increases, as does the perceived difference between water demand and available resources. As a consequence, a new hydraulic project is proposed following the highly unsustainable dynamics that have been so well documented in the Province of Murcia for more than 100 years.

The effects of the base trend scenario on the occupation of areas with a high ecological value were explored by a combination of the dynamic model, the potential distribution or environmental model and a GIS. A map was made with the potential spatial distribution of expected irrigated lands in 25 years as a function of the probability of the presence of irrigated land in each cell unit. The habitat loss of each species was obtained as the product of the probability of presence of irrigated lands and the probability of presence of the habitat in each cell unit. This can be interpreted as a risk analysis of habitat loss.

The results show new environmental costs associated with the quality of the occupied areas as expressed by the four indicators used. At the end of the simulation period, the extension of protected areas occupied by irrigated lands would reach around 3580 ha, which is double the current amount of 1850 ha. In the case of Special Conservation Areas, the occupied area would increase from the current 180 ha to 900 ha. The optimum habitat of *Testudo graeca* lost to irrigated lands would increase by another 2400 ha to reach more than 10 800 ha (Table 11.1). Additionally, there would be a habitat loss of *Periploca angustifolia*, which would increase from 3250 to 4800 ha.

Table 11.1 Current and expected optimum habitat of Testudo graeca *affected by irrigated lands under the base trend scenario*

Year	Irrigated lands (ha)	Affected optimum habitat (ha)	% total optimum habitat
1981	10 000	3 890	9.4
1999	17 000	8 440	20.3
2024	23 500	10 835	26.1

Figure 11.18 presents the spatial distribution of the risk of *Testudo graeca* optimum habitat loss, which would reach values higher than 75 per cent in a considerable number of cell units, especially along the coastal hillsides.

Figure 11.18 *Base trend scenario: spatial distribution of risk of optimum habitat loss of* Testudo graeca

Finally, it is interesting to consider the temporal evolution of the marginal environmental costs, that is, the high-quality area lost per newly irrigated hectare. Figure 11.19 presents the marginal cost of expanding irrigated lands in relation to the habitat of *Testudo* and *Periploca*. From this figure it can be seen that the marginal costs in the case of *Testudo graeca*, in terms of the proportion of optimum habitat lost for each new hectare of irrigated lands,

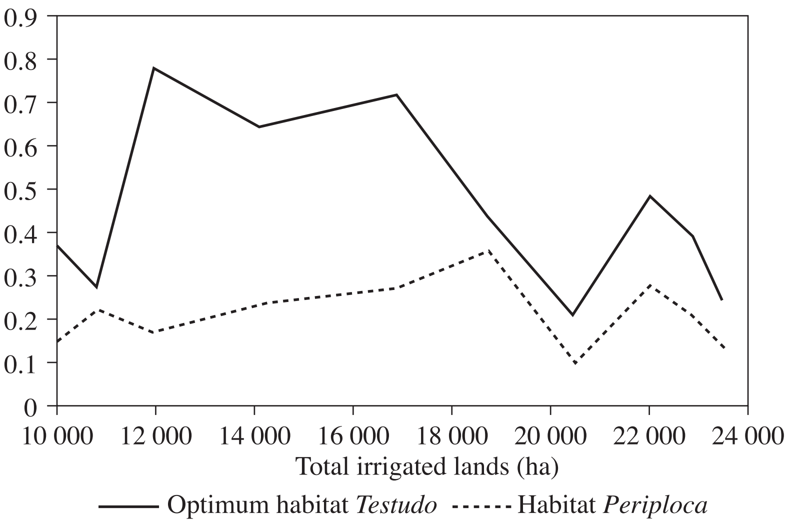


Figure 11.19 *Base trend scenario: proportion of optimum habitat of* Testudo graeca *and habitat of* Periploca angustifolia *occupied per hectare of new irrigated lands*

is greater than in the case of *Periploca angustifolia*, reaching 0.75 ha per new hectare of irrigated lands. For *Periploca*, in the case of protected areas and the Special Conservation Areas, the highest marginal environmental costs seem to be associated with the expected growth of irrigated lands during the next five years. These scenarios emphasize the need for urgent intervention methods which would explicitly consider nature conservation objectives.

In conclusion, the dynamic model and an analysis of the base trend scenario, which implies a significant increase in external water resources to overcome water scenarios, have revealed two key points. First, an increase in external water resources does not eliminate aquifer exhaustion or the water deficit problem because these also depend on other endogenous factors and system feedback loops, which lead to a further increase of irrigated lands and then to a new water deficit. Second, and most important, a different local limit appears: space and the elimination of areas of high ecological value. This represents a shift to a different local restriction on the sustainability of the system. In addition, this second restriction, which is not taken into account with current policies, has clear threshold values or technical standards as set out in the European Habitats Directive. These standards refer to the conservation of 100 per cent of some special and rare habitats such as that of *Periploca angustifolia* (Esteve and Calvo, 2000) and 75 per cent of the habitat of *Testudo graeca* (Giménez et al., 2001), standards which would be broken under this base trend scenario.

In regard to non-trend scenarios, the non-external water resources scenario generates a high water deficit which notably reduces the profitability index. This leads to the stabilization of and then to the progressive decrease of irrigated land. Additionally, this reduces the environmental effects associated with water and space consumption and pollution flows. The rest of the scenarios lead to an area of irrigated lands and environmental effects between those obtained in the base trend and the no external water resources scenario. The weak nature conservation scenario, close to the current situation, has practically no effect on the dynamics of land use changes, and so cannot be considered a suitable strategy for maintaining the areas of high ecological value in the study area. In contrast, the strong nature conservation scenario leads to significantly different results: total irrigated land at the end of the simulation period reaches 18 300 ha, an increase of only 1400 ha in 25 years (Figure 11.20).

In this scenario, not only the loss of areas of high ecological value but also the remaining environmental costs are notably reduced.

Whatever the adopted scenario, none reaches a dynamic equilibrium inside the considered time horizon. Environmental externalities increase to some degree in all scenarios, as demonstrated by several pressure and state sustainability indicators show. To achieve the more ambitious objectives

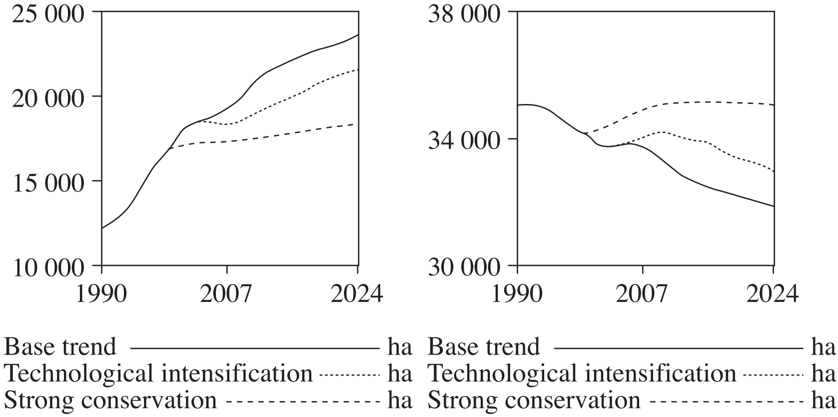


Figure 11.20 *Temporal evolution of total irrigated lands (left) and area with high-quality natural vegetation (right) under several scenarios*

of sustainability or to reverse some of the already existing environmental externalities would require more drastic initiatives probably associated with an active reduction of the current area of irrigated lands in Mazarrón and Aguilas and south-eastern Spain in general.

Main insights for the decision-making process

Most models dealing with the environmental effects of agriculture usually concentrate on several types of pollution production and do not consider the spatial dimension. However, the intensive agriculture of new irrigated lands in the Mediterranean area generates negative effects not only in terms of the production of pollution but also in terms of natural resources consumption, in particular water resources and the area available. Both water and land consumption have a major impact on the conservation of the valuable biodiversity of many Mediterranean areas, especially in arid and semi-arid ecosystems such as those of south-eastern Spain.

In Mazarrón, Aguilas and other arid Mediterranean areas, the dynamics between the increase in irrigated land, the growing inertia of the system, its incapacity to adapt to available resources and widespread aquifer over-exploitation clearly fits the general process of desertification. Unrealistic perceptions about the relationship between irrigated land and water resources also contribute to this. An increase in water resources does not eliminate the problem because several system feedback loops between different factors lead to a further increase in irrigated land and a continuation of the water deficit.

In fact irrigated land is the main factor inducing the water resources problem, in regard to both the intensive agricultural system (water deficit) and the natural systems (loss of springs and wetlands and associated biodiversity).

The real limiting factor for the growth of intensive irrigated lands in Mazarrón, Aguilas and south-eastern Spain in general is not only water availability but also the magnitude of environmental externalities associated with irrigated lands. This suggests that the system should be reoriented towards a greater sustainability through the stabilization and reduction of the area dedicated to irrigated lands, the application of an adaptive management plan in relation to existing natural resources and the prevention of irreversible processes in the management of land and water.

In general, the way in which land is irrigated in the Mediterranean area reveals a need to rethink the way in which the agriculture system is structured. In doing so, several socioeconomic and environmental indicators may lead to the characteristics and identification of those systems whose complex dynamics make them resemble other types of activity rather than to traditional agricultural environments. In this sense, the present work has shown that greenhouses in Mazarrón and Aguilas exhibit a degree of irreversibility in relation to land use changes typical of urban use and very different from other agricultural uses. This has profound implications in relation to environmental management and planning and the decision-making process.

Furthermore, the present study shows a need for an increase in approaches based on systemic views, for the integration of socioeconomic and environmental issues and for the explicit incorporation of temporal and spatial dimensions in order to properly understand and manage complex systems such as intensive agriculture. This can be achieved by combining dynamic system models with other methodologies such as environmental modelling and GIS. Such a combination will allow a better understanding of the environmental effects of land use changes and landscape evolution induced by the current expansion of new irrigated Mediterranean lands. It is hoped that this will serve to anticipate and prevent potential conflicts in the short and long term between such expansion and specific conservation policies as the establishment of Special Conservation Areas at a local level. The incorporation of such models into the decision-making process is imperative for greater sustainability, for the management of land and water and for the continued biodiversity of Mediterranean areas.

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Aquaculture

12 Aquaculture, environmental spillovers and sustainable development: links and policy choices

Clem Tisdell

Introduction

Although aquaculture as been practised for many centuries, it was in the past on quite a modest scale and limited to a few species, for example carp. However, in recent decades, aquaculture has shown very rapid expansion. This is partly because catches of wild fish have expanded at a slower rate than demand and many new scientific and technological advances have been made in aquaculture. Furthermore, by the mid-1990s evidence available to scientists indicated that catches of wild fish had either reached, nearly reached or even exceeded their sustainable limits (Williams, 1997). Consequently, according to Meryl Williams (1997, p. 18), then Director of ICLARM, now 'aquaculture is the major, though not sole hope, for improving the world's fish production'. Aquaculture, particularly marine aquaculture, has become a new economic frontier. Just as humankind in the past experienced the Agricultural Revolution, it seems now to be starting on an Aquaculture Revolution. Naturally, this raises the question of how sustainable it will be.

The purpose of this chapter is to discuss the sustainability of aquaculture production. If expanded aquaculture production sets in motion forces that make it unsustainable, economic development based on it will be short-lived. One should at least be aware how lack of economic sustainability of aquaculture production can arise, and be prepared to adopt policies to curb or prevent undesired trends in this.

In this chapter, it is pointed out that (a) factors endogenous to the productive unit and (b) factors exogenous to individual productive units (such as environmental spillovers or externalities) result in the unsustainable development of aquaculture. However, most attention in this chapter is given to adverse environmental spillovers as a contributor to lack of sustainability of aquaculture. This is because lack of sustainability in the endogenous case results from the rational choice of businesses involved in aquaculture, whereas the outcome when externalities exist can be inferior from the point of view of all or from a social viewpoint. There is consideration of the relative sustainability of extensive aquaculture systems versus intensive ones, and of the impact of aquaculture on the sustainability of natural fish stocks. Policies for regulating environmental spillovers to achieve a social economic gain, and thereby in most cases promoting greater sustainability of aquaculture, are outlined and discussed. By concentrating on a particular sector, it is possible to identify various policy issues raised by the quest for sustainable development that may be overlooked in a macroeconomic context.

Lack of sustainability in the absence of market factors

Even when markets work perfectly and market failures, such as may arise from environmental spillovers, are absent, unsustainable income paths may be chosen by economic agents in preference to sustainable ones (for details see Tisdell, 1999). Profit-maximizing or income-maximizing behaviour by individuals or business need not result in paths of sustainable income or of sustainable economic activity being chosen by them. This is so even when they are fully informed and rational.

In Asia, for example, landholders sometimes decide to farm shrimp knowing that this activity is unsustainable in the long run and that eventually their income will fall (Be et al., 1999; Alauddin and Tisdell, 1998). Figure 12.1 illustrates this choice. It is assumed that if only rice is grown on a farm the net income path GBH will apply. This is a sustainable income path. If, on the other hand, shrimp is raised on the land, the unsustainable net income path ABCDF applies. At time t_2, production of shrimp ceases because of falling shrimp yields, for instance due to mineralization in the fish ponds, and the land may be then too barren to grow rice or other crops. But if the landholder discounts the future strongly enough because of uncertainty or a high interest rate, the net present value of the income from the unsustainable path may well be in excess of that from the sustainable path. Therefore, lack of income sustainability is chosen in preference to sustainability. This is even more likely if the land is not rendered barren by shrimp cultivation and so will still grow a crop, such as rice, when shrimp production stops, albeit with much-reduced yield compared to the situation in which no shrimp cultivation occurs. In such a case, the alternative to the sustainable income path might be path ABCJ.

It seems that individuals are more likely to choose unsustainable paths for resource use when they leave greater scope for mobility or access to markets. Subsistence villagers with virtually no access to markets and with little mobility are more likely to choose sustainable income paths, as argued by Tisdell (1990, ch. 2). As outlined by Klee (1980, ch. 1), a similar point has been made by the geographer Raymond Dassman, namely that less sustainable systems are likely to be chosen as individuals change from a village to a global perspective as a result of the extension of markets.

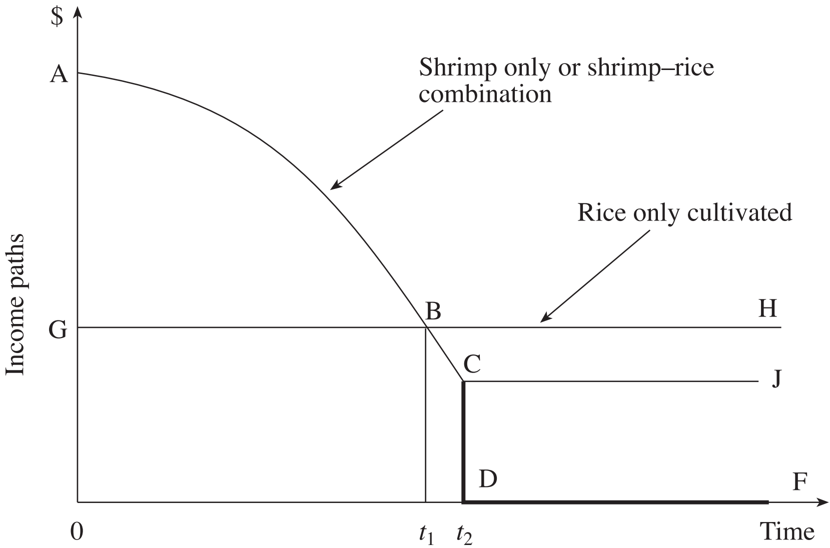

Figure 12.1 Rational individuals or businesses may choose unsustainable income paths in preference to sustainable ones in their use of land

But in any case, it ought to be clear that a perfectly working market system does not ensure sustainability of land use. Whether or not such sustainability is desirable is, however, a subject for debate. For example, sustainable income paths are more likely to be chosen if a zero or low discount rate is applied to future income, a policy favoured by economists such as Frank Ramsey and A.C. Pigou (Howe, 1979, p. 156).

Environmental spillovers as a source of inferior sustainability outcomes

As shown above, lack of economic sustainability in an industry or business programme can even arise in the absence of market failures. But market failures can increase the likelihood of unsustainable economic outcomes (see Tisdell, 1999). More importantly, they can result in unwanted lack of economic sustainability on the part of all, in contrast to the case just discussed in which unsustainable income paths may be chosen rationally. Environmental spillovers or externalities, such as these arising in aquaculture, can be used to illustrate the matter.

Consider the case of unfavourable externalities or environmental spillovers. When these arise the private costs of producers such as fish farmers are less than the costs to society of their production. Consequently their private benefits from production exceed its social benefits. This can result in private choices, by fish farmers in this case, resulting in an excessive level of economic production from a social economic point of view. This is illustrated in Figure 12.2. The curve 0AB represents the private benefit or returns to fish farmers in a region, and curve 0CDE indicates social benefits. Due to unfavourable externalities, curve 0CDE is below curve 0AB. The difference between these two curves measures externality costs. In the absence of control, fish farmers in the region will produce X_2 of farmed fish whereas X_1 is optimal from a social viewpoint. Market failure occurs and there can be a case for government intervention.

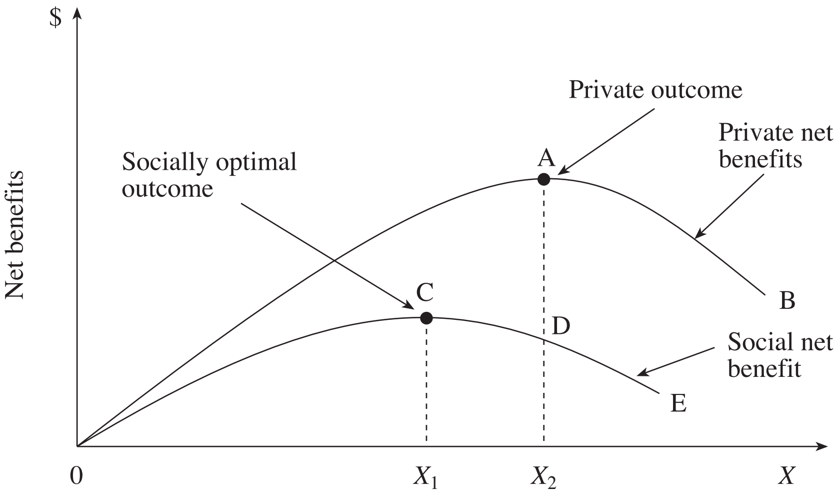

Figure 12.2 A case in which an unfavourable environmental spillover results in the market failing to bring about a social economic optimum

While environmental spillovers in the above case reduce the attainable level of social economic welfare, in some cases they may still result in sustainable social economic benefit, albeit it at an inferior level. However, in many cases, environmental spillovers result in individual producers not taking into account the full user costs of their actions, that is, their full impact on future incomes. For example, in drawing water from a shared water body or adding pollutants to it, each producer may consider his/her individual impact on the future availability of the water and its purity to be negligible. However, collectively this is not the case. Thus the natural resource may be utilized at an unsustainable rate. An unsustainable income path may be followed by all users of the resource that, from the point of view of each one, is less desirable than an available alternative involving greater prudence in their use of the resource. Hence the presence of the environmental externality promotes lack of economic sustainability and results in a Pareto-inferior result. In game-theory parlance, a prisoner's dilemma type of problem exists and the consequence is that a socially inferior Nash equilibrium eventuates.

This is illustrated in Figure 12.3. A community using a natural resource may have the possibility of following path I, a sustainable income path, or path II, an unsustainable income path. All may prefer I to II. However, because of the presence of adverse environmental externalities resulting in inadequate consideration of user costs by individual producers, path II may be followed. Or perhaps the community has a third possible path that it prefers, marked III. Although this path does not result in a sustainable level of income, it sustains income at a higher level than path II. Nevertheless, the presence of externalities could still result in the private uncoordinated choice of path II.

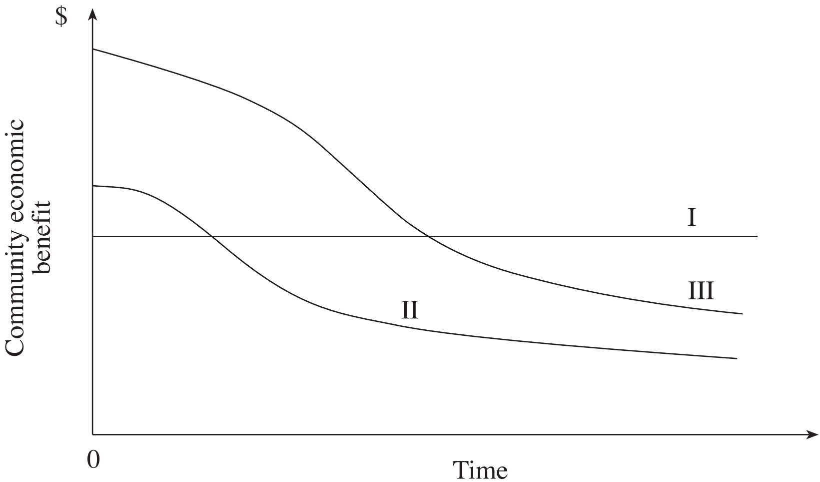

Figure 12.3 *Environmental spillovers can result in less sustainable income paths and socially inferior ones being followed in a community*

Thus it is clear that the presence of adverse environmental externalities can both reduce social economic benefits and prevent the desired social sustainability of these benefits being attained.

Specific observations on environmental spillovers, sustainability and aquaculture development

Depending upon the type of aquaculture practised and other circumstances, aquaculture can have positive or negative environmental spillovers, or no significant spillovers. Table 12.1 lists some possible adverse environmental externalities from aquaculture. These range from pollution of underground and other water supplies, land subsidence due to withdrawal of underground water, reduced stocks of wild fish used for commercial or subsistence purposes, loss of recreational space, greater spread of diseases associated with farmed species and increased resistance of disease-causing organisms as a result of medication, for example antibiotics; used in aquaculture.

