Environmental Modelling & Software 17 (2002) 209–217

Environmental Modelling & Software

www.elsevier.com/locate/envsoft

Progress in integrated assessment and modelling[1]

P. Parker [a,*], R. Letcher [b], A. Jakeman [b], M.B. Beck [c], G. Harris [d], R.M. Argent [e], M. Hare [f], C. Pahl-Wostl [f], A. Voinov [g], M. Janssen [h], P. Sullivan [i], M. Scoccimarro [j], A. Friend [k], M. Sonnenshein [l], D. Barker [m], L. Matejicek [n], D. Odulaja [o], P. Deadman [a], K. Lim [a], G. Larocque [p], P. Tarikhi [q], C. Fletcher [r], A. Put [s], T. Maxwell [t], A. Charles [u], H. Breeze [r], N. Nakatani [v], S. Mudgal [w], W. Naito [x], O. Osidele [c], I. Eriksson [y], U. Kautsky [z], E. Kautsky [aa], B. Naeslund [ab], L. Kumblad [ab], R. Park [ac], S. Maltagliati [ad], P. Girardin [ae], A. Rizzoli [af], D. Mauriello [ag], R. Hoch [ah], D. Pelletier [ai], J. Reilly [aj], R. Olafsdottir [ak], S. Bin [al]

[a] *Faculty of Environmental Studies, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1*
[b] *Centre for Resource and Environmental Studies, The Australian National University, Australia*
[c] *Warnell School of Forest Resources, University of Georgia, USA*
[d] *CSIRO Land and Water, Australia*
[e] *Centre for Environmental Applied Hydrology, University of Melbourne, Australia*
[f] *Swiss Federal Institute of Environmental Science & Technology, Switzerland*
[g] *Institute for Ecological Economics, Center for Environmental Science, University of Maryland, USA*
[h] *Free University, The Netherlands*
[i] *Department of Applied Mathematics, The University of Western Ontario, Canada*
[j] *Integrated Catchment Assessment and Management Centre, The Australian National University, Australia*
[k] *School of Community and Regional Planning, Canada*
[l] *University of Oldenburg, Germany*
[m] *Geostructures Consulting, United Kingdom*
[n] *Institute for Environmental Studies, Charles University, Czech Republic*
[o] *International Centre of Insect Physiology and Ecology, Kenya*
[p] *Natural Resources Canada, Canada*
[q] *Iranian Remote Sensing Center, Iran*
[r] *Gorsebrook Research Institute, Saint Mary's University, Canada*
[s] *Department of Biology, The Chinese University of Hong Kong, China*
[t] *University of Maryland, USA*
[u] *Management Science/Environmental Science, Saint Mary's University, Canada*
[v] *Osaka Prefecture University, Japan*
[w] *INERIS, France*
[x] *Yokohama National University, Japan*
[y] *Institute of Agricultural Engineering, Swedish University Of Agricultural Sciences (SLU), Sweden*
[z] *Swedish Nuclear Fuel and Waste Management Co., Sweden*
[aa] *Institute of Environmental Science and Technology, Yokohama National University, Japan*
[ab] *Department of Systems Ecology, Stockholm University, Sweden*
[ac] *Eco Modeling, USA*
[ad] *Department of Energetics "Sergio Stecco", University of Florence, Italy*
[ae] *INRA, Equipe Agriculture et Environment, France*
[af] *Instituto Dalle Molle di Studi sull'Intelligenza Artificiale (IDSIA), Switzerland*
[ag] *US Environmental Pizot Ag., USA*
[ah] *University of Kassel, Germany*
[ai] *Laboratoire MAERHA, IFREMER, France*
[aj] *New Jersey Office of State Planning, USA*
[ak] *Department of Physical Geography, Lund University, Sweden*
[al] *Department of Engineering and Public Policy, Carnegie Mellon University, USA*

Received 1 December 2000; received in revised form 23 March 2001; accepted 25 May 2001

