Decision support for river basin management

Experiences in northern Thailand

EDITED BY ANTHONY J. JAKEMAN, REBECCA A. LETCHER AND SANTHAD ROJANASOONTHON

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Foreword

Sustainable development requires land, water and vegetation management to be integrated with effects on ecosystems and the local communities and cultures that depend on those resources. Few experiences and technical tools exist to support such integrated management.

In a project supported by ACIAR, researchers have pioneered the development of an integrated water resources assessment and management (IWRAM) framework. A set of linked models, accessed through a computer-based decision-support system, allows users to explore the impacts of policy, planning and regulatory options on aspects such as soil erosion, water availability and the socioeconomic conditions of households and communities.

In Thailand, researchers built on the original project, transferring the framework to more-complex catchments and customising and implementing it for different agricultural, water regulation, social and vegetation systems.

The project demonstrated the suitability and versatility of the IWRAM approach which was relatively easy to modify and adapt to suit conditions in Thailand.

Both the Thai and Australian teams benefited from the sharing of ideas. The Thai researchers were able to apply, expand and modify the approach to suit their cultural practices and aspirations, while the Australians gained in knowledge from working with a new set of problems and disciplinary expertise.

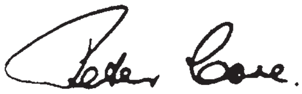
The project demonstrated that multi-disciplinary and multi-agency teams can be successfully built to tackle multi-issue problems.

In terms of modelling software, the project has provided resource managers at national, provincial and local levels with a robust, uncomplicated approach for investigating management scenarios and policy options for sustainable land and water use.

This technology is being used in the field to analyse hydrological, erosion, crop and economic data. The model is being applied and tested in different catchments, and integrated into the routine practices of the various agencies in Thailand that make up the user group.

The aim of this book is to share the project team's experiences in developing tools for assessing how to manage resources from a catchment or watershed-wide perspective. The achievements in this approach to integration and the lessons learnt should be of interest to all those involved or interested in natural-resource management—researchers, students, managers, technical advisers and the wider community.

ACIAR is pleased to publish this important book which can also be freely downloaded from our website at <www.aciar.gov.au>.



Peter Core
Director

Australian Centre for International Agricultural Research

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Preface

This book has arisen as a legacy of a series of projects that ran from 1997–2004 to support development of a framework for, and institutional strengthening in, integrated water-resource management in Thailand. This activity was a close collaboration between Australia and Thailand, financially supported by the Agricultural Systems Economics and Management research program of the Australian Centre for International Agricultural Research (ACIAR), the Thailand Government through its various agencies and the Royal Project Foundation of Thailand, and the Australian National University. The project aims were to support sustainable use of Thailand's rural catchments, specifically in relation to their land and water management, while maintaining a robust local economy.

The project was undertaken in two phases: the first saw the development of an integrated approach to water resources assessment and management (IWRAM) within a Thai context, the second the re-implementation of the approach to suit local expertise and support extension of the methods to river basins in northern Thailand. Key outputs have been the development of the IWRAM decision-support system (DSS), an IWRAM website at <http://www.iwram.org> and a series of publications in both Thai and English-language versions.

The writing of this book has provided the opportunity to reflect on this work and synthesise it into a form that can serve as a key reference in water-resources assessment and management for a broad audience of practitioners, managers, scientists and students.

In offering this work to the broader community, we wish to thank team members and participating agencies for their vision, dedication and expertise in tackling an issue that can be perplexingly complex, and have a far-reaching impact on all aspects of our society. All the team members devoted considerable time and energy to the various projects. The relationships have developed into a true partnership where each group and country's participants value and learn from the other. The partnership has not only advanced the 'discipline' of integrated assessment for water resources management, but also has turned into an enduring one in which we will work together for some time to come.

Acknowledgments

Many people and organisations have contributed to this project.

The project team thanks in particular the Thailand Royal Project Foundation and ACIAR for their contributions in developing and supporting this collaborative engagement between Thai and Australian researchers, and for the key role they have played and continue to play in the pursuit of sustainable development of natural resources within Thailand.

Other contributing organisations include:

- Royal Project Foundation of Thailand
- Land Development Department of Thailand
- Thailand Office of Highland Development
- Royal Forestry Department of Thailand
- Royal Irrigation Department of Thailand
- Thailand Department of Agriculture
- Office of the National Water Resources Committee of Thailand
- Asian Institute of Technology
- Chiang Mai University
- Maejo University
- Kasetstart University
- Australian National University.

The following people have made significant contributions to the IWRAM project: Chaiyasit Anechsamph, Nick Ardlie, Robert Argent, Artorn Boonsaner, Chris Buller, Thirayuth Chitchumnong, Barry Croke, Susan Cuddy, Boonma Deesaeng, Claude Dietrich, Fayen d'Evie, Benchaphun Ekasingh, Tony Jakeman, Penporn Janekarnkij, Voratas Kachitvichynukul, Nootsuporn Krisdatarn, Padma Lal, Rebecca Letcher, Sureewan Mekkamol, Wendy Merritt, Kamol Ngamsomsuke, Suwit Ongsomwang, Sura Pattanakiat, Pascal Perez, Jitti Pinthong, Suwanna Praneetvatakul, Somjate Pratummintra, Varaporn Punyawadee, Prapaddh Riddhagni, Santhad Rojanasoonthon, Helen Ross, Somporn Sangawongse, Parisa Saguantham, Kamron Saifuk, Sergei Schreider, Michelle Scoccimarro, Anthony Scott, Sompop Sucharit, Bandith Tansiri, Karn Trisophon, Andrew Walker, Pongsak Witthawatchutikul.

Prepared by IWRAM team, Royal Project Foundation

Sourcing of material

As mentioned earlier, this book is a synthesis of a team effort. While much of that effort has been documented in the literature (journals and conference prceedings), it is hoped that bringing it together in this book will make it accessible to a broader audience. This book then draws on a great deal of earlier project material, in particular documents written by team members Santhad Rojanasoonthon, Kamron Saifuk, Pongsak Witthawatchutikul, Benchaphun Ekasingh, Kamol Ngamsomsuke, Anthony Jakeman, Rebecca Letcher, Barry Croke, Wendy Merritt, Susan Cuddy, Anthony Scott and Pascal Perez. Special mention should be made of material derived from the PhD thesis of Wendy Merritt, and chapters by Jakeman and Letcher from an forthcoming book about integrated assessment.

The future

Since the formal completion of the project, the Thai and Australian teams have continued to work together. For example, in January 2005 they jointly organised the SIMMOD Conference in Bangkok (see <www.ise.ait.ac.th>). This was a simulation and modelling conference with the theme of integrating science and technology in support of resource management for sustainable development. It attracted some 200 participants from the region and produced a valuable set of conference proceedings. Both teams are now taking their experiences and applying them to projects in their own countries. And they are exploring ways to work together again in new partnerships in integrated assessment in the greater Mekong subregion.

Santhad Rojanasoonthon, Anthony Jakeman, Susan Cuddy and Parisa Saguantham

About the authors

Arthorn Boonsaner is a forest hydrologist in the Watershed Research Division, Office of Watershed Conservation and Management, National Park, Wildlife and Plant Conservation Department of the Thai Government. He received his Master's degree from the Earth Resources Department, Colorado State University in 1982. At present, he is in charge of Yom Watershed Research Station, Phrae Province. His research interests include land-use hydrology, erosion and sedimentation and water quality. Email: <arthorn@hotmail.com>.

Barry Croke is a research fellow at the Integrated Catchment Assessment and Management (iCAM) Centre, Australian National University, Canberra. He has a BSc in theoretical physics and a PhD in astrophysics from the University of New South Wales and has extensive work experience in the fields of hydrology and atmospheric research. Since joining iCAM in mid-1999, his research has focused on the development of models for prediction of streamflow and water quality, especially the prediction of flow at ungauged sites. Email: <barry.croke@anu.edu.au>.

Susan Cuddy is a researcher and projects manager at iCAM, and a senior experimental scientist at CSIRO Land and Water, Canberra. She has worked with multi-disciplinary research teams for over 20 years in developing underlying theory and practical applications of decision-support systems for integrated catchment management. Her research interests are in knowledge representation, explanation and computer-user interactions. Email: <susan.cuddy@anu.edu.au>.

Benchaphun Shinawatra Ekasingh is an associate professor in agricultural economics, Department of Agricultural Economics, Faculty of Agriculture and Multiple Cropping Center, Chiang Mai University. She received a PhD from Michigan State University in agricultural and natural-resource economics in 1985. She has extensive experience in highland and natural-resource development in Southeast Asia. She is active in international agricultural development and is currently the Chair of the Board of Trustees of the International Plant Genetic Resource Institute, one of 15 international research centres under the Consultative Group of International Agricultural Research. Email: <bench.ek@chiangmai.ac.th>.

Anthony Jakeman is a professor in the Centre for Resource and Environmental Studies and director of iCAM. He has been an environmental modeller for 28 years and has more than 300 publications in the open literature. His current research interests include integrated assessment methods for water and associated land-resource problems, as well as modelling of water supply and quality problems, including in ungauged catchments. Email: <tony.jakeman@anu.edu.au>.

Rebecca Letcher is an early-career research fellow at iCAM. She has degrees in science and economics (ANU, 1998), followed by a PhD (ANU, 2002) in 'Issues in integrated catchment assessment and management'. Her research interests are the application and development of integrated assessment methods for water-resource management, particularly participatory model-building approaches. Email: <rebecca.letcher@anu.edu.au>.

Wendy Merritt is a postdoctoral fellow at iCAM and the School of Resources, Environment and Society, Australian National University (ANU), Canberra. She has a BSc in natural-resource management from the University of Western Australia and a PhD (ANU, 2003) that involved the development and testing of biophysical models for assessing land- and water-resource management options in rural catchments in northern Thailand. Her research interests are in the broad field of resource assessment and modelling, particularly water and forest resources. Email: <wendy.merritt@anu.edu.au>.

Kamol Ngamsomsuke is a lecturer in the Department of Agricultural Economics, Faculty of Agriculture, Chiang Mai University. He received a PhD in agricultural economics from the University of the Philippines at Los Baños in 1995. He has extensive experience in socioeconomic study in highland and lowland agriculture of northern Thailand and a special interest in mathematical programming and economic modelling and simulation. Email: <agikngms@chiangmai.ac.th>.

Suwit Ongsomwang is Director of Information and Communications Technology of the Permanent Secretary Office, Ministry of Natural Resources and Environment, Thailand. He received a Doctor of Natural Sciences (Dr rer nat) from the Technical University of Berlin, Germany in the field of remote sensing in 1993. He has extensive experience in application of remote sensing and GIS in forestry. Email: <s_ongsomwang@mnre.go.th>.

Somjate Pratummintra is a senior expert of the Department of Agriculture, Thailand. He completed his PhD in studies shared between Ghent University, Belgium and Universiti Putra Malaysia and received a doctorate in physical land-resource management. He has extensive experience in rubber production modelling and rubber geo-informatics systems. He has a special interest in crop production modelling and simulation. Email: <spratummintra@yahoo.com>.

Santhad Rojanasoonthon is the Royal Project Foundation's Director of Research. He has been working with His Majesty within the Royal Project since its inception in 1969. He is also a Fellow of the Royal Institute of Thailand and the Chairman of the Executive Board of the National Research Council of Thailand. He has been president, chairman and a member of more than twenty societies, foundations and committees in agricultural science and scientific and technological organisations and has over fifty scientific publications covering soil science, land-use planning, science and technology, technology transfer, rural development and highland development. Email: <santhadr@hotmail.com>.

Kamron Saifuk is Chief of the Research and Land Development Practice Group, Thailand. He is a Thai researcher on the IWRAM project and worked specially on the erosion model and the decision-support system. Kamron received his Bachelor of Soil Science degree from Kasetsart University, Thailand and his Master of Soil Classification from the University of Aberdeen, UK.

Parisa Saguantham is a projects manager with the Royal Project Foundation, Thailand. She coordinated the Thai end of the second phase of the IWRAM project and worked closely with the Australian team. Her background is as a spatial analyst with the National Research Council of Thailand. Parisa received her Bachelor of Science from Chiangmai University, majoring in geography. Email: <iwram@yahoo.com>.

Anthony Scott is a visiting fellow at iCAM. After the award of his PhD from the University of Sydney, he gained 17 years work experience as an environmental scientist with various companies, government authorities, universities and CSIRO. He has particular interests in water-resource management, freshwater ecology and environmental history. Email: <anthonyscott@bigpond.com>.

Sompop Sucharit is a hydrologist in the Thai Royal Irrigation Department and is responsible for dam safety. He gained his PhD in the US in hydrological modelling.

Pongsak Wittawatchutikul is a senior researcher in the Watershed Research Division, Office of Watershed Conservation and Management, National Park, Wildlife and Plant Conservation Department. He received his PhD from Kasetsart University in 1997. His research interests include watershed sciences and management, hydrology and biodiversity. He is acting deputy director of the division and has been in charge of Rayong Watershed Research Station, Rayong Province since 1976. Email: <pongsak_rayong@yahoo.com>.

Integrated water resources assessment and management

ANTHONY JAKEMAN, REBECCA LETCHER, KAMRON SAIFUK AND SUWIT ONGSOMWANG

SUMMARY

THROUGHOUT the world, the pressures of agricultural intensification are leading to over-exploitation and non-sustainable use of available land, water and forest resources. In Thailand and other parts of the developing world, these problems are often more striking because of rapidly increasing demographic changes and the urgent need to improve food security and reduce poverty.

In northern Thailand, the pressure on the agricultural sector to increase both productivity and export earnings is very evident. Forested highland areas are being cleared for agricultural production, which is leading to soil erosion and fertility problems on the middle and upper slopes. Water use is also increasing and this is causing conflicts, for example between the highlanders and lowlanders. Declining water quality is being caused by increased

soil erosion and sedimentation, which are attributed in part to decreases in forest cover in the upland areas. Shifts are also occurring in the distribution of economic and social wellbeing between communities.

Integrated water resources management (IWRM) has been embraced internationally as a way forward to address the management of water, land and related resources in order to balance socioeconomic needs with the sustainability of vital ecosystems. As yet there are few case studies reporting on IWRM approaches in practice and, in particular, the assessment needed for such management. The aim of this book is to document and demonstrate our experiences in developing tools for assessing how to manage resources from a catchment or watershed-wide perspective. The achievements in our approach to integration, and the lessons learnt, should be of interest to all those involved or interested in natural-resource management — researchers, students, managers, technical advisors and the wider community.

Known as the Integrated Water Resource Assessment and Management (IWRAM) project, the work began in the late 1990s. The objectives broadly were to develop a framework and tools for assessing options to manage land and water resource issues in northern Thailand. The project was a partnership between the Australian National University and the Thai Royal Project Foundation, Thai Government agencies and universities. The partnership developed an integration framework whose main components were a set of biophysical models to assess hydrology, erosion and crop growth and integrated these with a socioeconomic model. These models were embedded within a decision-support system (DSS) that allowed users to test different land-use, climate and policy scenarios. These scenarios were run through the models, and the DSS provided a range of biophysical and socioeconomic indicators as outputs. The DSS was designed to assist stakeholders to identify and assess both socioeconomic and environmental impacts of the scenarios. This chapter introduces the concept of integrated water resources management and gives an overview of the IWRAM project.

Introduction

In developing countries throughout Asia, rapid population growth makes it difficult for agricultural production to keep pace with the rising demand for food. These countries are already cultivating most of the arable land and are now being forced to use marginal land. The problem is being exacerbated by the increasing degradation of land and water resources, which is being caused by deforestation, poor farming practices, extraction of surface- and groundwater for irrigation and urban supplies, and uncontrolled dumping of wastes and contaminants. The natural resources on which life depends — fresh water, cropland, fisheries and forests — are increasingly being depleted or strained.

Environmental degradation in Asia is accelerating, putting at risk people's health and livelihood and hampering the economic growth needed to reduce the level of poverty in the region. This is the scenario depicted by the Asian Environment Outlook 2001 released by the Asian Development Bank (ADB 2001).

Yet, economic productivity and environmental improvement are not mutually exclusive, and can go hand in hand, with significant improvements achievable at low cost. In order to achieve these gains, environmental and development policies must be integrated at national and regional levels.

The management of land and water resources increasingly faces the challenge of moving towards more-sustainable utilisation. Economic opportunities provided by development activities, such as clearing forests for agriculture and damming rivers for irrigation or hydro-electric generation, need to be balanced by conservation measures that reduce both on-site impacts (such as land degradation and biodiversity decline) and off-site impacts (such as the deterioration of downstream water quality).

This creates a challenging public-policy dilemma of balancing the conservation of land and water resources with the continued use of these resources by local communities.

Given the complexity of natural resource issues, there is an urgent need for integrated solutions based on an understanding of the whole system rather than addressing individual issues in isolation.

Integrated water resources management (IWRM)

During the past 15 years, the concept of sustainable development has become a major international policy initiative. There has also been an increasing realisation that water-resource and land-use planning can no longer be undertaken in isolation. This has resulted in a move towards integrated management at a catchment or watershed scale.

At the broadest level, the adjective 'integrated' in IWRM relates to the need to consider this so-called triple bottom line or three pillars of sustainability, as expressed in the following definition of IWRM, from GWP–TAC (2000), that has been adopted throughout the book:

> Integrated Water Resources Management (IWRM) is a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Integration can also be viewed as having several more-specific dimensions, as discussed below.

- **Integration of issues.** A typical but by no means exhaustive list from Jakeman et al. (2005) is:
  - the continuing need for new opportunities and new practices in agriculture and other industries, to feed the world
  - land and river degradation, including salinisation and erosion
  - surface- and groundwater allocation, including allocation for environmental needs
  - water quality protection
  - pest management
  - maintenance of terrestrial and aquatic biodiversity
  - indigenous and recreational value, and value for other non-extractive uses
  - equitable management and distribution of resources
  - changing patterns of settlement and an ageing population

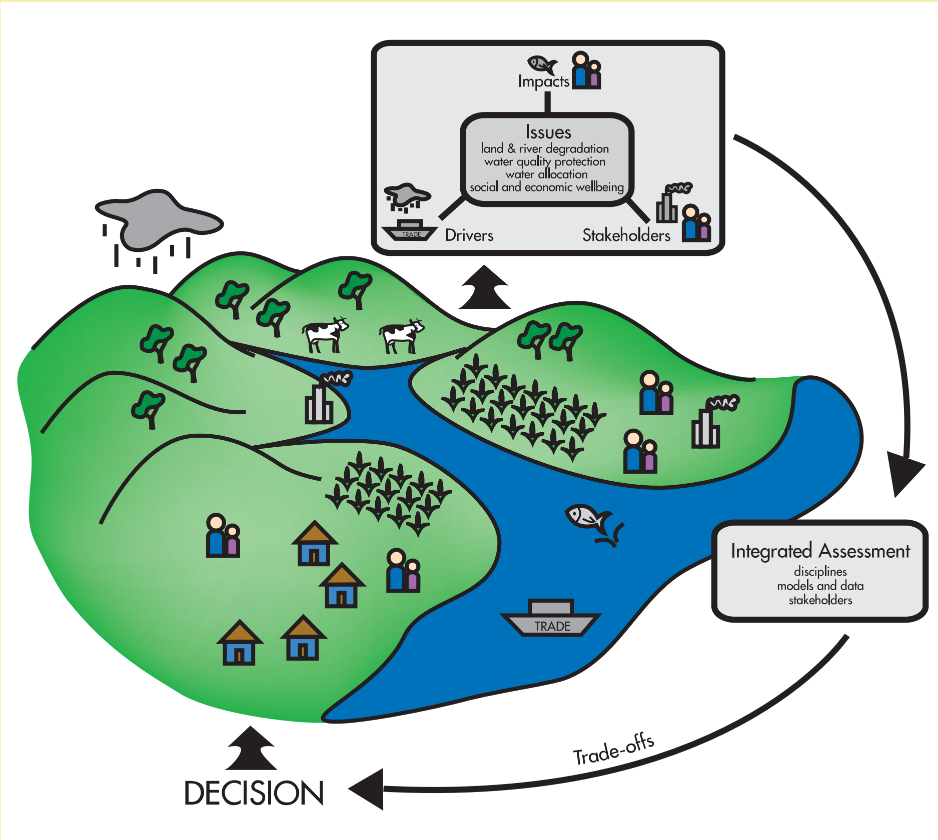


Figure 1.1 The different types of integration in water-resource management

- educating the public about the environment
- the potential impacts of climate change and climate variability.

IWRM avoids treating issues in isolation and aims for joint treatment of the major issues, for the simple reason that these may be in conflict and that trade-offs between their solutions might need to be sought.

- **Integration of the parts of a river basin.** This naturally follows if issues are being integrated. At the most aggregated spatial level this means relating the effects of different land uses to impacts on the waterways (streams, estuaries and groundwater systems). It also means selecting indicators of sustainability that can be used to compare trade-offs under different scenarios or management options. Trade-offs may be needed not only between and within various socioeconomic and environmental indicators, but also between different parts of a river basin and over different time frames.
- **Integration of major drivers.** Outcomes are determined by a range of drivers and system interactions. Drivers can be uncontrollable: like climate episodes, longer-term variability and change, or commodity prices and international policies. Controllable drivers are the ones that can be used to influence outcomes. These include instruments such as taxes, subsidies, trading schemes, regulations, public and private investments and education. Both categories of drivers need to be considered for integration.
- **Integration of different scientific, engineering and other disciplines.** To deal with the triple bottom line of IWRM, knowledge from a wide range of fields, such as economics, hydrology, earth sciences, sociology, psychology and ecology, needs to be targeted and integrated.
- **Integration of people involved or interested in a management problem.** This is usually referred to as public participation, which means that all relevant stakeholders, such as government at various levels, industry groups, environmental sectors and the wider community, are involved in assessment and decision-making processes.
- **Integration of models, methods, data and other information.** A wide range of assessment methods and software is available that can be used for IWRM. They must be carefully integrated to develop an overall framework that provides a valid assessment of the key issues.

Integrated assessment, discussed in chapter 3, is a 'whole of system' approach that provides a framework for linking the complex, interacting processes that occur within a catchment. It recognises both the individual components and the linkages between them, and that a disturbance at one point in the system might be translated to other parts of the system. It also recognises that there can be multiple stakeholders with different (and often conflicting) aims. In particular, trade-offs between economic, social and environmental outcomes must be considered to improve the sustainability of catchment systems.

These types of complex interactions lend themselves to consideration by modelling approaches. In particular, integrated models are required to describe the links between economic, social and environmental system outcomes under various management and climatic regimes. The development and application of these models can enhance communication and interaction between different disciplinary teams and stakeholders. They can also provide a clearer perspective on the integrated nature of the problem.

Modelling can also provide a focus for capacity-building through training and the development of training materials. This focus can have the benefit of exposing catchment managers, local stakeholders and researchers from more narrowly focused perspectives to other ways of thinking about change in the system. In this way it can enhance the integrated system understanding.

A growing body of work now exists which applies integrated modelling to water-management problems—see, for example, Greiner (1999), McKinney et al. (1999), Rosegrant et al. (2000) and Jakeman and Letcher (2003). Most of these integrated modelling approaches are still at early stages of development and are being refined for various geographic areas and management issues. The IWRAM project in northern Thailand, which commenced in 1997, is one such project. At the time of its commencement, there were relatively few applications that attempted to integrate so broad a range of disciplines (including environmental, social and economic), particularly for a case study in Southeast Asia. This meant that much of the understanding of the project team and methods for integration applied had to be developed within the project.

International approaches to water-resources management

Internationally, there are a many similarities in water-resource management approaches and objectives. The following section provides a brief overview of the approaches taken in Europe, the USA, Australia, Africa and Southeast Asia.

Europe

European water-resources management is being driven by the Water Framework Directive (WFD) (EC 2000). In summary, the WFD requires that all partners in a given river basin manage their waters in close cooperation, irrespective of administrative borders, and according to clear environmental objectives. Based on a catchment approach, it aims at:

(a) the provision of a sufficient supply of good-quality surface- and groundwater to ensure sustainable and equitable water use

(b) a significant reduction in pollution of groundwater

(c) the protection of territorial and marine waters

(d) achieving the objectives of international agreements, including those that aim to prevent and eliminate pollution of the marine environment.

Several key mechanisms are applied to make these aims operational. A crucial role is played by the 'river basin management plan', which is to be produced and updated every six years for each river basin (or catchment). Management objectives are coordinated through a set of targets for so-called 'good status' of both surface and groundwater. These consider both ecological protection, through targets for biological quality, and chemical protection, through a set of targets for minimum chemical quality. Good status targets should be achieved by 2015. Other objectives are defined for specific areas, such as bathing or drinking water, where more stringent conditions are required. For groundwater management, the basic assumption is that it should not be polluted at all. Management of groundwater includes a prohibition on any discharges to groundwater, and requirements to monitor all groundwater bodies to detect changes in chemical composition and to reverse any existing trends caused by anthropogenic pollution. Groundwater quantity is also protected.

Another key component of the WFD is the promotion of public participation in river basin management.

USA

In the United States, federal government policy has been developed to support locally based water-management groups and a watershed-management approach (US EPA 2001). In October 2000, the federal government issued the 'Unified federal policy for ensuring a watershed approach to federal land and resource management' (Federal Agencies 2000). This policy supports the watershed (or catchment) as the basis of management, and specifies that the federal agencies involved will work with 'States, Tribes, local governments and interested stakeholders' to identify and improve the condition of priority watersheds. The use of watershed-management plans and water-quality targets is also supported.

Regional watershed coordination teams have been developed in 12 large river basins, to improve inter-agency coordination and help leverage resources. Watershed teams work with local stakeholder and watershed groups to assist with coordination, monitoring and restoration. US EPA (2001) discusses the status of watershed management in the US and gives many examples of locally based watershed-management initiatives. It also identifies many of the problems or shortcomings with the practice of watershed management in the USA, including difficulties with partnerships and coordination, monitoring and research, funding, and technical assistance and evaluation.

Australia

In Australia, the Council of Australian Governments (COAG), consisting of the prime minister, State premiers, chief ministers and the president of the Australian Local Government Association, endorsed in 1994 an agreement on sustainable reform of the water industry. This agreement was aimed at achieving improved economic efficiency and environmental sustainability of the water industry. COAG supported the need for coordinated action to stop the widespread degradation of natural resources (COAG 1994), and identified a number of problems with the existing system including:

(a) cross-subsidies in the service provision to various groups

(b) impediments to the transfer of irrigation water from low- to high-value uses

(c) service delivery inefficiencies

(d) problems in clearly defining roles and responsibilities of many institutions in the water industry

(e) the need for massive asset refurbishment in rural areas.

The COAG agreement addressed many of these problems. For rural water provision, these included changes to pricing and water allocation. It was agreed that pricing regimes should be 'based on the principles of consumption-based pricing, full cost recovery and desirably the removal of cross subsidies which are not consistent with efficient service, use and provision'. Further, 'where cross-subsidies continue to exist, they be made transparent' (COAG 1994).

An important part of the COAG process involved the government consulting with the community on aspects of the framework (Russell 1996). For this reason, and because of the broad nature of the changes required, the initial implementation period for these reforms was set at five to seven years. It was agreed that a full framework should be implemented by 2001. Since that time, each of the States involved has moved to implement these reforms, with integrated catchment management and recognition of the need for improved stakeholder involvement in the policy development underlying much of this reform. Additionally, water quality and river flow objectives have been set for many catchments and detailed catchment-management plans drawn up.

Africa

Significant moves towards IWRM have been made in Africa, with policies very similar to those under the EU WFD being implemented. Van Koppen (2003) discusses water reform in sub-Saharan Africa, and the role that African governments have played in the move towards IWRM. Differences between these countries, and others elsewhere, in terms of initiating IWRM, are identified. In particular, the relative abundance of water resources, but scarcity of economic resources to harness the water, are identified as a key difference in the African context.

The Southern African Development Community (SADC), which consists of the governments of Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe, released a protocol on shared watercourses (SADC 1995, 2000). The objective of the protocol is to 'foster closer cooperation for judicious, sustainable and coordinated management, protection and utilisation of shared watercourses and advance the SADC agenda of regional integration and poverty alleviation' (SADC 2000). To achieve this objective, the protocol seeks to foster the introduction of sustainable and equitable utilisation of the shared watercourses by facilitating:

(a) the establishment of agreements and institutions for the management of shared watercourses

(b) the harmonisation and monitoring of legislation and policies for planning, development, conservation, and allocation of the resources

(c) research and technology development, information exchange, capacity building, and the application of appropriate technologies (SADC 2000).

Van der Zaag and Savenije (1999) present a comparison of management in the SADC and the EU, finding that there has been a significant convergence between the two organisations concerning the central role of the 'river basin' in management.

Another example of African IWRM is in the Nile River Basin, which is shared by 10 countries—Burundi, Democratic Republic of

Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda. IWRM is being implemented through the Nile River Strategic Action Program and the Nile Basin Initiative, which commenced in May 1999 (NBI 2003). The program stresses the requirement to work at local and national levels and focuses strongly on the need for stakeholder involvement.

Southeast Asia

Integrated water resources management is attracting interest in Southeast Asia, as pressures on water resources become more evident from local to international scales. These pressures are interrelated with forms of economic and social development, from changes in agricultural practices to industrial and urban development. Population increase, which demands higher agricultural productivity and fuels urban growth, plays an important role in these changes.

An example of IWRM in Southeast Asia is the management of the Mekong River Basin, which involves coordination of activities and decisions across Thailand, Vietnam, Laos and Cambodia—see, for example, Jacobs (1995). This coordination is undertaken through the Mekong River Commission. In 1995 an agreement was made between countries in the commission that shifted the management focus from development of large-scale projects to sustainable development and management of natural resources (MRC 1995). A basin development plan is being drafted (MRC 2003). This plan strongly supports community participation in natural-resource management in the basin. The overall approach of the plan is to achieve basin-wide benefits while taking account of national interests and balancing development opportunities with resource conservation (MRC 2003).

The plan is expected to involve themes of environment, human-resource development, socioeconomics, poverty reduction, gender equity and public participation (MRC 2003). Other programs, including an environment program, a capacity-building program and an agricultural, irrigation and forestry program are also being undertaken to implement the 1995 agreement.

Catchment issues in Thailand

Like many other countries in Asia, over-exploitation of land and water resources has accompanied Thailand's increasing population and rapid economic growth over the past few decades. Agricultural development has focused in many instances on short-term economic gains and neglected the longer-term social and environmental costs (TDRI 1995; Tungittiplakorn 1995).

Traditionally, the agricultural focus was the production of rice for subsistence purposes. However, over the past few decades, the system of agricultural production has undergone a dramatic transformation. Population growth has resulted in the expansion of paddy land, to the point where it now occupies almost all flat or near-flat land in Thailand. Forests have been cleared from the hillsides for cash crops, while rivers are being dammed for irrigation water and hydro-electricity generation. Although these activities have provided valuable economic opportunities and contributed to the reduction in rural poverty, they are becoming increasingly unsustainable because of their on- and off-site impacts. There are also increasing and highly publicised conflicts over the use and ownership of natural resources such as water and timber.

One of the main sources of conflict relates to the off-site impacts of deforestation in the highlands. Between 1961 and 1986, forest cover in Thailand declined from 53% of the total land area to 29%, corresponding to the clearing of about 45% of Thailand's forest resources (Phantumvanit and Sathirathai 1988). Lowland farmers claim that the clearing of vegetation on upland slopes has disrupted the hydrological cycle by reducing dry-season flows and leading to much higher risks of flash floods during the wet season (Walker 2003). An important task for resource managers is to demonstrate the validity of these claims and the extent to which changes in land use in the highlands contribute to downstream impacts.

Another management concern is the conversion of farmlands to non-agricultural uses, especially in the lowlands. Rapid urban and industrial growth has resulted in increasing demand for farmlands. Good agricultural land is being converted to housing projects, golf courses, resorts, hotels and industrial areas. These developments trigger increases in land prices and contribute to the scarcity of arable land, which in turn trigger increased conversion of forests to new farmland in the highlands and more-intense use of the existing farmland. Reducing fallow periods and cultivation of marginal land may exacerbate on-site soil erosion. In turn, increased soil erosion may contribute to increased turbidity and sedimentation downstream.

The environmental issues in Thailand's highlands are interrelated with social and cultural issues and attitudes. In addition to the ethnic Thai villages, around 700,000 hill people with nine distinct cultures inhabit the highlands. Impoverished local farmers, many of them members of these hill-dwelling ethnic minorities, are widely blamed for the destruction of forests and soil erosion, though in reality the causes of the current environmental problems are far more complex. Other causes, such as the effects of earlier commercial logging, as well as other development activities such as the construction of dams and increased water use for irrigation, receive less attention.

One of the challenges of northern development is to improve the economic welfare of the highland communities while maintaining their cultural traditions and minimising environmental impacts. While various highland development projects have raised the standard of hill-village infrastructure, the hill peoples still have less access to education and health services, and tend to earn lower incomes than other sectors of the Thai population. Through its National Policy on Hill Tribes, the Thai Government has an official commitment to integrate the hill peoples into the Thai state, to raise their economic welfare and to assist them to maintain their unique cultural heritage.

In Thailand, conventional approaches to natural-resource utilisation have tended to be top-down. Decisions about implementing large-scale developments have been based on economic appraisal of individual projects. The belief that all values are commensurable, and that economic (cost–benefit) analysis alone can help resolve conflicts in use, has led to its predominant use in the past. These appraisals have tended to focus on short-term economic gains and neglected the longer-term social and environmental costs (Godfrey-Smith 1979; Enters 1992, 1995). Such fragmented decision-making processes of the past have allowed the over-exploitation of land and water resources resulting in major impacts downstream.

More recently, Thailand has been moving towards formal catchment-based environmental management, with forests now managed according to a watershed classification system, and the Department of Land Development also conducting land-use planning by watershed units (Krairapanond and Atkinson 1998). Specific catchment-management projects, supported by research, have been conducted in catchments including the Mae Chaem (Roth et al. 1989) and Mae Taeng (TDRI–HIID 1995). Highland development projects such as the Sam Mun Highland Development project (SMHDP 1994) have included catchment-based participatory land-use planning.

A key challenge facing the Thai Government is to continue the development of integrated plans for the sustainable use of natural resources. These plans must consider the local people, the region or catchment and the nation as a whole, while maintaining a balance between environmental impacts and economic prosperity.

The IWRAM project in Thailand

In 1997 a collaborative project known as the 'Integrated water resources assessment and management' framework began between Australian researchers and the Thai Government. The overall aim of the project was to develop an integrated approach to water-resources assessment, in order to assist the Thai Government identify and assess options for use of land and water resources that would promote the inhabitants' socioeconomic and cultural welfare, while minimising impacts such as soil loss, flooding, drought and downstream water pollution. The project examined the implications of different levels and patterns of cultivation and water use in northern Thailand, using the Mae Chaem catchment of the Ping River basin as a case study, with a view to later extension to other catchments.

The Thai collaborators were organised under the auspices of the Royal Project Foundation, with much of the development activity contributed by the Department of Land Development and its Office of Highland Development. Other government agencies, such as the Royal Forestry Department, the Ministry of Agriculture, the Royal Irrigation Department and the Office of the National Water Resource Committee, contributed to the project in various ways. University collaborators included Chiang Mai, Kasetsart and Maejo universities. The Australian team members were all from the Australian National University (ANU), with the project managed by the Integrated Catchment Assessment and Management (ICAM) Centre. Australian funding came from the Australian Centre for International Agricultural Research (ACIAR).

The Thai partners' interest was initially in developing sophisticated land and water resources environmental modelling capacity, based on research work at ANU. In the process of developing the initial proposal, they became interested in the broader integration offered by including social and economic research. The project's environmental and socioeconomic assessment capabilities have since become focused on the development of a decision-support system (DSS) which is designed to address the issues which commonly arise in the decision-making process.

In a report on the 'National implementation of the Rio commitments' (UN 2000) there was recognition that Thailand had a large number of agencies involved in water resources, and that this could lead to conflicts in planning and management activities. The IWRAM DSS has been developed to assist these agencies to make more-informed and coordinated decisions about water-resource management. Development of the DSS has been undertaken in phases, so that there are several software systems that have been developed and implemented under the banner of the IWRAM DSS. Each new phase of development has been undertaken to deal with issues of adoption and extension identified in previous phases. Importantly, the integration framework and concepts underlying these different systems are the same.

The IWRAM DSS is a computer-based tool that comprises a database, a set of biophysical and socioeconomic models and a user interface. The biophysical models include crop, hydrologic and erosion models. These are linked to two socioeconomic models to explore economic trade-offs and impacts for the various scenarios being tested.

Scenarios may be developed around agricultural or conservation policies, demographic change, potential climate variability, or changes on the world market for exported goods. The complementary and competitive nature of particular policies or paths of development can then be explored by stakeholders.

It is important to note that the IWRAM DSS does not make decisions. Rather, it supports good decision-making by helping users to explore key relationships relevant to the various environmental and socioeconomic trade-offs in catchment management. Similarly, the DSS does not provide an 'optimal' outcome, as this is dependent on the perspective and objectives of the DSS user. By offering a transparent and repeatable process, it helps users to explore some of the expected and unexpected impacts of various scenarios.

A particular aim of the project was that the framework for evaluating water resources management could be easily applied to catchments other than the Mae Chaem catchment. Consequently, emphasis was placed on using a modelling framework that allows the addition of new models or tools and removal or replacement of obsolete tools.

As the outcome of the IWRAM project was the development of a DSS, some limitations were placed on the modelling approaches. Firstly, the chosen approaches could not be too complicated or data intensive. Otherwise, this may have led to problems of model identifiability where parameters possess a large range of uncertainty. Even technical stakeholders within government departments may not have the expertise or time required to use a complicated DSS. In addition, the availability of data as well as other resources did not warrant the development of highly complicated modules. Secondly, the choice of appropriate models for the crop, erosion and hydrologic modules was constrained by the availability of field and catchment data for calibration and validation of model behaviour. Additionally, the biophysical components of the DSS had to be integrated with social and economic modelling components (Letcher et al. 2002). The strength of the assumptions made in the socioeconomic modelling did not warrant a detailed biophysical modelling approach. Overall, the aim was to establish, for given scenarios, the directions and magnitudes of changes in indicators.

Although considerable effort has been made to keep the biophysical models relatively simple in terms of model structure and the number of model parameters, the DSS is still quite complex, particularly in terms of the interactions between the models.

The aim with integrated models of this type should not be to provide absolutely accurate estimates. This task proves too difficult given the inherent complexity of natural systems and the scant data usually available.

The IWRAM DSS was developed through strong collaboration with government agencies and universities in Thailand and, as such, represents the state of the art in Thai river management and modelling. The application demonstrates a conceptually strong and potentially transferable approach to integrated modelling of catchment-management questions.

Perhaps the most successful aspect of this project was the partnership that emerged and strengthened over time. It had the cooperation and full engagement of all relevant government departments (including Land Development, Royal Irrigation, Royal Forestry, Agriculture and the Office of the National Water Resources Committee). The DSS became the focal point for joint workshops, planning sessions and training courses, all of which encouraged a better understanding and an integrated approach to catchment management. The DSS has provided a common framework for planning and assessment.

This monograph gives a detailed account of the IWRAM project and the development of the DSS. It also describes the general framework and underlying principles of integrated water-resources assessment, with a particular emphasis on Southeast Asia, with the intention that similar projects might be initiated in other parts of the region.

Chapter 2 gives the context for this project by describing the various policies governing natural-resources management in Thailand. It also presents details of the case study site, the Mae Chaem catchment in northern Thailand. Chapter 3 reviews the principles and approaches to integrated assessment of water resources.

The next few chapters present the technical details of the biophysical and socioeconomic models, as well as a description of the integrated DSS. The results of the case study are then presented in Chapter 10. Finally, the conclusions and lessons drawn from the project are presented in Chapter 11.

References

ADB (Asian Development Bank) 2001. Asian environment outlook 2001. Manila, Philippines, Asian Development Bank.

COAG (Council of Australian Governments) 1994. Communique, report of the working group on water resource policy. Canberra, COAG.

EC (European Community) 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for community action in the field of water policy (OJL 327, 22.12.2000).

Enters, T. 1992. Land degradation of resource conservation in the highland of northern Thailand: the limits to economic evaluations. PhD thesis, Australian National University, Canberra.

— 1995. The economics of land degradation and resource conservation in northern Thailand: challenging the assumptions. In: Rigg, J., ed., Counting the costs: economic growth and environmental change in Thailand. Singapore, Institute of South East Asian Studies.

Federal Agencies 2000. Unified federal policy for a watershed approach to federal land and resource management, October 18, 2000. US Federal Register, (202): 62566-72, 65p.

Godfrey-Smith, W. 1979. The value of wilderness. Environmental Ethics, 1, 309–319.

Greiner, R. 1999. An integrated modelling system for investigating the benefits of catchment management. Environmental International, 25, 725–734.

GWP–TAC 2000. Integrated water resources management. Stockholm, Sweden, Global Water Partnership, Technical Advisory Committee Paper No. 4.

Jacobs, J.W. 1995. Mekong Committee history and lessons for river basin development. The Geographical Journal, 161, 135–148.

Jakeman, A.J. and Letcher, R.A. 2003. Integrated assessment and modelling: features, principles and examples for catchment management. Environmental Modelling and Software, 18, 491–501.

Jakeman, A.J., Letcher, R.A., Newham, L.T.H. and Norton, J.P. 2005. Integrated catchment modelling: issues and opportunities to support improved sustainability outcomes. In: Water capital. Proceedings of the 29th Hydrology and Water Resources Symposium, 20–23 February 2005, Canberra. Canberra, Engineers Australia.

Krairapanond, N. and Atkinson, A. 1998. Watershed management in Thailand—concepts, problems and implementation. Regulated Rivers—Research & Management, 1, 485–498.

Letcher, R.A., Croke, B.F.C., Jakeman, A.J., Merritt, W.S. and Perez, P. 2002. IWRAM: an integrated modelling toolbox for considering impacts of development and land-use change in Northern Thailand. In: Proceedings of the first biennial conference of the International Environmental Modelling and Software Society (iEMSs 2002), Lugano, Switzerland, 97–102.

McKinney, D.C., Cai, X., Rosegrant, M.W., Ringler, C. and Scott, C.A. 1999. Modeling water resources management at the basin level: review and future directions. Colombo, Sri Lanka, International Water Management Institute.

MRC (Mekong River Commission) 1995. Agreement on the cooperation for the sustainable development of the Mekong River Basin. At <http://www.mrcmekong.org/pdf/95%20Agreement.pdf>.

— 2003. Basin development plan, Mekong River Commission. At <http://www.mrcmekong.org/programmes/bdp/bdp.htm>.

NBI (Nile Basin Initiative) 2003. International Consortium for Cooperation on the Nile—Nile Basin Initiative. At <http://www.nilebasin.org/iccon-overview.htm>.

O'Callaghan, J. 1995. NELUP: an introduction. Journal of Environmental Planning and Management, 38, 5–20.

SMHDP (Sam Mun Highland Development Project) 1994. Final report: Sam Mun Highland Development Project. Chiang Mai, Office of the Director, SMHDP.

Phantumvanit, D. and Sathirathai, K. 1988. Thailand: degradation and development in a resource-rich land. Environment, 30, 10–15 & 30–36.

Rosegrant, M.W., Ringler, C., McKinney, D.C., Cai, X., Keller, A. and Donoso G. 2000. Integrated economic–hydrologic water modeling at the basin scale: the Maipo River basin. Agricultural Economics, 24, 33–46.

Roth, A.D. et al. 1989. Second evaluation of Mae Chaem Watershed Development Project. Washington, DC, Development Alternatives Inc.

Russell, L. 1996. Appendix I. Current Commonwealth and State organisations, policies and programs. In: Managing Australia's inland waters. Canberra, Department of Industry, Science and Tourism, 111–121.

SADC (Southern African Development Community) 1995. Protocol on shared watercourse systems. SADC, 28/08/1995, at <http://www.sadc.int/index.php>.

— 2000. Revised protocol on shared watercourse systems. SADC, 7/08/2000, at <http://www.sadc.int/index.php>.

TDRI (Thailand Development Research Institute) 1995. Natural resources management in mainland Southeast Asia. Bangkok, TDRI.

TDRI–HIID (Thailand Development Research Institute–Harvard Institute for International Development) 1995. The economics of watershed management: a case study of MaeTaeng. Natural Resources and Environmental Program, TDRI and HIID.

Tungittiplakorn, W. 1995. Highland–lowland conflict over natural resources: a case of Mae Soi, Chiang Mai, Thailand. Society and Natural Resources, 8, 279–288.

UN (United Nations) 2000. Natural resource aspects of sustainable development in Thailand. United Nations system-wide web site on national implementation of the Rio commitments. At <http://www.un.org/esa/agenda21/natlinfo/countr/thai/natur.html>, accessed December 2000.

US EPA (United States Environmental Protection Agency) 2001. Protecting and restoring America's watersheds: status, trends, and initiatives in watershed management. Washington, DC, EPA.

Van der Zaag, P. and Savenije, H. 1999. The management of international waters in EU and SADC compared. Physics and Chemistry of the Earth, 24, 579–589.

Van Koppen, B. 2003. Water reform in Sub-Saharan Africa: what is the difference? Physics and Chemistry of the Earth, 28, 1047–1053.

Walker, A. 2003. Agricultural transformation and the politics of hydrology in northern Thailand. Development and Change, 34, 941–964.

CHAPTER 2

Natural-resource-management policies in Thailand and their use in the Mae Chaem catchment

BENCHAPHUN EKASINGH, WENDY MERRITT AND ANTHONY SCOTT

SUMMARY

THIS chapter presents an overview of the natural-resource policies for land and water management in Thailand. If the objectives of the Integrated Water Resource Assessment and Management (IWRAM) project were to be achieved, it was essential to gain a clear understanding of these policies, and how they influence catchment-management decisions in northern Thailand.

The second part of the chapter presents a description of the Mae Chaem catchment in northern Thailand, which was used as a case study for the IWRAM project.

Introduction

Thailand's past three decades of rapid economic development stimulated a massive expansion in the demand for water: for power, irrigation, and domestic and industrial supplies. This growing demand is expected to continue, with a predicted increase of more than 100% between 2000 and 2010 (Lorsirirat 2004). In the past, the government devoted significant resources to the development of these new water supplies. But a different and more complex set of challenges is now being faced. These include the following:

- Is the resource base, including both water and the catchment, being managed in a sustainable manner?
- Are there opportunities for more-effective management of existing sources of water supply?
- How is water allocation and utilisation determined, to ensure equitable distribution and efficient use of water?
- Who will provide and deliver services, and who will pay for them?
- How will the availability of water for agricultural, urban and environmental uses change under future land-management policies?

Other water-management problems, arising from agricultural intensification, are the related issues of on-site erosion and declining water quality. Traditionally, shifting cultivation did not significantly elevate soil erosion compared with undisturbed land (e.g. Lal 1975). However, under increasing hill-tribe populations, this system of cultivation has become more intensive, with the cultivation period increasing and the regeneration period decreasing (Liengsakul et al. 1993).

In the steep highland regions of northern Thailand, which are inherently prone to erosion, agricultural intensification has led to elevated rates of erosion (Turkelboom et al. 1997). In an effort to minimise the impact of agricultural (and other human) activities, various Thai Government agencies and departments have developed policies for the improved management of land and water resources.

If the objectives of the Integrated Water Resource Assessment and Management (IWRAM) project were to be achieved, it was essential to gain a clear understanding of these policies, and how they influence catchment-management decisions in northern Thailand. Hence, the first part of this chapter presents a summary of the natural-resource policies that shape land and water management in northern Thailand.

The second part of this chapter presents an overview of the Mae Chaem catchment in northern Thailand, which was used as a case study for the IWRAM project.

Background

In Thailand, recent awareness of the threats that human activities pose to the environment has sparked considerable efforts from government to conserve natural resources and promote sustainable development. This culminated in 1997 with the adoption of a new constitution that required every person to conserve natural resources and the environment as provided by law (UN 2000).

The government body responsible for coordinating the management and development of water resources at the national level is the National Water Resource Committee, which was set up in 1996. Its main functions are (UN 2000):

- preparing and submitting for cabinet approval objectives and policies for water resources development at all scales
- providing guidelines, support, and coordination to other agencies in preparing development plans or projects
- approving and overseeing the plans
- prioritising and controlling the allocation of water resources between sectors
- supervising and maintaining water quality
- improving laws and regulations related to the development, control and maintenance of water resources and their quality.

The government agencies that coordinate water-resource management and development at a policy level include the Royal Irrigation Department (RID), the Department of Mineral Resources (DMR), the Department of Rural Development (DRD) and the Department of Health. Provincial governors' offices and local administration offices operate at the district level, and administration organisations play a role at the sub-district level. Table 2.1 details the mandates of the relevant bodies with regard to water management.

The state of water resources is closely linked to land use and management, and both land and water resources must be managed concurrently if management is to be successful. For example, under the 8th National Social and Economic Development Plan, the Land Development Department (LDD) undertook, between 1997 and 2000, to promote sustainable agriculture by considering land-use planning, land- and water-conservation systems, erosion-control systems, integrated agricultural systems, improved cropping systems, and forest expansion and conservation.

Table 2.1 Functions of government agencies involved in water-resources management in Thailand (UN 2000)

Agency	Function
Royal Irrigation Department	Development of water resources and management of irrigation and drainage systems nationwide
Department of Mineral Resources	Management of groundwater resources nationwide
Department of Rural Development	Rural development, including domestic water development
Department of Health	Freshwater quality monitoring nationwide
Office of the Permanent Secretary of the Ministry of Public Health	Hospital waste management
Provincial Governors' Offices	Management of provincial natural resources
Local Administration Offices	Management of resources and environment within their jurisdiction
Sub-district Administration Offices	Management of resources and environment within their jurisdiction

In 1997, the Thai Cabinet adopted a 'Policy and prospective plan for enhancement and conservation of national environmental quality, 1997–2016', prepared by the Office of Environment Policy and Planning. The plan details goals, policies, and implementation guidelines for the effective use of land resources (UN 2000). In the plan, the Thai Government is committed to a number of policies relating to the development, conservation and rehabilitation of water resources. Concerning surface-water resources, these are:

- to develop and conserve surface- and groundwater sources at the basin level, taking into account socioeconomic and environmental impacts
- to improve the efficiency of administration and management of surface-water resources
- to promote optimal use of surface-water resources so as to maximise benefits and minimise environmental impacts.

Similarly, the plan explicitly promotes the sustainable use of groundwater resources.

With respect to fostering the linkages between national forest programs and land-management policy in the highlands, the LDD has an Office of Highland Development which, in cooperation with the Watershed Management Division of the Royal Forest Department, coordinates and facilitates the implementation of policies and programs related to the management of highland areas. Tasks include:

- preparation of land-use plans that clearly identify watersheds
- identification of land-development activities suitable for highland areas
- participation in the preparation of management plans for the management of river basins impacting on highlands
- preparation of highland area management plans for each province, district and sub-district.

A number of policy and management options have been investigated in an effort to overcome emerging environmental concerns. The main government agencies in Thailand involved in the implementation of policies for agricultural and other land uses are the RID, the LDD and, more recently, the Ministry of Natural Resources and Environment, which was established in 2002.

The National Economic and Social Development Plans

Over the past five decades, Thailand has produced a set of national economic and social plans to guide the development of the nation, and this included plans for the management of water resources. The 1st national plan covered the period 1961–66. During this period, the emphasis for water-resources development was on the construction of irrigation schemes and dams and hydro-electric power generation. This focus continued through the 1960s and 1970s. In the 7th and 8th national plans, between 1992 and 2001, there was a changing focus to a more integrated catchment approach to water management, with consideration of a broader range of issues such as water quality, increasing water-use efficiency, improved coordination of efforts by different government departments, and involvement of the local people in the planning process.

The 9th national plan (2002–2006) builds on the objective of a *balanced development of human, social, economic, and environmental resources*. A priority goal is pursuance of *good governance* at all levels of Thai society in order to achieve real and sustainable people-centred development. In relation to water-resources management, priority is given to:

- shifting from investment in additional water-supply schemes to better and more-efficient management of existing water supples, and promoting the sustainable management of all natural resources
- development of comprehensive catchment-wide water-management strategies rather than a project-by-project approach
- better pricing of water to encourage more-efficient use and less wastage
- increased public participation in decisions and formulation of policy.

The national water vision and policy

The National Water Resources Committee (NWRC) was set up to coordinate a national approach to water management. One of the initial tasks of the NWRC was to develop water-resource management plans, which would be coordinated by river basin committees (RBCs), for the 25 river basins across Thailand. A sub-committee was established for the Chao Phraya basin as a pilot scheme. The RBCs were to have three major responsibilities: addressing priorities in water resource issues; promoting public education and sustainable water-resources management; and facilitating local public consultations with stakeholders and beneficiaries. A master plan was to be developed for each river basin. Each plan will include details about:

- future water development—to alleviate water shortages
- water allocation and utilisation—to ensure equitable distribution and efficient use of water
- water conservation—to maintain and improve the environmental condition of natural watercourses
- flood mitigation—to reduce the loss of life and property in flood-prone areas
- improving water quality by reducing or eliminating sources of pollution
- salinity treatment—to address natural and anthropogenic problems of salinity
- improved wastewater treatment in urban and industrial areas.

In 2000, a national water vision and national water policy were also developed and approved by the government. The vision states:

> By the year 2025, Thailand will have sufficient water of good quality for all users through an efficient management, organizational and legal system that would ensure equitable and sustainable utilization of its water resources with due consideration on the quality of life and the participation of all stakeholders.

The aim of the national water policy was to translate this vision into practical actions. The following are some of the many issues covered by the policy:

- development of new laws and improvement of existing laws related to the management of water resources

- creation of water-management organisations both at national and river-basin levels: the national organisation is responsible for formulating national policies; the river-basin organisations are responsible for preparing water-management plans through a participatory approach.
- emphasis on suitable and equitable water allocation for all water-use sectors, and fulfilling basic water requirements for agricultural and domestic use
- provision and development of raw water resources while ensuring suitable quality and conserving natural resources and the environment
- promotion and support for participation, including clear identification of its procedures, and clear guidelines on the rights and responsibility of the public, non-government and government organisations in efficient water management
- acceleration of preparation of plans for flood and drought protection, including warning, damage control and rehabilitation.

Challenges of water-resources management in Thailand

In a report on the national implementation of the Rio commitments, the United Nations (2000) recognised that having so many agencies involved in water-resources issues, combined with poor coordination between the agencies, is a major hurdle for the Thai Government in its effort to reach its water-management objectives. Currently, water resources are administered and managed by eight different ministries, each with different priorities and programs that are sometimes overlapping or in conflict. The National Water Resources Committee lacks the authority or operating mechanism to oversee and coordinate these different groups. Inadequate and sometimes conflicting legislation is also a problem. Conflict management too is becoming an important issue. With an increasing level of consultation with stakeholders and local communities, many conflicts centred around environmental issues and compensation for those affected by development projects are occurring. These conflicts are expected to increase as competition for water intensifies in the future.

Efforts are under way to address these problems and promote efficient water allocation through the development of integrated watershed management (IWM) strategies and revisions of water laws.

Natural-resources classification systems

Land use and watershed classification are closely linked activities which play a significant role in the integrated management of natural resources. In Thailand, there are three key classification systems: the Watershed Classification System, a modified FAO framework for land evaluation, and the National Forest Zones classification.

Watershed classification system

In 1982, the Office of the National Environment Board (ONEB) was commissioned to devise a detailed national watershed classification system (Krairapanond and Atkinson 1998). Watershed classes were derived from topographic, soil, geology and forest maps and reflect the sensitivity of the land to erosion and other forms of degradation. Multivariate analyses were carried out to determine statistical relationships between variables and a general equation for the prediction of watershed classes (WSC) was determined as:

$$WSC = a + b.(\text{slope}) + c.(\text{elevation}) + d.(\text{landform}) + e.(\text{geology}) + f.(\text{soil}) + \text{forest}$$

where *a* to *f* are constants, and the landform variable reflects the recent erosion history (Krairapanond and Atkinson 1998).

Between 1985 and 1995, the total land area of the entire country was classified into watershed classes (WSC) 1–5 (Table 2.2). In 1995, the Thai Cabinet approved the use of this watershed classification system by all government agencies involved in land management.

However, it is important to note that the system classifies broad land areas and, before it can be used as a management tool, considerable work is needed to designate detailed land uses within each class. A detailed description of the watershed classification system is provided by Krairapanond and Atkinson (1998).

There have been some criticisms of this classification system (Sathirathai 1995), in particular that the guidelines are too crude to be used for land-use planning, as they do not provide sufficiently detailed information for management at a farm level. It has also been suggested that the classification should include socioeconomic and cultural factors.

Table 2.2 Watershed classification system implemented in Thailand

Class	Landform/erosion hazard	Land-use prescription
WSC1A	High elevation and very steep slopes. Extremely prone to erosion.	Comprise protected forest and headwater source areas. Should remain as permanent cover.
WSC1B	As above.	Similar physically and environmentally to 1A, although portions have been previously cleared for agriculture or villages. Special conservation and protection measures. Reforestation and/or agroforestry encouraged.
WSC2	Less subject to erosion than WSC1A or WSC1B.	Areas of protection or commercial forests. Logging and mining allowed within legal boundaries. Grazing and certain crop production can occur if soil-conservation measures are in place.
WSC3	Upland areas with steep slopes. Less prone to erosion than WSC2.	May be used, with appropriate soil-conservation measures, for commercial forest, grazing, fruit trees or certain crops.
WSC4	Gently sloping land.	Arable crops, fruit trees and grazing. Moderate need for conservation measures.
WSC5	Gentle slopes to flat areas.	Paddy fields or other intensive agricultural uses. Few restrictions.

Land evaluation and planning

For its land-use planning projects, the Land Development Department (Land Use Planning Division) in Thailand adapted the land-evaluation methodology proposed by the Food and Agriculture Organization of the United Nations (FAO 1976, 1983). While the approach still retains the structure of the FAO (1976) framework for land evaluation, it has been modified for use in Thailand to incorporate previous policies relating to forestry, particularly those concerning watershed classes.

FAO framework

The FAO (1976) framework for land evaluation sets out basic concepts, principles and procedures for land evaluation and is primarily designed to provide tools to support rural land-use planning. The framework defines principles on which land evaluation should be based (FAO 1976, 1983). Land suitability appraisals should explicitly consider the proposed land use and assess its long-term profitability and sustainability. These appraisals are defined by economic criteria and require a comparison of the outputs of, and the inputs needed for, different types of land use. A multidisciplinary approach is required to adequately represent the physical, economic, social and political context. Key to the evaluation framework is that multiple land-use types are compared to identify the optimal use.

The framework sets out the general procedure by which the suitability of a land type for different land uses can be classified (Figure 2.1). Land-use types are matched with land units to construct suitability classes. Land units reflect unique combinations of soil, vegetation, hydrology, landform and climate. In order to identify appropriate land uses, land units are assigned land-quality ratings (from very good [1] to very poor [5]). Land-quality ratings include factors such as erosion hazard or climate regime, and are compared with land-use requirements to give suitability classes of: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N). Land-use requirements express acceptable limits in terms of the land-quality rating (e.g. an erosion limit of 31.25 t/ha).

The LDD approach: defining land units

The Land Development Department in Thailand has developed a land-unit approach that defines the given yield of a crop for a particular land unit (or land-suitability class) based on the FAO land-evaluation procedures (FAO 1976). Liengsakul et al. (1993) applied the FAO framework to a district in the Chiang Mai province of northern Thailand to locate new sites for permanent cropland in the highlands.