In the light of the debate about strong or weak conditions for sustainable development, it is interesting to speculate about whether intensive or extensive aquaculture is likely to cause greater environmental damage. Intensive systems usually involve high man-made-capital-to-land ratios and high-man-made-to-labour ratios. Intensive systems may be more likely to be closed or nearly closed, so reducing their interdependence with natural environments. Thus it is possible for intensive systems to be environmentally friendlier than extensive ones. In many cases, they probably have lower adverse environmental externalities for the same level of output. Therefore, in some circumstances, they could result in greater conservation of natural resources. For example, extensive farming of shrimp, as practised in Bangladesh and some other developing countries, although (appropriately) reflecting local relative abundance of man-made capital and labour, can be highly destructive of natural environments. Low-tech methods and methods with low man-made capital requirements in relation to other resources do not always foster sustainable development. Frequently these methods cause a high level of environmental destruction because they actually require considerable utilization of natural resources in relation to man-made capital. While superficially extensive production methods may at first seem to accord with strong conditions for sustainable development, in reality they often fall into the category involving weak conditions. While few natural resources may be converted directly into man-made capital when using such techniques, the use of natural resource capital relative to man-made capital can be high when extensive production methods are employed because their adverse environmental spillovers seriously reduce natural capital stocks. However, as pointed out in Tisdell (1997c), the position is complex. None the less, it is worthwhile linking macroeconomic requirements for sustainable development with microeconomic applications, for it is at the microeconomic level that development policies are really put into practice.

I do not wish to give the impression that aquaculture is always environmentally unfriendly or that it always hinders sustainable development. In

Table 12.1 Some possible adverse environmental spillovers from aquaculture

Adverse spillovers	Comments
1. General subsidence due to use of underground aquifers	This is a problem in Taiwan Buildings may subside and land my be flooded, for example by high tide
2. Withdrawal of underground water may reduce the quality of the remaining water	For example, intrusion of salty water may occur
3. Brackish water used for aquaculture, for example of shrimp, may seep into underground water and cause it to become saline	As a result, the water may become unfit for human consumption and for agriculture
4. Nitrates and chemicals used in aquaculture can contaminate water bodies	This can make the water unfit for aquaculture, agriculture and human consumption
5. Clearing of trees and vegetation for aquaculture, for example, by removal of mangroves for shrimp farms	Results in coastal erosion in some cases, loss of cleansing function of vegetation, loss of habitat of some commercial species and their recruiting grounds
6. Spread of diseases and pests	Aquaculture can accelerate spread of disease and pests injurious to aquaculture
7. Competition indirectly with the capture fisheries because food of wild fish is harvested to supply aquaculture	'Trash' fish caught to produce pelleted food or meal for cultured fish such as eel or Atlantic salmon
8. Sometimes juveniles or fry of wild stock are captured for culture	Reduces wild stocks, for example, collection of prawn juveniles in Bangladesh
9. Conversion to aquaculture farms of habitats used by wild stocks	Reduction in wild stocks
10. Loss of recreational space to aquaculture	Can affect swimming, boating, recreational fishing and other pursuits
11. Intrusion of salt into agricultural land from brackish water aquaculture	Caused by seepage from brackish water ponds. May affect rice land, coconut, etc.
12. Frequent and widespread use of pharmaceuticals, especially antibiotics, may accelerate resistance of disease organisms	Reduced effectiveness of treatments in aquaculture, possible reduced effectiveness of drugs for human use
13. Crowding of filter feeders such as molluscs, crowding of organisms extracting nutrients from shared water columns, for example seaweed	Reduced yields from aquaculture or smaller specimens of reduced value. Increased risk of disease transmission within aquaculture
14. Some types of aquaculture produce nutrient-rich wastewater, for example water high in nitrates and phosphorous	May result in aquatic weed growth, eutrophication, and stimulate red tides

some circumstances, aquaculture can have very positive sustainability consequences. As Anderson (1985) points out, aquaculture can increase the sustainability of wild stocks of fish and other gathered organisms by increasing supplies and reducing harvesting pressure. Such a favourable case is illustrated in Figure 12.4.

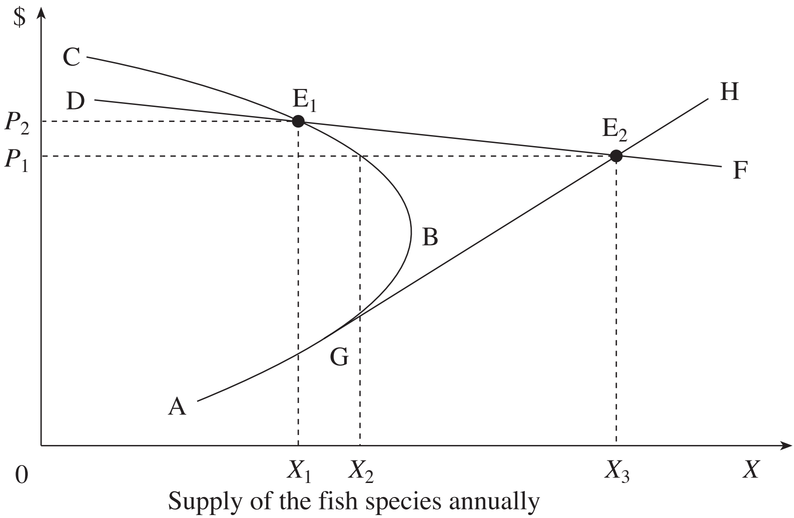

Figure 12.4 In some cases, farming or aquaculture favours the sustainability of the farmed species in the wild

In Figure 12.4, the backward-bending curve ABC represents the wild-caught supply of a fish species. It bends backward because, after some degree of harvesting effort is exceeded, available natural stocks of the fish fall significantly, so increasing the per unit cost of their capture. The line DF represents the demand curve for this fish. In the absence of its aquaculture, market equilibrium is established at E_1 with the fish selling at P_2 per unit and with X_1 being supplied annually.

Now suppose that aquaculture of the wild-caught species becomes possible and that the total annual supply of it from farming and capture is as shown by AGH in Figure 12.4. If the captures and the farmed suppliers are perfect substitutes a new market equilibrium is established at E_2. The market price of this farmed species falls from P_2 to P_1 and its supply expands from X_1 to X_2. $X_3 - X_2$ of the increased supply is accounted for by aquaculture and $X_2 - X_1$ arises as a result of greater supply from the capture of fishery. The latter occurs because a fall in market price reduces harvesting effort.

Hence natural stocks of the fish increase and per-unit and cost of capture declines. Thus, in this case, aquaculture is environmentally favourable.

However, the matter is much more complicated in practice, and in some cases unfavourable environmental results eventuate from farming. This can occur via two different mechanisms. See Tisdell (2003) for details. Aquaculture may stimulate the demand for the farmed species causing the market demand curves for supplies of the farmed species to shift upwards. Second, it may cause a shift to the left of the supply curve at wild-caught fish for reasons partly highlighted in Table 12.1. It may reduce the natural resources available to wild fish populations, for example as a result of wetland destruction, lower their population by their capture at an immature stage to provide seed stock or fingerlings, and by other mechanisms.

This means that considerable care is needed in assessing each aquaculture situation for its sustainability implications. Hasty generalization should be avoided.

Some other ways in which aquaculture can have positive environmental spillovers and add to sustainability might be noted. Fish farming is, for example, possible in conjunction with artificial wetlands. Such wetlands have been successfully used to reduce nutrient loads in water bodies. Polyculture and appropriate combinations of agriculture and aquaculture can also be used to lower nutrient loads entering common water bodies from private property. In Calcutta, fish aquaculture is engaged in ponds and supplied with the city's sewage. Thus aquaculture in this case assists with sewage disposal and helps reduce biological oxygen demand in common waters. Furthermore, when agriculturalists engage in fish culture in farm ponds and dams, they are less likely to use dangerous agricultural pesticides and chemical fertilizers capable of adverse externalities on fish production. Scope exists for expanding the development of aquaculture for beneficial environmental spillovers, but more research is needed in this regard. Since aquaculture includes botanic species, they should also be considered. In this respect, note that seaweeds and some molluscs can utilize the nutrients in nutrient-rich seawater and so could reduce dangers of red tides and other unwanted environmental effects.

Regulating adverse environmental spillovers from aquaculture – general considerations

Environmental externalities are generated by many social and economic activities, and aquaculture is both a source and a victim of several such adverse spillovers (Tisdell, 1994, 1995; Shang and Tisdell, 1997). As is clear from the above discussion, unfavourable externalities threaten sustainable development and are often sources of economic inefficiency and market failure. Their control can help to sustain economic development and improve the ability of economies to satisfy human wants.

None the less, some caution needs to be exercised before deciding to regulate environmental spillovers from aquaculture. It should be borne in mind that economic regulation is not costless, is likely to be imperfect, and different policy instruments often have divergent side-effects, some of which may be unwanted. Furthermore, the economic impact of environmental regulation is liable to vary with the attribute of production to which the controls are applied. For example, impacts vary depending upon whether regulations are applied to inputs, outputs or emissions from productive activity.

In assessing alternative policy instruments for the control of spillovers from aquaculture, account must be taken of the comparative agency costs involved in each and limitations on the knowledge available to policy-makers. The relative adaptability of alternative policy instruments to changing circumstances also needs to be considered. As discussed here, these and other factors influence the practicality of using alternative policy instruments to regulate environmental externalities from aquaculture and achieve sustainable outcomes.

An economic system is only fully efficient if the relevant impacts of an economic agent's activities on others are fully priced. If this is not done, externalities or spillovers are said to occur. These unpriced economic effects result in the marginal private net benefits obtained by economic entities from their activities (for example, marginal profit of aquaculturalists) diverging from the marginal social net benefits of these activities. In all but very exceptional cases (Tisdell, 1993, chs 3 and 4), this causes economic inefficiency and a loss of economic welfare, assuming that economic entities act in their own self-interest to maximize their private welfare.

These externalities can in principle be addressed by policy measures in two general ways:

1. Policy instruments such as emission taxes or trading in pollution rights may be used to price these, thereby making them a part of the private costs or benefits of the economic entities involved. Economists describe this as internalizing externalities.
2. Prohibitions or limits on environmental use may be imposed. Thus fiat, rather than guidance by means of pricing, is used to alter private behaviour.

Sometimes a combination of pricing and prohibitory methods may be employed. For example, a tax on particular types of emissions such as nitrogenous and phosphorous emissions from artificial fishponds, and a ban on the use of particular chemicals or pharmaceuticals in fish farming may be simultaneously imposed.

Within the pricing and prohibitory approaches to regulating environmental spillovers, a variety of policies is possible. These will be discussed after the broad principles of evaluating policies for regulating environmental spillovers in aquaculture are outlined.

Broadly, economic assessment of the regulation of spillovers involves two parts:

3. Costs and problems involved in the administration of the regulations, often described as agency costs; and
4. Consequential economic costs and impacts of the regulations.

Agency costs can be regarded as a form of transaction costs. Even when private property solutions of the type suggested by Coase (1960) are adopted with a view to eliminating externalities by negotiation, transaction costs are involved, particularly if agreements need to be enforced in the courts.

Policies for regulating environmental spillovers from aquaculture vary in terms of their agency and transaction-type of costs, and in terms of their consequential economic impacts. Both sets of factors must be taken into account in assessing environmental regulations; a holistic approach is needed. Table 12.2 summarizes the type of factors to be considered in deciding on policies to control environmental spillovers. These are classified into considerations arising from agency and transaction-type costs, and consequential impacts. These considerations are quite general and apply not just to aquaculture but also to all economic activities giving rise to environmental spillovers. Until recently, economists tended to concentrate on consequential impacts, giving most of their attention to item 12 listed in Table 12.2, impacts on allocative efficiency. However, with growing interest in institutional economics, the other aspects are getting more attention.

Many methods traditionally recommended by economists for the control of environmental spillovers from economic activities are impractical or uneconomic for aquaculture, mainly because of the level of transaction costs involved. For example, where aquaculture is conducted in a shared water body, emissions from cages or plots for aquaculture are non-point and can be very difficult, if not impossible, to monitor. Even when aquaculture involves pond cultivation and water withdrawal from a common body of water with release of wastewater via a point outlet (or a few outlets), effective monitoring of the quality of the water released may be difficult or costly. Where will the aquaculture water samples be analysed, how quickly, how frequently will they be taken and when? Especially when small-scale scattered aquacultural enterprises are involved, as is sometimes the case in

Table 12.2 Types of agency and transaction costs involved in environmental regulations and the consequential economic impacts of such regulations

Policy factor or impact	Comment
Agency and associated transaction-type costs	
1. Administrative outlays	Such as salaries for the general staff of the agency.
2. Monitoring or inspection costs	These policing costs can be high.
3. Enforcement costs	These include the legal costs of enforcement.
4. Political capture	The regulated may politically capture or influence the regulators. Regulators may prefer a quiet life and may not enforce the regulations rigorously.
5. Bribery	Regulators may take bribes and ignore infringements.
6. Imperfect information	Regulators have bounded rationality and thus have to act on imperfect information. Regulations may be inadequately drafted and values of policy instruments may be inappropriate.
7. Adaptability or flexibility of regulations	As economic and environmental conditions change, variations in policy may be necessary. Are the regulations adequate in that regard?
8. Uncertainty of regulations for the regulated	Uncertainty about the rights and obligations of the regulated and about enforcement of regulations may add to the costs of those regulated.
Transaction-type costs involved in private-property type of situations	
9. Negotiation costs	Note that many of these costs are similar in nature to those incurred by agencies but they fall on private individuals in this case.
10. Monitoring, inspection and enforcement costs	
11. Imperfect information of the parties involved	Asymmetry of information
Consequential economic impacts	
12. Allocative economic efficiency	To what extent do the regulations improve allocative economic efficiency, for example, bring private marginal cost into line with social marginal cost?
13. Change in income distribution	Different regulations have dissimilar impacts on income distribution. This should be taken into account.
14. Consequences for 'dynamic' efficiency – evolutionary impacts	How do the regulations affect technological progress, especially whether they encourage the development of technology for pollution abatement? Do the regulations encourage the development of environmental management skills?

less developed countries, the cost of sampling may be high. Furthermore, aquaculturalists may be able to time their noxious water releases so these do not coincide with the visit of a pollution-control inspector. Moreover, in some less developed countries, considerable scope exists for bribery, given prevailing socioeconomic conditions.

Pricing and market-making approaches to environmental regulation of aquaculture

In regulating environmental spillovers from aquaculture, it is important to decide initially which aspect of aquaculture activity is to be controlled to address an environmental problem. For example, is the control designed to affect the level of production, stocking rates, use of inputs, emissions of pollutants, location of activities or use of particular technologies or farming methods? Depending upon where the controls are applied, they are liable to have different economic consequences. For instance, if the emission of a particular pollutant is the main problem, limitations on aquaculture production levels, on stocking rates, or on inputs containing the major source of the pollutant will reduce emissions of the pollutant but may fail to encourage development of techniques to reduce its emission. Thus these policies may be ineffective in encouraging dynamic or evolutionary efficiency in pollution reduction. Nevertheless, agency costs involved in regulating emissions directly may be so high that it is not economical to do this. Thus in Europe, stocking rates on fish farms are regulated in some countries and in Denmark, the nitrogen and phosphorous content of fish food is limited (New, 1995). However, taxation or charging for pollution emissions from many forms of aquaculture has proven to be impractical.

Economists have traditionally favoured pricing and market-making approaches to environmental regulation on the grounds of their allocative efficiency (Tisdell, 1993, ch. 4). Unfortunately, as is clear from Table 12.2, the economic value of a policy cannot be judged solely from its ability to promote allocative efficiency or from its consequential economic effects. Furthermore, the simplicity of pricing-type policies is lost when environmental spillovers vary in their economic impact according to their location, as is mostly the case in aquaculture.

On the other hand, one should not be too ready to dismiss pricing approaches in favour of prohibitions. In some cases, very little extra cost is involved in adopting a pricing approach. Since it usually involves the 'user-pays' principle, the pricing approach can help fund the cost of administration of regulations and prevent this cost becoming an impost on the general state budget. Some also find this approach appealing because it can provide public funds for supporting research into methods of pollution reduction.

For example, instead of setting an administrative upper limit to the stocking rate on aquacultural farms, an alternative is to impose a tax or fee on this rate. The overall fee or charge should be determined to achieve the aggregate rate of environmental impact aimed for. This measure enables those farmers who find higher stocking rates to be more economical to have these, although they would have to pay extra for this. A disadvantage of this method from the point of view of the aquaculture sector is that (at least in the short term) it distributes income away from producers in this sector. Hence this policy may be politically unpopular from the point of view of the regulated industry. Similarly, instead of regulating the maximum nutrient content of manufactured fish food, one could impose a levy increasing with the nutrient content of this food.

Pricing and market-making approaches to control of environmental externalities may involve the following:

1. The levying of taxes or charges on economic activities giving rise to environmental spillovers.
2. The payment of subsidies to producers to provide them with an incentive to reduce or refrain from activity resulting in adverse environmental spillovers.
3. The marketing of pollution rights or environmental-use rights. These may be transferable.
4. Extension of private property rights in an effort to eliminate the occurrence of the externality.

Subsidizing pollution reduction is an alternative to taxing pollution creation, and in theory, it can achieve the same degree of allocative efficiency. However, in contrast to taxation, subsidization involves a charge on the state budget. Moreover, it has the opposite income distribution consequences to taxation. Worrall (1995) argues that a subsidy to aquaculture, for example, for shrimp farming, may be justified because aquaculture is likely to reduce harvesting pressure in the capture fisheries. However, this is a controversial matter and it is clear that aquaculture does not always have this consequence (see Tisdell, 1991, section 6.4). In fact, as pointed out above, just the opposite can occur.

Marketing of pollution or environmental-use rights has recently captured the interest of many economists. In theory, this policy approach can have similar allocative and dynamic economic consequences to the pricing control methods just mentioned. Nevertheless, actual schemes for marketing such rights can vary greatly. For example, depending upon how the rights are distributed, they may bring in little or no revenue for the state or considerable revenue. In this regard compare the policy which allocates initial pollution rights free to existing stakeholders in the industry and allows recipients to market these with the method by which the state auctions or sells rights (available only for one year) taking account of the market. The latter provides the state with revenue whereas the former method does not. Nevertheless, agency costs, sometimes considerable, have to be met when marketing of pollution rights is adopted as a policy (Tisdell, 1997a, 1997b).

In the case of aquaculture, many environmental spillovers are site-specific or vary in their consequences according to their location. In these circumstances, uniform rates of taxes, subsidies or prices for rights for environmental use do not promote economic efficiency (Tietenberg, 1974). Thus extra administrative costs involved in adjusting these refer appropriately by regions or locations, so reducing their value as regulatory instruments. This is not to say that adjustments are impossible. For example, marketed pollution rights may be designated for use in particular regions. However, in this case, it is possible that the market for such rights will become 'thin'.

As for the view of Coase (1960) that the strengthening of private property rights is likely to eliminate spillovers, this approach is only likely to be a success if the cost of enforcing those rights is low. Unfortunately, these (transaction) costs are usually quite high in aquaculture, especially if non-point pollution occurs. This limits the scope for private property solutions to environmental problems caused by aquaculture.

The nature of most aquaculture is such that traditional economic pricing and market-making approaches to pollution control and environmental use have limited application or can only be imperfectly applied. This is not to say there is no scope for such regulations. They may be used in controlling use of underground water, for example. Furthermore, if such methods are used, they often have to be modified to suit actual circumstances. For example, taxes or prices on using the environment may have to be varied according to the locality involved. Furthermore, the stage of economic development of a country can limit the practical use of instruments that are employed in more developed countries.

Prohibitions and administrative-type regulations

Prohibitive and administrative-type regulations are usually not favoured by economists because their allocative and dynamic economic consequences are believed to be less favourable than pricing and market-making approaches to the control of environmental use. However, the comparison is often made while ignoring the transaction costs involved in environmental pricing and market-making approaches to control of environmental use. When all costs are taken into account, prohibition and administrative-type regulations will sometimes be the most economic means of controlling use of the environment.

The nature of such regulations can vary greatly, as does their cost and overall effectiveness. This may take the form of (1) emission standards, (2) controls on inputs used in aquaculture, (3) controls on stocking rates, (4) preservation orders, for example, requirements that a certain amount of vegetation such as mangrove cover be retained, and (5) zoning affecting the location and nature of operations of aquaculture farms and other enterprises.

These methods need to be assessed by taking into account all the factors listed in Table 12.2. This means that alternative environmental policies should not be evaluated just in terms of their possible consequential economic effects.

Some prohibitions can be costly to enforce whereas others may be relatively inexpensive. For example, it is likely to be more costly to monitor compliance with emission standards than to enforce zoning regulations or maximum stocking rates of fish. One has to balance the agency costs against their contributions otherwise to improving the overall level of economic welfare. In reality, achieving a utopian or ideal solution to controlling environmental spillovers from aquaculture seems impossible.

Further discussion of sustainability implications

Traditional economic approaches to environmental regulation are based on social cost–benefit analysis. Such analysis requires account to be taken of spillovers as well as private net benefits. While it is impossible to go into details here, a major issue raised by social cost–benefit analysis is how empirically to place economic values on the spillovers or externalities that arise. Where there is loss of marketed production or commodities because of such spillovers, measuring the economic loss arising from these can be straightforward, in principle. However, in some cases, aquacultural activities can affect the supply of non-marketed goods and the reduction in their supply will need to be valued. Methods such as contingent valuation have been developed for this purpose, but they are not without their limitations (Tisdell, 1991, ch. 9).

Some authors have suggested that because of the uncertainty involved in evaluation of environmental effects, systems of safe minimum standards should be adopted (Bishop, 1978, 1979). In some instances, such standards can be combined with the use of transferable pollution rights. A further modification to the traditional economic approach to environmental regulation has arisen from debate about sustainable economic development. While most parties to the debate agree that externalities need to be taken into account to achieve sustainability, some parties believe that this is insufficient.