PII: S1364-8152(01)00059-7

Abstract

Environmental processes have been modelled for decades. However, the need for integrated assessment and modeling (IAM) has grown as the extent and severity of environmental problems in the 21st Century worsens. The scale of IAM is not restricted to the global level as in climate change models, but includes local and regional models of environmental problems. This paper discusses various definitions of IAM and identifies five different types of integration that are needed for the effective solution of environmental problems. The future is then depicted in the form of two brief scenarios: one optimistic and one pessimistic. The current state of IAM is then briefly reviewed. The issues of complexity and validation in IAM are recognised as more complex than in traditional disciplinary approaches. Communication is identified as a central issue both internally among team members and externally with decision-makers, stakeholders and other scientists. Finally it is concluded that the process of integrated assessment and modelling is considered as important as the product for any particular project. By learning to work together and recognise the contribution of all team members and participants, it is believed that we will have a strong scientific and social basis to address the environmental problems of the 21st Century.

Keywords: Integrated assessment and modelling; Integration; Communication; Multi-disciplinary teams

1. Introduction

The modelling of environmental processes has been undertaken for decades (e.g. Jakeman et al., 1993), but the need for integrated assessment and modeling (IAM) has heightened as the extent and severity of environmental problems in the 21st Century worsens. The scale of IAM is not restricted to the global level as in climate change models, but includes local and regional models of environmental problems. Recognised in new IAM approaches, the earlier forms of systems modeling are being replaced with new integrated models that incorporate human components that facilitate scenario generation and decision support functions. This paper presents the deliberations of forty-five scientists from Africa, Asia, Australia, Europe and North America who are directly involved with and concerned about the direction of environmental research in the future. Their shared vision and advice for future directions in research, application development and communication in IAM are offered to encourage progress in the development of tools to help address future environmental problems. However, consensus was not reached on all points in this discussion and the paper also identifies points where opinions differed and debates are expected to continue.

The paper first discusses various definitions of IAM and identifies five different types of integration that are needed for the effective solution of environmental problems. The future is then depicted in the form of two brief scenarios: one optimistic and one pessimistic. The current state of IAM is then briefly reviewed. The issues of complexity and validation in IAM are recognised as more complex than in traditional disciplinary approaches. Communication is identified as a central issue both internally among team members and externally with decision-makers, stakeholders and other scientists. Links with other research groups are recognised and points of shared interest identified. Finally it is concluded that the process of integrated assessment and modelling is considered as important as the product for any particular project. By learning to work together and recognise the contribution of all team members and participants, it is believed that we will have a strong scientific and social basis to address the environmental problems of the 21st Century.

2. Integration

Given the wide acceptance of the need for an integrated approach to environmental assessment and modelling, as well as to environmental management more generally, it may be somewhat surprising that there is no generally agreed upon definition of what constitutes integration, or more specifically what is IAM. Risbey et al., 1996 state that the linking of mathematical representations of different components of natural and social systems in a computer simulation model is one way in which integration is undertaken. More broadly, a model is a simplification of reality. People think and communicate in terms of models. These may include:

—Data models that are representations of measurements and experiments;
—Qualitative, conceptual models as verbal or visual descriptions of systems and processes involved;
—Quantitative numeric models that are formalizations of the qualitative models;

* Corresponding author. Tel.: +1-519-888-4567; fax: +1-519-746-0658.
E-mail address: pparker@fes.uwaterloo.ca (P. Parker).

[1] A Summary of a workshop on Integrated Assessment and Modelling, held at EcoSummit 2000: Integrating the Sciences, Halifax, June 18–22, 2000. See Costanza and Jorgensen (2001) for a further report on Ecosummit.

—Mathematical methods and models used to analyze the numeric models and to interpret the results;
—Decision-making models that transform the values and knowledge into actions.

Within the IAM process we attempt to integrate these various models in a transparent and interactive framework that allows for the participation of stakeholders in all the stages of the process. This framework offers a means to integrate the individual models of stakeholders at a variety of scales and it organizes the stakeholders' community by helping them communicate understanding, values, and concerns. Most important is not a unique model implementation that is developed, but the ongoing process of integrated assessment. As Risbey et al., 1996 stress, IAM is more than just a model building exercise, it is also a "methodology that can be used for gaining insight over an array of environmental problems spanning a wide variety of spatial and temporal scales".