The approach adopted by the LDD within the IWRAM project is illustrated in Figure 2.2. Data requirements are provided in Table 2.3. Defining land units is not a purely biophysical procedure. The land-use, irrigation, land-improvement and forest-policy maps are constrained by socioeconomic and political contexts in addition to the biophysical characteristics of the land. The incorporation of previous policies for land evaluation appears to be the major modification of the FAO framework. The land units that are derived are used to develop land-suitability classifications according to the FAO framework. The land-use requirements for a certain land use include the consideration of crop requirements (e.g. moisture availability), management requirements (e.g. soil workability) and conservation requirements. Key diagnostic factors used to develop land-quality ratings are listed in Table 2.4.

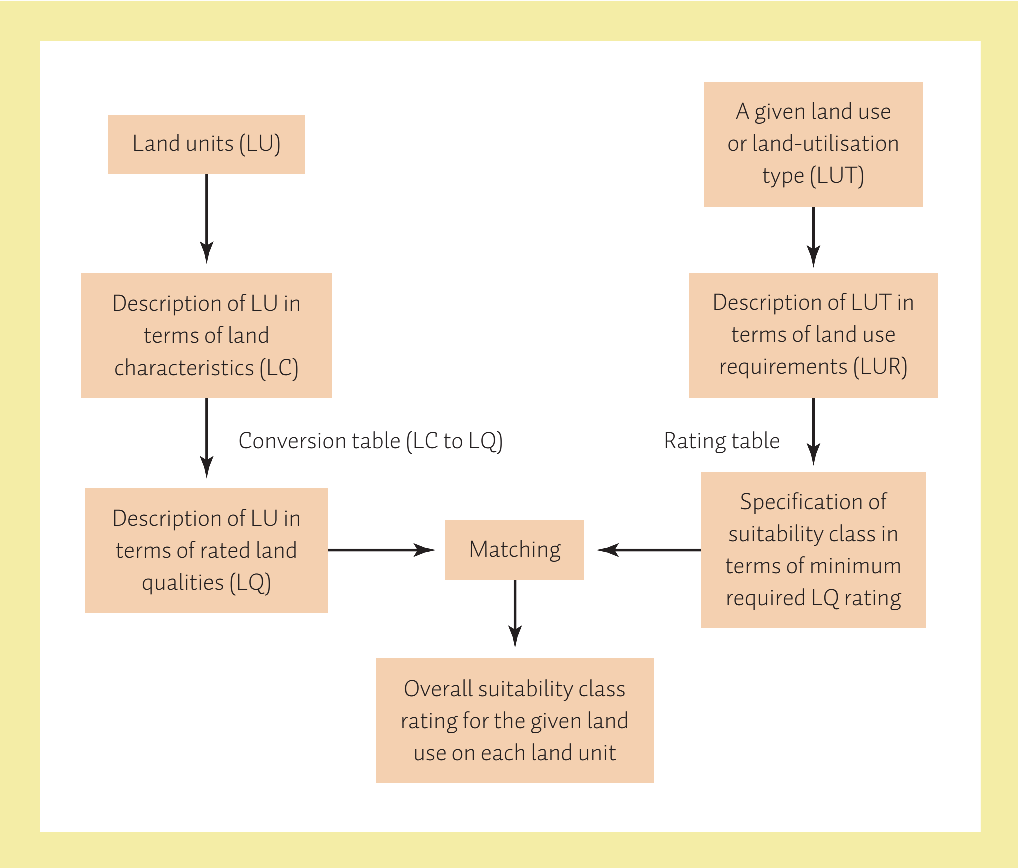


Figure 2.1 Schematic representation of the determination of the suitability of land units for a given use on the basis of land qualities. Source: van Diepen et al. (1991)

National forest zones

The Forestry Department and Land Reform Department classify forests into four zones:

A – those areas suitable for agricultural activities

B – areas designated for economic uses

C – conservation zones

N – not considered.

Natural and disturbed forests are managed differently in conservation areas than in other zones. In conservation zones and watershed classes 1 and 2, natural forest areas are protected, while in disturbed areas, reforestation—as either natural forests or plantations—is a priority. Areas currently forested are nominally protected in the remaining forest zones and watershed classes. If disturbed forest areas are unsuitable for alternative land uses, they are forested. Otherwise, the land can be used for agriculture, agroforestry or other appropriate land uses.

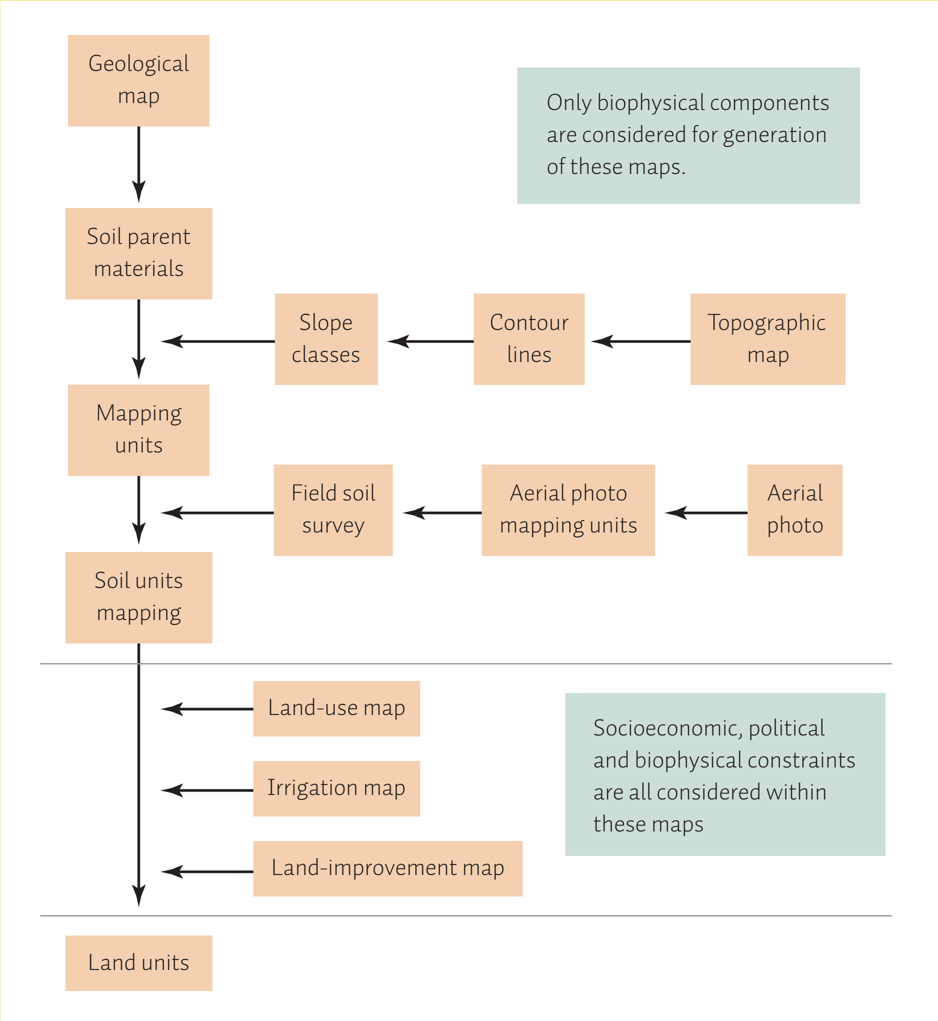


Figure 2.2 Procedure for the generation of 'land units' employed by the Department of Land Development (DLD) in Thailand. Source: DLD

Table 2.3 Mapping requirements for land-use planning in the highlands of northern Thailand

Material	Description of Mae Chaem data
Topographic map (1:50,000)	
Geological map (1:250,000)	
Soil unit mapping (1:10,000)	Generated from topographic and geological map, with the exception of Wat Chan for which a detailed soil map exists.
Aerial photo (1:15,000)	Used (along with ground surveys) as a 'ground check' of the soil map generated.
Land-use map (1:10,000)	Classifies land use according to paddy field, terraced paddy field, annual crop, perennial crop, shifting land, natural forest and plantation forest (LANDSAT imagery 1995–96).
Irrigation map	Indicates areas of rainfed and irrigated agriculture within the site (obtained from Land Development Department Division 6).
Land-improvement map	Land improvements include terracing and hillslope ditches (management improvements in the land-unit methodology include these two in addition to irrigation).

The Royal Project Foundation

The Royal Project Foundation (RPF) of Thailand was officially founded in 1991 by His Majesty the King of Thailand with the objectives of assisting hill tribes to:

- reduce the destruction of natural resources (forests and watersheds)
- stop opium production
- appropriately use the land (by farming only on suitable land)
- produce crops that benefit Thailand's economy (RPF 1995, 2004).

The RPF operates 4 research stations and 34 development centres across the Chiang Mai, Chiang Rai, Lamphun, Mae Hong Son and Phayao provinces. The research stations largely focus on developing crops that are suitable for the cooler, mountainous regions of Thailand and fostering cooperation between universities, government agencies and local hill tribes. The development centres concentrate on communicating to farmers recent results from the research stations, as well as encouraging the use of appropriate soil and conservation practices. Although not officially founded until 1991, the Royal Project has been operating in some form since 1969. Since that time, the organisation has been involved in the establishment of fisheries, land acquisition for needy farmers, development of irrigation structures, reforestation of water catchments, animal husbandry, education and improving medical standards. The RPF works closely with government departments, such as the RID, LDD and the Royal Forestry Department. The RPF played a key role in the IWRAM project, coordinating work and promoting communication between the various groups involved.

Table 2.4 Land-use requirements as prescribed by the Land Development Department, Land Use Planning Division Thailand. Source: Tansiri and Saifuk (1999)

	Land quality	Diagnostic factor
A. Crop requirements		
	Radiation regime	Radiation
	Temperature regime	Mean temperature in growing period
	Moisture availability	Requirements in growing period (mm), inundation (month)
	Oxygen availability	Soil drainage (class)
	Nutrient availability	Nutrient availability (N, P, K, organic matter), nutrient status (class), reaction
	Nutrient retention	Cation-exchange capacity, base saturation
	Rooting conditions	Effective soil depth (cm), watertable depth (cm), root penetration (class)
	Flood hazard	Frequency (years/episode)
	Excess of salts	Electrical conductivity of saturation (mmho/cm)
	Soil toxicities	Jarosite depth
B. Management requirements		
	Soil workability	Workability (class)
	Potential for mechanisation	Slope (class), rock outcrop (class), and stoniness (class)
C. Conservation requirements		
	Erosion hazard	Slope (class), soil loss (tonne/rai/year)

The Mae Chaem catchment

The Mae Chaem catchment, situated in the northwest of the Ping River basin (Figure 2.3), was selected as the focus for the first phase of the IWRAM project. The Ping River basin (33,900 km²) is one of the main feeders of the Chao Phraya River flowing south before being joined by the Nan River. As is typical of much of Thailand, and indeed much of the world, stakeholders in the Ping River basin are experiencing difficulties in developing policies to plan for the sustainable use of land and water resources (Jakeman et al. 1997). These difficulties are often exacerbated by the fact that the relationships between biophysical and sociocultural processes are highly complex, particularly the influence of changes in land use on natural resources (Enters 1995; Scoccimarro et al. 1999).

Figure 2.3 Regeneration on an abandoned upland field in the Mae Pan sub-catchment of the Mae Chaem catchment, northern Thailand. Photo by Integrated Water Resource Assessment and Management team

Human settings

In the Mae Chaem catchment, the population of the highland regions is comprised mostly of hill-tribe people (Karen, Hmong, Akha and Lisu), while in the lowland regions Thai locals are predominant. The hill-tribe population migrated from Laos, Myanmar and China over the last century.

Policy and management settings

The watershed classification of the Mae Chaem catchment (see Figure 2.4) shows that much of the catchment, particularly in the northern and western regions, has been classified as WSC1A. This class is to be protected from any exploitation of natural resources unless necessary for forest and ecological rehabilitation (Krairapanond and Atkinson 1998). All residents located in these areas were to be evacuated and relocated. This is not reflected in the land-cover maps from the late 1990s, where existing areas of agriculture within the region have remained, despite the policy of relocation.

Combined with forest zoning policy undertaken by the Land Reform Department (LDD, pers. comm. 2000), there is little remaining land available for development within the Mae Chaem catchment. This is illustrated in Figure 2.5 for the Upper Mae Yort sub-catchment (148 km^2) located on the western side of the Mae Chaem catchment. Overlaying the watershed classes (A) with the forest zoning plan (B) leaves two small areas (12.4 km^2) in the south of the catchment legally available for alternative land uses (C). Also, much of the existing agriculture from the 1997 land cover (D) would not be allowed.

Climate

Thailand has a monsoonal climate for up to seven months of the year (Turkelboom et al. 1997). Annual rainfall within the region is highly variable from year to year, ranging, for example, from 745 mm in 1993 to 1804 mm in 1994 at Ban Mae Mu. The wet season starts in mid-to-late May and extends through to October, reaching a peak in July–August (Figure 2.6). Approximately 95% of rainfall in the Mae Chaem catchment occurs during the wet season. The mean annual rainfall surface in Figure 2.7, generated using the ANUSPLIN program (Hutchinson 2000) and data from 79 stations in the Chiang Mai and Mae Hong Song provinces, shows a general trend of decreasing rainfall westwards across the catchment.

Topography

Elevation within the Mae Chaem catchment varies from 475 m to 2560 m above sea level (Figure 2.8), and slope ranges from 0° to 78°.

Land use

Three time slices (1985, 1990 and 1995) of land-cover information were obtained for the entire Mae Chaem catchment from the National Research Council (NRC) of Thailand. A summary of the land cover for these time slices is shown in Table 2.5. Between 1985 and 1990, the percentage of land classified as forest fell by 10%, from approximately 3380 km^2 to 2980 km^2. This was converted mainly to upland agriculture—fields and fallow fields—in the upper half of catchment, with slight increases in the amount of paddy.

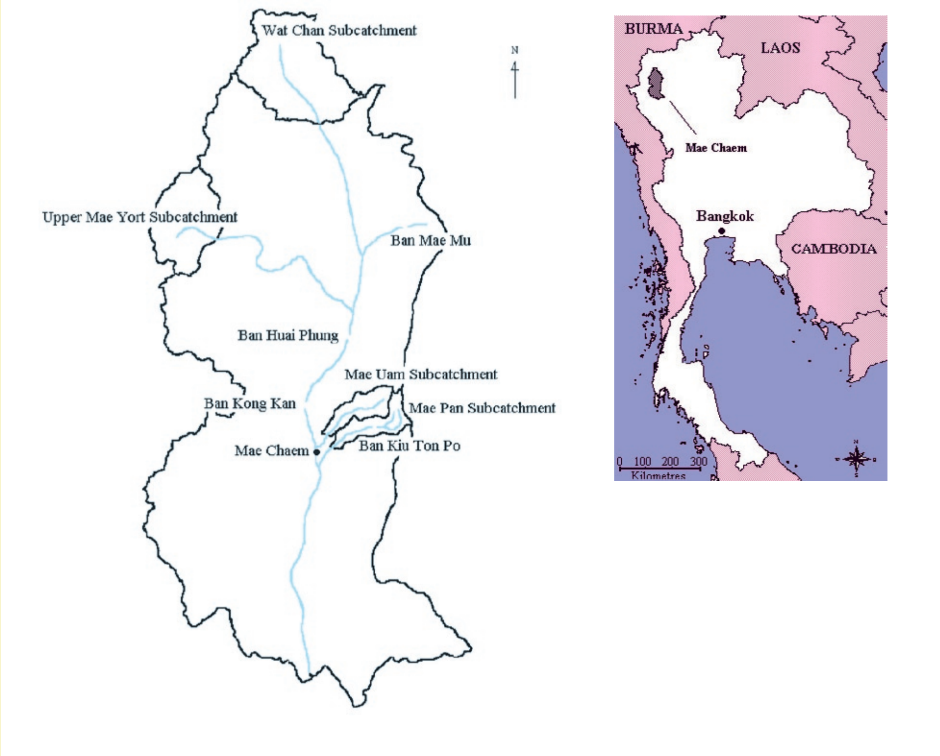


Figure 2.4 Location of the Mae Chaem catchment in northern Thailand

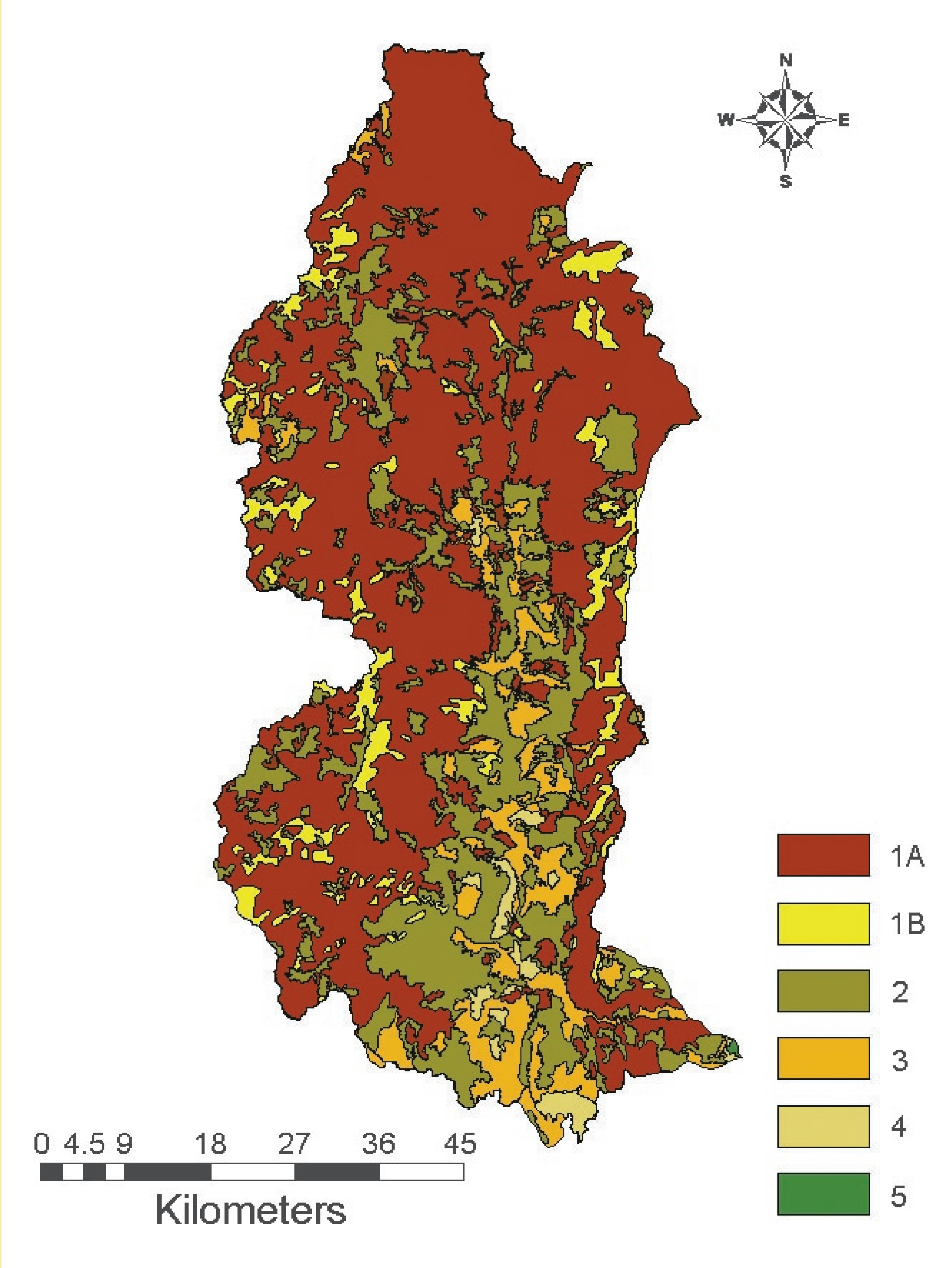


Figure 2.5 Watershed classes within the Mae Chaem catchment provided by the National Research Council of Thailand. Details of the watershed classes are provided in Table 2.2.

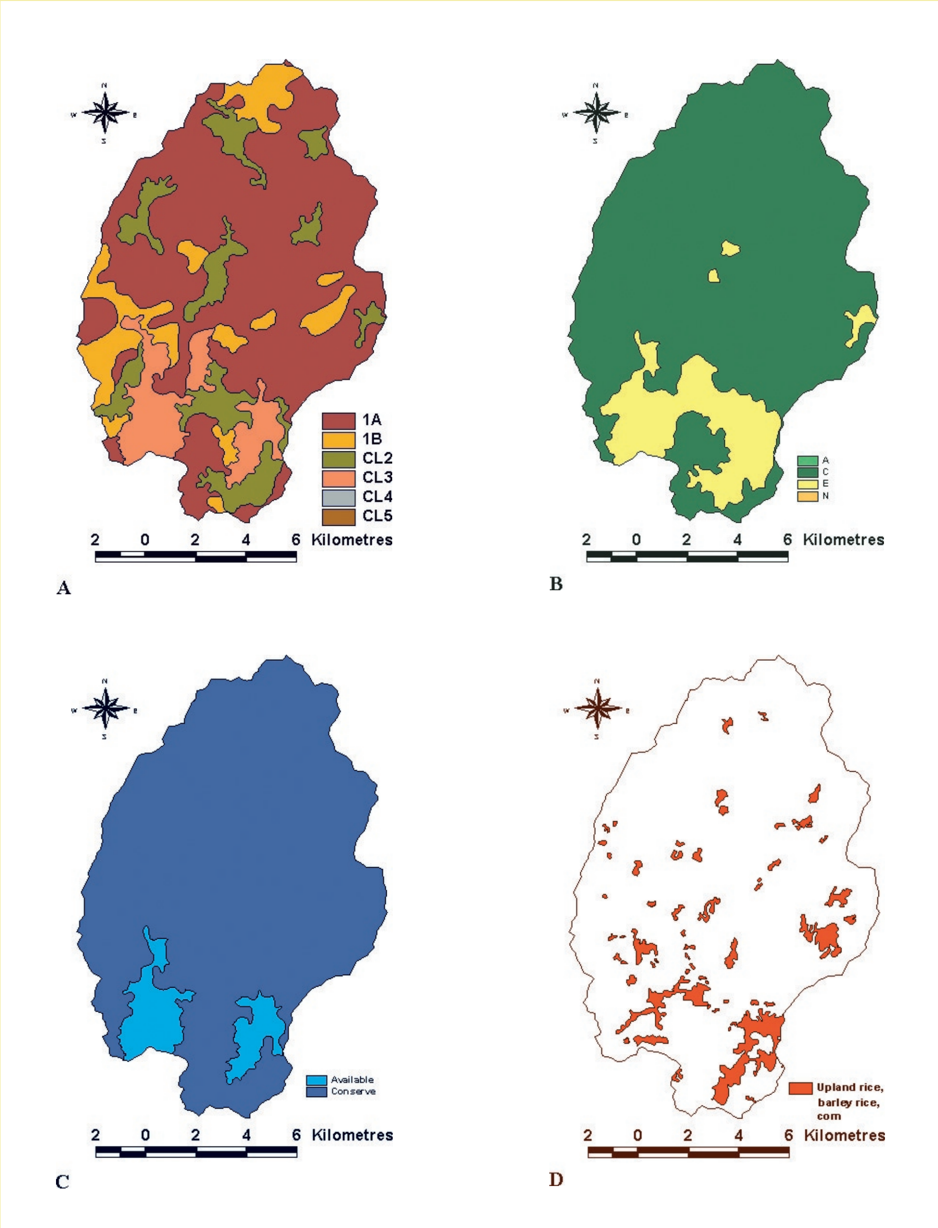


Figure 2.6 Policy effects on land availability for agriculture: A, watershed classes; B, forest zones; C, available land use; and D, 1997 agricultural areas within the Upper Mae Yort sub-catchment. Source: A, B and D were provided by the Land Development Department in Thailand.

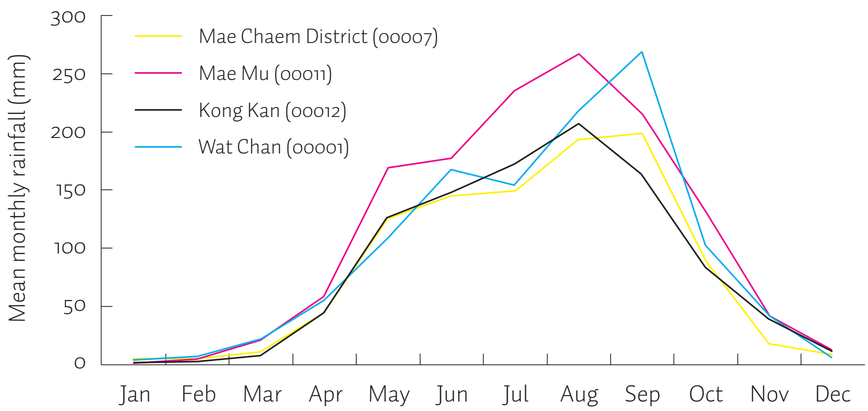


Figure 2.7 Mean monthly rainfall (mm) for four rain-gauge stations in the Mae Chaem catchment, northern Thailand

Table 2.5 Percentage land use for Mae Chaem catchment in 1985, 1990, and 1995 (original land-cover data were a product of the IGBP–START project and were provided to the Integrated Water Resource Assessment and Management project by the National Research Council of Thailand)

Land cover class	Percentage area		
	1985	1990	1995
Forest	88.07	77.71	79.80
Paddy	0.93	1.43	1.62
Urban	0.01	0.05	0.06
Upland field	5.17	7.49	5.77
Water	0.01	0.02	0.02
Upland fallow field	5.81	13.31	12.75

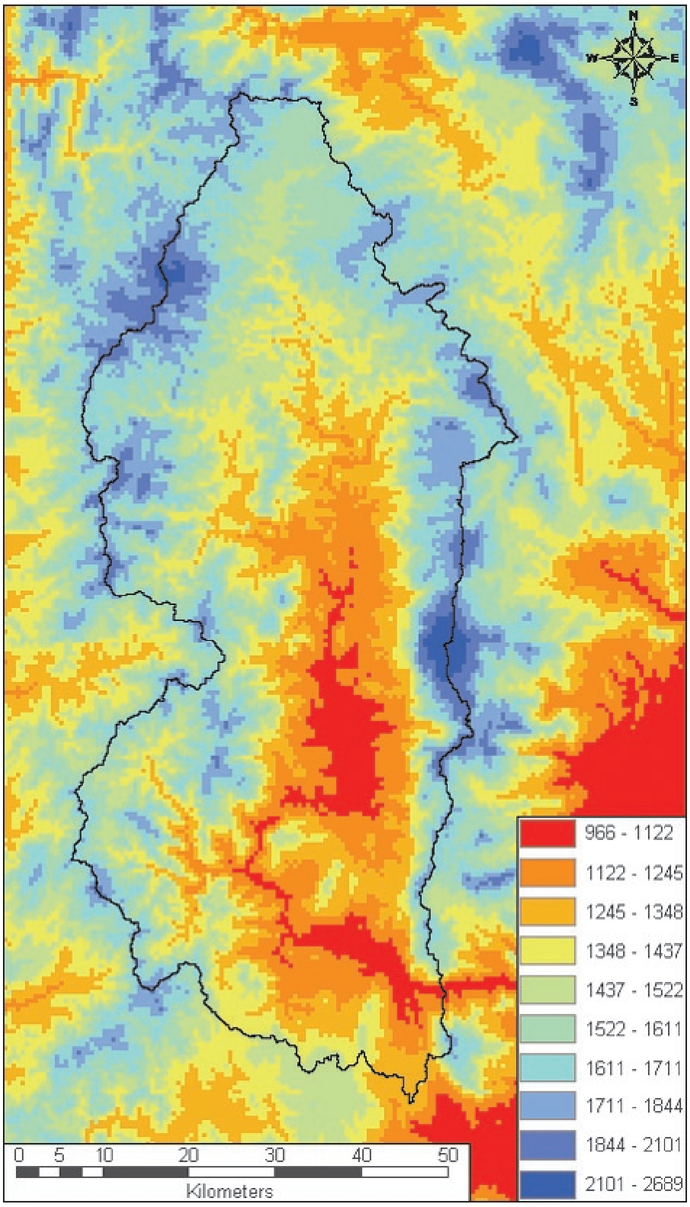


Figure 2.8 Map of mean annual rainfall (mm) across the Mae Chaem catchment and surrounding areas of northern Thailand

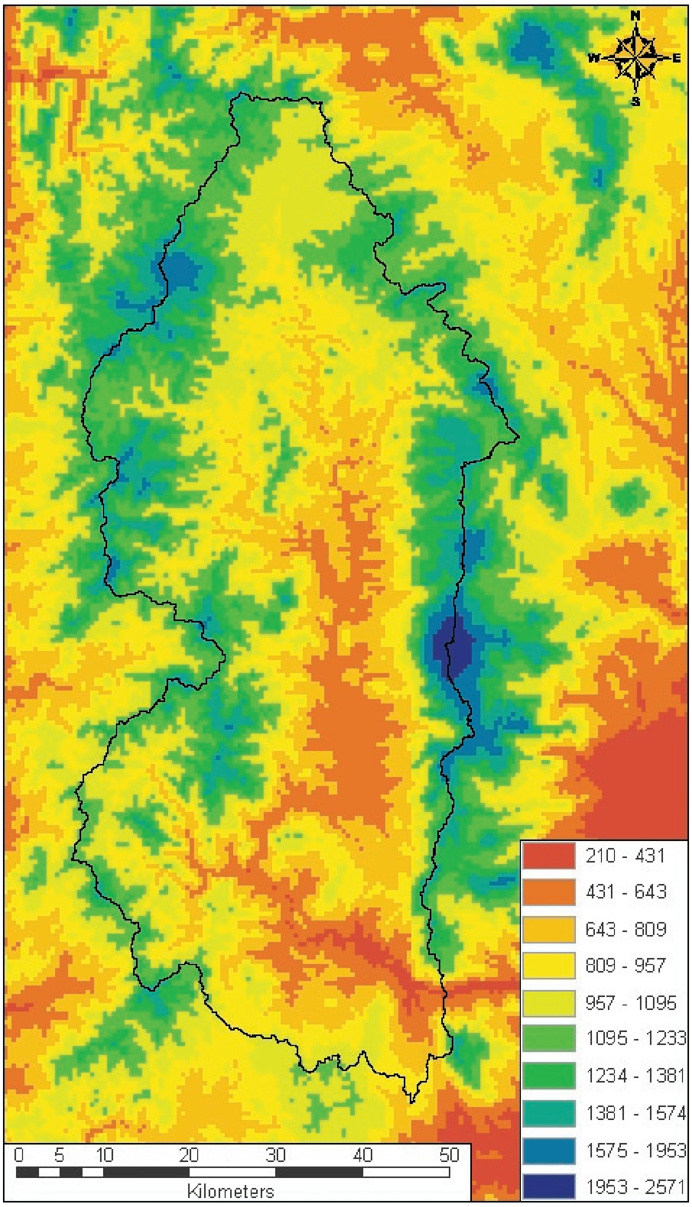


Figure 2.9 Digital elevation model for the Mae Chaem catchment, northern Thailand.
Source: Dr Somporn Sangawongse

There was relatively little change in land cover between 1990 and 1995, with slight increases in forest area observed. Agriculture within the Mae Chaem catchment predominantly involves the growing of crops such as upland rice, maize and some vegetables. Figure 2.10 shows some examples of these agricultural activities. Terraced agriculture commonly exists on moderately to steeply sloping lands (Figure 2.10A). Some fruit orchards exist within the catchment, such as the orchard shown in Figure 2.10B. On gently sloping lands, intensive agriculture such as paddy fields is undertaken (Figure 2.10C). Figure 2.10D shows mixed agriculture including a longan orchard and Figure 2.10E shows an upland rice field after harvesting. The major crop grown in the wet season is rice for subsistence purposes, combined with limited agricultural cash crops.

Figure 2.10 Examples of agricultural activities within the Mae Chaem catchment, northern Thailand: (A) terraced agriculture within steep headwaters; (B) remains of an orchard on a slope affected by mass movement; (C) intensive agriculture on paddy fields with furrow irrigation; (D) longan orchard near San Kieng village in Mae Pan; and (E) upland rice field after harvest. Photos A and C by S. Yu. Schreider, and B, D and E by W.S. Merritt

The Mae Chaem catchment has only relatively small-scale streamflow regulation compared with catchments located closer to Chiang Mai. Examples of engineering structures present in the catchment are shown in Figure 2.11. A common form of irrigation used on fields of low slope in the Mae Chaem catchment is the basin irrigation method (Figure 2.12), otherwise known as paddy irrigation (Stein 1979). This method requires the division of a field into small units with a level surface. Small banks (or bunds) 30–50 cm high are constructed around each unit to form a basin. For crops that require periods of inundation, such as paddy rice, the basin is filled with water that is retained until it infiltrates into the soil or until the farmer drains off the excess water.

Soils and land units

The LDD provided land-unit information for the Wat Chan, Upper Mae Yort, Mae Uam and Mae Pan sub-catchments of the Mae Chaem catchment. The dominant land unit in the sub-catchments is land unit 49 (dark green in Figure 2.13), which comprises silty textured soils on steeply sloping land. The Mae Uam and Mae Pan sub-catchments have a large proportion of low-sloping clay soils suitable for paddy agriculture (land units 88 and 99), although the extent of these land types is limited in the Wat Chan and Upper Mae Yort sub-catchments. Table 2.6 describes the soil and topographic classes of the Upper Mae Yort, Wat Chan, Mae Uam and Mae Pan sub-catchments and the areal extent of each land unit.

Figure 2.11 Examples of irrigation structures in sub-catchments of the Mae Chaem, northern Thailand: (A) a small irrigation canal in the Mae Pan sub-catchment; (B) a weir in the Mae Pan sub-catchment. Photos by W.S. Merritt, November 2000

Figure 2.12 Paddy agriculture in the Mae Chaem catchment, northern Thailand, showing small banks (bunds) bordering plots on gently sloping lands

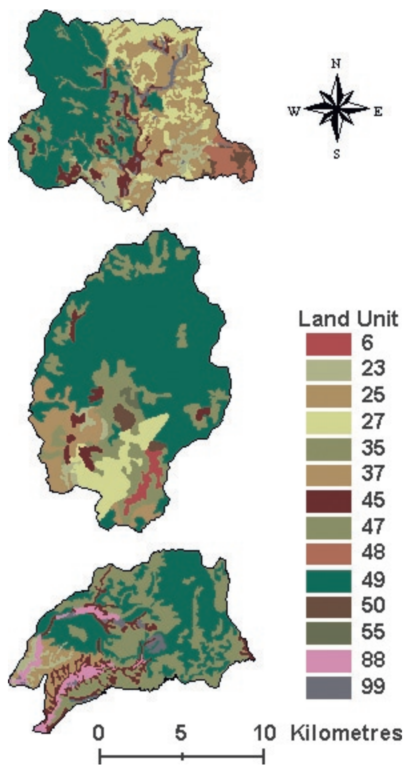


Figure 2.13 Land-unit classification for the Integrated Water Resource Assessment and Management study sub-catchments of the Mae Chaem catchment, northern Thailand (from top to bottom: Wat Chan, Upper Mae Yort, Mae Pan and Mae Uam sub-catchments. GIS coverages were provided by the Land Development Department, April 2000.

Discharge

There are five streamflow gauges in the Mae Chaem catchment, of which three were used in the development of the hydrology models. These stations were the Kong Kan, Huai Phung and Mae Mu stations (Figure 2.14). The Kong Kan sub-catchment drains an area of 2157 km^2 above Mae Chaem city—the largest urban settlement in the Mae Chaem catchment.

The Huai Phung catchment is located further upstream, draining an area of 1180 km^2, and the Mae Mu catchment is an upland catchment draining an area of 68.5 km^2. Table 2.7 shows annual discharge and run-off coefficients for the three stations. The data from the other two gauging stations were of dubious quality and were excluded from the analyses.

Table 2.6 Land units in the Mae Chaem catchment of northern Thailand. Source: provided by Land Development Department, April 2000

Land unit	Soil texture/description	Slope class	Wat Chan	Upper Mae Yort	MaeUam/ Mae Pan
6	Shallow loam and gravel soils	D or E	0.0	2.6	0.0
23	Deep loam soils	A or B	7.6	2.1	2.4
25	Deep loam soils	C	27.5	2.9	5.7
27	Deep loam soils	D or E	14.8	11.2	0.0
35	Shallow clay and gravel soils with 2–10% rock outcrops	C	0.0	5.8	0.0
37	Shallow clay and gravel soils with 2–10% rock outcrops	D or E	0.0	10.0	0.0
45	Deep clayey soils	A or B	6.9	3.7	7.6
47	Deep clayey soils	C	10.7	21.2	35.0
48	Deep clayey and gravel soils	B	4.0	0.0	0.0
49	Deep clayey soils	D or E	41.6	0.0	0.0
50	Deep clayey and gravel soils	D or E	1.8	0.0	0.0
55	Medium deep clayey and gravel soils	D or E	0.0	84.5	0.0
88	Deep clayey irrigated paddy soils	A or B	0.0	1.9	5.1
99	Deep clayey paddy soils	A or B	2.7	0.8	1.8

Note: A – 0–8%, B – 8–16%, C – 16–35%, D – 35–60%, E – > 60%

Conclusions

In most countries throughout the world, there has been an increasing realisation that water-resource and land-use planning can no longer be undertaken in isolation. In Thailand this has resulted in a number of government policies that aim to protect these natural resources and encourage sustainable development of agricultural systems.

However, there are many government departments and agencies that are involved in the management of land and water resources, and poor coordination of activities has been recognised as a major hurdle for the Thai Government. In addition, the exact impacts of forestry and agricultural activities on land and water resources are often hotly contested—due to a limited understanding of the key biophysical processes and complex

Figure 2.14 Discharge gauging stations in the Mae Chaem catchment, northern Thailand, used in the application of the discharge regionalisation procedure. The focus catchments of the Integrated Water Resource Assessment and Management project are shown. Mae Chaem city is indicated by the large dot.

Table 2.7 Run-off coefficients for the Kong Kan, Mae Mu and Huai Phung sub-catchments of the Mae Chaem catchment, northern Thailand

	Nam Mae Chaem at Ban Huai Phung	Nam Mae Chaem at Ban Huai Phung	Nan Mae Mu at Ban Mae Mu
Mean slope (°)	19	19	14
Forest area (km²)	2024	1113	65.0
Annual run-off (mm)	274	243	463
Average run-off coefficient[a]	0.23	0.20	0.34*
Long-term mean annual rainfall (mm)	1191	1214	1362

[a] Average run-off coefficient calculated over 1988 to 1994.

social characteristics of the catchment. Efforts are now under way to address these issues, and promote the sustainable management of water resources through the development of integrated watershed management (IWM) strategies and revisions of water laws. The techniques developed in the IWRAM project can help the various government agencies improve coordination and explore solutions to water resource conflicts, through the use of decision-support systems (DSS).

It is important to note, however, that the IWRAM DSS does not make decisions. Instead, it supports good decision-making by helping users to explore key relationships relevant to the various environmental and socioeconomic trade-offs in catchment management. Similarly, the DSS does not provide an 'optimal' outcome, as this is dependent on the perspective and objectives of the DSS user. By offering a transparent and repeatable process, it helps users to explore some of the expected and unexpected impacts of various policy options that are being considered by the government.

The Mae Chaem catchment is a typical example of the issues and pressures facing natural-resources management in northern Thailand. It provided a good case study for testing the IWRAM–DSS. The catchment also had the advantage of having relatively good sets of environmental, social and economic data available for use.

References

Enters, T. 1995. The economics of land degradation and resource conservation in northern Thailand: challenging the assumptions. In: Rigg, J., ed., Counting the cost: economic growth and environmental change in Thailand. ISEAS Environment and Development Series, 90–110.

FAO (Food and Agriculture Organization of the United Nations) 1976. Framework for land evaluation. Rome, FAO, Soil Bulletin 32.

— 1983. Guidelines: land evaluation for irrigated agriculture. Rome, FAO, Soil Bulletin 55.

Hutchinson, M.F. 2000. ANUSPLIN version 4.1. user guide. Canberra, Australian National University.

Jakeman, A.J., Saowapon, C., Jintrawet, A., Trisophon, K., Evans, J. and Wong F. 1997. Biophysical component of an integrated water resources assessment project in the Upper Chao Phraya headwaters, northern Thailand. In: Proceedings of the international congress on modelling and simulation (MODSIM 1997), Hobart, Tasmania, Australia, 687–691.

Krairapanond, N. and Atkinson, A. 1998. Watershed management in Thailand—concepts, problems and implementation. Regulated Rivers–Research & Management, 14, 485–498.

Lal, R. 1975. A brief review of erosion research in the humid tropics of south east Asia. In: Greenland, R., ed., Soil conservation and management in the humid tropics. John Wiley & Sons Ltd.

Liengsakul, M., Mekpaiboonwatana, S., Pramojanee, P., Bronsveld, K. and Huizing, H. 1993. Use of GIS and remote sensing for soil mapping and for locating new sites for permanent cropland—a case study in the highlands of northern Thailand. Geoderma, 60, 293–307.

Lorsirirat, K. 2004. Thailand. In: Land use classification for integrated watershed management. Asian Productivity Organization. (Paper initially presented at the APO seminar on land use classification for integrated watershed management, Seoul, Republic of Korea, April 2001.)

RPF (Royal Project Foundation) 1995. Royal Project Foundation booklet (Thai/English). Thailand, RPF, 38p.

— 2004. Projects undertaken through the initiative of His Majesty the King Bhumibol Adulyadej of Thailand. Thailand, RPF. At: <http://www.geocities.com/RainForest/Vines/1701/kingm12.htm>, accessed May 2004.

Sathirathai, S. 1995. Roles of property rights on the adoption of conservation practices in northern Thailand. TEI Quarterly Environment Journal, 3(2), 41–54.

Scoccimarro, M., Walker, A., Dietrich, C., Schreider, S. Yu, Jakeman, A.J. and Ross, H. 1999. A framework for integrated catchment assessment in northern Thailand. Canberra, Australian National University, Integrated Catchment Assessment and Management (ICAM) Centre, Working Paper 1999/1.

Stein, P. 1979. Small scale irrigation. Intermediate Technology Publications Ltd and International Irrigation Information Centre, 152p.

Tansiri, B. and Saifuk, K. 1999. Qualitative land evaluations. Bangkok, Thailand, Land Development Department.

Turkelboom, F., Poesen, J., Ohler, I., Vankeer, K., Ongpraseet, S. and Vlassak, K. 1997. Assessment ot tillage erosion rates on steep slopes in northern Thailand. Catena, 29, 29–44.

UN (United Nations) 2000. Natural resource aspects of sustainable development in Thailand. United Nations system-wide web site on national implementation of the Rio commitments. At <http://www.un.org/esa/agenda021/natlinfo/countr/thai/natur.html>, accessed December 2000.

van Diepen, C.A., van Keulen, H., Wolf, J., and Berkhout, J.A.A. 1991. Land evaluation: from intuition to quantification. In: Stewart, B.A., ed., Advanced in soil science, volume 15. Springer-Verlag, 139–204.

Principles of integrated assessment

REBECCA LETCHER, ANTHONY JAKEMAN AND BENCHAPHUN EKASINGH

SUMMARY

To meet the challenges of sustainability, catchment management and natural-resources management in general, requires an approach that utilises an integrated assessment of resource-use options and environmental impacts. The assessment must include the consideration of multiple issues and stakeholders and the key disciplines within and between the human and natural sciences, and multiple scales of system behaviour. Integrated assessment is an emerging discipline that attempts to address the demands of decision-makers for management that has ecological, social and economic values and considerations. This chapter outlines the principles of integrated assessment that were applied and extended in the Integrated Water Resources Assessment and Management project.

Highland village in northern Thailand, surrounded by small plantings of mixed crops and orchard tress, northern Thailand. Photo by Anthony Scott, June 2004

Introduction

In many regions of the world, the degradation of river basin catchments is having significant long-term impacts on the environment and agricultural productivity. There is an urgent need for a coordinated response. However, researchers and managers have lacked comprehensive tools for assessing all of the issues and impacts in a collective manner.

In the past, natural-resource decisions tended to be narrowly focused and disjointed—see, for example, Ewing et al. (1997). Earlier approaches failed to deal with the many interconnections and complexities within and between the physical and human environment. In the management of water resources, decisions focused on only a portion of the catchment and were implemented incrementally, with little consideration for the long-term impacts. Development activities concentrated on the physical control of water for economic gain, while environmental and social effects were, at best, given token consideration. Local communities were also rarely involved in decision-making processes. Integrated water-resources management (IWRM) and integrated catchment management (ICM) are management approaches that were proposed to deal with these issues. These concepts were introduced in chapter 1. They involve a holistic approach to management, considering multiple issues involving many stakeholders and interest groups and requiring the input of a range of sciences and social sciences. This integrated management approach requires consideration of many different types of impact trade-offs, and relies on a policy-focused approach to research and assessment that integrates understanding from many sciences and social sciences. This approach is referred to as integrated assessment (IA).

In the following sections, the features of IA are outlined, starting with different uses of the term 'integration'. A definition of the term 'integrated assessment' is also provided before the features and issues associated with IA are discussed.

What is integration?

In terms of modelling and assessment, there are at least five main types of integration that are referred to under the generic term 'integration', as summarised by Letcher and Bromley (2005) and Parker et al. (2002). The most demanding integration problems, such as those involving the wellbeing and equity of current and future generations, will involve all the types. Examples of each type of integration are presented below.

1. **Integration of models.** This requires combining two or more models of catchment processes at a variety of scales. These processes may be biological, chemical, physical, economic or social. Commonly, models may be combined to describe more than one aspect of the physical or biological features of the catchment, such as the surface- and groundwater systems. However, integration may also entail combining modelling techniques from a broad range of disciplines such as hydrology and economics. Obviously, this type of integration may embrace not just the integration of models but also the integration of different disciplines, scales and issues.
2. **Integration of disciplines.** This involves the integrated consideration of two or more disciplinary views of a catchment problem. For example, a hydrogeologist may consider a dryland salinity problem to be a consequence of deforestation in the upper catchment, whereas an economic view of this may be that off-site impacts of deforesting the upper catchment are not being incorporated in the decision to deforest. An integrated approach to such a problem typically needs to reconcile these two views of the causes and effects of the problem.
3. **Integrated treatment of issues.** Suggested management options for many catchment problems have impacts on other resource and environmental issues within catchments. For example, management options for dryland salinity often involve reforesting a significant proportion of the upper catchment. This may also reduce the amount of erosion in the upper catchment, improving water quality and reducing sediment and nutrient discharge to the lower catchment. However, large-scale reforestation may also affect the amount of run-off that is generated, potentially 'drying up' the catchment, and reducing water availability to downstream users. Considering the effects of management options on a range of resource and environmental issues within the catchment may improve management decisions and reduce the chance of unforeseen negative impacts.
4. **Integration of scales of consideration.** The resource and environmental components of a system may operate at different spatial and temporal scales.

While catchment boundaries may be most appropriate for considering hydrologically related issues such as run-off generation or erosion, social and economic boundaries are unlikely to coincide with these boundaries. Important processes in the economic system may occur in households or on farms, whereas social boundaries may follow electoral boundaries or may be linked to infrastructure such as roads and schools. Even within the physical system of the hydrological cycle, the ground- and surface-water systems operate at very different spatial and temporal scales. The surface-water system is likely to respond to a rainfall event within hours or days, while the groundwater system may continue to respond for many years. Treatment of issues at different scales requires some degree of compromise, and often a more simplified representation of parts of the system.

5. **Integration with stakeholders.** The level to which research outcomes are applied and adopted will often depend on how connected are stakeholders to the research output and how relevant research outcomes are applied to policy and extension activities. Integration with stakeholders may vary from simple education and communication of research findings to large-scale inclusion of stakeholder views and knowledge at all stages in a project (co-design).

These types of integration are not totally independent of one another. In many cases, the distinction between these types of integration is not clear. An integrated treatment of environmental, social or economic issues may require an integration of modelling techniques at a variety of scales. Some level of stakeholder integration is likely to be a feature of any integrated modelling exercise.

Features of integrated assessment

Integrated assessment has been defined as (Pahl-Wostl 2003, p.465) the:

> …integration of knowledge from different disciplines with the goal to contribute to understanding and solving complex societal problems, that arise from the interaction between humans and the environment, and to contribute in this way to establishing the foundation for sustainable development. Modelling and participatory processes should include stakeholder groups and the public at large.

Integrated assessment provides a vehicle for addressing all key issues affecting the sustainability of a catchment by combining the knowledge and understanding from different research areas, such as economics, psychology, ecology and hydrology. A better understanding of the complex interactions occurring within a catchment must include the needs and concerns of communities and industries, as well as the environment.

The key features of IA, summarised by Jakeman and Letcher (2003), are that it:

- is a problem-focused activity using an iterative, adaptive approach that links research and policy
- possesses an interactive transparent framework that enhances communication
- is a process enriched by stakeholder involvement and is dedicated to adoption
- connects complexities between the natural and human environment, recognising spatial dependencies, feedbacks and impediments
- attempts to recognise essential missing knowledge.

Tools and techniques are now available to assess the effects of resource use and management in an integrated way that provides good guidance for decision-making. The increasing availability of spatial databases and improving information technology are facilitators for such assessment. More importantly, the science of IA is maturing to the point where knowledge acquisition and practise of this discipline should now accelerate to provide positive benefits for assessing the ecological, social and economic effects of decisions, as well as guidance on the ways that management might be effective.

The role of models and decision-support systems in integrated assessment

The development and use of models is a major activity of IA. This is because people think and communicate in terms of models as simplifications of reality. The types of models include:

- data models that are representations of measurements and experiments
- qualitative conceptual models as verbal or visual descriptions of systems and processes
- quantitative numerical models that are formalisations of qualitative models
- decision-making models that transform the values and knowledge into action.

Figure 3.2 describes the role of models in IA and shows the links between policy and other stakeholder communities and researchers. Model conceptualisation can act as a focus for dialogue and communication of system understanding, issue definition and development of a shared understanding of trade-offs and impacts.

Documenting models and/or putting them into computer code makes their nature and assumptions more explicit and facilitates integration with other models. Such explicit models allow us to represent the complexities and interactions within human and environmental systems. When incorporated in computer software, models allow us to run scenarios more efficiently and, in particular, to calculate and assess the ensuing trade-offs among indicators of environmental, economic and social outcomes.

A major advantage of integrated models is their ability to capture the dynamics of the whole system, not just of individual components. This allows the exploration of feedbacks between different processes and models, such as the economic and physical systems or other processes occurring over different spatial and temporal scales.

Computer-based decision-support systems (DSS) can increase the value of models and information being used for integrated assessment. Ewing et al. (1997) describe DSS as 'computer based simulation models designed to enable the user to explore the consequences of potential management options'. The benefits of a DSS are in providing:

- a way of interconnecting different models and exploring trade-offs
- a library of integrated data sets
- a library of models, methods, visualisation and other tools
- a focus for integration across researchers and stakeholders
- a training and education tool
- a potentially transparent tool.

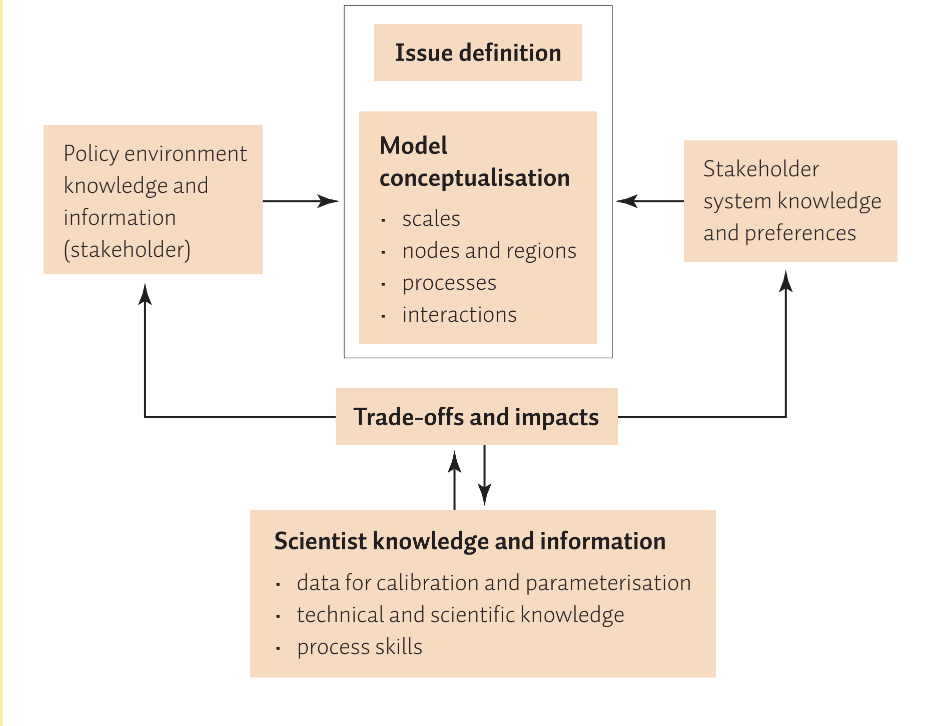


Figure 3.2 Models and their role in integrated assessment. Source: Letcher and Jakeman (2003)

Key issues in integrated assessment

What to include and what not to incorporate in an IA modelling activity should be determined at the outset as explicit considerations. The system being modelled should be defined clearly as well as its physical, socioeconomic and institutional boundaries. Boundary conditions can then be modelled as constraints or as input scenarios whose values can be perturbed in line with stipulated assumptions. Some of the following modelling considerations should commonly arise with respect to the management of natural resources:

- Climate variability and episodes – These often have a profound effect on outcomes. Variability can affect the returns of an investment in production as well as the response of an ecosystem, while episodes such as floods can have an inordinate effect on outputs. Both raise issues of appropriate time periods and time steps over which to model.

- Model process complexity – Once the basic processes and causal relations are decided upon, often there is still much scope for selecting the level of underlying detail, including the spatial and temporal discretisation. Data paucity, especially of system behaviour, should limit the model complexity. For example, in modelling of flow and transport, spatial data on catchment attributes may be very useful to structure and discretise a model in fine detail but this complexity is unwarranted if flux measurements used for model calibration cannot support the level of parameterisation—see, for example, Jakeman and Hornberger (1993).
- Beyond business-as-usual scenarios – The nature of environmental or social decline may mean substantial changes to the current situation are required. Other public and private investments, policy incentives and institutional arrangements will be needed to change resource activities.
- Modelling long leads and time lags – The time frames for returns on investments and for ecosystems to respond to changes affect both the period and the temporal resolution over which models are run and indicators computed.
- Narrowing modelling objectives – In addition to simplifying types of models, scales, system boundaries etc., it is critical to keep the level of integration of issues and disciplines manageable.
- Model uncertainty – It is desirable to reduce and, where possible, characterise uncertainty; the latter needs methodological attention by IA researchers.
- Error accumulation – This can occur in models when the outputs for one time step become the inputs for the next time step, and any errors or offsets can gradually accumulate. It also occurs when the outputs from one model are transferred to another model. Error accumulation is often ignored, but in reality can be a significant issue and deserves considerable attention.
- System representation – There is a need to balance the extent of the capacity to characterise feedbacks and interactions with keeping model components and linkages effective but efficient.

Recognising broad objectives

Given the complexities and uncertainties of integrated modelling, it should be accepted that its broad objective is to increase understanding of the directions and approximate magnitudes of change under different options. Typically, it cannot be about accepting or treating simulation outputs as accurate predictions. An advance that is required is to make possible qualitative differentiation between outcomes, with at least qualitative confidence; for example, a particular set of outcomes or indicator values might be categorised as overall better than, worse than or negligibly different from another set (for instance the do-nothing, current situation) with high, moderate or low confidence. This is enough to facilitate a decision as to the worth of adopting a policy or controllable change. Results from IA modelling must be able to differentiate between policies and specify what knowledge or data will provide leverage to improve the differentiation. Ideally, predictions would be produced with a quantitative confidence level, but in most situations this is impracticable at present. Currently, methods for quantifying uncertainties have limitations; Norton et al. (2003) and Jakeman and Letcher (2003) discuss new research required to address this deficiency.

Participatory modelling

Public participation can be defined as direct involvement of the public in decision-making. Clearly, it can occur at various levels. Arnstein (1969) describes a ladder of citizen participation. According to Mostert (2005) there are several reasons for organising public participation. These include the possibility of:

- more informed and creative decision-making
- greater public acceptance and ownership of the decisions
- more open and integrated government
- enhancing democracy
- social learning, the ultimate objective, to manage issues.

Mostert also states that it is important that public participation is organised well, so as to avoid limited and unrepresentative response from the public, disillusionment, distrust, less public acceptance, more implementation problems, less social learning, and complication of future participatory processes. He stresses the need for sensitive processes, taking into account the culture (e.g. natural and socioeconomic conditions, ideology) and subculture (e.g. environmentalists, industrialists, managers). He argues that if water management is to be participatory, research supporting water management should also be participatory. Not only should the public have access to research results, presented in an understandable way, but also it should have a say in what is researched and how, and participate in the research process itself.

Integrated assessment and 'independent' experts can provide an important and useful mechanism for raising the level and quality of public participation in environmental management. Involving communities in model development can not only add to the validity of the final model developed but also can create an opportunity for constructive interaction between stakeholders. This allows them a less-threatening focus for developing a shared system understanding than would interactions focused on resolution of specific environmental conflicts. An integrated model can capture a shared understanding of system processes and can allow people to manage disagreements about system assumptions. Delivery of models through software or development of a DSS can permit the model developed to be reused to make management decisions after the end of the research project. Conflict over management options can often be resolved as conflict over key system assumptions. In these cases, conflict may be managed by identifying areas of disagreement or gaps in knowledge, and by improving system understanding through targetted data collection or system observation. Any such resolution of the conflict is usually positively received by most stakeholders, as they feel their concerns were heard and responded to by the process.

In the setting of targets to achieve greater sustainability, subjectivity, uncertainty, potential conflicts and the specifics of the river basin all imply that a process is required that must involve continuing choice for the community. There will always be trade-offs to be identified across a multidimensional spectrum of possible system states. Selection of targets may initially be based on a relatively narrow vision, but eventually should be based on broad perceptions of benefits and costs. The selection should also be moderated by the quality of existing knowledge and the capacity to effect actions to meet those targets. This means that all targets are interim, and the process of both assessment and management must explictly allow for improved knowledge and understanding, as well as new conflicts and issues arising as old solutions cause new, unforeseen problems. A long-term vision of the aims of assessment and management, and monitoring for both improvements in sustainability and unforeseen consequences of actions, are necessary to create sustainable landscapes. Landscapes evolve, so solutions that improve short-term sustainability may be inadequate or may become problematic in the long term. Management and assessment processes must acknowledge and embrace the dynamic nature of landscapes.

Adaptive management

Adaptive management (Holling 1978) and active adaptive management (e.g. Allan and Curtis 2003) are laudable principles with the potential to improve our management of the environment through learning. With respect to modelling, adaptive management can involve the development of: ways to gather, record and share conventional and unconventional environmental system information; improved tools to capture and express qualitative knowledge; methods for testing knowledge, identifying gaps and designing experiments; development of monitoring techniques able to distinguish the effects of changed management practices from the large natural variations associated with most systems; approaches to screening and testing a broad range of alternative policies; and incorporation of the principles of feedback control to achieve acceptable behaviour insensitive to disturbances and modelling error.