These individuals argue that strong conditions need to be enforced to achieve economic sustainability.

This group claims that it is now necessary to hold the world's remaining natural resource and environmental stock at approximately current levels (see Pearce, 1993). This means that any new economic activity should have a zero net effect on the environmental stock. In relation to aquaculture, this approach may require zero net emissions of pollutants by an aquaculture farm, water recirculation and so on. In other cases, offset policies may be allowed. For example, where an aquacultural development destroys a natural wetland, the developers may be required to establish an artificial wetland at least equivalent environmentally to the one destroyed. Alternatively, artificial or augmented natural wetlands may be required to be established to help process effluents from aquaculture farms.

In the 1990s, in Queensland, Australia introduced legislation intended to force aquaculture farms to have zero net emissions of nitrogen and phosphorous in their wastewater. But the standard could not be achieved. Furthermore, the question arises of whether such stringent standards are desirable, even if they can be physically and biologically achieved. The *ad hoc* promulgation of such rules can certainly add to economic costs and create economic inefficiencies. Furthermore, there could be *some* circumstances in which the release of nutrient-enriched water adds to the natural environmental resource stock and so creates a positive externality.

Economists have traditionally suggested that when environmental spillovers are optimally regulated, some degree of spillover or pollution is *likely* to be optimal from an economics viewpoint. Nevertheless, strong sustainability advocates may call for a zero *net* environmental effect. Their main argument is that aggregate stocks of natural environmental capital are now at critically low levels. Any further reduction is likely to endanger the welfare of future generations.

Concluding comments

As pointed out, aquaculture is a rapidly expanding 'new frontier' industry, and has the ability to add considerably to national income and wealth. But that also raises the question of whether its development is liable to be sustainable. It was shown that lack of sustainability of aquaculture development is sometimes a desired alternative even when market failure does not occur. Nevertheless, some concerns have been expressed about resource choices in such cases that adversely impact on sustainability. There is, however, less controversy about the idea that adverse environmental spillovers can result in income or economic paths being followed that are less sustainable than socially preferred and available alternative paths.

This discussion is specifically linked to environmental spillovers arising from aquaculture.

Particularly in the case of environmental spillovers from aquaculture, analysis was undertaken of policies that can and should be adopted to regulate these spillovers so as to increase economic welfare and contribute to sustainable development. A considerable number of policy instruments for regulating such spillovers were shown to exist. However, it seems that no single policy instrument or class of instruments constitutes the best choice in all circumstances.

Although economists favour pricing and market-making methods of regulation because of their favourable economic consequences, when all costs are taken into account there can be circumstances where these methods are not the best available. As a rule, one has to select the best among imperfect methods of regulation and the appropriate type of regulation or combination of regulations is likely to vary with the cases requiring attention. For this reason, policy-making in aquaculture cannot be a mechanical affair. Furthermore, it has become more complicated with growing interest in conditions required for sustainable development. There is still much to be learnt about appropriate economic ways to satisfy strong conditions for sustainability. Nevertheless, the continuing importance of environmental assessment, planning and management of aquaculture development for sustainable development has been underlined by the FAO (1995).

Unfavourable externalities are generated by many social and economic activities. Aquaculture is both a source and a victim of several of these spillovers. Such externalities threaten sustainable development and often are sources of economic inefficiency and market failure. Their control can help to sustain economic development and improve the ability of economies to satisfy human wants. However, economic regulation is not costless and different policy instruments often have different side-effects, some of which may be unwanted. Furthermore, their impact can vary depending on the attribute of production to which they are applied, for example, to inputs, outputs, emissions, and so on. Consequently, the assessment of alternative economic instruments for regulating environmental spillovers from aquaculture is much more complicated than some economists and non-economists have led us to believe. In assessing alternative policy instruments for control of spillovers from aquaculture, account must be taken of the comparative agency costs involved in each and limitations on the knowledge available to policy-makers. These, and other factors, influence the practicality of using the available alternative policy instruments as a means to support sustainable development.

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Infrastructure

13 Decision support systems for ecosystems management: a Singerian approach to urban infrastructure decision-making[1,2]

James F. Courtney, Sandra Richardson and David Paradice

Sustainable development and ecosystems management

The World Commission on Environment and Development (WCED) suggests that development is sustainable when it 'meets the needs of the present without compromising the ability of future generations to meet their own needs' (www.wbscd.ch). Sustainable development is a strategy by which communities seek economic development approaches that preserve and maintain the local environment and enhance the quality of life. Through this approach a framework is provided under which communities can protect environmental resources by using resources efficiently, create efficient infrastructures, protect and enhance quality of life, and create new businesses to strengthen their economies (US Dept. of Energy, 2001).

Ecosystems management attempts to deal with complex environmental issues by fostering sustainable development that recognizes the complex web of natural, economic, social and political factors that affect environmental systems. Effective management of these systems requires an understanding of their properties and in particular knowledge of the dynamics of these systems, and the cultures that rely upon them (Mäler, 2000).

The United Nations sponsored a global study on the conditions of the world's principal ecosystems. A report emanating from this study states alarmingly that 'The current rate of decline in the long-term productive capacity of ecosystems could have devastating implications for human development and the welfare of all species' (United Nations et al., 2000, p. 6).

The report calls for an ecosystems approach to managing the world's resources. This approach emphasizes the 'system' in ecosystem and manages resources holistically rather than sectorally, realizing that they cross jurisdictional boundaries. It also specifically includes human beings and 'integrates social and economic information with environmental information, thus explicitly linking human needs to the biological capacity to fulfill those needs' (p. 21). The report calls for a careful weighing of the trade-offs among various ecosystem goods and services, and among environmental, political, social and economic goals. It includes the public in the management of ecosystems, particularly local communities and urban areas, whose stake in and impact on ecosystems is often the greatest. Finally the report calls for addressing the 'information gap' (p. 21) relating to ecosystems by assembling, organizing and distributing knowledge and information about ecosystems and the political, social, cultural and economic environment in which they exist.

Thus integration of information regarding the natural ecosystems that are affected through development, and the information regarding human and social factors involved in the ecosystems decision-making processes is necessary for sustainable development to occur. The areas covered by these two sides of sustainable development are complex and cover a wide range of topics. For example, in any one project information regarding the impact of development on an ecosystem, how changes in a local system might affect larger ecosystems, societal issues, and economic and political factors, among others, all need to be addressed during urban planning and ecosystems management, as urbanization places severe pressures on ecosystems today. Currently there is a gap in the information available when planning and implementing projects. A decision support system for sustainable development based on an ecosystems approach would close the information gap and allow integration of information from all areas to support the attainment of sustainable development.

Clearly ecosystem management and sustainability are complex issues. They are linked, in that they embrace a long-term view of development, one that considers the needs of our progeny. They are what Rittel and Webber (1973) refer to as a 'wicked' problem because they involve so many issues and viewpoints, and are extremely difficult to solve. Ackoff (1999) simply calls such problems a 'mess,' in the sense that each element of a mess is itself a complex problem that strongly interacts with every other element of the mess. Churchman's (1971) Singerian inquiring system, and Mitroff and Linstone's (1993) unbounded systems thinking provide a framework for dealing with problems of this type.

Singerian inquiry and sustainable development

Churchman's Singerian inquiring system is well suited to dealing with wicked, messy, highly ill-structured problems (Mitroff and Linstone, 1993; Courtney et al., 1998, 2001; Richardson et al., 1999, 2001), such as those of ecosystems management. In describing the Singerian inquirer, Churchman says it 'is above all teleological, a grand teleology with an ethical base' (1971, p. 200). Singerian inquirers seek a highly idealistic purpose, the creation of 'exoteric' knowledge, or knowledge for 'every man', as opposed to scientific, esoteric knowledge that, as it matures, becomes relevant to an increasingly smaller audience. It seeks this knowledge in such a way as to take human and environmental considerations into account. In other words, the Singerian inquirer seeks the ability to choose the right means for ethical purposes for a broad spectrum of society; it seeks goals consistent with ecosystem management and sustainable development.

The Singerian inquirer views the world as a holistic system in which everything is connected to everything else. From the Singerian perspective, problems and knowledge domains (disciplines) are highly non-separable. Complex social and managerial problems must be analyzed as wholes (Mitroff and Linstone, 1993). The artificial division of knowledge into disciplines and the reduction of complex problems into simple components inhibit the solution to social and management problems. Solving complex problems may require knowledge from *any* source and those knowledgeable in *any* discipline or profession.

Linstone's multiple perspectives approach (Linstone, 1984) and Mitroff and Linstone's (1993) unbounded systems thinking (UST) are based on the Singerian model and promote heterogeneous views of organizational decision-making. A synthesis of broad worldviews is developed, rather than adopting the limited view of a single perspective. The Singerian style and UST also recognize the connectedness of things in the universe, especially of complex social problems. They realize the non-separability and irreducibility of elements in complex problems and issues. The development of multiple perspectives is the very core of UST. A critical aspect of developing multiple perspectives is open, honest, effective dialogue among all relevant stakeholders in the problem involved. Managers in such an environment must be careful to respect the rights and viewpoints of the parties involved, and be open and honest themselves in order to gain the trust of those who will be affected by the decision.

The Singerian approach and UST develop multiple perspectives in several ways. First, as Singer (1959), Churchman (1971), and Mitroff and Linstone (1993) put it, the system 'sweeps in' other problem-solving styles, which means it uses any or all of them where appropriate in decision-making processes, and may include any knowledge as needed from any discipline or profession to assist in understanding the problem. Mitroff and Linstone (1993) contrast the Singerian approach to the four non-Singerian (Leibnizian, Lockean, Kantian and Hegelian) models described by Churchman.

The Leibnizian model is based in the concepts of formal logic. The notion of a formal proof dictates how data are analyzed and how conclusions based on the data are made. The Lockean model is data-driven and based in consensus. A Delphi process for reaching conclusions reflects a Lockean system. The Kantian model considers multiple perspectives, but is a hybrid of the Leibnizian and Lockean approaches. It also depends heavily on the notion of an *a priori* theory which drives data collection. The Hegelian model is a dialectic approach. The thesis and antithesis reflect two perspectives of a situation, but the synthesis of them ultimately generates a single perspective and there is no mechanism for considering a divergent view in the future. Mitroff and Linstone assert that the four non-Singerian models reflect more of a technical perspective than any other type of perspective. All of these approaches are mechanistic and analytical in nature, although the reliance of the Hegelian approach on dialectics mitigates this somewhat.

To overcome the limitations of the technical perspective, UST sweeps in what Mitroff and Linstone call organizational and social, and personal and individual perspectives. These perspectives 'bring to the forefront human beings collectively and individually in all their complexity' (p. 99). Thus Singerian inquiry, consistent with the needs of ecosystem management and sustainable development, integrates knowledge and information from a variety of domains, including both social and 'hard' sciences, politics and from the public in general.

Decision support for Singerian inquiring organizations

Decision support systems (DSS) take an analytical approach to decision-making by building mathematical models of the structured parts of ill-structured problems (Sprague and Carlson, 1982). Yet the wickedness of ecosystems management problems goes well beyond the bounds of the ill-structured problems conceived of by most of the DSS literature. A new approach to dealing with wicked problems is needed. Unbounded systems thinking and the multiple perspectives approach offer a potential solution, but bring a host of new factors into the picture for organizational decision-making. One might even consider this to be an alternative decision-making paradigm, or at least a major overhaul of the conventional DSS view of decision-making, which scarcely considers anything other than the technical perspective of a problem (that is, the quantitative/analytical aspects).

The new decision-making paradigm for DSS is illustrated in Figure 13.1 (from Courtney, 2001). At the heart of the process are mental models. As Churchman and Mitroff and Linstone point out, mental models and the data selected by them (and hence what is defined as a 'problem' in the first place) are strongly inseparable. Mental models, either personal or collective, determine both the data and perspectives used to examine and resolve problems in a world of overabundant data sources. Mental models influence and are influenced by every step of the process; they determine the information that is gathered and what perspectives are developed. As perspectives develop, insight is gained, and the mental models are updated.

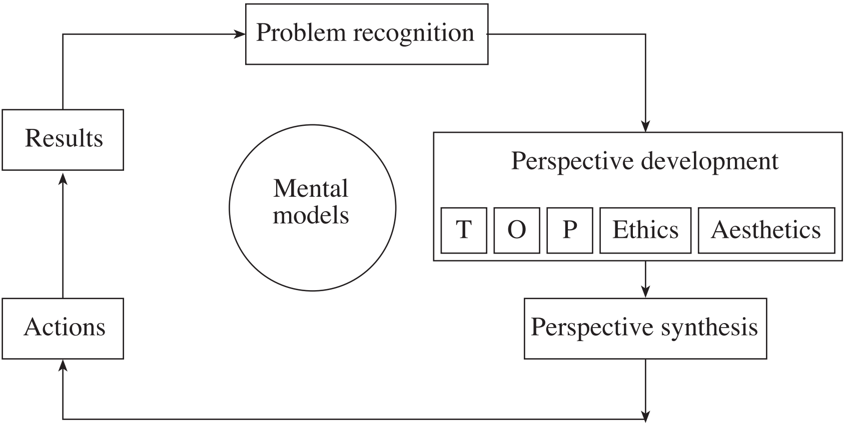

Figure 13.1 An expanded decision-making paradigm for DSS

Source: Courtney (2001).

That is, learning takes place. However, if the mental model or models reflect only a technical perspective, then only technical problems are addressed. Wicked problems such as those posed by ecosystems management require the inclusion of many perspectives.

In the proposed paradigm, the decision process begins as usual with the recognition that a problem exists; that is, a decision needs to be made. But rather than moving simply into analysis (the technical perspective, or T in the figure), the process consists of developing organizational (O), personal (P), ethical and aesthetic perspectives. Different perspectives can yield quite distinct pictures of a situation. The P perspective provides an immediate grasp of the essential aspects of a situation, but it also reflects the bias of the analyst that constructed it. The T perspective can be similarly criticized, as it reflects analysts' biases in the choice of assumptions, variables, and simplifications. (In the case of a strong organizational leader, one can argue that the O perspective is similarly biased, since the strong leader's P perspective becomes adapted as the O perspective.) An ethical perspective weighs the consequences of actions being considered. An aesthetic perspective considers that a proposed action will impact the quality of life attained by the stakeholders in a situation (Paradice, 2001). These biases act as filters, blocking some aspects of a situation from view and allowing other aspects to be recognized. The process of collecting multiple perspectives is intended to provide much greater insight into the nature of the problem and its possible solutions than the heavy reliance on the technical perspective that DSS has advocated in the past. It is suggested that diagramming tools such as cognitive maps (Axelrod, 1976), influence diagrams (Ramaprasad and Poon, 1985), entity-relationship diagrams (Chen, 1976), and object diagrams as expressed, for example, by the Unified Modeling Language (UML) (Popkin Software Systems, 1998), may be of great use both in showing the connectedness of elements in wicked systems and in surfacing assumptions that people hold about wicked problems. For example, it has been shown that having groups draw cognitive maps leads to surfacing of differences in assumptions about variables and relationships in a problem and more effective communication during the decision-making process (Loy, 1986; Massey and Wallace, 1996). The next section presents an example of a wicked problem situation, urban infrastructure management decisions. The subsequent section applies the proposed paradigm and illustrates the use of UML diagramming tools to decisions related to the development of infrastructure, such as roads, streets, water supply and sewers, for an urban area. UML has been chosen for use in the project because it has been adopted as the standard modeling language for object-oriented systems development and provides a complete set of diagramming tools for specifying object systems down to the level of software components.

An urban infrastructure management illustration

A project under way at Texas A and M University (Lomax et al., 1998) and the University of Central Florida exemplifies use of Courtney's (2001) DSS decision-making model, Churchman's Singerian inquirer and unbounded systems thinking in studying ecosystems management. The objective of the project is to develop decision support systems that will lead to improved decision-making regarding urban infrastructure investments, that is, investments in roads and bridges, freshwater supply systems, wastewater treatment, drainage systems, and the like. Infrastructure constitutes a complex system of public assets, which vary in their nature, but which serve the common purposes of fulfilling basic needs of the public, improving quality of life, preserving environmental quality, and providing for the health and well-being of citizens in general. The project adopts a holistic view of infrastructure as a system, consisting of a confluence of natural, built and human domains. The natural domain is the ecosystem; the built domain consists of infrastructure assets themselves, including buildings and other structures; the human domain includes all the various stakeholders involved in providing, managing and using infrastructure assets. A plethora of stakeholders is involved, ranging from citizens, businesses and the public in general who use the services, to the mayor and city council who make the final decisions, city departments, such as public works, that plan and maintain the infrastructure, and finance that administers funds. Also heavily involved are contractors and developers that build the infrastructure, and numerous other city, county, state and federal agencies that regulate, provide funds, or otherwise affect infrastructure decision-making in some way. Thus the scope of the project is quite vast, and coincides well with the call for urban management studies in the UN-sponsored world ecosystems report described above. The city of Houston, Texas, which is cooperating in the project, is serving as the test bed for the development of the infrastructure DSS.

The first phase of the project consisted of the project team familiarizing itself with infrastructure management on a general level, by reading about infrastructure management, and sharing extant knowledge among team members via presentations and briefings. The team itself is quite diverse and consists of individuals knowledgeable in transportation systems, water supply and wastewater treatment, ecosystem management, political science, sociology, economics, geographic information systems and decision support systems. Once each team member's specialized knowledge had been broadened with general knowledge of infrastructure management, the team prepared to interview relevant stakeholders. Questionnaires reflecting the Singerian perspective and the new decision-making model were developed to guide structured interviews for interviewees representing five different perspectives: elected officials, governmental personnel, businesses, contractors and developers, residents of selected neighborhoods, and media representatives. When the questionnaires were complete, the team began to interview appropriate individuals in Houston to understand specifically how infrastructure decisions are made there. Approximately 100 interviews are planned, and about fifty have been conducted at the time of this writing.

Tentative conclusions have been reached regarding technical, individual and organizational perspectives. These will be discussed in turn. (Note: some of the points below refer to interviews, but respondents must remain anonymous under terms of the agreement with them.)

The technical perspective

As expected, the technical perspective, as evidenced by formal models, is most prominent in the public works department, but some models and databases are used in the planning department and the mayor's office. The public utilities division of the public works department maintains a Water Distribution System Model for the City's freshwater supply. It is used, for example, to determine the effects of taking a portion of the system off-line if it needs to be repaired. The planning department is still developing a geographic information system (GIS) that is already used by a wide variety of city personnel and developers and contractors. It works in conjunction with an information management system (IMS) maintained by public works to monitor complaints about sewer and water supply. The IMS keeps track of the status of repairs and the GIS shows where the problem is located. Various other models are used in the transportation department in designing and constructing streets and roads. As the technical dimension is not the main focus of this chapter, it will not be discussed further.

Individual perspectives

Individual perspectives are as diverse as the individuals themselves. As described in more detail below, a political respondent thinks Houston faces a wicked problem in the form of a 'three-headed monster' in terms of the confluence of environmental issues, transportation and economic development. One businessman, who also remarked on the importance of environmental and transportation issues, noted, not surprisingly, that money is a critical factor in infrastructure decision-making. Very early on in the interview this respondent was asked what the team should do to understand infrastructure decision-making in Houston. The response was 'Follow the money.' At the end of the interview the final comment was also 'Follow the money.'

A respondent in the planning department seemed to agree, saying 'Economics drives everything.' Yet a cohort in planning thinks that politics is the prime mover, saying 'Everything boils down to political considerations.' Media representatives agreed that it is a highly political process, heavily influenced by developers. However, one media person also felt that nothing gets done unless the people want it. That is, citizen groups can block a project if it is antithetical to their self-interest.

One businessman seemed to think the system worked pretty well, as did an administrator in the public works department. However, a respondent in another department, when asked what made the system work, looked out at the construction site below and said incredulously 'You think this works?'

Individual perspectives will be discussed further when environmental and quality of life concerns are discussed. First, however, the organizational perspective that provides the context for those individual perspectives will be considered.

The organizational perspective

Conclusions reached with regard to the organizational perspectives include the following:

- The mayor's office is especially important in infrastructure decisions in Houston. Houston has a strong mayoral form of government. Several respondents indicated that all the mayor has to do is 'count to eight,' as the mayor has the primary responsibility for setting council meeting agendas, and a simple majority of eight votes is needed to pass motions and resolutions.