This view of the importance of the process of IAM rather than just the model building aspect is supported more generally. Rotmans and Van Asselt, 1996 provide a definition of IAM stating "Integrated Assessment is an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena". They stress the importance of integrated assessment models as frameworks to organise recent disciplinary research and note that the explicit purpose of IAM is to inform policy and to support decision making. They state that IAM, as an intuitively based process, is not new and conclude that the new element in IAM is the use of integrated frameworks such as conceptual frameworks or computer based simulation models. Finally they note the ideal state of IAM as an iterative process of investigation and recommendation, stressing the importance of communication not only of results from scientists to decision-maker, but also of lessons learned by decision-makers and the visions and views expressed by society, from stakeholders back to the scientist.

Margerum and Born, 1995 in their discussion of Integrated Environmental Management note that while integration is a goal that is often strived for, in practice it is never truly achieved. This is an important observation for IAM, in that while the ideal of IAM may be difficult or even impossible to achieve, focusing on the process of IAM allows important lessons to be learnt. In many ways it is the process, rather than the outcome, which is of paramount importance in IAM.

To meet the need for integration or integrated scientific studies to address environmental issues, the various definitions of integration used by authors should be incorporated in a multi-dimensional form of IAM. The term 'integrated' has been used by different authors as describing various forms of integration, such as linking models with GIS (Geographic Information Systems), integrating software, or even stakeholder participation in the IAM process. At least five different types of integration can be identified within IAM. These integration types are illustrated in Fig. 1. Issues are the centrepoint of integration as IAM seeks to avoid the fragmented approach traditionally adopted by science and recognises links between environmental issues and the need to include such interactions as part of the study. The integration of different issues is reinforced with the integration of multiple stakeholders as part of the research process. Conversely, models designed to depict processes at the local scale may not be appropriate to apply at a larger scale. Different disciplines may focus on different scales and this creates challenges for the integration of modules from these different sources.

The integration of different disciplines is required to gain insights into complex processes. Scale is important as IAM studies are often designed at one scale, yet decision-support is required at the local or catchment scale. Decision-support requires application development where the general scientific model is embedded in a 'user-friendly' application to meet the needs of decision-makers. The integration of models or linking of discrete modules is a common method adopted in IAM. Figure 1 shows that in IAM, a variety of *stakeholders*, *scales*, *disciplines* and *models* are integrated for the consideration of integrated environmental management issues. This is in many ways the ideal of IAM, whereas in practice one or more of these forms of integration may be ignored, often for good reason. In some cases, practitioners even argue about the necessity of models as a part of IAM, that is, about the role of non-model based integrated assessment. However, in its most comprehensive form IAM contains all five elements of integration.

More broadly, the term 'integrated' is often used interchangeably with similar terms in the environmental management literature. Downs et al., 1991 reviewed terms used when referring to Integrated River Basin Management. In particular, they found that four terms — comprehensive, integrated, ecosystem, and holistic — are

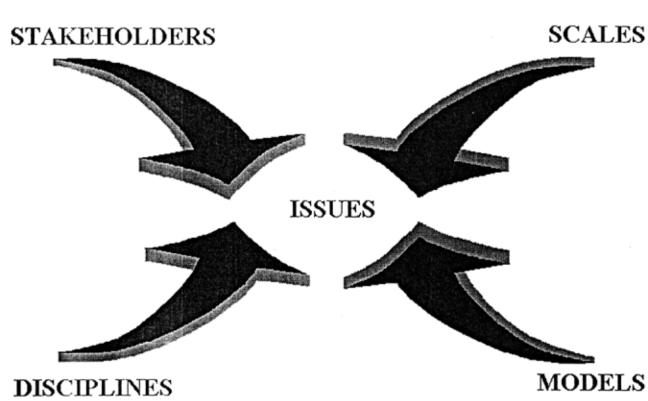

Fig. 1. Types of integration to address environmental issues.

used interchangeably to some extent, even though they have slightly different meanings. We accept the overlap in meanings of these terms and assert that IAM seeks to achieve multiple forms of integration in its approach to environmental issues.