In essence, adaptive management can usefully be about developing management-revision principles, experiment designs, outcome indicators, and monitoring practices to achieve sustainable management in evolving environments. This must include the monitoring and evaluation of active and passive experiments to see what does and does not work and where there are gaps.

Some of the essential issues confronting adaptive management can be identifited by examining what factors are crucial in the long-established use of designed feedback in control engineering:

- simplification of dominant behaviour
- measurement of the output variables whose behaviour is to be controlled
- consideration of robustness of control-system performance
- observability and controllability
- comparison between measured and desired output to determine error and the formation of control action.

Such ideas are commonplace in control engineering, but it is suprising how little discussion there has been about their relevance to environmental modelling and management.

Targeting disciplinary gaps

We know some of the important information that needs to be gathered to progress the management of sustainability through IA. The social sciences can offer insight and information into decision-making and adoption processes previously ignored in many scenario-based models. In particular, social survey data, linking information about decision-making and adoption to the biophysical and socio-economic characteristics of farmers, industries or households, is crucial to developing more sophisticated integrated scenario modelling and other policy analyses (e.g. Allan and Curtis 2003). Very little of this type of data exists for river basins. In addition, biophysical scientists are often not in a position to extract and understand the implications of such data. Further use and development of participatory methods (e.g. Haslam et al. 2003) for integrated model building is one way of extracting and using such information. These techniques have the bonus of allowing stakeholders into the model development phase, to ensure they have a better understanding of, and opportunity to feed into, the assumptions underlying these types of models. Hare et al. (2003) present one of the recent comparisons of different participatory processes.

Artificial-intelligence techniques offer an interesting and useful alternative to theory-based models of socioeconomic processes. Many economic and social models are based on theoritical assumptions of the drivers of decision-making, such as maximisation of profit or utility. These models can be very difficult to validate, as sufficient information on people's responses to changes in the components of the system of interest is often not available. Artificial-intelligence techniques offer an opportunity to develop data-driven models of these processes, through use of interview and survey data. This development would then allow testing of the performance of these models and the management recommendations arising from them. Importantly, it is possible to investigate whether or not the management recommendations coming from theory-based socioeconomic models differ from those derived from data-driven modelling approaches, or whether the relative differences in system performance are similar regardless of the approach used. This would allow more-focused development of these approaches for management, and would assist modellers in determining the appropriate level of complexity to add to these models, giving a better grasp of the robustness of the approaches they currently apply.

Discussion and conclusions

Effective and equitable management of our natural resources has many dimensions. Integrated assessment is a process that attempts to address these dimensions and the need for more informed management. Integrated assessment modelling and information systems recognise the complexity of natural systems and human interactions with them. The following are our conclusions about the development of IA:

- Analysis frameworks for characterising integration problems have come of age, but there is still much that is problem-specific: scales, models and their linkages vary. However, it is mainly by continuing to perform IA on specific problems that this emergent discipline will fully mature.
- There is a need for more-comprehensive model testing and, in particular, the development and application of methods for quantifying the sensitivity and uncertainty associated with the results. For complex, data-deficient systems of the type that occur in IA problems, this is a challenge that is essential to meet.
- Data availability is a severe constraint for obtaining more-informed and confident decision-support, and this was a particular issue in northern Thailand. Typically, more measurement information is required about system behaviour such as fluxes of water and pollutants, as well as key information on social and economic systems within catchments.
- Further core disciplinary research is required which targets the questions that need to be answered by researchers in IA:

for example, in socioeconomic models, how to incorporate aspirations and capacity for change; and in biophysical models, how to make flow prediction in ungauged catchments.

- Software platforms that facilitate the IA process are being developed, but more work and technical support of products are required. Platforms that integrate spatial data with modelling and facilitate model reuse and integration are a priority.

How much, however, should we expect IA to take a similar form in Southeast Asian countries to that in the West? Even within the broad principles outlined in this chapter, there is considerable diversity among Western countries in management and hence in some of the IA methods required. Across Australia, for instance, different States have different approaches to the structure and operation of their catchment management. At the scale of large river basins around the world, the Murray–Darling Basin Commission, the Columbia River basin, the Great Lakes, and the Fraser River basin (Dorcey 2004) have adopted somewhat different structures, necessarily because of differences in their institutional settings and the issues they address.

Some of these differences in approaches to management are due to scale. Face-to-face processes are workable in small catchments (Landcare scale), but highly institutionalised forms representing governments and other established organisations (e.g. Murray–Darling Basin Commission, Columbia River Task Force, Mekong River Commission) have so far been chosen for large catchments. Such structures may or may not be supplemented with broad public-participation processes.

On what dimensions is IA likely to develop differently in Thailand and Southeast Asia? Different legislative and administrative frameworks will certainly have a bearing, but need not be limiting. Approaches to participation will need to be somewhat different and (as in Western countries) cater for differences in political culture, social structure and scale. In information terms, Southeast Asian countries have far less extensive and reliable biophysical and socioeconomic data available to assess the state of the environment and the potential impacts of planned interventions and unplanned changes. Even data known to exist may be hard to procure. With such data quantity and quality problems it will be necessary to rely more on subjective, expert advice about biophysical outcomes in relation to the effects of different resource use and management. In particular, simpler biophysical models with modest input requirements must be developed and their uncertainties quantified and communicated as far as practicable.

An important question is how appealing IA and other forms of integrated resource management will prove in Thailand. Incentives in other countries have included resource-use conflicts, such as conflicts between upstream and downstream water users, or recognition of land degradation on a scale that requires a co-operative solution. These ingredients are certainly present in northern Thailand, where concerns about forest cover, water resources, and the agricultural activities and livelihoods of the ethnic groups of the mountains, meet. They are also present in surrounding countries, especially with respect to the water resources of the Mekong River. There is no reason to assume, however, that the introduction of IA will ensure that the environmental and social considerations integral to the process will be assessed on an equal footing with the more conventional logic of 'economic development'.

The following chapters on the Integrated Water Resources Assessment and Management project in Thailand illustrate the potential value of IA and the associated modelling in quantifying the biophysical and socioeconomic impacts that may result from management interventions and uncontrollable factors.

References

Allan, C. and Curtis, A. 2003. Learning to implement adaptive management. Natural Resource Management, 6, 23–28.

Arnstein, S. 1969. A ladder of citizen participation in the USA. Journal of American Institute of Planners, 35, 216–224.

Dorcey, A.H.J. 2004. Evolution of estuarine governance in a metropolitan region: collaborating for sustainabillity in the Fraser River estuary. In; Groulx, B.J. et al., ed., Fraser River delta, British Columbia: issues of an urban estuary. Geological Survey of Canada Bulletin, 567, 247–263.

Ewing, S.A., Grayson, R.B. and Argent, R.M. 1997. Research integration in ICM: review and discussion document. University of Melbourne, Australia, CEAH Report 1/97.

Hare, M., Letcher, R. and Jakeman, A.J. 2003. Participatory modelling in natural resource management: a comparison of four case studies. Integrated Assessment, 4(2), 62–72.

Haslam,S.A., Eggins, R.A. and Reynolds, K.J. 2003. The ASPIRe model: actualising social and personal identity resources to enhance organisational outcomes. Journal of Occupational and Organisational Psychology, 76, 83–113.

Holling, C.S., ed. 1978. Adaptive environmental management and assessment. Chichester, UK, John Wiley & Sons.

Jakeman, A.J. and Hornberger, G.M. 1993. How much complexity is warranted in a rainfall–runoff model? Water Resources Research, 29, 2637–2649.

Jakeman, A.J. and Letcher, R.A. 2003. Integrated assessment and modelling: features, principles and examples for catchment management. Environmental Modelling and Software, 18, 491–501.

Letcher, R.A. and Bromley, J. 2005. Typology of models and methods of integration. In: Giupponi, C., Jakeman, A.J., Karssenberg, D. and Hare, M., ed., Sustainable management of water resources: an integrated approach. Edward Elgar, in press.

Letcher, R.A. and Jakeman, A.J. 2003. Application of an adaptive method for integrated assessment of water allocation issues in the Namoi River catchment, Australia. Integrated Assessment, 4, 73–89.

Mostert, E. 2005. Participation for sustainable water management. In: Giupponi, C., Jakeman, A.J., Karssenberg, D. and Hare, M., ed., Sustainable management of water resources: an integrated approach. Edward Elgar, in press.

Norton, J.P., Nathan, R., Podger, G. and Vertessy, R. 2003. Sensitivity assessment needs of complex simulation models for integrated catchment management. In: Post, D.A., ed., Proceedings of the modelling and simulation society of Australia and New Zealand, MODSIM 2003, Townsville, Queensland, 14–17 July, 4, 1667–1672.

Pahl-Wostl, C. 2003. The importance of the human dimension in integrated assessment models and processes: actor based analysis and modeling approaches. In: Post, D.A., ed., Proceedings of the modelling and simulation society of Australia and New Zealand, MODSIM 2003, Townsville, Queensland, 14–17 July, 2, 465–472.

Parker, P., Letcher, R.A., Jakeman, A.J. et al. 2002. Progress in integrated assessment and modelling. Environmental Modelling and Software, 17, 209–217.

Designing the Integrated Water Resources Assessment and Management project framework

Requirements and their implications

REBECCA LETCHER, SUSAN CUDDY AND SANTHAD ROGANASOONTHON

SUMMARY

DECISION-SUPPORT systems (DSS) are a common tool for formalising system knowledge or understanding and delivering this to a decision-making user group. These systems are commonly computer-model based, although it is possible to produce non-computer-based DSS. Designing a DSS requires consideration of the user group, the problem focus of the research and the requirements these place on both component models and the integrative framework underlying the system. This chapter provides an introduction to the DSS framework, the approach adopted and its components. The component models are described in detail in chapters 5–8.

Introduction

In northern Thailand, agricultural expansion has produced competition for water at various scales and has resulted in erosion problems, downstream water quality deterioration, groundwater depletion, biodiversity loss, and shifts in the distribution of economic and social wellbeing and equity. The monsoonal nature of rainfall also intensifies demand for water in the dry season and, with the seasonal shift in flow regimes, especially at larger scales where dam regulation is more considerable, this exacerbates the impacts on in-stream biodiversity and habitat.

The Integrated Water Resource Assessment and Management (IWRAM) project developed a methodology to assess these issues. The project's environmental and socioeconomic assessment capabilities focused on the development of decision-support software designed to address the issues which commonly arise in each stakeholder's decision-making—and especially where their responsibilities and activities affect one another. Attention was given to the issues of water supply, erosion, rice deficit and farm income in relation to input drivers such as climate, commodity prices, technological improvements, government regulations and investments. Data collection focused on the subcatchment scale (approx. 100 km^2) within the Mae Chaem catchment (4000 km^2) in northern Thailand (Figure 2.4). Decision-support system (DSS) development has occurred in phases, with several different products being generated using the same integration concepts to meet different delivery and adoption requirements.

The main stakeholder focus for the DSS was the Land Development Department, which aims to utilise the DSS to assist its land-use planning activities. However, other government agencies and universities also became involved in the development of the DSS, and this provides them with the capacity to undertake their own integrated assessments of future development and policy scenarios. Adoption by government departments and universities was facilitated by training workshops on both the individual model components and the DSS itself. The development of the DSS had three primary objectives:

- to provide a common tool for the government agencies concerned with water-resource management
- to investigate the benefits and impacts of land-use change and land conversion that might occur in the catchment
- to recommend alternative crops and management practices for sustainable land and water management, as well as income sustainability.

Requirements of the Integrated Water Resource Assessment and Management decision-support system

The term 'decision-support system' has been used to describe a number of different approaches to the provision of information for decision-making for many types of systems, including environmental, health and business systems. Many authors have attempted to provide a definition of the term, to the point where the definition is arguable—see, for example, Simon (1973), Lowes and Bellamy (1994), Abel et al. (1996), Gough and Ward (1996), Kersten and Micalowski (1996), Wu (1996), Ewing et al. (1997) and Rizzoli and Young (1997). The definitions provided in the literature range from the view that any computer-based system that supports decision-making is considered to be a DSS, to the other extreme where a DSS is considered to be a system which has modelling capabilities and is used by decision-makers to solve unstructured problems (Kersten and Micalowski 1996). A more general definition provided by Ewing et al. (1997) is that DSS are 'computer based simulation models designed to enable the user to explore the consequences of potential management options'.

Rizzoli and Young (1997) provided a review of environmental DSS and suggested that an ideal DSS should have a number of properties. It should assist in decision-making for unstructured and semi-structured tasks and support and enhance managerial judgment. A DSS should be aimed at improving the effectiveness, rather than the efficiency, of decision-making. It should combine the use of models or analytical techniques with data access functions while still focusing on the features that provide ease of use for inexperienced users. Lastly, it should be flexible and adaptable to allow for changes in the decision-making context.

Decision-support systems generally include three main components: a database, a model base and a user interface. The model base can include features to aid in connecting tools and models. Kersten and Micalowski (1996) stress that a DSS should be simple and consistent, stating that a DSS should 'present a simplified version of the problem to the decision maker while maintaining its underlying complexity' and asserting that DSS should be consistent in their representation of processes and calculation of solutions and that the needs of the user must be addressed by the DSS.

Rizzoli and Young (1997) propose that the desirable features of environmental DSS, when intended only as an end user application, are:

- the ability to deal with spatial data—that is, the inclusion of a geographic information system (GIS) component
- the ability to provide expert knowledge specific to the issue of interest
- the ability to be used for diagnosis planning, management and optimisation
- the ability to assist the user during problem formulation and the selection of solution methods.

Where the DSS is intended as a development tool, Rizzoli and Young (1997) suggest that two additional properties are of interest:

- the ability to acquire, represent and structure the issue of interest.
- the capacity to separate data from models for model re-usability and prototyping.

The properties identified by Rizzoli and Young (1997) are all technical requirements on the construction of the DSS and, by extension, on the software used to create the DSS. El-Swaify and Yakowitz (1998) provide a less technically based introduction to multiple objective DSS suggesting that

> Ideal decision tools for valid recommendations on land, water, and environmental management must include quantitative and analytical components; must span and integrate the physical, biological, socioeconomic, and policy elements of decision making; and must be user-friendly and directly relevant to client needs.

The IWRAM framework is a DSS that uses an integrated scenario modelling approach, rather than an optimisation-based approach. That is, the DSS framework has been developed to consider 'what if' questions relating to policy and management of the system, rather than to provide the model user with the 'best' option under given criteria. It should be noted, however, that optimisation-based applications could be developed using the same framework but would require a different 'front-end' or decision-support platform.

The framework needed to bring together knowledge and understanding of the key issues facing the catchment in the short, medium and long terms. It needed to represent the key biophysical processes in the catchment that support analysis of the key issues, as well as key social and economic motivators, dependencies and impacts. It also needed to provide meaningful and compatible measures (indicators) to assess the likely impacts of various scenarios within the catchment, as well as to capture the linkages between processes and their representations.

The IWRAM framework achieves this through:

- scenarios that capture the key issues under investigation
- models that simulate key biophysical processes and have predictive capability
- models that simulate key socioeconomic processes and have predictive capability
- indicators that support impact assessment and comparison of scenarios
- an integrating engine that links scenarios, models, data and indicators, and supports 'what if' analyses.

Figure 4.1 shows the linkages between the IWRAM approach and the IWRAM framework.

The sophistication and complexity of the models and the integrating engine are totally dependent on the selection of scenarios and indicators, themselves dependent on the particular application.

The design of the DSS was based around three basic concepts:

- the DSS outputs were to allow spatial analysis and display
- the DSS must be easy to modify and be applicable to different catchments and environments
- each module must be able to stand alone.

The ability to visualise outputs as maps and networks is now a standard feature of DSS. This can be achieved through: (1) developing the DSS in a GIS package; (2) incorporating GIS-type functionality into the DSS; or (3) through exchange of data in a compatible format. The particular implementation chosen is determined by the sophistication desired of the DSS, access to GIS software and the programming resources and skills available to the DSS development team.

Decision-support systems are designed to support the exploration of unstructured questions, i.e. 'what-if' analysis. As the extent and range of the 'what-if' questions changes during the lifetime of the DSS development, it is important that it has clear and easily accessed data structures that can be readily modified by the users (not just the DSS developers).

Capability to extend a DSS to other catchments is dependent on the specificity of the issues (and the models chosen to support exploration of those issues), and the DSS design. For the IWRAM project, it was important that the same DSS software could be applied to all catchments in the study area.

The development of stand-alone modules reflected two realities: team members came from different government agencies with different computing standards; and the DSS design had to allow sub-teams to work independently as they rarely had the opportunity to work together. The integration is then achieved through design and data standardisation, rather than through integration of the models per se. Of course there are inherent dangers in this approach, such as incompatibility of models. However, such dangers can be managed by strict adherence to design principles, good communication and rigorous project management.

Role of stakeholders

Effective and sustainable catchment management can be achieved only through development of appropriate policies and adoption of appropriate on-ground husbandry. Experience confirms that strong involvement of key players in the policy development phase is crucial to adoption and compliance. This extends to development of any DSS that purports to support catchment management. There is little gain in developing a DSS to support the analysis of a range of initiatives if it is not accompanied by an analysis of attitudes, opportunities and barriers that limit local communities from accepting and implementing those initiatives.

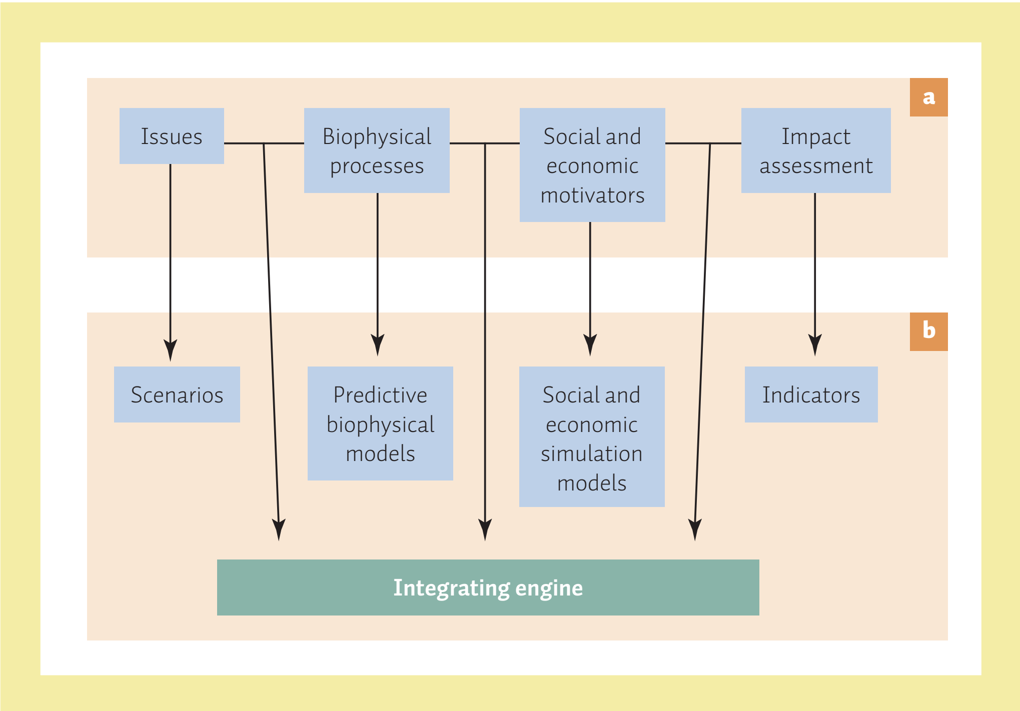


Figure 4.1 Relationship between the Integrated Water Resources Assessment and Management (IWRAM) approach and the IWRAM framework showing the linkages between the components: (a) gives the components of the IWRAM approach; (b) is the IWRAM framework

The intended use of the DSS will determine the appropriate participation program, which can range from inclusion in data collection, to DSS design, development of scenarios for analysis and their assessment. Mostert (2005) provides a good overview of participation in IWRM.

The IWRAM project in northern Thailand substantially enlarged the number of government organisations involved, from the Land Development Department to include Royal Forestry, Royal Irrigation, Agriculture, and the Office of the National Water Resources Committee. These agencies saw themselves contributing to the development of modelling tools in order to understand and assess options to address erosion, water supply, forestry protection, subsistence needs and agricultural development. The departments worked together in developing and incorporating the modelling components in a software system for widespread application. The modelling also provided a focus for capacity-building through training and the development of training materials. This focus has had the benefit of exposing managers and researchers from otherwise fairly narrowly focused disciplinary perspectives to other ways of thinking about change in the system. In this way it has enhanced their integrated-system understanding.

Participation occurred at two main levels in the IWRAM project. At the government-agency level, stakeholders were essentially involved in a co-design process. This meant that researchers and government agency staff were equal partners in the design of the project and methods. This was necessary to ensure uptake of results by government-agency decision-makers and to make sure that tools being developed were appropriate to the Thai situation. This participation was enabled through workshops and a collaborative project approach involving many project partners. The second form of participation was less collaborative and focused more on information gathering. This participation involved surveys of farmers and households in the study area and was used to develop an understanding in the project team of the ways in which decisions are made by these groups, and the constraints under which they operate.

Framework development

Within the framework there are four interrelated components. The choices of what constitutes these components—i.e. what models, what indicators—is iterative and may finally be decided by the limiting factor (which is often availability of data). This section discusses the components and how they were selected for the northern Thailand IWRAM project.

Issues and scenarios

Together with stakeholders, the issues to be addressed by the DSS were articulated and focused around the relationships between

- water (supply and demand)
- agricultural land use (tradition and practice)
- poverty alleviation (farmer net income) and subsistence production
- environmental state (erosion, forest maintenance, and sustainability of land and water resources).

The driver for the DSS design was then the formulation of these issues into scenarios and the indicators and models that would be required to satisfy their analysis. These scenarios fall into the following broad classification.

Climate scenarios

Climate variability and extreme events can often have a profound effect on outcomes. Short-term fluctuations such as droughts or floods can affect agricultural production, water availability, and rates of environmental degradation, such as soil erosion. Three typical climate scenarios might consist of a 'normal' hydrologic year, a 'wet' year and a 'dry' year.

Long-term shifts in climate can also have major effects on the catchment, such as altering the average annual rainfall or temperature, which in turn might affect the economic viability of different types of crops or land uses. In this case, the integrated models might be tested for consistent but small increases or decreases in climate variables (such as annual rainfall) over a time interval of 10 years or more.

Forest-encroachment scenarios

For these scenarios, it is assumed that forest encroachment occurs through current householders in the catchment increasing the amount of land available for their own agricultural use, as opposed to additional migration of families into the catchment. Forested areas on steeper slopes of the upper catchment are converted to farmland, while the existing cropping in the cleared valleys remains unchanged. Increasing the amount of land available to the existing households for production, increases their socioeconomic wellbeing, as both household cash and rice production rise, implying increased food security and increased disposable income to households. However, this increase in social and economic wellbeing would be expected to come at the expense of the environment, with a likely increase in erosion and reductions in biodiversity related to the removal of forest.

Migration scenarios

The forest encroachment scenarios are based on current landholders increasing their access to land and water by removing forest in the catchment. An alternative scenario of concern in many catchment areas in northern Thailand is where migration of new landholders into the catchment occurs. Lowland farmers are often concerned about how such migration is likely to affect their access to water. Resource-management agencies are also concerned with potential increases in erosion as a result of this type of forest encroachment. A migration scenario might include an increase in the number of farmers in the upper reaches of the catchment and a change in land use from forest to farmland along some of the upper slopes.

Price-shock scenarios

The impact of a change in the price of agricultural products can also be tested. A typical scenario might be a drop in the price of rice and soybeans. This would be expected to affect household income and might also influence the relative mix of crops grown.

Deforestation scenarios

Scenarios of forest conversion might range from the extreme scenarios of 30–50% deforestation across all land units and removal of forest from steeply sloping land, to the more probable scenarios of removal of forest from the more-accessible land suitable for agriculture.

Land-management scenarios

Another potential use of the DSS is to help government departments with their land-use planning activities. The DSS can be used to estimate the economic, social and environmental effects of different crop and land-management combinations across different parts of the catchment.

A conceptual framework to support all these scenarios may be very complex and trade-offs between complexity and practicality are required. A sample conceptual framework that would support a range of price-shock scenarios is given in Figure 4.2.

In addition to the above, a 'base-case' scenario is always defined which describes the current land-use and management practices. This is often used to provide a comparative measure of improvement/degradation for the 'what-if' scenarios.

Finally, note that a scenario is a modelling tool that allows a user to explore a change in natural-resource management on biophysical and socioeconomic processes. Scenarios thus reflect stakeholders' different interests and objectives. In this regard, while an individual stakeholder may have a single objective, the multi-objective nature of natural-resource management is embedded in the IWRAM DSS by illustrating the consequences, spatially and temporally, of management strategies on a range of biophysical and socioeconomic indicators.

Regional structure

The temporal and spatial scales at which processes are represented are influenced by a wide range of factors, including the scale at which management decisions are taken, the scale at which the DSS is to be used, the scale of available data and the emphasis of the investigation (e.g. on analysis of policy or of particular management practices).

The IWRAM models operate at a number of spatial and temporal scales. These are described in detail in chapters 5–8 and in summary in chapter 9.

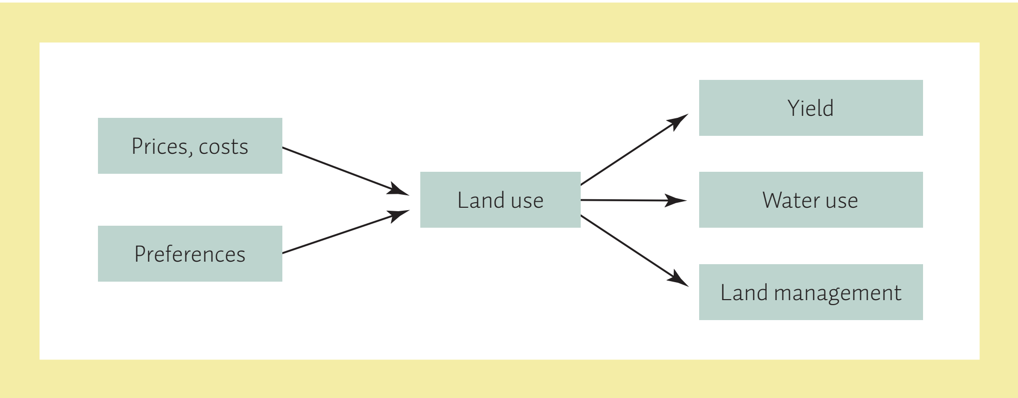


Figure 4.2 Example of conceptual framework: an agricultural catchment affected by changes in crop prices

The unifying spatial scale for all modelling was the node. Nodes are identified through the stream network as distinct zones of activity in catchments where information on the trade-offs between indicators is required. Thus, the spatial and temporal scales of the various models are synchronised at these nodes.

Nodal network approaches are a common framework for considering water-allocation problems—see, for example, Fedra and Jamieson (1996), Jamieson and Fedra (1996a,b), ESS (1999), McKinney et al. (1999), Rosegrant et al. (2000), Letcher and Jakeman (2003) and Letcher et al. (2004). In this type of model framework, a river basin is represented as a series of nodes. Nodes represent points where extraction and other activities impacting on the stream are aggregated for a region and modelled. Regions refer to land or users attached to a node. These may be defined by physical boundaries (e.g. sub-catchment areas) or by social, economic, technical or political boundaries, depending on the problem being addressed by the model. An example of this type of boundary may be the property areas of irrigators extracting along a reach of the stream between two nodes. Flows are generally routed from upstream nodes to downstream nodes and thus impacts of upstream land and water-use activities on downstream users are modelled.

Spatial representation

The treatment of space, and how the catchment is delineated, is important both from the perspective of how scenarios are cast (e.g. 'What is the effect on "the catchment"/"the household"/"the river network" of ...') and the style of modelling that is selected as most appropriate to underpin the analysis.

There are basically four different approaches to treating space in a model.

1. **Non-spatial models** do not make reference to space. For example, regional and national economic impacts arising from a change in the management of a system (e.g. modelled using a choice-modelling approach) may not refer to any particular spatial scale.
2. **Lumped spatial models** provide a single set of outputs (and calculate internal states) for the entire area modelled. For example, the impact of a change in management practice on soil erosion may be modelled using a simple function as a total change in erosion for the entire catchment. In this case, the catchment is not disaggregated into smaller units and the interactions between parts of the landscape are not considered.
3. **'Region'-based spatial models** provide outputs (and calculate internal states) for homogeneous sub-areas of the total area modelled. These sub-areas are defined as homogeneous in a key characteristic(s) relevant to the model, e.g. homogeneous soil types or similar production systems. For example, the catchment may be disaggregated into smaller regions that are homogeneous in one or more attributes, such as drainage, soil type, slope class etc. Interactions between these three 'regions' are then considered by the model. The model can also output impacts for each of these regions.
4. **Grid or element-based spatial models** provide outputs (and calculate internal states) on a uniform or non-uniform grid basis. Neighbouring grid cells may have the same characteristics but will still be modelled separately, as opposed to homogeneous

region-based spatial models where these areas would be lumped together. For example, when considering the impact of land-use changes on terrestrial ecosystems, the landscape may be divided into a uniform grid, where the descriptors of that grid cell are based on either a single measurement or an average of measurements in that cell (e.g. landcover, species distribution, soils). These cells may then be modelled either independently or as a connected series of cells (i.e. each cell affects the outcomes in neighbouring cells) depending on the way in which the model has been conceptualised.

For integrated models the entire model may not operate using a single approach. For example, a grid-based model of rainfall run-off may be used to feed a single, spatially averaged output to an economic or ecological model. The spatial approach of the integrated model is generally at most as disaggregated as the least spatially distributed model in the integrated system. Disaggregation of models to different spatial scales can lead to many difficulties in integrated models, as the spatial scales of interest in one component model may be quite different from those of a model from a different discipline.

Spatial representation in the IWRAM framework

Three main spatial representations are used in the IWRAM framework. Two of these—land units and land-modelling units—are used to underpin 'region-based' spatially explicit models. The third is a standard, grid-based approach to modelling, where the catchment area is divided into a uniform grid. In addition, some socioeconomic models in the system were focused on household scales. The term 'resource management unit' was used to represent households that shared specific characteristics, such as access to irrigated paddy land or to rainfed upland fields. Land units and land-modelling units are explained in more detail below.

Land units

Land units are a basic delineation of a region. It is a term familiar to agricultural practitioners worldwide. A land unit is defined using the FAO land-evaluation definition (FAO 1976) as an area with homogeneous land qualities influencing crop performance, and with the same management and practices.

Land-modelling units

A common unit used in IWRAM is the land-modelling unit (LMU). This is a 'homogeneous' area used to disaggregate a catchment for the purposes of modelling. The concept of 'homogeneous' is applied in terms of various appropriate ecological, physical, social or economic characteristics, usually defined by the model question being considered. Common characteristics underlying the definition of LMUs in the model are topography, climate, soils, geology, ecological community, farm production or industry type and policy scales. LMUs are generally considered to be intersections of these key characteristics so that each region or modelling unit considered by the model is 'relatively homogeneous' in terms of these characteristics. LMUs are generally associated with a set of activities that interact with the hydrological cycle in a defined way. More than one LMU can be linked to each node.

Within IWRAM, LMUs are commonly derived from the intersection of land units with another attribute. If this attribute is land use (the pattern of which may change from one scenario to the next), then LMU maps need to be created dynamically as part of the scenario investigation. For example, a scenario to explore the impact of an increase in area of a particular land use, would firstly create a new land-use map. This would then be intersected with the LU map to create a new LMU map, which is the spatial representation input to the various IWRAM models.

Model requirements and implications

In terms of water allocation, integrated assessment models must be able to consider a range of land-use and management activities that impact on catchment yields. They must be able to consider the impact of changes in flow on water use, as well as the influence of land- and water-use decisions on water availability. Aspects of the catchment system that may need to be represented include agricultural practices that affect water use or the generation of rainfall run-off, the impacts of changed vegetation cover including forest area, the impact of water availability on crop and livestock production, and the impacts of changed water- and land-management policies on households, farms and regional communities.

The detail with which these system components are considered and represented depends on the scale at which the management questions are to be answered, the types of land- and water-use activities present in the catchment, and the type of management options to be considered.

Model selection is also influenced by data and resource availability, including access to professionals with modelling skills. It is far better to develop less-complex models with a local flavour, that address the issues and match the data, than use imported models that over-parameterise, over-complicate and side-track the development. These models also have limited scope for broad-scale adoption.

Scenario requirements

The scenarios to be explored place several requirements on the structure, components and conceptualisation of the IWRAM DSS.

Climate scenarios

To address these scenarios, the DSS should be capable of predicting streamflow and water availability in response to a range of rainfall sequences.

Forest-encroachment scenarios

The DSS should be capable of defining new land-use maps that represent the reduced area of forest (and the land uses that replace it). It would need to support analysis of the impact on farmer income of access to agricultural land, but be able to trade this off against the environmental degradation caused by removal of forests. This degradation may be measured in terms of consequent water quantity and quality, soil erosion, reduction in biodiversity etc. In particular, the influence of deforestation on streamflow yields and erosion must be represented.

Migration scenarios

Scenarios of this class are similar to the forest-encroachment scenario in that the conversion of forest to agricultural land is a trade-off between the environmental impact of that reduction and the potential increase in income to the community. However, in this case, the increased income is not captured by the residents, but by the immigrants. To support this analysis, the DSS should be capable of differentiating between residents and immigrants and adjusting any economic analysis as a consequence. In addition, the off-site impacts of greater demand and use of resources in the upper catchment on downstream availability needed to be represented.

Price-shock scenarios

To support assessment of these scenarios, the DSS should be capable of incorporating changes in crop prices and reflect the connection between farmer decision-making and crop prices.

Deforestation scenarios

To support analysis of such scenarios, the DSS would need to be capable of knowing the extent and location of the forest areas, and be capable of selecting a sub-set of these based on the intersection of one or more attributes (e.g. proximity to another land use, forest area of a particular slope class). It would need to be capable of replacing the forest with an alternative land use. It may need to know about soil types if soil movement is to be considered as part of the scenario analysis.

Land-management scenarios

The DSS should be capable of differentiating between alternative land-management policies that vary spatially across the catchment. It should consider the mix of land uses and their management, and support analysis of the impacts of these. Ideally, it should also consider the attitude of residents to the introduction of alternative management practices and the need to provide incentives for their adoption.

Implications

These scenario requirements have a number of implications for the conceptual structure and component models of the DSS. These are summarised in Table 4.1.

Remembering the need to have stand-alone modules, these requirements can be met by the development of a small number of models, namely a crop model, hydrology model, erosion model and two socioeconomic models (decision and impact). These model components are described in detail in chapters 5–8.

Model selection

Despite the apparent availability of biophysical models from the scientific literature, all of the models integrated into the DSS required some adjustment to take into account the environmental factors of Thailand's highland areas, such as the steep slopes and high monsoonal rainfall or the agricultural factors associated with the crop- and land-management techniques of the highland farmers. Some models also needed further development to account for the data inadequacies, either in the form of inputs and parameters to drive the models or as outputs to assist in their calibration.

Thailand represented both challenges and opportunities for the development of models of decision-making and socioeconomic impact. Survey data for households within catchment areas could be collected and analysed relatively cheaply (compared with working in Australia), allowing for a comprehensive data-set with which to design and test models. Most stakeholders, however, were biophysically focused and had a strong resistance to adopting overly complex representations of economic processes, such as optimisation-based investment models. Economic research thus focused on providing useful, accurate tools and information that was accessible to a broad range of project partners.

Table 4.1 Model requirements and their implications in the Integrated Water Resources Assessment and Management decision-support system

Requirement	Component model affected	Model implication
The integrated model had to be as simple as possible while retaining accuracy to allow for shorter run times, simpler integration and more uptake of the DSS.	All model components	Models should be as simple as possible. Adding complexity to component models should occur only where this is necessary for the model accuracy and usefulness.
Capable of predicting crop yield and water use under variable climatic conditions and with different access to irrigation water	Crop model	A crop model was required that was detailed enough to represent key processes in the water-limited growth of crops.
A large variety of crops able to be simulated for yield and water use	Crop model	The model had to be available or able to be calibrated to locally produced crops. This meant that a locally available model or one that had already been used in northern Thailand was desirable.
The availability of surface water under different climatic and land-cover conditions had to be simulated	Hydrology model	The model had to be sensitive to rainfall, temperature and changes in forest cover.
Erosion should be able to be simulated under different crop-choice and land-management options, on a variety of slopes and soil classes.	Erosion model	The model needs to be adapted for the local conditions experienced in Thailand (including very steep slopes).
The impact of changes in water availability on people in different parts of the catchment should be able to be estimated. These should include 'economic' and 'social' indicators, including the capacity of people to meet their subsistence needs.	Economic impact model	The model must consider cash and subsistence production given different crop yields under various climatic and irrigation-access scenarios.
The model should reflect farmer preferences in cropping patterns in response to changes in prices and water availability.	Decision model	The model should contain a decision component that simulates changes in farm production decisions under different price, climate and irrigation access scenarios.

In practice, most models represent a compromise between rigour and utility. In other words, they are generally not purely empirical or mechanistic. These 'intermediate approaches' are very useful for resource-management evaluation if correctly constructed, and provide a good compromise between empirical and mechanistic models.

One common misconception is that model accuracy invariably increases with model complexity. In fact, the opposite can sometimes be true. A model with fewer parameters can be easier to calibrate and can give more accurate predictions than a complex model, even though it has lower explanatory value. Williams and Probert (1983) identified the importance in restricting the number of parameters without significantly sacrificing the theoretical principles or predictive capacity of the model.

Intended model use

Perhaps the most important factor in determining the appropriateness of a model is its intended use. This determines the processes to be considered and their level of detail, and the model accuracy required. For example, an emphasis on erosion–productivity requires detailed consideration of soil processes, but this may not be as important for, say, pest damage studies. Intended use also determines the complexity of the model—that is, the number of processes to be included and the level of detail. For example, if an annual crop yield is all that is required, a relatively simple empirical approach may be perfectly adequate, if not more appropriate, than a more-complicated mechanistic approach.

Data availability

In catchment- or regional-scale studies, the issue of data availability becomes of utmost importance. Mechanistic models often require a large amount of physical data, such as a variety of soil parameters, which are rarely collected during land surveys and are available at only a few experimental sites. Empirical models tend not to require such large quantities of data and are computationally simple, but have limited meaning. Therefore, intermediate approaches may represent a suitable compromise between data requirements and physical meaning. Problems of data availability are exacerbated in developing countries, where detailed information for supporting complex models is less often collected.

Outputs and indicators in the IWRAM decision-support system

The IWRAM DSS was developed to allow users to understand socioeconomic and environmental trade-offs resulting from a variety of management and climate scenarios. These trade-offs include the off-site impacts of upstream resource-use decisions on water availability, erosion and household poverty downstream, as well as the on-site benefits of such changes. Indicators and outputs of the IWRAM DSS have been designed to allow these trade-offs to be estimated and understood for the scenario types outlined previously.

The biophysical indicators used in the IWRAM DSS can be summarised as follows:

1. Crop yield (tonnes/ha)
2. Crop water demand (mm). This is the total crop water demand required for the crop to evaporate at full potential.
3. Irrigation (mm). This is the total irrigation applied throughout the season. If crop water demand does not exceed the amount of water available within the stream then irrigation is the same as crop water demand.
4. Residual streamflow (ML). This indicator shows wet-season, dry-season and annual streamflow following abstractions for crop irrigations.
5. Erosion (tonnes/ha)
6. Forest area (ha).

The socioeconomic indicators are provided at different spatial scales in different implementations of the DSS. They allow for changes in the social and economic 'performance' of a household, due to different climatic and upstream land-use-choice scenarios, to be investigated and potentially traded-off. Where a multi-year scenario is run, a time series chart of the output is provided. Tables of values are also given for all scenario runs. The indicators provided are as follows:

1. Cash per household (baht). This indicator describes the 'economic performance' of households.
2. Total household income from agriculture (baht). This indicator describes the agricultural income from their land-use choices.
3. Off-farm (household) income (baht). This indicator shows the reliance of different households on off-farm income.
4. Hire cost (baht). This indicator shows the total wages paid per household to hired labour in each year. It shows the extent to which production relies on hired labour.
5. Rice production per person (kg). It is assumed that each person in a household requires 300 kg of rice per year to survive. This indicator shows how close households come to meeting their subsistence requirements. Most households have a strong preference to produce their own rice.
6. Cost of rice deficit (baht). This indicator shows the cost to the household of purchasing unmet rice requirements.

Regardless of the particular models used, the IWRAM approach identifies a range of indicators to evaluate the impact of alternative management scenarios. Indicators are a product of the models that have been selected—they are either model outputs or a transformation (e.g. re-expressed as a rating rather than a raw number, or aggregated in some way) of those results. The choice of indicators is an iterative process between end-users and model developers (and, in fact, also influences the choice of models in the first place).

For integrated assessment, they must provide meaningful measures so that scenarios can be 'weighed up' according to their likely impact on the state of both the natural and human resources of the catchment. For more-complex assessments, this may extend to include externalities such as impacts on upstream and downstream users.

Linking it all together — the integrating engine

Within the DSS framework, the integrating engine has the role of pulling together (and executing) the component models, and providing the interface for describing and analysing scenarios. Each variant of the IWRAM DSS uses a different integrating engine, though they are all examples of a coupled-model approach to integration.

The engine, or core module, has the job of 'translating' scenarios into the parameter sets of the component modules, scheduling and executing the component models in the right order, and configuring the spatial and temporal outputs from the models.

Importantly, an integrating engine enforces consistency of catchment representation (e.g. delineation of the landscape into homogeneous modelling units) as the component models share a common database. The interface should also be independent of the underlying models so that it can be easily adapted to reflect user feedback.

Implementation

As with development of any software tool, no code should be written without an analysis of end-user needs, team skills, software life cycle (including maintenance and distribution) and training and extension.

All of the integrated approach projects in which we have participated have reinforced the rather obvious point that software development must be undertaken with a clear picture of the target audience, the specific issues and the uses. Thus, while a sophisticated, object-oriented software platform may be both useful and desirable in some circumstances, in other cases a spreadsheet-based model may be more useful for extending project ideas and science. Having different software products aimed at different audiences can also be a useful outcome of a project. On the other hand, software development should not be the primary objective of the work undertaken. The software is a tool to enhance communication and interaction between different disciplinary teams. It should be a focus of the project mainly in so far as it encourages communication of ideas and enhanced understanding of the integrated nature of the problem.

Conclusions

This chapter summarised the requirements placed on the DSS and its components and gave a brief overview of the ways in which they were addressed in the IWRAM framework. This provides some background for the challenges in developing a tool and improved understanding for integrated water-resources management. Chapters 5–8 describe each of the component models and their implementation in detail. The description focuses on ways in which the design of these components was affected by the model requirements.

References

Abel, D.J., Taylor, K.L., Walker, G.C. and Williams G. 1996. The design of decision support systems as federated information systems. UNU/IIST–IDC expert group workshop on decision support systems for sustainable development.

El-Swaify, S.A. and Yakowitz, D.S. 1998. Introduction to multiple objective decision making for land, water and environmental management. In: El-Swaify, S.A. and Yakowitz, D.S., ed., Multiple objective decision making for land, water and environmental management. Boca Raton, Florida, St Lucie Press, 3–7.

ESS (Environmental Software and Services) 1999. WaterWare: a water resources management information system. ESS GmbH at <http://www.ess.co.at/WATERWARE/>.

Ewing, S.A., Grayson, R.B. and Argent, R.M. 1997. Research integration in ICM: review and discussion document. University of Melbourne, Australia, CEH Report 1/97.

FAO (Food and Agriculture Organization of the United Nations) 1976. Framework for land evaluation. Rome, FAO, Soil Bulletin 55.

Fedra, K. and Jamieson, D.G. 1996. The WaterWare decision-support system for river-basin planning 2. Planning capability. Journal of Hydrology, 177, 177–198.

Gough, J.D. and Ward, J.C. 1996. Environmental decision-making and lake management. Journal of Environmental Management, 48, 1–15.

Jamieson, D.G. and Fedra, K. 1996a. The 'WaterWare' decision-support system for river-basin planning 1. Conceptual design. Journal of Hydrology, 177, 163–175.

— 1996b. The 'WaterWare' decision-support system for river-basin planning. 3. Example applications. Journal of Hydrology, 177, 199–211.

Kersten, G.E. and Micalowski, W. 1996. The DSS phenomena: design, functions and management. UNU/IIST–IRDC expert group workshop on decision support systems for sustainable development.

Letcher, R.A. and Jakeman, A.J. 2003. Application of an adaptive method for integrated assessment of water allocation issues in the Namoi River catchment, Australia. Integrated Assessment, 4(2), 73–89.

Letcher, R.A., Jakeman, A.J. and Croke, B.F.W. 2004. Model development for integrated assessment of water allocation options. Water Resources Research, 40, W05502.

Lowes, D. and Bellamy, J.A. 1994. Object orientation in a spatial decision support system for grazing land management. AI Applications, 8(3), 55–66.

McKinney, D.C., Cai, X., Rosegrant, M.W., Ringler, C. and Scott, C.A. 1999. Modeling water resources management at the basin level: review and future directions. Colombo, Sri Lanka, International Water Management Institute.

Mostert, E. 2005. Participation for sustainable water management. In: Giupponi, C., Jakeman, A.J., Karssenberg, D. and Hare, M., ed., Sustainable management of water resources: an integrated approach. Edward Elgar, in press.

Rizzoli, A.E. and Young, W.J. 1997. Delivering environmental decision support systems: software tools and techniques. Environmental Modelling and Software, 12, 237–249.

Rosegrant, M.W., Ringler, C., McKinney, D.C., Cai, X., Keller, A. and Donoso, G. 2000. Integrated economic–hydrologic water modeling at the basin scale: the Maipo River basin. Agricultural Economics, 24, 33–46.

Simon, H.A. 1973. The structure of ill-defined problems. Artificial Intelligence, 4, 181–201.

Williams, J. and Probert, M.E. 1983. Characterisation of the soil–climate constraints for predicting pasture production in the semi-arid tropics. Proceedings of the international workshop on soils, Townsville, Australia.

Wu, J.K. 1996. DSS: state of the art. UNU/IIST–IRDC expert group workshop on decision support systems for sustainable development.

Modelling socioeconomic impacts and decision processes

REBECCA LETCHER, BENCHAPHUN EKASINGH AND KAMOL NGAMSOMSUKE

SUMMARY

Social and economic sciences play an important role in any integrated assessment of natural-resource-management issues. Land and water use and management decisions made by farmers, industry and community groups impact on the environment and on individuals in, and sometimes outside, the catchment. These groups are also affected by the decisions of others and are constrained by characteristics of the landscape in which they live. Economics and the other social sciences offer tools to assist in understanding these drivers and impacts. They can assist in developing models of decision-making, to help simulate changes in land and water use and management in response to changes in climate, policy, prices or other influences. They can provide models for simulating the impact of changes on economic prosperity and subsistence production and they can be used to design better participatory processes used to

develop integrated models. This chapter describes the role of social science and economics in the modelling and analysis aspects of the Integrated Water Resources Assessment and Management (IWRAM) project. Participation in the IWRAM project was described separately in earlier chapters.

Introduction

At the most basic level, the role of economics and the social sciences in the development of an integrated water-resource-assessment model can be considered to be comprised of three main tasks: representing and understanding decision-making processes and their impact on the catchment system; understanding and evaluating the impacts of changes in management and catchment conditions on the community and the values they place on different outcomes; and designing and implementing participatory approaches to ensure greater stakeholder involvement in assessment and management. This chapter considers the representation of decision-making and understanding of socioeconomic impacts. Participation in the Integrated Water Resources Assessment and Management (IWRAM) project was dealt with in chapters 3 and 4.

Decision-making

In order to understand the impact of changes in policy or the management of a catchment, the way in which decisions affecting resource use and management are made and respond to changes in factors such as climate, policy, prices, taxes and subsidies must be understood. Decisions that need to be understood and represented may include agricultural production decisions, industrial and urban water-use decisions as well as decisions to plant areas of the catchment to forestry, to clear areas for agricultural use, or to capture run-off for production purposes before it reaches the stream. For any given type of decision, many different approaches may be taken to modelling this decision.

Considerations in developing decision models

The key issues to consider when developing decision models are as follows:

1. The spatial scales at which decisions are to be modelled and how decisions should be spatially disaggregated. Many decision models simulate decisions for representative households, farms or firms. These decisions do not usually correspond to specific areas in the landscape. In the IWRAM project, two separate approaches to simulating decisions were developed. The first was a lumped approach, which required aggregated household decisions by representative households, then disaggregated these decisions by land unit. The second was a grid-based approach where decisions were simulated by grid cell.
2. The temporal scales at which decisions are to be considered. These time scales may include the representation of tactical or strategic decisions and the time step over which decisions are updated, the nature of cropping decisions being made (e.g. perennial crops versus annual or seasonal

cropping decisions) and the choice between simulating short-run decisions, where farmers are constrained by their available capital and infrastructure, or long-run decisions where decision-makers are able to adjust the amount of capital available to them.

3. The appropriate level of complexity in the model representation. Optimisation-based decision models are often considered by stakeholder groups to be overly complex or difficult to understand. A simpler approach may be as accurate (or more accurate) and may be more intuitive. This can be a distinct advantage where the model needs to be transparent to a range of stakeholders.

4. The types of trade-offs that need to be considered will inform most of the conceptualisation of the model. The decision to aggregate the decisions of specific groups of decision-makers into a single decision model or to treat them separately will depend on the type of impacts and distributional effects being considered by the model, as well as the trade-offs that need to be investigated. For example, if the decisions and impacts of changes in resource availability are expected to differ between households based on their level of resource availability, and this is of concern to the assessment, then these different groups will need to be treated separately. Otherwise it may be possible to aggregate and treat them with a single decision model.

5. The level and source of uncertainty with which decision-makers are faced may be of concern in an assessment. Decisions can be modelled using various assumptions relating to both the types of uncertainty facing decision-makers and their attitudes to risk (e.g. risk neutral, risk loving, risk averse). The model representation and structure will depend on both the sources of uncertainty considered and the attitudes of decision-makers towards risk assumed.

6. Key decision groups affecting resource use or being affected by resource availability will affect the types of decisions to be modelled. Common decision-making groups represented are farmers or other agriculturalists, hydropower personnel, and industrial or urban water users.

Some common approaches to modelling decision-making

Frequently used methods for simulating decisions include optimisation-based approaches, based on the assumption that individuals and firms act to maximise profits or utility, and decision-tree approaches, where decisions are simulated using empirically derived 'rules of thumb'. This section reviews some common approaches to modelling decision-making. Later sections provide examples of the use of decision-tree and optimisation-based approaches to simulating decision-making in the IWRAM framework.

Regional-scale production models

Regional-scale production models are generally used to consider the regional-scale, spatial distribution of impacts and trade-offs resulting from changes in policy or other factors. These types of models normally divide an area, such as a catchment or basin, into a number of regions (e.g. sub-catchments) on the basis of 'relatively homogeneous' production systems and policy scales. Each of these regions is then treated as though it is managed by an individual farmer. This allows 'averaging' or aggregation of decision-making to a scale appropriate for the types of impacts being considered. This assumption basically means that resources such as land and water are assumed to be transferable between farmers within a region. These models place emphasis on the differences between farmers from different regions rather than on differences within regions. This enables large-scale water trading and reform issues to be considered. In particular, conflicts between upstream and downstream use can be identified.

Regional-scale production models are commonly used for integrative studies at a catchment scale. This is because the scales within these models are commensurate with the required catchment scale and because the types of questions that they are designed to answer are those most frequently asked of integrative studies at this scale. In particular, questions on the spatial distribution of socioeconomic and environmental impacts resulting from changes in water policy or water trading are frequently considered using this type of model. Letcher et al. (2004) developed an integrated model for considering a variety of water-allocation policy options in the Namoi River catchment. This model used a regional-scale production model underlain by a hydrologic network to assess spatial and temporal trade-offs associated with a number of water-allocation policy changes. Trade-offs considered were both economic (between regions) and environmental, with impacts of extraction on streamflow considered.

Regional-scale production models can also indicate where water is likely to be bought into or sold out of a region given alternative production options. They can be applied to consider 'optimal' allocation of water within a basin given an objective. Impacts are generally limited to first-order impacts (i.e. impacts on agricultural production in the region). This means that secondary impacts on towns and agriculture-dependent industries are not considered. These models may be used to identify whether or not first-order impacts are large enough to warrant further investigation of these types of second-order impacts.

Hall et al. (1994) used a spatial equilibrium model, a variant of a regional-scale production model, to consider water markets in the Murrumbidgee River catchment in southeastern Australia. They used 18 regional-scale linear programming submodels, linked with a model of the river system and a model of product supply and demand, to analyse the impacts on irrigated agriculture of changing water prices and trade between regions in the southern Murray–Darling Basin. This model was later updated, with the regional structure being altered for changes in water management. This type of spatial equilibrium model was also applied by Branson et al. (1998) in the southern Murray–Darling Basin to investigate the structural adjustment implications of water reform.

Jayasuriya and Crean (2000) and Jayasuriya et al. (2001) developed a regional-scale production model to consider the trade-offs between ecological benefits and reduced irrigation production associated with environmental flow rules in the Murrumbidgee valley. The model divided the Murrumbidgee catchment into eight separate production zones and then maximised gross margins for each of these, given resource constraints in the zone. This model was linked to hydrological data from a hydrological model.

Eigenraam (1999) and Branson et al. (1999) developed a spatial equilibrium model based on regional-scale production models for irrigation areas in New South Wales and Victoria, Australia. This model was used to consider the impacts of trade, environmental-flow rules and changes in water pricing on these irrigation districts. This model was able to show the pressures for water trading in these areas and to provide information on their likely extent and direction.

The strength of the approach of regional-scale production models is their ability to consider spatial trade-offs, both socioeconomic and environmental, at reasonably large scales. They do not, however, allow the user to consider impacts on individual farmers who are constrained by their resource availability within these regions. Nor do they consider the second-order impacts on towns, agriculture-dependent industries and employment. Limited information about first-order impacts on employment may be obtained, so long as regional labour-supply constraints are included in the model formulation.

Representative farm (household) models

Representative farm models are very commonly used to consider the impact of water reforms and other policy changes on individual farmers or households. This type of model relies on identification of a 'typical' or 'representative' farm (or household) in a given area. Production decisions made by this farm subject to various resource constraints are generally considered by the model. This model may take the form of a simple farm budget, or may be a complex simulation or optimisation-based procedure.

Jayasuriya and Crean (2001) used a representative farm modelling approach and whole-farm budgeting, to evaluate the on-farm impacts of environmental flows in the Murrumbidgee catchment. Three representative farm types were used: one typical, rice-based farm in the Murrumbidgee Irrigation Area and two rice-based farms of differing sizes in the Coleambally Irrigation Area. Impacts on farm profitability were assessed in terms of whole-farm gross margin, net farm income, and business return.

Jayasuriya (2000) developed two representative farm-scale models (one rice-based, the other a non-rice-based farm undertaking maize, soybean, canola and wheat cropping) for considering the impacts of reduced groundwater availability in the lower Murrumbidgee catchment. These models focused on short-term responses to changes in groundwater availability and so did not include consideration of potential investments in irrigation infrastructure or water-saving technologies in the model formulation.

One common issue with developing representative farm models is deriving 'typical' or representative farms for an area. In some cases, clustering and analysis of statistical data, such as farm survey data, are used.

Jayasuriya and Crean (2001) used a local consensus data approach, relying on feedback from meetings with focus groups of farmers in the area to indicate the 'typical' or representative farmers that should be modelled. The information obtained using this method was then cross-checked against other sources. Jayasuriya and Crean (2001) say that this technique is able to produce typical figures for a target group that are more representative than simple averages of statistical data, given the distortions often present due to sampling errors arising from variability in the survey population. However, they also point out that figures derived in this way cannot be easily aggregated for a regional analysis.

The main strength of this approach is its ability to consider the way in which resource constraints at the farm level constrain decision-making and influence the impact of policy changes on farms.

Urban water demand models

These models are generally based on the estimation of demand curves for urban water, assuming a given functional form and using observations of water demand. Empirical relationships between household water demand and price are generally calculated. Factors such as rainfall or evaporation may also be used to explain seasonal fluctuations in demand. These models are generally constructed by water-supply authorities for demand forecasting and pricing purposes. They assume that all households in a city or some subgroup can be represented using a single demand function, which is generally of a specific form.

The most common, and simplest, functional form for estimating urban water demand is:

$$Q = aP^b$$

where Q is household water demand, *P* is price and *a* and *b* are parameters derived from analysing observed demand and price data. This form of the demand curve is often used, as it readily allows a constant price elasticity of demand to be estimated (*b*). In order to improve the fit of the model to observations, it is often assumed that this function holds only for excess water use, above some minimum necessary threshold (sometimes considered to be equal to indoor water use).

Many other forms of demand model have been used in the past, including more-complicated econometric models of demand as a function of both price and climate—see, for example, Renwick et al. (1998). Other functional forms of the demand curve have also been assumed.

Urban demand models allow predictions of demand to be made given changes in price (demand management). Where the model is being used to simulate future water demand, a model of population growth is also required to obtain total demand.

Ringler (2001) used a net-benefit function for municipal and industrial water use, derived from an inverse demand function for water, as part of an integrated study into the optimal allocation of water in the Mekong Basin. This model and other agronomic production models were integrated with a hydrologic model using a nodal network approach.

Agent-based models

An agent-based model considers a system to be made up of a number of individual 'agents' who interact with each other—see, for example, Hood (1999). These models are based on the theory that detailed knowledge and information are available only on the properties of individuals and that system properties are a potentially non-linear consequence of agent properties (Hood 1999). Agent-based models are used mainly to understand the consequences of these types of interactions between individuals for the whole system. Thus, the concept of investigating 'emergent behaviour' of the system as a result of individual interactions is considered to be a key concern of agent-based modelling.

Hood (1999) recommends that agent-based models be used to complement 'top-down' modelling approaches, where assumptions of linearity are often made, rather than as prescriptive models. One strength of agent-based models is said to be the way in which they are not constrained by the system, rather the system properties emerge from agent interactions (Hood 1999). Also, assumptions of linearity and equilibrium, common in economic models, do not need to be made.

These models rely on detailed knowledge of individual characteristics and representation of a large number of individuals. As such, data and computational limitations generally mean that only a relatively small number of individuals (e.g. hundreds) can be considered. This limits the spatial scale at which they can be used, restricting their capacity to consider catchment or basin-scale problems.

Hare et al. (2001) considered a number of agent-based modelling case studies from around the world to develop a taxonomy of agent-based models. This taxonomy was to aid modellers in choosing the agent-based technique that matched their modelling requirements. Other applications of agent-based methods for considering natural-resource problems can be found in Barreteau and Bousquet (2001) and Becu et al. (2001).

One common use of agent-based models is as a negotiation support tool, to support 'bottom-up' or participatory decision-making. These models are generally used for investigation of the system rather than to estimate the impacts of policy changes on individuals or communities.