- Houston's development is based on a growth paradigm. Houston has no zoning, and the planning department is relatively weak, one respondent referred to it as a 'permitting agency.' One of the media representatives indicated that Houston was thus known as a 'developer's town.' This has led to problems. For example, in the past, developers were allowed to put in small wastewater treatment plants to serve neighborhoods they developed. These tended to be both ineffective and inefficient. Early in the 1980s, the US Environmental Protection Agency required that Houston decommission these small plants, and upgrade to larger, more effective systems at an ultimate cost of about US$2 billion.
- Infrastructure projects are divided into maintenance and capital improvement categories, the latter being more political in nature, as a five-year capital improvement plan (CIP) is updated annually, and must be approved by the city council. This is a highly political process also. The mayor's office plays the central role in the CIP process, with advice and input from many sources, especially public works and city council members. A unified modeling language (UML) class diagram showing the main object classes and relationships occurring in the CIP process is given in Figure 13.2 and a use case diagram is shown in Figure 13.3. UML is a standard notation for the modeling of real-world objects as a first step in developing an object-oriented design methodology. It is designed to foster communication about a model. Among the concepts of modeling that UML specifies how to describe are object class, object, association, responsibility, activity, interface, use case, package, sequence, collaboration and state.
- The project team is using diagrams such as these to document the system and to communicate among themselves and with the appropriate people in Houston as to exactly how the process works. The diagrams are proving to be an invaluable means of improving the communication process. The objective is ultimately to use software to produce source code directly from the diagrams, thereby generating at least a portion of the DSS itself.
- The emphasis on growth and development has led to public works playing an important role in infrastructure decisions and management. One respondent indicated that the goal of public works is to spend all the funds allocated in the CIP. Politically, it is popular to spend capital funds, and to attempt to cut the operating budget. At the end of the fiscal year, some projects may have been delayed for various and sundry reasons, and public works may be looking for approved

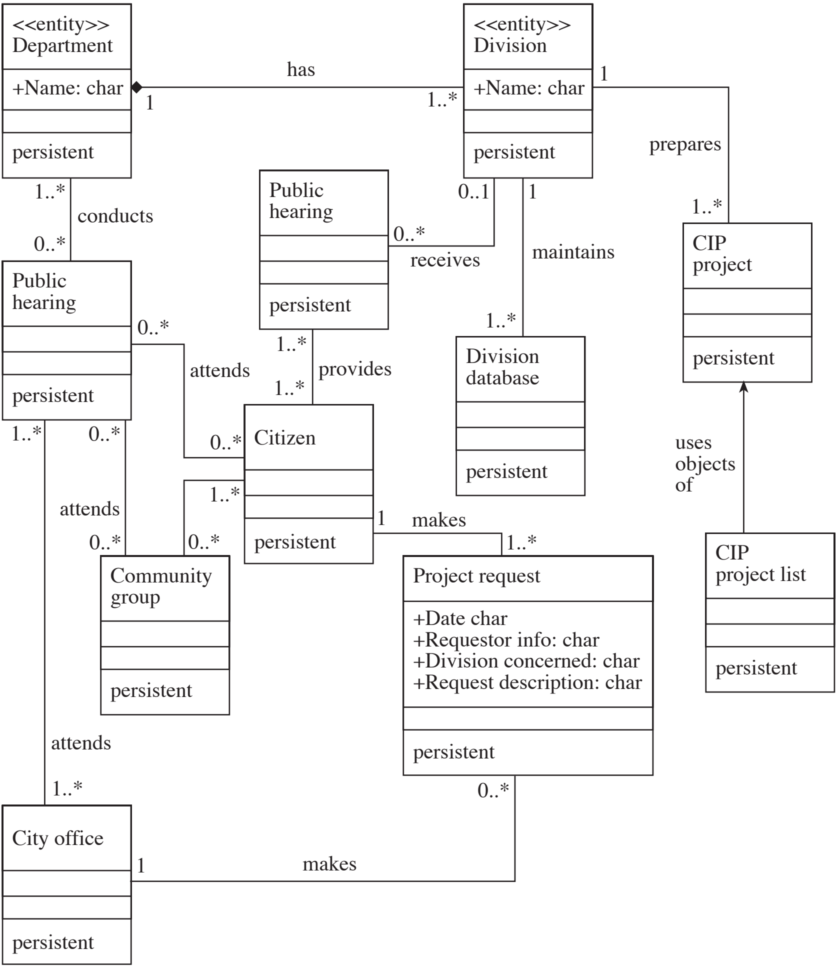

Figure 13.2 Capital improvements projects unified modeling language (UML) class diagram

projects to fund. Thus to buffer the process, some projects may go through a design phase early; in the event that some other project is delayed, the design can be taken 'off the shelf' and started immediately. Otherwise, capital funds would languish. This does lead to a problem in that some designs, if done early and not implemented, may be obsolete and have to be redone when their time does come.

- Funding for freshwater supply and wastewater treatment is less politicized, because they have dedicated 'enterprise funds' emanating

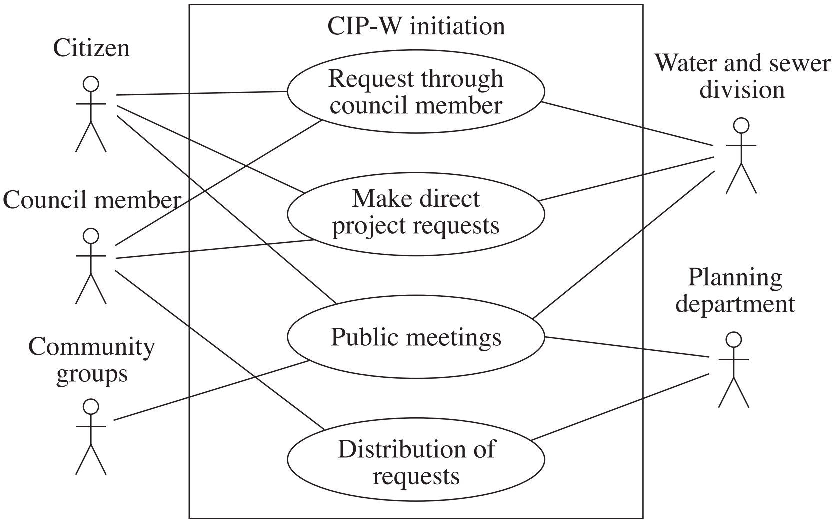

Figure 13.3 *Use case diagram for the initiation phase of the CIP process*

from billing for water and sewage treatment, respectively. Transportation has some funds from the gasoline tax, but relies mostly on other sources. Drainage has no such dedicated fund and depends upon general revenue funds, which are under political control. Drainage is presently one of the most problematic areas for Houston, with the exception of air quality.

- Agencies and departments and other stakeholders tend to be 'silos,' sharing little information about projects and the status of systems. Further expansion of the GIS and IMS may go a long way in alleviating this problem.

Environmental concerns and quality of life

The emphasis on growth and development in the past has apparently relegated environmental and quality of life concerns to the back burner. Few respondents in any of the departments seemed to put much emphasis on these factors in making infrastructure decisions. This situation may be changing, however. One of the council members indicated that quality of life is an 'extremely important' concern, but another said it was not important, as it is difficult to measure. A member of the planning department felt that environmental and quality of life issues were becoming more important, as did a media representative.

Applying the model to urban infrastructure management

While it is too early to make final conclusions regarding the project at this point, some tentative conclusions have been reached, both with regard to the use of the approach illustrated in Figure 13.1 and to the specific project in Houston.

The urban infrastructure decision-making environment

Courtney's approach to complex problem formulation provides a constructive way of identifying the stakeholders and their concerns in this complex decision-making environment (see Table 13.1). In the table, we have augmented Courtney's basic approach with an additional 'political perspective'. Notably, this additional perspective is not necessarily unique to this particular decision-making situation. A political perspective is relevant and needed in many, if not all, organizational decision-making situations.

Associated with each perspective is the type of model that can dominate analysis from that perspective. The technical perspective relies on well-formulated models that are typically specified quantitatively. Individuals rely on their mental models, or worldviews. When a well-developed technical perspective quantitative model supports an individual perspective mental model, the quantitative model is often subsumed into the individual's world view. Enterprise models describe the organizational perspective. This perspective has a broader scope than the technical and individual perspectives and incorporates (where feasible) aspects of those perspectives. The political perspective extends the scope of analysis even further. It incorporates multiple organizational perspectives.

Across the top of the table we have placed the four categories of decision factors that have surfaced from the analysis: needs, economics, the environment and politics. Within the table we note how a particular perspective can be realized in a particular category. Examining the table brings to light how different stakeholders in a problem come to have such different views of how the problem should be solved. The solution that is obtained from a focus on any particular cell in the table will likely differ significantly from a solution generated from focus on a different cell. Similarly, a focus on any row (or column) will likely generate a solution that differs significantly from a focus on a different row (or column).

Only when the entire table is considered can an ecosystems approach to problem solution be developed. Here is where Singer's ethics become relevant. Ethics govern the interaction between stakeholders that have different perspectives. Ethics can govern the synthesis of problem formulations that focus on different categories.

Singerian inquiry also emphasizes the aesthetics of inquiry. Aesthetics refers to the philosophy of beauty. In this case, the aesthetics of the situation

Table 13.1 Decision factor categories and the multiple perspective approach

Categories → Perspectives ↓	Needs	Economics	Environment	Politics
Technical perspective (Quantitative models dominate)	Well-developed quantitative models in some areas but they may be biased by assumptions in other categories.	Well-developed quantitative models but they typically have restrictive assumptions.	Partially developed quantitative models on a holistic scale (ecosystems) but some well-developed models of specific processes exist.	Poorly developed quantitative models but models of negotiation/ bargaining may be applicable.
Individual perspective (mental models dominate)	Maslow's hierarchy describes holistic view; quantitative models used where available within that hierarchy.	In spite of well-developed quantitative models, individuals exhibit subjective utility, 'satisfice' and otherwise deviate from pure economic rationale.	Most people do not utilize technical perspective quantitative models here. Once needs are satisfied, any concern for environment is primarily driven by either ethic or aesthetic beliefs.	Individual actions may be generally proscribed by political orientation, but often only after 'needs' and 'economics' issues have been resolved.
Organizational perspective (enterprise models dominate)	Corporate leadership determines 'needs' which include need to be an ongoing concern, need to provide adequate return to stock-holders, etc.	Enterprise model in this category is driven by macro-economic philosophy.	Enterprise model in this category is only partially defined for most, except possibly in focused groups (e.g. Greenpeace).	Enterprise model in this category is driven by doctrine (political platform).
Political perspective ('platform' models or doctrines (Liberal, Conservative, etc.) dominate)	'Needs' in this perspective may be more likely 'wants'.	Economics of re-election may take precedence over other concerns.	Issues here dominated by doctrines and economics except in extreme cases.	Simple models ('count to eight'), bargaining, negotiation and coalition-building.

may be viewed in terms of how the participants in the process feel about the 'beauty' of the final problem formulation. Or it may be defined in terms of how the final problem formulation compares to some abstract notion of a 'perfect' formulation. If the synthesis of problem formulations is successful, consensus should be obtained regarding the aesthetics of the final problem formulation.

Some general conclusions have been reached about the approach, and some specific conclusions have been reached about infrastructure decision-making in Houston. General conclusions about the approach are presented first, followed by a discussion of specific findings regarding technical, individual and organizational perspectives.

General conclusions about the decision-making model

First, it seems apparent that urban infrastructure decision-making environments indeed qualify as a wicked problem or one of Ackoff's (1999) messes. Every subsystem is related to every other subsystem and each is caught in a quagmire of political, social, economic, cultural, technical and environmental factors that defy easy solutions. To paraphrase one of the political interviewees:

> The infrastructure needs are going to be compounded significantly in the next decade. The city faces a three-headed monster in terms of transportation, environment, and economic development. The environmental component … if we don't come to standards, and we don't develop a plan that allows us to meet EPA requirements … is going to eventually choke our economic growth and development. Companies are not going to want to move here. People are not going to want to come to Houston. It's going to hurt our small businesses. And, a lot of our problem environmentally is driven by transportation, by automobiles. While at the same time, we want to consider light rail and other rail possibilities. Well, again, you've got to have the dollars, economic development to push that, to design that, to get that. So we're headed toward a showdown with these three issues … they are going to be so overlapping that you're not going to be able to distinguish them and whatever the issue is. And then on top of that, if you add infrastructure, water, sewer, streets, you've got major problems. You've got major problems ahead.

Second, consistent with previous studies (Richardson et al., 2001), results thus far seem to indicate that the Singerian model, unbounded systems thinking, and Courtney's (2001) paradigm for DSS decision-making provide a structure that is helpful in dealing with the 'mess.' The concept of multiple perspectives was helpful in creating the five different questionnaires for the various types of respondents, and in developing the questions that would be included. This structure has also been helpful in compiling responses, as indicated in the organization of the discussion above.

Third, because the process is inherently political in nature, involving the mayor's office, city council and voters, it is imperative that a political perspective be developed in addition to the perspectives in the Courtney model.

Fourth, the decision factors tend to cluster into four broad categories: need, based on engineering studies, healthcare concerns and so forth; economics, based on the revenue and expenses the city expects, and the expected cost of possible projects; environment, the ecosystem itself; and politics, based on parties in power and their constituents.

Fifth, each group of participants in the 'process' (if it really is a process) uses factors from all four categories in making their decisions. For example, it's not just the politicians that use political considerations in their decisions. Public works, for instance, dedicates a percentage of its infrastructure budget to members of the city council, who can choose projects in their district however they want. This helps to keep the council members from complaining to public works that they don't get their share of infrastructure dollars, and allows council members to direct resources at specific problem areas in their district, or to specific target populations.

Other general conclusions

Other, perhaps more tentative, conclusions are:

- Developing decision support systems for factors in the needs and economics categories will probably not be difficult, as some computer-based models already exist in these areas, and the other problems are relatively well defined. A more difficult task will be developing models in the political and social arena, as that is where the really messy problems occur.
- There is a basic need for sharing more information among all groups involved in infrastructure decision-making, especially between the mayor's office, city council members and public works. An effective DSS could go a long way towards improving communication among stakeholders, especially if it is integrated with the GIS currently under development by the planning department. Although shared information would greatly improve this decision-making environment, integrated *applications* would be an even greater benefit. A DSS that integrates technical, organizational and personal perspective models in a way that all of these perspectives can be brought to bear on a decision-making problem will improve the quality of decisions made in 'messy' situations such as these.
- The sustainability aspect of these situations must be addressed in the DSS. A simple approach would be to incorporate automated reviews of

the solution applied to determine whether it is satisfying sustainability criteria. Solutions failing the sustainability test should automatically trigger the creation of a new decision problem to be addressed.
- DSS for these types of decision-making problems must incorporate ethical issues. Ethical issues are wicked problems in their own right. Thus incorporating an ethical perspective into the DSS will be difficult. However, a recursive application of the unbounded systems thinking approach to incorporate an ethical perspective seems feasible.

Development of the DSS

As mentioned previously, an object-oriented approach is being taken to the development of the decision support system. At present, the project is still in the early stages of design. To reduce the scope somewhat, the project is limited to freshwater supply, wastewater treatment, drainage and transportation. Thus far, class diagrams and use case diagrams such as those in Figures 13.2 and 13.3 have been developed for freshwater supply, wastewater treatment and drainage. The approach being taken is an iterative one in which the design team produces tentative diagrams that are shown to other team members at bi-weekly project meetings. Input from other team members is sought, and the diagrams are modified. Once the project team is satisfied that the diagrams adequately reflect their knowledge of the process, the diagrams are then taken to the appropriate stakeholders in Houston, additional input is gathered and the models are updated. This is a lengthy, time-consuming process but it seems to be an effective way of communicating among the design team, the others on the team and the stakeholders in Houston.

As the project progresses, activity and component diagrams that specify system behavior at a more detailed level will be developed. Ultimately it is planned that the system will be deployed on the World Wide Web as Java applets. These applets will provide access to the system by any stakeholder who has access to a Java-enabled browser. Thus individual citizens, contractors and builders, agencies and others will have access to the same models and data and will be able to explore the effects that different decisions may have on development in Houston. In the spirit of the Singerian approach, the design team is attempting to develop quality of life measures that will be used in the models, in addition to the typical economic and technical factors that are generally employed.

Summary

In recent years increased attention has been given to the negative impact of contemporary lifestyles on the environment. Current rates of population growth, agricultural practices and energy use have made evident the effects of individual, government, and business impacts on ecosystems. Issues such as the environment, financial accounting practices, business decision-making, city infrastructure and governments, each often viewed as separate or abstract, are now being incorporated into a holistic approach to solving sustainability problems. These recent trends in thought have taken the focus away from blaming environmental problems on those organizations whose impact is most obvious, such as logging and industrial plants, and toward viewing environmental problems holistically, recognizing numerous factors are involved on every level. This chapter first recognizes the current issues facing the environment and then defines sustainability and points out the business impacts and implications on sustainability. Courtney's decision-making model for DSS, combining the Singerian inquirer with unbounded system thinking, is proposed as an effective approach to working through complex issues, and lastly an example of some current work is provided to illustrate the role of urban infrastructure decision-making on sustainable development.

As increased attention is directed toward issues of sustainability, two important issues have emerged. First, if the status quo is maintained, the planet may not survive. Second, the issues surrounding changes in practice are exceedingly complex.

The Singerian model is proposed as a useful tool for solving the current problems, as this is a model born in complexity. It views all things as being related, pulls in knowledge from every conceivable source without regard for traditional compartmentalization of knowledge, emphasizes a team approach to problem-solving, bringing together all of the players involved, and encourages all players to work cooperatively toward the benefit of all humankind, and in this case the planet as a whole.

The Houston project, an example applied to the sustainability issue through the Singerian model, allows us to begin to see the complexities of the problems. This model also illustrates ways in which previously fragmented players can come together to address environmental issues, recognizing the role that each plays in the overall picture. Also emphasized is the importance that sharing of information may have in solving complex, messy problems.

Notes

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2. A preliminary version of this chapter was presented at the August 2000 Americas Conference on Information Systems and was published in the conference proceedings.

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14 Infrastructure development as a policy lever for sustainable development

Khalid Saeed and Honggang Xu

Introduction

Infrastructure investment is an important expenditure instrument employed by developing country governments over the past 40 years to affect economic development (Krueger, 1992). A World Bank study examining a cross-section of developing countries shows that infrastructure typically represents about 20 percent of their total investment and 40 to 60 percent of their public investment. Although private sector participation in infrastructure services delivery is on the rise, its volume remains under 10 percent of the total annual outlay (World Bank, 1994). Since the governments in most developing countries do not have the necessary institutions to implement many fiscal policies to facilitate economic growth and influence income distribution, infrastructure development is often seen as an effective tool to achieve those ends, albeit its performance has varied widely (Van de Walle and Nead, 1995; Boadway and Marchand, 1995).

The spread of benefits of infrastructure investment has also been quite limited in most developing countries. It might even have contributed to a worsening of income distribution, which is widely recognized to be detrimental to sustaining economic growth and human security. Large farmers have been observed to receive more benefit from infrastructure provision than small farmers during the early stages of development (World Bank, 1994; Van de Walle and Nead, 1995; Knudsen and Nash, 1990). The urban sector has received more benefit than the rural sector (World Bank, 1994; Lipton, 1967) and the urban formal or capitalist sector has received more benefits than the urban informal or self-employed sector (World Bank, 1994).

We feel that the failure of the infrastructure policy to create a larger spread of benefits arises from the fact that the economic models underlying policy design are unrealistic. While these economic models assume a homogeneous socioeconomic structure, in reality, there pervasively exists a dual economic system consisting of a profit-maximizing capitalist sector and a consumption-maximizing self-employed sector no matter how one slices the economy. Any infrastructure policies implemented by the government will alter resource reallocation between these two sectors. Hence policies ignoring the dynamic interaction between these two sectors may not perform as expected.

In this chapter, we analyze the efficacy of public provision of infrastructure in developing countries by constructing and experimenting with a system dynamics model of a developing economy, incorporating its dual structure and other realities existing on the ground. This model provides an opportunity to experiment under controlled conditions with the various infrastructure polices proposed and implemented in the past and to understand their performance. Such experimentation helps to resolve some of the debates on development policy arguing for and against infrastructure provision. It also helps to outline an operational policy framework for effective use of infrastructure development as a policy lever for sustainable development. Experimentation with our model shows that infrastructure development alone – even if targeted at the poor – will not improve income distribution. Only when this instrument is combined with the taxation of unearned income, as suggested earlier in Saeed (1988), will income distribution improve. We also observe that building public infrastructure may not be more effective than providing modern private capital for facilitating economic growth. Technical details of the model, including a machine-readable listing in VENSIM® simulation software[1] for replicating the experiments discussed in this chapter and for further experimentation, are available from the authors on request.

Observed patterns of economic growth and infrastructure performance

Infrastructure services have special economic characteristics that make them difficult to handle by the private sector. The demand for infrastructure does not change significantly with the change in the price of the infrastructure service, while the supply-side characteristics of infrastructure feature a high sunk cost and increasing returns to scale (World Bank, 1994; Brown and Sibley, 1986). These characteristics make it difficult to deliver infrastructure services through the private sector without risking market failures, making public investment essential (FAO, 1996; World Bank, 1994; Shah, 1992).

The precise link between infrastructure and economic development is not clear. The literature indicates that infrastructure research has developed in isolation from the extensive literature on economic growth (Holtz-Eakin and Schwartz, 1995). Researchers gradually began to pay attention to this topic after Aschauer (1989a, 1989b) attempted to explore the relationship between infrastructure services and economic growth. Aschauer assumed that infrastructure is an unpaid factor in the production function and he placed the public infrastructure stock in the production function to estimate private production. The marginal returns to workers and to capital with the unpaid factor in the production function diverge from the marginal returns without the unpaid factor. Therefore, the production factors get reallocated with infrastructure provision, which should improve economic efficiency and generate a higher output. An opposite view appears when infrastructure costs are considered. Many researchers argue that infrastructure is not an unpaid production factor and is always financed by tax money. The price of infrastructure consumption is the tax rate that reduces the return on capital investment, thus reducing the incentive for the private sector to invest (Munnell, 1992). The high cost and the long delay in the delivery of infrastructure by government further reduce its efficacy (World Bank, 1994). Both these arguments have received support from empirical research on the estimation of elasticity of infrastructure investment with respect to total output. Contradictory empirical results are created probably also by unreliable measures of public capital stock (Duffy-Deno and Eberts, 1991; Eberts and Fogarty 1987; Munnell, 1990). Hence policy designs based only on estimates of elasticity of infrastructure stock or infrastructure investment with respect to regional production or regional income are unreliable.

Notwithstanding the large variation in its efficacy, public provision of infrastructure has been considered an important instrument for economic development and welfare delivery in the developing countries. Hirschman (1958) suggested that infrastructure investment be used as an initiative for economic growth. It has also been generally believed that allocation of expenditures within the infrastructure sub-sectors could yield high investment returns when guided by consideration of the country's underlying development goals. Indeed, infrastructure investment was accorded high priority in stimulating economic growth in the 1950s, particularly in China, India and Taiwan (World Bank, 1994; Minami, 1994).