3. Visions of the future

The use of IAM tools to solve environmental problems in the future could follow one of several paths. To illustrate the range in future possibilities, two brief scenarios are offered: the optimistic view and the pessimistic view.

3.1. Optimistic view

The optimistic view foresees new IAM tools being used to better manage the environment of our planet. The new tools successfully integrate insights from the natural and social sciences. The future 'knowledge-based' economy enables teams to use their brainpower to integrate models developed by scientist partners and to convert scientific models into practical application packages for use by the decision-maker partners. The results from the modelling and testing of alternate future scenarios are used to depict scenarios that extend beyond the recent range of experience to assist in the evaluation of more extreme events or frequencies and to develop appropriate environment and resource management policies. These results are effectively communicated to politicians, decision-makers, and community partners who then use the findings in their decisions about future actions. The overall pattern is one of integrated modelling, integrated application, integrated communication and integrated decision-making. The new underpinning to this integrated approach is an integrated scientific education where the insights and skills of single disciplines are not left in isolation, but are set within the broader context of other disciplines and processes that also influence the overall pattern. Environmental science, by being grounded in the complexity of real environmental problems, thus serves as the base for the development of a new integrated science education that incorporates rather than isolates core features. An enhanced environmental future is the expected outcome.

3.2. Pessimistic view

The pessimistic view foresees IAM tools failing to influence decision-making regarding the management of the Earth's environment. Fragmented, piece-meal, or single-purpose decisions prevail. The result is unintended consequences where harvest techniques reinforced with new technologies result in unsustainable harvests, population collapse and rapid ecosystem change. The cumulative impacts of many independent decisions also create environmental problems on a scale and magnitude that were not foreseen by the individual decision-maker. Following this pattern, major environmental catastrophes occur before society moves away from the dominant economic growth paradigm. Crisis-based reactions prove insufficient to address the complex problems that arise. In some cases, the species, ecosystem, or resource may be lost and consequently not be available for any form of assessment or management. The failure of the fragmented approach leads to the belated realization that an integrated response is needed. A shift is made to adopt an integrated approach, but valuable time has been lost and environmental problems worsened. The outcome is a recognised need for integrated approaches, but the environment has suffered increased damage and its natural capital has been eroded.

Some of the barriers to achieving the first scenario are built into our current global system and need to be addressed if the environmental damage of the second scenario is to be avoided. These barriers include:

—Separation between scientists in different disciplines
—Separation between scientists and application modelers
—Separation between application modelers and software interface designers
—Separation between scientists and decision-makers
—Separation between scientists and the community
—Fragmentation in education

In each case, integration is proposed as a means to overcome the separation and fragmentation. A core question is how to teach the next generation of scientists to avoid the current fragmentation. The need is recognised for multi-disciplinary tuition that focuses on collaboration and accepts responsibility for its vision of the future as value based. Dominant social values and welfare goals shape science so an open and honest approach is advocated to recognise these links. For example, by changing the social values, the objectives of environmental decision-making may change from maximum sustainable yield of species *x* to maintenance of species diversity in habitat *y*. The consensus opinion of the workshop participants is that an integrated approach is required to address environmental problems in the 21st Century. The uncertainty discussed is over the timing and priority placed on developing the required integrated tools. To set the context for future development of integrated models and assessment approaches, a brief review of the evolution of IAM is provided.

4. IAM current position: points of agreement

From our discussion we conclude that (IAM) in its current state has several distinctive features. IAM is currently a *problem-focused area of research*, with research often being *project-based*, and undertaken on a *demand-pull*, or *stakeholder needs* basis. IAM projects are generally undertaken to address specific sustainability or management issues, in contrast to previous systems modelling when research was often science driven and focused on providing complex systems descriptions and prescriptions for decision makers. IAM aims to be responsive to different groups of stakeholders, including client groups, government and policy makers, and community members and organisations. It combines the natural and social sciences to provide a broader view of the system and the impediments to better management and sustainability. It also seeks to enhance communication both between researchers and stakeholders, and among IAM participants.