Decision-tree approaches

Decision trees generally consist of a set of 'if…then…' rules that define the way in which decisions change in response to specific triggers. These decision rules may be derived using data-mining techniques directly from data—see, for example, Whitten and Frank (1991)—or may be postulated from a mixture of theory and qualitative information derived from interviews with decision-makers.

Ashby and De Jong (1982) use information derived from interviews with farmers to derive a decision-tree model describing farmers' tillage decisions in Colombia. The model consists of a set of decision criteria dictating the form of tillage applied. This model was tested against a second set of data.

An example of the implementation of a decision-tree approach derived from data mining of survey information, used as part of the IWRAM model framework, is given later in this chapter.

Socioeconomic impacts

The other key socioeconomic consideration explicitly considered in many integrated assessment projects is the issue of socioeconomic impacts. A very simple approach to incorporating economic and social considerations, which is commonly applied in more biophysically focused projects, is to evaluate the direct costs associated with a change in land use or management. This is the most basic approach to considering socioeconomic impacts and is more often undertaken than any representation of decision-making. A more holistic approach includes evaluation of a much broader range of impacts and considers the capacity of people to adjust away from these impacts through the decisions they make. Key social and economic impacts that may be considered include impacts on household and firm incomes and financial viability, impacts on subsistence production, employment or leisure time, changes in the recreational, environmental or amenity value associated with natural or human-derived resources and impacts on the regional economy. Again, the scale and range of impacts to be considered dictates the type of modelling approach used.

There is a clear link between representing and understanding people's decisions and considering the social and economic impacts associated with any change in the catchment system. This is particularly important where people may change their decisions to adjust away from the social and economic impacts of any intervention. These adjustments may reduce the size of impacts, or may create new impacts on others in the catchment. They may also lead to second-order environmental or biophysical impacts, which will be unexpected if potential adjustments are not considered in the assessment. In some cases, the model representing decision-making may also calculate many of the socioeconomic impacts to be evaluated. Where decisions are modelled assuming perfect knowledge, then the decision model will also include assessment of the socioeconomic impacts associated with the change on the decision-maker. Where decisions are based on uncertain expectations, a separate socioeconomic impact model will be required to estimate impacts on the decision-maker. This model may be very simple, as with the examples shown at the end of this chapter.

Common impact models

The decision models described above can often be considered to be 'impact' models as well—that is, these models usually consider not only the decisions of individuals or groups in a catchment but also calculate the impact of changes in prices, climate, or policy on these groups. However, other types of models exist that provide information purely about the nature of socioeconomic impacts, not about decision-making. This section briefly outlines two types of socioeconomic impact models.

Input–output models

Input–output models are used to consider the flows of goods and services in the economy—see, for example, Black (1997). These models assume that the economy can be divided into a number of sectors. Horton (2002) states that:

> ...the fundamental premise of this technique is that changes in production levels of an economy's basic industries, arising from either changes in output or changes in demand, will, through various and extensive inter-industry linkages, produce an iterative process of spending, income creation, and re-spending, thereby changing the production levels of other, directly and indirectly related industries

Thus, when undertaking analysis of the impacts of water trading or changes in water-allocation policies, these models are often used to consider the second-order impacts on regional industries, employment and regional income. They assume fixed-input coefficients, which are generally derived from data at one point in time, as well as linearity (i.e. constant returns to scale and constant ratios of inputs to production for each sector). Multipliers are used to indicate the strength of linkages between a particular sector and the regional economy—see Morison and Zorzetto (1995). A lack of supply-side constraints is also assumed.

Woodlock (1996) used an input–output model to consider the impact of the introduction of environmental flows policies on the regional economy of the Namoi River catchment, Australia. This model did not consider the flow-on effects to the regional economy or the environmental impacts of policy implementation. It focused on the impacts on the agricultural industry of the Namoi region. The model used a linear programming formulation to optimise the present value of regional gross margins over a three-year period, subject to resource availability. The entire area sown to crops and pastures was treated as one large farm and cropping enterprise in the model.

Leistritz et al. (2002) consider the impact of a proposed emergency outlet for Devils Lake, North Dakota, USA. The regional economic impact of various management scenarios was estimated using an input–output model. The regional economic effects considered by the model include transportation, agriculture, residential relocations and outlet construction expenditures. These effects were measured in terms of gross receipts for different sectors, secondary employment and tax collection.

Fischer and Sun (2001) address the impact of future land-use scenarios on China's economy using an input–output model. Impacts on the entire Chinese economy and on seven individual economic regions were produced.

DLWC (1999) warns that input–output models are primarily designed to support measurement of economic activity rather than to support the evaluation of changes in the economy itself. As such, it is suggested that these types of models are likely to overestimate the static flow-on effects on income or employment while potentially underestimating the long-term flow-on effects, because they ignore government and capital expenditure induced effects as well as demographic effects of population change. These models are useful, however, in indicating the likely magnitude of effects and points of pressure within the regional economy.

Choice models

Choice modelling, or a choice experiment, is one of a number of stated-preference techniques used to estimate the value that the community places on various environmental outcomes. This method is capable of producing estimates of the values of changes in individual attributes as well as the value of aggregate changes in environmental quality (Morrison et al. 1996). This method uses surveys to identify respondents' preferences for environmental outcomes. Respondents choose their most-preferred resource option from a number of alternatives. This allows estimation of the value of multiple resource options. Choice modelling is based on the assumption that consumers seek to maximise utility when they make choices.

Choice modelling differs from other stated-preference techniques, such as the contingent valuation method or contingent ranking, by the design of the survey used to elicit respondents' preferences and by the statistical models used to analyse the results of the survey. Morrison et al. (1996) reviewed a number of stated-preference techniques and concluded that choice modelling had considerable potential for providing useful and valid estimates of environmental values.

Whitten and Bennett (2001) used choice modelling to estimate the non-market values of wetlands in the upper southeast of South Australia and of wetlands on the Murrumbidgee floodplain in New South Wales. The values estimated in this report were used in a cost–benefit framework, including both monetary and non-monetary costs and benefits of wetland management, to advise policy makers on the aggregate benefits of pursuing alternative wetlands policies. Bennett and Morrisson (2001) used choice modelling to estimate the environmental values of a number of rivers in New South Wales, including the Murrumbidgee River catchment.

The strength of choice modelling is in its ability to consider the impacts of policy change on non-monetary values, such as recreational or environmental values.

Two examples of decision-models in the Integrated Water Resources Assessment and Management framework

Two separate approaches were used to represent decision-making in the IWRAM framework. These approaches represent very different ways of dealing with decision-making. Importantly, both can be used to link in with the same set of biophysical models, stressing the importance of the separation between the conceptual framework underlying the interactions between system components and the specific models chosen to represent individual processes. In many ways, the choice of individual models is secondary to determining the nature of interactions occurring between system components. To illustrate these considerations, this section outlines the two approaches to representing decision-making that have been implemented in the IWRAM framework.

Household decision models

The integrated modelling approach developed in the first phase of the IWRAM project considered resource-management decisions as taking place at the household scale. This scale was chosen as it was considered that the household was the main driver of agricultural production decisions in northern Thailand (Scoccimarro et al. 1999).

Decision model formulation

With decisions on land and water use being modelled in the IWRAM decision-support system as taking place at the household level, decisions are made in response to expectations of the level of land, water and labour available to a household. Households are classified into a number of different types called resource management units (RMU), on the basis of biophysical, economic and sociocultural attributes. For a detailed discussion on RMUs and their application in the IWRAM project, see Scoccimarro et al. (1999). It should be noted that individual households are not modelled, but that separate household models are run for each household type, then the results aggregated by the number of households of each type. Thus, household models essentially estimate decisions on a 'per household per RMU' basis.

RMU types differ according to their access to land and water in the catchment. For example, one RMU type may contain households that own only irrigated paddy land, while households in another RMU may own some irrigated paddy and some rainfed upland fields. The types of RMU that may be seen in a catchment are summarised in Table 5.1. Classification of households into RMUs was undertaken using household survey data collected in the catchment. Only types 2, 3 and 8 are considered in this paper, as these were the only types seen in the survey data for the Mae Uam sub-catchment. Households of RMU2 have access to irrigated paddy land only. Households of RMU3 have access to rainfed upland fields only, while those of RMU8 have access to both irrigated paddy fields and rainfed upland fields.

Each household is assumed to be constrained in its activities by its access to land, water and labour. Households are modelled as aiming to generate as much household income as possible given a choice of crops, and expectations on the amount of land, water and labour that will be available to them. Social constraints, such as the desire to grow rice as a subsistence crop during the wet season, are included as constraints on household decision-making. For example, households are limited to growing mainly rice in the wet season in order to meet their subsistence needs. A level of 300 kg per year is assumed to be required per person to eliminate the subsistence deficit. Cash cropping is assumed to take place in the dry season. The model allows for different choices of fertiliser level on crops as well as for the choice of whether or not to irrigate a crop. The crops that can be chosen by each household type differ. For the Mae Uam: RMU2 can choose irrigated paddy rice in the wet and dry seasons, and irrigated sorghum in the dry season; RMU3 can choose rainfed upland rice in the wet season and rainfed sorghum in the dry season; and RMU8 can choose irrigated paddy rice and rainfed sorghum, upland rice and groundnut in the wet season and irrigated and rainfed sorghum in the dry season. These crop choices were derived from survey data.

It is possible to run the DSS over several years or for a single year. If the model is run over multiple years, then the expected volume of irrigation water available to a RMU for each successive year (used in the household decision model) is updated on the basis of events in previous years. In the first year, the expected quantity of irrigation water is that which is initially assumed by the user. In all other years, the expected value is the actual amount of irrigation water used by the household in the previous year (i.e. naive expectations are assumed). Climate data for each year also affect flows, erosion, crop yields and irrigation demands calculated by biophysical models in the DSS.

Table 5.1 Possible resource management unit (RMU) types for use in the Integrated Water Resources Assessment and Management decision-support system

RMU	Description
1	rainfed paddy only
2	irrigated paddy only
3	rainfed upland only
4	irrigated upland only
5	rainfed and irrigated paddy
6	rainfed paddy and upland
7	rainfed paddy and irrigated upland
8	irrigated paddy and rainfed upland
9	irrigated paddy and upland
10	rainfed and irrigated upland
11	rainfed and irrigated paddy and rainfed upland
12	all types
13	irrigated paddy and upland and rainfed upland
14	rainfed paddy and upland and irrigated upland

Linear programming is invoked to solve the constrained optimisation, using separate components for wet- and dry-season decisions. At present, only seasonal cropping decisions can be accounted for in the model. Decisions to grow perennial produce, such as fruit trees, are not currently incorporated in the model. In most cases, Base-case values were determined from the household survey data.

Spatial disaggregation of household decisions and links to the biophysical models

The modelling uses a nodal-network where nodes represent aggregated points of extraction along the river system. Each node is associated with an area of land containing many households and land uses. This means that household extraction decisions in an area are aggregated and are modelled as occurring from a specific point along the river. Total water supply, simulated using the hydrological model (see chapter 6), is also an output at this point or node. Households in an area are divided into a number of representative RMUs and the decisions of individual households are aggregated by summing the decisions of each RMU type present at the node.

Households of the same RMU type are modelled as having the same access to land, water and labour at a node. This means that within any one nodal area the same land-use decision is assumed to be made by each of these households in a specific RMU type. Household decisions for each RMU type present at the node are aggregated across individual RMUs and then across RMU types. This aggregate land-use decision is fed to the biophysical models as an aggregated land-use and management decision for the node. These models consider biophysical processes on a land-unit basis. Land units correspond to unique soil types and slope classes (for further details see chapter 3). Household decisions for each RMU type need to be disaggregated to individual land units then summed over the entire catchment in order to be passed to the biophysical models. The decision disaggregation model (DDM) uses a procedure to disaggregate crop decisions to each land unit, using the household decisions for each RMU and the number of households of each RMU type in the catchment. The DDM outputs the total area of crops in each season on each land unit as well as the total forest cover in the catchment.

Users of the model can change the total number of households of each RMU type at each node, as well as the access that each of these RMUs has to land, labour and water resources. In this way, they are able to explore changes that could occur in the catchment, for example as a result of forest clearing for agriculture, or migration into the catchment.

Decision-tree approach

In the second phase of the IWRAM project, an alternative, decision-tree approach was used to simulate production decisions in the catchment. This approach was chosen to overcome several limitations of the more-complex linear programming approach described above:

- The decision-tree approach can simulate grid-based land-use decisions, a key desire of Thai management authorities (improving uptake and adoption).
- No assumptions (such as profit maximisation) are made about decision-making, instead the drivers of land-use decisions are derived directly from detailed survey data collected in the catchment.

- The decision-tree approach is relatively simple to implement and can be readily understood by non-technical users. As such, it is more accessible to a broader range of stakeholders, increasing the likelihood that the decision-support tool will be adopted.

These advantages have driven the choice of approach in this project. However, use of this approach relies on extensive data frequently not available in an integrated assessment. Thus, choice of the appropriate approach should be made considering the characteristics of the problem at hand, including available data, user requirements and the spatial and temporal scales required of simulations.

Data collection

Two surveys were conducted of households in the three catchment areas as part of the socio-economic component of the second phase of the IWRAM project. In the first stage, a survey of farmers was conducted by the Department of Land Development (DLD) covering 23 land units (312 households; 212 from Mae Ping Part II Watershed and 100 from Mae Kuang). This survey was conducted in 2000. In the second stage, another farmer survey was conducted (in 2001) by a team from Chiang Mai University covering 23 land units and 284 households (50 from Mae Rim Watershed, 109 from Mae Kuang and 125 from Mae Ping Part II watersheds). After major land units together with their administrative boundaries were identified, sample households were selected based on these land units. These households were chosen to supplement the survey previously done by DLD, so that land units surveyed did not overlap with those previously surveyed. Global positioning system (GPS) equipment together with detailed administrative maps were used to pinpoint the exact location, and farmers in these land units were selected for interviews. Approximately 4–8 households having the same cropping pattern were selected at each location.

Together, the two surveys covered 37 land units and 596 households. There were about eight farm households interviewed in each land unit. In addition, informal interviews and socio-logical studies were conducted to supplement understanding of farming systems in the area. Questions asked related to cropping patterns, problems of farming, use and management of irrigation systems and environmental problems.

Table 5.2 summarises the main information sought from households during the survey conducted by Chiang Mai University. The final data-set collected represents a comprehensive database of crop activities and household characteristics suitable for classifying decision-making behaviour in the study area. Data-mining techniques were then used to derive from this data-set a set of decision rules, describing wet- and dry-season cropping decisions using these household attributes.

Analysis of the survey data

In order to derive decision trees from the survey results, the crops were grouped into several categories. These were based not only on economic characteristics of the crops, but also on advice from agronomists in the project team. The labels used to identify crop categories are given in Table 5.3, with a suffix used to indicate if the crop is grown in the wet or the dry season.

The variables considered from the survey by the data-mining analysis as possible descriptors of crop choice were: the estimated profit level; cost of production; farm size per unit of household labour; total farm size; household labour units; the number of household members; whether or not the household would consider an alternative crop; farmers' willingness to participate in off-farm employment; whether the farm has livestock; the land-tenure status of the farm; the incidence of waterlogging on farm; the incidence of drought periods on farm; the availability of irrigation water; membership in a water-users association; and household capital availability. In some cases, these variables were grouped into discrete classes to aid with the analysis.

Wet- and dry-season crop choices were analysed separately using the data-mining algorithm. In both seasons, the data could be classified accurately using only four attributes: land unit, estimated cost of production, the land–labour ratio and estimated profit level. These four variables and the classes used for each in the analysis are described in Table 5.4.

Given these decision trees, each land unit can be divided into many wet- and dry-season crops depending on the farmers' profit expectations and their resources, e.g. capital (estimated cost of production, land and labour availability). The decision tree can be used predict what crops a representative farmer will grow in the study areas, given different assumptions about resource availability.

A brief summary of the decision trees is given below.

Wet- and dry-season decision trees

Separate decision trees were determined for wet- and dry-season cropping decisions. These decision-trees are shown in Figures 5.1 and 5.2.

These decision trees demonstrate that decisions on which crop to plant depend not only on the physical characteristics of the land but also on characteristics of the farmers, such as how much land they have, how much money they have, how much labour they have and how much their decision is driven by profit maximisation. The data-mining results indicate that many different crops can be grown on any land unit in each season, depending on the farmers' characteristics. This information can be used to simulate changes in farmer decision-making given changes in the distribution of many of these farm characteristics.

Table 5.2 Survey information collected by the Chiang Mai University team for use in socioeconomic modelling in phase II of the Integrated Water Resources Assessment and Management project

Information requested	
Part 1	General, household characteristics, farm and household size
Part 2	Land type, tenure and land utilisation, crop year 2001
Part 3	Production costs for annual crops and perennial crops including fertilisers, materials, machinery and labour use
Part 4	Output, product sold and income for annual or perennial crops
Part 5	Income for other sources and capital availability
Part 6	Environmental problems
Part 7	Past use of land, competition of annual crops, farmers' attitudes
Part 8	Use and management of irrigation water

Implementation of decision trees for simulating land-use decisions

A decision simulation model was then constructed using these decision trees. The framework of this decision simulation model is show in Figure 5.3. This shows that GIS data are used to determining the farmers' level of investment. This then feeds into the wet-season crop decision tree, where wet-season crop choice is simulated. This choice is checked against system constraints before dry-season crop choices are simulated. Wet-season choice of perennial crops, including fruit trees and forest, is also passed as a constraint to the dry-season crop choice. The final output is a GIS-based output of wet- and dry-season crop choice.

An example of the type of output produced by this model is shown in Figures 5.4 and 5.5. These figures show different wet- and dry-season land-use choice maps under two scenarios: scenario 1, in which households are without additional credit; and scenario 2, where each household has 10,000 baht in additional credit.

Table 5.3 Crop groupings used for analysis of survey data collected by Chiang Mai University during phase II of the Integrated Water Resources Assessment and Management project

Crop type	Category (Label)	Crops included in category
Rice	rice_wet, rice_dry	glutinous rice, non-glutinous rice
Non-rice field crops	maize_wet, maize_dry	maize (corn), baby corn and sweet corn
Non-rice field crops	bean_wet, bean_dry	green soybean, groundnut, sweet bean, soybean and yardlong bean
Vegetables	leafveg_wet, leafveg_dry	head lettuce, bakchoi cabbage, Chinese cabbage, spinach, kale, green cabbage, cabbage, cauliflower, michilli
Vegetables	rootveg_wet, rootveg_dry	carrot, Chinese radish, potato, gobo, garlic and shallot
	othveg_wet, othveg_dry	bitter gourd, chilli, bunching onion, tomato, sweet basil and basil
Other annual crops	flower_dry	marigold and curcuma
Other annual crops	tobacco_dry	tobacco
Tree crops	banana	banana
Tree crops	longan	longan
Tree crops	lychee	lychee
Tree crops	mango	mango
Tree crops	tea_coffee	tea, coffee
Tree crops	ornamental	ornamental trees

Table 5.4 Final decision-tree variables used to represent decision-making in phase II of the Integrated Water Resources Assessment and Management project

Variable	Description	Values used for analysis
LU	Land unit as defined by the Department of Land Development	Values as defined by DLD
Profitgrp	This is calculated from gross margin level. Profit aspiration is divided into five groups. Certainly, a farmer wants more profit rather than less, but usually more profit means more risk, skills and management. One can think of these as a variable indicating risk and skill levels. Level one of profitgrp is low risk, low return and easy skills. Level two and three being medium risk, return and medium level of skills. Level four and five being high risk, return and high skills level.	<=3000 baht: profitgrp=1 >3000 to ≤6000 baht: profitgrp=2 >9000 to ≤12000 baht: profitgrp =3 >12000 to ≤15000 baht: profitgrp 4 >15000: profitgrp=5
Costrd	This is redefined from the actual cost of production. This variable indicates the level of investment farmers want to make in a particular crop.	cost 2 ≤2000 baht: costrd=2000 >2000 to ≤4000 baht: costrd=4000 >4000 to ≤6000 baht: costrd =6000 >6000 to ≤8000 baht: costrd 8000 >8000 to ≤10000: costrd=10000 >10000 to ≤12000 baht: costrd= 12000 >12000 to ≤15000: costrd=15000 <15000: costrd=20000
Landlabor	This is farm size divided by the units of household labour. Low values indicate land scarcity in relation to labour. High values indicate relative land abundance in relation to labour.	

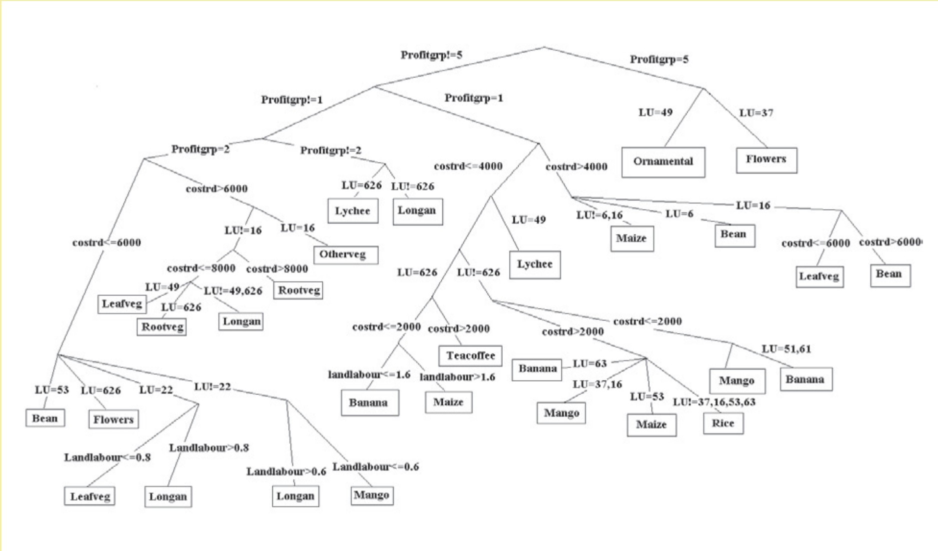


Figure 5.1 Wet-season decision tree derived from survey data collected during phase II of the Integrated Water Resources Assessment and Management project

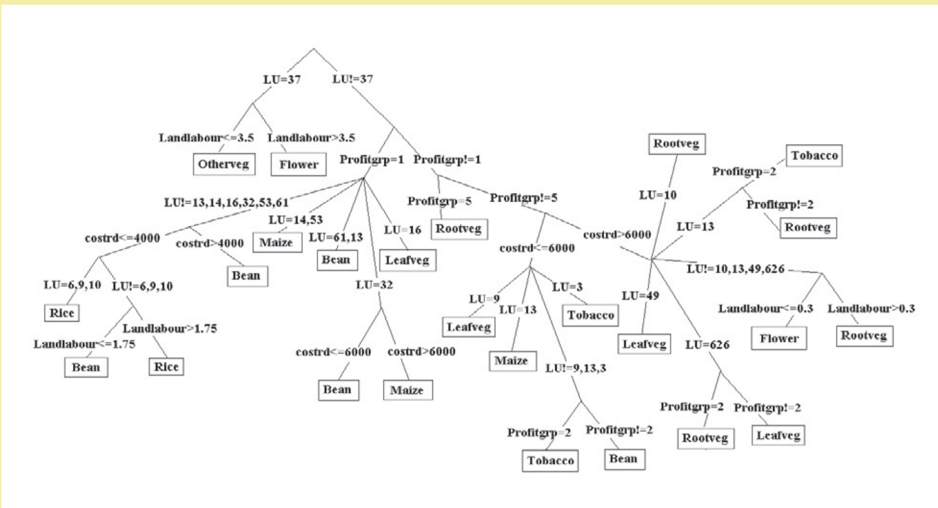


Figure 5.2 Dry-season decision tree derived from survey data collected during phase II of the Integrated Water Resources Assessment and Management project

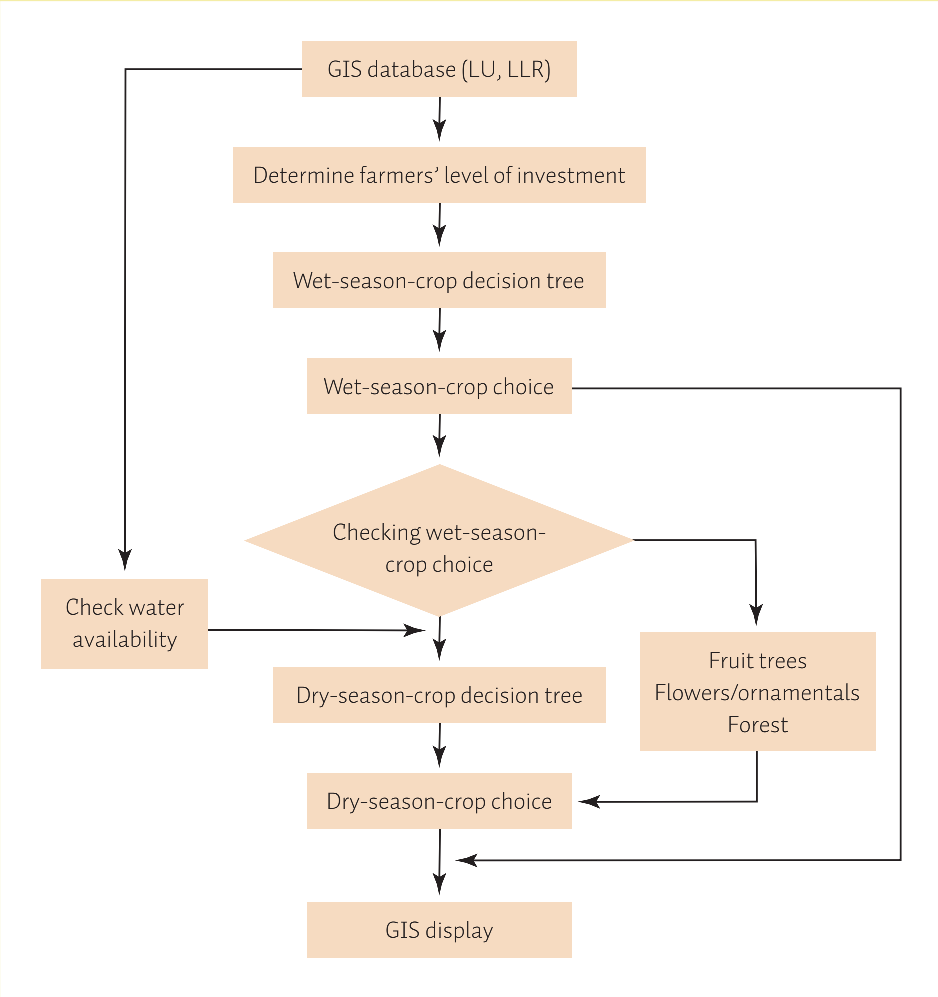


Figure 5.3 Decision model structure, incorporating wet- and dry-season decision trees, implemented in phase II of the Integrated Water Resources Assessment and Management project decision-support system

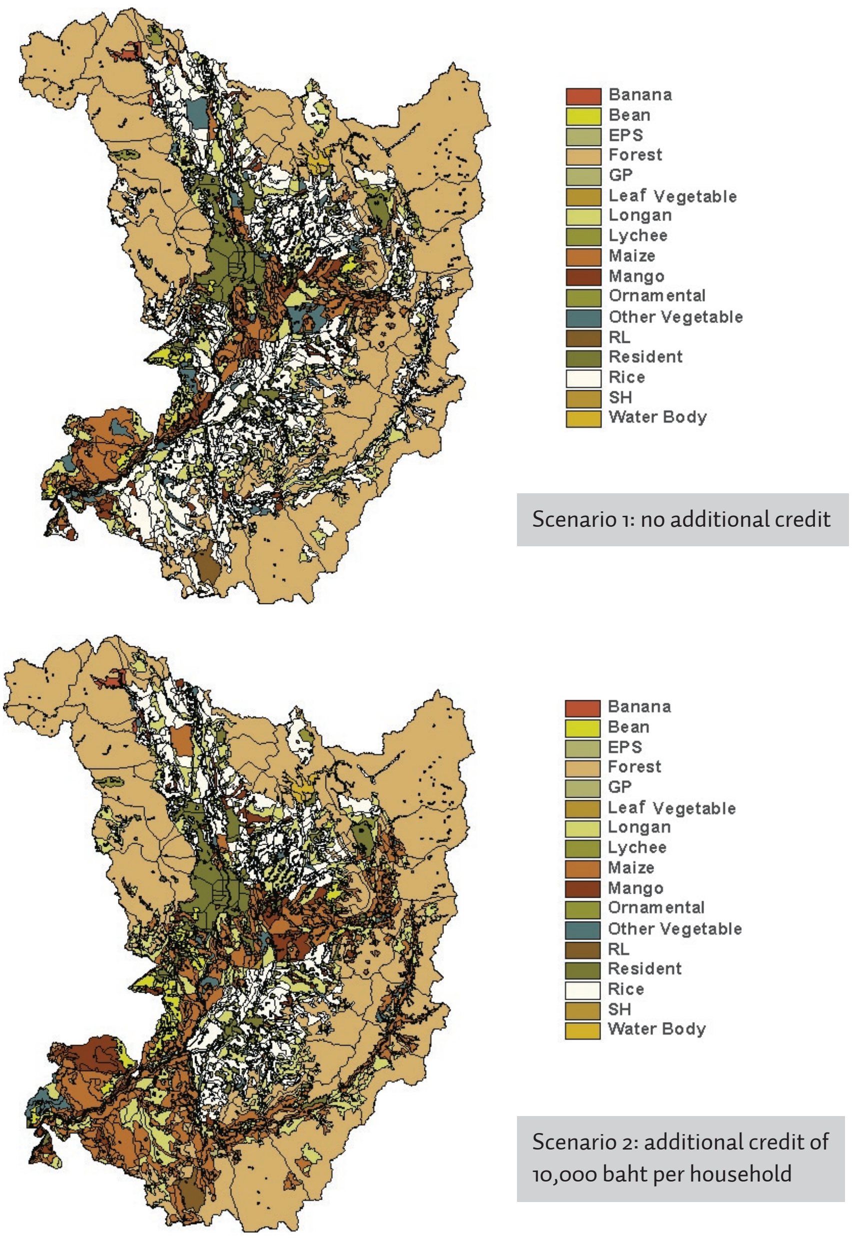


Figure 5.4 Example of decision model output for phase II of the Integrated Water Resources Assessment and Management project decision-support system: wet-season crop choice

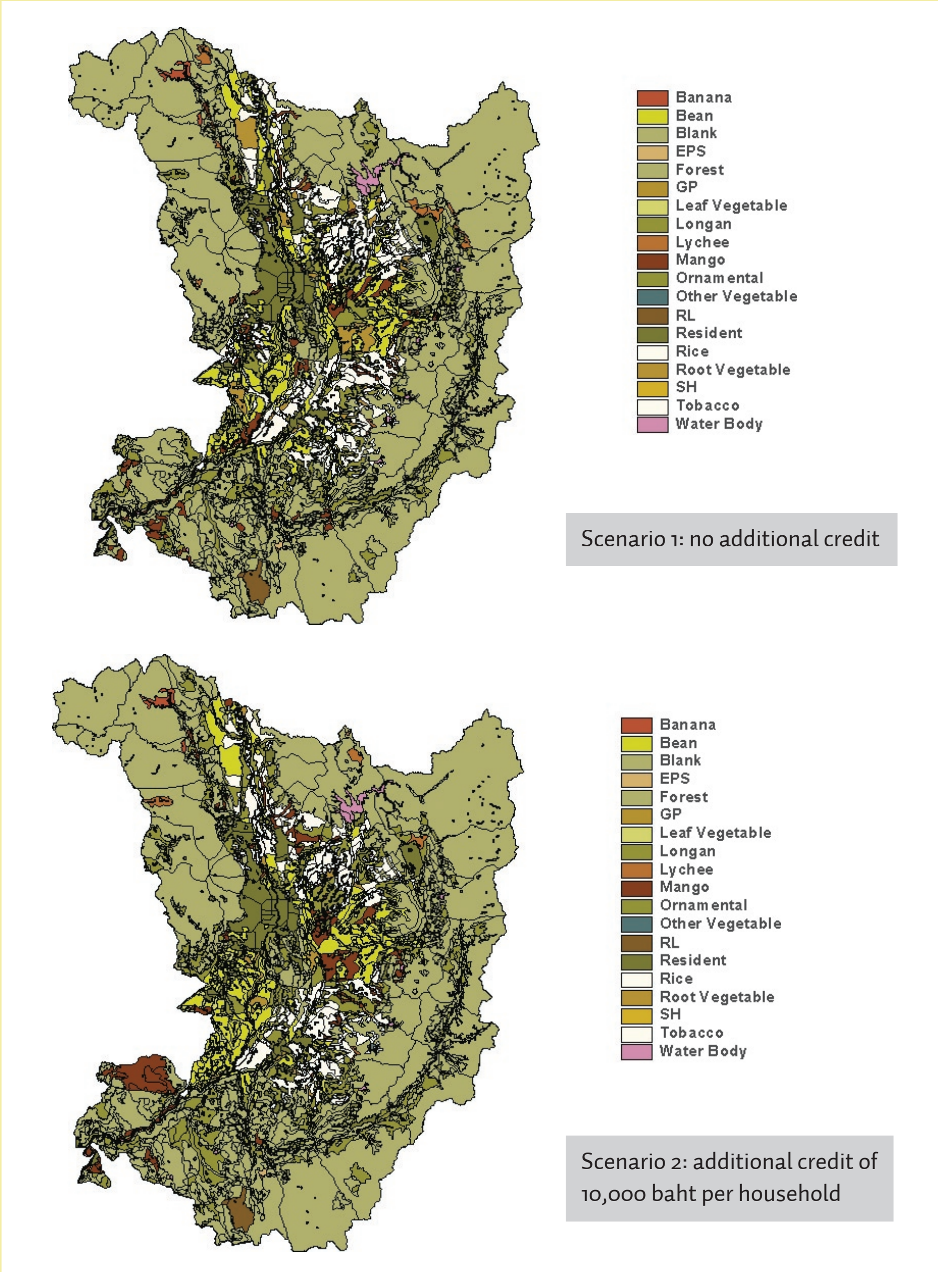


Figure 5.5 Example of decision model output for phase II of the Integrated Water Resources Assessment and Management project decision-support system: dry-season crop choice

Treatment of socioeconomic impacts in the Integrated Water Resources Assessment and Management project

In the IWRAM project, assessment of socio-economic impacts was limited to the first-order impacts of changes in land and water availability on agricultural households. The decision models used in both phases of the project assumed expectations-based decision-making, so a separate socioeconomic impact model was required to assess the final impact of decisions and resource availability on household performance. This impact was assessed in terms of farm gross margin and subsistence rice production, given crop yields simulated by the biophysical models in the framework and the areas planted to different crops.

The socioeconomic impacts arising from a scenario where agricultural expansion leads to increases in the land available to individual households is shown in Figure 5.6. The model was run over five years using climate data from 1989 to 1993. Results from only the upstream node in the Mae Uam catchment are shown.

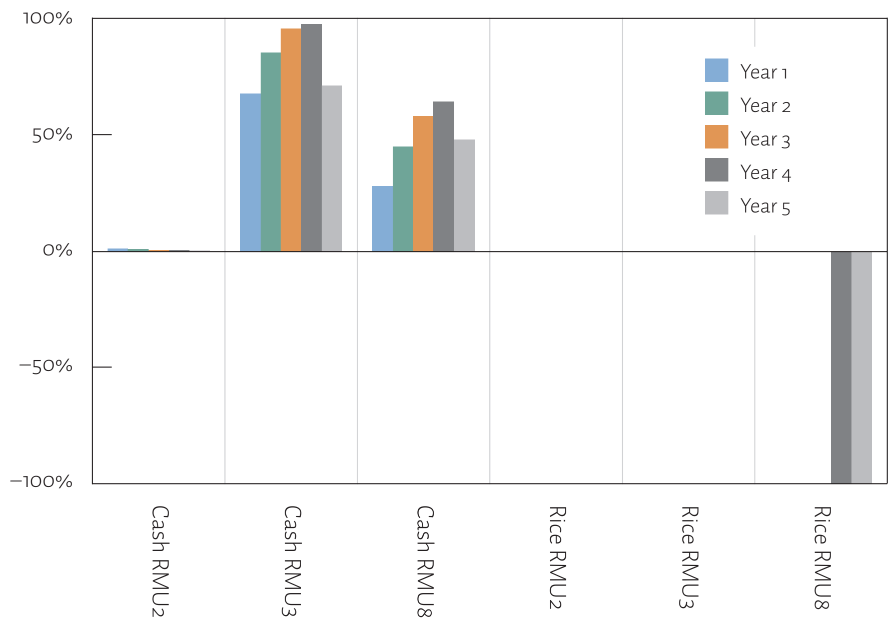


Figure 5.6 Socioeconomic impacts of agricultural expansion in the Mae Uam catchment, northern Thailand

The socioeconomic models (household decision models and socioeconomic impact models) from phase 1 of the IWRAM project were used to produce these results.

Households of RMU2 receive a very small benefit (i.e. increase in household cash) from the increase in land available. These households are constrained by their access to other resources (water and labour) more than land and so do not receive large benefits from the increase in area available. Households of both RMU3 and RMU8 have access to rainfed fields and benefit to a much greater extent than those of RMU2. In some years, household income in these RMUs more than doubles under these scenarios. Also, these households have a small rice deficit under the base-case assumptions. Increases in land lead to the removal of this rice deficit. This means that increasing the land area available to these households helped them meet their subsistence requirements and increased their cash wealth.

Conclusions

This chapter outlined the role of socioeconomic analysis and modelling in the IWRAM framework. In terms of modelling, this role can be divided into two components: modelling decision-making; and simulating socioeconomic impacts from changes in climate, policy, access or other drivers. Two approaches to modelling decision-making were applied in the IWRAM framework. The first was an optimisation-based approach to modelling decision-making on a household scale. The second used data-derived decision trees to simulate grid-based land-use decisions. The choice of approach depends on many factors including the availability of survey data, the comfort levels of stakeholders and users with more complex optimisation-based approaches, the drivers of decision-making that need to be captured in the analysis and the need for spatially explicit model outputs. Regardless of the choice of model, the same framework is used to integrate decision-making with models of biophysical processes. This means that the focus in model development should be on developing the framework within which components will be integrated, and understanding the requirements that this and the problem place on each of the component models. Different models can then be used to meet these requirements.

References

Ashby, J.A. and de Jong, G. 1982. Farmer field preparation and tillage practices. Implications for fertilizer technology research. Soil and Tillage Research, 2, 331–346.

Barreteau, O. and Bousquet, F. 2001. From a conceptual model to its artefacts: building experiments using the SHADOC model. In: Proceedings of the international congress on modelling and simulation (MODSIM2001), Canberra, Australia, 2001, 1123–1128.

Becu, N., Perez, P., Walker, A. and Barreteau, O. 2001. Catchscape: an integrated multi-agent model for simulating water management at the catchment scale, a Northern Thailand case study. In: Proceedings of the international congress on modelling and simulation (MODSIM2001), Canberra, Australia, 2001, 1141–1146.

Bennett, J.W. and Morrisson, M.D. 2001. Estimating the environmental values of New South Wales rivers. Canberra, Australian National University.

Black, J., ed. 1997. A dictionary of economics. Oxford University Press.

Branson, J., Eigenraam, M., Stoneham, G., Crean, J. and Pagan, P. 1998. Structural adjustment pressures in irrigated broadacre farming in the southern Murray–Darling Basin. Natural Resource Management Strategy MDBC I&E Project No. I6041. Economic Services Unit, NSW Agriculture; Economic Branch, Victorian Department of Natural Resources and Environment, Australia.

— 1999. Structural adjustment pressures in irrigated broadacre farming in the southern Murray–Darling Basin. Final report to the Australian Bureau of Agricultural and Resource Economics. NSW Agriculture and Victorian Department of Natural Resources and Environment.

DLWC (Department of Land and Water Conservation) 1999. The regional socio-economic impacts of changes in groundwater use for irrigation to sustainable yields in the Namoi groundwater systems. Technical report prepared for the Namoi Groundwater Expert Panel by the Socio-Economic Services Unit, NSW Department of Land and Water Conservation, Sydney.

Eigenraam, M. 1999. Economic assessment of water market reform using the water policy model. Division of Agriculture, Victorian Department of Natural Resources and Environment, Australia, Economics Branch Working Paper.

Fischer, G. and Sun, L. 2001. Model based analysis of future land-use development in China. Agriculture, Ecosystems and Environment, 85, 163–176.

Hall, N., Poulter, D. and Curtotti, R. 1994. ABARE model of irrigation farming in the southern Murray Darling Basin. Canberra, Australian Bureau of Agricultural and Resource Economics, Research Report 94.4.

Hare, M., Deadman, P. and Lim K. 2001. Towards a taxonomy of agent-based simulation models in environmental management. In: Proceedings of the international congress on modelling and simulation (MODSIM2001), Canberra, Australia, 2001, 1115–1122.

Hood, L. 1999. Agent based modelling. Presented at: Greenhouse beyond Kyoto, Canberra, 31 March–1 April 1998. Canberra, Bureau of Rural Sciences. Available at: <http://www.brs.gov.au/social_sciences/kyoto/hood2.html>.

Horton, G.A. 2002. Glossary of selected terminology relating to input–output (I–O) models and economic impact analysis. Nevada, USA, Division of Water Planning.

Jayasuriya, R. 2000. The on-farm impacts of groundwater management scenarios in the lower Murrumbidgee. Report to the Murrumbidgee Groundwater Management Committee. Orange, NSW Agriculture, Economic Services Unit.

Jayasuriya, R. and Crean, J. 2000. The agricultural impacts of environmental flow rules in the Murrumbidgee valley. Report to the Murrumbidgee River Management Committee. Orange, NSW Agriculture, Economic Services Unit.

— 2001. The on-farm impacts of environmental flow rules in the Murrumbidgee valley. Report to the Murrumbidgee River Management Committee. Orange, NSW Agriculture, Economic Services Unit.

Jayasuriya, R., Crean, J. and Jones, R. 2001. Evaluation of environmental flow rules in the Murrumbidgee valley. In: Proceedings of the 45th Conference of the Australian Agricultural and Resource Economics Society, Adelaide, 23–25 January 2001.

Leistritz, F.L., Leitch, J.A. and Bangsund, D.A. 2002. Regional economic impacts of water management alternatives: the case of Devils Lake, North Dakota, USA. Journal of Environmental Management, 66, 465–473.

Letcher, R.A., Jakeman, A.J. and Croke, B.F.W. 2004. Model development for integrated assessment of water allocation options. Water Resources Research, 40, W05502.

Morison, J. and Zorzetto, A. 1995. The economic impact of irrigated agriculture in the Namoi Valley region, Department of Land and Water Conservation, New South Wales, Australia.

Morrison, M.D., Blamey, R.K., Bennett, J.W. and Louviere, J.J. 1996. A comparison of stated preference techniques for estimating environmental values. Canberra, University of New South Wales, Choice Modelling Research Reports No. 1.

Renwick, M., Green, R. and McCorkie, C. 1998. Measuring the price responsiveness of residential water demand in California's urban areas: report prepared for California Department of Water Resources.

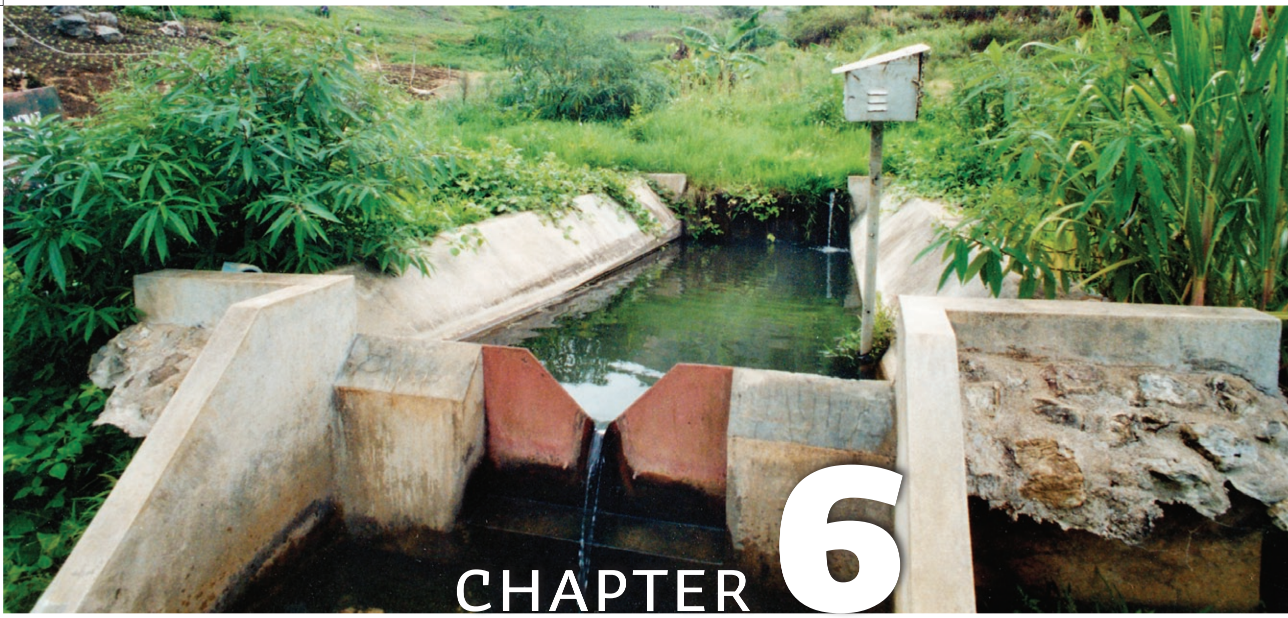
Ringler, C. 2001. Optimal water allocation in the Mekong River Basin. University of Bonn, Germany, Centre for Development Research, Discussion Papers on Development Policy 38.

Scoccimarro, M., Walker, A., Dietrich, C.R., Schreider, S.Y., Jakeman, A.J. and Ross, H. 1999. A framework for integrated catchment assessment in northern Thailand. Canberra, Australian National University, ICAM Working Paper 99/1.

Whitten, I.H. and Frank, E. 1991. Data mining: practical machine learning tools and techniques with Java implementations. Morgan Kaufmann Publishers, 265–320.

Whitten, S.M. and Bennett, J.W. 2001. Non-market values of wetlands: a choice modelling study of wetlands in the Upper South East of South Australia and the Murrumbidgee River floodplain in New South Wales. Canberra, University of New South Wales, Private and Social Values of Wetlands Research Reports No. 8.

Woodlock, A. 1996. The impact of interim river flow objectives on the regional economy in the Namoi Region. Unpublished report submitted to the River Flow Objective Working Group. Parramatta, New South Wales Department of Land and Water Conservation.



CHAPTER 6

Simulating the effects of land-cover change on streamflows

BARRY CROKE, WENDY MERRITT, PONGSAK WITTAWATCHUTIKUL, ATTHORN BOONSANER AND SOMPOP SUCHARIT

SUMMARY

The potential impacts of deforestation on hydrological response are of significant importance worldwide, and especially in highland regions of northern Thailand and other parts of Southeast Asia. In these regions, where climate exhibits strong seasonality, the availability of water in the dry season determines the feasibility of multiple crop rotations. This chapter presents two approaches to the prediction of hydrologic response to land-use changes as well as prediction of flows in ungauged catchments. These approaches are based on the IHACRES rainfall–run-off model (applied to the Mae Chaem catchment) and the US Soil Conservation Service curve-number approach (applied to gauge P37 in the Mae Ping basin). Both of these approaches have been used within the Integrated Water Resources Assessment and Management decision-support system.

The prediction of flows in ungauged catchments is a major hurdle in water-resource analyses in regions like northern Thailand where there is a lack of stream gauge instrumentation, or where assessment of water availability is required at locations between gauging sites, or under conditions of changes in forest cover, as input to agricultural production models.

Small stream flowing through the Mae Chaem catchment, northern Thailand

Introduction

The type and complexity of a hydrological model used in an integrated modelling framework depends on what management decisions are to be considered, the spatial and temporal scales considered in the integrated framework, and what outputs are required by other models within the framework. For example, for a rural environment, the hydrological model may need to be sensitive to the pattern of land use, or just the relative areas of each land use. The primary role is to estimate the streamflow for a given land-use pattern or management scenario. The model may also need to supply additional water-related information required by other models; for example, soil moisture variations (spatial and/or temporal) for crop modelling.

Thus, the structure of the integrated framework dictates what the inputs and outputs of the hydrological model should be. Ideally, the simplest model that fulfils these basic requirements should be used, as more-complex models will require more resources to develop, due to increased data requirements and difficulty in calibration. The two examples presented here differ mainly in the degree of spatial sensitivity included in the models and, as a result, differ slightly in their complexity, the data requirements and the difficulty in calibration.

Role of hydrological models

One of the key roles of hydrological models in an integrated modelling framework is to provide estimates of the streamflow for a particular land-use/management scenario. This can be used to estimate water availability for downstream users such as irrigators, and hence determine what type of crops can be grown. Generally, the effect of a land-use scenario on streamflow is limited to the effect of the vegetation cover across the catchment (divided into broad types such as evergreen forest, cropland, pasture etc.), as the effects of finer land-use classifications and spatial distribution are difficult, if not impossible, to determine from gauged streamflows.

Hydrological models are also used to infer the effects of climate variability and climate change, though results become increasingly uncertain the further catchment and climatic conditions are from those used to calibrate and validate the model. For a review of the current state of knowledge on forest hydrology and related land- and water-management issues in the humid tropics see the compendium by Bonnell and Bruijnzeel (2005).

Model types

There have been many reviews of the status of catchment hydrology as a science, and our ability to make predictions (e.g. Klemeš 1986; Beven 1987; Goodrich and Woolhiser 1991; Wheater et al. 1993; Hornberger and Boyer 1995; Croke and Jakeman 2001). In this section, a brief summary of the different model types is presented.

Wheater et al. (1993) classified rainfall–run-off models into four categories: metric, conceptual, hybrid metric-conceptual and physics-based. Metric models are based primarily on observational data, and attempt to characterise system response using that data. As a result, these models do not attempt to describe the physical processes taking place. An example is the earliest unit-hydrograph methods. Conceptual model types represent the next step up in model complexity. These models attempt to represent all the important hydrological processes at the catchment scale, based on other prior knowledge. These are generally spatially lumped—e.g. MODHYDROLOG, Chiew and McMahon (1994), though distributed models also exist—e.g. LASCAM, Viney and Sivapalan (1999). While the models are based on the important processes taking place, generally the parameters cannot be measured in the field due to the lumped nature of these models (even the distributed ones). The structure of conceptual models is defined a priori, in accordance with the perception of the important processes. Hybrid models combine the metric and conceptual paradigm—e.g. IHACRES, Jakeman and Hornberger (1993)—utilising data to discriminate among many hypotheses about the appropriate model structure. All these models need to be calibrated against observed data, with limited ability to transfer parameters to other catchments.

Physics-based models use a more classical mathematical form to describe hydrological processes (such as the Richards' equation for vertical transport). Such models—e.g. TOPOG_IRM, Zhang et al. (1999) and ANSWERS, Connelly et al. (1997)—are necessarily distributed, and require that each cell be homogeneous, or at least that the heterogeneity within each cell does not significantly affect the model's accuracy, or the ability to derive the necessary parameter values from field measurements. While distributed models have the highest potential for yielding information, particularly in studies of the effect of land-use change on flow volumes, they also require more extensive validation than lumped models.

Woolhiser (1996) noted that, even if the physical entities represented by the parameters vary smoothly in space and are constant in time, the parameters are actually lumped to some extent (and hence may be impossible to measure directly) due to the use of discrete time steps. To avoid this difficulty, the time step used in the model must be small enough to approximate the continuity of the system. The necessary time step depends primarily on the temporal nature of the precipitation, with storm events requiring a much finer time step. The question here is: at what temporal resolution does the discrete nature of the model affect the representation of the processes? For storm events, high spatial and temporal resolution data are needed, and so a major limiting factor for physics-based models is the availability of rainfall data.

Three of the issues related to complexity of a model are over-parameterisation, computational demands and error accumulation.

Grayson et al. (1992) discussed the merits of process-based, distributed-parameter models, arguing that the real uses of such models are research-related, including: analysis of data, testing of hypotheses in conjunction with field studies and improving our understanding of processes and their limitations. The large data requirements of such models essentially limits their use to well-instrumented test catchments. For management purposes, simpler models that require fewer data and have clearly stated assumptions may be a more realistic approach.

Hydrological data

It is becoming increasingly accepted that the complexity of hydrological models used for prediction should not exceed that warranted by the information content and accuracy of the field data (Jakeman and Hornberger 1993). However, overly complex models continue to be reported and used, and it seems that the appropriate level of complexity warranted is still being over-estimated. While more complex models can provide more information than just streamflow prediction (spatial distribution of soil moisture content, for example), they require more-extensive testing and so-called validation. Therefore, such models can be reliably tested only in well-instrumented catchments.

Hydrological information for the Integrated Water Reources Assessment and Management project

For the Integrated Water Resources Assessment and Management (IWRAM) project, the hydrological focus was on volume of streamflow. As such, the model developed addressed this issue only. Other potential issues such as water quality (including turbidity, sediment load, nutrients, heavy metals, pesticides and pathogens) and groundwater resources were not considered. Inclusion of such issues would require a more-complex hydrological model that simulated the effects of management options on these aspects of the system. For example, in areas with significant groundwater extraction, then the impact of changes in the extraction rate on the groundwater level would have to be included within the model, so that future availability of groundwater, as well as the impact of falling groundwater levels on streamflow, could be evaluated.

For an integrated model that is required for integrated assessment purposes, information on streamflow is needed by that model at locations that have no recorded streamflow. In such cases, the hydrological model component is required to estimate the flow at these sites, requiring methods for estimating the values for the model parameters. This can be done using regionalisation techniques, where the parameter values for gauged sites are related to catchment attributes, thus permitting the attributes for the ungauged catchment to be used to estimate the parameter values. An alternative approach was adopted within the IWRAM decision-support system (DSS), where deep drainage and run-off estimated by the crop model were used to adjust the values of the parameters in the hydrological model.

Choosing suitable models

The requirement of the hydrologic component of the IWRAM project was a model capable of: showing sensitivity to broad-scale land-cover changes; predicting hydrologic response over a range of spatial scales from tens to thousands of square kilometres; incorporating a parsimonious approach to model parameterisation; partitioning flow between quick flow (dominant during the wet season) and slow flow (dominant during the dry season); and allowing parameter values to be related to catchment attributes in ungauged catchments. The catchments to which the procedure was applied are sparse in hydrologic and climatic data. The above factors strongly influenced the selection of an appropriate model structure. There were few data to support complex representations of the hydrologic system, let alone verify the performance of such models.

Physics-based models were deemed to be not applicable in the catchments used in this study. Despite the benefit of using such models—that is, the use of measurable properties potentially reduces the need for calibration—data limitations in the catchment studied here prevent application of these models. Conceptual models provide a much more appropriate alternative. The IHACRES metric–conceptual rainfall–run-off model (Jakeman et al. 1990; Jakeman and Hornberger 1993) is the basis for the hydrological modelling in the Mae Chaem catchment. This is a lumped model that considers the catchment as a single unit (though the parameter values were adjusted for changes in land use based on the results from a semi-distributed crop model). As an alternative, a distributed model based on the United States' Soil Conservation Service (SCS) curve-number approach was also developed and applied in the P37 catchment, giving the hydrological module greater spatial sensitivity at the cost of increased complexity.

The IHACRES model

The IHACRES rainfall–run-off model has been applied across a wide range of climates and catchment sizes. It has a parsimonious approach to model parameterisation (six parameters in the version used in this project). This parsimony facilitates regionalisation to ungauged catchments. Simple catchment attributes, such as forest cover area and catchment area, can be used to regionalise its parameters and thereby predict streamflow in ungauged catchments (e.g. Post et al. 1998; Post and Jakeman 1999).

The IHACRES model consists of a non-linear loss module that converts rainfall to rainfall excess, and a linear routing model that converts the rainfall excess to streamflow (Figure 6.2).

There are several formulations developed for the non-linear loss module—see Jakeman and Hornberger (1993), Ye et al. (1998) and Croke and Jakeman (2004). All of these formulations calculate the amount of rainfall excess based on the input rainfall and a catchment moisture indicator (*sk*). Typically, the non-linear loss module has three parameters, though the model of Ye et al. (1998) has five (additional parameters needed to model ephemeral catchments in Australia). For the IWRAM project, the Jakeman and Hornberger (1993) form was used,

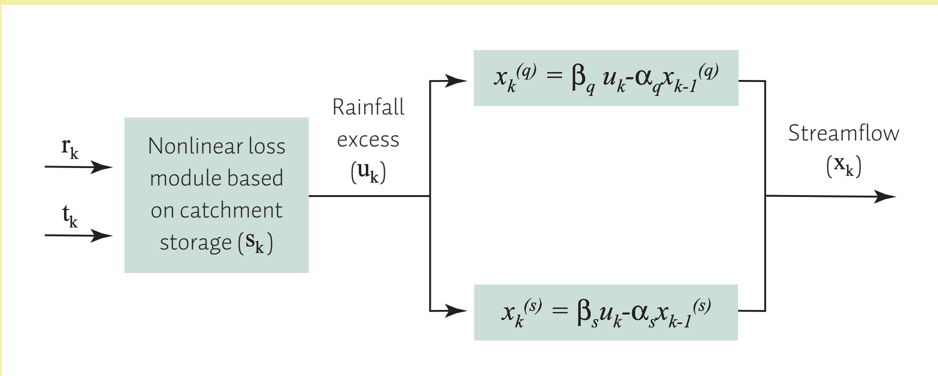


Figure 6.2 Generic structure of the IHACRES rainfall–run-off model. The climate inputs are rainfall (*rk*) and temperature (*tk*), though the temperature can be replaced by an estimate of the potential evaporation or potential evapotranspiration if this is available.

with the non-linear loss module comprising a storage coefficient c, a time constant for the rate of drying τ_w of the catchment at a fixed temperature (20°C), and a factor f that modulates τ_w for changes in temperature.

The linear routing module converts the rainfall excess (u_k) into modelled streamflow (x_k) using a unit-hydrograph approach. The usual structure is two exponentially decaying stores in parallel, representing quick- and slow-flow components (as shown in Figure 6.2), though for ephemeral catchments where the baseflow component is very weak or absent, a single store can be used. Each storage is characterised by a time constant (or equivalently the rate) of its unit-hydrograph recession (α_q and α_s). The proportional volume of the quick-flow (v_q) to slow-flow (v_s) storage response completes the parameterisation of the linear routing model.

The IHACRES model assumes that the partitioning of rainfall excess into quick- and slow-flow components is constant and thus does not depend on rainfall amount or intensity, or catchment condition. This assumption is inherent in any rainfall–run-off model incorporating a constant unit hydrograph approach. In order to represent the influence of land use on the strength of the slow-flow component, estimates of the run-off and deep drainage derived using the crop model (Chapter 7) were used to modify the quick- and slow-flow volumes (see Figure 6.3). The influence of land use on volume of streamflow produced was included in the integrated model by varying the catchment storage coefficient c by the variation in the combined run-off plus deep drainage calculated using the crop model. This technique was also used to estimate the model parameters for ungauged sites (sites where information on the streamflow was needed by the integrated model, but no stream gauging had been carried out).