In spite of the attention given to their development, infrastructure services have also become a bottleneck in most developing countries, necessitating a call for foreign investment in infrastructure. In Thailand, Indonesia and the Philippines, electric power, water supply and transport have been the principal targets for foreign investment (Abegglen, 1994). Meanwhile, since the governments have a propensity to consider economic efficiency more than welfare delivery, public provision of infrastructure has usually resulted in delivering a subsidy to the rich instead of helping the poor (World Bank, 1994; Clements, 1995). Hence the view that infrastructure is essential to economic development and the delivery of welfare to the public has come under serious criticism. On one hand, present theories attempt to demonstrate that public provision of infrastructure is not an effective tool for achieving development targets and that the public provision of infrastructure should be replaced by the private sector. On the other hand, it has been pointed out that no matter how much an economy is opened to the private sector, government must still provide a substantial share of the infrastructure (Stephanedes, 1990).

We feel that a policy design framework cannot be divorced from a concerted effort to understand the logic of the information relationships underlying past performance. Public infrastructure provision in a developing economy is a complex process. The infrastructure service includes a large category of 'basic services – public utilities, which are necessary to production'. The degree of usage of public infrastructure depends on the nature of the production process in a firm, while the efficiency of infrastructure policy is usually related to the economic structure (Nadiri and Mamuneas, 1994), which is changing rapidly in developed countries. The developing country economies were dominated by the agricultural sector in the early stages of development, while coexistence of the agricultural and industrial sectors appeared in the transition stages and the industrial sector became the dominant sector in the later stages. The dynamically changing economic structure has constantly changed the optimal composition of the infrastructure needed. As there are considerable delays in constructing infrastructure, bottlenecks will invariably hamper economic performance over the course of development.

A developing economy is also characterized by its duality. In each stage of development, two sub-economies often exist side by side. In the agricultural stage, large-scale commercial farms coexist with small farms in the self-employed peasant sector. In the industrial stage, large industrial firms run on commercial lines coexist with small firms run by self-employed entrepreneurs. In the transition stage, the duality becomes more complex. The rural economy, in which large commercial farms coexist with the small self-employed peasant farms, also coexists with the urban economy, in which large commercially run industrial firms co-exist with small firms run by self-employed entrepreneurs. An aggregate capitalist sector, including the commercial farms in the rural sector and commercial firms in the urban sector, attempts to maximize profit. On the other hand, an aggregate self-employed sector, including small peasant farms in the rural sector and self-employed family work units in the urban sector, attempts to maximize consumption. This classification has been referred to variously in the literature, for example, as formal and informal, capitalist and self-employed, commercial and peasant, capitalist and worker (Dalziel, 1991; Fazi and Salvadori, 1985), capitalist and subsistence (Lewis, 1958) and modern and traditional sectors or sub-economies (Fei and Ranis, 1966), but all those contexts refer to the existence of an economic duality. Due to this duality, economic growth may not necessarily signal a general improvement in welfare, when the distribution of income in the dual economy and the transfer of value between the capitalist and self-employed sectors are also taken into consideration. Any policies implemented in the face of this duality would cause a reallocation of resources between the two sectors in a way that greatly diminishes the benefit for the poor, which is borne out by experience.

We address in this chapter the public infrastructure provision in a dual economic structure in a broad sense. The results of our analysis can be extended to more specific contexts, for example to formulate an analytical framework for policy design on infrastructure provision during the initial developmental stages when the agricultural sector dominates the economy, the transition period when an urban–rural duality is experienced and also in the newly industrialized countries where this duality takes the form of an aggregate formal sector consisting of a capitalist urban–rural coalition and the informal sector appearing as an aggregate of the urban as well as rural self-employed sub-economies.

There is ample empirical evidence of a pervasive existence of a dualist structure in the developing countries. Table 14.1 shows the proportions of wage-employed workers in either rural areas or nationwide in selected Asian countries, which range between 30 and 70 percent, meaning that the self-employed, informal or peasant sector and its counterpart capitalist, commercial or formal sector are equally significant.

Table 14.1 Percentage of wage-employed labor in the workforce in selected Asian countries

Countries	Wage-employed labor in rural area (%)	Date	Wage-employed labor nationwide (%)
Indonesia	70	1983	(–)
Nepal	66	1981	(–)
Pakistan	50	1981	26.6
Philippines	66	1988	45.8
Bangladesh	(–)	(–)	43.3
Korea	(–)	(–)	57.4
Malaysia	(–)	(–)	62.7

Sources: ILO (1983, 1986, 1990).

It is widely recognized that the levels of financial capacity, labor productivity, capital intensity, and accessibility to public infrastructure are much higher for the capitalist sector than for the self-employed sector (Lewis, 1958; Boeke, 1976). Although the factor proportions, the productivity of labor, and capital–worker ratio in the two production modes vary from country to country and sector to sector, there appear to be many similarities in the overall pattern. These similarities are manifest in the side-by-side existence of both production modes with a relatively low productivity in the self-employed or informal sector and a relatively high capital–worker ratio in the capitalist or formal sector.

Before economic development effort began, the developing countries were largely closed economies. Most production was carried out in family work units, both for producing basic commodities and other services. These family units often worked in a feudalist environment with a considerable separation between asset ownership and labor. The mechanism of renting allowed self-employed workers to get access to land and production capital largely owned by the formal sector (Lipton, 1967; Samuelson and Nordhaus, 1985). When the government used infrastructure investment as a policy to increase productivity through constructing production infrastructure, such as irrigation facilities, electricity grid, water supply and drainage, and so on, and to expand trade through transportation, the formal sector began to shift a part of their land and capital resources from renting to production since it could make a better use of this free production factor than the self-employed family units. Evidence of this phenomenon has been found in Japan, Taiwan, Korea and Pakistan (Kikuchi and Hayami, 1979; Akino, 1979). The introduction of modern capital that could be rapidly adopted by the capitalist sector further increased the volume of formal production, although the self-employed units were never fully displaced.

The first system dynamics model incorporating a dual economic structure was developed by Saeed (1980) to explain the income distribution and wage determination in an agricultural economy. This model was later employed to explain the behavior of the capitalist systems operating under different social and legal norms (Saeed, 1987; 1988; 1994) and the implications of free trade and capital movements in a dual global economy (Saeed, 1998). The model was furthermore extended to incorporate endogenous technological growth to replicate the behavior of the present-day technological and economic systems and to understand the implications of technology policy levers (Saeed and Prankprakma, 1997).

We have in this chapter extended Saeed's model to endogenize public infrastructure provision. Experimentation with this extended model shows that many proposed and implemented policies related to infrastructure – for example, stepping up infrastructure investment, developing infrastructure for the poor, and reducing delays in infrastructure provision – are not effective in alleviating income disparities if they are implemented alone. However, both an increasing income level of households and an increasing rate of economic growth can be obtained when especially targeted infrastructure policies are implemented together with a critical income distribution policy suggested by Saeed (1980, 1994), namely taxation of unearned income. The way infrastructure policies are targeted may, however, dilute or enhance the effect of the impact of such a taxation policy.

A system dynamics model of public provision of infrastructure in a dual economy

The information structure of the model of this chapter is adapted from Saeed (1980). Saeed's original model draws on neoclassical economics to construct a basic economic growth and market-clearing system; he modifies this system by relaxing its simplifying assumptions about aggregation of sub-economies, saving and investment behavior, ownership of production resources, financial markets and wage determination. His model subsumes the concept of economic dualism first recognized by Boeke (1953) and developed further by Lewis (1954), Sen (1966), Bardhan (1973) and others to represent the multiple sub-economies coexisting in developing countries. In such a dual economic system two sub-economies function side by side: a capitalist sector operating on the premises of profit maximization, and a self-employed sector attempting to maximize consumption for the labor it internalizes. The two sectors interact with each other as they bid for the resources of the economy. However, the surplus labor not hired by the capitalist sector is accommodated in the self-employed sector, while surplus production resources (such as capital and land) not employed by the capitalist sector are rented out to the self-employed sector. Saeed's original model incorporated the following behavioral assumptions governing the roles of its actors:

1. Both capitalist and self-employed sectors of the economy carry out production using capital, workers and land – land being a proxy for physical land area, mineral resources and environmental capacity. Investment in capital and land is driven by their profitabilities, which are given by their respective marginal revenue products and marginal factor costs determined by interest rate. Investment is, however, constrained by the financial capacity of a sector. Land is fixed. Both land and capital can be freely bought, sold or rented.
2. The changes in the quantities of the production factors owned or employed by each sector are governed by the decisions of the suppliers of the production factors acting rationally according to their respective motivations – the capitalist sector striving to maximize profit, the self-employed sector striving to maximize consumption for its members.
3. Workers can be wage-earners or self-employed. Wage-earning workers are hired on the basis of their marginal revenue product compared with their average wage. Workers unable to find employment in the capitalist sector

are absorbed in the self-employed sector. Both wage and self-employed workers constitute worker households, whose average consumption represents the opportunity cost of leaving any form of employment.
4. The average wage rate is set not according to the average marginal revenue product of workers as postulated in the equilibrium models of economic growth, but according to the bargaining power of the workers, which depends on the opportunity cost of leaving any form of employment (Sen, 1966; Sraffa, 1960).

In the absence of an explicit infrastructure supply process, Saeed's original model assumed by default that infrastructure supply is infinitely elastic; hence infrastructure could not be factored in as a policy lever. In the extended model, we provide policy space to control the magnitude, the supply delay, the mix and the targeting of infrastructure, so these attributes could be tested for their implications in meeting objectives of growth and equity laid out in the original model. The model of this chapter further incorporates the structure representing government provision of economic infrastructure through taxation.

We have added three sub-sectors to Saeed's original model: (1) development of infrastructure for facilitating production (irrigation, electricity, communication networks and so on); (2) development of transportation infrastructure that mainly facilitates growth in distribution and sales; and (3) allocation of resources by the government to its service functions and infrastructure development. This allows public provision of infrastructure to be determined by the government on the basis of infrastructure productivity and the financial capacity of the government. The revised model tracks the decisions of the government concerning infrastructure provision and its impact on the allocation of production resources in the economy, economic growth and income distribution. Figures 14.1, 14.2 and 14.3 illustrate the overall structure of the revised model, our additions mainly appearing in Figure 14.3.

Figure 14.1 shows how land, workers and capital might potentially be retained and employed by the two sectors in the model. Rectangles represent stocks, valve symbols flows and circles intermediate computations following the diagramming convention of system dynamics modeling. The size of each sector is not specified and is determined endogenously depending on goals created by the dynamic interaction between the two sectors as also assumed in Saeed's original model.

Figure 14.2 illustrates how income is disbursed to the two sectors and applied to consumption, saving and internal finance of investments. Capitalist income share consists of revenue from its production and rents less the wages paid out. Worker income share consists of revenues from self-

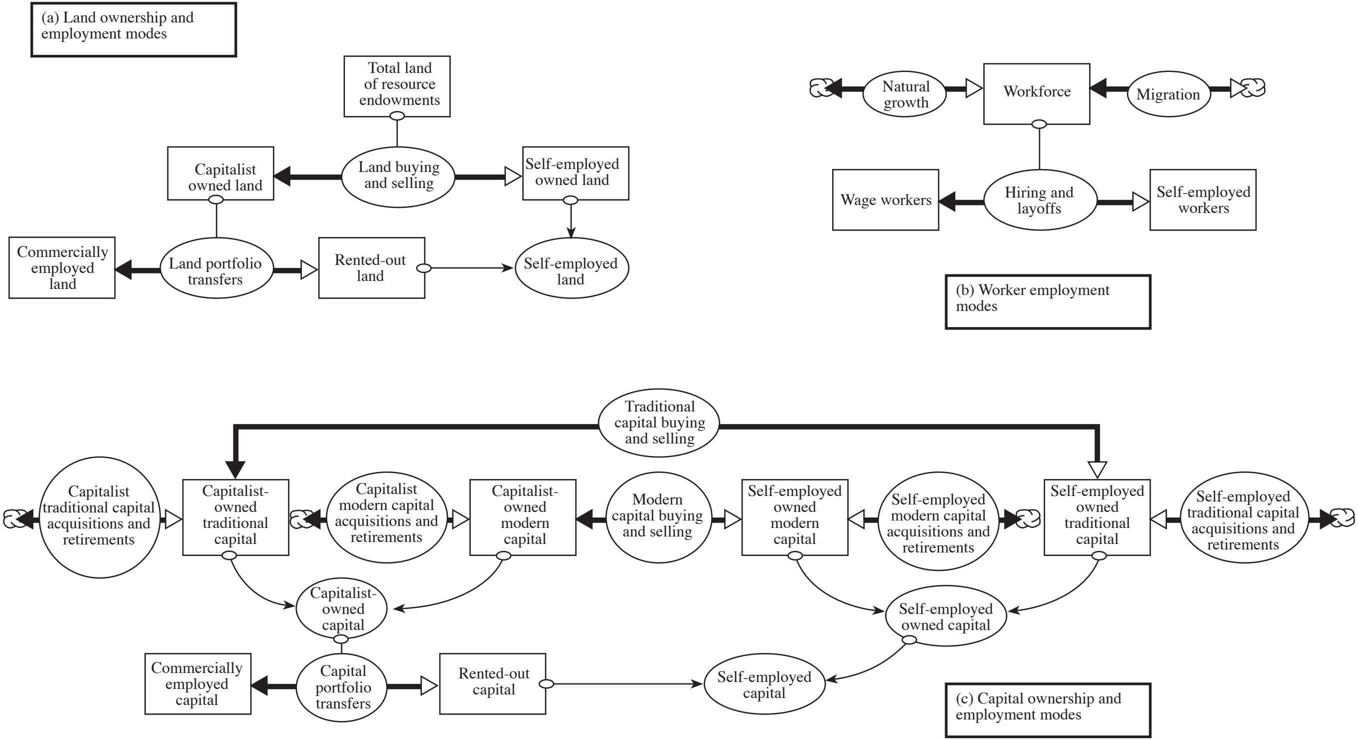


Figure 14.1 Allocation of production resources in a dual economic system

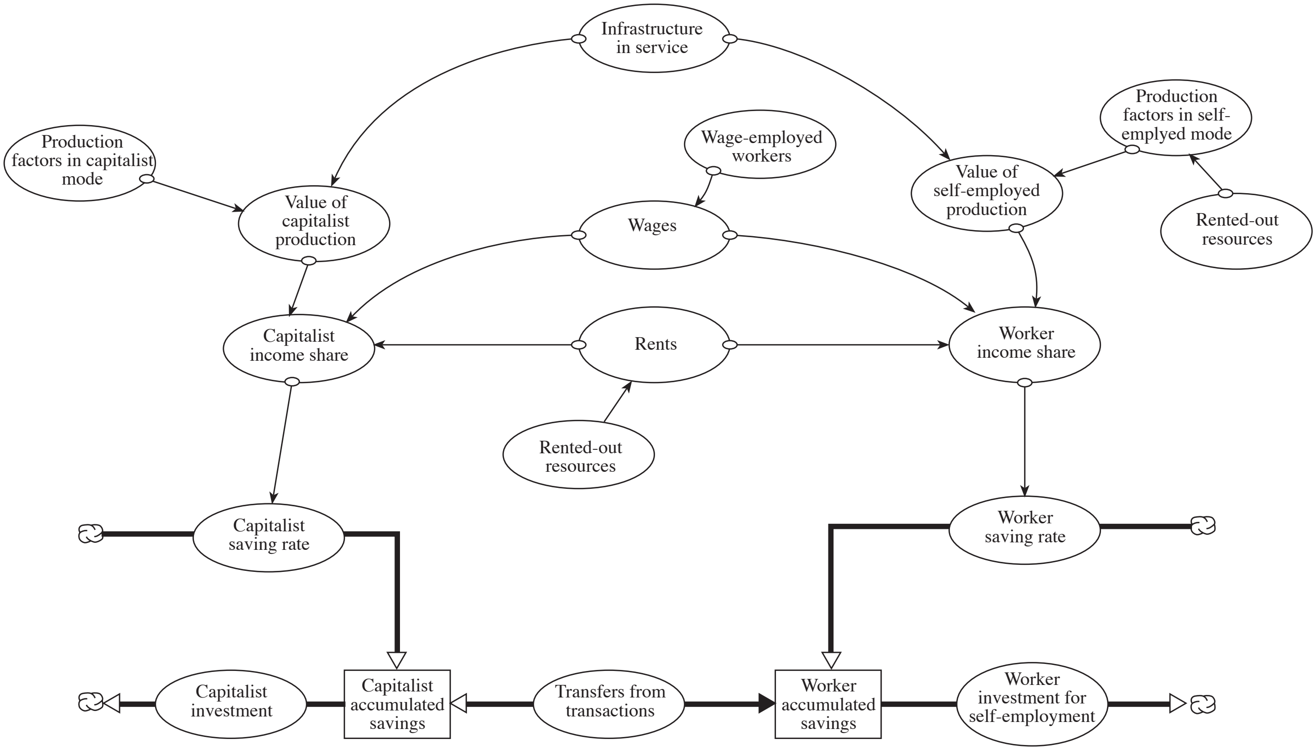


Figure 14.2 Disbursement of income in a dualist economic system

employed production and wages received less rents paid out, meaning that, as households, all workers are a homogeneous community comprising the majority of the households, whether wage-employed or self-employed. The saving propensity is assumed not to be uniform in the capitalist and worker households. The saving rate of capitalist households is assumed to be stable, while the saving propensity of the worker households depends on their need to save to support investment for self-employment and on how their absolute level of income compares with their inflexible consumption.

Infrastructure factors in to determining production in addition to land, labor and capital as a departure from Saeed's original model that considers only the latter three factors. As suggested by Biehl (1986) and Nadiri and Mamuneas (1994), the stock of public capital must be adjusted by an appropriate index to demonstrate the degree of their usage by the producers. In the model, the impacts of infrastructure on production are determined by the infrastructure service levels and not by the infrastructure stocks *per se*. The production infrastructure service level is the accessible production infrastructure facility per unit of land (or natural resources processed). The transportation service level depends on the market accessibility represented by transportation capacity per unit of demand for tradable products as suggested by Liang (1981). Both production and transportation service levels in the capitalist and self-employed sectors can be different and are controlled in the model by the respective accessibility parameters, which are exogenously specified to represent the various policy options considered.

Literature has well documented the differences in the accessibility to the infrastructure service for the formal and informal sectors. A higher accessibility to the infrastructure service is reported in the formal sector than in the informal sector (Hirschman, 1958; Samuel, 1991; World Bank, 1996). In the model a high production infrastructure service level yields a higher productivity for production resources, meaning a greater added value on resource inputs in an industrial context. A high transportation service level has an impact on the preference for tradable goods production and improves the marketability of tradable goods which, in turn, impacts on the total demand and sales in the two sectors, as pointed out by World Bank (1994) and FAO (1996).

Figure 14.3 illustrates how government allocates its revenue to its various service functions, including the development of infrastructure facilities delivering transportation and production and expenditure on other services it provides.

The government collects taxes and makes decisions to allocate its revenues to public expenditure. The government is the only provider of the infrastructure services in the model, which it finances through general tax collection; however, this assumption does not strictly exclude the building of

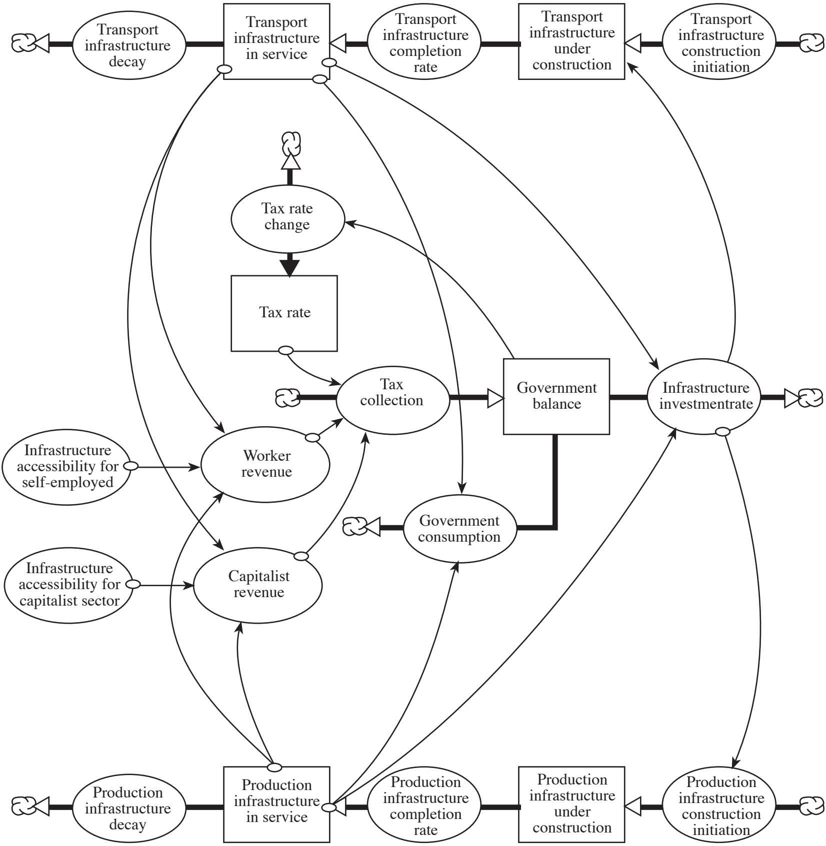


Figure 14.3 Taxation and allocation of government revenues to infrastructure investment and other expenditure

infrastructure by the private sector when infrastructure usage fees are seen as taxes. Indeed, Munnell (1992) points out that the price of infrastructure consumption is the tax rate, and Musgrave and Musgrave (1976) suggest that even though money to cover cost can be borrowed from banks, the payback would still be realized through taxation. Public infrastructure provision only means that the public sector makes the taxation and investment decisions, provides the resources for infrastructure building, or allows a price to be charged for the privately delivered infrastructure services which covers both public and private modes of infrastructure services delivery.