We agree that the science behind IAM is often not new, rather the current state of IAM has been enabled by new technologies. In many ways IAM can be considered to be the combining of old areas of science and research to consider problems in new, more holistic ways. This more holistic approach to science raises additional problems, outside of those experienced in disciplinary research, which are the core issues requiring resolution and innovation in IAM research.

We consider that one of the main methodological problems in IAM is scale, and the resolution of different scales for different system components. Global system models differ greatly from local catchment models and creating links between models designed for different scales remains a major challenge. Even in catchment models, the boundaries and scale of hydrological aspects can be very different than the boundaries and scale of socio-economic aspects. Uncertainty and error estimation are also more challenging when modules based on different scales and different approaches are combined.

While there is no single way in which to perform IAM, the success of individual research efforts in IAM in the past has been dependent on a number of common features. Janssen and Goldworthy, 1996 discuss the importance of multidisciplinary research for natural resource management and the attributes of multidisciplinary teams and research efforts that are required for success. They emphasise the importance of the *teams developing their own sets of norms and values*, aside from norms and values which each team member experiences within their own discipline, and the need for individual team members to be prepared to respect contributions from other disciplines and to view their disciplinary ability as a contribution to a joint goal. They see the problem-solving orientation of multidisciplinary teams and their shared objectives as the foundation on which these norms and values may be established. They conclude that due to the difficulty in imposing rigid scientific norms on multidisciplinary teams, there is a need for multidisciplinary teams to establish their own standards of excellence, from very basic things such as presentation, to more complex details such as module integration and error estimation. While the ideal qualifications for team members have not been well documented, Janssen and Goldworthy, 1996 state that attitude, communication skills, education and experience are all important attributes.

Another important aspect of IAM, which often affects the success of the IAM process, is the way in which stakeholder participation is managed throughout the project. Margerum and Born, 1995, in their discussion of Integrated Environmental Management (IEM), note that for integration to be successful in IEM "provisions must be made to include the fullest range of participants who accurately reflect the set of concerns of the public". This statement is equally applicable to stakeholder participation in IAM. They conclude that IEM, and we would argue IAM, "requires participants to: take a more inclusive view that considers the scope of environmental and human systems; examine interconnections; identify common goals; and selectively identify the key elements on which to focus attention". Morgan and Dowlatabadi, 1996 describe a number of attributes, which they feel are the hallmarks of good integrated assessment. These include the characterisation and analysis of uncertainty as a central focus of assessments, the use of an iterative approach and the recognition and inclusion of parts of the problem about which there is little information, by using techniques such as expert opinion, where formal models are inappropriate.

5. Important features of IAM

5.1. Model complexity

It is hard to imagine succeeding with mere simplicity in the form of models developed and employed in integrated assessment, unless this is in the use of simple relationships, regressions for example, in one of the constituent knowledge domains (and where integrated assessment is being implemented largely without the use of models). We take it for granted, therefore, as the preceding discussion has shown, that all integrated assessments address complex situations, so that the IAMs developed for exploring such situations are necessarily complex, that is, they tend to be of a high order, with many state variables and dense interactions among those states. Furthermore, the goal of integrated assessment is not to enquire into the nature of complexity itself, in the popularly understood manner of the agenda of the Santa

Fe Institute in the early 1990s (Waldrop, 1992). Rather, in the process of integrated assessment we may assemble the constituent, disciplinary parts of the overall model according to what is thought to be appropriate to the problem at hand (along the lines of what has been called "demand-side" modeling). The goal is not to end up with a model as a finished product (transferable to many like situations elsewhere), but to adapt it within the process of integrated assessment, as a vehicle of problem exploration, for instance, or as a device for communicating the relevant science to a lay audience. The resulting complexity is a blend of the complexity of the constituent disciplines and the exigencies of the stakeholders hopes and fears for the future. For example, the investigation of the propagation of pathogens through a foodweb requires a greater degree of model complexity than the foodweb model itself, without even beginning to consider incorporating the simulation of human agency as it interacts with the environmental system. Complex interactions can generate counter-intuitive results and these need to be verified as valid before decision-makers are willing to initiate prescribed actions.

Scale issues are extremely important when describing processes and in some cases proper scaling may dramatically decrease complexity. The hierarchical/modular approach can be used so that the complexity in certain modules may not appear in higher hierarchical levels and thus simplify analysis and the interpretation of results.