Direct calibration and regionalisation results

The hydrologic module was developed and tested in sub-catchments of the Mae Chaem catchment in northern Thailand (Figure 6.4). In the Mae Chaem catchment, rapid agricultural intensification, rural development initiatives, and government conservation policies have created points of tension in relation to land- and water-resource management. Environmental and social issues of particular relevance for the Mae Chaem catchment are the distribution of dry-season flows between upland and lowland farmers, increased rates of erosion from agricultural land and surface water quality.

Results of using the combined IHACRES model and the crop model to predict flows at ungauged sites and in response to land-cover changes are reported comprehensively in Croke et al. (2004). Procedures of direct calibration to stream-gauge data and regionalisation from any one gauge were undertaken for three sub-catchments: Kong Kan, Hai Phung and Mae Mu (Figure 6.4).

Consider direct calibration for the Kong Kan site from its gauged rainfall–discharge time series for the period of available records (1985–1994). Reasonable model performance was obtained—except for the 1987–1988 hydrological year (Figure 6.5). The bias (in mm) in simulating Kong Kan ranges from 0.4% of annual rainfall in 1986 to 18% of annual rainfall in 1987.

Consider using the gauged data and IHACRES model for each of the three catchments in turn as reference catchments in order to regionalise the flows in the other two catchments. Figure 6.6 shows volumes of observed versus predicted discharge for each hydrologic year and its wet- and dry-season divisions. The procedure seems capable of predicting the year-to-year

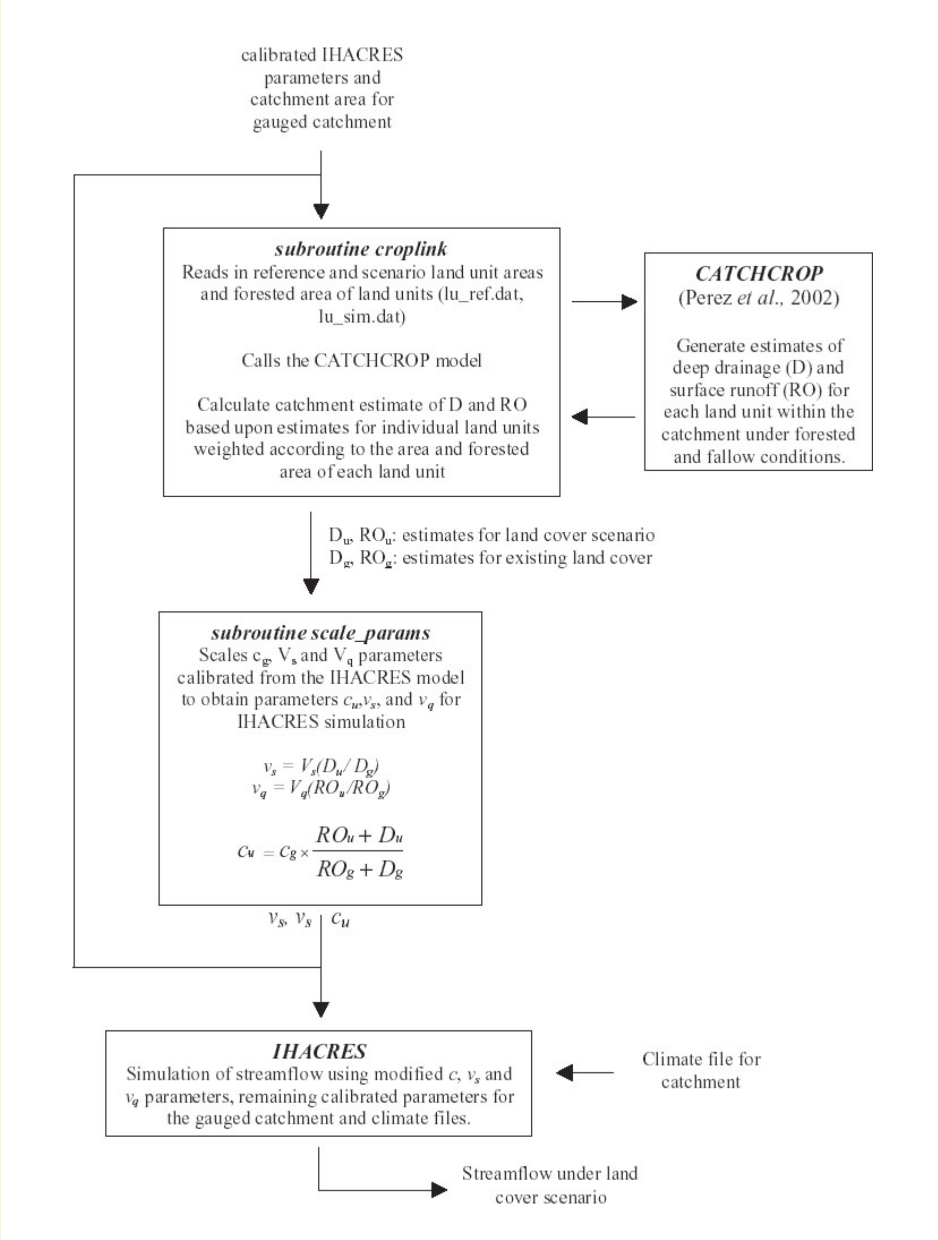


Figure 6.3 Flow diagram outlining procedure used to estimate the effect of land-use change on streamflow at gauged sites, as well as estimation of the flows at an ungauged site. Source: Merritt et al. (2004)

Figure 6.4 Location of discharge gauges and the ungauged Mae Uam sub-catchment used to test the regionalisation procedure and model response to forest-cover changes. The large dot gives the location of Mae Chaem city. Source: Merritt et al. (2004).

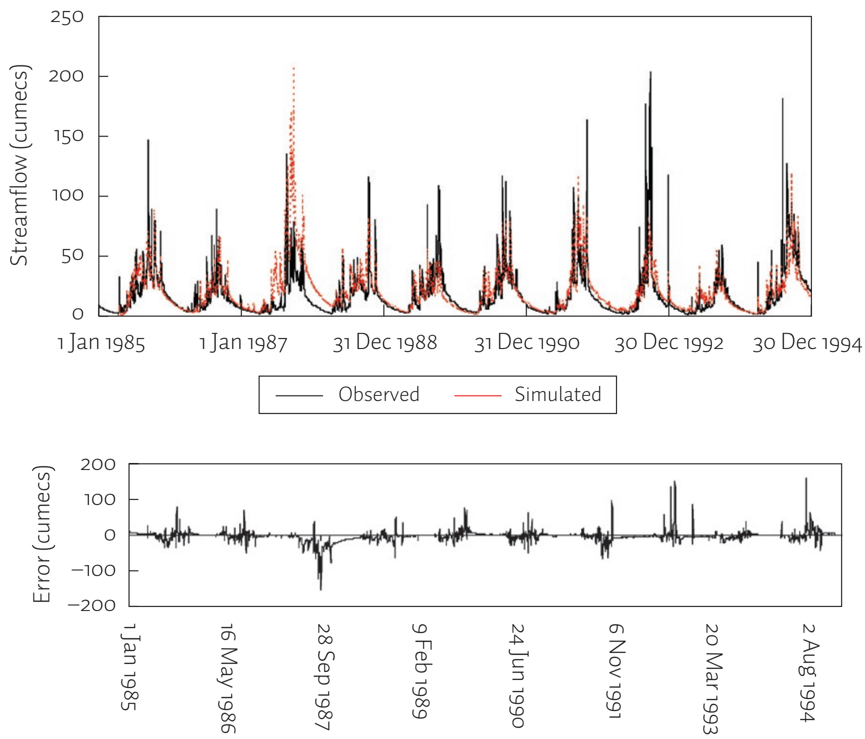


Figure 6.5 Observed and predicted streamflow for the Kong Kan sub-catchment using direct calibration, and the error in modelled flow for the simulation period (1985–1994)

flow pattern for all three sub-catchments. This is more evident in the estimates of wet-season and annual discharge than in the dry season. In the dry season, discharge estimates for the Kong Kan sub-catchment are between 57% and 95% of observed discharge when simulating from Huai Phung and over-estimated by between 9% and 70% when regionalising from Mae Mu (Figure 6.6a). For the Huai Phung sub-catchment (Figure 6.6b), the dry-season performance is poor. Whatever the reference catchment, neither magnitude nor relative flow pattern is being captured. In the wet season, the relative increase in discharge with increasing rainfall is much improved and the predicted magnitude of discharge is superior to that for the dry season.

Patterns in annual, wet- and dry-season discharge are captured reasonably well for simulations of Mae Mu, except for the wet test years (Figure 6.6c). The performance in the dry season where regionalising information from both Kong Kan and Huai Phung does lead to an under-estimation of dry-season flows by, on average, between 28% and 42% based on Kong Kan and Huai Phung calibrated parameters, respectively.

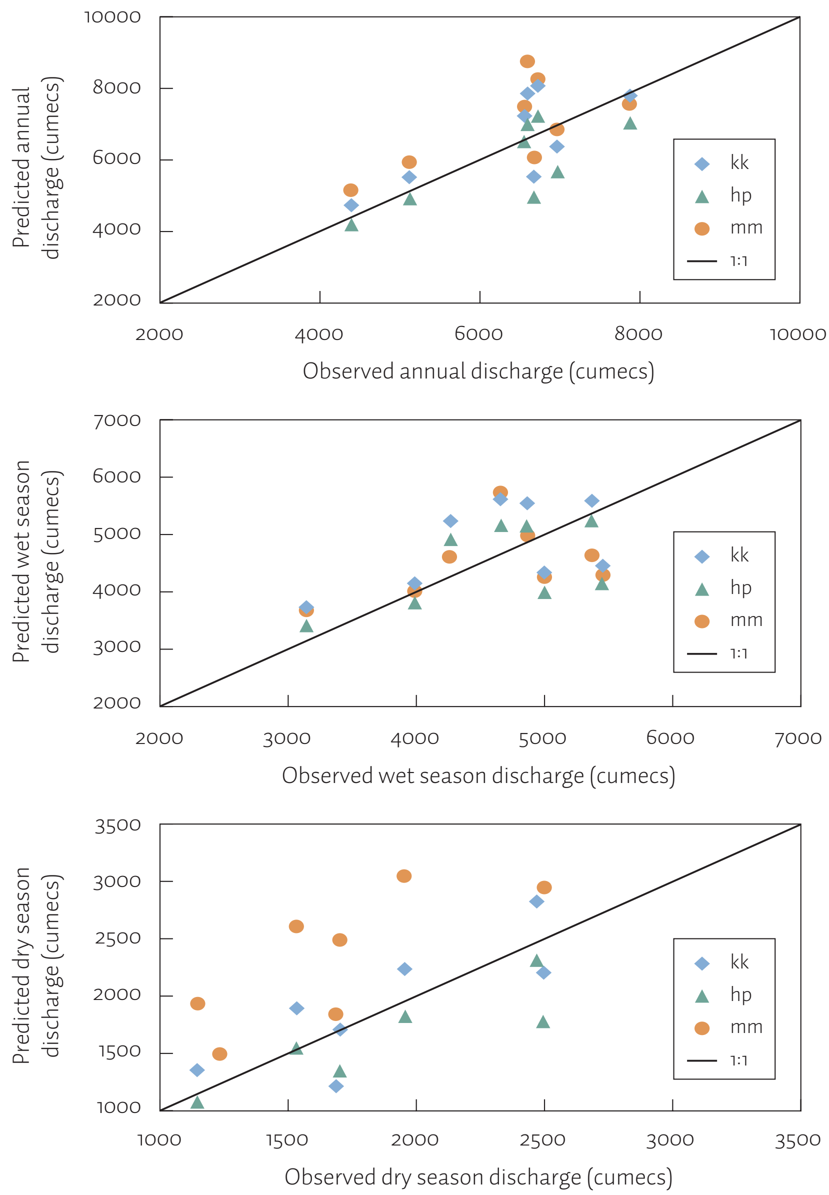


Figure 6.6a Observed versus predicted annual, wet-season and dry-season discharge for Kong Kan. Estimates are provided for all reference sub-catchments: Kong Kan (kk), Huai Phung (hp) and Mae Mu (mm).

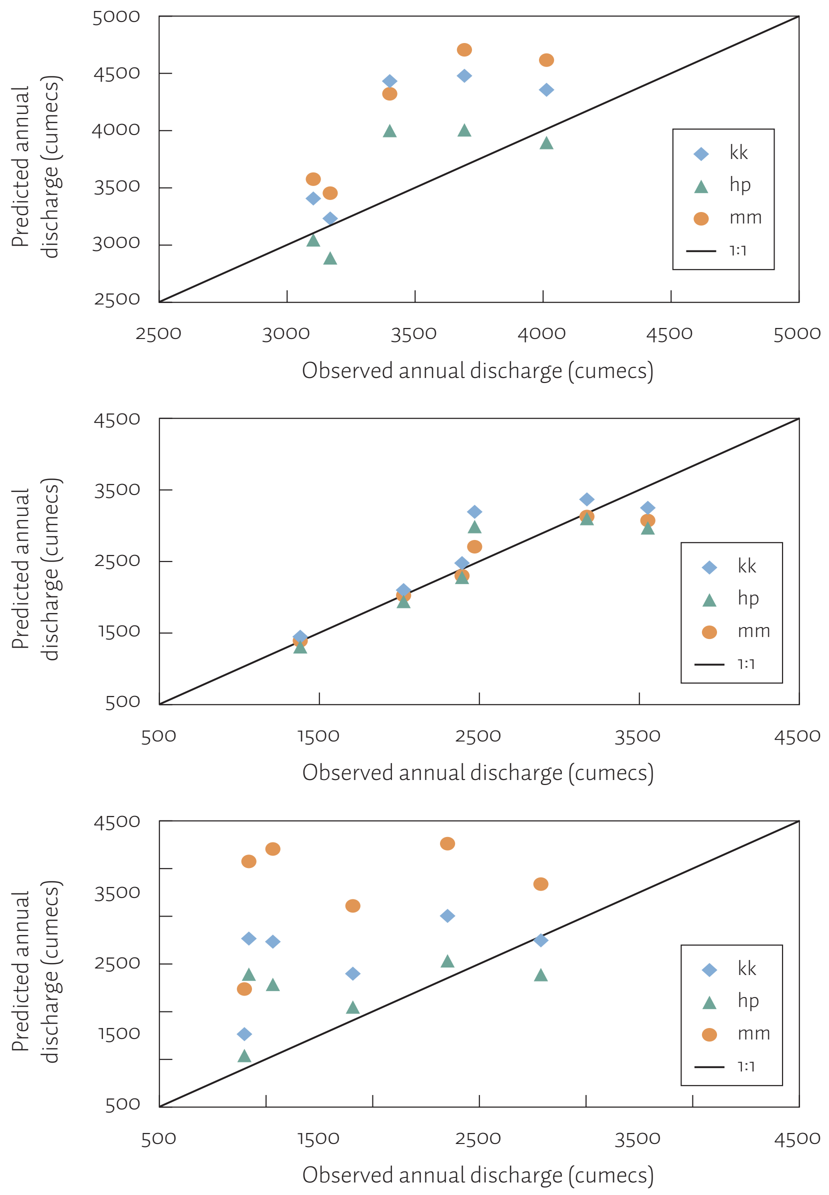


Figure 6.6b Observed versus predicted annual, wet-season and dry-season discharge for Huai Phung. Estimates are provided for all reference sub-catchments: Kong Kan (kk), Huai Phung (hp) and Mae Mu (mm).

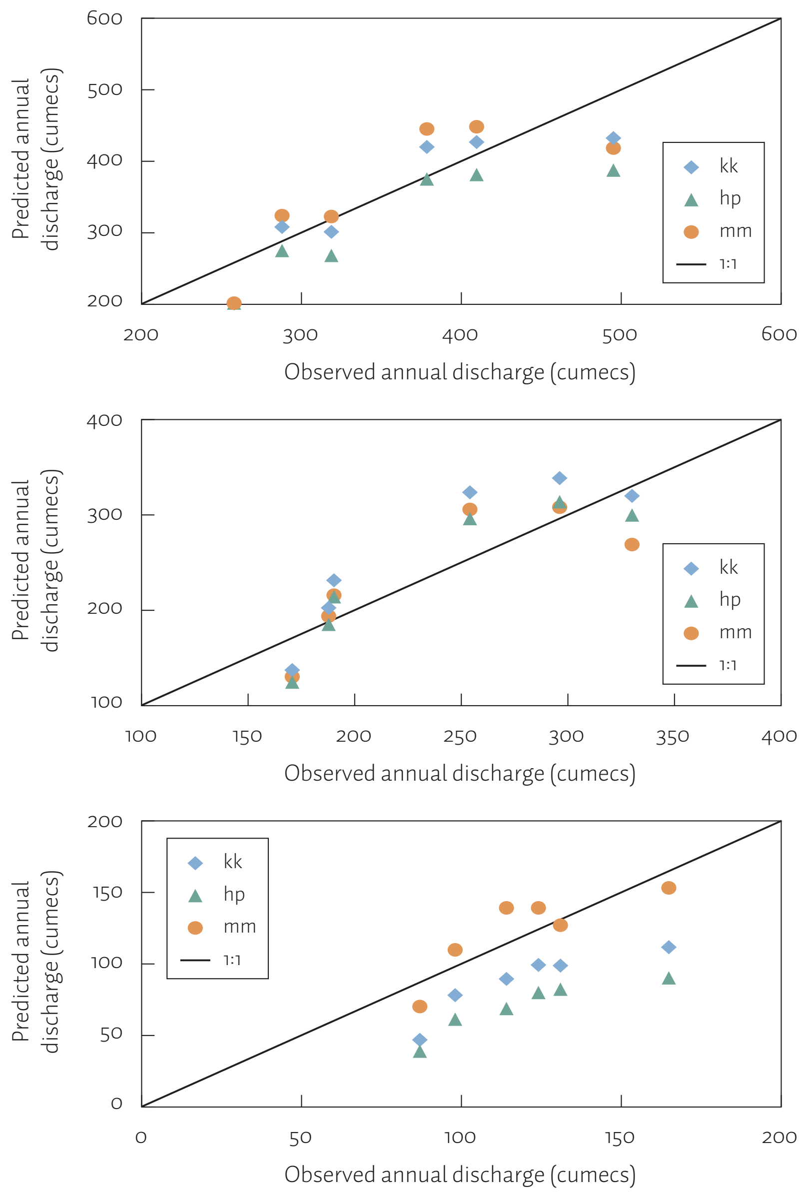


Figure 6.6c Observed versus predicted annual, wet-season and dry-season discharge for Mae Mu. Estimates are provided for all reference sub-catchments: Kong Kan (kk), Huai Phung (hp) and Mae Mu (mm).

This partial success of the regionalisation approach warrants its testing in other catchments with higher-quality rainfall and discharge data. Nevertheless, its it remains useful in the current situation.

Predicting flows under forest cover changes

The influence of changes in forest cover on the quick- and slow-flow volume components of the IHACRES model were investigated for the 45.3 km² Mae Uam sub-catchment. The sub-catchment is ungauged, although the Land Development Department in Thailand provided land-unit information for this catchment. Thus, the regionalisation approach described above was used to model flows in the Mae Uam sub-catchment, using the gauged Mae Mu sub-catchment as the reference catchment. As none of the gauged sub-catchments had significant forest-cover change over the period of record, Mae Uam was selected to look at the model response to forest change. The catchment is largely dominated by steeply sloping, loamy soils in the upper catchment (land units 47 and 49), with gently sloping paddy land and mid-sloping gravel soils in the lower catchment.

Twelve scenarios of forest conversion were run to illustrate the effect of forest cover on the catchment estimates of drainage and run-off and hence the impact on the quick- and slow-flow volume components of the IHACRES model and predicted streamflow. The net change in forest cover in Table 6.1 is in relation to the forest cover in 1990 (sc1) where forest cover is 90.4% of the catchment. Table 6.1 illustrates the impact of forest cover on mean annual, wet season and dry season discharge under the same climatic series over the period 1985 to 1993.

Decreasing forest cover increases the catchment estimates of surface run-off while decreasing deep drainage for an average rainfall period corresponding to the 1990 hydrologic year (Figure 6.7a). Given our assumption that the slow-flow volume component of the IHACRES model, *vs*, is dominant during the dry season—where the majority of streamflow derives from water that has percolated through the soil subsurface—deforestation increases the quick-flow component, *vq*, relative to the slow-flow component, *vs* (Figure 6.7b). With decreasing forest cover, increases are seen in the total annual discharge predicted by the procedure. The increase in annual discharge from 1990 land-cover conditions (sc1) to complete deforestation (sc12) corresponds to 1214 ML in the driest hydrological year (April 1989–March 1990) and 3592 ML in the wetter hydrological year of April 1985–March 1986.

The response of the hydrologic model to forest-cover scenarios is consistent with other observations in the literature. Changes in annual, wet-season and dry-season discharge under deforestation scenarios in Mae Uam show limited response in discharge until forest removal of the order of 13%. From the literature, it appears that, at least in small catchments, a change in forest cover of approximately 20% is necessary before changes in streamflow are observed (e.g. Bruijnzeel 1990; Johnson 1998). This suggests that the hydrologic module is sensitive to forest-cover changes to a degree similar to that observed in the field. In large catchments or at basin scales, the change in forest cover required to observe changes in hydrologic response is not well established. Some literature has identified that changes in hydrologic response in large catchments may not be obvious even with large forest-cover changes (e.g. Wilk et al. 2001).

Table 6.1 Effect on discharge of land-cover scenarios and change in forest cover from 1990 (± afforestation). Also shown is percentage change from the 1990 land cover scenario (sc1) for mean-annual, wet-season and dry-season yields (– indicated as the decrease from sc1). Yields (in ML) are provided for sc1.

	Description		Discharge (ML)		
			Mean annual	Wet-season	Dry-season
sc1	1990 forest cover	––	18,271	13,433	4838
		Net change (%)			
sc2	100% forest cover on all land units	+9.6	–1.2	–2.5	2.2
sc3	0% forest cover on paddy fields (land units 88 and 99)	–3.0	0.3	0.3	0.4
sc4	70% forest cover on land units with slopes less than 16° (land units 23, 88, and 99)	+1.9	–0.2	–0.2	0.3
sc5	50% forest cover on land units with slopes less than 16° (land units 23, 88, and 99)	–0.6	0.1	0.3	–0.5
sc6	70% on land unit 49 (slopes greater 35°)	–13	2.4	4.5	–3.5
sc7	70% forest cover on land units with slopes less than 35° (land units 23, 25, 45, 47, 88, and 99)	–8.1	2.3	4.0	–2.5

US Soil Conservation Service curve-number approach

The IHACRES model is a lumped parameter rainfall–run-off model. As a result, there is no representation of the spatial variability in the catchment included within the model (though this may be included in the model parameters if these are estimated by a spatially distributed cross model). One alternative would be to divide the catchment into zones with similar hydrologic response (hydrologic response units) and run the non-linear loss module separately on each of these (e.g. Carlile et al. 2002). Another alternative is to use a hydrological model that attempts to model the spatial movement of water through a catchment in addition to the temporal movement out of the catchment. An example of such an approach is presented here using a simple flow-generation algorithm based on the SCS curve-number approach. The SCS approach uses empirically derived 'curve numbers' that can be used to estimate the run-off generated based on the combination of soil properties, topography and vegetation cover, as well as antecedent moisture, at a particular site.

While the SCS curve number approach was developed in the USA, the method has been employed across many regions of the world, though care must be taken to check that the

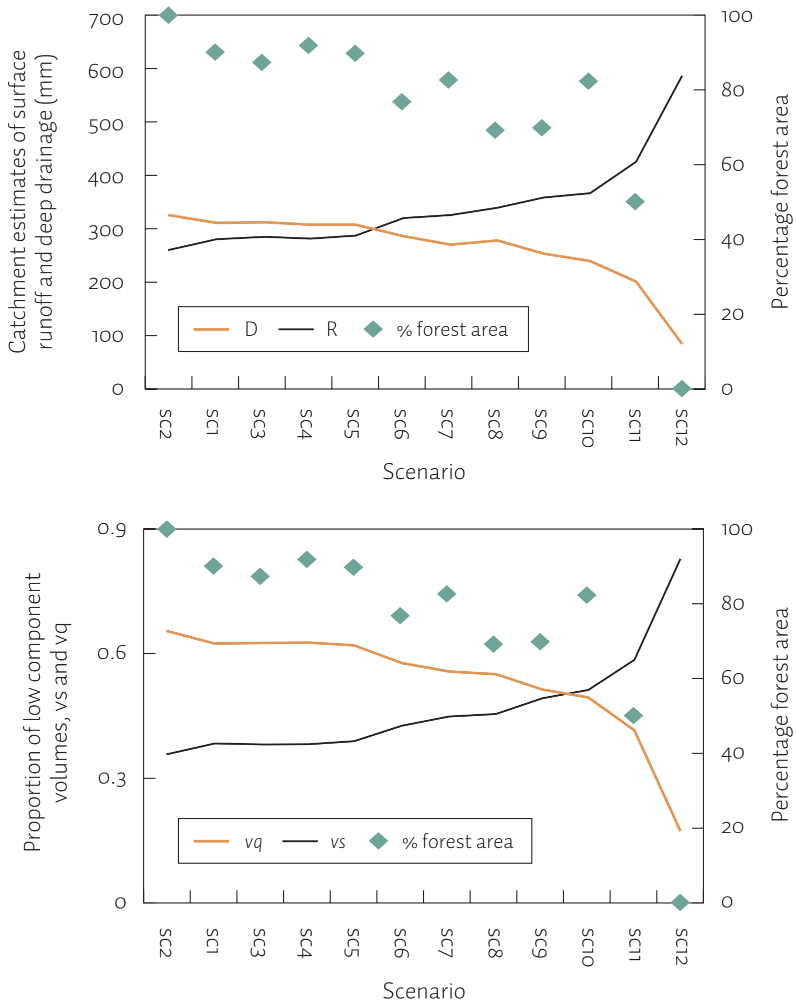


Figure 6.7 Effect of forest-cover-change scenarios on (a) deep drainage (D) and surface run-off (R) estimates for Mae Uam, and (b) the IHACRES quick (*vq*) and slow (*vs*) flow volume components. Total forest area under each scenario is also shown (x).

coefficients apply in each region. Small experimental watersheds at Rayong (southeastern Thailand) were selected for construction of the model, with regression relationships for the variation in the streamflow recession rate as well as the streamflow volume being defined, based on the observed time series (Witthawatchutikul et al. 1985).

The primary purpose of this model is to simulate the influence of the pattern of land use across the catchment, rather than just the relative fractions of each land use within the catchment, and to produce a spatial map of the effective rainfall needed by the crop model. This gives both the hydrological and crop models greater sensitivity to the spatial pattern of land use.

This model is currently under development, and when completed, it will provide the IWRAM DSS with additional predictive powers and flexibility (Witthawatchutikul et al. 2005).

Integrating the hydrology model into the Integrated Water Resources Assessment and Management decision-support system

The requirement of the hydrologic component of the IWRAM DSS was a model capable of showing sensitivity to broad-scale land-cover changes, and of predicting hydrologic response over a range of spatial scales from tens to thousands of square kilometres. The catchments in northern Thailand that were being studied were sparse in hydrologic and climatic data, and this prevented any complex representations of the hydrologic system from being applied.

The hydrology model is a key component of an integrated framework for water-resource assessment, as it provides the volume (and timing) of water for irrigation of crops.

The IHACRES rainfall–run-off model had previously been applied across a wide range of climates and catchment sizes and requires only a small set of parameter values. Also, simple catchment attributes, such as forest-cover area and catchment area, can be used to regionalise these parameters and thereby allow the prediction of streamflow in ungauged catchments. This made the IHACRES model particularly suitable for incorporation in the IWRAM DSS. One limitation is that the model cannot easily represent spatial variability in the catchment. Therefore, another model that can represent spatial variability and uses an algorithm based on the SCS curve-number approach is also being developed. Of course, the increased complexity of this model has the drawback that it has increased data requirements. Hence, it is more difficult to apply in catchments where there is little or no monitoring taking place.

The two hydrologic models developed for the IWRAM DSS are focused on the availability of surface water in rivers and streams for crop irrigation. Other potential issues such as water quality (including turbidity, sediment load, nutrients, heavy metals, pesticides and pathogens) and groundwater resources were not considered. Inclusion of such issues would require a more-complex hydrological model that simulated the effects of management options on these aspects of the system as well. For example, in areas with significant groundwater extraction, then the impact of changes in the extraction rate on the groundwater level would have to be included within the model, so that future availability of groundwater as well as the impact of falling groundwater levels on streamflow, could be evaluated. Nevertheless, such inclusions would not change the basic framework of the DSS, just some details in the component models.

References

Beven, K. 1987. Towards the use of catchment geomorphology in flood frequency predictions. Earth Surface Processes and Landforms, 12, 69–82.

Bonnell, M. and Bruijnzeel, L.A. 2005. Forests, water and people in the humid tropics. International Hydrology Series. Cambridge University Press, 925p.

Bruijnzeel, L.A. 1990. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. UNESCO International Hydrological Programme, 224p.

Carlile, P.W., Jakeman, A.J. and Croke, B.F.W. 2002. Using catchment attributes to identify the scale and values of distributed parameters in surface and sub-surface conceptual hydrology models. In: Rizzoli, A. and Jakeman, A.J., ed., Proceedings of the 1st Biennial Meeting of the International Environmental Modelling and Software Society, University of Lugano, Switzerland, I, 346–351.

Chiew, F. and McMahon, T. 1994. Application of the daily rainfall-runoff model MODHYDROLOG to 28 Australian catchments. Journal of Hydrology, 153, 383–416.

Connolly, R.D., Ciesiolka, C.A.A., Silburn, D.M. and Carroll, C. 1997. Distributed parameter hydrology model (ANSWERS) applied to a range of catchment scales using rainfall simulator data. IV Evaluating pasture catchment hydrology. Journal of Hydrology, 201, 311–328.

Croke, B.F.W. and Jakeman, A.J. 2001 Predictions in catchment hydrology: an Australian perspective. Marine and Freshwater Research, 52, 65–79.

— 2004. A catchment moisture deficit module for the IHACRES rainfall-runoff model. Environmental Modelling and Software, 19, 1–5.

Croke, B.F.W, Merritt, W.S. and Jakeman, A.J. 2004. A dynamic model for predicting hydrological response to land cover changes in gauged and ungauged catchments. Journal of Hydrology, 291, 115–131.

Goodrich, D.C. and Woolhiser, D.A. 1991. Catchment hydrology. Review of Geophysics, Supplement, US National Report to International Union of Geodesy and Geophysics 1987–1990, 202–209.

Grayson, R.B., Moore, I.D. and McMahon, T.A. 1992. Physically based hydrologic modeling 2. Is the concept realistic. Water Resources Research, 28, 2659–2666.

Hornberger, G.M. and Boyer, E.W. 1995. Recent advances in watershed modelling, Review of Geophysics, Supplement, 33, 949–57.

Jakeman, A.J., and Hornberger, G.M. 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research, 29, 2637–2649.

Jakeman, A.J., Littlewood, I.G. and Whitehead, P.G. 1990. Computation of the instantaneous unit hydrograph and identifiable component flow with application to two small upland catchments. Journal of Hydrology, 117, 275–300.

Johnson, R. 1998. The forest cycle and low river flows: a review of UK and international studies. Forest Ecology and Management, 109, 1–7.

Klemeš, V. 1986. Operational testing of hydrological simulation models. Hydrological Sciences Journal, 31, 13–24.

Merritt, W.S., Croke, B.F.W., Jakeman, A.J., Letcher, R.A. and Perez, P. 2004. A biophysical toolbox for assessment and management of land and water resources in rural catchments in northern Thailand. Ecological Modelling, 171, 279–300.

Post, D.A. and Jakeman, A.J. 1999. Predicting the daily streamflow of ungauged catchments in S.E. Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model. Ecological Modelling, 123, 94–104.

Post, D.A., Jones, J.A. and Grant, G.E. 1998. An improved methodology for predicting the daily hydrologic response of ungauged catchments. Environmental Modelling and Software, 13, 395–403.

Viney, N.R. and Sivapalan, M. 1999. A conceptual model of sediment transport: application to the Avon River basin in Western Australia. Hydrological Processes, 13, 777–787.

Witthawatchutikul, P. 1985. Water research at Payong. In: Proceedings of the seminar on watershed research and management practices. Laguna, Philippines, ASEABN–US Watershed Project, 57–68.

Witthawatchutikul, P., Boosaner, A. and Sucharit, S. 2005. Hydrological model for integrated water resource assessment and management. In: Kachitvichyanukul, V., et al., ed., International conference on simulation and modeling (SIMMOD 05). Bangkok, Asian Institute of Technology, 353–359.

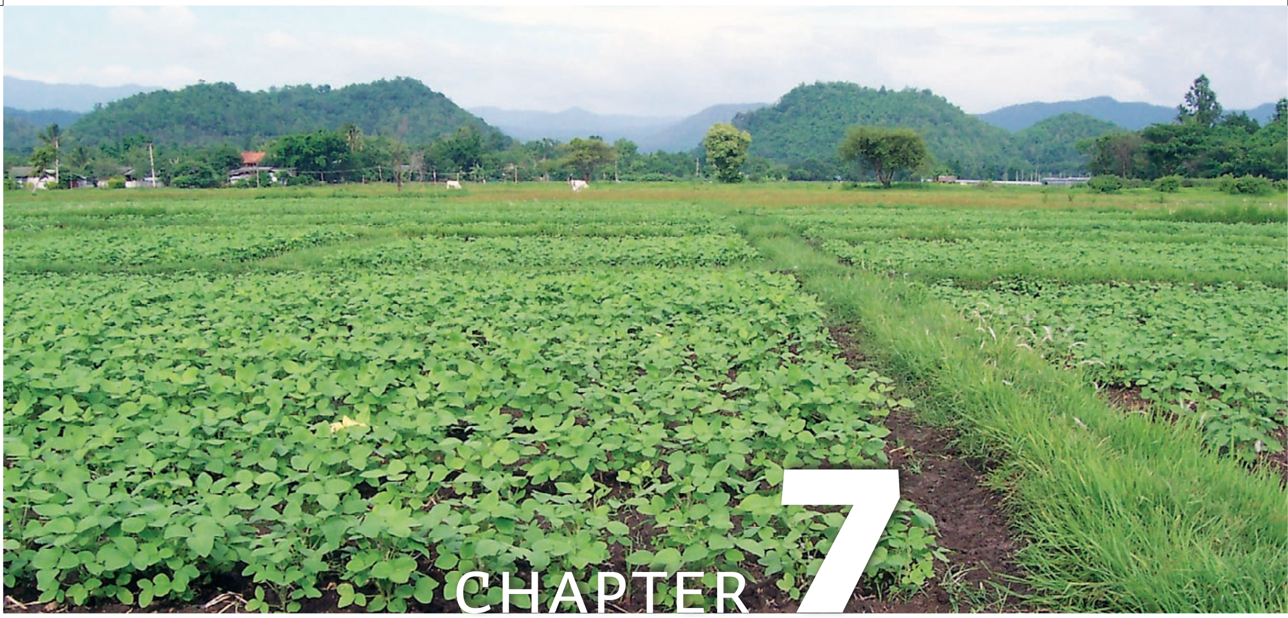
Wheater, H.S., Jakeman, A.J. and Beven, K.J. 1993. Progress and directions in rainfall-runoff modelling. In: Jakeman, A.J., Beck, M.B. and McAleer, M.J., ed., Modelling change in environmental systems. John Wiley & Sons Ltd, 101–132.

Wilk, J., Andersson, L. and Plermkamon, V. 2001. Hydrological impacts of forest conversion to agriculture in a large river basin in northeast Thailand. Hydrological Processes, 15, 2729–2748.

Woolhiser, D.A. 1996. Search for physically based runoff model—a hydrological El Dorado? Journal of Hydraulic Engineering, 122, 122–129.

Ye, W., Jakeman, J.A. and Young, P.C. 1998 Identification of improved rainfall-runoff models for an ephemeral low-yielding Australian catchment. Environmental Modelling and Software, 13, 59–74.

Zhang, L., Dawes, W.R., Hatton, T.J., Reece, P.H., Beale, G.T.H. and Packer I. 1999. Estimation of soil moisture and groundwater recharge using the TOPOG_IRM model. Water Resources Research, 35, 149–161.



Determining crop yield and water use

WENDY MERRITT, BARRY CROKE AND SOMJATE PRATUMMINTRA

SUMMARY

A key component of an integrated model for land- and water-resource assessment in agricultural districts is a crop model that is capable of providing estimates of crop water-use and of seasonal crop yields. The crop model provides the link between land use, water management, economic costs and benefits, and environmental impact.

Crop models can vary from simple, empirical growth functions to more complex mechanistic models that simulate the chemical and physical processes of plant growth.

This chapter will focus on crop-modelling approaches suitable for inclusion in an integrated framework for water-resources assessment. In particular, it will describe the two crop models developed for the Integrated Water Resources Assessment and Management project in northern Thailand.

Agricultural fields in the Mae Chaem catchment after harvesting

The role of crop models

In terms of their role, crop models can be split into three main groups: research; crop systems analysis at a farm level; and policy analysis at a catchment or regional level. Crop models can also be used for educational purposes.

Research models have tended to focus on linking the physical processes (such as the availability of sunlight, water and nutrients) with the more traditional discipline of plant physiology. Relative to the other roles of crop models, the function of research models, as a tool for understanding plant-physiological processes, ensures that such models are generally more complex than those developed for farm management, catchment policy analysis or educational purposes.

Crop models that are developed to assist farm management are used to assess alternative crop practices and assist decision-making, for issues such as water use, fertiliser use, erosion control, and pesticide use (Boote et al. 1996). These models have also been incorporated into decision-support systems (DSS) to provide an integrated-assessment tool that can be used for developing optimal farm-management strategies.

Crop models also have the potential to be used as policy analysis tools. For example, the use of crop models to develop land suitability classes may be applicable in development of land-use planning policy. In particular, crop-simulation models or some form of crop yield relationships are being increasingly applied to assess yield potentials of crops at regional or greater scales. The crop model used to predict yield for each land unit can vary from simple empirical growth functions (Liengsakul et al. 1993) to the incorporation of more complex crop-simulation models (Bouman 1994; Roetter et al. 1998).

This chapter will focus on crop-modelling approaches suitable for inclusion in an integrated framework for water-resources assessment at a sub-catchment or catchment scale.

Crop modelling approaches

Two distinct model classifications have been presented in the literature. Models have conventionally been classified according to the methodology by which they are developed as:

- mechanistic—processes are described with explicit biological and physical functions
- empirical—processes are described with statistical fitting functions.

As with other modelling disciplines, most crop models are neither purely mechanistic nor empirical, rather they contain a mix of both approaches.

Empirical models

Empirical approaches include simple linear, non-linear and multivariate analyses used to fit historical yield data to average temperature and precipitation records. Perhaps the greatest disadvantage with empirical approaches to crop modelling is that they tend to be site specific. That is, the relationships used to predict yield for one site may not be valid for sites with different conditions. Despite this, empirical models have the potential to remain an important tool for land evaluations and yield prediction. This is especially so in areas where it is inappropriate to apply more-complex models due to data limitations. Hence, these models are still used widely and are likely to continue serving a purpose for some considerable time to come. This is enhanced by the ease with which these models can be applied, thus increasing their attractiveness for policy or decision-makers. Care must be taken to ensure that these models are not applied outside conditions for which the model was developed.

Mechanistic models

Mechanistic models range in their complexity and specificity in representing the biological and physical processes controlling plant growth. They can be further classified into sub-groups of *crop specific* and *generic* models.

Mechanistic models tend to allow dynamic simulation on a number of time steps and in-depth consideration of the processes underlying crop growth. Consequently, these models are more complicated and computationally demanding than empirical models.

An advantage of mechanistic crop models is that the explicit relationships within the model have a physical basis. However, even the most process-oriented crop models still contain empirically determined constants or relationships.

Use of mechanistic models is potentially constrained by a lack of physical data for calibration and validation.

Intermediate approaches

In practice, most models represent a compromise between rigour and utility. In other words, crop-simulation models are generally neither purely empirical nor mechanistic. These ‘intermediate approaches’ are very useful for resource-management evaluation if correctly constructed, and provide a good compromise between empirical and mechanistic models.

Comparative analysis of crop-modelling approaches

The applicability of a modelling approach is determined by a number of factors, the two most important being:

- the intended use of the model
- data availability.

Intended use

Perhaps the most important factor in determining the appropriateness of a model is its intended use. This determines the processes to be considered and their level of detail, and the model accuracy required. For example, an emphasis on erosion–productivity requires detailed consideration of soil processes but this may not be as important for, say, pest damage studies. Intended use also determines the complexity of the model—that is, the number of processes to be included and the level of detail. For example, if an annual crop yield is all that is required, a relatively simple empirical approach may be perfectly adequate, if not more appropriate, than a more-complicated, mechanistic approach.

Data availability

In catchment- or regional-scale studies, the issue of data availability becomes of utmost importance. Mechanistic models often require a large amount of physical data, such as a variety of soil parameters, which are rarely collected during land surveys and are available at only a few experimental sites. Empirical models tend not to require such large quantities of data and are computationally simple, but have limited meaning. Therefore, intermediate approaches may represent a suitable compromise between data requirements and physical meaning. Problems of data availability are exacerbated in developing countries, where detailed information for supporting complex models is less-often collected.

Incorporating crop models within integrated modelling frameworks

Currently, there is also a need for the development of catchment-scale approaches that integrate agronomic factors (crop growth) with socioeconomic and land-degradation factors. A number of complexities must be addressed when developing such an integrated approach. These can be summarised as:

- the large number of crops that are grown within a catchment
- the different types of cropping systems within the catchment
- the different scales of analysis at which the system can be modelled
- distribution of water within the catchment
- the accentuated problem of data availability.

Realistically, it is not possible to model every single crop grown within a catchment, so some simplification of the system is necessary.

Approach for crop modelling in northern Thailand

The crop-modelling approach used in the Integrated Water Resources Assessment and Management (IWRAM) project for northern Thailand needed to be directly linked with the socioeconomic and physical models within the integrated DSS, with particular emphasis on scenario simulation. The objective of the crop modelling was to develop an understanding of both yield variability over time and water use for a range of crops typically grown in northern Thailand. It also needed to simulate yield response to water deficit and fertility depletion, both of which are important factors determining final yield in this region. The model was to be linked with an economic model, so that the relationships between farmers' decisions and variable production of different crops could be explored.

There was little need for complex models that considered large numbers of processes, primarily because of the limited amounts of data available for use within the catchment. This indicated that a relatively simple, crop-yield model, capable of simulating crop stages throughout the season and yields at the point of harvesting, would be most suitable. The outputs required were crop water-use through the season and final crop yield. Two alternative crop models were adapted for this application, the CATCHCROP model (Perez et al. 2002) and a crop model developed for the Food and Agriculture Organization of the United Nations (FAO 1978). Both of these models were tested in the IWRAM DSS, and are described in detail below.

Beans are not only a valuable cash crop but also increase fertility of the soil by fixing nitrogen. Photo by Anthony Scott, June 2004

The CATCHCROP model

The CATCHCROP model can predict crop water-use in addition to crop yield for a number of different crop types. It was developed in response to the recognition that many existing crop models required large amounts of highly specific data, such as detailed soil information (e.g. conductivities of each soil layer, and cation-exchange capacity), to drive them. These are rarely collected outside experimental stations.

CATCHCROP is a plot-based model that is applied over areas considered homogeneous in terms of soil, crop and climate properties and inputs.

The model involves a number of sub-routines (Figure 7.1) whereby:

- run-off over a 10-day time step is estimated
- water balances are constructed for the reservoirs of soil and crop available and for deep drainage
- maximum, sub-optimal and actual evapotranspiration are calculated at the current time step
- water demand for the next 10-day time step is calculated.

At the end of each season, yield is calculated according to a crop's potential yield, the water stress of the crop, and the ratio of actual and maximum evapotranspiration.

CATCHCROP is a simplified conceptual crop model that attempts to account for the effects of soil type, fertility, landform and water availability on crop yield. It does not attempt to include the radiation limits to crop growth (i.e. the model assumes that growth is limited by soil characteristics and water availability only).

Applying CATCHCROP to the Mae Chaem catchment in northern Thailand

In the IWRAM project, CATCHCROP was applied on a land-unit basis, where each land unit is considered homogeneous in terms of soil, crop, climate properties and other inputs. The Mae Chaem is a complicated agricultural catchment; over 100 crops have been grown within it (Scoccimarro et al. 1999). Not only is the number of crops large, but also the types of crops grown are varied, ranging from rainfed crops to irrigated crops such as paddy rice, and from annual crops to perennial crops. For purposes of simplification, the crops that that were considered in the IWRAM DSS were generally limited to the major crops found in the catchment: upland and paddy rice; soybean; groundnut (peanut); maize for grain or forage; cabbage; potato; onion; and temperate and tropical fruit trees. Despite this simplification, the model still needed to account for a mix of irrigated, rainfed, annual and perennial crops.

An example of the outputs produced by the CATCHCROP model is shown in Table 7.1 for the Mae Uam catchment. In this example, the model was run outside the DSS, so the water available for irrigation was unknown. Thus, the amount of water used for irrigation was set to the water demand for each crop. The yield estimates for wet-season rice were very close to the average observed value, as were the run-off estimates, suggesting that the model assumptions were adequate for this purpose. The yield estimate for soybean was slightly high, possibly due to the assumption that the irrigation equalled the water demand (i.e. unrestricted water availability in the dry season).

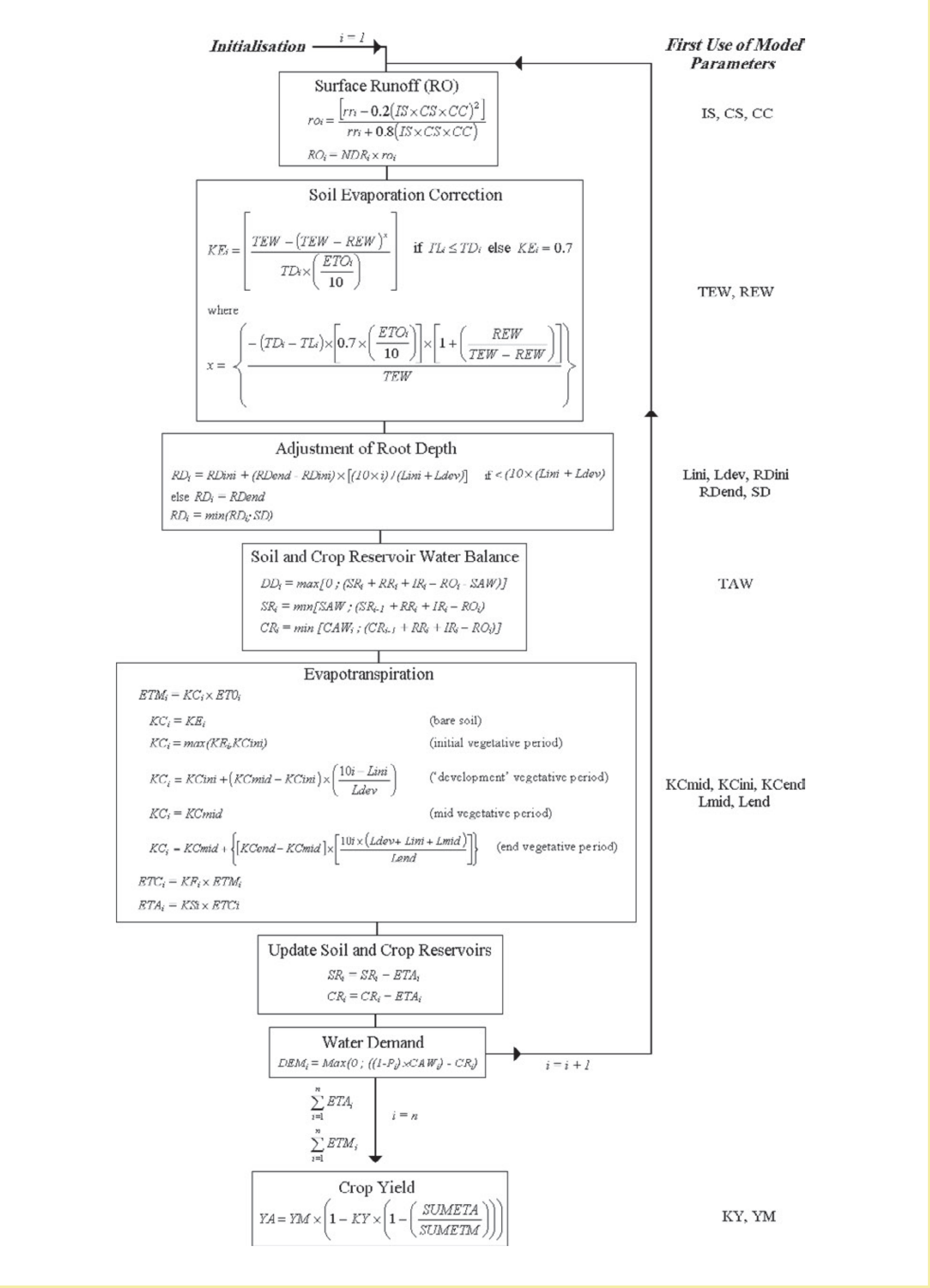


Figure 7.1 Detailed flow-chart of the CATCHCROP model. From Merritt et al. (2004)

Table 7.1 Average simulated yields and water balance derived using the CATCHCROP model for the Mae Uam catchment, 1988–1992. From Perez et al. (2002)

	Paddy field wet-season rice	Dry-season soybean	Upland field wet-season cabbage	Dry-season cabbage
Irrigation (mm)	150	233	0	339
Run-off (mm)	93	17	621	37
Percolation (mm)	409	12	35	0
Evapotranspiration actual (mm)	675	241	485	320
Yield (kg/ha)	3207	1419	15284	16184

The performance of the CATCHCROP model in estimating the water balance was also tested by Perez et al. (2002) for the Mae Mu catchment, which has almost 100% forest cover (see Table 7.2). Generally, the model was able to reproduce the seasonal discharge volume, though there is a tendency for the model to over-estimate the dry-season flows.

Sensitivity analyses have been performed on the CATCHCROP model by Merritt et al. (2005) for a range of different management practices (presence or absence of bunding, fertiliser levels and irrigation status) and also for different crop and soil parameters. The model behaved as expected and the analysis indicated where the model structure could be simplified.

Table 7.2 Comparison of simulated and observed discharge (mm) for Mae Mu catchment. From Perez et al. (2002)

Year	Season	Run-off	Drainage	Simulated discharge	Observed discharge
1988	Wet	452	174	452	423
	Dry	26	3	203	213
1989	Wet	361	224	361	381
	Dry	0	0	224	147
1990	Wet	358	148	358	328
	Dry	75	0	223	160
1991	Wet	252	82	252	243
	Dry	73	6	161	169
1992	Wet	305	111	305	245
	Dry	61	0	172	121

For irrigated crops, less irrigation was required with bunds, as water was retained within the plot. As crop water demand is less than the amount of water available for irrigation, significant differences in crop yields were not observed. Non-irrigated crops generally showed increased crop water demands and decreased actual evapotranspiration and deep drainage compared with irrigated crops. The greater the fertility of the plot, the more the crop was able to transpire. Hence, crop water demand and actual evapotranspiration both increased with more fertile plots, thus increasing crop yields. Deep-drainage estimates in plots that are bordered by bunds were considerably greater than in non-bunded plots.

Radiation- and water-limited crop-production model

The CATCHCROP model considers only the water limitations for crop growth, and not the radiation limitations. In order to make the crop model more broadly applicable (both spatially and in crops included), a second model is being developed for the IWRAM DSS. The new model is based on a crop-production model originally developed for the Agro-ecological Project of the Food and Agriculture Organization of the United Nations (FAO 1978).

General description

Crop production is estimated from the product of:

- the radiation-limited growth
- the water-limited growth
- a harvesting index for each crop
- a site index accounting for topography and soil characteristics (texture, structure and fertility).

The main components of the model are as follows:

Radiation-limited growth module. Crop production under optimal conditions (production potential) is calculated using a radiation model for each of the major crops being grown in the catchment. Growth is calculated from the amount of solar radiation intercepted by the leaves. This model assumes ideal water and nutrient supply, and a disease-free crop. Crops are divided into groups (I to IV) according to their photosynthetic pathway and optimum growth temperatures, with C_4 plants generally having a higher heat tolerance than C_3 plants (see Table 7.3).

Water-limited growth module. Because of several limitations on ideal growth rates, it is rare for a crop to reach full production potential. One of these is the availability of water. Water-limited growth is calculated using a water balance that provides an estimation of water availability in the soil layer.

The model provides similar outputs to the CATCHCROP model, including crop yield and a soil water balance. This model is still undergoing development and validation trials, and will be a useful addition to the suite of models available in the IWRAM DSS.

Table 7.3 Crop groupings according to photosynthetic pathways and optimum growth temperature

Group	Photosynthetic pathway	Optimum temperature	Examples
I	C3	15–20	Wheat, white potato and Phaseolus bean
II	C3	25–30	Soybean, rice, cotton and sweet potato
III	C4	30–35	Sorghum, maize, pearl millet, sugarcane
IV	C4	20–30	Maize (temperate and tropical high-altitude variety)

Note; C3 plants use a photosynthetic pathway in which the first stable compound formed from carbon dioxide (CO_2) is a three-carbon compound. C4 plants are so-named because the first organic compound incorporating CO_2 is a four carbon compound.

Integrating the crop models into the Integrated Water Resources and Management project decision-support system

The purpose of the IWRAM DSS is to investigate the influence of land-use scenarios on water availability (both locally and for downstream users), on the economics of crop production, and on environmental impacts (such as erosion rates). Different combinations of crops, soil and topography can have significant differences on the hydrological, environmental and economic impacts. As such, the DSS needs to be sensitive to the water demands of various crops on different land units included in each scenario, as well as the crop yield. The role of the crop module is to:

- supply the hydrology module with the effects of changes in land use so that the impacts of land-use change on streamflow can be estimated
- estimate the amount of water extracted for irrigation, so that the impacts of the land-use scenario on downstream users can be assessed
- provide the economic module with crop yields so that the economic return can be determined.

There are two key inputs that must be supplied to the crop model. These are the distribution of crops on the different land units within the catchment, and the water that is potentially available for irrigation use. The distribution of crops is supplied as part of the input data for each land-use scenario being investigated, and comprises the fraction of the area of each land unit planted with each crop. The amount of water that is available for irrigation is supplied by the hydrology module. Where there are significant water storages within a catchment, the hydrology module can be used to predict the inflow to these storages as well as the natural flow in the irrigation areas. The release of water from the dams for irrigation then has to be included separately.

Conclusion

The crop models incorporated in the IWRAM DSS must provide a compromise between complex deterministic models with large data requirements, and overly simplistic empirical relationships. The CATCHCROP model meets these requirements and has been tested for sub-catchments in northern Thailand. It behaved as expected under different management conditions and parameter values and provides a useful tool for integrated water-resources assessment on a catchment scale. A second crop model has been developed, based on a crop-production model originally developed by FAO (1978). This model has the advantage that it not only takes into account water limited growth, but also considers radiation-limited growth. However, this added complexity does have the disadvantage that the data requirements for the model are greater.

The crop model is a key component of an integrated framework for land- and water-resource assessment in agricultural districts because it provides estimates of both crop water use (which affects the catchment water balance) and of crop yields (which directly affects the economic costs and benefits of different land-use scenarios). The crop model provides the link between land use, water management, economic costs and benefits, and environmental impacts.

References

Boote, K.J., Jones, J.W. and Pickering, N.B. 1996. Potential uses and limitations of crop models. Agronomy Journal, 88, 704–716.

Bouman, B.A.M. 1994. A framework to deal with uncertainty in soil and management parameters in crop yield simulation—a case study for rice. Agricultural Systems, 46, 1–17.

FAO (Food and Agriculture Organization of the United Nations) 1978. Report on the agro-ecological zones project. Volume 1. Methodology and results for Africa. Rome, FAO, World Soil Resources Report, 48, 158p.

Liengsakul, M., Mekpaiboonwatana, S., Pramojanee, P., Bronsveld, K. and Huizing, H. 1993. Use of GIS and remote sensing for soil mapping and for locating new sites for permanent cropland—a case study in the highlands of Northern Thailand. Geoderma 60(1–4), 293–307.

Merritt, W.S., Croke, B.F.W. and Jakeman, A.J. 2005. Sensitivity testing of a model for exploring water resources utilisation and management options. Environmental Modeling & Sotfware, 20, 1013–1030.

Perez, P., Ardlie, N., Kuneepong, P., Dietrich, C. and Merritt, W.S. 2002. CATCHCROP: modelling crop yield and water demand for integrated catchment assessment in northern Thailand. Environmental Modelling and Software, 17, 251–259.

Roetter, R., Cabrera, J.M.C.A. and Hoanh, C.T. 1998. Development and evaluation of crop models for yield estimation at different scales. A systems approach to analysing land use options for sustainable development in south and south-east Asia. IRRI Discussion Paper Series, No. 28.

Scoccimarro, M., Walker, A., Dietrich, C., Schreider, S. Yu., Jakeman, A.J. and Ross, H. 1999. A framework for integrated catchment assessment in northern Thailand. Canberra, Australian National University, ICAM Working Paper 1999/1.

Estimating the effects of changed land use and management on soil loss

WENDY MERRITT, BARRY CROKE, KAMRON SAIFUK AND ANTHONY SCOTT

SUMMARY

ACCELERATED soil erosion in the highland regions of the world is a result of land clearing and agricultural activities, and has been recognised as a serious problem in Thailand for over 30 years. The hills of northern Thailand have steep slopes and the soils are exposed to an erosive monsoonal climate for seven months of the year. The rate of erosion depends on the timing and amount of rainfall, the slope of the hillside, soil type, land use and land-management practices. Soil erosion can cause declines in agricultural productivity, reduce water quality in nearby streams, and cause siltation problems downstream.

Erosion models can be used to estimate soil loss from agricultural catchments, which can assist with soil-conservation planning, land-use planning, soil-erosion inventories, and regulation. The erosion model used in the Integrated Water Resource Assessment and Management project decision-support system was based on the universal soil loss equation (USLE), modified to suit conditions in northern Thailand. The USLE is widely applied worldwide and is also used by Thailand's Land Development Department for land-use planning. The USLE is capable of providing estimates of potential erosion within the catchment, for different scenarios of land-management planning.

Introduction

Soil erosion by water is a natural process involving the detachment and transport of soil particles, caused by rainfall and overland flow of water. 'Natural' soil erosion has been occurring ever since the first soils were formed, but 'accelerated' soil erosion is a much more recent problem. It is a result of the unwise actions of humankind, such as the clearing of forests on sloping lands, overgrazing by domestic stock, and unsuitable cultivation practices, which leave the land vulnerable during times of heavy rainfall.

Accelerated erosion can result in rapid loss of topsoil, and this can cause decline in agricultural productivity. Eroded soil is washed into nearby streams and rivers, reducing water quality and causing siltation problems in the lower catchment.

Increasing awareness of the impacts of erosion has stimulated a large amount of research. There are three main focuses of this research: the erosion process itself, the effects of soil loss on crop productivity, and the effect of erosion on the water quality of nearby streams. Historically, much of the research was focused on the productivity of agricultural lands (e.g. Loch and Silburn 1996), but more recently there has been an increasing interest in the off-site impacts that sediment, and associated nutrients, have on water quality.