The model also assumes that the financial resources allocated by the government to infrastructure building must compete against those consumed for other government services delivery, transferred out of the economy through inter-sector exchanges and out of the country through international trade or used up for external defense and overcoming internal strife. The financial resources consumed for government services delivery are linked to the number of infrastructure projects and the stock of infrastructure in service as suggested by Hirschman (1958, 1967) and UNPAD (1977). The volume of infrastructure provided is determined by the financial capacity of the government, infrastructure resources demanded to finance ongoing projects and the economic returns on infrastructure. The fraction of resources transferred away from the system is a fixed fraction. The literature on the determination of infrastructure resource allocation is quite fragmented. The determination of the volume of infrastructure construction by the financial capacity of the government is supported by the work of Dudley and Montmarquette (1992), Musgrave and Musgrave (1976), and Raj (1993). These authors also point out that whenever the government is facing a financial shortage, infrastructure investment is the first expenditure to be cut. The process of allocation of infrastructure investment to finance ongoing projects is supported by the work of Hirschman (1958), UNPAD (1977), Garn and Fosler (1987) and Mashaiyekhi (1996). Allocation based on the economic returns on infrastructure is supported by the work of Simon (1975), Glover and Simon (1975), Frederiksen and Looney (1980), Frederiksen (1981), Kikuchi and Hayami (1979) and Clements (1995).

There are two categories of infrastructure facilities in the model: production infrastructure and transportation infrastructure. The allocation of infrastructure resources between the two portfolios is assumed to be based on their respective productivities and demand to finance the ongoing projects. The infrastructure sector of the model also takes into consideration the long supply chain for infrastructure planning, design and construction before it becomes available for use. This long delay, which is embodied in the supply chain of infrastructure, has been recognized by many researchers (Hirschman, 1958; Biehl, 1986). The infrastructure project start-up rates for planning are determined by the availability of infrastructure resources and the productivity of infrastructure. Infrastructure project startup rates for construction are also affected by the availability of infrastructure resources. The infrastructure project completion rates are determined by the available infrastructure resources and the unit costs of infrastructure facilities. The model endogenously determines the unit costs of infrastructure facilities. They are increased by resource scarcity, due to the creation of bottlenecks and delays, and reduced by the economy of scale (World Bank, 1994; Hirschman, 1958; Mashaiyekhi, 1996).

Simulation experiments to test model behavior against historical experience
Four simulation experiments were conducted to test the model behavior against historical experience. Each experiment was run for a simulation length of 120 years so that a new equilibrium appears, although the tendency towards an expected equilibrium is evident by about the fiftieth year. The results of these experiments are summarized in Figure 14.4.

The first experiment represented in the plot of Figure 14.4(a) is replicated from Saeed (1994) as a starting point for further analysis. In his original model, Saeed conducted this experiment to explain how a feudal economic pattern emerges in the absence of technological differentiation between the two sectors when the simplifying assumptions of an aggregate neoclassical system are relaxed. Saeed's model showed that resources get concentrated in an absentee ownership mode, creating the occurrence of what has been described in the literature as feudalism. The implicit assumption about infrastructure in this experiment is that its supply is completely elastic.

The second experiment represented in the plot of Figure 14.4(b) repeats the first experiment with the extended model imposing restrictions on infrastructure supply depending on government's financial capacity and infrastructure productivity. The behavior in this experiment is more or less similar to the first experiment except that there is a slight falling off in output due to the limitations of the infrastructure supply.

The third experiment represented in Figure 14.4(c) assumes that the access to infrastructure for the producers in the two sectors is different – the self-employed sector having limited access. This unequal access arises out of the technological differences between the two sectors – as is often the case in reality. This experiment shows that production in the capitalist sector increases while production in the self-employed sector decreases until the two sectors have comparable capital productivities. This creates side-by-side existence of both capitalist and self-employed production modes, which is a pervasive experience and well documented in the literature (Kikuchi and Hayami, 1979; Akino, 1979).

The fourth experiment represented in Figure 14.4(d) assumes a further technological differentiation created between the two sectors by making modern capital available to the capitalist sector and maintaining the assumption of differentiation in the accessibility to infrastructure between the two sectors. This is the background against which many development policies have been implemented. Due to the combined influence of differentiation in capital and infrastructure access, the capitalist sector production gets a further impetus, reinforcing the dual economic structure, but with a larger role for its production than in the third experiment.

These experiments lead to the conclusion that a dualist economy is created when the production in the self-employed sector is constrained due to its limited access to infrastructure as well as to modern capital. The former policy is a manifestation of capital formation in the public sector that mostly supports the large-scale capitalist production mode, while the latter arises from the promotion of capital formation in the private sector also mainly supporting the large-scale capitalist production mode. Both these policies have formed an important part of the developmental agenda in the developing countries over the past half-century. Indeed, the pervasive duality experienced in the developing countries is most likely a manifestation of those two policies. The technological differentiation between large-scale capitalist production and small-scale self-employed production created by international technology transfer efforts has further exacerbated this duality (Saeed and Prankprakma, 1997).

Infrastructure provision as a policy lever for economic development

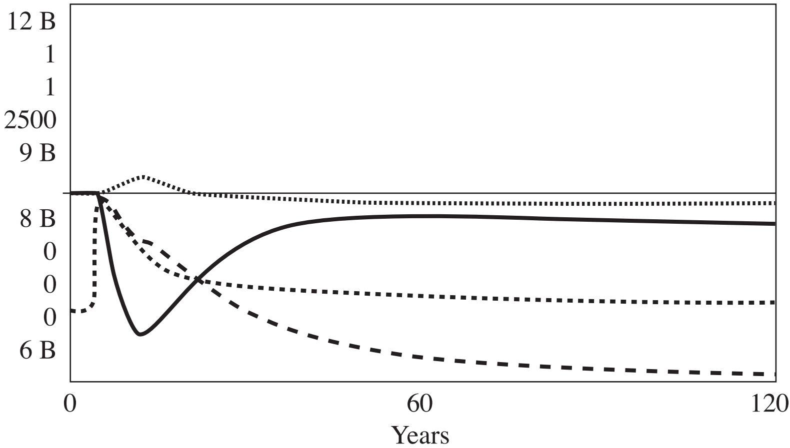
The experiments in this section of the chapter attempt to understand the variability of performance of selected development policies, including public infrastructure provision, and also to identify guidelines for an effective infrastructure strategy that could serve as an alternative policy lever for economic development. The policies selected for the experiments are based on two considerations:

1. The promise of infrastructure provision as a policy lever should be investigated against the backdrop of the dual economic system to understand its performance and ways found to increase its effectiveness.
2. The performance of the widely implemented and proposed development policies should be understood with realistic infrastructure constraints added.

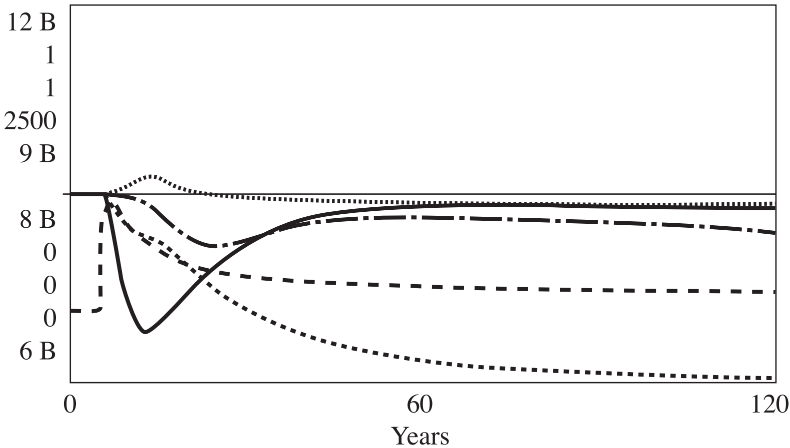
Two experiments were conducted to address the first consideration. These explored the explicit infrastructure polices suggested by researchers or used by the infrastructure policy decision-makers. They included increasing allocation of funds to upgrade infrastructure (Hirschman, 1967; Hansen, 1955) and improving infrastructure services for the poor (World Bank, 1994, 1996; Besley and Kanbur, 1993).

Additionally, three policies were selected for experimentation with our extended model to address the second consideration. These included building financial institutions to improve the working of the financial markets, organization of the self-employed sector into cooperatives to increase the scale of their operations so they become competitive with the capitalist sector firms in terms of access to infrastructure and technology, and taxation of unearned income that should discourage absentee ownership of production resources. The last policy was proposed as a critical instrument to redistribute income by Saeed (1980, 1994), while the first two were suggested

(a) Creation of feudalism without modern capital and with completely elastic infrastructure



(b) Creation of feudalism without modern capital and with elastic infrastructure



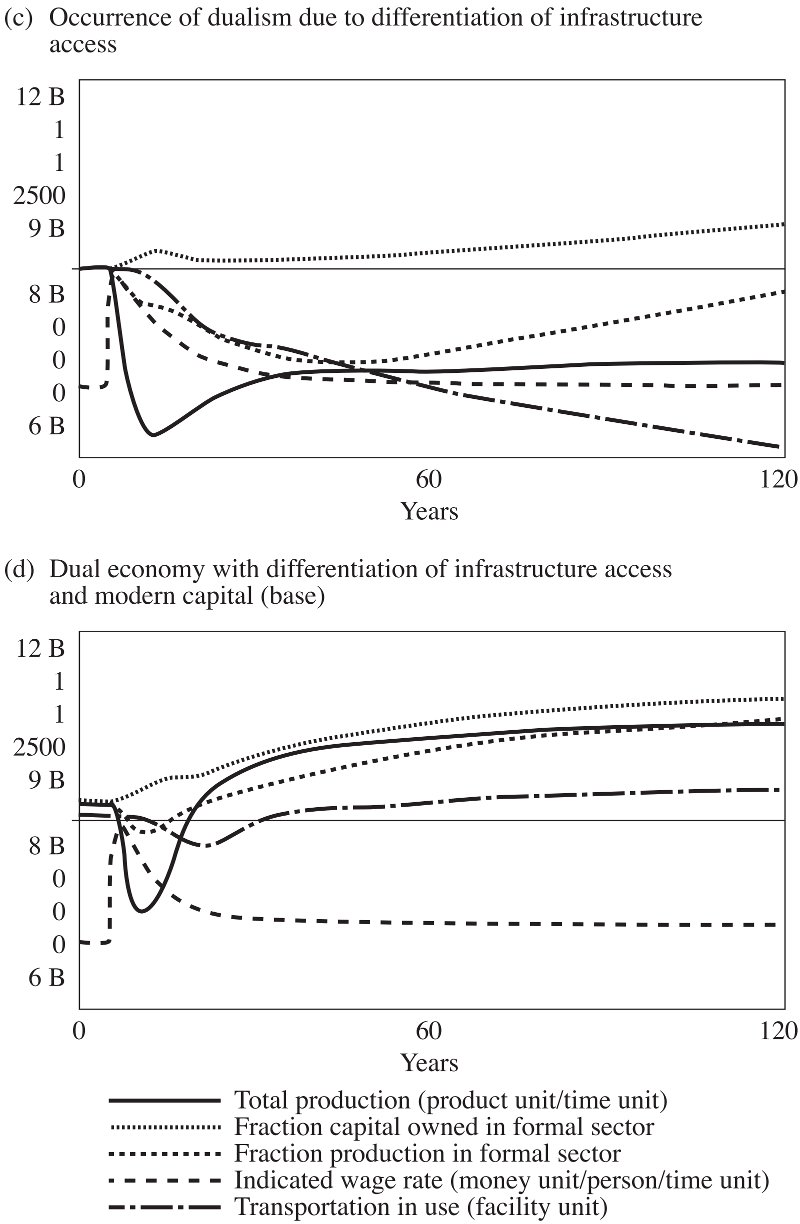


Figure 14.4 *Simulation experiments showing creation of dualist scenarios and the effect of infrastructure access on the dualist structure*

as facilitators. The facilitators were found by Saeed to be effective only when the critical policy, that is, taxation of unearned income, was in place. This was seen to be true also in the case of our extended model.

The efficacy of each policy tested was evaluated by comparing the new simulation patterns in the policy experiments with those of experiment 4 designated as the base run. Table 14.2 summarizes the criteria for the evaluation of policies. The policy tests conducted are discussed below in three groups: (a) individual policy instruments; (b) policy combinations incorporating increased investment in infrastructure building; and (c) policy combinations without incorporating increased investment in infrastructure building. Finally, we recapitulate what is learnt from policy experimentation.

Table 14.2 Indicators for policy evaluation

Indicators	Meaning
Total production	**Economic growth**
Production in the capitalist sector	Economic growth and sector contribution
Production in the self-employed sector	Economic growth and sector contribution
Fractional revenue share of the capitalist sector	Income distribution
Capital owned by the capitalist sector	Wealth distribution, asset ownership
Rent payment as a fraction of revenue in the self-employed sector	Value transfer from the self-employed sector to the capitalist sector
Average wage rate	Median household income level
Capital–worker ratio in the self-employed sector	Productivity in self-employment sector
Production infrastructure facility level	Access to production infrastructure provision
Transportation facility level	Access to transport infrastructure provision

(a) Individual policy instruments

With the base run as an ambient condition, individual policies to be tested were implemented at time 120 when the model reached a new equilibrium with its base run assumptions. Table 14.3 summarizes performance of the individual policies tested.

Table 14.3 Performance of individual policy instruments

Normalized value of end points Simulation run	Total production	Production in capitalist sector	Production in self-employed sector	Fraction revenue to capitalist sector	Capital owned by capitalist sector	Rent burden of self-employed sector	Capital–worker ratio, capitalist sector	Average wage rate	Production infra-structure facility level	Transport-ation facility level
Base run	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 Increase infrastructure investment	1.05	0.76	1.85	0.92	1.00	4.41	1.26	1.43	1.20	1.39
2 Build infrastructure for self-employed sector	1.02	0.83	1.53	0.98	1.06	3.38	0.99	1.02	1.00	1.00
3 Organize cooperatives for self-employed sector	1.00	0.91	1.24	0.99	1.16	1.90	0.98	0.98	0.99	0.98
4 Develop financial institutions	1.00	0.99	1.01	0.99	0.99	0.94	1.00	1.00	1.00	1.00
5(a) Tax unearned income but unequal access to infrastructure	0.97	0.87	1.26	0.84	0.78	0.00	1.10	1.09	0.98	0.96
5(b) Tax unearned income but equal access to infrastructure	1.00	0.54	2.25	0.51	0.54	0.17	1.59	1.51	1.04	1.07

Policy 1: Increasing infrastructure investment Over the past half-century, many countries have attempted to step up infrastructure investment to facilitate economic growth. As seen in policy run 1 recorded in Table 14.3, this policy leads to an increase in output, with average wage rate rising to a higher level than in the base run. Yet it does not change the wealth distribution and the share of revenue in the capitalist sector representing inequality in income distribution. Towards the end of the simulation run, the shares of revenue and capital owned by the capitalist sector reach new equilibria slightly lower than the base run, however, rent payments from the self-employed sector to the capitalist sector rise to a much higher level than the base run. These changes are explained as follows.

When infrastructure investment is stepped up, the total demand for products increases while the infrastructure facilities in service increase after a certain delay. Fueled by demand and increased infrastructure availability, production in the self-employed sector increases. Hence the average consumption expenditure per worker rises. Production and revenue in the capitalist sector also increase because of better infrastructure access; therefore, the marginal revenue product of workers in this sector also rises. However, since the average consumption expenditure of workers includes entitlements both from value additions through labor and capital, the market wage rate exceeds the marginal revenue product of workers in the capitalist sector. Thus the profitability of production in the capitalist sector declines. Consequently, the capitalist sector begins to lay off workers, who enter the self-employed sector. The capitalist sector also begins to sell or rent out its capital to the self-employed sector. The demand for capital in the self-employed sector remains high because of the crowding of workers in it and the growth in demand for products. The financial capacity of the self-employed sector improves initially and it is able to acquire more capital. However, as more and more workers are laid off by the capitalist sector and accommodated in the self-employed sector, the financial capacity of the latter worsens rapidly, constraining its ability to continue to invest. The rising demand for capital in the self-employed sector is met, however, through renting; hence the total rent payments to the capitalist sector from self-employed sector rise rapidly. Hence, due to the capitalist sector's ability to transfer resources from the production to the renting portfolio, the capital owned by the capitalist sector is only slightly lower towards the end of the simulation compared with the base run.

Policy 2: Building infrastructure to serve the self-employed sector Although there are many technical difficulties in the design of infrastructure for the poor, the model assumes that these difficulties can be overcome so both sectors can have equal access to infrastructure facilities. When the model is simulated with this additional assumption, capital acquisitions by capitalist sector slow down relative to the base run (Table 14.3). The share of capital assets owned by the capitalist sector and its revenue share reach new equilibria, which are slightly lower than in the base run. However, capital owned by the capitalist sector still increases after the implementation of the policy as the rent payments received by it rise to a level higher than in the base run.

It is interesting to compare this run with the previous policy run. In this run, production in the self-employed sector rises at a faster rate than in the previous run since this sector is able to utilize infrastructure services more effectively. The average consumption expenditure per worker in the self-employed sector also rises more rapidly at the beginning of the policy implementation. However, since the wage demanded rises faster than in the last case, the capitalist sector also shifts financial resources more rapidly from production to renting. Therefore, workers laid off by the capitalist sector crowd into the self-employed sector faster. It follows that the policy of unequal access to infrastructure is more effective in helping income redistribution than equal access when the self-employed sector is financially constrained while the capitalist sector is free to shift its resources from production to renting.

Policy 3: Organizing cooperatives for the self-employed sector The policy of organizing the self-employed sector into cooperatives allows this sector to compete favorably with the capitalist sector for modern capital, which allows it to expand production. As the demand for capital for production in the self-employed sector rises, rents are bid up and the capitalist sector begins to transfer these resources from production to renting. The share of capital assets owned by the capitalist sector and the revenue share of the capitalist sector reach new equilibria slightly lower than the base run, but still higher than the policy starting point. Although a substantial part of production shifts to the self-employed sector, resource ownership is still concentrated in the capitalist sector.

There are many similarities between policy runs 3 and 2. Both the policy of forming cooperatives, which equalizes access to modern private capital, and the policy of equalizing access to infrastructure are intended to improve the production conditions for the self-employed sector. The cooperatives policy operates through the market mechanism, while the policy of improving access to infrastructure operates through the expenditure policy of the government. In both cases, production in the self-employed sector increases but its asset ownership and revenue share are not improved very much, while the total rent payments from the self-employed sector to the capitalist sector rise.

The cooperatives policy creates a low efficiency for the following reasons: labor-saving modern capital is not as effective in the self-employed sector as in the capitalist sector when an influx of surplus workers laid off by the capitalist sector increases labor intensity in it, and production in the self-employed sector is constrained by the low infrastructure service level even when it is able to acquire modern capital.

Policies 1, 2 and 3 are all effective in promoting economic growth through the promotion of production in the self-employed sector. However, they all fail to change the asset ownership pattern and revenue shares of the capitalist and the self-employed sectors. All three policies lead to increased rent payments from the self-employed sector to the capitalist sector, which constrains the former's investment ability.

Policy 4: Developing financial institutions Developing financial institutions so that both sectors are able to get equal access to finance reduces the dependence of investment on internal savings economy-wide. When this policy is implemented in the model, capital ownership by the self-employed sector rises slightly, while that by the capitalist sector shows a slight decline.

There are two reasons for the ineffectiveness of the financial policy. First, when this policy is implemented, the capitalist sector increases its bids for capital for production since it can achieve a higher efficiency due to its better access to modern capital and infrastructure. The profitability of production in the self-employed sector, however, remains low due to the low productivity of the traditional capital and the limited access to infrastructure service. Hence its intrinsic demand for resource acquisition is also low and improving its financial capacity does not help.

Policy 5: Taxation of unearned income Experimenting with his original model, Saeed (1980, 1994) found that a fiscal policy to levy a tax on unearned income accrued in the form of rents on absentee-owned capital is a critical policy for changing income distribution patterns. A rent income tax depresses renting activity, hence the capitalist sector has either to transfer the rented capital to production or sell their resources to the self-employed sector. When there is no capital differentiation between the sectors, the capitalist sector tends to sell a greater share of its resources to the self-employed sector. Therefore, asset ownership and income distribution are improved. However, with capital differentiation, capitalist production appears as an alternative to renting, which limits the transfer of resources to the self-employed sector.

An unearned income tax is simulated in our modified model by deducting a tax equal to 20 percent of the rent income at time 120. Surprisingly, this policy is not very effective in changing income distribution, while it also slightly reduces output for three reasons: financial constraints slow down the acquisition of capital resources by the self-employed sector. Production efficiency is lower in self-employed sector; and low accessibility to infrastructure reduces production efficiency in the self-employed sector. Since this experiment is conducted with modern capital supply, it is difficult to understand whether the inability of fiscal policy to affect income distribution arises only from private capital differentiation between the two sectors or from public provision of infrastructure.

Therefore, a comparative policy analysis is conducted with the assumption of equal access to infrastructure in both sectors. This assumption is put into place at time 120 in addition to taxation of unearned income. In this comparative run, since the production of the self-employed sector is not especially constrained by infrastructure service compared with the capitalist sector, production and revenue received in the self-employed sector further rise. However, this also increases the bargaining power of the workers, which fuels the wage rate. Hence the profitability of the capitalist sector to produce is reduced and it lays off workers. Meanwhile, the demand for capital in the self-employed sector increases. However, since the tax on rent income has depressed renting, the capitalist sector is forced to sell its resources to the self-employed sector.

Thus income and asset distribution patterns change radically. It can be concluded that the policy to tax unearned income is effective in changing income distribution, provided it is not offset by compensating advantages available to the capitalist sector in terms of infrastructure access and modern capital.

(b) Policy combinations incorporating increased investment in infrastructure building

Many infrastructure researchers and policy-makers have recognized that individual policies are not effective, hence combinations of policies are often suggested. These combinations typically include instruments targeting the poor, improving market functions, taxation and expenditure. Unfortunately, such policy combinations fail to recognize the dynamic changes in the role of renting in a dual economic system, and their efficacy is low, which is borne out by our experiments discussed below and summarized in Table 14.4.