So crucial issues are: can we comprehend what we have done with the model, sufficient to interpret its results in ways that will be understandable to the professional scientist and communicable to an audience of scientifically lay stakeholders; and how valid, or trustworthy, has the model been, as it has evolved throughout this process?

5.2. Validation

What constitutes validation of a model, without entering into what we now know is the vexed question of finding the right label for it (Oreskes, 1998), has arguably changed significantly in the past decade. At one time "history matching" and "peer review" were the two necessary and sufficient cornerstones of the process. But with the increasing difficulties of actually being able to match history and increasingly an absence of observed history to be matched (in part, because we move on to ever more extensive, more avowedly inter-disciplinary problems) has come a dissatisfaction with the sufficiency of these conventional cornerstones (Beck et al. 1997, 2000).

In lay terms, the following are the essential, contemporary questions one would like to have answered in seeking to evaluate a model:

(i) Has the model been constructed of approved materials, i.e., approved constituent hypotheses (in scientific terms)?
(ii) Does its behaviour approximate well that observed in respect of the real thing?
(iii) Does it work, i.e., does it fulfil its designated task, or serve its intended purpose?

We are familiar with peer review as the means of answering the first of these, and of matching history being directed at the second. The third question, of course, has always been vitally important, yet we have rarely been able to address it in a manner allowing us to discriminate between a process of model design, construction, and application deemed to be superior and another deemed inferior. Moreover, the purpose to which a model might be put may be quite varied, for instance, to provide:

(i) a succinctly encoded archive of contemporary knowledge for storage and retrieval;
(ii) a collation tool for allowing different sets of data to be viewed or examined together;
(iii) to help develop an understanding of the system being managed and the types of interactions that exist between, for example, the social, economic and biophysical sub-systems:
(iv) an instrument of prediction in support of decision making or policy formulation;
(v) a device for communicating scientific notions to and/or from a scientifically lay audience:
(vi) an exploratory vehicle for scenario building and the discovery of our ignorance.

The last pair of purposes (arguably of particular significance to integrated assessment) is notably not what one would normally expect of a model, at least not when considering how its design (and performance) should be evaluated. Significantly too, the terms embedded in these statements (archive, instrument, device, vehicle) evoke the image of the model as a tool, not a truth-generating theory, and thus prompt the insight of judging the trustworthiness of the model on such a basis, of whether the model is ill or well designed for its purpose (Beck et al., 2000).

Evaluating IAMs, therefore, is likely to be less dependent on the previous conventions of classical peer review and history matching, and more dependent upon protocols and tests yet to be developed. For they are distinctively defined as serving the needs ultimately of mostly lay stakeholders and, perhaps ever more frequently, of incorporating the human dimension of environmental problems within them. The constitution of a "peer group" can therefore be expected to be very different and more varied than just the former sub-groups of model builders and model users, steeped largely in the professional training and standards of science. While there may be scope for modest parts of evaluation by mono-disciplinary (scientific) peers, there will be few renaissance (wo)men capable of reviewing the whole and fewer still who will be able to claim no conflict of interest as the model evolves over possibly many years in the light of successive reviews by these few. And whereas, likewise, there may be scope for parts of the model to be evaluated against part histories, it is highly unlikely that a "whole history" will be available for evaluating the whole IAM, considered as a single computational complex (even if it were technically possible to match a model to such a whole history, which arguably is no longer feasible; Beck et al., 2000).

In short as apparent in Ravetz, 1997, the path towards a "good practice" of evaluating IAMs and of integrated assessment itself is likely to be one the community of persons engaged in IA will have to construct itself, and uncomfortably so, precisely because of this. Insofar as it is the process, not the final product of an integrated assessment, for which a code of good practice is required, so too may it be that a protocol of validation (or evaluation) is needed more for the evolving structure and content of an IAM, as opposed to the eventually finished product. The difficulty and discomfort of this challenge notwithstanding, we should be encouraged by the fact that we are today armed with a wider pallette of metaphors and analogs (quality assurance in the design and construction of tools; quality assurance in controlling procedures in an analytical laboratory; the legal process; and, as promoted by Ravetz, 1997, the discipline of historical analysis) with which to fashion a broader protocol for the conduct of evaluating IAMs.