This chapter provides a brief review of erosion processes and the different forms of erosion that can take place. More-detailed information is then presented for the humid tropics, in particular for northern Thailand. The mathematical modelling of erosion is then introduced, followed by a description of the modified universal soil loss equation (USLE) computations that were applied in the Integrated Water Resource Assessment and Management (IWRAM) project.

Accelerated erosion leads to loss of topsoil

One analysis of soil erosion on a global scale, estimates that, depending on the region, topsoil is being lost 16 to 300 times faster than it can be replaced. Soil-making processes are extremely slow, requiring from 200 to 1000 years to form 2.5 centimetres of topsoil under normal agricultural conditions.

Processes of soil erosion by water

The process of erosion can be described in three stages: detachment, transport and deposition.

Detachment of sediment from the soil surface is caused either by the impact of rain droplets, or by the shear forces of overland flow. Rainfall-induced detachment will often be the dominant process on relatively flat regions of small extent. In regions with long, steep slopes, detachment is often dominated by the very high shear-stresses induced by fast-flowing overland flow.

Transport of sediment is initiated when detached particles are washed downstream along gullies, streams and rivers. As the velocity of flow (and hence the water turbulence) increases, larger soil particles will remain suspended in the water and the capacity for sediment transport increases.

Deposition of sediment is the final process in soil erosion. When there is not enough energy (or turbulence) to transport the sediment, it gradually settles out of the water and comes to rest. Sediment sinks, or depositional areas, can be visible as newly deposited silt or sand on a flood plain, as bars and islands in a river channel, and as mudflats at the mouth of a river.

Types of soil erosion

There are six main types of soil erosion by water: sheet, rill, gully and streambank, mass movement (or landslides) and road erosion.

Sheet erosion refers to the uniform detachment and removal of soil or sediment particles from the soil surface by overland flow evenly distributed across a slope. Sheet erosion is often considered to be the most serious type of erosion from an agricultural viewpoint as it tends to strip nutrients concentrated in the surface layer of the soil. This has the potential to lead to reduced fertility and decreased productivity.

Rill erosion occurs when water moving over the soil surface starts to concentrate down preferential pathways, forming an easily recognisable channel, or rill. These rills are defined as being 'small flow channels that can be obliterated by tillage'.

Gully erosion, in contrast to rill erosion, describes channels of concentrated flow too deep to be obliterated by cultivation. Gully development is controlled by thresholds related to slope and catchment area. Two main stages in gully development can be identified:

- There is an initiation period where there is rapid erosion and massive movement of sediment as the head of the incised gully moves rapidly up hill. The gully bottom is also scoured out and becomes deeper.
- This is followed by a period during which the gully bottom remains fairly stable, with equal amounts of scouring and sedimentation, while the gully width increases due to lateral erosion and collapse of the side banks.

Gullies have been identified as potentially contributing large amounts of sediment if connected to the river network.

Streambank erosion occurs along rivers and streams, particularly when riparian vegetation has been removed. The vertical side banks are undermined by the water flow until they collapse into the river.

Mass movements, or landslides, occur on steep slopes after intense rainfall periods. The soil weight is increased dramatically by saturation with water and exceeds its restraining capability. Alternatively, a zone of weakness in the underlying material is further weakened and lubricated by infiltrating water. Disturbances to slopes that increase the weight factor (such as large buildings or stockpiles of earth or rock), or reduce the restraining capability (such as road cuttings), will greatly increase the risk of failure.

Road erosion has the potential to be a significant source of sediment in some catchments. Four features of paved and unpaved roads that can increase erosion in mountainous catchments are:

- the highly compacted road surfaces and disturbed roadside margins reduce infiltration, thereby increasing surface run-off and the associated erosive forces
- road cuttings can intercept sub-surface flow then re-route it via overland flow mechanisms toward the stream channel
- ditches and culverts capture both sub-surface flows and surface run-off and channel it more directly to streams,
- road cuttings can reduce the strength of steep slopes and increase the risk of landslides.

The degree to which each factor contributes to erosion from a segment of road differs between sites and particular circumstances.

Characteristics of erosion in the humid tropics

The overall rate of soil erosion in Asia far exceeds that of any other region of the world (Chang 1993). Froehlich and Starkel (1995) note that rains in the humid tropics are more erosive than in temperate regions due to the high rainfall intensities that commonly occur during storm events. In the humid tropics, the number of thunderstorm days exceeds 30 per year, and in Bangladesh, southern Burma, southern Thailand, Malaysia and the western part of Indonesia this increases to more than 60 (Chang 1993). In these circumstances, the potential for the generation of overland flow, when rainfall intensity exceeds the infiltration capacity of tropical soils, is extreme. This excess run-off has been identified as a dominant source of erosion in the humid tropics, particularly on steep lands (Yu and Rose 1999).

The humid tropics are also under increasing pressure from rapid population growth in rural areas, and farming on steep lands has continued to increase in recent years, especially in developing regions of Southeast Asia. Steep lands have been identified as being highly prone to erosion. Traditional shifting-cultivation practices of long-rotation systems have, in many areas, been converted to more-intensive, shorter-rotation systems, thus presenting increased problems with soil fertility and soil erosion in the steeper areas (Turkelboom et al. 1997). In traditional shifting-cultivation systems, soil loss is generally very small as the roots of the fallow vegetation bind the soil together and help limit erosion.

In summary, erosion in humid regions can largely be attributed to the timing and amount of rainfall, the importance of overland flow and slope, and changes in land uses and land-management practices arising from increasing population pressures.

Extent and types of erosion in Thailand

Accelerated soil erosion in the highland regions of Thailand, as a result of land clearing and agricultural activities, has been recognised as a serious problem for over 30 years (Lal 1975; Liengsakul et al. 1993). Lal (1975) reported that the most serious erosion problems are in the northern highland region because of the rainfall patterns and landforms. The hills of northern Thailand are rugged, with steep slopes and soils that are exposed to an erosive monsoonal climate for seven months of the year. When the forests are cleared for agriculture, these lands are highly prone to accelerated erosion.

Previously, the more traditional practice of shifting cultivation had not been identified as a significant cause of accelerated soil erosion (e.g. Lal 1975; Turkelboom et al. 1997). However, with increasing hill-tribe populations, this traditional system of cultivation has become more intense, with the length of the cultivation period increasing and the period of regeneration becoming shorter. Hussain and Doane (1995) noted that, for northeastern Thailand, the period of fallow (that is, the recovery of the land) had fallen from 10–15 years to only 3–4 years. This places a much greater pressure on soil resources and increases the risk of erosion.

What are the impacts of erosion?

On-site impacts. Loss of topsoil not only reduces the depth of soil but also its capacity to hold water and the amount of nutrients it contains. This can lead to a reduction in crop productivity. Other on-site impacts include damage to embankments, earth walls, roads, trails and fences.

Off-site impacts. These include increased sediment, nutrient and pollutant loads in rivers and streams, degrade the quality of household water supplies downstream and reduce ecological health. Siltation of dams and irrigation channels reduces their capacity. The sediment also deposits in estuaries, smothering aquatic plants and other food supplies for fish.

Land-use impacts upon erosion

The rate of erosion on a hillside depends strongly on the land use. Several projects have attempted to quantify this relationship for Thailand (see Table 8.1, for example). These have included projects run by government agencies in Thailand (e.g. the Land Development Department), as well as international agencies. The Australian Centre for International Agricultural Research (ACIAR) funded two collaborative projects with field sites in Malaysia, Thailand, the Philippines and Australia (Coughlan and Rose 1997). Table 8.1 shows the measured average annual soil losses for the sites in Thailand, indicating the effect of different cultivation practices on erosion. The complexity of the erosion process is demonstrated by a comparison of these two plot sites, which have different soil types, rainfall and slopes.

Sumrit et al. (1993) classified soil erosion in Thailand into five categories (Table 8.2) and summarised the land uses observed in each of the categories. While most of the country fits into the slight and very slight categories, a large area of the country still has considerable erosion problems. Most of this land is associated with field crops and horticultural practices. Although the authors do not split the land into lowlands and highlands, some inferences can be made from looking at the land uses. Paddy, situated on lowlands, is usually associated with low levels of erosion, while shifting cultivation generally occurs on the steeper slopes. Table 8.2 provides an indication of the land uses that pose a greater risk of erosion. However, this needs to be related to position within the landscape to be of real use for identifying erosion 'hotspots'.

With increasing land-use pressure and rising populations in the highlands of Thailand, an expansion of road networks is to be expected (Ziegler and Giambelluca 1997). Hence, erosion generated from roads is likely to be of increasing importance in its contribution to the total eroded sediment leaving a catchment. There

Table 8.1 Average annual soil loss and sediment concentrations from ACIAR plots at Khon Kaen and Nan, Thailand (uses data over a three-year period for Khon Kaen and one year for Nan). Source: Coughlan and Rose (1997)

Site	Treatments	Average annual soil loss (t/ha)
Khon Kaen, loamy sand, 4% slope, average annual rainfall = 913 mm	Bare plot	48
	Cultivation up and downslope	2.8
	Cultivation across slope	1.0
Nan, clay, average slope ≈ 30%, annual average rainfall = 1886 mm	Bare plot	7.2
	Clean cultivation farmers practice	0.6
	Tephrosia hedgerows	0.4
	Natural vegetation	Trace

Table 8.2 Soil erosion in Thailand. The proportional area of each erosion category is indicated in parentheses. Source: Sumrit et al. (1993)

Categories	Soil loss (t/ha/year)	Area (ha)	Land use
Very slight	0.06–0.63	18,995,500 (0.37)	Forest, paddy
Light	6.3–31.3	14,444,200 (0.28)	Forest, rubber, orchards, paddy
Moderate	31.3–125.1	4,146,000 (0.08)	Rubber, orchards, field crops, forest + field crops
Severe	125.1–625.1	6,819,300 (0.13)	Rubber, orchards, field crops, forest + field crops, shifting cultivation
Very severe	625.1–6042	6,265,100 (0.12)	Field crops, forest + shifting cultivation field crops
Others	––	729,900 (0.01)	Coastal area, mangrove forest, shrimp farms etc.

has been little research into the extent of road erosion in Thailand, but those studies that have considered it, have indicated that it has the potential to contribute significantly to the total sediment budget of a catchment.

Soil conservation, or erosion mitigation, can be achieved by reducing the run-off rate, either by engineering structures (e.g. ditches, terraces) or by using strips of vegetation that capture water and eroded sediment (e.g. alley cropping). Any attempt to predict the rate of erosion from a particular land use needs to account for these different management practices (see Table 8.3).

Introduction to erosion models

Erosion models can be used to estimate soil loss from agricultural catchments. This can assist with soil-conservation planning, land-use planning, soil-erosion inventories, and regulation. Erosion models are a necessary component of an integrated water-resource management approach. Given the constraints that are commonly encountered with large-scale field measurements (e.g. money, time and resources), erosion models can provide a viable alternative for assessing erosion risks across an entire catchment or region, as well as considering likely changes in erosion as a response to land use or management changes.

The demand for erosion-assessment tools, has led to the development of a wide range of models, some of which are summarised in Table 8.4. These models vary, among other things, in the erosion processes considered, and the level of detail included. Some models are based on an empirical approach using statistically fitted functions. Others use a more mechanistic approach where the physical processes of erosion are described by mathematical equations.

Most models focus on one erosion process such as overland flow (sheet and rill), gully or in-stream erosion. Rarely does a model have the capacity to deal with two or more of these erosion types. For example, the USLE (Wischmeier and Smith 1978) and WEPP (Laflen et al. 1991) models have been designed to study erosion in situations of overland flow only.

Table 8.3 Erosion rate under different erosion control measures. Source: Ongprasert and Turkelboom (1995)

Cropping packages	Median erosion rates (t/ha/year)	Median run-off rates (% of annual rain)	No. of data points
'Traditional package'	60	11	91
Alley cropping with grass strips	0.4	2	128
Alley cropping with nitrogen-fixing trees in hedgerows	4.4	2	71
Hillside ditches	13	10	12
Bench terraces	01	1	35

Table 8.4 Some erosion and sediment-transport models (classifications are based upon the main processes modelled)

Model	Type	Scale	Output	Event/ non event	Spatially distributed	Comments
CREAMS	Physical	Field size 40–400 ha	Erosion, deposition, transport (slope to 2nd order channels)	Event	No	Catchment assumed to be uniform in soils, topography and land use
EPIC	Conceptual	field size, less than 250 acres (usually approx. 1 ha)	Nutrients, sediments, run-off, pesticides, plant growth	Event	No	Weather, soils and management considered homogeneous; considers N, P, pesticides, sediment; USLE based (i.e. sheet erosion)
EUROSEM/LISEM	Physical	Catchment	Run-off, sediment yield	Event	Yes	Does not model erosion in rills and gullies
GUEST	Physical	Field	Soil-loss predictions	Event	–	Sheet and rill erosion
PERFECT	Physical	Field	Run-off, erosion, crop yield	Event	–	Incorporates a crop-growth simulation module
Reid and Dunne (1984)	Empirical	Road segment	Sediment concentration	Non-event	No	Relates concentration to discharge, road segment length, gradient, and road type
USLE/RUSLE/ MUSLE/ USLE-M	Empirical/ conceptual	Hillslope	Average annual soil loss due to rainfall	Non-event[a]	No[b]	Many modifications of the original model (MUSLE, USLE-M). Model has also been revised to include new information (RUSLE). This revised USLE has been implemented locally in the SOILOSS model. Does not model gully or in-stream erosion.

a modified versions may be event based

b can model spatial variation when considered in grid

Table 8.4 (continued) Some erosion and sediment-transport models (classifications are based upon the main processes modelled)

Model	Type	Scale	Output	Event/ non event	Spatially distributed	Comments
WEPP hillslope model	Physical	Hillslope	Run-off, sediment characteristics, form of sediment loss	Both	Yes	Does not account for gully erosion or mass movement
WEPP watershed model	Physical	Hillslope	Run-off, sediment characteristics, form of sediment loss	Both	Yes	The watershed model comprises hillslope model with channel erosion component, impoundment component, and irrigation component.

Although the importance of road (and trail) erosion in terms of contribution to total sediment yield has been acknowledged (e.g. Douglas et al. 1993; Wallin and Harden 1996), there is relatively little literature about the prediction and simulation of road erosion either on its own, or incorporated into catchment-scale models. One exception is the extension of the WEPP model to predict road erosion. Also, the KINEROS2 model has been applied to unpaved mountain roads in northern Thailand to simulate total discharge, sediment transport and sediment concentration on small-scale road plots (Ziegler et al. 2001).

Identifying the most appropriate model for a particular study requires consideration of catchment characteristics, data availability, model assumptions and the desired outputs of the model, including the scale at which model outputs are required.

The universal soil loss equation erosion model

One of the most widely used models for predicting soil loss in agricultural regions is the USLE, which was developed by the United States Department of Agriculture. Annual soil loss (A) is calculated in tonnes per hectare:

$$A = R.K.LS.C.P \qquad (8.1)$$

where R is rainfall erosivity, K is soil erodibility, LS is the topographic factor, C is the cropping factor and P is a management-practice factor.

Although the USLE has a number of limitations, it is easy to use and, unlike more complex models, does not require large amounts of field data. The model's main strength is that it can be used to develop indicators of potential erosion across catchments in relation to rainfall and land-cover scenarios. The USLE approach is widely used by the Land Development Department (LDD) in Thailand for land-use planning.

A description of each term used in the USLE is provided below.

Rainfall erosivity (*R*). The impact of raindrops on the land surface loosens soil particles and makes them susceptible to erosion. As rainfall intensity increases, the impact of raindrops increases, leading to a greater displacement of soil particles. Heavy rainfall also leads to overland flow of water, and this can lead to sheet, rill and gully erosion. As rainfall intensity and duration increase, the rates of erosion from overland flow also increase.

Rainfall erosivity in the humid tropics is calculated using the equation developed by El-Swaify et al. (1987):

$$R = 38.5 + 0.35(p) \tag{8.2}$$

where p is annual precipitation (in mm). R is in units of tonnes per hectare per year. This equation is more suitable for tropical climates than the EI_{30} index of Wischmeier and Smith (1978) and has been successfully applied in Thailand.

Soil erodibility (*K*). Some soils are naturally more prone to soil erosion due to their physical and chemical structure. Erodibility is dependent on soil texture, organic matter content and permeability.

The LDD in Thailand provided values (Table 8.5) of the soil erodibility factor, K, for the each of the land units mapped within the catchment of the Mae Chaem in northern Thailand. Within each land unit, the soil erodibility was assumed to be homogeneous.

Slope factors (*LS*). The slope of the land has a major effect on the rates of soil erosion. As slope increases, the velocity (and hence energy) of overland flow increases, thus increasing the shear stresses applied to soil particles on the surface. As slope length increases, the volume of overland flow and its velocity also steadily increase, leading to greater erosive forces applied to the soil surface.

Slope in the Mae Chaem catchment ranges from 0° to 78°. For slopes less than or equal to 8%, the topographic factor (LS) is calculated using the Wischmeier and Smith (1978) equation:

Table 8.5 *K* (soil erodibility) factors for the Mae Chaem catchment. Source: provided by the Land Development Department, Thailand, May 2000

Land unit(s)	Soil texture	K factor
6, 8, 10	Loam + gravel	0.25
12	Loam	0.25
23, 25	Loam	0.27
27	Clay + gravel	0.27
45, 47, 49	Clay	0.24
46, 48, 50, 55, 35, 37	Clay + gravel	0.22
88, 99	Clay	0.17

$$LS = [(\text{length(m)})/22.13)^{0.5}] \times (0.065 + 0.0456(\text{slope})) + 0.0065(\text{slope})^2 \quad (8.3)$$

and for slopes greater than 8% the Hellden (1987) equation is used:

$$LS = (0.799 + 0.0101(\text{length(m)})) \times (0.344 + 0.0798(\text{slope})) \quad (8.4)$$

where slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient falls enough that deposition begins, or run-off water enters a well-defined channel.

Cropping factor (*C*). The vegetation cover, or type of crop planted, plays a critical role in determining the rate of erosion. The leaves of plants protect the soil from raindrop impact, and the roots hold the soil together. Plants also tend to increase infiltration of water, thus reducing the volume of overland flow running down the slope.

Crop-management factors (*C*) have been provided by the LDD in Thailand for a large number of individual crops in addition to mixed-farming systems. Table 8.6 shows the crop-management factors for selected crops in the Mae Chaem catchment. The value for *C* was set to 0.001 for bunded plots (Saifuk, pers. comm.).

Management-practice factor (*P*). A number of land-management practices have been developed that can significantly lower the rates of soil erosion. This is generally achieved by reducing the run-off rate, either by engineering structures (e.g. ditches, terraces, contour banks), or by using strips of vegetation that capture water and eroded sediment (e.g. strip cropping).

Values of *P* were provided by the LDD for a number of management practices on different slope classes (Table 8.7). The value of the *P* factor has been set to 0.1 for bunded plots (Saifuk, pers. comm.).

Applying the universal soil loss equation to northern Thailand

In this project, only sheet erosion from agricultural fields and forested areas was modelled, using the USLE-based approach modified to suit conditions typical of northern Thailand highlands. Anecdotal evidence and personal field surveying in the case-study sub-catchments of the Mae Chaem suggested that gully erosion was not a major source of sediment in this region. Erosion along roads and trails can also contribute to sediment loads, but a lack

Table 8.6 *C* (crop-management factors) for the Mae Chaem catchment. Source: provided by the Land Development Department, Thailand, November 1999

Crop	Crop-management factor (C)
Paddy rice	0.28
Upland rice	0.7
Soybean	0.421
Groundnut (peanut)	0.406
Maize (grain)	0.28
Maize (forage)	0.1
Cabbage	0.6
Potato	0.6
Onion	0.34
Temperate fruit trees	0.3
Tropical fruit trees	0.15
Fallow	0.09
Forest	0.001

Table 8.7 *P* (management-practices factors) for Thailand. Source: provided by the Land Development Department, Thailand, November 2000

Slope (%)	*P* factor				
	None	Contour cultivation	Strip cropping around contours	'Arable' land terrace	Bench terrace
0–2	1.0	0.6	0.3	0.4	0.12
2–7	1.0	0.5	0.25	0.5	0.1
7–12	1.0	0.6	0.3	0.6	0.12
12–18	1.0	0.8	0.4	0.8	0.16
18–24	1.0	0.9	0.45	0.9	0.18
24–100	1.0	1.0	0.5	1.0	0.19

of field data prevented inclusion of this type of erosion. However, it would be relatively easy to incorporate an additional component capable of predicting sediment sources from roads if sufficient data were collected in the future.

As a departure from the standard, annualised application of USLE, in northern Thailand it was applied separately for both the wet (April–November) and dry (December–March) seasons. This was done to allow for the running of scenarios affecting cropping patterns during the wet and/or dry season.

Over large scales, the area to which the model is applied is broken into segments in which the USLE factors are assumed to be uniform. For the case studies in northern Thailand, the USLE was applied to each land-unit type within the catchment.

Results for northern Thailand case study

Figures 8.1 shows plots of erosion rates predicted by the erosion model for a range of crops and land covers for the wet season of 1990 for land unit 88 and Figure 8.2 for land units 47 and 49 in the Mae Chaem catchment. The predicted erosion rates for most crops and management types on land units 88 and 99 are within the LDD-prescribed threshold of 31.25 t/ha. In comparison, for upland fields in land units 47 and 49, most crops are prone to extreme rates of erosion, with only maize, fallow and forest types yielding less than the LDD-prescribed threshold. In practice, policy designates land unit 49 for forest cover only. No differences in erosion rates are distinguished between land units 47 and 49, despite land unit 49 being generally much steeper, as the land units fall into the same slope category for defining the *P* factors for the USLE. In reality, it would be expected that considerably more erosion would occur on land unit 49 than on land unit 47.

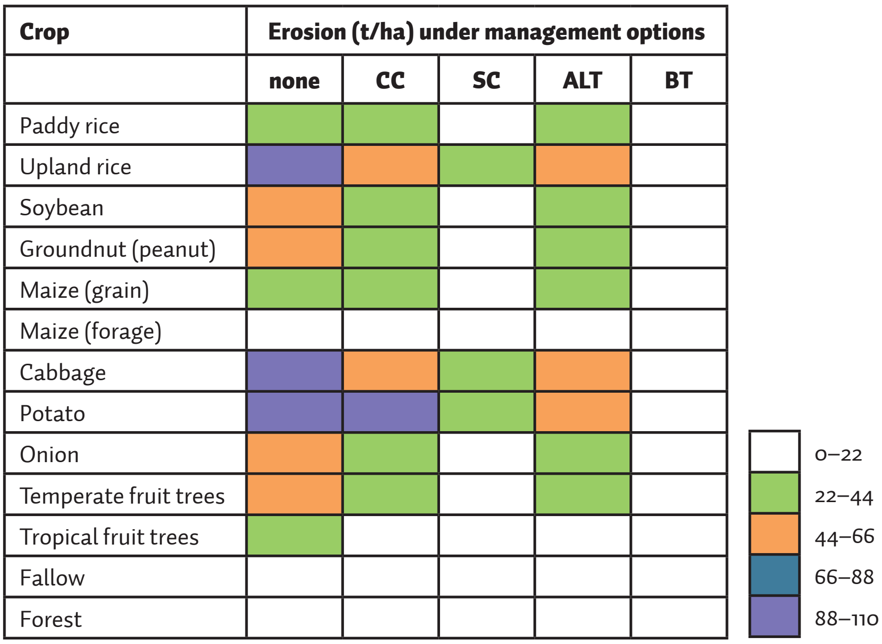


Figure 8.1 Erosion rates (t/ha) on land unit 88 under available management options for 13 crop or land-cover types on low-sloping land units suitable for paddy agriculture (BT: bench terrace, ALT: 'arable' land terrace, SC: strip cropping around contours, CC: contour cultivation)

Integrating the erosion model with the Integrated Water Resources and Management project decision-support system

The erosion model, based on USLE, was easy to implement and could be readily integrated into the DSS framework. It was also widely used by staff of Thai Government agencies, so increasing the likelihood of the DSS being adopted by these agencies. Since the erosion model is calculating only local soil loss (and not downstream sediment movement), the integration of the erosion model with the DSS involved only the crop and land-management options being passed from the land-use decision tool. Interaction with the hydrology model would be needed only if water quality impacts on downstream users were being considered, as the flow volume would determine the capacity of the channel to transport suspended sediment.

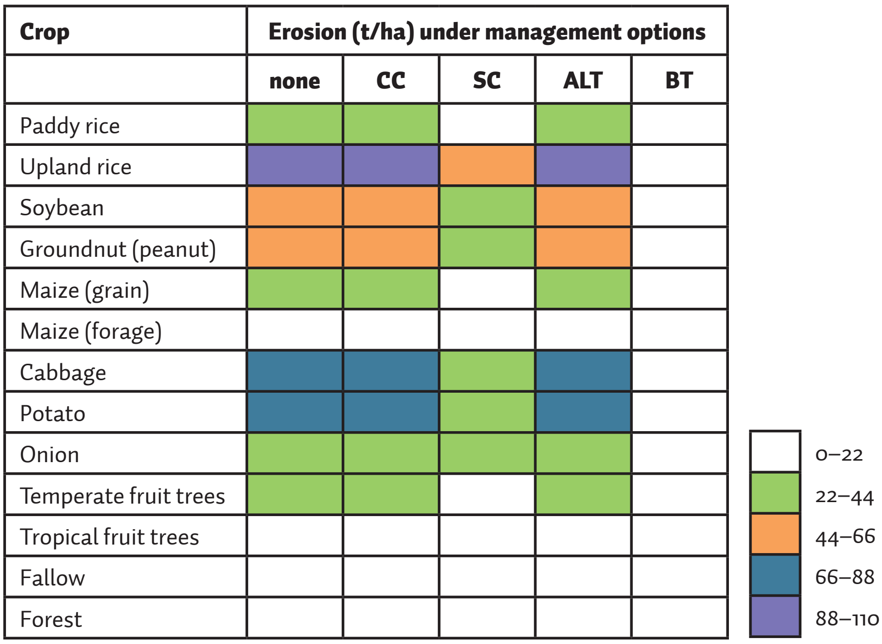


Figure 8.2 Erosion rates (t/ha) on land units 47 and 49 under available management options for 13 crop or land-cover types on low-sloping land units suitable for paddy agriculture (BT: bench terrace, ALT: 'arable' land terrace, SC: strip cropping around contours, CC: contour cultivation)

The USLE can be used to provide spatial estimates of annual erosion and is of low complexity. Another major advantage of the technique is that explicit consideration is given to crop type and management practices (within the *C* and *P* factors)—a requirement for scenarios of land and water management. The USLE has been used over a range of scales from small plots, from which the original equations were developed, to large-scale projects to determine soil erosion hazard within a catchment.

Although the USLE has a number of limitations, the paucity of data for the sub-catchments used in this study made it inappropriate to use more data-intensive erosion models. The model's main strength was that it could be used to develop indicators of potential erosion across entire catchments in relation to rainfall and land-cover scenarios. The USLE approach is also widely used by the LDD in Thailand for land-use planning. The LDD was a primary target user for the IWRAM DSS as a whole, so using the USLE approach increased the likelihood that the IWRAM DSS would be adopted by LDD for investigating the impacts of management options on catchment-scale erosion.

References

Chang, J.H. 1993. Hydrology in humid tropical Asia. In: Bonell, M., Hufschmidt, M.M. and Gladwell, J.S., ed., Hydrology and water management in the humid tropics: hydrological research issues and strategies for water management. Cambridge University Press, 55–66.

Coughlan, K.J. and Rose, C.W. 1997. Field experimentation results—runoff, soil loss and crop yield, a new soil conservation methodology and application to cropping systems in tropical steeplands. ACIAR Technical Reports, 40, 9–23.

Douglas, I., Greer, T., Bidin, K. and Sinun, W. 1993. Impacts of roads and compacted ground on post-logging sediment yield in a small drainage basin, Sabah, Malaysia. In: Hydrology of warm humid regions. Proceedings of the Yokohama symposium. Yokohama, IAHS Publication No. 216, 213–218.

El-Swaify, S.A., Gramier, C.L. and Lo, A. 1987. Recent advances in soil conservation in steepland in humid tropics. In: Proceedings of the international conference on steepland agriculture in the humid tropics. Kuala Lumpur, MARDI, 87–100.

Froehlich, W. and Starkel, L. 1995. The response of slope and channel systems to various types of extreme rainfall—a comparison between the temperate zone and humid tropics. Geomorphology, 11, 337–345.

Hussain, M.J. and Doane, D.L. 1995. Socio-ecological determinants of land degradation and rural poverty in northeast Thailand. Environmental Conservation, 22, 44–50.

Laflen, J.M., Lane, L.J. and Foster, G.R. 1991. WEPP: a new generation of erosion prediction technology. Journal of Soil and Water Conservation, 46, 34–38.

Lal, R. 1975. A brief review of erosion research in the humid tropics of south east Asia. In: Greenland, R., ed., Soil conservation and management in the humid tropics. John Wiley & Sons Ltd.

Liengsakul, M., Mekpaiboonwatana, S., Pramojanee, P., Bronsveld, K. and Huizing, H. 1993. Use of GIS and remote sensing for soil mapping and for locating new sites for permanent cropland—a case study in the highlands of northern Thailand. Geoderma, 60, 293–307.

Loch, R.J. and Silburn, D.M. 1996. Constraints to sustainabilitysoil erosion. In: Clarke, A.L. and Wylie, P.B., ed., Sustainable crop production in the sub-tropics: an Australian perspective. Brisbane, Queensland, Department of Primary Industries.

Ongprasert, S. and Turkelboom, F. 1995.Twenty years of alley cropping research and extension in the slopes of northern Thailand. Proceedings of the highland farming and the future conference, Chiang Mai, Thailand, 55–71.

Reid, L.M. and Dunne, T. 1984. Sediment production from forest road surfaces. Water Resources Research, 20, 1753–1761.

Sumrit, D., Srikhajon, M. and Pothiswan, U. 1993. Thailand: country paper. Report of an Asian Productivity Organisation study meeting on agricultural diversification in monsoon areas, Tokyo, 18–23 January 1993. Tokyo, Japan, APO.

Turkelboom, F., Poesen, J., Ohler, I., Vankeer, K., Ongprasert, S. and Vlassak, K. 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. Catena, 29, 29–44.

Wallin, T.R. and Harden, C.P. 1996. Estimating trail-related soil erosion in the humid tropics—Jatun Sacha, Ecuador, and La Selva, Costa Rica. Ambio, 25, 517–522.

Wischmeier, W.H. and Smith, D.D. 1978. Predicting rainfall erosion losses—a guide to conservation planning. US Department of Agriculture, Agriculture Handbook No. 537.

Yu, B. and Rose, C.W. 1999. Application of a physically based soil erosion model, GUEST, in the absence of data on runoff rates – I. Theory and methodology. Australian Journal of Soil Research, 37, 1–11.

Ziegler, A.D. and Giambelluca, T.W. 1997. Simulation of runoff and erosion on mountainous roads in north Thailand: a first look. In: Human impact on erosion and sedimentation. Yokohama, IAHS, Publication No. 245.

Ziegler, A.D., Giambelluca, T.W. and Sutherland, R.A. 2001. Erosion prediction on unpaved mountain roads in northern Thailand: validation of dynamic erodibility modelling using KINEROS2. Hydrological Processes, 15, 337–358.

CHAPTER 9

Supporting management decisions

Implementation of the Integrated Water Resource Assessment and Management project decision-support system

SUSAN CUDDY, REBECCA LETCHER, KAMRON SAIFUK AND PARISA SAGUANTHAM

SUMMARY

The likely success of any decision-support system (DSS) depends strongly on the design process used to develop the system. Design usually depends on the types of scenarios and management options to be considered, budget and other resource constraints, client and stakeholder preferences and the desired re-usability and flexibility of the approach. This chapter describes the three DSS that were built during the Integrated Water Resource Assessment and Management project to underpin the scenario-modelling approach to integrated assessment. It is structured so that the key elements of the scenario-modelling framework are described for each DSS. The chapter concludes with a brief discussion of the software development life cycle, emphasising the importance of post-delivery planning.

Introduction

The decision-support system (DSS) that was constructed as part of the Integrated Water Resource Assessment and Management (IWRAM) project went through several developments. These developments reflected the changing balance between needs (driven by assessment imperatives) and reality (driven by resources and purpose). Phase I of the project included a significant investment in building the DSS that provided scope for increasing complexity to support assessment of a wider range of issues. Phase II was a hand-over phase where the emphasis was not on the DSS per se, but on using the DSS to build and transfer capability in integrated assessment (IA) using an integrated scenario modelling (ISM) approach.

Three variants of the IWRAM DSS are described here:

- integrated modelling toolbox
- IWRAM DSS
- IWRAM XL (eXtension Layer).

The integrated modelling toolbox comprises a biophysical toolbox linked to socioeconomic models. This is a quite complex software application using a node-link framework. It was developed and coded by the Australian team during phase I of the project.

IWRAM DSS is a Thai version of IWRAM built during phase II. It is a much simpler software application and provides assessments within, but not between, catchments.

IWRAM XL (EXtension Layer) was built during Phase II to support training in IA and ISM concepts. It served as a prototype for the development of IWRAM DSS.

From a software development perspective, the progression of ideas and their implementation in the various DSS clearly demonstrate the importance of taking the time to understand the issues, and respect local knowledge and expertise when building decision-support systems.

While the first two variants were developed as land-use planning tools, the last was developed primarily as an educational tool. The following sections contain a discussion of the components of the framework and how they have been implemented, before going on to describe the (three) implementations, in terms of:

- issues
- design imperatives
- stakeholders
- study area representation
- models and their selection
- the integrating engine
- uses and assessment.

The chapter also contains a general discussion of other important elements of DSS implementation; namely data integration, deployment, maintenance and training.

Scenarios

While the IWRAM DSS supports the creation of many scenarios, three key methods identified by the natural-resource management agencies were incorporated, being scenarios based on:

- existing land use, i.e. the base case
- 'biophysical selection only', which uses erosion as the main criterion for ranking scenarios
- 'economically optimal selection', which incorporates socioeconomic values into both the design and assessment of scenarios.

Existing land use

For this class of scenario, land-management units (LMUs) are based on the current land-use map. The IWRAM DSS is run to analyse whether erosion thresholds are maintained. If not, then the user would be expected to run either a new 'biophysical' or 'socioeconomic' scenario.

'Biophysical selection only'

Scenarios in this class are based on a trial-and-error approach to modifying crop and management options to determine whether or not these can be used to reduce erosion below the nominated thresholds. The IWRAM DSS provided various interfaces to allow the description of these scenarios, always resulting in the production of a new LMU map as input to the models.

'Economically optimal selection'

For scenarios in this class, the new LMU map is created, not by trial and error but by the use of a farmer decision-making model to create new land-use maps and constraints, based on economic and social drivers (see chapter 5). The effect of these crop choices on biophysical and socioeconomic indicators is then assessed.

Regionalisation

The IWRAM models operate at a number of spatial and temporal scales. Consider, for example, the Mae Uam sub-catchment (see Figure 9.1). It is an upland sub-catchment with a large proportion of steeply sloping lands as well as paddy areas, which are located close to the stream network. In paddy fields, the dominant issue is crop water-use, whereas in upland fields the susceptibility of agricultural fields to elevated erosion rates also becomes important.

In the first phase of the project, the conceptualisation relied upon the idea of land holding of paddy or upland. The primary unit of analysis was the resource-management unit (RMU), a classification of households on the basis of access to paddy and/or upland fields (see chapter 5). Thus, the RMUs were not unique in soil characteristics and land qualities, such that different RMUs had the same soil type. The crop and erosion models operated on a land-unit basis defined by soil type and topography, with no consideration of internal spatial variation. The crop model operated on a 10-day time step and the erosion model was an annual model—although it could be applied by season. The hydrology model, on the other hand, yielded lumped catchment estimates of daily discharge. In the case of the Mae Uam catchment, these estimates were provided at two ungauged points (nodes) in the sub-catchment, so that the crop and hydrologic models could be linked.

The spatial scale of the socioeconomic modelling was at the level of the household (chapter 5). This scale was chosen as it was considered that the household was the main driver of agricultural production decisions in northern Thailand. The IWRAM framework, however, was sufficiently generic to allow applications at different scales (e.g. the regional or village scale).

In phase II, the conceptualisation moved to a more usual mapping approach whereby the unit of analysis was formed from the intersection of land units (described in chapter 4) with land use. These formed a new LMU map. This approach defines the given yield of a crop for a particular land unit (or land suitability class) based on the FAO land-evaluation procedures (FAO 1976). A single land unit reflects a combination of soil class and topography. While the land-unit map is static (and provided by a government department), the land-use map (and thus the LMU map) usually changes with the different scenarios under investigation.

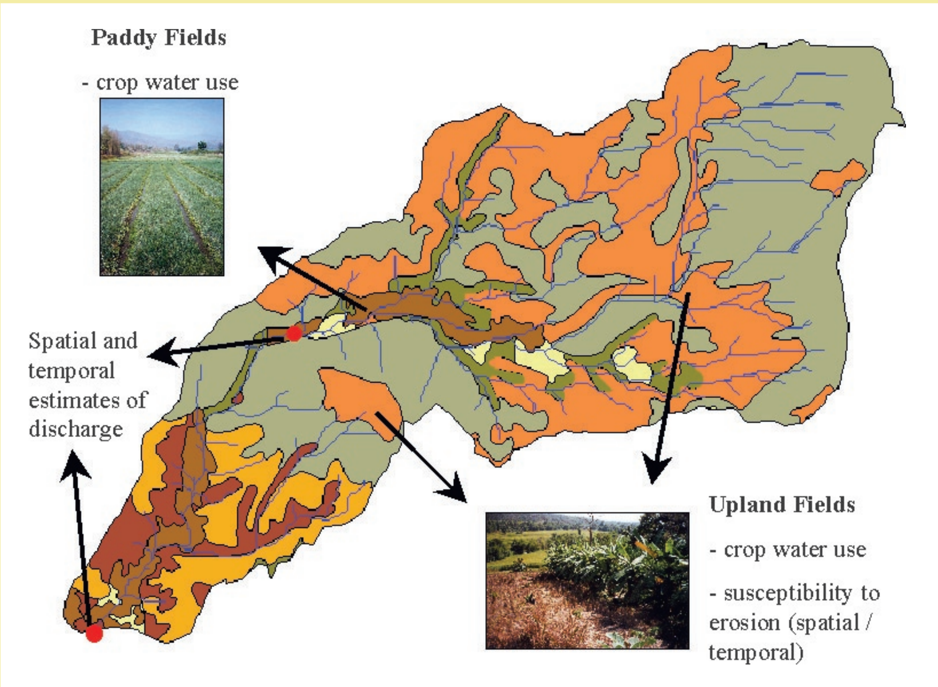


Figure 9.1 The Mae Uam catchment, northern Thailand, showing the nodal structure implemented within the Integrated Water Resource Assessment and Management project decision-support system.

Integrated Water Resource Assessment and Management project decision-support system implementations

The integrated modelling toolbox

Issues

The toolbox was designed to explore the spatio-temporal interactions between water supply, erosion, rice deficit and farm income. Input drivers are climate, commodity prices, technological improvements, government regulations and investments. The purpose of the DSS was to assist the Land Development Department (LDD) in its land-use planning activities.

Design imperatives

The choice of the household as the decision-making unit, and the need to look at downstream impacts of land-use activities, were major design drivers. The former determined the spatial aggregation and the style of economic model. The latter resulted in the adoption of a nodal network structure. The focus of the design was then to develop an integrative framework to support prediction at each node in the network.

As with most DSS development, the design was heavily influenced by budgets (time and resources) and biased the developers to adopt approaches and model styles with which they were familiar.

Scale and study-area representation

The models in the integrated toolbox are based on a spatially lumped representation of processes. Spatial scales of the biophysical models vary from nodes, to land units to sub-land-unit scales. Time steps of the models range from daily to 10 days. while outputs may be aggregated up to seasonal, annual and higher depending on the length of simulation. The spatial scale of the economic modelling in the initial project is at the level of the household where activities are optimised with respect to income and constraints subject to the land and water resources available and external drivers mentioned previously. The temporal scales of the economic modelling are seasonal (wet, dry) and annual.

A unifying spatial scale for the modelling is the node. Nodes are identified through the stream network as distinct zones of activity in catchments between which trade-off of indicators is required. Thus, the time clocks of the various models are synchronised at these nodes.

The toolbox uses a nodal structure to represent the stream network. This supports modelling of trade-offs between upstream and downstream users. Household decisions in a catchment upstream of a node are aggregated and modelled as occurring from a specific point along the river. Households in an area are grouped into a number of representative resource-management units (RMUs) and household decisions aggregated by summing up the decision of each RMU type present at the node. The rainfall–run-off model provides estimates of stream discharge at each node.

The land-unit classification system is used to describe the soil and topographic characteristics of the RMUs. A land unit is an area with homogeneous land qualities influencing crop performance, and with the same management and practices. As an example, the Mae Uam sub-catchment contains large areas of land units 88 and 99—low-sloping clay soils suitable for paddy agriculture. This system is described in chapter 2.

Model selection

The toolbox contains socioeconomic decision-making models, a biophysical modelling toolbox, and a socioeconomic impact simulation model. The biophysical toolbox contains a crop model, a hydrological model, a water-allocation model, and a soil-loss model (USLE).

The crop model was developed to support dynamic simulation of crop yields, without requiring large amounts of highly specific soil data. The CATCHCROP model (see chapter 7) predicts crop yield, actual evapotranspiration, surface run-off, deep drainage and crop water-demand.

The hydrological model was based on the IHACRES rainfall–run-off model (see chapter 6). This model was favoured by the Australian team as it performs well yet requires only rainfall and temperature (or pan evaporation) data for input, and stream-discharge data for calibration. IHACRES can also be regionalised to predict flows at ungauged nodes.

The soil-loss model to estimate gross erosion is based on the universal soil loss equation (USLE) modified to suit conditions in northern Thailand (see chapter 8).

The integrated modelling toolbox models household-scale decisions on land and water use.

The socioeconomic decision-making model uses a linear program to solve a constrained optimisation. Constraints can range from social constraints, such as the preference to grow rice as a subsistence crop during the wet season, to 'typical' economic constraints of maximising profit or minimising risk (see chapter 5).

The socioeconomic impact model then calculates the impact of actual yield and water availability on household income and total rice deficits.

Despite the apparent availability of model component candidates from the literature, much innovation was required in the modelling. All of the models integrated into the toolkit and DSS required some development to take into account data inadequacies, either in the form of inputs and parameters to drive the models or as outputs to assist in the calibration of models. Least modification was required for the erosion model, where the inputs (rainfall erosivity factor and topographic factor) were adjusted for the higher rainfall and steeper slopes of Thailand compared with the original areas in the USA where the USLE was developed. The crop model required simplification of the detail, in infiltration, run-off and percolation processes to circumvent the lack of comprehensive field measurements in the study catchments. The simulation of discharge provided perhaps the greatest challenge because of the need to predict flows at nodal sites that were ungauged, and to predict nodal flows under changes in land-cover conditions. This required a regionalisation approach to relate the ratio of parameters of the IHACRES model (from gauged calibrated nodes to ungauged and/or land-cover-modified nodes) to the ratios of either run-off, deep drainage or run-off plus deep drainage inferred by the crop model (see chapter 6).

Model integration

The toolbox underwent a number of design and platform changes. The final product is a collection of programs (Matlab, Fortran, Java) that can be run separately or in combination, with clearly defined execution sequences and data flows. The integrative framework is graphically represented in Figure 9.2.

Land-use decisions, based on expected returns and water availability, are simulated within the socioeconomic decision models. These decisions are passed to the biophysical toolbox, which simulates the impact of climate on crop yields, water use, water availability and erosion. Actual yields and water use are then transferred from the biophysical toolbox to the socioeconomic impact model, where the impact of actual yields on a series of socioeconomic indicators is calculated.

Uses

This selection of models suits the types of scenarios identified in phase I. A large number of scenarios (climate, crop selection, land-use change, land-management practices, price shocks, forest encroachment, migration) have been developed and run through the biophysical and integrated toolboxes. In hindsight, perhaps the most important use of the toolboxes was their role in building a local multidisciplinary team that can promote IWRAM principles and practices.

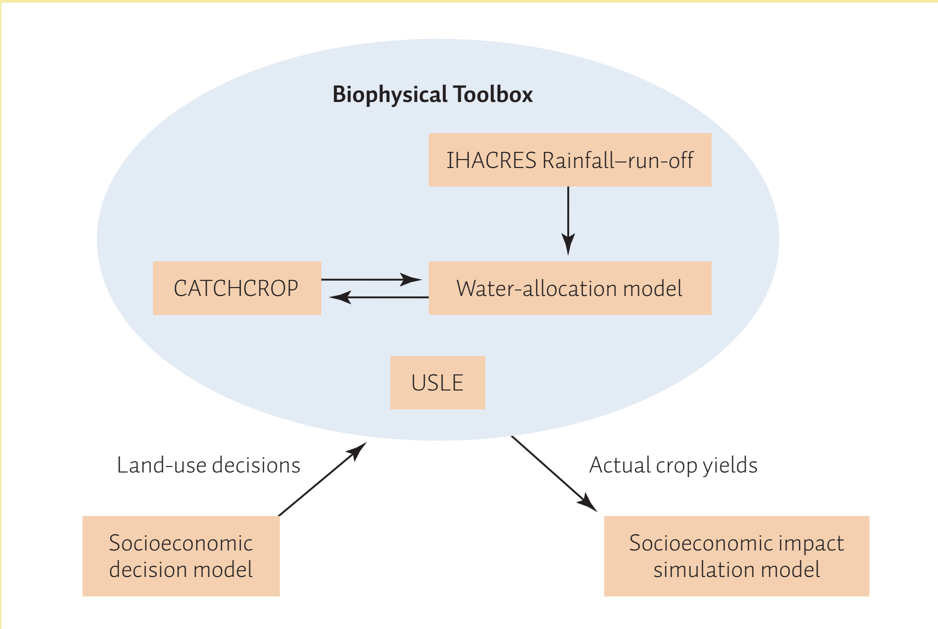


Figure 9.2 The integrative structure of the integrated toolbox used in the Integrated Water Resource Assessment and Management project, showing the main models and their linkages

Assessment

From a technical perspective, the toolboxes have been successful, as evidenced by the fact that they continue to support refinement of IWRAM principles. In retrospect, the emphasis on the development and delivery of the DSS compromised joint and mutual learning. At the end of the project, the Thai team identified conceptual and technical problems that hampered their application and adoption of the DSS. These problems related mainly to the choice of land classification and the selection of models.

Of greater consequence, the development of the toolboxes informed a real understanding of the meaning of integrated catchment management in the Thai context. Natural-resource management in Thailand is fragmented and spread across many government agencies. The IWRAM project provided an opportunity for agency staff to work together, learn from each other, and develop a shared vision for natural-resource management that would work across government agencies. A locally developed DSS was a key part of this, and their IWRAM DSS is described below.

Integrated Water Resource and Assessment and Management decision-support system

Issues

The benefit of shared experience clarified the approach that the Thai team wished to follow. The initial toolbox developments taught the Thai and Australian teams a great deal about integration of models and scenario development. The second phase of the project focused on putting this knowledge into practice, with the Thai team taking greater ownership of the component models, DSS and the integrative framework, while the Australian team moved to playing more of a support role. In addition, other initiatives were undertaken to support the uptake and delivery of IWRAM, including extensive fieldwork, an information website at <http://www.iwram.org>, development of training materials, and extension of the IWRAM program into neighbouring regions.

IWRAM DSS design has the benefit of strong formulation of preferred scenarios for investigation developed by Saifuk and Ongsomwang (2003). These are described in later sections.

Design imperatives

The first imperative was to select a land-classification scheme that conformed to the Thai land-use planning system. Land modelling units were devised, as described in chapter 4.

The second design imperative was to couple the DSS with a geographic information system (GIS) to provide high-resolution mapping capability. This would be possible with the revised land-classification scheme.

The third design imperative was to replace the linear programming approach used in the socioeconomic model. This was driven by three factors: (1) the processing within linear programming algorithms is not obvious (i.e. 'black box') and does not engender interdisciplinary learning; (2) the optimisation paradigm does not sit comfortably with the world view of the biophysical modellers; and (3) the need to disaggregate results beyond the 'representative' decision-maker (as used in a linear-programming approach).

Study-area representation

The RMUs of the toolbox have been replaced by LMUs. These are intersections of land units and 'current' land use as demonstrated in Figure 9.3. The land-unit map does not change, but the land-use map may (and usually will) change according to land-use scenarios. A LMU is homogeneous in land qualities (attributes of the land unit) and land use. The use of LMUs is the fundamental key to support a GIS interface and spatial data analysis.

To use this scheme for all the models requires that survey and other biophysical and socioeconomic field data can be mapped to the same units.

Model selection

A decision-tree approach was selected to replace the linear program in the *socioeconomic decision model*, as described in chapter 5. The revised model is a crop-choice model whose structure (a decision tree) has been generated using a data-mining algorithm. It simulates farmers' decisions on crop choice (based on decision rules). Important variables determining crop choice include land-unit class, season, water use, size of land, labour, capital, costs and profits; outputs are wet- and dry-season crops, keyed to LMU. A land-use map can be generated for use by other component models.

The economic-impact model is simply a calculation of the gross margin (the economic indicator) for the designed land-use pattern. This uses the simulated yield from the crop model.

The erosion model is a re-implementation of the USLE model developed for the toolbox.

This phase of the development had the benefit of a Thai crop modeller as a team member (not available in phase I). The crop model is a modified FAO crop-production model based on thermo-radiation and water-use efficiency (see chapter 7).

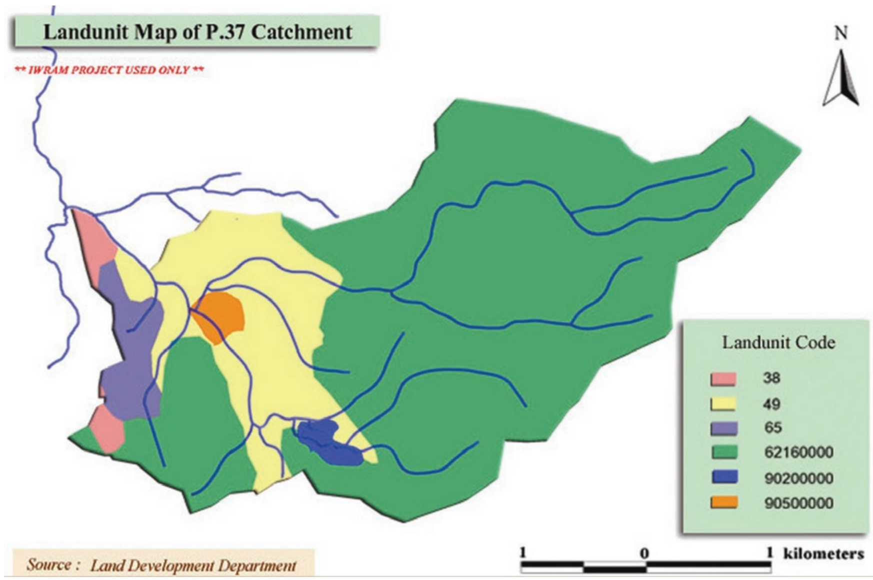
The hydrology model is very different to that in the toolboxes, using the US Soil Conservation Service's curve-number approach to estimate direct run-off from rainfall events. This has been implemented in a prototype version of the model (see chapter 6).

Model integration

IWRAM DSS has two development paths—a GIS-coupled application and an Excel/VBA application (a consequence of the IWRAM XL development described in later sections). It is anticipated that the two paths will merge with the add-in of GIS functionality to the VBA application (via Arc-Objects).

In the GIS version, the GIS itself provides the integrative functionality (see Figure 9.4). This approach has the benefit of direct linkage to agency databases (thus avoiding the complications that come with data acquisition and transfer).

The Excel version is stand-alone and, most importantly, is very portable, being easily installed on most personal computers. It operates via a set of workbooks, and worksheets within those workbooks. Model selection and execution is controlled by the interface. Figure 9.5 is a screen grab of the main worksheet and exemplifies its open and transparent style. The user can select a component model, or go to another worksheet to build LMU scenarios.



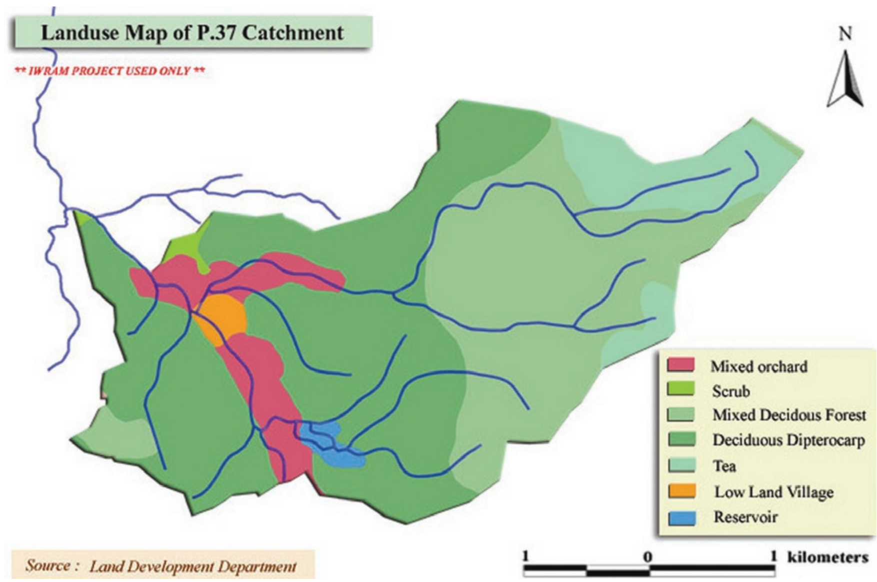


Figure 9.3 Land units and land-use maps for P37 catchment of the phase II study area in the Integrated Water Resource Assessment and Management project. These maps are intersected to produce a land-modelling unit map.

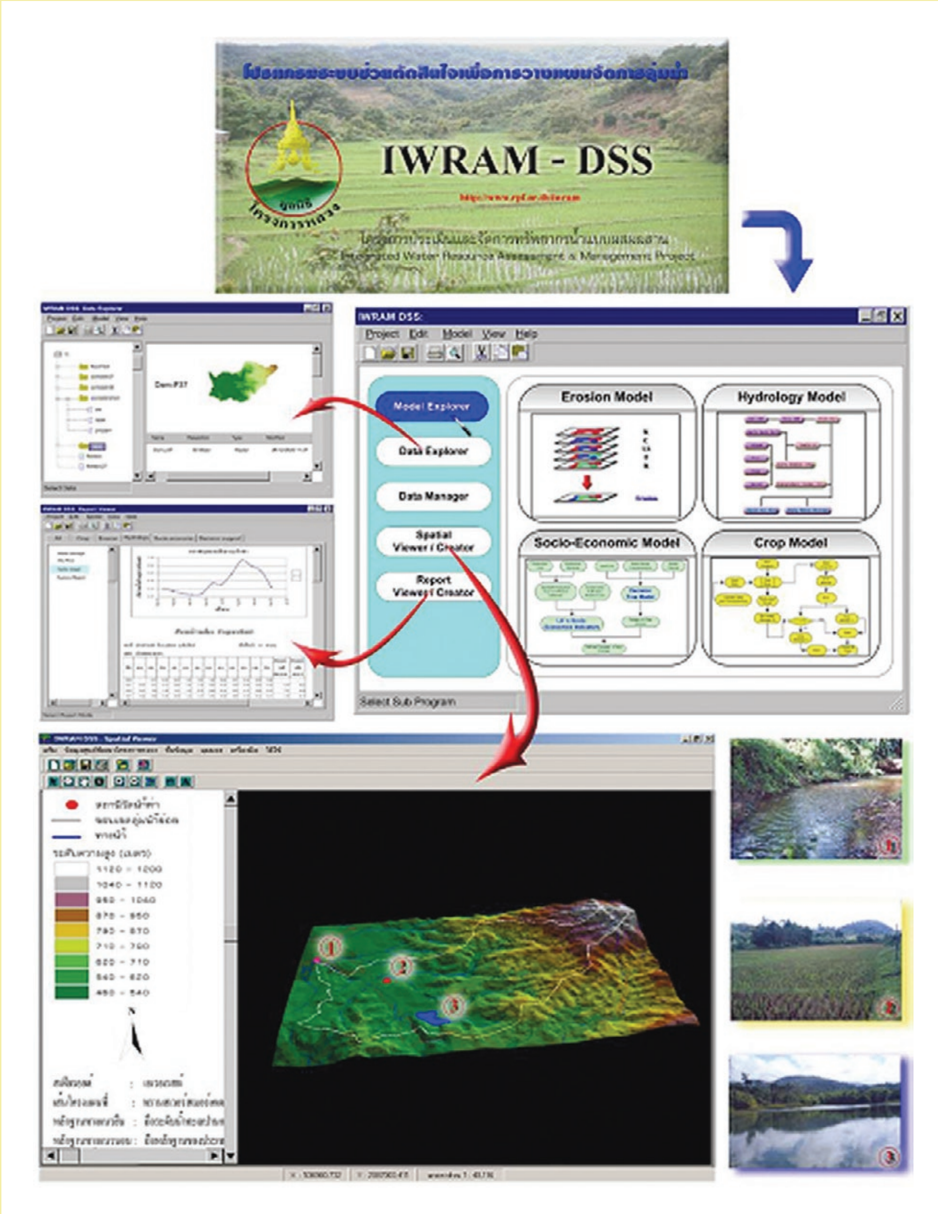


Figure 9.4 Integrated Water Resource Assessment and Management project decision-support system GIS framework

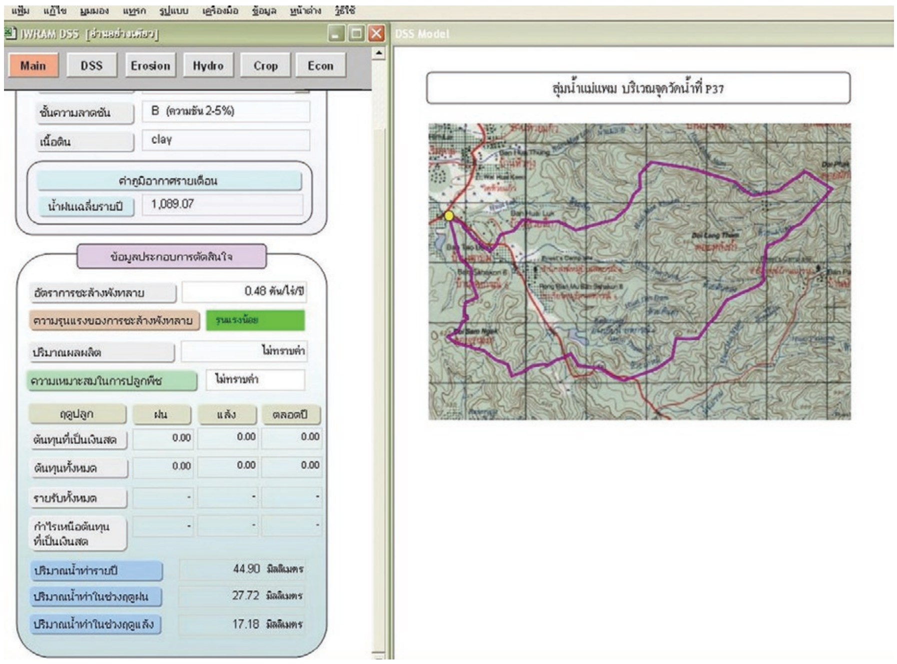


Figure 9.5 Integrated Water Resource Assessment and Management project decision-support system main window, showing tools for selecting land-modelling unit and crop type. Results are then displayed under the right-hand map.