Policy combination 1: Increasing infrastructure investment and developing infrastructure services for the self-employed sector This policy combination aims at directing government expenditure to infrastructure building and designing infrastructure facilities so that equal access is obtained by the two sectors. The model behavior under this policy combination is similar

Table 14.4 Performance of policy combinations incorporating increased allocation of funds to infrastructure building

Normalized value of end points Simulation run	Total production	Production in capitalist sector	Production in self-employed sector	Fraction revenue to capitalist sector	Capital owned by capitalist sector	Rent burden of self-employed sector	Capital–worker ratio, capitalist sector	Average wage rate	Production infra-structure facility level	Transport-ation facility level
Base run	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 Increase infrastructure investment + develop infrastructure services for self-employed sector	1.00	0.54	2.25	0.51	0.54	0.17	1.59	1.51	1.04	1.07
2 Increase infrastructure investment + develop financial institutions	1.10	0.60	2.44	0.93	1.19	8.52	1.26	1.53	1.22	1.44
3 Increase infrastructure investment + tax unearned income	1.05	0.75	1.86	0.9	1.14	4.02	1.26	1.43	1.19	1.38
4 Increase infrastructure investment + develop infrastructure services for self-employed sector + tax unearned income	1.00	0.67	1.9	0.6	0.71	0.22	1.57	1.67	1.17	1.34
5 Increase infrastructure investment + tax unearned income + develop financial institutions	1.04	0.52	2.43	0.48	0.51	0.56	1.61	1.98	1.20	1.40
6 Increase infrastructure services + Tax unearned income + develop financial institutions + organize cooperatives + develop infrastructure services for self-employed sector	1.01	0.66	1.94	0.59	0.70	0.18	1.56	1.65	1.17	1.34

to policy 1 in Table 14.3. However, compared with the base run, policy 1 and policy 2, the overall output increases to a higher level, yet this policy combination has little effect on average wage rate and asset ownership. Production in the self-employed sector increases greatly and production in the capitalist sector declines while the average wage rate rises to a higher level. However, the share of revenue received in the self-employed sector rises only slightly compared with the base run and stays at the same level as the policy starting point since rent payments from the self-employed sector to the capitalist sector increase sharply.

Policy combination 2: Increasing infrastructure investment and developing financial institutions The simulation of individual policy 1 demonstrates that financial constraints are one of the limiting factors for the self-employed sector to acquire capital when the capitalist sector decides to review its asset ownership upon recognizing an increase in government investment in infrastructure building. Therefore, this policy combination proposes that when infrastructure investment is stepped up, a financial policy to improve the financial capacity of the self-employed sector should be implemented simultaneously so both sectors have equal access to finance.

When this policy combination is implemented, more resources are invested for infrastructure building and the production and revenue of the self-employed sector increase. The average wage rate also increases; hence profitability of production in the capitalist sector declines. The capitalist sector begins to lay off workers, who then enter the self-employed sector. The capitalist sector also begins to sell or rent out capital formerly employed in production. The improved financial capacity in the self-employed sector allows it to acquire some of the capital, which lowers rent payments to the capitalist sector. Therefore, revenue received by the self-employed sector increases. The wage rate further increases. Yet, as more workers are laid off and the financial capacity of the self-employed sector worsens, the capacity of the self-employed sector to acquire capital is reduced. Toward the end of the simulation run, there is little change in the capital ownership pattern.

Policy combination 3: Increasing infrastructure investment and taxation of unearned income From previous individual policy analysis, it is clear that when renting is an important economic activity in a dualistic economy, taxation of unearned income is an effective tool to radically change the income distribution pattern. This policy combination implies that when infrastructure investment is stepped up and the self-employed sector has a chance to increase its production, unearned income is simultaneously taxed to enable the self-employed sector to acquire vacated production resources during the course of the development effort. This policy effectively suppresses the renting activity and radically changes the income distribution pattern. After implementing this policy combination, not only is the formerly rented capital gradually transferred to the self-employed sector but also the capitalist sector begins to sell its commercially employed assets to the self-employed sector when the average wage rate rises due to an improved wage bargaining position created by the growth in self-employment. Yet when this policy is implemented, the total output does not increase as much as when infrastructure investment is stepped up alone, which can be attributed to the sub-optimal allocation of production factors over the course of change.

Policy combination 4: Increasing infrastructure investment, developing infrastructure services for the self-employed sector and taxation of unearned income This combination yields drastic changes in the asset ownership pattern. Rent payments are reduced as more production is shifted to the self-employed sector. The share of revenue of the self-employed sector in the economy rises as average household consumption increases. The average wage rate also rises to a higher level compared with policy combination 3. However, compared with the policy combination 1, total production is lower since the resource reallocation process created by the taxation policy yields sub-optimal allocation efficiency as in case of policy combination 3.

Policy combination 5: Increasing infrastructure investment, developing financial institutions and taxation of unearned income This policy combination attempts to reduce the inefficiencies created by resource reallocation arising from taxation of unearned income. Developing financial institutions simultaneously with the taxation of unearned income enables the self-employed sector to bid for the formerly rented capital. Simulation of this policy combination returns a pattern more or less similar to policy combination 3, with a slight improvement in the total output, asset ownership and a reduction in rent payments to the capitalist sector.

This policy combination is not as effective as policy combination 4, which targets the improvement of the production potential of the self-employed sector through increasing its access to the infrastructure services, making it more competitive with the capitalist sector.

Policy combination 6: Increasing infrastructure investment, developing financial institutions, developing infrastructure services for the self-employed sector, organizing cooperatives and taxing unearned income This policy combination is aimed at allowing the self-employed sector an equal opportunity to expand production with its own resources and thereby accruing benefit when more public resources are invested in infrastructure.

The increase of investment in infrastructure with equal access to service for both sectors stimulates production and hence the desire to expand capital. The development of financial institutions empowers the self-employed sector to acquire capital when it expands production. The cooperatives policy enables the self-employed sector to increase its productivity and its capacity to compete favorably with the capitalist sector. Simulation of this policy combination shows that the patterns created are similar to those with policy combination 4; however, a higher level of economic growth and a better income distribution is achieved. Taxation of unearned income alleviates the tendency for the wealth to accumulate in the capitalist sector, while the financial policy improves the reallocation efficiency. When the production in the self-employed sector expands, a higher level of infrastructure service and access to modern technology sustains economic growth in that sector while it also contributes to the overall growth of the economy.

(c) Alternative policy combinations without increasing infrastructure investment

Increasing infrastructure investment is sometimes difficult and involves a long time delay. A policy combination without increased infrastructure investment can interestingly also achieve the developmental goals of growth and equity. Both organization of cooperatives and creating equal access to infrastructure services can promote production in the self-employed sector. When either of these policies is implemented together with the implementation of taxation of unearned income, the growth and distribution patterns obtained are almost as good as those with increased infrastructure investment. If financial institutions are also developed, resource reallocation transactions are further improved, which further improves overall growth rates. Four additional experiments are recorded in Table 14.5 to explore policy combinations not involving stepping up infrastructure investment.

The first of these (policy combination 7) includes directing existing infrastructure services to the self-employed sector together with developing financial institutions and organizing cooperatives. Taxation of unearned income is excluded. The simulation results show that total production increases but it is mainly carried out in the self-employed sector. However, the average wage rate, capital owned by the self-employed sector and the revenue share of the self-employed sector do not increase, since the economic benefit from increased production in the self-employed sector is transferred to the capitalist sector through rent payments.

Policy combination 8 includes taxation of unearned income and developing infrastructure structure services for the self-employed.

Table 14.5 Performance of alternative policy combinations without increasing infrastructure investment

Normalized value of end points Simulation run	Total production	Production in capitalist sector	Production in self-employed sector	Fraction revenue to capitalist sector	Capital owned by capitalist sector	Rent burden of self-employed sector	Capital–worker ratio, capitalist sector	Average wage rate	Production infra-structure facility level	Transport-ation facility level
Base run	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7 Develop financial institutions + develop infrastructure services for self-employed + organize cooperatives for self-employed	1.02	0.67	1.95	0.94	0.97	5.28	0.98	1.01	0.99	0.98
8 Tax unearned income + develop infrastructure services for self-employed sector	0.98	0.66	1.86	0.63	0.67	0.06	1.16	1.23	0.98	0.97
9 Tax unearned income + develop infrastructure services for self-employed sector + develop financial institutions	0.99	0.66	1.86	0.63	0.67	0.05	1.15	1.23	0.98	0.97
10 Tax unearned income + develop infrastructure services for self-employed sector + develop financial institutions + organize cooperatives for self-employed	0.98	0.38	2.59	0.44	0.49	0.52	1.15	1.26	0.96	0.92

Policy combination 9 consists of taxing of unearned income, developing infrastructure services for the self-employed and developing financial institutions.

Policy combination 10 includes taxing unearned income, developing infrastructure services for self-employed sector, developing financial institutions and organizing cooperatives for self-employed sector.

The last three policy combinations lead to patterns of economic growth with radical changes in asset distribution and increasing wage rates (see Table 14.5). Comparing policy combinations 8 and 9, the development of financial institutions in policy combination 9 does not further change the capital ownership pattern since the self-employed sector has improved cash flow and can self-finance its investments if economically justified.

Compared with policy combinations 8 and 9, policy combination 10, which also enhances competitiveness of the self-employed sector, increases the production and revenue received in the self-employed sector at the fastest rate and to the highest level.

Recapitulation

Our experiments show that any single development policy targeting economic growth or income distribution either is ineffective or creates a problematic transition process. While there are many policy measures to promote economic growth, the taxation of unearned income is a critical instrument to change the income distribution pattern. The efficacy of this policy and the transition process created by it are, however, influenced by how infrastructure provision and modern capital provision are targeted. Comparing the policy combinations without and with stepping up infrastructure building, it seems that all policy combinations which increase infrastructure investment result in a higher output and a better income distribution.

Conclusion

Developing-country economies have been observed to incorporate two equally significant production modes: a profit-maximizing capitalist sector and a consumption-maximizing self-employed sector. Most development policies, especially those related to infrastructure, have not differentiated between the two production sectors; hence their performance has varied widely. This chapter has attempted to explore the efficacy of infrastructure policy for the developing countries, whose economies are pervasively dualist, by using a system dynamics model of economic growth, income distribution and public infrastructure provision based on an earlier model developed by Saeed (1994).

Experimentation with this model shows that public infrastructure provision can be a promising facilitating policy to achieve economic growth and income distribution when it is implemented in conjunction with other policies, especially with taxation of unearned income. A policy combination which relieves the financial and technological limitations of the self-employed sector through the establishment of cooperatives, allows equal access to infrastructure and discourages absentee ownership of production resources, gives the best performance in terms of meeting the development goals of growth and equity.

In the developing countries, government provision of infrastructure has been a traditional expenditure instrument to deliver public welfare, although the performance of this policy has shown a great deal of variability. This policy can still be effective when it is implemented with the other policy instruments indicated in this chapter. Since the developing countries often have limited policy levers to create economic growth and improve income distribution, the possibility of assuring the functionality of infrastructure policy offers a promising prospect.

An important focus of infrastructure policy over the past decade has been privatization. The authors posit that privatization of infrastructure delivery would do little to achieve the developmental objective of growth and improvement of income distribution, while it would create many organizational problems since private sector organizations are often not designed to deliver public goods.

Our conclusions and their policy implications can be extended to the various contexts of economic duality, for example, the capitalist and self-employed sectors with the agricultural and industrial economies, the agricultural and industrial sectors in a country, the economically growing and lagging areas in a region, and the industrialized and developing countries in the global economy. The underlying structure in other forms of duality is not fundamentally different from that elaborated in this chapter. In fact, Saeed and Prankprakma (1997) have used a variation of the model to explore technological policy options in the industrial sector in developing countries, while Saeed (1998) has considered the global economic structure as having the characteristics of a dual economy in which free movement of production factors and commodities might be poised to create global feudalism. Further exploration with the dualist structure may result in more insights.

Note

1. A trade mark of Vantana Systems, Inc., 149 Waverly Street, Belmont, MA 02178, USA.

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PART III

FUTURE DIRECTIONS

15 Future directions on sustainable development planning using DSS tools

M.A.B. Siddique and M.A. Quaddus

Introduction

With the publication of *The Limits to Growth* in 1972, *Our Common Future* in 1987, and *The Agenda 21* in 1993, model-based systems have continued to play an important role in sustainable development planning. However, very few attempts have been made in the past to publish a book containing articles in this increasingly important area. Although fragmented applications of these model-based systems in sustainable development planning have appeared in the literature, we strongly believe that many more have not been reported. This book is a modest attempt to publish the contributions from the scholars who have dedicated their research efforts to model-based systems in sustainable development planning.

Methodology

In our call for chapters on specified topics we went through various e-mail lists. Personal invitations were also sent to target authors. All the chapters received from the contributors were assessed by independent reviewers. Their reports were then sent to the authors to include changes on the basis of comments made by the assessors. The final versions of the chapters have been edited and included in this volume.

Research categories

The chapters thus compiled are classified under three main categories following the structure of the handbook. The first category examines the nature and the dimensions of sustainable development and model-based systems for sustainable development planning. The second category deals with the application of such systems in the following important areas: environmental management, mining, energy management, land and water management, agriculture, aquaculture and infrastructure. The current chapter summarizes and synthesizes all the previous chapters and discusses the emerging trends and challenges in using model-based systems in the decision-making process for sustainable development planning in the coming years.

Sustainable development and modelling for sustainable development planning

The four chapters in the first part of the book shed light on the current evolution of the notion of sustainability in general, and more specifically on the application of model-based systems in sustainable development planning. The debate, centring on the concept of sustainable development and different approaches to modelling sustainable development planning, highlights the fact that there is no single definition of sustainable development. Therefore it becomes very difficult to plan it without knowing what has to be sustained and how.

In Chapter 1, Quaddus and Siddique review how modelling and decision support activities have been applied in sustainable development planning. The review is based on published articles in the area in English-language journals, books, monograms, conference proceedings and so on. The authors review over 70 articles on sustainable development planning area, and only 19 are found to satisfy the requirements for modelling and decision support. This uncovers the fact that much remains to be done in the area. The authors prepare a table which shows, for each article, the research type, modelling type, extent of DSS, and brief outcomes. On modelling type, the authors conclude that most of the applications used quantitative modelling. On the extent of DSS use, about half the applications have used or suggested using DSS-type approach. This chapter highlights some gaps in future directions of modelling and DSS in sustainable development planning.

Moffatt (Chapter 2) defines sustainable development as the 'processes by which sound economic systems can operate well within the biophysical constraints of the ecosystem to provide a good quality of life that is socially just for current and future generations'. He argues that although there is no general agreement regarding how to make sustainable development operational, significant progress has been made in recent years by researchers in developing various models to plan for sustainable development with the aim of achieving it within certain restrictions. Policy-makers have also come forward to develop strategies to move societies into sustainable paths of development. Moffatt also applies the *dynamic hierarchical approach* (based on systems dynamics) in an attempt to model sustainable development using Scotland as an example.

In his provocative chapter on modelling long-term sustainability, Yamaguchi (Chapter 3) defines sustainability as the economic process of physical, social, and ecological reproduction. He then develops a *system dynamics model* of sustainability based on a simple macroeconomic growth model of five equations. He describes in detail different concepts that he finds essential to understand the system dynamics model. The notions of time, unitary value, model consistency, feedback loop, and steady state equilibrium are explained. Yamaguchi uses a four-step approach, adding new equations to the basic macroeconomic growth model. From this model, he develops a progressively more complex system dynamics model by including one by one the concepts of physical, social, and finally ecological reproducibility. At each level of the elaboration, the author draws some conclusions that help further development of the system dynamics model of sustainability.

From the basic macroeconomic growth model, Yamaguchi develops a physical reproducibility model. He adds the equations relating to capital depreciation, non-renewable resource depletion and raw material input to his basic model. He observes that there is a continuous depletion of non-renewable energies, even when a steady state equilibrium (a non-growing economy) is simulated. The author offers two solutions to counter such depletion: to invent an efficient use of non-renewable energy, and to discover or develop some substitutes. If those solutions are not found, two self-regulating forces will appear in the economy. The first is the regulation of non-renewable energies by increasing their price, and the second is the reduction of productivity when non-renewable energies start to be depleted. Unfortunately, feedback loops show that those two forces will act negatively on population growth. Social reproducibility will no longer be sustained. Hence Yamaguchi includes population growth in the model; a social reproducibility model is thus developed. He disagrees with the neoclassical view that social reproducibility is always maintained. Rather, he argues that social reproducibility needs to be related to non-renewable resources in order to have a realistic view of the problem. He states that depletion of non-renewable resources leads to an unavoidable 'economic trap'. Indeed, according to his model of physical reproducibility, the depletion of non-renewable resources implies a decrease in productivity, and accordingly a decrease in output. Yet, as non-renewable resources will continue to be depleted in the long term (in the absence of maintenance of physical reproducibility), social reproducibility conditions will also be violated. In order to avoid this, per capita consumption must be reduced. To maintain physical reproducibility as well, per capita consumption must be restricted to a level equal to per capita net output. Nevertheless, in the very long term, per capita consumption will decline to a level too low to maintain physical reproducibility. This will increase the death rate, and will therefore impede social reproducibility. To avoid the economic trap, Yamaguchi looks at substitutes to non-renewable resources. However, substitutes can at best postpone the economic trap to the twenty-second century. They cannot consequently enable achievement of long-term sustainability.

Finally, Yamaguchi further develops the system dynamics model towards a model of ecological reproducibility by adding seven new equations. He discovers two conditions for sustainable ecological reproducibility: the total amount of garbage, wastes and capital depreciation must be inferior to the earth's ecological dumping capacity to absorb and dissolve the sink; and those newly regenerated sources have to add a sufficient amount of renewable sources for continued production activities. With this new system dynamics model, Yamaguchi provides a simulation for sustainable growth. The results are that the three processes of reproducibility are interconnected in a negative way. If economic growth is sustained, a continuous ecological unsustainability will occur. It would be possible to restore ecological sustainability, but this will lead to unsustained social reproducibility. Ecological feedback loops may help to avoid the problems of over-accumulation of the sink and the depletion of resources. Yet a sustainable path over the twenty-second century seems almost impossible.

Based on the final system dynamics model that he develops, Yamaguchi claims that the system dynamics model can become genetic for sustainability modelling. The elaboration of such a complex SD model, which integrates economic processes of physical, social and ecological reproduction, leads him to a controversial conclusion that long-term sustainability is not achievable by using non-renewable resources.

Tisdell (Chaper 4) questions the role of economics as the bottom line for sustainability. He first concentrates on the meaning, the desirability and the possibility of achieving sustainability, and claims that a common definition of what has to be sustained is required for the discussion. There is consensus that sustainability depends on the capability of the current generation to leave an appropriate bequest for future generations. However, opinions differ on how to achieve sustainability. Orthodox economists see accumulation of man-made capital as the solution, while neo-Malthusians focus on the conservation of natural resources and environmental capital. According to orthodox economists, only weak conditions are necessary to achieve sustainable development, whereas neo-Malthusians see the imposition of strong conditions as crucial. Orthodox economists and neo-Malthusian believe therefore in a different economic bottom line for sustainable development. The author argues that the capitalist system of our society favours the orthodox economists' views. He claims that, although neo-Malthusians are probably right, their views are not supported because of the 'short-sighted nature' of politics.

In the second part of the chapter, Tisdell questions if economics is the bottom line for sustainability or not. He asserts that economic systems are embedded in social and natural systems. These systems are interdependent. Economics accounts for only one aspect of many bottom lines for sustainability. Tisdell also underlines the importance of values in the debate. Theoretical positions on sustainability are influenced by different values, which are mainly determined by cultural factors. Orthodox economists' values are often anthropocentric, opposed to ecocentric values (deep ecologists). This leads to conflicting views on what should be sustained. Hence Tisdell claims that economics should not be the final judge for social decisions and that it is not the bottom line for social evaluation, only a part of it. Finally, he argues that a sustainable economic system might simply not be achievable. In fact, social choices and decision-making should focus on selecting systems that would enable us to get closer to sustainability, instead of trying to choose unrealistic systems to attain absolute sustainability.

It appears from the above analysis that although the authors of the first four chapters emphasize the need for a more balanced approach to sustainable development, a pessimistic view of sustainable development is largely present, as its complete feasibility is doubted. However, it is strongly argued that sustainable development can be achieved to the highest possible extent through proper and scientific planning with the application of model-based systems. The next section aims at identifying model-based systems that can be used in the decision-making process for planning sustainable development in certain critical areas.

Case studies and applications of model based systems (including DSS and GDSS) in sustainable development

Since the emergence of the concept, many model-based systems have been developed and used in various fields of sustainable development. All these models have brought great insights into specific areas, helping to move towards the path of sustainable development. Various tools have been employed to make the complex model-based systems operational. The most challenging task for a sustainable development planner is to take into consideration the interests of all the stakeholders of development (that is, the economic agents, the civil society and the environmentalists). Planning should not be constrained to benefit the economic agents only. The more the stakeholders are involved in planning and decision-making, the better the quality of the decisions will be. The case studies summarized below are some examples of the most recently developed model-based systems by various researchers with the aim of facilitating the achievement of sustainable development in seven crucial and important fields: environmental management, mining, energy management, land and water management, agriculture, aquaculture and infrastructure.

Environmental management

The impact of natural disasters is a significant threat to environment. In Chapter 5 Aurum, Handzic and Van Toorn argue that disaster planning must form an essential element of sustainable development planning. Unfortunately, no appropriate decision support tool has yet been developed to assist natural disaster planning. While DSS and GDSS are useful to address multiple criteria and group issues, they have limited relevance to unexpected and unknown situations resulting from natural disasters. The three authors develop a *creative decision support system* (CDSS) to assist planning and decision-making in the context of environmental disasters. They convincingly argue that CDSS aims at enhancing the creativity of planners, helping them to identify relevant issues and evaluate alternative solutions. The CDSS is based on the assumption that it is possible to develop, to learn, to practise and to use 'thinking application' for generating ideas. The 'solo brainstorming' method is used to develop the computer-based CDSS.