5.3. Communication

Communication was agreed to be the critical factor in the success or failure of integrated studies. To achieve integrated environmental management, integrated modelling, integrated assessment, or integrated knowledge, communication is required. The need for iterative dialogue is recognised to both improve the exchange of information and to build the trust relations among partners. Communication among members of the scientific team is just as important (and challenging) as communication between modellers and stakeholders. Communication within the scientific community is required to advance the collective pool of knowledge as well as to encourage review and dialogue.

Different forms of communication may be required and used by different parties depending on the range of functions they are performing. For example, scientists may engage directly in the delivery of models to decision-makers or they may have software designers who specialise in interface design to undertake the design of the tool that enables decision-makers to use the scientist's model. When many tasks are separated and undertaken by different parties, communication is essential to ensure that the final product achieves the initial objectives without compromising the integrity of the model as a whole.

Communication tools may be designed to simplify complex models to simple indices or indicators that are easily understood by the general public and decision-makers. Graphic presentations may effectively summarise a large quantity of information. In each case decisions need to be made that are appropriate for communication with the audience (scientific, policy maker or general public).

5.4. Values in models

The different values represented by multiple stakeholder groups need to be recognised and explicitly included in models. Previous models often made allocations based on implicit value choices. In the future, the selection of values should be open and transparent. In this way, the effect of changing values can be seen in the allocation scenarios.

5.4.1. Points of continuing disagreement: cultural relativism

Although most voices called for an open and clear identification of the values incorporated in models, others argued that models are objective. The two views are articulated below:

> "All models have values throughout. The human dimension permeates everything. There is no pure science free of subjective opinions, we make choices about what we include and exclude."

> "The product of modelling is as culturally bound as other social products."

The counter argument was also voiced.

> "No! Cultural relativism is limited, the physical world has constants."

> "We build rational (objective) models to be viewed and evaluated by peers (scientists) and stakeholders (public, etc.)."

As well as concern over the challenge about value systems, concerns were also expressed about the conflict and debate over the numerical values attributed to particular variables.

"Now everything is challenged, even atmospheric dispersion coefficients are challenged."

To preserve the integrity of science, the focus should be on transparency to allow for criticisms of models, their selected variables and the values used. The accounting for environmental services and other features important to people should be made explicit. In this way honest endpoints can be generated which are key policy endpoints where sensitivities can be examined to explore scenarios and inform decision-makers. In this way decision-makers will have confidence in the models, knowing which parts are built on solid knowledge and which are dependent on particular values.

6. Future of IAM

The future of integrated assessment and modelling builds on the best elements from its past and adopts inclusive partnerships to address new environmental problems. The consensus among participating scientists is that models and the whole modelling process needs to be *open*, *honest* and *transparent*. Communication is an integral feature of the process at all stages. It is accepted that other people view the world differently. The development of a model starts with a storyline or preliminary model. Qualitative as well as quantitative elements should be included as an iterative approach is taken to enable the model to evolve with improved understanding of the system under investigation. Failure is recognised as an important part of the learning process that helps refine the model and move research in an agreed (the right) direction. In particular it was agreed that IAM requires a validation of processes and outcomes, rather than strictly of model outputs. It was seen that the first step in achieving this is the development of guidelines on methods and standards representing best practice in IAM.

New tools are needed to achieve integration, but the components required may change from one environmental problem to the next. Integrated models often include biophysical and socio-economic components and some have decision support functions. However, the biophysical component may itself integrate modules, e.g. physical hydrology modules with biological modules, while the socio-economic component integrates economic modules with psychological or sociological modules. The particular combination depends on the environmental problem being investigated: water allocations within a catchment, fisheries, forest functions, wetlands, nuclear waste storage, etc.

New challenges that need better representation include the issue of criticality and how to identify and represent thresholds where systems may flip from one state to an entirely different discontinuous state. The transfer of new models from physical systems to biological systems also poses particular challenges for future IAMs.