Uses

Just as it should be, IWRAM DSS is a system under continuing development. The model-building teams are developing scenarios to demonstrate the capacity of the system. These revolve around the three scenario conditions formulated by Saifuk and Ongsomwang (2003), namely:

- existing land uses—this 'base' scenario is the benchmark for further land-use improvements, in both utilisation and management
- 'ideal' biophysical land uses—these scenarios are based on a trial-and-error approach to modifying crop and management options to determine whether or not these can be used to reduce erosion below the nominated thresholds
- 'economically optimum' land uses—these scenarios incorporate socioeconomic values into both their design and assessment. These are scenarios that achieve sustained yields and income with minimum environmental impact.

The socioeconomic team is using the crop-choice model to evaluate the influence of government policies on farmers' crop choices. In the first instance, this has been limited to the role of credit availability in farmer decision-making.

Assessment

As with much DSS development, time and resource pressures force the disciplinary experts to build their models independently, resulting in mismatched interfaces and delivery timetables. The threat of this approach is that the focus, by default, shifts from the integration to the component parts. Careful planning and project management are required to ensure that the models serve the needs of the DSS, not the other way around.

Having said that, the principles of integrated assessment, and the development of DSSs to support it, have been well learnt and continue to inspire the team.

Integrated Water Resource Assessment and Management XL (EXtension Layer)

Issues

IWRAM XL was originally conceived as a prototype to advance debate on the form of the IWRAM DSS. However, it proved very useful as a pilot for teaching IWRAM principles and was successfully trialled in an IWRAM training workshop in Thailand in mid 2004.

Design imperatives

The first design imperative was to demonstrate that a powerful integrative framework can be built using simple tools (such as Microsoft® Excel).

The second design imperative was to demonstrate that the overall framework is the hub of a DSS. Model selection is then to serve the purpose of the DSS, not the other way around. In fact, few new models were built for this version of the IWRAM DSS.

The third design imperative was to demonstrate the usefulness of centralised databases to rationalise and synchronise information. For example, the economists, the crop modeller and the land-use planner used three different crop lists. Was it possible to construct one crop database that satisfied all members of the team, and the needs of the scenarios and analyses?

Study-area representation

A small sub-catchment (called P37) of the Mae Kuang watershed (a tributary of the Ping River) was chosen for the development of IWRAM XL, mainly because of the existence of good hydrological and socioeconomic data. Working with only one sub-catchment avoided the need to consider the complexity of spatial relationships such as on-site and off-site impacts, water transfers etc. This is appropriate for a training and educational tool (but not for a production DSS).

Within IWRAM XL, only one 'map' is stored—the LMU map—and the spreadsheet cells are used to represent a map grid.

Scenarios

Once again, with a very simple suite of models, IWRAM XL supports exploration of a range of scenarios. These include: climate change (different rainfall patterns); changes in type and extent of land use, especially crop type (revised land-use map); changes in crop prices; and changes in cultivation practice.

Model selection

As IWRAM XL is a teaching tool only; it does not have a complete suite of fully functional models. The hydrology, crop and socioeconomic models are those of the integrated toolbox and are not resident within IWRAM XL.

The soil-erosion model is an Excel implementation of the USLE approach and has been complemented with an 'erosion explorer' module to explicitly investigate the likely impact of alternative crops and practices on soil erosion.

A new component was developed to construct LMU maps (by converting current land uses and/or changing management practices). This component is called the LMU maker. It allows the user to develop sets of land-use change rules or manually edit the existing land uses to 'make' new LMU maps for assessment.

Design of, and technical specifications for, a socioeconomic LMU maker to construct a new LMU map based on socioeconomic decisions were written, and later implemented in IWRAM DSS. As such they were never implemented in IWRAM XL

Model integration

IWRAM XL consists of three main components: LMU maker, model engine, and output display and export module—linked as shown in Figure 9.6.

Figure 9.7 shows the data flows between the component models and the integrating module. The input data are the LMU map, climate data, erosion factors, management practices, economic data and soil properties; the output data are erosion, economic returns, streamflow, water use (extraction) and crop yield.

The Excel workbook has a series of worksheets for storing and manipulating data, for look-up tables and maps, and for model execution. The key input is the LMU map. This is first assessed against erosion thresholds. If the LMU map exceeds these thresholds, then the user is expected to create an alternative biophysical or socioeconomic scenario.

The 'economically optimal selection' scenario would use the socioeconomic LMU maker to create broad land-use maps and constraints. Crop choices are then modified from this to determine a modified land use that meets erosion thresholds.

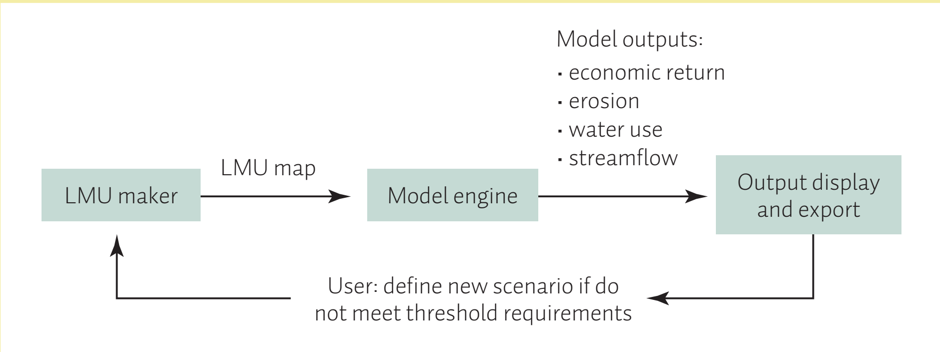


Figure 9.6 Integrated Water Resource Assessment and Management project XL (EXtension Layer) components

Uses

IWRAM XL has been, and will continue to be, used for training in IWRAM concepts. Its value as a training tool is that it has sufficient content to provide training in the individual components as well as in their integration. Its value as a prototype for IWRAM DSS is that it provides a testing ground for analysis of model simplifications and assumptions, and supports staged development and implementation of the component models.

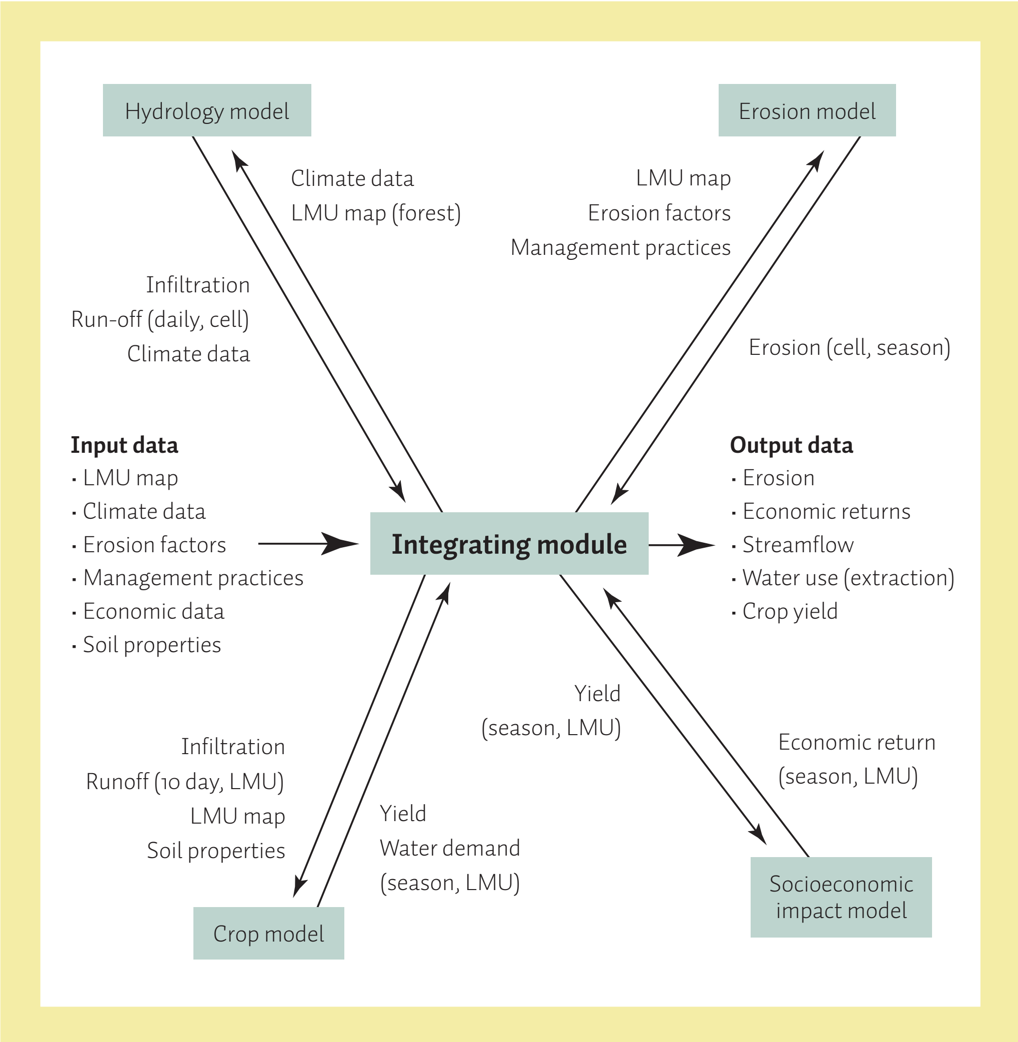


Figure 9.7 Integrated Water Resource Assessment and Management project XL (EXtension Layer) modules and data flows

Assessment

This approach to DSS development is very different to its predecessors, in that it is very 'low-tech'. While still requiring programmer assistance (to code the minimal VBA routines in Excel), it demystified the DSS development process for the scientists.

It is very much a work-in-progress that would benefit from additional investment so that it could serve as a general training tool in IWRAM principles throughout Australia and the Asia–Pacific region.

Data integration

An important component of developing integrated assessment tools is to tackle the issue of integration of input data-sets. While Thailand has a standard land-unit mapping scheme (developed by the Land Development Branch) that has been adopted by other agencies, this is not always the case. In fact, it is more normal that different agencies use different land disaggregation schemes, and different soil classifications (because the scheme that is appropriate for, say, erosion-risk mapping, is not particularly useful for crop-suitability mapping).

The degree of integration of these data into 'common' data-sets depends on many issues, including determining the need for commonality, how the common set will be maintained if changes are made to the parent sets etc.

The IWRAM experience identified the crops data-set as the most difficult to standardise. The crop modeller had a very detailed list of crops, with a large number of attributes differentiating (or not) each crop. The soil conservationist had a smaller set, classified by their cultivation practices. The economists had another set, classified by price structure. And these classifications were widely used within those disciplines. In fact, the development of a common data-set was an important part of the educative process about integrated assessment, and contributed to a shared understanding of the different approaches and needs. An example of an integrated common set is shown in Figure 9.8.

Pre- and post-development

Pre and post-development issues have not been mentioned elsewhere in this book. While they are not core to the IWRAM approach, they are a very important part of DSS development and should influence the design of the DSS in terms of the functionality, and genericness of the implementation.

Design approach

Is the DSS one-off or re-useable? Serious questions such as this must be confronted early in the design phase. These questions may be difficult to resolve at this time because it is often the case that the appropriateness and usefulness of the DSS for other study areas is not recognised until after construction is near completion. A prototyping approach may be all that is required in the first instance to allow for an assessment about further application to be made later on.

An early decision that the DSS should have general applicability has enormous overheads that must be identified and costed. These include the need to have robust and efficient data formatting and import functionality, ability to describe a very wide range of scenarios across multiple issues, good and considerable documentation, development of sample

Database (standard table)

Crop data	Climatic data Decade data	Land characteristics	Socioeconomic data
Crop cycle	Tmin	Soil type or series	Capital resource
LAI	Tmax	Soil structure	Labour and human resource
KLAI	RHmin	Soil fertility	Land capability
Max height	RHmax	Soil chemistry	Production value
Max root depth	U	Soil water storage	Management cost
Crop group	Sunshine H	Topology and slope	Market and transport
Harvesting index		Soil drainage	

Figure 9.8 Example of centralised data-sets created to support model coupling in the Integrated Water Resource Assessment and Management project

applications for training purposes, and a great deal more effort and time spent on all phases of the software life cycle—especially design, specifications, coding and testing. In particular, coding style is affected, as it must ensure total separation of the interface from model execution from the data. There can be no assumptions about the format of data; e.g. the number of land-use classes, the duration of time series data, the number of sub-catchments.

At the other end of the scale is the rapid development of applications that do the job, and nothing more. These require little investment in formal software engineering and may be all that is required.

Of course, awareness of the computer resources of potential users—both in terms of hardware and literacy—is crucial to making sensible design decisions. While government departments may be able to upgrade their computers or purchase particular software if required, this is rarely the case with extension officers and local agency offices.

Data management

Data and its management need careful consideration. Will the data be updated by multiple users? If so, do you want to maintain quality of data editing and track changes? Do you want users to be able to share scenarios and results? Being able to provide this functionality will consume considerable programming resources before you have even started on the purpose of the exercise, which is to build an integrated assessment tool.

A design ethos, which seems to fit well with the case-study approach recommended for IWRAM, and which has been adopted in the development of the IWRAM DSSs, is to build one-off, stand-alone applications, that store only the latest 'state' of the data (and possibly a default state for re-setting). Changes to the data (such as new crop classes or revised model coefficients) are permanent. In our experience, this is a sensible approach, as it puts the focus on the process and the integration, not the product.

Adoption and deployment

The DSS has to be portable and distributable. How is this to be done? Do the data need to be distributed separately from the software because their distribution is restricted? Can the DSS run with no data anyway? Does the DSS require specialised software and high-end computers, or can it run on standard desktop computers? Should the DSS and/or the data be covered by a licence agreement?

The answers to such questions depend on their expected use. If the DSS is to be used by many agencies within the same study area, then it could be shipped as one package combining software and data. If it is to be used in different catchments, then it may be shipped without data, or with a small sample data-set to help with training.

Maintenance

DSS are often developed and delivered with scant attention to maintenance. This can be an unfortunate consequence of fixed-term projects that focus on delivery of the DSS. Some issues that must be considered are:

- who will 'own' the DSS?
- who will maintain the DSS code and data?
- who will provide user support?
- what training materials are required, who writes them, and who delivers them?
- is there an upgrade program (even if just for bug fixes)?
- who will manage licences and to whom is the DSS distributed?
- what is the life span of the DSS?

Training

Training is an important part of IWRAM and integrated assessment, and includes building capability and capacity in the ability to:

- inform others (often senior departmental staff) of the benefits and uses of the DSS
- instruct colleagues in the principles of integrated assessment and how they are implemented in the DSS
- train in the use of the DSS (building scenarios, running, analysing and interpreting results)
- teach others to train.

These all rely on the preparation of appropriate training and instruction material. In our experience, putting resources during the life of the project into preparation of train-the-trainer, rather than training, material is important. Integrated assessment, by definition, is across disciplines—so trainers need to be capable of giving instruction in each component model (i.e. the crop model, the hydrology model etc.) and their integration. Trainers, at least in the first instance, are usually members of the in-country project team. While they have become familiar with the other DSS component models during the course of the project, it is still challenging to be asked to instruct in an area outside your expertise (e.g. a hydrologist needs to know what 'rice deficit' means if that is one of the indicators available in the DSS).

This emphasis is particularly appropriate when dealing with different language and cultural groups, where it is important that the trainers are not from out-of-country. The train-the-trainer packages should provide resource material that describes the theory and the science (and how that science is represented in the models in the DSS), how to build scenarios, how to run the DSS, and how to extract and analyse results. It could also cover how to format, import and export data, and how to source the data.

This material is then tailored, at the direction of the trainers, for different audiences. This may require translation.

During the IWRAM project, most training was conducted as workshops, as these could be co-ordinated with project meetings. These workshops included in-country team members and invited colleagues from their respective government agencies. While the out-of-country team members were the initial trainers, the final workshop (June 2004) was a truly collaborative effort with the in-country team providing instruction, and most of the workshop being in Thai. The first Thai-only workshop was held in January 2005 with material prepared by Thai team members. This workshop covered training in the component models by their developers, and hands-on use of the IWRAM DSS. While very successful, it did rely on the model developers being present. The next step is for the trainers to develop confidence in training in all aspects of the DSS and its use, without the full IWRAM team. This will be a true indication of successful adoption of the IWRAM approach.

Conclusions

The development of the DSS was to 'support sustainable use of Thailand rural catchments, specifically in relation to their land and water management, while maintaining a robust local economy' (Royal Project Foundation 2003). The DSS used a scenario-modelling approach to formulate and provide assessment tools to evaluate a range of scenarios based on their likely effects on the natural environment and the livelihoods of the local people.

The range of approaches to scenario development, model and indicator selection, and choice of integrating engine described above, demonstrate the flexibility of the IWRAM approach, which is neither prescriptive nor dogmatic.

In the short term, the primary role of the IWRAM DSS is to promote more-sustainable outcomes and educate. The best investment is in people, not products. In the words of the Thai team (Royal Project Foundation, 2003):

> The project team has developed expertise in IWRAM principles and has developed its own decision support software that predicts likely effects of a range of alternate crops and cropping practices on soil erosion, water availability and consumption, and economic return to local farmers.

References

Royal Project Foundation 2003. Integrated Water Resource Assessment and Management Project website. Chiang Mai, Thailand, Royal Project Foundation. At <http://www.iwram.org> [accessed 30 November 2004].

Saifuk, K. and Ongsomwang, S. 2003. A decision support framework for catchment based natural resource management. In: Post, D., ed., Proceedings of the international congress on modelling and simulation (MODSIM2003), 1645–1648. Available online via <http://mssanz.org.au/modsim03/Media/menu.pdf> [accessed 18 October 2004].

Using the Integrated Water Resource Assessment and Management Project decision-support system to understand trade-offs and improve decision-making

WENDY MERRITT, REBECCA LETCHER, BARRY CROKE AND KAMRON SAIFUK

SUMMARY

THE Integrated Water Resource Assessment and Management project decision-support system (IWRAM DSS) is a computer-based tool that links a set of biophysical and socioeconomic models to facilitate integrated assessment of land- and water-resource use options. Basically, it uses a scenario-indicator approach, allowing investigation of the spatio-temporal effects of postulated scenarios (model drivers or inputs) on indicators (model outputs) of catchment health. Previous chapters have described the

individual models, as well as the integrating framework that connects each of these models within the DSS. The aim of this chapter is to demonstrate how the IWRAM DSS can assist with the planning of integrated land and water management, by presenting a set of case studies for the Mae Uam sub-catchment in northern Thailand. The first set of case studies applies only the biophysical models to a set of scenarios that consider forest conversion, land management, and changes in climate. These case studies demonstrate the potential of the IWRAM DSS to explore the environmental effects of various land- and water-management options. In the second set of case studies, the full set of biophysical and socioeconomic models within the IWRAM DSS is employed to assess both the socioeconomic and environmental trade-offs associated with increasing the area of land available for agricultural production (and hence decreasing forest cover).

Introduction

The Integrated Water Resource Assessment and Management project decision-support system (IWRAM DSS) is a computer-based tool comprised of a set of biophysical and socioeconomic models. The biophysical models include a crop, hydrologic and erosion model. These are linked to a set of socioeconomic models that can be used to explore economic trade-offs and impacts of the various scenarios being tested, as well as the capacity for households to adjust their behaviour to a change in government policy, prices or resource constraints.

Scenarios may be developed around agricultural or conservation policies, demographic change, potential climate variability, or changes in the world market for exported goods. The complementary and competitive nature of particular policies or paths of development can then be explored by stakeholders.

It is important to note that the IWRAM DSS does not make decisions. Instead, it supports good decision-making by helping users to explore key relationships relevant to the various environmental and socioeconomic trade-offs in catchment management, using a 'what if' scenario-based approach. Similarly, the DSS does not provide an 'optimal' outcome, as this is dependent on the perspective and objectives of the DSS user and its clients. By offering a transparent and repeatable process, it helps users to explore some of the expected and unexpected impacts of various scenarios.

The first half of this chapter tests the biophysical models within the IWRAM DSS by running a series of climate, deforestation, and other land use scenarios—see also Merritt et al. (2004). The results demonstrate not only the types of scenarios and land-use planning issues that can be evaluated, but also the plausibility of the model behaviour. The results will provide, in addition, a basis for future developers and model users to question the behaviour of the models and make improvements.

The second half of the chapter combines the biophysical models with the socioeconomic models to assess the socioeconomic trade-offs of a development scenario in which the total area of agricultural land is increased. Instead of the user defining the land-use scenarios (as in the stand-alone application of the biophysical models presented above), the land use is passed on to the biophysical models from an economic decision model. This decision model simulates the choice of crops to be grown in a particular season, and on a particular land unit, in response to expected constraints on land, water and labour availability. The subsequent results from the biophysical models are then fed back into another socioeconomic model that estimates 'socioeconomic performance' for that particular scenario.

The DSS implements a scenario-indicator approach whereby users can test a number of scenarios and compare outputs of the models by looking at changes between the indicator sets. The DSS incorporates a nodal structure, where nodes represent the locations at which indicators are computed. The common spatial scale of the indicators is the sub-catchment upstream of a selected node in the river network. Figure 10.1 shows the locations of two nodes selected for calculation of indicators and evaluation of upstream–downstream impacts in the Mae Uam sub-catchment. Note that if a selected node (e.g. node 2 in Figure 10.1) has an upstream sub-catchment (e.g. node 1 in Figure 10.1) nested within it, then the area of the smaller upstream sub-catchment is subtracted from the larger downstream sub-catchment to provide the 'residual' sub-catchment area at the lower node (node 2 in Figure 10.1).

Biophysical models—scenario runs

To illustrate the capacity of the biophysical models to assist decision-making, simulations based on a set of scenarios considering changes in annual rainfall, and changes in forest cover and cultivation area, were performed for the two nodes in the Mae Uam sub-catchment of the Mae Chaem catchment (Figure 10.1). A set of different land-management scenarios was also simulated. Cropping details for each land unit in the wet season (April–November) and dry season (December–March) are provided in Table 10.1. The base forest cover used in the scenario runs is presented in Table 10.2. The base scenario corresponds to the 1990 forest cover provided by the National Research Council of Thailand.

The indicators evaluated by the biophysical models within the DSS can be summarised as: crop yield (t/ha), crop water-demand (mm), irrigation (mm), streamflow (ML), residual streamflow (ML), gross erosion loads (t), and erosion rates for land units and crops (t/ha). The crop water-demand is the total water over the growing season required to reach the potential evapotranspiration for a given crop. The irrigation indicator is the total irrigation (in mm) applied to a crop throughout the season. If the crop water-demand does not exceed the amount of water available within the stream, then irrigation is the same as crop water-demand. For this work, only surface water sources were used to irrigate crops. Other sources, such as shallow groundwater, were not considered. The streamflow indicator is the streamflow before irrigation abstractions. The residual streamflow indicator is the streamflow following abstractions for crop irrigations, assuming 100% irrigation efficiency.

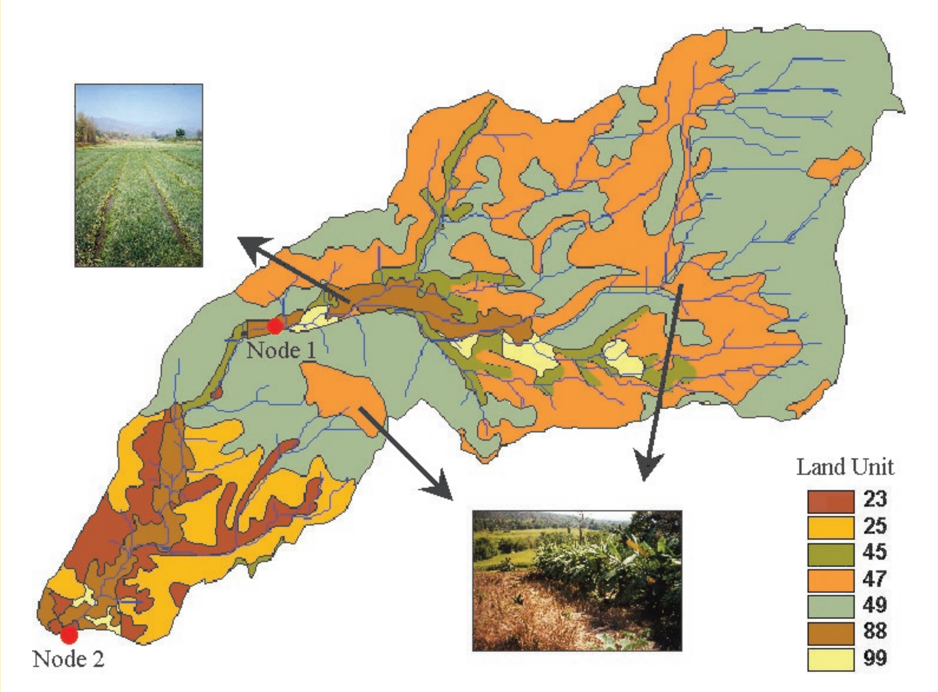


Figure 10.1 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: the sub-catchment, showing the location of nodes, the land unit types present and typical agricultural landscapes

In order to indicate some general features of the output, Figure 10.2 illustrates the erosion, yield, and water demand for the 1990–1991 hydrological year for four crops. In the wet season, agricultural fields are prone to elevated rates of erosion. In the dry season, there is very little rainfall (and hence negligible surface run-off) and so erosion rates are very low. Of concern in the dry season, however, is the availability of water for irrigation of crops. Note that, in the dry season, soybean and maize grain were irrigated. Hence, water demand by these crops is not as high as the non-irrigated fallow because, at each time-step, the crop is irrigated (thus reducing the initial crop water-demand for the next time-step to zero, while the fallow vegetation is increasingly water-stressed).

Climate scenarios

Three climate scenarios were simulated, corresponding to the 1990–91 hydrological year (1250 mm of rainfall), the 1988–89 year (1322 mm of rainfall), and the 1993–94 year (1026 mm of rainfall). Due to the short period of daily records available in the catchment, these scenarios do not

Table 10.1 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: proportion of agricultural area cropped on different land units

	Paddy fields (Land Unit nos 88 and 99)	**Upland fields** (land unit nos 23, 25, 45, 47 and 49)
Wet season	100% paddy rice Crops are fully irrigated on bunded plots, with medium fertiliser levels and no extra management.	23: 50% maize 25: 50% soybean 45: 50% soybean 47: 50% maize 49: 15% soybean Non-irrigated crops; medium and low fertiliser levels for maize and soybean, respectively; plots on land units 23 and 25 are contour cultivated; no management practices are employed on land unit 45; arable land terraces are used on land unit 47; land unit 49 has strip cropping around contour plot.
Dry season	88: 25% soybean 99: 25% maize Both crops are fully irrigated on bunded plots, with low fertiliser levels for soybean and medium fertiliser levels for maize	23: 10% maize 25: 10% soybean 45: 10% soybean 47: 10% maize 49: no cropping Irrigated crops; medium and low fertiliser levels for maize and soybean, respectively; plots on land units 23 and 25 are contour cultivated; arable land terraces are used on land units 45 and 49.

reflect the true variability of climate. Despite this, the three climate scenarios implemented in this paper still show considerable variability (Figure 10.3). For instance, only 10 mm of rain fell in the 1990–91 dry season, compared with 102 mm in the 1993–94 dry season. Three forest-cover scenarios were considered: 1990 forest cover; a 30% decrease in the 1990 forest cover across all land units; and a 50% decrease across all land units.

Table 10.3 illustrates the effect of climate on catchment streamflow and residual stream-flow (streamflow after irrigation abstractions), as well as the total crop water-demand at the downstream node (node 2). An increase in annual water demand from the agricultural area of approximately 70 ML is seen when simulating the 1993–94 scenario compared with the 1988–89 scenario. The difference in annual rainfall between these two scenarios is 296 mm. The crop water-demand in Table 10.3 includes demand from fallow land. This land is not irrigated and this is why the residual streamflow and demand do not add up to the total streamflow. The total crop water-demand in the 1993–94 hydrological year is higher than the 1990–91 hydrological year despite higher annual rainfall, due to the timing of the rainfall.

Table 10.2 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: land-unit area (km^2) and 1990 forested area (km^2) for land units within nodes 1 and 2

Land unit no.	Description	Slope class[a]	Node 1 area (km^2)		Node 2 area (km^2)	
			Forest	Land unit	Forest	Land unit
23	Deep loam soils	A or B	0.00	0.00	1.76	2.40
25	Deep loam soils	C	0.00	0.00	3.01	3.39
45	Deep clay soils	A or B	1.70	2.01	0.20	0.24
47	Deep clay soils	C	12.30	12.78	0.94	1.05
49	Deep clay soils	D or E	15.95	16.22	3.78	4.01
88	Deep clay irrigated paddy soils	A or B	0.54	1.01	0.39	1.46
99	Deep clay paddy soils	A or B	0.37	0.66	0.06	0.13
Total	–	–	30.86	32.68	10.14	12.68

[a] A: 0–8%, B: 8–16%, C: 16–35%, : 35–60%, E: > 60%

Table 10.3 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: summary of impacts of climate scenarios upon the volumes (ML) of catchment streamflow, crop water-demand at node 2, and streamflow following abstractions for the wet and dry seasons

	Streamflow (ML)			Residual streamflow (ML)			Crop water-demand (ML)			Rainfall (mm)
	Base	30%	50%	Base	30%	50%	Base	30%	50%	
Wet season										
1988–89	12,579	13,957	15,114	12,028	13,341	14,445	841	1,597	2,114	1,231
1990–91	14,563	15,436	15,346	16,127	14,043	15,505	646	1,087	1,390	1,240
1993–94	9,871	10,854	11,592	9,405	10,351	11,059	819	1,678	2,263	925
Dry season										
1988–89	6,797	6,045	5,347	6,723	5,933	5,210	433	773	1,001	92
1990–91	3,955	3,258	2,662	3,864	3,122	2,495	524	940	1,220	10
1993–94	2,670	2,476	2,269	2,579	2,338	2,101	526	948	1,231	102

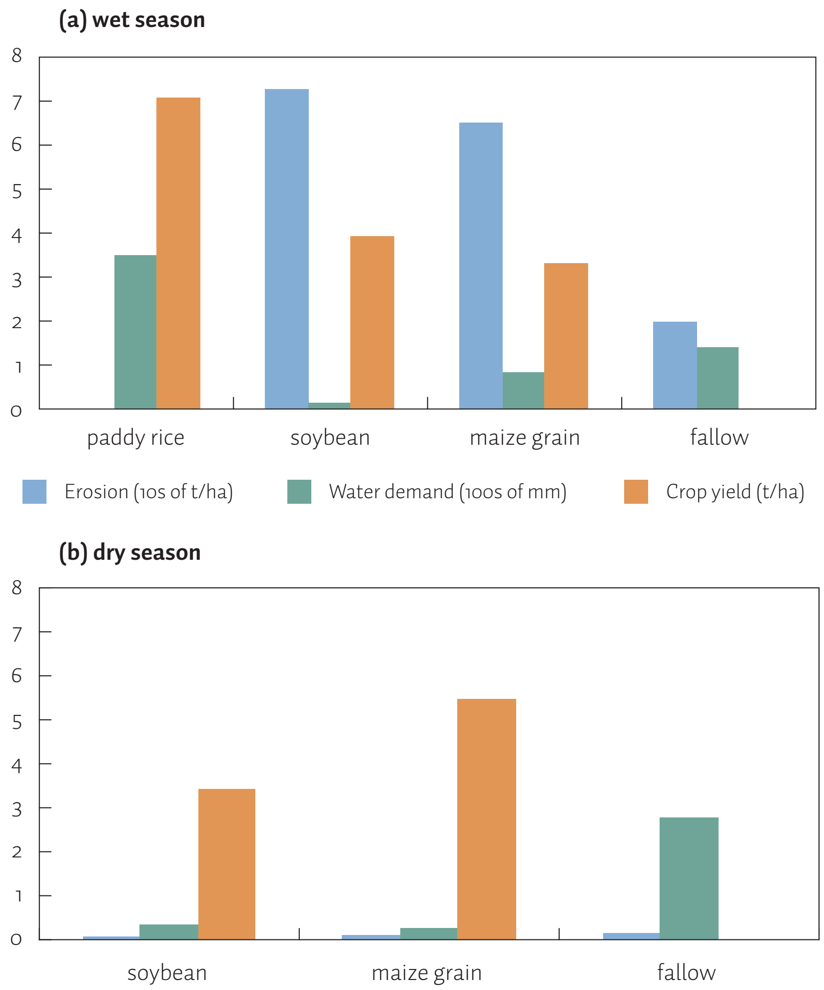


Figure 10.2 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: changes in yield, erosion rates, and water demand in the (a) wet and (b) dry seasons of the 1990–1991 hydrological year

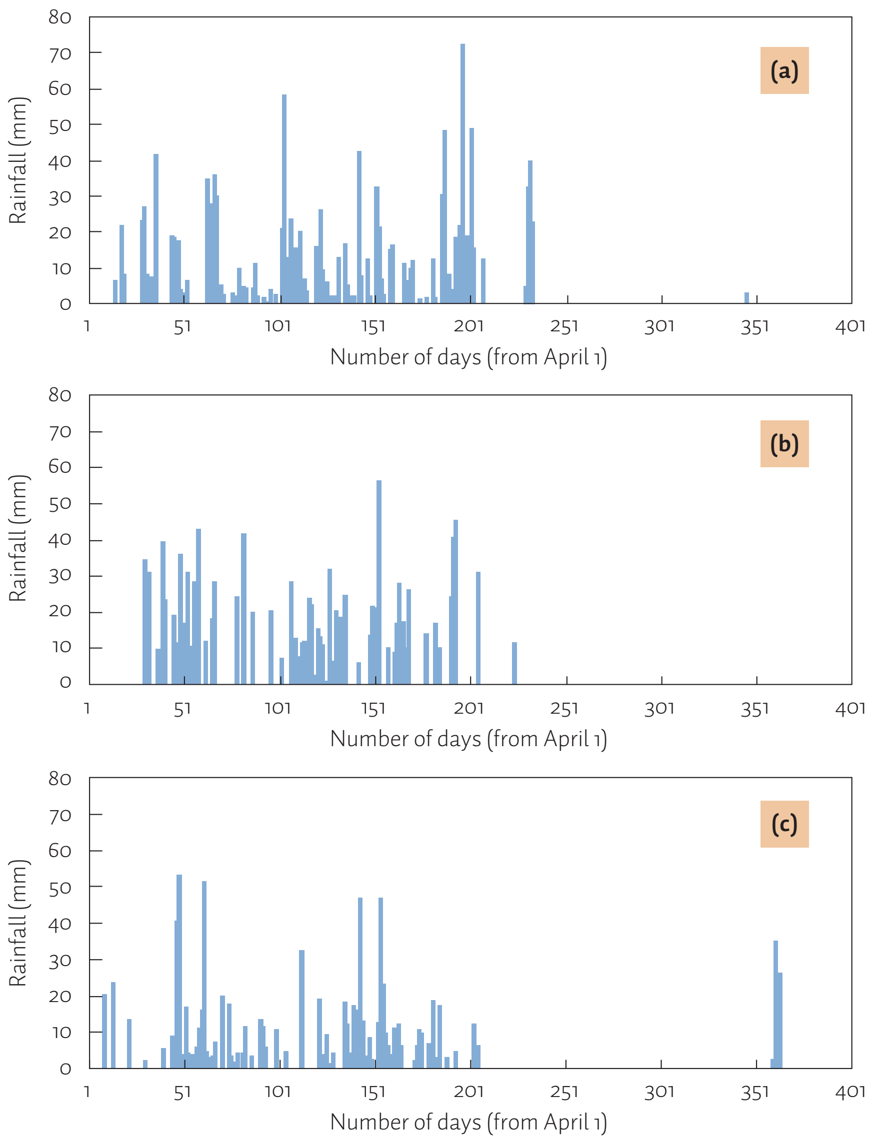


Figure 10.3 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: daily rainfall for the climate scenarios: (a) 1988–89, (b) 1990–91 and (c) 1993–94

Figure 10.4 illustrates the predicted wet- and dry-season erosion loads from the agricultural area in the upstream node of Mae Uam (node 1). The same three forest-cover-change scenarios are considered. Total erosion yields increase linearly with a change in forest cover. The wet seasons of the 1988–89 and 1990–91 years are similar in terms of precipitation, and this is reflected in similar erosion-load estimates.

The similarity between wet-season precipitation in the 1988–89 and 1990–91 hydrological years is further illustrated in Table 10.4. Here, the impact of climate scenarios on the mean erosion rates (t/ha) and average crop yields (t/ha) is shown. (Cropping patterns and land-management practices for each land unit are detailed in Table 10.1.) Table 10.4 illustrates the susceptibility of the upland land units (45, 47 and 49) to elevated levels

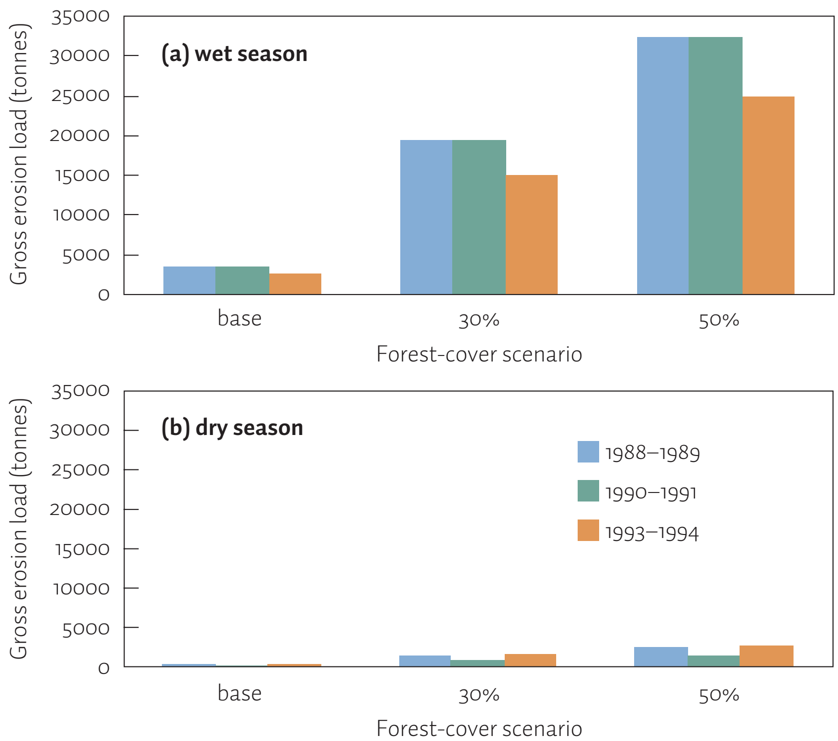


Figure 10.4 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: gross erosion loads (for wet and dry seasons) from agricultural land in node 1 under the 1988–89, 1990–91, and 1993–94 climate scenarios and 1990 forest cover (base), and 30% and 50% reduction in forest cover

of erosion under agricultural activities. On most of the land units, the only exception being land units 88 and 99, erosion rates are higher under most crops than under forest. For comparison, predicted erosion rates for forest with no bunds or land-management practices in the 1990–91 hydrological year are detailed in Table 10.4. The Land Development Department (LDD) uses a threshold of 5 tonnes per rai (31.25 t/ha) as an acceptable level under crops. This raises the possibility that many combinations of crops and management practices are likely to exceed this threshold. In particular, land unit 45—where soybean was grown with no management practices in place to mitigate soil erosion—is particularly prone to erosion. While the steep land unit 49 is highly susceptible to erosion, the management practice selected was strip cropping around contours—a practice that the model outputs suggest is sufficient to ensure that erosion rates are within the 'acceptable' rates of soil loss.

Deforestation scenarios

Scenarios of forest conversion that were tested ranged from the extreme cases of 30–50% deforestation across all land units, and removal of forest from steeply sloping land (on land unit 49), to the more-probable scenarios of removal of forest from the more-accessible land suitable for agriculture (e.g. land units 88 and 99). These scenarios are shown in Table 10.5. The absolute values for the erosion load, streamflow, residual streamflow, and crop water-demand indicators for the base forest-cover scenario are shown in Table 10.6. While node 1 land (upland) is more prone to erosion than the lower elevation land (node 2), only a small proportion of the steeper land units is cropped. This, combined with improved erosion mitigation factors on the steeper land units (e.g. bench terracing), explains the greater rates of erosion predicted for node 2.

Table 10.4 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: impacts of climate scenarios upon mean annual erosion rates (t/ha) and average yields for crops (t/ha) in node l (w = wet season, d = dry season)

Land unit no.	Erosion (t/ha) for forest (1990–91)	Erosion (t/ha)			Crop yields (t/ha)		
		1993–94	1988–89	1990–91	1993–94	1988–89	1990–91
45	0.203	37.3	48.4	48.3	2.0 (w) 1.7 (d)	2.0 (w) 1.7 (d)	2.0 (w) 1.9 (d)
47	0.253	33.2	43.0	43.0	3.1 (w) 2.0 (d)	3.3 (w) 2.0 (d)	3.0 (w) 2.4 (d)
49	0.253	19.1	24.8	24.8	1.9 (w) –	1.9 (w) –	1.9 (w) –
88	0.164	0.01	0.02	0.02	3.6 (w) 1.7 (d)	3.5 (w) 1.7 (d)	3.4 (w) 1.9 (d)
99	0.149	0.01	0.01	0.01	3.6 (w) 3.7 (d)	3.5 (w) 3.5 (d)	3.4 (w) 3.5 (d)

Figures 10.5–10.8 show the results for each of the deforestation scenarios, as a percentage of the base scenario for node 1.

With deforestation across all land units (Table 10.5) we see some extreme increases in the model's estimated gross annual erosion load. Node 1 has a high potential for erosion due to the high proportion of upland units, especially land unit 49, within its catchment area. While the results in Table 10.4 suggest that this land could be utilised with acceptable levels of erosion, it is highly dependent on the use of costly land-management practices. For this reason, it has been recommended that these areas should remain as natural forest. Despite more-intensive agriculture being assigned to other land units (see Table 10.1), their lower slopes counteract this effect. Hence, these other land units are less prone to erosion than land unit 49. Thus, fully utilising land units 88 and 99, which commonly support paddy agriculture, did not dramatically increase erosion because of their low areal extent and their flat topography (scenario 9 in Table 10.5 and Figures 10.5–10.8).

For all deforestation scenarios, there is a slight increase—up to 7.5% for scenario 5 (Figure 10.6)—in annual and wet-season streamflow at node 1 compared with the base forest-cover scenario. This reflects the structure of the hydrological model described in chapter 6, where it is assumed that forests evaporate at a greater rate than non-forest vegetation. More importantly, there is a marked decrease in dry-season streamflow of up to 15–20% (Figure 10.6). This is in response to the increase in rapid surface run-off during the wet season (quick flow) and reduction in deep percolation (slow flow) predicted under non-forest vegetation covers compared with forested land. For the more extreme deforestation scenarios (on the land units dominant in node 1), the large crop water-demand greatly increases the irrigation extractions, thus reducing the residual discharge (Figures 10.7 and 10.8).

Land-management scenarios

The biophysical models can be used to assist with land-use planning activities. The models can provide estimates for key indicators for each land-unit type and relate these back to thresholds to identify whether or not a crop or particular land use is suitable. This section looks at the changes in indicators under different crop and land-management combinations.

Table 10.5 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: forest conversion scenarios

Code	Description
sc1	Base 1990 forest conditions
sc2	30% decrease in forest cover on low sloping land units.
sc3	30% decrease on low to mid sloping land units
sc4	30% decrease on steeply sloping land units
sc5	30% decrease across all land units
sc6	50% decrease in forest cover on low sloping land units.
sc7	50% decrease on low to mid sloping land units
sc8	50% decrease on steeply sloping land units
sc9	0% forest on low sloping land units

Table 10.6 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: key biophysical indicators under the base forest-cover scenario and 1990 climate

	Erosion (t/ha)	Total streamflow (ML)	Residual streamflow (ML)	Crop water-demand (ML)
Node 1				
Wet season	43	10,725	10,378	589
Dry season	2.1	2,732	2,671	339
Annual	45	13,457	13,049	928
Node 2				
Wet season	74	14,563	14,043	646
Dry season	4	3,955	3,864	524
Annual	78	18,518	17,907	1,170

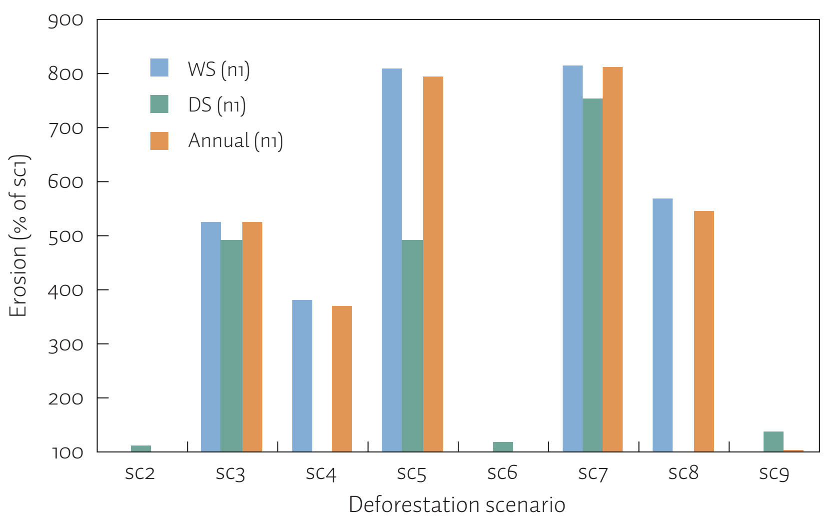


Figure 10.5 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: changes in erosion at node 1 for deforestation scenarios as a percentage of the base scenario (WS = wet season, DS = dry season)

The models were run for a range of combinations of land units, crops and land-management combinations (Table 10.7). The land-management options included fertility level, irrigation status and whether or not the plot is surrounded by bunds.

Crop yield

Figure 10.9 shows a plot of crop yields (in t/ha) for onion under the management combinations detailed in Table 10.7. Outputs are provided for the 1990–91 hydrological year. The fertility level of the plot has a greater impact on the model outputs than whether or not the crop is rainfed or bunded. When the fertility of a plot is low, the crop model predicts yields of about 15 t/ha, increasing to 20–22 t/ha for most combinations of medium fertility and 23–28 t/ha for high-fertility crops. The model outputs suggest that vegetable crops like onion are more suited to the low sloping and more clayey soils of land units 88, 99 and 45 than they are to the steeper land units (land units 47 and 49) if the crops are not irrigated. In this manner, the predicted response is plausible, as these land units will retain more moisture and allow the crop to meet more of its water requirements. If the crop's water requirements are met, then there is little difference between the yield on upland and lowland sites. This reflects the similarity in soil types of different land units (shallow loamy clays) and the parameterisation of the CATCHCROP model (see chapter 7).

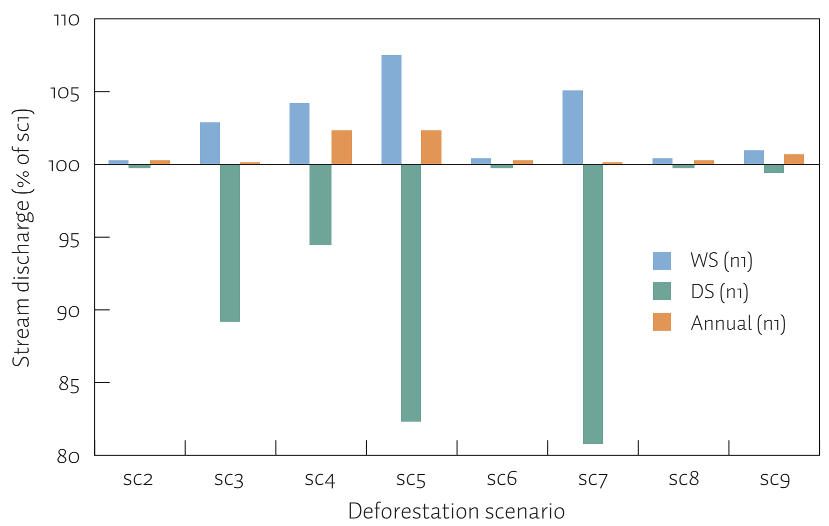


Figure 10.6 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: changes in streamflow at node 1 for deforestation scenarios as a percentage of the base scenario (WS = wet season, DS = dry season)

Erosion rates

Erosion predictions depend on both the cropping factor (*C*) and management factor (*P*) within the universal soil loss equation (USLE; see chapter 8). For crops that were grown in paddy fields with bunding, the *C* and *P* factors were greatly reduced. The flat surface of bunded plots ensures that there is negligible erosion on such lands, and the raised banks mean that little sediment leaves the plot. Erosion rates on bunded plots are thus low, regardless of the land-unit type, ranging from 0.015 t/ha on land units 88 and 99 to 0.023 t/ha in upland land units.

Figures 10.10 and 10.11 show plots of erosion rates under different crops and land covers for the wet season of 1990–91 for land unit 88 and land units 47 and 49. For most crops and management types on land units 88 and 99, the model suggests that erosion rates are not extreme. Estimates of erosion rates for paddy rice, maize, fruit trees, fallow and forest are generally within the LDD-prescribed threshold for erosion of 31.25 t/ha. In upland fields, most crops are prone to high rates of erosion. Only maize, fallow and forest cover-types yield less than the 'acceptable' level of erosion. Land units 47 and 49, in particular, have a high erosion potential. Under current government policy, land unit 49 is designated for

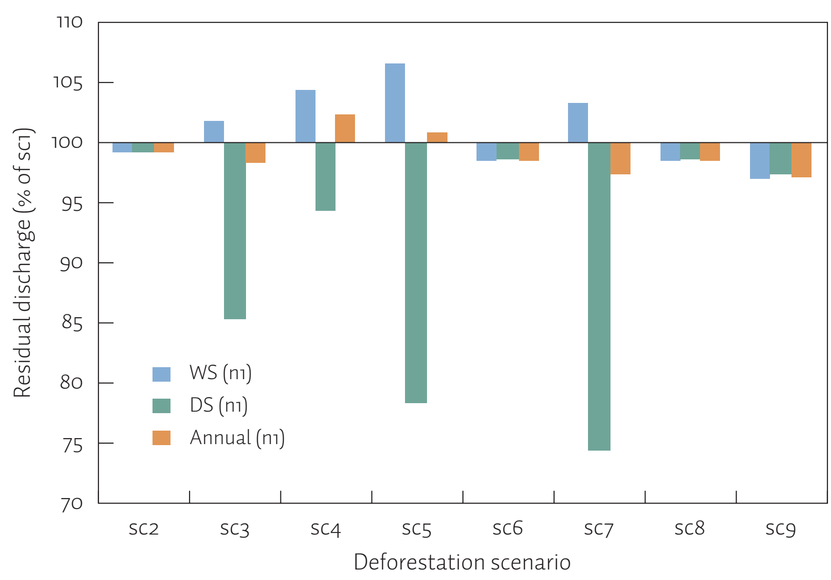


Figure 10.7 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: changes in residual streamflow at node 1 for deforestation scenarios as a percentage of the base scenario (WS = wet season, DS = dry season)

forest cover only. No differences in erosion rates are distinguished between land units 47 and 49, despite land unit 49 being generally much steeper, as the land units fall into the same slope category for defining the *P* factors for the USLE. In reality, it would be expected that considerably more erosion would occur on land unit 49 than on land unit 47.

Water balance and crop water-demand

Table 10.8 shows water-balance components and crop water-demand under paddy rice on land unit 88 in both the wet and dry seasons of the 1990–1991 hydrological year, under the land-management combinations shown in Table 10.7.

Actual evapotranspiration (ETA) is maximised under high-fertility, irrigated conditions. Under high-fertility conditions, crop water-demand is not sensitive to whether or not the plot is bunded. However, crops grown on low-fertility plots that are not bunded have a much higher water-demand than on equivalent bunded plots. The main difference between irrigated and non-irrigated crops is the deep drainage and the crop water-demand (DEM). Rainfed crops generally have a higher DEM than irrigated crops over the cropping season. In the CATCHCROP model, DEM is defined as the difference between ETA and the potential evapotranspiration (ETC) of a crop. For irrigated plots, the soil reservoir is

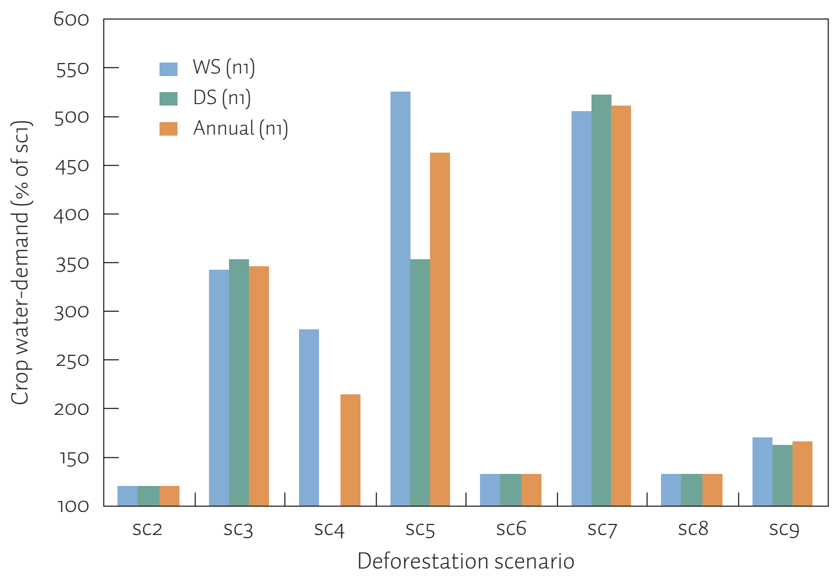


Figure 10.8 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: changes in crop water-demand at node 1 for deforestation scenarios as a percentage of the base scenario (WS = wet season, DS = dry season)

replenished at each time step, allowing ETA to approach ETC and reduce the DEM for that time step. Over the cropping season, this shows up as the difference between rainfed and irrigated crops. In the wet season, rainfall is sufficient to ensure that the crop can get most of the water it requires, such that ETA is not greatly reduced. Similar trends occur across all land units, although between crops there is a great deal of variation. Actual evapotranspiration is extremely low in rainfed crops, as crops are unable to get sufficient water to transpire, unlike crops under high-fertility, irrigated conditions. As with the wet season, under high-fertility (irrigated) conditions, crop water-demand is not as sensitive to whether or not the plot is bunded. Deep drainage is minimal, as most of the water that infiltrates into the soil is taken by the plants. Similar trends occur across all land units.

Table 10.7 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: combinations of land-management practices. The code refers to the land-management combinations in Figures 10.9 to 10.11.

Code	Fertility level	Irrigation status	Bunded
s1	low	Rainfed	no
s2	medium	Rainfed	no
s3	low	Rainfed	yes
s4	low	Irrigated	yes
s5	medium	Rainfed	yes
s6	medium	Irrigated	yes
s7	high	Rainfed	no
s8	high	Rainfed	yes
s9	high	Irrigated	yes

Discussion of biophysical case studies

The scenario runs for the Mae Uam sub-catchment highlight some of the trade-offs among indicators and raise questions about perceived impacts. For example, they suggest that while substantial conversions of forest to agricultural land do not impact greatly on the amount of water remaining in the stream, the potential erosion increases are extreme. Even though the USLE methodology applied in the toolbox provides only coarse estimates of gross erosion, it is reasonable to expect that the elevated rates of erosion would translate to increased sedimentation in the catchment's water resources.

Reported water shortages within the lowland regions of catchments in northern Thailand have been attributed to increased agricultural activities in the upland areas. This extreme case was not shown in the model outputs for the scenarios performed within this paper. The deforestation scenarios applied to node 1 of the Mae Uam catchment, where the forest is replaced by crops in the same proportion as used in the base scenario, did not increase crop water-demand to an extent that threatened water availability to agricultural areas in node 2. This is the result even when the agricultural area, and hence crop water-demand, is increased within node 2. However, not all the land that was converted from forest was utilised in either the wet or dry seasons. Only 10% of the agricultural area of land units 23, 25, 45, and 47 was cropped in the dry season, while on land unit 49 no land was cropped. Likewise, 25% of the agricultural area of land units 23, 25, 45 and 47 and 15% of land unit 49 was cropped. Utilising a larger proportion of agricultural land in the upland land units would substantially increase abstractions during the dry season and may place water resources under further pressure.

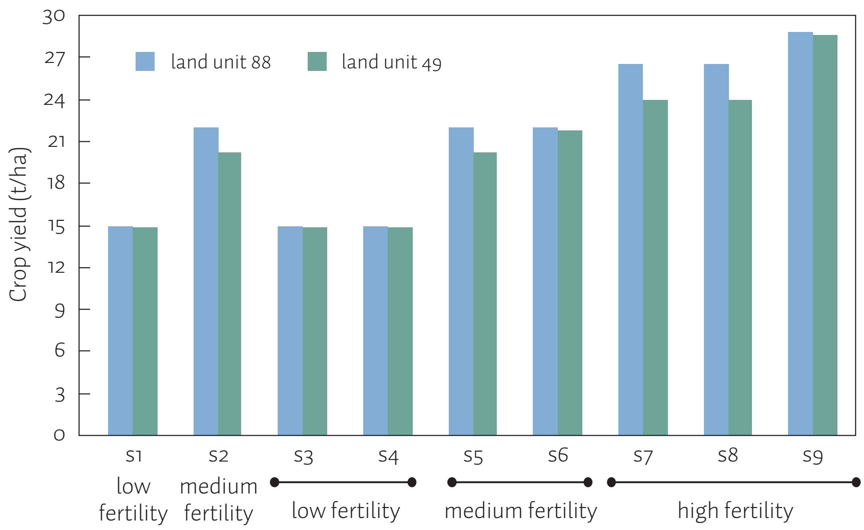


Figure 10.9 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: plot of crop yields (t/ha) for onion under varying land-management combinations. All model parameters are kept constant.

It is expected that application of the toolbox in more-intensively used catchments with greater competition and demand for water resources would produce effects like those reported in the lowland areas of this region. In such regions, where more land suitable for intensive agriculture is available, increased cropping and hence demand for water may place water resources at risk. In the Mae Uam sub-catchment, the amount of land suitable for cropping is restricted by topography. Much of the land suitable for paddy has already been utilised, and much of the remaining catchment is nominally protected as it has been designated as watershed classification 1A.

Running all combinations of land-management options provides an understanding of the model responses to changes in inputs, particularly with respect to the outputs of the CATCHCROP model. The model outputs suggest that, in the wet season, the fertility of the plot influences yield more strongly than whether or not the plot is irrigated or bunded. In the dry season, irrigation becomes significant. Most crops fail completely and produce no yields unless they are irrigated. In the field, many plots during the dry season are not utilised because transporting water to them is not practical.