The authors then apply CDSS to bushfire planning in New South Wales, Australia. Both individual and collective performances of CDSS users are assessed and analysed. The result of the application shows that CDSS increases the creativity of its users. Both the quality and the quantity of the planners' ideas can be enhanced through CDSS. Their findings also suggest that nominal groups of people are likely to perform better than individuals on the task of critical issue identification for planning purposes. The authors rightly claim that their study contributes a new and successful computer-based approach to support environmental disaster planning.

Sarkis and Talluri (Chapter 6) review application of data envelopment analysis (DEA) for measuring the ecological efficiency of an organization. They argue that DEA is capable of supporting the managers and the researchers to design measures for ecoefficiency. They critically assess three categories of DEA models that have been developed in the past: basic ratio-based technical and scale efficiency DEA models, cross-efficiency DEA models and discriminatory DEA models. The usefulness of these models is then illustrated with the help of an example using published environmental data for 48 electric utility plants in the USA. The three categories of models are used in a sequential manner in order to gain more insights into the ecoefficiency of each of the electric utility plants.

Their findings suggest that DEA can be used to help organizations to carry out benchmarking and performance evaluation. As a benchmarking tool, DEA enables organizations to identify their weaknesses in environmental performance and ecoefficiency and address these issues. From the managerial perspective, DEA serves as a multiple criteria decision-making tool. Sarkis and Talluri also demonstrate that the application of DEA is not limited to ecoefficiency; it could be expanded to other fields of sustainable development and at different levels (corporate, industry, national).

Mining

In Chapter 7, Quaddus and Mukherjee develop a hierarchical framework for evaluating mine projects for sustainability and apply it to a real-world mine evaluation problem in India. The hierarchical model categorizes mine evaluation for sustainability into 'internal' and 'external' impacts. The internal impacts are then broken down into various financial measures (for example net present value, return on investment and so on). The external impacts are broken down into three important sustainability criteria of 'physical and environmental', 'economic' and 'social' dimensions. Each of these sustainability criteria is then broken down into various specific criteria. The key to the success of this approach is the measurement of these criteria by the stakeholders with respect to the mines to be evaluated. For this the authors use a well-known approach from the literature, called 'analytical hierarchical process'. The model is then applied to evaluate two mines in India. Real-world data are collected and two executives take part in the measurement and evaluation process. One specific mine emerges as the clear winner in the evaluation process. Further sensitivity analyses also show that the mine in question is most preferable.

Energy management

The links between energy strategies and sustainable development are examined by Qudrat-Ullah in Chapter 8. He is of the view that the energy policies of a country should not only be confined to supply the necessary and increasing demand for energy, but also to promote the sustainable consumption of available natural resources. He develops the MDESRAP (model for dynamics of electric supply, resources and pollution), based on *system dynamics (SD) methodology* and applies it to develop the energy policy design for electricity supply in Pakistan. The model is organized into seven sectors: electricity demand, investment demand, capital demand, resource demand, production demand, environment demand, and cost and pricing demand. It is implemented in POWERSIM software. The structural and behavioural validities are examined by multiple tests (trend comparison and removal, autocorrelation function test for period comparison, cross-correlation function test for phase lag detection, comparing the means and the amplitude variations). The historical fit of the model is also tested thanks to Theil's inequality statistics. The author claims that an SD modelling approach to economy-wide energy policies provides an adequate representation of the interplay between energy, economy and the environment. Contrary to other approaches (large, non-linear, general equilibrium economic approach), this modelling approach permits the planners to address the short-term effects on transition policy issues, and is also relevant for evaluating the practical implications of those policies.

Land and water management

The links between land management and water consumption are investigated by Roggio, with the assistance of Nath, Quinn and Weaver (Chapter 9). They develop a *system dynamic model* combining the policy choices that address the need for unfiltered water in New York City, preserve the environment and maintain the socio-economic development in the watershed regions. The model is elaborated by using VENSIM software. It is drawn from Forrester's urban model and Simonovic's analysis of water resources policy modelling. There are four main loops in this model, that is, the watershed expansion loop, the conservation loop, the land consumption loop and the water quality loop. These loops give insight into policy issues. The watershed expansion loop indicates NY City's original preferred policy to address growing water demand. The conservation loop shows the more recent policy adopted by the City, while the behaviours involved in the land consumption loop illustrate a common problem faced by sustainable development planners: an increased population leads to a greater demand for development and hence a greater need for employment. Finally, the water quality loop demonstrates that increased development has a detrimental effect on water quality. The four loops show the complex and conflicting relationships between the interconnected subsystems and the priorities of the watershed communities and the city of New York. The model demonstrates that consideration of water management policies is very important for sustainable development planning. The authors conclude that the experience of NY City should be fruitful and that lessons should be drawn from it in order to raise issues relating to sustainable watershed development and water quality.

Water is a limited but very valuable resource and its efficient use plays an important role in the achievement of sustainable development. The scarcity of water is indeed a great 'determinant of economic growth, industrial structure, and national trade' for many countries. Hence water management is a real challenge for sustainable development planners. Bartoszczuk and Nakamori (Chapter 10) discuss the issues relating to the pricing of water resources in Central Europe. Water consumption in this region had begun to increase since the 1990s. This was checked with successful application of pricing policies based on market principles. The authors assess the impact of economic incentives on the consumption of water in central Europe with the help of an *applied economic model* in Chapter 10.

Their model first examines the key principles for setting water prices, such as providing incentives for efficient use of water, distributing the cost in a equitable way, taking into account social issues and keeping the tariff rate structure simple for easier implementation. They demonstrate that appropriate pricing can play a positive role in using water in a 'sustainable way'. Hence it is essential to develop a water pricing system that aims at promoting sustainability of water management. Economic incentives are necessary for consumers to encourage them to pay attention to their water consumption. Without such incentives, water consumption would rise, which would necessitate further development of the supply and sewerage systems. In the 1990s, such a situation emerged in the Central European countries.

The authors assert that a full cost pricing (via increased water prices) will reduce or at least slow the demand for water systems expansion. They also claim that the impact of such a policy on a long-term basis largely compensates for the increase in prices. Water pricing should be used both to reach environmental goals and to ensure the recovery of the costs of water services.

Agriculture

Past research in sustainable agriculture has generally focused on the generation of various types of pollution through the production of residuals. Fernández and Selma (Chapter 11) point out the necessity for developing an approach in the decision-making process that will help planners to achieve greater sustainability through better management of land, water and biodiversity. They make a bold attempt to assess the sustainability of Mediterranean intensive agricultural systems through the combined use of *dynamic system models, environmental modelling* and *geographical information systems (GIS)*. Their research focuses not only on the production of residuals but also on the consumption of natural resources (such as water and land) while modelling sustainable intensive agricultural systems in the Mediterranean irrigated lands. Their model also incorporates spatial and time dimensions.

Fernández and Selma combine the environmental response models with a geo-referenced database and GIS, and develop a dynamic system model, integrating socio-economic and environmental factors for generating a spatial projection of several management scenarios, and for analysing their environmental externalities. Environmental response models are elaborated through the study of changes in land use based on an extensive, detailed and systemic sampling of land use for the period 1981–99. These data are then combined with a geo-referenced environmental database which enables the authors to environmentally define each type of irrigated land for each year, and to analyse the land use transition matrix. This matrix detects the environmental characteristics of the main changes in the use of irrigated lands. Then the environmental models for each type of irrigated land are elaborated by using generalized linear models and forward stepwise procedures for selecting the descriptive variables.

The combination of environmental response models with a geo-referenced database and GIS generates potential distribution maps on different dates. These maps are used to analyse past, current and potential conflicts due to spatial competence between irrigated lands and other policies such as nature conservation. It then becomes possible to develop a detailed and realistic description of the irrigated lands.

As for the dynamic system model, it is developed using the software VENSIM. The modelling process includes four main stages: conceptualization, data acquisition, formulation of the model equation, and calibration. Validation of the model is done by various structural tests.

The case study of Mediterranean irrigated lands demonstrates that the intensive agricultural systems generate negative effects in terms of residuals and use of natural resources. Hence the authors recommend stabilizing and reducing the area of irrigated lands in the region of Murcia, and applying adaptive management in relation to existing natural resources. Their research highlights the fact that research in agricultural systems requires an integrated framework of methodology which combines the dynamic system models with environmental models and GIS. The incorporation of such models into the decision-making process is vital to achieve greater sustainability for the management of land water, and biodiversity in the Mediterranean area.

Aquaculture

Tisdell (Chapter 12) discusses some issues associated with sustainability of aquaculture production. He demonstrates that even in the absence of market failures, economic agents may choose unsustainable income paths instead of sustainable ones. This arises when private benefits from production are higher than its social collective benefits. In many cases, adverse environmental spillovers result in individuals not taking into account the full impact of their actions on future incomes. The author also points out that there is no correlation between the intensity of aquaculture and environmental damages. Aquaculture may have positive, negative, or even neutral environmental spillovers. It is then pointless to generalize about the assessment of the aquaculture situation for sustainability implications. Bad and good examples can be found. Tisdell recommends that more research should be done to expand aquaculture towards positive environmental spillovers.

Tisdell also suggests a broad range of policies that can be implemented to regulate adverse environmental spillovers from aquaculture. They are divided into three main categories: control of environmental spillovers, prohibition and administrative-type regulations, and pricing and the market approach. However, it seems that there is no perfect choice of policy instruments. While the control of environmental spillovers is costly and difficult to practise, and the cost and efficiency of prohibition and administrative-type regulations is very uneven, pricing and market-oriented policies are not always the best methods available, contrary to what economists tend to claim. Tisdell states that environmental spillovers cannot simply be assessed in economic terms. Negative externalities are indeed created by various social and economic activities. Hence the choice of policies for controlling environmental spillovers from aquaculture must take into consideration comparative agency costs involved and limitations of the knowledge available to policy-makers.

Infrastructure

Courtney, Richardson and Paradice (Chapter 13) apply a new DSS model for ecosystems management (EM) to Houston's infrastructures management involving transportation, water supply, wastewater treatment and drainage. They are of the view that a holistic approach of ecosystems linking human needs with social, economic, and environmental conditions is essential to achieve sustainable EM. To deal with these issues, they develop a *Singerian inquiring model*. Their model integrates knowledge and information from the diverse fields of social and hard sciences as well as from the public in general. Contrary to other models, such as the Leibnizian, Lockean, Kantian or Hegelian ones, the Singerian model allows the researchers to adopt a real holistic approach. They claim that their new model is effective in dealing with the complex issues of EM and sustainability. Then the role of urban infrastructure decision-making on sustainable development is illustrated with the example of a project implemented in Houston, Texas. From this project, two main issues emerge: if no changes are made, the planet will not survive, and the changes to be made involve extremely complex issues. The authors claim that the Singerian model is a useful device to face these issues since it views all things as interrelated, draws knowledge from any source available, underlines a team approach to problem-solving involving all stakeholders, and encourages them to work together in a cooperative way, with the common aim to protect the planet. Through the Houston project, it is possible to understand how complex the problems relating to EM and sustainability are. It shows how stakeholders interact and work together in order to solve environmental problems. It also demonstrates the importance of sharing information in solving complex and 'messy' problems.

Infrastructure development is seen in developing countries (DCs) as one of the necessary conditions for economic development. It boosts economic growth and improves income distribution. However, in certain cases the development of infrastructure may worsen income distribution, which negatively affects sustainable economic growth and human security. Saeed and Honggang (Chapter 14) argue that the main reason behind the failure of infrastructure development policies in the DCs is the lack of awareness of the specific economic system prevailing in these countries. They argue that DCs are characterized by a dual economic system consisting of 'a profit-maximizing capitalist sector' and 'a consumption-maximizing self-employed sector'. It is then essential than the planners of infrastructure development in these countries take into account the dynamic relationships that exist between these two sectors. They therefore develop a *system dynamics (SD) model* with the aim to realistically address public infrastructure provision in DCs by taking into consideration these two sectors. Their model also includes a construction sector representing government provision of economic infrastructure through taxation. Three new subsectors appear in the extended model: development of infrastructure for facilitating production, development of transportation infrastructure, and allocation of resources by the government. This enables the planners to follow governmental decisions in terms of infrastructure provision and its effects on allocation of resources, economic growth and income distribution.

Simulation tests for a period of 120 years are then conducted to examine the behaviour of the model against historical experience. Four experiments are conducted. The first is based on Saeed's model; the second is based on the new model, the third takes into consideration the fact that access to infrastructure by the producers varies depending on the sector to which it belongs (the profit-maximizing capitalist or self-employed sector); and finally, the fourth experiment assumes a technological difference between the two sectors. The fourth simulation experiment shows that the limited access to infrastructure and to modern capital of the self-employed sector has far-reaching consequences in terms of the creation of a dual economy system in DCs. This duality is reinforced by the technological gap between the two sectors.

The findings of Saeed and Honggang suggest that infrastructure development alone cannot act as a driver for improving income distribution. For change in the distribution of income, infrastructure development must be combined with taxation of unearned income. Finally, the authors claim that privatization of infrastructure provision will not make economic and income distribution objectives more feasible, and that it would actually cause organizational problems since private institutions are not well adapted to provide public goods.

How has the modelling of sustainable development planning advanced in recent years?

Agenda 21 (UNCED, 1992) advocates the need for a good balance between the three dimensions of sustainable development – economic, ecological and social. It would seem, however, that the consideration of these three dimensions by the researchers remains unbalanced. Although the authors are positive and encouraging about a more balanced approach to sustainable development, a pessimistic view of sustainable development is also present. Its complete feasibility is doubted by Yamaguchi (Chapter 3). He underlines the disequilibria between the different dimensions of sustainable development and claims that social and environmental sustainability are far from being automatically guaranteed. Tisdell (Chapter 4) is of the view that the economic dimension is still largely prevalent. However, it is strongly argued in the book that sustainable development planning can be improved and supported with the application of model-based decision support systems.

Part II of the book convincingly demonstrates that many model-based systems (such as the Singerian model, the creative DSS, the MDESRAP model, the DEA and the system dynamics model) have been developed and used in various fields of sustainable development planning in recent years. All these models have brought great insights into specific areas of sustainable development planning and have aided various agents of development to move further towards sustainable development. Various tools have also been developed in order to make possible the construction and application of the model-based systems.

As stated earlier in this chapter, it is essential that all three stakeholders (economic agents, civil society, and environmentalists) are taken into consideration seriously when planning for sustainable development. The planning should indeed not be restricted to economic agents only. The more the stakeholders are involved in the planning and decision-making process, the better the quality of the decisions will be. It will enable the acquisition and use of as much useful information as possible.

It also appears from the experience of modelling for sustainable development planning that there is no universally acceptable modelling technique that can be applied to all the case studies. Modelling of sustainable development planning depends on what has to be sustained and why.

It is likely that recent trends in developing and applying model-based systems will continue in the coming years. The scope of the models that have been developed so far is still limited and is too specific. Continuous research in this area is expected to occur in order to further enhance the attributes of the existing models and to explore the application of these models to other fields of sustainable development. Innovative tools, new techniques, indicators, standards and softwares will probably be developed and further improved in the coming years.

One of the great challenges of sustainable development planning will be to focus more on the social dimension, which has historically been neglected. This aspect will no doubt be formidable, as the collection of data and the identification of standards and indicators in this field remain difficult tasks. The role of the civil community and, in particular, the NGOs must be taken more seriously by planners and is likely to play an increasingly significant role in the foreseeable future.

Another issue that may dominate the literature in sustainable development planning in the coming years is good governance. Accountability and transparency in both the public and private sector certainly influence the individual's choice in the decision-making process of sustainable development planning. The notion of governance will appear as a new concept when planning for sustainable development and will play an increasingly important role in the decision-making process. Planners are becoming more and more conscious of transparency and accountability while planning for sustainable development.

Although *Agenda 21* (UNCED 1992) is addressed to the international level, it becomes clear from Chapter 13 that one cannot see sustainable development in the same way in poor and rich countries. Differences have to be taken into account in particular when planning for sustainability in developing countries. These countries, which often do not have access to the same level of information and technology as developed countries, have various basic problems that must be solved in the short term.

Thus there is a clear need and demand for new ways of thinking about sustainable development planning. Some theories, such as the evolutionary theories presented by Mulder and Van Den Bergh (2001), account for a step towards such progress. Further theories integrating as many variables and information as possible should be developed in order to model sustainable development planning. In the same way, planners should be trained so that they become multi-skilled, open and flexible in order to respond to the nature and complexities of the tasks they have to achieve.

Finally, the greatest challenge for the application of model-based systems in sustainable development planning is to change the way of thinking and comprehending planning and the decision-making process. Sustainable development implies great changes that have not been experienced before.

Future directions of decision support in sustainable development planning

We discussed some generic issues of sustainable development planning in the previous section. In this section we propose some future directions of utilizing decision support tools in sustainable development planning in the light of our review in Chapter 1 and the collection of chapters in this volume. As discussed in Chapter 1, DSSs are computer-based systems which use models and data and support decision-making in an interactive fashion. Since planning of any kind essentially deals with integrated decision-making, sustainable development planning is a fertile area where DSS tools can be used effectively.

The review in Chapter 1 shows that out of 70 papers studied, only 19 deal with modelling and/or decision support. Although the review was not comprehensive, it sheds some light on the extent of use of DSS tools in sustainable development planning. Table 1.1 of Chapter 1 and its subsequent analysis reveal a number of gaps in applying DSS tools. On 'research type' it was revealed that about 50 per cent of the studies deal with frameworks, conceptual overview and so on. In general, the literature on sustainable development is full of concepts and overviews. One important future direction could be to take these concepts and apply models and use the DSS approach in real-world applications of sustainable development planning. On 'modelling type' our review revealed that most of the studies used a quantitative approach. Thus the use of a qualitative approach and a mixed qualitative–quantitative approach is also an important area where future research and development could be directed. We will expand the future directions of modelling in sustainable development planning shortly. On the 'extent of DSS' use, our review revealed that about 50 per cent of the papers studied directly or indirectly use DSS-based analysis. This is encouraging. But it was also found that full-blown use of DSS was very limited.

It is thus observed that the future of modelling and decision support in sustainable planning is very fertile. Let us expand the nitty-gritty of modelling. The detailed review of Chapter 1 revealed that sustainable development planning is a complex process. It is complicated by three dominant factors: uncertainty, multiple objectives and multiple stakeholders. Planning of any kind and hence sustainable development planning must deal with a great number of uncertain parameters. Various dimensions of sustainable development, environmental, social and economic, are inherently uncertain (Quaddus and Siddique, 2001). Because of multiple dimensions, sustainable development planning must deal with multiple objectives or criteria. Our review in Chapter 1 revealed that the multiple-criteria decision-making tool is the most widely used modelling tool for sustainable development planning. As pointed out in the last section, for the success of the sustainable development planning process three stakeholders (economic agents, civil society and environmentalists) must take an active part.

The three factors of sustainable development planning can be developed as shown in Figure 15.1. In total there are eight categories of models which are formed by the factors. While any model from Figure 15.1 (or for that matter any other model from elsewhere) can be used for sustainable development planning, the most suitable one is as shown by path 8 (see Figure 15.1). Our review in Chapter 1 has shown that most of the DSS-based modelling tools used were of path 3 type, that is, certain, multiple objectives, but in a single stakeholder environment. We could not find any DSS-based modelling application in sustainable development planning that explicitly deals with path 8, except the one by Quaddus and Siddique (2001).

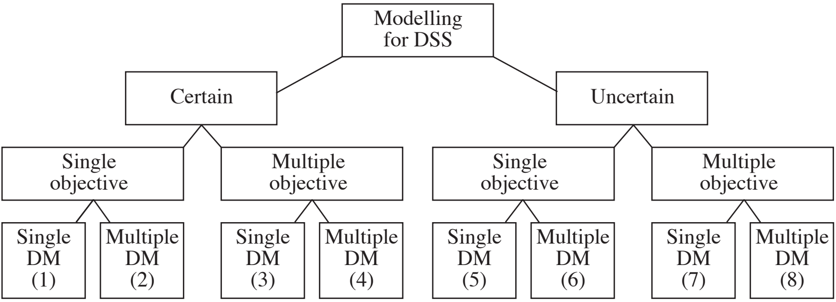

Figure 15.1 Modelling types for sustainable development planning

We believe that the future of modelling activities in sustainable development planning must address path 8 of Figure 15.1 and it must be DSS-based. Quaddus and Siddique (2001) has proposed a decision conferencing approach which brings the stakeholders together in a face-to-face environment and develops the planning model in a participative environment using a multiple-criteria decision-making modelling tool. This is just one of many approaches that could be adopted for path 8. It is noted that the uncertainty factor of path 8 can be handled either by explicit stochastic modelling or by a range of sensitivity analyses as suggested by Quaddus and Siddique (2001). To handle multiple objectives one must deal with a multiple-objective decision-making tool and there are plenty of those (Bogetoft and Pruzan, 1991). The issue of multiple stakeholders can be handled either in a face-to-face environment or via a dispersed mode. For the latter the corresponding DSS must also handle a dispersed mode (Tung and Turban, 1998). It is also suggested that future modelling applications in sustainable development planning should concentrate on using path 3 to path 8.

Finally, it is also suggested that more DSS-based applications should be practised. As has been observed, there is a scarcity of full-blown DSS-based applications. This area therefore provides tremendous opportunities for applications in sustainable development planning.

Conclusions

This chapter provides a synthesis of all the previous chapters in this volume. In doing so, it also discusses generic issues of successful sustainable development planning. The chapter then highlights future directions of model-based decision support systems. In short, the future of DSS in sustainable development planning is very bright. We develop a tree structure of modelling for DSS based on significant factors of sustainable development planning. Each branch of the tree represents a specific type of model. We highlight some of the branches which should be targeted for further research and development of model-based DSS in sustainable development planning.

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