7. Conclusion

Integration is essential to address future environmental problems. Integration goes beyond IAM to include integrating the sciences, knowledge, and our understanding of the future. The old descriptive systems models are being replaced with integrated models that are designed to address particular management issues. The role of humans, both as decision-makers in management roles and as agents causing environmental change, has become an integral part of new models. The next challenge is to improve on the existing suite of modules by relating each one to broader ecological sustainability. The environmental problems of the 21st Century cannot be considered in isolation, but need to be set within the broader sustainability context.

IAM needs to focus on moving forward beyond single issues to improve broader ecological sustainability, to improve decision-making, to integrate insights from natural and social sciences, to seek validation of IAM processes, and to maintain integrity and rigor through openness, transparency and honesty in the processes used. Overall, there is a strong desire to work together as part of a team to address the environmental challenges ahead. An integrated approach, a participatory process, an interdisciplinary team, and a visible research program that is conducted with integrity and trust, are key ingredients that need to be combined in a framework where communication is continuous.

Integrating the sciences starts with an integrated problem. Environmental problems of the 21st century are public and non-exclusive. They affect the Earth's ecosystems and all inhabitants. Separating mediums, inputs, or vectors is inadequate. Integrated science also means generating integrated knowledge. We must invest time and ability to create a shared pool of knowledge and understanding. This result can only be achieved through integrated scientific efforts. To achieve an integrated future, instead of a fragmented disciplinary future, there is a call for integrated environmental science as its base. Rather than simply debate over the components of the curriculum, it is time to take action. The goal cannot be achieved unless we take integrated action. IAM is not limited to a particular model, but argues the importance of process. We seek to bring dispersed data and stakeholders together to gain improved understanding and enhanced environmental quality for future generations.

References

Beck, M.B., Chen, J., 2000. Assuring the quality of models designed for predictive tasks. In: Saltelli, A., Chan, K., Scott, E.M. (Eds.), Mathematical and Statistical Methods for Sensitivity Analysis. Wiley, Chichester, pp. 401–420.

Beck, M.B., Ravetz, J.R., Mulkey, L.A., Barnwell, T.O., 1997. On the problem of model validation for predictive exposure assessments. Stochastic Hydrology and Hydraulics 11 (3), 229–254.

Costanza. R. and Jorgensen, S.E. (Eds.), 2001. Understanding and Solving Environmental Problems in the 21st Century: Toward a New, Integrated "Hard Problem Science". Elsevier, Oxford.

Downs, P.W., Gregory, K.T., Brookes, A., 1991. How integrated is river basin management? Environmental Management 15 (3), 299–309.

Jakeman, A.J., Beck, M.B., McAleer, M.J. (Eds.), 1993. Modelling Change in Environmental Systems. Wiley, Chichester. Wiley Series on Principles and Techniques in the Environmental Sciences, 584pp. (Hardback). (Paperback version 1995).

Janssen, W., Goldworthy, P., 1996. Multidisciplinary research for natural resource management: conceptual and practical implications. Agricultural systems 51, 259–279.

Margerum, R.D., Born, S.M., 1995. Integrated environmental management: moving from theory to practice. Journal of Environmental Planning and Management 38 (3), 371–391.

Morgan, M.G., Dowlatabadi, H., 1996. Learning from integrated assessment of climate change. Climatic Change 34, 337–368.

Oreskes, N., 1998. Evaluation (not validation) of quantitative models for assessing the effects of environmental lead exposure. Environmental Health Perspectives 106 (6), 1453–1460.

Ravetz, J.R., 1997. Integrated Environmental Assessment Forum: Developing Guidelines for 'Good Practice', Working Paper WP-97-1, ULYSSES Programme, Darmstadt University of Technology, Germany.

Risbey, J., Kandlikar, M., Patwardhan, A., 1996. Assessing integrated assessments. Climatic Change 34, 369–395.

Rotmans, J., Van Asselt, M., 1996. Integrated assessment: growing child on its way to maturity. An editorial essay. Climatic Change 34, 327–336.

Waldrop, M.M., 1992. Complexity: the Emerging Science at the Edge of Order and Chaos. Touchstone, New York.