Erosion rates were shown to be particularly high for upland rice and vegetable crops compared with other vegetation or cover types. The outputs suggest that forest and fallow covers fall within the LDD-defined threshold of 31.25 t/ha on all land units, while covers like maize and fruit trees tend to fall within 'acceptable' soil loss under most management types. Upland rice and vegetable crops are generally suitable under the more-advanced management practices such as bench terracing on low-sloping land, although are susceptible to 'unacceptable' erosion rates on steeply sloping lands, unless highly effective erosion-mitigation practices are implemented.

Although considerable effort has been made to keep the biophysical models relatively simple in terms of the structure and number of model parameters, the biophysical framework as a whole is reasonably complex and the interactions between the models—particularly the crop and hydrology model—can be quite non-linear. Merritt et al. (2002) assess the sensitivities of model outputs to perturbations in parameter values and the underlying assumptions.

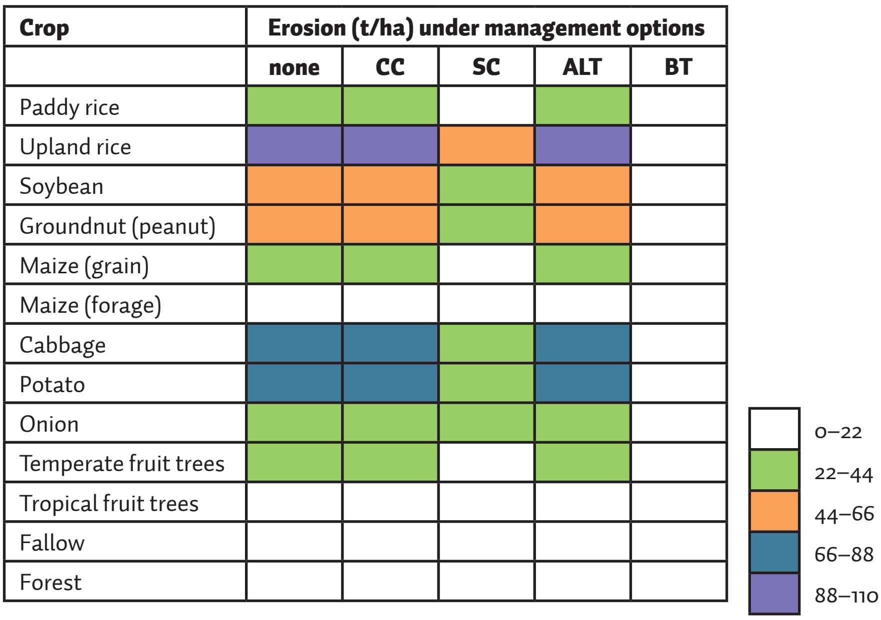


Figure 10.10 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: erosion rates (t/ha) on land unit 88 under available management options for 13 crop or land cover types on low-sloping land units suitable for paddy agriculture (BT = bench terrace, ALT = 'arable' land terrace, SC = strip cropping around contours, CC = contour cultivation)

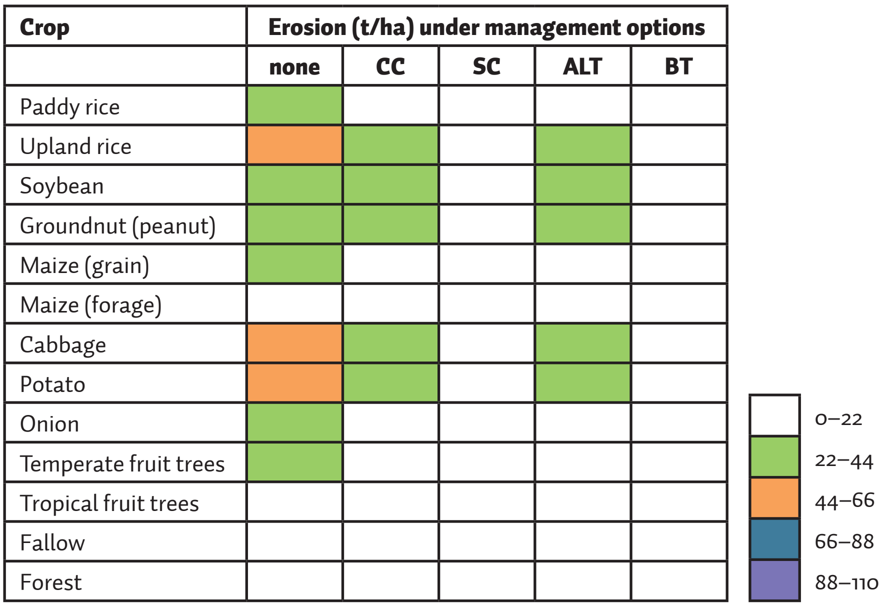


Figure 10.11 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: erosion rates (t/ha) on land units 47 and 49 under available management options for 13 crop or land-cover types on low-sloping land units suitable for paddy agriculture (BT = bench terrace, ALT = 'arable' land terrace, SC = strip cropping around contours, CC = contour cultivation)

Integrating the biophysical and socioeconomic models

The IWRAM DSS can also be employed to assess the socioeconomic trade-offs of a wide range of management and development scenarios. Instead of the user defining the land-use scenarios (as in the stand-alone application of the biophysical models presented above), the land use is passed on to the biophysical models from an economic decision model. This decision model simulates the choice of crops to be grown in a particular season, and on a particular land unit, in response to expected constraints on land, water and labour availability as well as to changes in prices, costs and expected yields. The subsequent results from the biophysical models are then fed back into another socio-economic model that estimates 'socioeconomic performance' for that particular scenario. This framework, depicted in Figure 9.2, provides an integrated assessment of the biophysical and socioeconomic impacts of a particular scenario.

The socioeconomic models currently incorporated in the IWRAM DSS include a household decision model, a decision disaggregation model (DDM), and a socioeconomic impact simulation model (SISM), all of which are described in chapter 5.

It is assumed that agricultural production (or crop choice) decisions take place at the household scale. These household decisions, including remaining forest cover, are then aggregated for each land unit within a node along the river and passed as an input to the biophysical models. The hydrologic model calculates the pre-extraction flow at each river node on a daily time step for the year, given the rainfall and temperature. This flow is sensitive to changes in forest cover. The crop model then runs for each land unit and crop combination defined by the land-use decisions for the node. The water demand is calculated by the crop model on a seven-day time step. A water-allocation model, containing a crop prioritisation list defined by catchment stakeholders, is used to determine the order in which crops are able to access the available water for irrigation. Crop demands are sequentially compared with the remaining quantity of water available for extraction. Yield penalties occur for crops that do not receive sufficient water.

The erosion model is also run to calculate wet- and dry-season erosion, given the crop choice and climatic conditions. The actual water available is then calculated and is used to update households' expectations of water availability for the next year in the household decision models. Actual yields are passed to SISM to consider the impact of actual water

Table 10.8 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: wet- and dry-season crop water-demand (DEM), irrigation (IR), actual evapotranspiration (ETA), deep drainage (DD) and crop yields for paddy rice on land unit 88 for the 1990 hydrological year

Crop	DEM (mm)	IR (mm)	ETA (mm)	DD (mm)	Yield (t/ha)
Wet season					
s1	443	0	397	0	1.80
s2	707	0	471	0	2.34
s3	308	0	472	530	2.17
s4	286	286	489	799	2.29
s5	510	0	623	378	3.28
s6	456	456	658	799	3.54
s7	698	0	729	272	4.06
s8	698	0	729	272	4.06
s9	617	617	820	799	4.73
Dry season					
s1	834	0	34	0	0.00
s2	862	0	34	0	0.00
s3	834	0	34	0	0.00
s4	328	328	294	0	1.99
s5	862	0	34	0	0.00
s6	472	472	438	0	3.46
s7	870	0	34	0	0.00
s8	870	0	34	0	0.00
s9	606	606	572	0	4.82

availability on household performance and, in particular, on total rice production per person, which is considered to be a social indicator of the impact of a scenario option.

The socioeconomic indicators are given by RMU (resource management unit—see chapter 5 for a description) and by node. They allow changes in the social and economic 'performance' of a household, due to different climatic and upstream land-use-choice scenarios, to be investigated and potentially traded-off. Where a multi-year scenario is run, a time-series chart of the output is provided. Tables of values are also given for all scenario runs. The procedure yields the following socioeconomic indicators:

1. Cash per household (baht). This indicator describes the 'economic performance' of households of each RMU type.
2. Total household income from agriculture (baht). This indicator describes the agricultural income from their land-use choices.
3. Off-farm (household) income (baht). This indicator shows the reliance of different households on off-farm income.
4. Hire cost (baht). This indicator shows the total wages paid per household to hired labour in each year. It shows the extent to which production relies on hired labour.
5. Rice production per person (kg). It is assumed that each person in a household requires 300 kg of rice per year to survive. This indicator shows how close households come to meeting their subsistence requirements. Most households strongly prefer to produce their own rice.
6. Cost of rice deficit (baht). This indicator shows the cost to the household of purchasing unmet rice requirements.

Socioeconomic case studies

This section provides a brief description of two scenarios for which the socioeconomic models of the IWRAM DSS are used. They demonstrate the types of environmental and socioeconomic trade-offs that can be calculated. The scenarios (for the Mae Uam sub-catchment) show the effects of agricultural expansion (and hence clearing of forest) leading to increases in the land available to individual households as summarised in Table 10.9. The model was run over five years using climate data from 1989 to 1993. Results for nodes 1 (upstream) and 2 (downstream) are shown.

Results for nodes 1 and 2 from the two scenarios are shown in Figures 10.12–10.15.

These figures demonstrate the trade-offs associated with increasing the amount of land available to households. Households of RMU2 receive a very small benefit (i.e. increase in household cash) from this increase in available land. These households are more constrained by their restricted access to other resources (water and labour) than to land and so are not able to receive large benefits from this increase in the area available. Households of both RMU3 and RMU8 have access to rainfed fields and benefit to a much greater extent than those of RMU2. In some years, the household income within these RMUs more than doubles under these scenarios. Also, these households have a small rice deficit under the base-case assumptions. Increases in land lead to the removal of this rice deficit. This means that increasing the land area available to these households helps them meet their subsistence requirements and increases their cash wealth.

Table 10.9 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: scenario input assumptions by three types of resource-management unit (RMU) (areas in hectares)

	Base case		Scenario 1		Scenario 2	
	Paddy	Upland	Paddy	Upland	Paddy	Upland
Node 1						
RMU 2	0.4	0	0.496	0	0.592	0
RMU 3	0	0.336	0	1.6	0	2.864
RMU 8	0.432	0.208	0.544	0.992	0.64	1.776
Node 2						
RMU 2	0.496	0	0.56	0	0.624	0
RMU 3	0	0.4	0	0.912	0	1.424
RMU 8	0.368	0.192	0.416	0.432	0.464	0.688

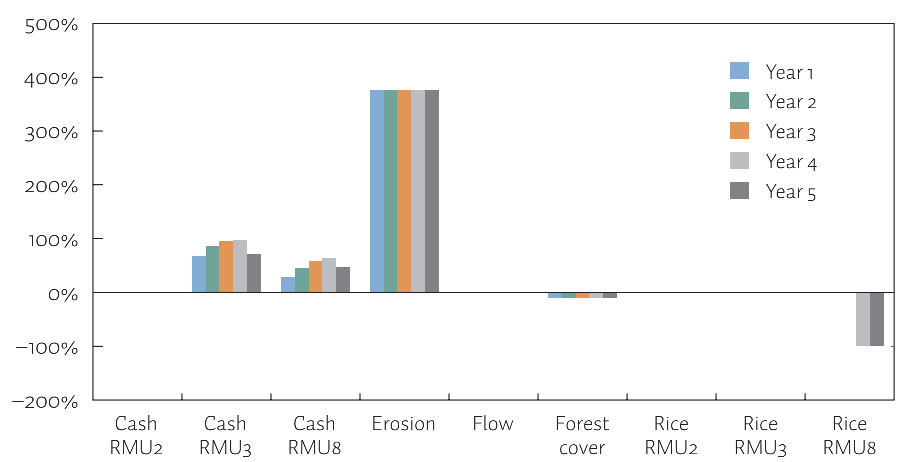


Figure 10.12 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: change in indicator values from base case, scenario 1, node 1

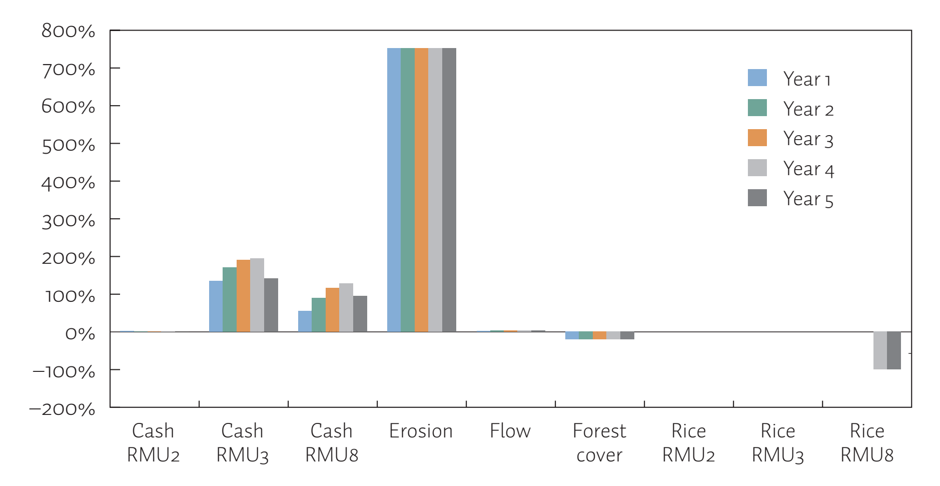


Figure 10.13 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: change in indicator values from base case, scenario 2, node 1

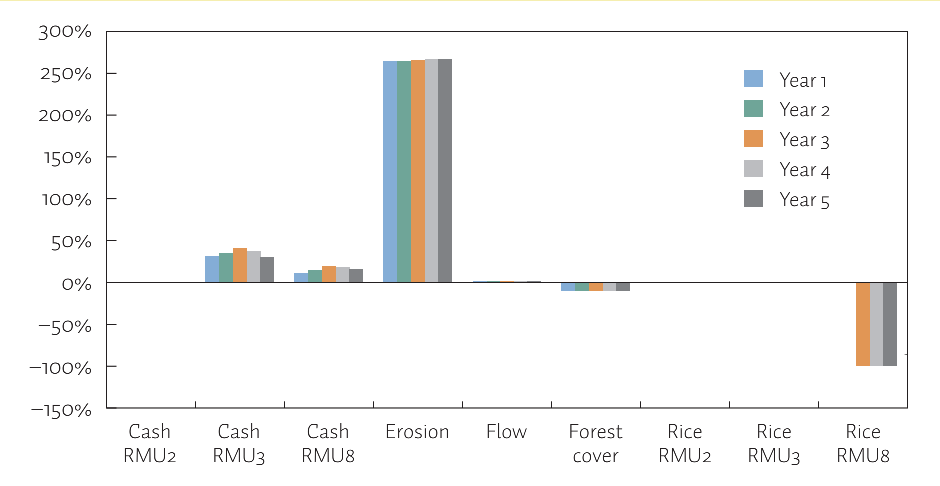


Figure 10.14 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: change in indicator values from base case, scenario 1, node 2

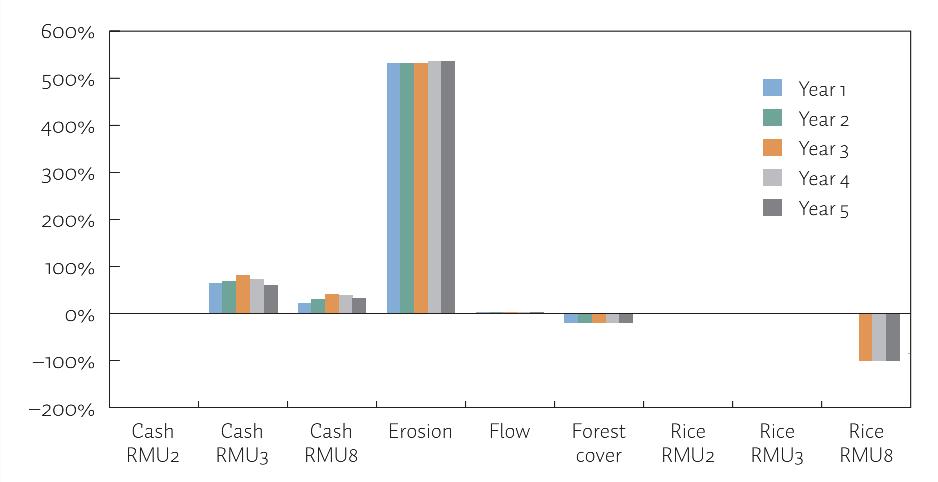


Figure 10.15 Application of the Integrated Water Resource and Management (IWRAM) decision-support system in case studies in the Mae Uam sub-catchment of the Mae Chaem catchment, northern Thailand: change in indicator values from base case, scenario 2, node 2

Nevertheless, as can be seen in Figures 10.12–10.15, these economic and social benefits are at the expense of higher environmental impacts. Relatively small increases in flow are experienced at both nodes. This implies that the increase in flow resulting from a decrease in the area of forest cover is greater than the additional extraction occurring across the year. This relates to the way in which changes in forest cover can affect flow: a decrease in forest cover increases wet-season flows, increasing overall annual flows, but decreases dry-season flows which are used for irrigation. Thus, flow increases annually but less water is available for extraction in the periods when it is most required. Agricultural expansion also leads to large increases in erosion, and to substantial areas of the remaining forest cover being lost.

As would be expected, both costs and benefits are greater when larger areas of agricultural expansion occur. But the relative impacts are not proportional to the level of change in forest area in all cases. The change—from the base case—in household cash at RMU2 is less than proportional to the change in forest cover. This is the case at both nodes, but the effect is more pronounced at node 1, possibly because flows are smaller at this upstream node. The increase in flows is also less than proportional to the change in forest cover in most years for both nodes. The change in household cash is more than proportional to the change in forest cover. The relative impacts of both scenarios are the same across all years, and show the same pattern for both nodes.

Discussion of socioeconomic case studies

The case studies presented here illustrate the types of scenarios and trade-offs that can be considered by the IWRAM DSS. While the application presented is specific to the Mae Uam sub-catchment in northern Thailand, the modelling approach is more generally applicable.

A key difference between this approach and previously developed integrated models is the use of uncertain expectations as the basis for household decision-making. The socioeconomic models within the IWRAM DSS assume rather naive expectations; that is, that farmers expect this year's water availability to be the same as that of last year. However, the model framework means that it is relatively simple to assume different forms of, or complexity in, expectations, so the effects of these assumptions could be tested in future work.

A related issue is the treatment of household cash as temporally independent; that is, the assumption that cash does not carry over between years, or affect the decisions of households in future years. This assumption relates to the short-run nature of decision-making, and is of less importance given that 'longer-term' crop-planting decisions, such as horticultural crops or decisions not returning income in the current year, are not currently considered by the socioeconomic models. Modification of the approach to consider the constraints presented by available cash or credit, and longer-term planting or investment decisions would be an interesting and relevant future development path for the model.

Another key issue when considering the robustness of the approach used in the IWRAM DSS, is the sensitivity of the 'qualitative result' or recommendation to climate and uncertainty in parameter values. The scenarios demonstrated in this chapter give a similar pattern of impacts, with the direction and approximate magnitude of change of indicators being consistent across nodes and scenarios. Further testing of the model's sensitivity to changes in parameter values has been undertaken by Letcher et al. (2005). Overall, the model appears to provide consistent recommendations, regardless of climate or small levels of uncertainty in parameter values.

Finally, the integrated model developed is balanced in terms of the complexity of each of the disciplinary components represented. Each component model runs on an appropriate 'lumped' or disaggregated spatial scale. Temporal scales vary between models, but essentially correspond to the largest temporal scale appropriate. For example, household decisions and erosion are simulated seasonally (twice yearly), while crop and flow models run over smaller time scales to allow meaningful comparison of water availability and demand. The style and detail of process representation for each of the components are also similar.

Conclusions

This chapter has demonstrated how the IWRAM DSS can assist with the planning of integrated land and water management, by presenting a set of case studies for the Mae Uam sub-catchment (within the Mae Chaem catchment) in northern Thailand.

The first set of case studies applied the biophysical models to a set of scenarios that considered forest conversion, land management and changes in climate. These case studies demonstrated the potential of the IWRAM DSS to explore the environmental effects of various land- and water-management options. In the second set of case studies, the full set of biophysical and socioeconomic models within the IWRAM DSS was employed to assess both the socioeconomic and environmental trade-offs associated with increasing the area of land available for agricultural production (and hence reduced forest cover).

Currently, the IWRAM DSS includes model components that address the key issues at play within catchments in northern Thailand. Future work will need to extend the applicability of the tool in other catchments across Thailand and globally. Inclusion of models that address additional issues within the catchment are foreseen, including groundwater extraction, water extraction for urban and industrial use, more-intensive land use for agricultural production, and stream regulation.

Although considerable effort has been made to keep the models within the IWRAM DSS relatively simple in terms of the structure and number of model parameters, the integrated framework as a whole is still reasonably complex and the interactions between the models can be quite non-linear.

The aim with integrated models of this type should not be to provide absolutely accurate estimates, a task rendered too difficult by the inherent complexity of natural systems and the scant data often available. The focus should be on being able to discriminate between, and be confident about, the relative changes in indicator output sets. The analysis reported in this chapter is a step in this direction. Ultimately, a methodology is needed which will also provide the level of confidence in the results.

References

Letcher, R.A., Merritt, W.S., Jakeman, A.J. and Croke, B.F. 2005. An integrated modelling toolbox for water resources assessment and management in highland catchments in Northern Thailand: model description, Agricultural Systems, in press.

Merrit, W.S., Croke, B.F.W. and Jakeman, A.J. 2002. Sensitivity testing of a biophysical toolbox for exploring water resources utilisation and management options. In: Proceedings of the first biennial meeting of the International Environmental Modelling and Software Society (iEMSs), Lugano, Switzerland, 24–27 June 2002, 1, 311–316.

Merritt, W.S., Croke, B.F.W., Jakeman, A.J., Letcher, R.A. and Perez, P. 2004. A biophysical toolbox for assessment and management of land and water resources in rural catchments in northern Thailand. Ecological Modelling, 171, 279–300.

Scoccimarro, M., Walker, A., Dietrich, C., Schreider, S. Yu., Jakeman, A.J. and Ross, H. 1999. A framework for integrated catchment assessment in northern Thailand. Environmental Modelling and Software, 14, 567–577.

Improving integrated assessment approaches

Lessons from the Integrated Water Resources Assessment and Management project experience

ANTHONY JAKEMAN, SANTHAD ROGANASOONTHON, REBECCA LETCHER AND ANTHONY SCOTT

SUMMARY

THE Integrated Water Resources and Management (IWRAM) project was an innovative attempt to use an integrated-assessment approach to understand the trade-offs involved with managing river systems in northern Thailand. When the project commenced, the science of integrated assessment was in its infancy, with new methods and approaches being developed by diverse groups internationally and little formal structure or method to fall back on. In particular, the challenges of working across the Thai and Australian cultures, in a developing country setting, had not been faced or documented previously. The IWRAM project therefore needed to develop its own approach to dealing with

the complex management and communication issues involved in working across a broad river-basin management setting in the north of Thailand. The experience of the IWRAM partnership in managing these issues, and the difficulties faced by the team in implementing such a challenging approach to science in this setting, provide a valuable lesson for future research and management exercises in Thailand and elsewhere. This chapter outlines the lessons learnt through the IWRAM project and outlines the likely future directions of the project and approaches developed.

Introduction

With rapid intensification of agricultural catchments in northern Thailand, a suite of environmental issues has surfaced. These include upstream–downstream conflicts over water availability, increased erosion and contamination of waterways, and an increase in the production of cash crops changing the pattern of cropping and fallows. In addition, there is a need for poverty alleviation. The Integrated Water Resources and Management (IWRAM) project was instigated in response to these issues. The project developed a decision-support system (DSS) for the exploration of biophysical and socioeconomic trade-offs of water- and land-resource use and management options. Initially, the focus of the project was on the development of an integrative framework that was captured in the form of a DSS. This was followed by the development of the various biophysical and socioeconomic models and their verification. The final stage of the project involved the application of the DSS to demonstrate its utility. This product of the IWRAM partnership is now being adopted more widely throughout Thailand to evaluate land- and water-use options and support related decisions.

Inevitably, as with any emerging technology, there were many unforeseen problems that had to be solved during the course of the project, and the need to add or modify model components, and/or general approaches, to ensure that the integrated package met the needs of the users.

There were many lessons learnt during this project and the aim of this chapter is to present the key lessons, in the hope that these will assist similar projects in the future. This follows the principles of adaptive management, which aim to 'increase our understanding of systems through active participation and learning, evolving experimentation, reviewing and responding' (Lee 1999).

The second part of this chapter will provide some insights into the future of the IWRAM project methods, and also the future of integrated water-resources assessment in general.

Technical lessons

Lack of field data

In catchment- or regional-scale studies, the issue of data availability becomes of utmost importance. Problems of data availability are exacerbated in developing countries, where detailed information for supporting complex models is less-often collected. Although Thailand is comparatively well supplied in environmental and agricultural data, they are seldom sufficient to cover the complex sets of variables demanded by many of the existing models of biophysical and agricultural processes. Many of the data needed to run these models are very specific and might only be collected at a few experimental sites, but are generally not collected during land surveys.

Finding out what data exist, and gaining access to the data (especially in digital form), proved highly time-consuming and required that considerable effort be invested in building relationships with the organisations that hold the information. For integrated catchment management, there was the additional requirement that biophysical, economic and social data be available for the same places, at least for the development of the models. When developed, they may often be extrapolated to places where data are less complete. In choosing the Mae Chaem and a set of its sub-catchments for study, the original members of the Thai research team took into account access to existing biophysical and socioeconomic data. They recognised that most sub-catchments lacked streamflow gauges, making the hydrological modelling task difficult. Similar problems existed for the crop and erosion models.

In the socioeconomic field, published data were highly aggregated, providing information such as the total area under each crop, or the populations of villages. Although useful, these data did not provide a picture of individual households, how they lived or the constraints they faced in making decisions. There were also very few data on some household activities such as the gathering of forest products, which literature and qualitative information have shown to make important contributions to the livelihoods of some communities. Aggregated data do not provide sufficient basis for assessing current, let alone potential, resource-use behaviour. While we were able to conduct our own surveys, albeit with some logistical difficulties, the need for primary socioeconomic data will continue to be a significant requirement when extending our DSS to other catchments. Integrated water resources management (IWRM) will ultimately need alternatives to such powerful socioeconomic models that are less reliant on detailed primary data, so that 'scaling up' to large basins such as the Chao Phraya or Mekong can be successfully achieved. There is also scope for the creative use of existing data and, over the long term, tailoring government and academic data collection to serve IWRM needs more effectively. Finally, it is important to link socioeconomic data with biophysical data. One simple but effective method is to take global positioning system readings at all sites where any type of data is collected.

Robust, simple models

One implication of the lack of suitable data-sets is that the models we, or other teams, develop need to be robust and relatively simple. In many cases, it will not be possible, or desirable, to develop complex mechanistic models that require large amounts of field data for calibration and validation. However, it should not be assumed that the use of less-complex models will necessarily reduce the accuracy or usefulness of predictions. For example, many of the simpler catchment models perform as well as, or at least are not substantially outperformed by, more complex models (Loague and Freeze 1985). Jakeman and Hornberger (1993) confirm this result for different levels of complexity in conceptual hydrologic models, as have many other authors, including Kokkonen and Jakeman (2001) and Perrin et al. (2001). Perrin et al. (2001) note that:

> ...simple catchment models that lump catchment heterogeneities and represent the transformation of precipitation into streamflow, conceptually or empirically, are generally easy to use tools with low data requirements. In spite of the crude approximations resulting from their lumped and simple structure, such models have proved efficient in many studies.

They concluded this from an assessment of 19 daily lumped rainfall–run-off models of 429 catchments in France, the United States, Australia, the Ivory Coast and Brazil. If only limited catchment data are available, such as lumped daily rainfall and evaporation, then it seems unnecessary to develop spatially explicit and complex model structures (Wooldridge et al. 2001).

It is also not worth spending large amounts of time on one particular model, particularly if another model within the integrated framework is highly simplified or considerably less advanced. The overall results can only be as good as the weakest link (or model) of the integrated system. It is more important to get the overall framework and key linkages between models correct. More detailed models can then be developed and incorporated over time.

Issues of scale

Natural systems, from plot to catchment scale, tend to show a great deal of variation, both temporally and spatially. Selection of scales for the different models and model components of an integrated assessment (IA) problem is one of the key considerations at the beginning of any new project. The scale selected should be fine enough to capture the required level of variability of system response but not finer than is warranted by the availability and quality of corresponding input data and other model calibration data—a trade-off between model sensitivity to inputs and model parameter uncertainty.

There can also be vast differences in the scale at which different biophysical or socioeconomic models operate. Batchelor et al. (1998) identify potential social and biophysical forces that drive a hydrologic system, which range in scale dependency from a few hectares (farm water use, soil type, vegetation distribution) to the regional or national scale (e.g. commodity prices, infrastructure development, government policies).

Whenever possible, it is advisable to choose scales that are complementary. This becomes even more important when the outputs of one model are used as inputs to another. For instance, it may not be necessary to run an erosion model at the plot scale if the associated hydrologic model operates at only the catchment level.

The issues and problems associated with scale are clearly demonstrated by considering the modelling of agricultural systems at a catchment scale. Easterling (1996) states that it is unlikely that crop models will ever be capable of accurately simulating crop growth at a resolution of hundreds of kilometres because they are designed to simulate growth processes of a single plant or across a hectare. Other scaled-related issues that need to be overcome before successfully modelling agricultural systems for an entire catchment or region, can be summarised as follows:

- the large number of crops that are grown within a catchment, often in small paddocks owned by individual farmers
- the wide variations in biophysical properties across the catchment, such as soil types, soil moisture, and slope, all of which affect the type of crop grown in a particular paddock
- the different types of cropping systems within the catchment
- distribution of water within the catchment and the amount available for irrigation of crops.

The diversity of the cropping systems and the average plot area are two of the key constraints for modelling crop productivity and water use in many catchments. For instance, a survey undertaken in small sub-catchments of the Mae Chaem has recorded approximately 60 crops grown (IWRAM project survey undertaken in 1997). Realistically, it would not be possible to model every crop. Some simplification of the system was necessary. Three options exist for predicting broad-scale crop yield in such a situation:

- consider only the major crops and use a specific crop model for each
- combine similar crops into a representative simulated crop
- use a conceptual, generic crop model.

Ultimately, the selection of model type and scale will depend on the type of model outputs required by catchment managers and policy-makers, whether it be farm-level or catchment-wide data. This is true also for the temporal scale. There might be no need for a complex hydrologic model with daily time steps, if a simpler lumped parameter model with monthly time steps provides the necessary outputs required by other models (such as the crop model and erosion model) and by decision-makers.

Integration between models

As the name suggests, IA requires a number of joint biophysical and socioeconomic disciplinary assessments. The development of integrated models requires that feedbacks and linkages between models be accurately portrayed. This can be very complex. Many existing biophysical models have not been developed with this in mind. There can be conflicting structures and flow paths between disciplines, particularly when attempting to link biophysical models to socioeconomic models. For instance, the IWRAM biophysical models required inputs describing land use and water use in the catchment. These are partly determined by the decisions and outputs stemming from the socio-economic module. Consequently, this required a conscious effort to ensure compatibility with socioeconomic factors during the development of the biophysical modules.

Parson (1996) recommends that IA should highlight broad links, and suggests that, to achieve this, simple representations should be implemented over more-detailed—and possibly more physically correct—representations. In summary, it is critical to keep the level of integration of issues and disciplines at a manageable level. It should also be noted that the main function of IA modelling is to discriminate between different scenarios by providing the relative changes in key outputs, and not necessarily provide absolutely accurate values.

Propagation of model uncertainty and errors

The variation and complexity of natural systems, a lack of high-quality field data and the simplifying assumptions of both the mathematical models and their linkages, all tend to create a relatively high degree of uncertainty in the results of IA modelling. Uncertainty also tends to accumulate as simulations progress sequentially—as outputs of one model are used as inputs to another.

There is very little technology that has been directed towards assessing uncertainty of integrated models and their outputs. If reliable conclusions are to be drawn from complex models, a key task is to assess the sensitivity of outputs to uncertainty in input data, calibrated model parameters and the model structure and assumptions. A new approach (Norton et al. 2003) currently being investigated by the Australian National University entails use of a sensitivity analysis to explore the feasible set of parameter values, input data and model structures, so as to provide a specified range of output behaviour. The output behaviour is defined as a set characterised by a collection of constraints on realistic, acceptable behaviour or the boundaries of behaviour leading to a given qualitative solution. The focus on sets removes the need to assume linearity between cause and effect, continuity of the output or a quantification of the output. The new approach will be adaptive, combining searches, Monte Carlo trials and feature extraction by descriptive multivariate analysis.

Modelling the long leads and lags of environmental systems

A challenge for the future is to develop models that sufficiently represent the long lag times associated with some aspects of environmental systems. A simple example would be the planting of trees within a catchment where the benefits (and impacts) might not be felt for many decades. Very few models accurately represent these lag times, and this poses a challenge for future modellers.

Specialists must be flexible

The ultimate success and lessons leant through an IA modelling project will depend critically on the personalities and aims of those involved in the project. One key requirement is that the parties involved are able to respect and acknowledge the contribution from other disciplinary components. During some of our early experiences in the IWRAM project, we found that different disciplinary teams were often too tied to their own software or modelling concepts, and ended up developing their own independent modelling systems which displayed their prior ideas largely without change. In these cases, many of the participants did not want to compromise or to use the knowledge of the other teams so that a truly interdisciplinary framework could be developed. Where these problems can be overcome, the project value can be much greater than the sum of its parts. Integration is not just about linking different components models. It should also enhance participants' understanding of the interactions between system components, and increase awareness of how the impacts and effects stemming from each disciplinary model can affect the overall outcome.

Lessons about communication and adoption

Different modelling approaches for different purposes

During the IWRAM project, three different DSS were developed. Although the three DSS had the same basic framework, they each had a different level of complexity and were aimed at different audiences and applications. The different approaches also reflected the adaptive nature of the project. The phase 1 DSS was developed by the Australian researchers and had a relatively high level of complexity. This DSS was more suitable for research work, specifically for developing integrative frameworks and understanding the requirements of the problem, rather than for catchment planning at a local or regional level. There were also ownership issues where the Australian models and framework were readily accepted by the Australian researchers but not by the Thai project team. This problem was resolved when the Thai project team used the same framework to build their own DSS. The third version was a simplified DSS developed in Microsoft® Excel for training purposes. This version was very easy to use, and allowed training in the underlying principles of each model and how they interacted with each other within the integrated framework.

Although it might seem inefficient to develop three DSS, each had a different purpose and all of them played key roles during the development of the project. Most importantly, the DSS developed by the Thai project team has reinforced a strong feeling of ownership, and this has paved the way for increasing adoption of IA principles in Thailand.

Constraints with inter-agency communication and decision-making processes

Our experiences in promoting integrative environmental analysis, and our Thai team's experience in coordinating a diverse set of academic and public-service contributors, has given some insights into the demands on current institutional processes in adopting an integrated management approach. We were well aware before commencing the IWRAM study of constraints on inter-agency decision-making processes in Thailand, despite much goodwill to overcome communication and co-ordination problems. The structure of district offices, in which representatives of a number of departments are co-located and serve under a district officer, helps co-ordination at the local level. District officers also have a systematic and regular method of communication with village headmen. At the regional level (the north) departmental activities require hierarchical (and mostly 'top-down') communication between local officials and their Bangkok offices, which inhibits lateral inter-departmental communication except where special projects or committees are formed. Even staff in different divisions of the same department may not have close communication, since authority devolves from Bangkok. Despite constraints inherent in the structure of government, there is nevertheless a good base for integrating government agencies' aims in the highlands, where policies and strategies to deter opium production, ensure national security and protect the environment, all through agricultural and social development, are already well-integrated. Specific development projects such as Sam Mun and the Thai–German Highland Development Project, and the initiatives of the Royal Project Foundation, have contributed markedly to integration.

Practice in communication with local people varies a great deal both within and between Thai Government departments, with much depending on the character and inclinations of the local staff. Communication issues go far beyond willingness to talk and listen: they may involve quite fundamental differences in assumptions. For instance, the adoption of government agricultural advice has often foundered because of prescriptions which run counter to indigenous and local knowledge guiding conservation and agricultural management practices, or reliance on inputs which the people cannot afford. Although the formal system of government remains 'top-down', there are numerous examples of participatory land-development projects in which government departments have encouraged local inputs and initiatives. Meanwhile, the policy environment has recently become much more conducive to participatory approaches in resource management, with the new constitution, the Eighth National Plan, and a proposed Community Forestry Bill all mandating greater community or local-government participation in (or responsibility for) resource management. These provide an imperative to change communication processes between government and other stakeholders, opening up future potential for institutional arrangements.

Stakeholder participation

There is a general convention in Western approaches to stakeholder participation that stakeholders should be invited to participate in any planning or management process on an 'equal' basis, which is usually interpreted to include contacting them at the same time and involving them to the same degree. Our project evolved differently, with sequential incorporation of government stakeholders, which continued throughout the life of the project. By the end of the project, all key government departments, and two Thai universities were directly or indirectly involved. Some departments took an active role in the project while others seemed more content to simply stay informed through attendance at meetings and workshops. We found this to be a useful approach to increasing the adoption and utility of the DSS.

In most cases, people needed to see a prototype of the application to understand the concepts and power behind an IA approach before they felt comfortable in committing time and resources to the project. At this point they were also often in a better position to advise on the ways in which the current framework and structure did not meet their needs and to help develop the approach to overcome these problems. Staged involvement and continued development of the IWRAM approach allowed for a compromise between early inclusion, to ensure adoption and a broad system perspective, and allowing for enough development to take place for stakeholders to grasp the potential of the approach for their management problem before committing to the project.

An important factor in the success of the project, and the active involvement of the various government departments, was the coordinating role of the Thai project manager (or national coordinator) who was based within the Royal Project Foundation. This appears to have been far more preferable to having the project officer based within one of the government departments (which might have caused a bias in priorities or alienated other departments) or a project officer based in Australia. This person has a good understanding of how the government departments and hierarchy operates, and valuable knowledge of how to make things happen.

It was also important to involve and consult regularly with high-level government decision-makers in project strategic issues, so that they could reflect on project progress and outcomes. High-level decision-makers also have the influence to make things happen! Involvement of key decision-makers throughout the project life can also provide good guidance and resolve issues before they become problems.

Although some communication and coordination problems still occurred, the project facilitated an increased level of communication and understanding between officers from different government departments and also opened up links with Australian and Thai universities.

Adapting to limits on resources and finances

In 1997, many countries in Southeast Asia, including Thailand, suffered a financial crisis. This had impacts on the availability of both staff and resources from Thailand's government departments during the first few years of the project, causing some delays in progress. During this crisis, the project lost some of its key research people, while other members of the Thai team continued to assist the project, but were forced to work in their own time. These problems reinforced our view that participatory processes must be attuned to the current issues or constraints being faced by departmental staff, and the time and resources they have available. These management issues have provided a useful 'reality check' and remind us that IA must expect and adapt to such limitations.

Communication is time-consuming but essential

The communication required within the research team and between researchers and stakeholders is extremely time- and energy-consuming. A significant component of any IA project is communication between these groups. This becomes even more important when team members are spread across universities and government departments of two countries with different cultural and professional outlooks.

Capacity-building and collaboration take a long time but are ultimately worth the investment. They can ensure that ideas and methods are taken up in the long term and can also develop long-term relationships for cooperation. Without this, the ideas and frameworks will not be adopted and will almost certainly collapse when the project finishes. They also ensure that methods and understanding are able to evolve over the life of the project. A project that claims to be participatory but that does not allow appropriate time and resources for building trust between the different team members and stakeholders, risks alienating, as well as disenfranchising, some members, and making future management efforts more difficult.

The value of study tours

Study tours (or field trips) proved very effective in generating dialogue within the project team. The study tours allowed all participants to gain first-hand experience of issues related to land use, water resources, agriculture and the livelihoods of the local people. Study tours should be planned well in advance and should visit typical farms at a number of different sites within the catchment. Ideally, study tours should also occur at different times of the year, for instance the wet and dry seasons, when conditions might be quite different.

Case studies are essential

Case studies were found to be a very efficient way of testing both the integrated framework and the models (both biophysical and socio-economic) and ensuring that the models were practical and useable. They also highlighted practical issues such as the availability of field data, the complexity of the biophysical landscape, and the difficulties of obtaining good socioeconomic data. Case studies were also used as a basic approach to capacity-building, i.e. training should deal with reality, not theoretical situations.

Adoption of DSS and software

The end users needed to be directly involved with software development so that they had ownership. Without this involvement and a strong sense of ownership, there is a much lower chance of long-term adoption. Ownership can also be enhanced through the use of local case studies, and by conducting training workshops.

Project life

A three-year project was found to be too short to meet the overall objectives and successfully develop the IWRAM approach in partnership in a new region or country. Project development, and the development of communication and trust, both take time. The project inevitably hits hurdles and must adapt to new circumstances. This all takes time. These types of projects tend to evolve as they progress. A project life of 5–6 years increases the chances of adoption and application of the IWRAM approach.

Our final advice: Give it a go! Be prepared to make mistakes and learn from them.

Future of the Integrated Water Resources Assessment and Management approach in Thailand and surrounding countries

Further training and adoption

The IWRAM approach to date has been focused firstly on establishing a framework for integrated water-resources assessment in Thailand, on integrating the modules into the DSS, and on verification of both the models and the DSS. Emphasis may now be given to making use of the DSS toolkit routine, institutional strengthening and adoption through further training, which are all likely to occur through the need to apply it to other catchments. Inevitably, as with any emerging technology, there will be teething troubles to be addressed and the need to add or modify components to ensure that the integrated package continues to meet the needs of the users.

The project team has supported capacity-building within Thailand, so that the IWRAM approach can be implemented and extended throughout the country. The future of the IWRAM approach, both in Thailand and in surrounding countries, will include the following developments:

(1) The Thai team has re-implemented the underlying models to suit the level of expertise available within government departments and agencies. The models will continue to be refined and calibrated using new field data.

(2) The Thai team is actively engaged in extension of IWRAM to the rest of Thailand and neighbouring regions through national research projects, with support from the Australian team.

(3) Customisation and implementation of the DSS to different agricultural, water regulation, social and vegetation systems is being undertaken.

(4) New modules are being developed to address other issues such as water storage and allocation, water quality, groundwater systems, in-stream habitat quality, other sources of erosion such as landslips and from roads, sediment transport, and incorporation of ecological indicators.

(5) Links between GIS spatial data and the DSS modules are being improved.

(6) Development of the IWRAM website as a communications tool for team members and the public is being continued. This provides updates on progress and links to other users or sites and ongoing technical support.

(7) There is continuing development of reference materials and training manuals.

The Royal Project Foundation will remain the co-ordinating agency in Thailand and a 'users group' comprising the Royal Forestry Department, the Land Development Department, the Royal Irrigation Department, the Department of Agriculture and the Office of National Water Resources Committee will be the priority client group.

The building of an integrated approach to water-resources assessment has necessarily drawn together researchers and practitioners from many disciplines and agencies, and has aligned well with a national initiative to implement integrated catchment management.

The project has provided for strong linkages to be built between government departments responsible for natural-resource management and socioeconomic research being undertaken in universities.

As in all countries, planning is nothing without adoption. Farmers are the principal custodians of land in most countries. It is difficult to convince them to adopt sustainable management practices when they are desperately striving to provide food and an income stream for their families. Planning for sustainable water management must therefore consider not only environmental outcomes and constraints but also local capacity to bring about change and poverty alleviation. In many cases, win–win situations may be available that both increase quality of life and are sustainable. Local capacity may need to be developed to identify and enable these types of changes.

The future of integrated water resources management

As the research effort builds in the field of integrated water resources management (IWRM), old challenges are replaced with new ones. Much relevant research is currently under way, among other things, in terms of developing integrated frameworks, modelling techniques, software platforms and tools, and creating productive links between science, management and the general public. There are, however, some pressing issues that need to be addressed. A discussion of these follows.

New modelling tools for integrated water resources management

Decision-support systems can be a useful ally in connecting the interface between science and policy. Such tools must find the correct balance between the need for simplicity and ease-of-use for stakeholders on the one hand, and the implementation of rigorous scientific approaches on the other. Certainly, transparency of DSS, where model limitations and assumptions are clearly acknowledged, is essential if trust, engagement and final agreement and adoption of recommendations are to be realised. Moreover, in the future, developers of DSS should be less focused on developing 'one-off' visualisation and interface tools for specific applications, and more focused on extracting generic features that are common to many applications. As far as possible, development of DSS should be an investment in learning what is frequently useful, not in generating software that has little capacity for re-use.

Quality assurance and uncertainty management for credible models and data

To enhance the credibility and utility of scientific approaches, quality assurance must become mainstream. Quality assurance relates to the development of standards and protocols for model and data reporting and distribution—see, for example, Rykiel (1995) and STARS (2004). These standards and protocols are required because environmental and natural-resource data and models are used to make management decisions, but they often have very large uncertainties or underlying assumptions associated with them (e.g. Anderson and Bates 2001). In order to ensure models and data are used in an appropriate way, and that decision-makers have access to information about the limitations of these models and data-sets, reporting standards for model testing, assumptions, appropriate scales and inherent uncertainties must be developed and used. The new models should devote special attention to the management and communication of uncertainty. Although some standard procedures for quantifying uncertainties in model outputs are available (e.g. Heuvelink 1998), these have not yet been implemented in modelling tools that are used for decision-making, although some first steps have been taken (e.g. HarmoniRib 2004; Karssenberg and de Jong 2005).

The key message is that model credibility can be enhanced by a serious two-way modeller–manager dialogue, appropriately rigorous model-evaluation tests, sensitivity and uncertainty assessments, and peer reviews of models at their various stages of development (Refsgaard et al. 2005).

Integrating disciplines and knowledge

It is a fundamental challenge that IA calls for a new breed of researchers who are much more interdisciplinary and interested in spending much of their time understanding other points of view and communicating widely. Typically, paradigms and methods are different between the biophysical sciences, economics and the social sciences. Ways must therefore be found to encourage scientists to be more open-minded towards a broader range of knowledge from different disciplines and stakeholders, while continuing to maintain proper critical standards.

There is also a clear need for the disciplinary focuses of scientists to be sharpened by management questions. This is a serious but simpler challenge that implies closer and more continuous dialogue between discipline specialists and their clients in natural-resource management, so that the nature and scale of disciplinary enquiry is more relevant. The research community, as a result, should co-operate with decision-makers and jointly develop new application tools framed within the changing needs of the evolving policies.

Knowledge acquisition and knowledge generation for IWRM can be accelerated by more-systematic testing and comparison of theoretical approaches and methods in case studies. This can be facilitated by more-collaborative and strategic science, funded to bring groups together internationally and to execute comparative studies.

More research is needed to manage the wealth of heterogeneous information types (soft, hard, qualitative, quantitative, beliefs, knowledge, expert, non-expert) that is acquired and generated during the course of carrying out IWRM, involving as it does different disciplines, as well as scientists, practitioners and the broad public. Such research needs to include the development of better data-mining and navigation techniques for heterogeneous information retrieval to aid quick and efficient access to gathered information, the development of a common approach to quality assurance (see above) for these different information types, and the development of guidelines as to how and when different types should be used in decision-making.

Approaches supporting integrated water resources managements—adaptive management

Adaptive management (Holling 1978) and active adaptive management (e.g. Allan and Curtis 2003) are principles with the potential to improve our management of the environment through a process of continuous learning. In essence, adaptive management is about developing management-revision principles, experiment designs, outcome indicators, and monitoring practices to achieve sustainable management in evolving environments (e.g. STARS 2004). This must include the monitoring and evaluation of active and passive experiments to see what does and does not work and where there are gaps. Examples are improved tools to capture and express qualitative knowledge and approaches to screening and testing a broad range of alternative policies.

Public participation: methods, techniques and institutional setting

In terms of participatory methods, more effort needs to be placed on developing meaningful techniques for evaluating participatory processes. This is needed not only to provide evidence to scientists on whether or not their methods have been successful, but also to help improve participatory approaches in a rigorous way. Assessment of this nature is also useful in convincing future participants to take part in new processes or to keep current participants actively involved.

Simply introducing new regulations calling for public participation will not be enough. Experience has shown that participation does not always translate into meaningful new inputs into the traditional management decision-making process. Poor participatory methods are one cause of such problems but, crucially, unless there are transparent management procedures in place that can guarantee and illustrate that the inputs from public participation are influencing actual decision-making, then both decision-makers and citizens may end up perceiving public participation simply as a new form of bureaucratic burden without real benefits for the community (Mostert, in press{?not listed}).

Integrated water resources management by doing

We conclude by saying that we have no doubt that good progress is being made in the science of IWRM. There is a basic understanding and acceptance of the challenges. As this book shows, the scientific community has been developing many useful methods and models for achieving more sustainable outcomes. There is, however, a general need to accelerate the development of integration methods by learning from practical applications and sharing these experiences widely. Only by doing and showing, will we handle the complexity and difficulties of integration.

Conclusions

For the researchers involved with this project, the major impact has been the development of new skills and tools that can play a pivotal role in regional sustainability.

Within the natural-resource management sphere, the major impact has been at the 'middle' level, i.e. agency professionals. This group is crucial in convincing policy-makers to legislate for, and farmers to implement, sustainable land use and natural-resources management. The researchers play a key role in informing extension officers on the suitability of crops and management practices.

A major aim of the Royal Project Foundation through the activities of this project has been to identify crops and cropping practices that raise the standard of living for local farmers, especially hill tribes, while conserving the environment and anticipating future demands on water supply. The extensive catchment activities associated with the project (field trips, surveys) have provided strong positive signals to the local communities that they are valued by the Royal Project Foundation and the government.

At the regional scale, the development of expertise in whole-of-catchment assessment, using a range of social, economic and biophysical indicators, gives the Thai team the ability to play a key role in the region in the development of bilateral and trans-boundary water- and land-management issues. They intend to use this expertise to work with their regional neighbours to develop sustainable use of their watersheds.

The impact of the IWRAM project cannot be judged in the short term. In the complex world of integrated water-resource management, it provides a robust framework to consider and incorporate economic, social and biophysical condition and values within national and regional planning and management agendas. Adoption of the IWRAM approach has occurred at a high level in government departments and they are now incorporating the principles into routine practices within their agencies. This will ultimately see the IWRAM approach extended throughout Thailand.

At the national level, the project has indeed been influential. The IWRAM approach has been adopted as the framework for a major initiative of the National Research Council, which will see Thailand work with neighbouring countries in the greater Mekong sub-region to implement IWRAM.

Through the project, the Royal Project Foundation has played a key facilitation role in focusing government-agency support in the northern catchments. There has been a significant investment by the foundation and government agencies in understanding the environmental, social and economic impact of changes in water use and management practices in the catchment, with the key word being 'sustainable.' This is strong emphasis on ensuring economic return to the local farmers in exchange for modifying agricultural practices.

The impact of the project is very evident in the continued partnership and collegiate nature of relationships within and between the Thai and Australian members of the project team. The impact and influence of goodwill and mutual respect cannot be underestimated.

At the local scale, the development of the IWRAM DSS means that researchers will be providing extension officers and farmers with farming 'solutions' that are better for the environment without compromising economic return.

We draw the following specific conclusions:

- Analysis frameworks for characterising integration problems have come of age, but there is still much that is problem-specific: scales, models and their linkages vary. However, it is mainly by continuing to perform IA on specific problems that this emergent discipline will fully mature.
- Enhanced credibility and utility of IA for decision-makers necessitates more-comprehensive model testing and, in particular, the development and application of methods of uncertainty characterisation. For complex, data-deficient systems of the type that occur in IA problems, this is a challenge that must be met.
- Data availability is a severe constraint for obtaining more-informed and confident decision-support. Increased confidence in outputs of IA exercises begs for high leverage measurements, on the nature of which modelling itself can provide guidance. Typically, more measurement information is required about system behaviour, such as fluxes of water and pollutants, as well as key information on social and economic systems within catchments.
- Further core disciplinary research is required which targets the questions that need to be answered by researchers in IA. For example, in socioeconomic models, how to incorporate aspirations and capacity for change; and in biophysical models, how to make flow prediction in ungauged catchments.
- Software platforms that facilitate the IA process are being developed but more work and technical support of products are required. Platforms that integrate spatial data with modelling and facilitate model re-use and integration are a priority.
- Above all, IA, and the associated construction of information systems, constitutes an adaptive process that incorporates many dimensions and stakeholders. The assessment process itself requires a high level of validation and testing to ensure that the assumptions, simplifications and assessment framework provide a true and

equitable representation of the system being assessed. Adaptive management also encourages researchers and managers to continually refine their assessment tools by learning from their experiences.

We see several ways to achieve greater progress in future assessment of sustainability outcomes. Some lie predominantly in the hands of politicians and policy advisors, others with the scientists and social scientists. To avoid policy compartmentalisation and instil system learning, the processes of adaptive management (Holling 1978) and active adaptive management (e.g. Allan and Curtis 2003) of our 'environment' must be institutionalised and adopted across all relevant sectors. This must include the monitoring and evaluation of active and passive experiments to see what does and doesn't work and where there are gaps. Systematic representation of our knowledge and how it changes and accrues is vital to ensure that we have a platform on which to build and test. IA and modelling in general have a role here. One of the challenges is not to disenfranchise catchment communities, and perhaps politicians also, by increasing the uncertainty in their eyes through unsystematic representation of accrued knowledge.

Given the complexities and uncertainties of integrated modelling, it should be accepted that its broad objective is to increase understanding of the directions and magnitudes of change under different options. Typically, it cannot be about accepting or treating simulation outputs as accurate predictions. A key advance required is for IA modelling to allow differentiation between outcomes, at least with qualitative confidence; for example, a particular set of outcomes or indicator values might be categorised as overall better than, worse than or no different from another set (for instance a do-nothing, current situation) with high, reasonable or low confidence. This is enough to facilitate a decision as to the worth of adopting a policy or controllable change. IA must be able to differentiate between policies and specify what knowledge or data will provide leverage to improve the differentiation. Ideally, predictions would be produced with a quantitative confidence level but in most situations this is impracticable at present. Currently, methods for quantifying uncertainties have limitations; Norton et al. (2003) and Jakeman and Letcher (2003) discuss new research required to address this glaring deficiency.

We know some of the important information that needs to be gathered to progress the management of sustainability through IA. The social sciences can offer insight and information into decision-making and adoption processes previously ignored in many scenario-based models. In particular, social survey data linking information about decision-making and adoption to biophysical and socioeconomic characteristics of farmers, industries or households is key to developing more sophisticated IA and other policy analyses. Very little of this type of data exists for most catchment situations. In addition, biophysical scientists are often not in a position to extract and understand the implications of such data. Further use and development of participatory methods (e.g. Haslam et al. 2003) for model-building is one way of extracting and using such information. These techniques have the bonus of allowing stakeholders inside the model-development phase, to ensure they have a better understanding of, and opportunity to feed into, the assumptions underlying these types of models.

IA takes time. This needs to be recognised by all parties involved in sustainability and related projects. The time scales necessary for

IA to take place mean that the nature of the management problem and stakeholders views will change throughout the life of the project. Problem definition needs to be sharp enough to allow for useful interaction between researchers and stakeholders, but also flexible enough for the tools and understanding being developed to be useful at the end of the IA project. While success of IA projects will breed interest from decision-makers, the latter group needs to allow sufficient time for assessments and policy implementation, thereby reducing the current piecemeal approach to sustainability.

While improved sustainability is a principal aim of any IA project, it is important to recognise that the most useful outcome may be in the learning experience of researchers and stakeholder groups. In other words, it may be over-optimistic to assume that any single research project will, on its own, greatly improve the sustainability of the system. We argue that in many cases the concept of sustainability is not fixed and that improved understanding of the integrated nature of sustainability attained by participants in the project is also an outcome worth achieving.

References

Allan, C. and Curtis, A. 2003. Learning to implement adaptive management. Natural Resource Management, 6, 23–28.

Anderson, M.G. and Bates, P.D., ed. 2001. Model validation: perspectives in hydrological science. Chichester, UK, John Wiley & Sons Ltd.

Batchelor, C., Cain, J., Farquharson, F. and Roberts, J. 1998. Improving water utilization from a catchment perspective. International Water Management Institute, SWIM Paper 4.

Easterling, W.E. 1996. Spatial resolution of crop models in the estimation of regional agroecological effects of climate change: how fine is fine enough? In: Proceedings of 3rd International Conference on Integrating GIS and Environmental Modelling, Santa Fe, New Mexico, 263–273.

HarmoniRib 2004. Info at <http://www.harmonirib.com/>.

Haslam, S.A., Eggins, R.A. and Reynolds, K.J. 2003. The ASPIRe model: actualising social and personal identity resources to enhance organisational outcomes. Journal of Occupational and Organisational Psychology, 76, 83–113.

Heuvelink, G.B.M. 1998. Error propagation in environmental modeling with GIS. London, Taylor & Francis.

Holling, C.S., ed. 1978. Adaptive environmental management and assessment. Chichester, UK, John Wiley & Sons Ltd.

Jakeman, A.J. and Hornberger, G.M. 1993. How much complexity is warranted in a rainfall–runoff model? Water Resources Research, 29, 2637–2649.

Jakeman, A.J. and Letcher, R.A. 2003. Integrated assessment and modelling: features, principles and examples for catchment management. Environmental Modelling and Software, 18, 491–501.

Karssenberg, D. and de Jong, K. 2005. Dynamic environmental modelling in GIS: 2. Error propagation modelling. International Journal of Geographical Information Science, in press.

Kokkonen, T.S. and Jakeman, A.J. 2001. A comparison of metric and conceptual approaches in rainfall–runoff modeling and its implications. Water Resources Research, 37, 2345–2352.

Lee, K.N. 1999. Appraising adaptive management. Conservation Ecology 3(2), 3. Online at <http://www.consecol.org/vol3/iss2/art3/>.

Loague, K. and Freeze, R. 1985. A comparison of rainfall–runoff modelling techniques on small upland catchments. Water Resources Research, 21, 229–248.

Norton, J.P., Nathan, R., Podger, G. and Vertessy, R. 2003. Sensitivity assessment needs of complex simulation models for integrated catchment management. In: Post, D.A., ed., Proceedings modelling and simulation society of Australia and New Zealand (MODSIM 2003), 4, 1667–1672.

Parson, E.A. 1996. Three dilemmas in the integrated assessment of climate change. Climatic Change, 34, 315–326.

Perrin, C., Michel, C. and Andreassian, V. 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. Journal of Hydrology, 242, 275–301.

Refsgaard, J.C., Henriksen, H.J., Harrar, W.G., Scholten, H. and Kassahun, A. 2005. Quality assurance in model based water management — review of existing practice and outline of new approaches. Environmental Modelling and Software, in press.

Rykiel, E.J. 1996. Testing ecological models: the meaning of validation. Ecological Modelling, 90, 229–244.

STARS 2004. Network for Sustainable Terrestrial, Aquifer and Riverine Systems. Information at <http://stars.net.au>.

Wooldridge, S., Kalma, J. and Kuczera, G. 2001. Parameterisation of a simple semi-distributed model for assessing the impact of land-use on hydrologic response. Journal of Hydrology, 254, 16–32.